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Power Generation Using Simultaneous Capture of Solar Photovoltaic and Solar Thermal Energy

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ABSTRACT

This paper describes a research project that was conducted to determine if it is technically feasible to use the heat reflected from Photovoltaic (PV) solar panels to produce additional electrical power using Concentrating Solar Power (CSP) generators. The researchers reviewed the surface reflectivity characteristics of PV panels, considered whether various available coatings and reflective films could be used as wavelength dividers, and assessed common CSP generator designs to determine the potential for incorporating PV panels into concentrating mirror systems. A small-scale test device was constructed to explore the effects of coatings and films on the amount of electrical energy captured by PV panels. The lead author constructed an experimental collector using a heat-reflecting film to reflect thermal energy from a PV panel to a concentrating Sterling engine. Field tests were conducted to determine the amount of usable electrical and thermal energy collected. Finally, the data was used to estimate the potential effect on net energy that can be captured by incorporating PV panels into full scale CSP power generating facilities. This analysis determined that it is possible to gain a net increase in energy gathered by using a combined PV and CSP collection system.

INTRODUCTION

Solar energy reaching the Earth's surface is comprised of approximately 5% ultraviolet (UV), 42% visible, and 53% Infrared (IR) wavelengths (Chow, 2006). Commercially available Photo-Voltaic (PV) solar panels do not utilize the infrared portion of the solar spectrum. PV panels convert specific wavelengths to electricity efficiently, while other wavelengths are wasted, heating the panels unnecessarily. PV panels are negatively affected by temperature, so manufacturers use a variety of thermal management methods to reduce the effects of heat, including surface coatings and coverings which reflect IR. Heat-reflecting PV panels have the potential for use in a Concentrating Solar Power (CSP) system, while still utilizing the non-thermal portion of the solar spectrum.

The impetus for this study was a desire to determine whether a combined system that utilizes the thermal energy in the sun's spectrum, plus the PV energy in the visible and UV wavelengths, has the potential to significantly increase the net energy captured from the sun, compared to either PV or CSP alone.

Large CSP generating facilities may benefit by incorporating PV panels, utilizing selected portions of the solar spectrum directly. The Abengoa PS10 facility in Spain, for example, is able to convert an impressive 40% of the boiler heat into electricity, but this represents just 14% of the solar energy captured (Abengoa PS10 Project Final Report, 2006, p. 5).

Substituting PV panels, at 16% efficiency, for the heliostats at the PS-10 plant in Spain, and not using the steam turbine at all, would generate slightly more power than CSP alone, but are assumed to have been a more expensive option at the time. Economic considerations are likely to be the most important factors when considering different plant designs. Incorporating PV into a CSP plant design is worth investigating for its economic potential.

The use of PV panels with heat reflecting cover films was investigated for their potential to increase net energy output from a CSP plant. Surface characteristics of PV panels and heat-reflecting films were assessed for their potential use in the two most common CSP plant designs: heliostats/solar tower, and parabolic trough reflectors. Commercial PV panel manufacturers would not divulge proprietary surface treatments used, so part of the literature search focused on suggested surface treatments reported to be commonly used in the industry.

PURPOSE

The purpose for this study was to determine if it is technically feasible to use the heat reflected from PV panels to produce net additional electrical power when used in combination with CSP systems.

METHODOLOGY

The concept behind the field tests was to compare the usable amount of heat reflected onto a CSP from samples of heat-reflecting film to direct solar exposure. In addition, the output of a PV module, with and without a variety of heat reflecting film covers, was also measured.

A model Stirling Engine was used to represent a CSP (Figure 1). The Stirling Engine incorporated a parabolic dish concentrating reflector, which focused the energy onto the cylinder head. A thermocouple welded to the cylinder head was used to monitor the Cylinder Head Temperature (CHT). An equatorial mount with stepper-motor drive maintained orientation of the parabolic dish with the sun as it moved across the sky. The drive system allowed the dish position and tracking speed to be adjusted electronically. When properly adjusted, the focused sunlight formed a bright ring around the cylinder head. Test run data was gathered only after the dish tracking had stabilized.

FIGURE 1. TYPICAL FIELD TEST ARRANGEMENT, SHOWING THE SAMPLE REFLECTING FILM UNDER TEST, THE STIRLING ENGINE WITH ITS PARABOLIC CONCENTRATING DISH, AND THE TRACKING DRIVE.

The field tests were comprised of six elements:

1. Preliminary tests, to establish test equipment requirements.
2. Calibration of the test fixture, to establish the response of the Stirling Engine to varying amounts of solar energy.
3. Tracking system requirements, to establish how to maintain consistent solar input.
4. Heat-reflecting film tests, to gather data on energy reflection and transmission.
5. PV power tests, to gather data on the influence of heat-reflecting film when used to cover a PV panel.
6. Scattering Angle test, to determine the ability of heat-reflecting films to perform as heat-reflecting (heliostat) mirrors.

Limitations

1. Transmission losses and inverter conversion losses after energy generation were ignored.
2. Commercially-available reflective films were used, and the suppliers did not disclose proprietary information about the chemical composition of the film coatings or the design parameters for reflective properties. Therefore it was not possible to correlate performance with types of coatings or with design specifications.

Delimitations

1. This study was conducted at one geographic location and at a single time of year.
2. This study was conducted using three types of commercially-available reflective film.
3. Solar thermal energy was concentrated onto a Stirling engine using a parabolic dish concentrator. Other methods of thermal energy conversion and other types of concentrators were not used.
4. This study explored only the technical feasibility of simultaneously capturing solar PV and solar thermal energy. Economic feasibility of constructing new facilities and retrofitting existing facilities was not investigated.

Assumptions

1. Modifications to existing tracking systems, to accommodate a reflecting PV conversion, are assumed to be negligible, when analyzing large solar installations.
2. The Model Stirling motor is assumed to respond to direct and reflected solar energy in the same way that a full-scale CSP system would respond.
3. The Brunton 1-watt PV panel is assumed to respond the same as large-scale PV systems, in both direct sunlight, and when covered by heat-reflecting film.

Preliminary Tests

Preliminary tests were performed to insure that the test equipment was properly designed and configured, to insure that the test methods were properly specified, and to insure that the test methods could be applied consistently. For example these tests helped to determine which instrumentation to use, to verify that the tracking drive would maintain constant, accurate alignment with the sun, and to determine the best time of day to obtain nearly-constant test conditions. The preliminary tests also helped to determine a method for mounting the heat reflecting film so as to achieve sufficiently flat reflecting surfaces

Calibration Tests

Initial calibration runs compared the Stirling Engine speed to the amount of sunlight allowed directly into the parabolic dish. Additional runs compared the Cylinder Head Temperature (CHT) of the Stirling Engine, with and without the engine running, with respect to the amount of sunlight allowed into the dish. Opaque cardboard wedges were used for precise incremental shading of the dish, covering a range between zero and 60% opacity, as illustrated in Figure 2. Data from the calibration tests was used to generate a best-fit linear formula that correlated solar input to CHT. This calibration formula was then used to determine the amount of energy being reflected from a heat-reflecting film, relative to direct exposure to the sun.

FIGURE 2. STIRLING CONCENTRATOR, 60% BLOCKED

Tracking Requirements

The apparent motion of the sun is 15deg/hr across the sky. To allow sufficient time to take steady-state readings, an equatorially mounted tracking system was built to maintain focus of the sun on the cylinder head. The device is shown in Figure 3.

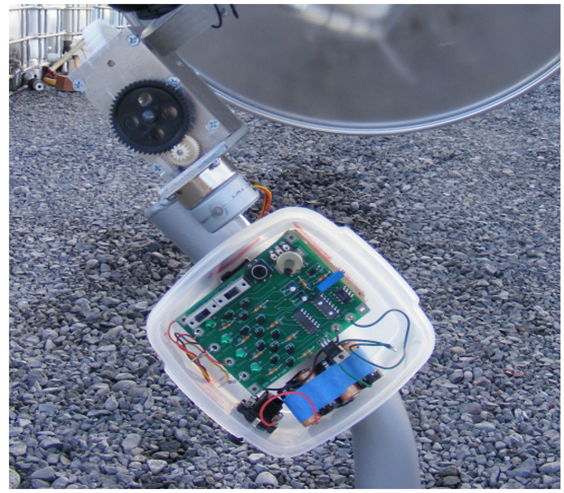


FIGURE 3. STIRLING ENGINE TRACKING DEVICE.

Heat Reflecting Film Tests

Three samples of heat reflecting film were tested. The first two were provided by Southwall Technologies of Palo Alto, CA (see southwalltechnologies.com). The third sample was unlabeled mirrored window shading film donated by a local school, which had the material left over from an old construction project. The type of material, its source, and its date of manufacture were unknown, although in appearance it resembles heavy-duty Mylar.

The Southwall samples were designed for use in modern window construction. The Southwall KIR 72-41 sample was designed to be sandwiched inside "low-E" windows, reflecting heat while allowing visible light to enter. The appearance is a perfectly transparent window with a slight green tint. The Southwall Solis-VK70 film sample was designed to be adhered to the interior surface of a glass window, but was otherwise identical to the KIR film in appearance.

PV Power Tests

The three samples of heat-reflecting film were tested for their influence on PV power output from a small solar panel. The tests were conducted with the film and PV panel at angles to the sun necessary for CHP heliostat function. A wooden frame was built to hold the plastic film samples during tests, as shown in Figure 4.

FIGURE 4. SOUTHWALL SOLIS-VK70 FILM TEST FRAME, NEXT TO PV PANEL

Scattering Angle Tests

Cylinder Head Temperatures (CHT) were recorded with the Stirling engine parabolic reflector located at two distances from the heat-reflecting film, and the difference in energy at the two locations was used to calculate the scattering angle caused by the reflecting surface. Prior to these tests, it was not known if the film reflected heat wavelengths, or scattered them. Details of this procedure are included in the appendix.

RESULTS

PV Test Results

As shown in Table 1, the "mirrored" film produced the greatest drop in PV output, to just 8% of direct sunlight power. The KIR film allowed 85% of normal power output, and the VK70 allowed 84% of normal power output when the PV panel was placed behind each film sample, compared to output in direct sunlight.

Calibration and Scattering Angle Test Results

Calibration and scattering angle test data are given in Table 2, and are plotted in Table 3. Calibration testing established a reliable relationship between CHT and the amount of solar energy reaching the parabolic reflector. Ambient temperature at the time of calibration testing was 90 °F, providing a "zero" point for calculating the best fit line (Table 3). The following linear-regression formula was generated by Excel, as shown in Equation 1.

$$\mathbf{Y}\ °F = 833.14 * \mathbf{X}\ °F + 90\ °F$$

Where **Y** = CHT and **X** = fraction of the baseline energy reading that entered the dish. The resulting R^2 value of 0.992 indicated a good fit of the line to the data points, so it was used to estimate the equivalent amount of energy received when the dish was pointed at the reflection from the film

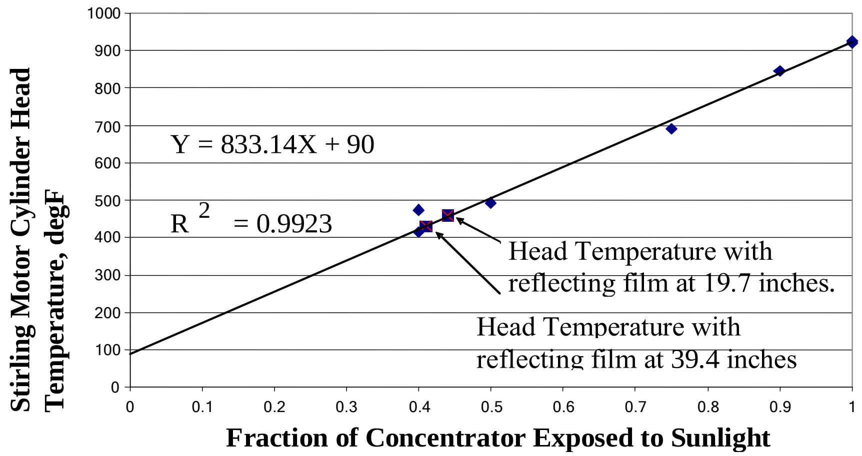
TABLE 1. *RESULTS OF THE PV AND HEAT REFLECTING FILM TESTS*

TIME	VOLTS	AMPS	WATTS	FRACTION OF BASELINE	COMMENT
11:20	11.93	0.079	0.942	BASELINE	NO FILM
11:21	10.89	0.073	0.794	0.843	VK70
11:38	3.59	0.02	0.072	0.076	"MIRRORED" FILM
11:51	12.01	0.067	0.805	0.854	KIR
11:54	11.99	0.079	0.947	1.005	NO FILM

TABLE 2. *CALIBRATION AND SCATTERING ANGLE TEST DATA*

TIME	% EXPOSED	CHT °F	COMMENT
11:46	100	920	1-SUN BASELINE
11:49	90	846	10% WEDGE
11:52	100	925	1-SUN
11:54	75	690	25% WEDGE
11:59	50	493	2 X 25% WEDGE (50% OBSCURED)
12:04	40	474	ALL 3 WEDGES (60% OBSCURED)
12:10	100	926	1-SUN
12:16		460	REFLECTED FROM KIR FILM, 0.5 METER FROM DISH
12:21		432	REFLECTED FROM KIR FILM, 1.0 METER FROM DISH
12:25	40	414	ALL 3 WEDGES (60% OBSCURED)
12:31	40	393	BREEZE

TABLE 3. STIRLING ENGINE CHT CALIBRATION, INCLUDING KIR FILM



samples.

The KIR film reflector produced a CHT of 460 °F, at a distance of 19.7 inches. Solving for **X** yielded X=(**Y**– 90)/833.14 =0.44. This indicated that 44% of the heat was reflected to the dish. The Stirling Engine was moved to 39.4 inches and the test was repeated, producing a CHT of 432°F (see Table 2). The reduction in CHT at that distance equates to a scattering angle of 1.2 degrees from imperfections in the reflecting surface. Calculation details are given in the appendix.

The mirrored film reflected the most solar radiation and produced the highest CHT, but it proved to be infeasible for the hybrid system. It reduced the power output of the PV panel to just 7% of full sunlight output.

DISCUSSION

Initial tests of the Stirling Engine showed that RPM was not a useful indication of energy level; see Table A1 and Figure A3 in the appendix. The RPM varied significantly and without direct correlation to temperature. CHT measured when the engine was not running was a more direct indicator of the amount of energy reflected onto the cylinder head, so was used for all subsequent tests.

Because only relative changes in CHT were used to measure the relative amount of captured solar energy, the specific energy available from the sun was unknown. This meant that the calibration figures were only useful while the test conditions did not change.

In mid-summer, conditions suitable to take a series of measurements occur during a mid-day period lasting approximately 90 minutes. The temperature measured at the cylinder head reached a stable peak beginning roughly 30 minutes before local noon, and did not begin to drop until nearly an hour afterwards. During the mid-day period, the temperature varied a degree or two every few minutes, apparently at random. With the instrumentation available, any actual change in temperature during the mid-day period was not readily detectable.

One challenge in building and implementing reflective solar concentrators is the scattering of solar radiation from irregularities in the mirror surfaces. During field tests, scattering of the solar radiation caused a slight decrease in the efficiency of concentrating energy on the parabolic collector. As mentioned above, and detailed in the appendix, the radiation was scattered at an angle of 1.7 degrees, and 1.2 degrees of this scatter was attributed to the film. Wrinkles in the film samples were possibly a significant contributor to the amount of scatter indicated. Improved reflecting film mounting methods would be necessary for any practical application.

Another challenge in implementing concentrating solar collectors is the occasional presence of thin clouds or haze. Total solar energy arriving at the surface of the Earth may be relatively unchanged by haze, but the proportion that can be concentrated will decrease. Even at the best locations, such as are found at high altitude dry deserts, the proportion of sunlight diffused by the atmosphere will be at least 20% (Zweibel, 1990). The effect of thin, high clouds was experienced during the initial Field tests. The temperature measured at the cylinder head changed over a span of a few minutes, just as it would if a cloud passed over the sun, yet the PV output remained steady. The sky appeared to be practically cloud-free to the unaided eye, but thin clouds were visible when viewed through a welding helmet filter (Figure 5). Concentrating systems cannot use the scattered portion of the solar energy, but PV can.

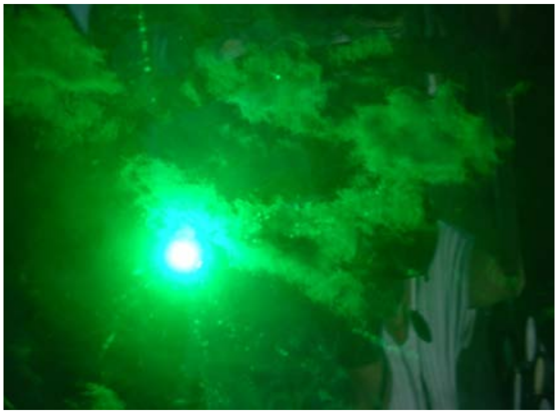


FIGURE 5. **HAZE IN THE SKY, INVISIBLE TO THE NAKED EYE**

A similar effect would be expected on a large heliostat array focusing sunlight on a solar tower. Scattering of sunlight by clouds, or simply by atmospheric moisture, would be expected to reduce the power generation dramatically, despite the majority of the solar energy that might still reach the heliostats as diffuse radiation. This would argue against concentrating (CSP) designs in all but the most favorable locations, and might argue for converting an existing thermal-solar installation to PV or hybrid design.

Modeling

To put the results into perspective, the data was used to estimate the effect converting existing thermal collector installations to hybrid systems might have on their total energy output. The observed ability of film coatings to transmit visible portions of solar radiation to PV panels while reflecting infrared radiation onto solar collectors was used to estimate the output of two existing sites, if they were to be converted into hybrid facilities.

CSP plants selected for evaluation were the PS-10 plant in Spain, and the Nevada Solar One facility. The PS-10 plant is a solar concentrator system that focuses reflected solar energy onto towers that contain steam turbine generators. The Nevada Solar One facility uses parabolic trough concentrators to heat fluid in pipes; the heat is then transferred to steam turbine boilers, or stored in beds of molten salt.

PS-10 Plant

The PS-10 plant in Spain, which is rated at 11 megawatts (MW), has 624 Heliostats, each having a reflector area of 124 square-meters, for a total collecting area of 77,376 square-meters. Total solar energy reaching the mirrors would be approximately 77 MW at mid-day. If the heliostats were replaced with 16% efficient PV panels, the energy generated directly from the solar cells would be roughly 12.3 MW, an 11% increase compared to the existing CSP system. If the PV panels were covered with a heat-reflective material equivalent to KIR, their PV output would be expected to drop to 10.5 MW, 85% of normal. The heat reflected from the KIR-covered PV panels would be expected to reduce the CSP-system (solar tower/steam boiler/turbine/generator) to 4.4 MW, 40% of normal, as demonstrated in the Field Tests, but the combined output of the solar panels plus the CSP system would be 14.9 MW, 35% more than the existing CSP-system by itself, and 21% more than an equal-sized PV-system.

At times when the plant experiences periods of slight cloudiness, when the sunlight is diffused, the PV-portion of this hybrid system would continue to produce significant power, whereas the thermal-portion of the system might be idle. Because published reports contain average values, it is possible that this extra production time could further increase the plant's yield. Were such a system to be built in an area with frequent haze or clouds, it is likely the majority of electrical production would be from the PV panels, and only occasionally would the thermal plant operate at peak output, when the skies were clear.

Nevada Solar One Facility

The field of parabolic trough concentrators at the Nevada Solar-One CSP has a combined solar capture area of 1.2 square kilometers (Nevada Solar-One, 2007). Total solar insolation at mid-day from this area should be roughly 1,200 MW, giving an efficiency figure of approximately 5% at the rated 64 MW nominal output, or 6% efficiency at the peak rated output of 75 MW. If the parabolic mirrors were replaced with a heat-reflecting film equivalent to KIR, and 16% efficient PV panels were installed behind the plastic film to yield output equivalent to the Field Test (retaining 85% of their full-sun energy output after transmission losses through the plastic film), then the nominal CSP output would be expected to drop by 40% to 25.6 MW, while the PV output would add 163 MW, for a combined output of 188 MW, an apparent increase of 294%. This potential increase may be substantial enough to warrant studying the economic feasibility of redesigning the plant.

The plant uses molten salt to store thermal energy overnight, extending its generating capability into the evening, when electricity has a higher market value, and giving it the ability to adjust to variable grid loads. It is not known what this has on the plant's efficiency, other than to say that it seems reasonable to assume that the thermal storage system is responsible for the apparent low output. Nevada Solar-One cost $240M, putting the installed cost at just $3.75/watt, equivalent to the cost of PV, although requiring 3X the area. The economics due to thermal storage are favorably improved by offering power to the grid during peak demand, after sunset. This offers a significant market advantage not available to PV (Jones, 2007). Converting Solar One to a hybrid system would reduce the amount of thermal energy produced and thus there might be less electricity production after dark, when the price for electricity is at its peak. It is possible that the reduction in output during peak demand hours might make a hybrid conversion economically infeasible, even with the net increase in power output. Then again, economics might dictate that it would be best to store all of the daytime thermal energy for night use, and to only use PV power when the sun shines.

REFERENCES

Abengoa PS-10 project final report (2006). *10 MW Solar Thermal Power Plant for Southern Spain* (Project No. NNE5-1999-356). Retrieved from http://ec.europa.eu/energy/res/sectors/doc/csp/ps10_final_report.pdf

Chow, T. (2006). Hybrid Photovoltaic and thermal solar-collector designed for natural circulation of water, Applied Energy 83(3), 199-210. doi:10.1016/j.apenergy.2005.02.007

Erdil, E., Ilkan, M., Egelioglu, F. (2008). An experimental study on energy generation with a photovoltaic (PV)-solar thermal hybrid system. Energy 33(8), 1241-1245. doi:10.1016/j.energy.2008.03.005

Jones, J. (2007). *CSP lifts off: Nevada Solar One comes to life* | Renewable Energy World Magazine Article. Retrieved from http://www.renewableenergyworld.com/rea/news/article/2007/05/csp-lifts-off-nevada-solar-one-comes-to-life-51525

Kreith, F. and Goswami, D. (2007). *Handbook of Energy Efficiency and Renewable Energy* (Boca Raton, Florida: CRC Press)

Maycock, P., Stirewalt, E. (1985). *A guide to the photovoltaic revolution* (Emmaus, Pennsylvania: Rodale Press).

Nevada Solar-One (2007) *Nevada Solar-One, Project Overview.* Retrieved from http://www.Acciona-na.com/about-us/our-projects/U-S-/Nevada-Solar-One.aspx

Quaschning, V. (2004). Technical and economical system comparison of photovoltaic and concentrating solar thermal power systems depending on annual global irradiation Solar Energy,77(2), 171-178. doi:10.1016/j.solener.2004.04.011

Seraphin, B.O. (Ed.). (1979). *Topics in applied physics: solar energy conversion* (Vol. 31). Heidelberg, Germany: Springer-Verlag.

SunPower Corporation (2010), retrieved from http://us.sunpowercorp.com/residential/products-services/products/panels.php

Technology Review (2010), retrieved from http://www.technologyreview.com/energy/17577/page1/

Zondag, H. (2007). Flat-plate PV-Thermal Collectors and systems: A review Renewable and Sustainable Energy Reviews 12(4), 891-959. doi:10.1016/j.rser.2005.12.012

Zweibel, K. (1990). *Harnessing Solar Power: The Photovoltaics Challenge.* (New York, NY. Plenum Press)

APPENDIX

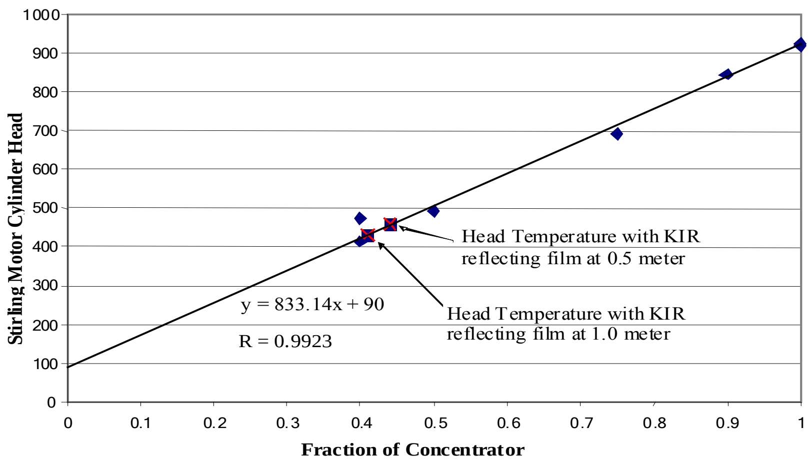
Scattering Angle Test Calculations

Assumption: The solar radiation level arriving at the entrance plane of the parabolic mirror is proportional to the temperature measured at the cylinder head, as expressed in the following formula: **Y** °F = 833.14 * **X** °F + 90°F. In this formula, **Y** = CHT and **X** = fraction of the baseline reading of the energy that entered the dish. Rearranging and solving for **X:**

X = (**Y**–90)/833.14. For Y = 460 °F, X = 0.44 (44 %) at 0.5 meters, and for Y = 432 °F, X = 0.41 (41 %) at 1.0 meters.

The data may be plotted on the linear regression line, showing their position relative to the measurements taken from the calibration test, as shown in Figure A1.

FIGURE A1. **CYLINDER HEAD TEMPERATURE AS A FUNCTION OF CONCENTRATOR AREA EXPOSED TO SUNLIGHT.**



Assumption: The reduction in solar radiation, as the parabolic mirror is moved from 0.5 meters to 1.0 meters from the reflecting surface, is due to the divergence of the energy beam in a conical pattern. The diverging angle of the conical pattern may be determined by calculating the increased area necessary to capture the same amount of energy, see Figure A2. The diverging beam forms an annulus at the entrance plane of the parabolic reflector:

A_1 = Area of the conical pattern at 50 cm, equal to the area of the parabolic reflector at the entrance plane [Pi * (22.5 cm) ^{2}] = 1590 cm^2
A_2 = Area of the conical pattern at 100 cm = $A_1 + A_{annulus}$
$A_{annulus} = A_1$ * (0.44 - 0.41) / 0.44 = 1590 * (0.07) = 108.4 cm^2
A_2 = 1590 cm^2 + 108.4 cm^2 = 1698 cm^2
Radius of the conical pattern at 50 cm meters = 22.5 cm (the radius of the parabolic reflector at the entrance plane)
Radius of the conical pattern at 100 cm = $(A_2 / \text{Pi})^{-2}$ = 23.25 cm
Annulus width = 23.25 – 22.5 = 0.75 cm

The width of the annulus equals the Sine of the conical pattern half-angle , over a 50 cm distance:

Sine a= 0.75 cm / 50 cm = 0.015
a = 0.86 (Sine law)

The divergence angle of the conical pattern is twice the

angle of a, or 2 x 0.86 = 1.7° (see Figure B1)

The sun already subtends an angle of 0.5°, so the net contribution to scattering angle by the reflecting surface is the difference:

1.7° – 0.5° = 1.2°

FIGURE A2. SCATTERING ANGLE TEST SETUP

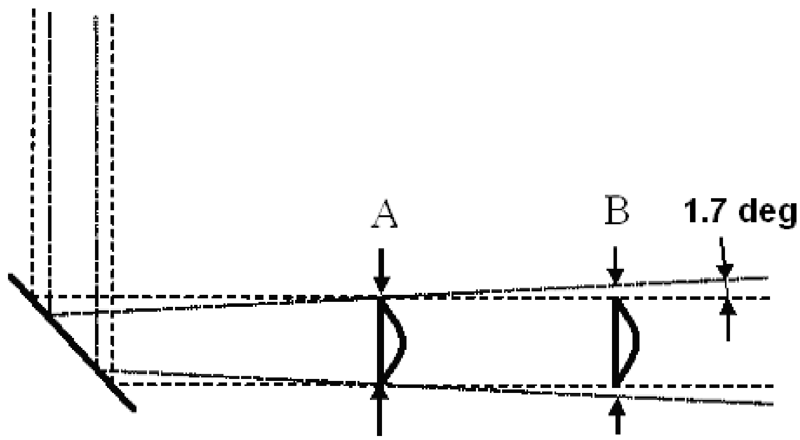


FIGURE A3. **GRAPH OF CHT VS. RPM**

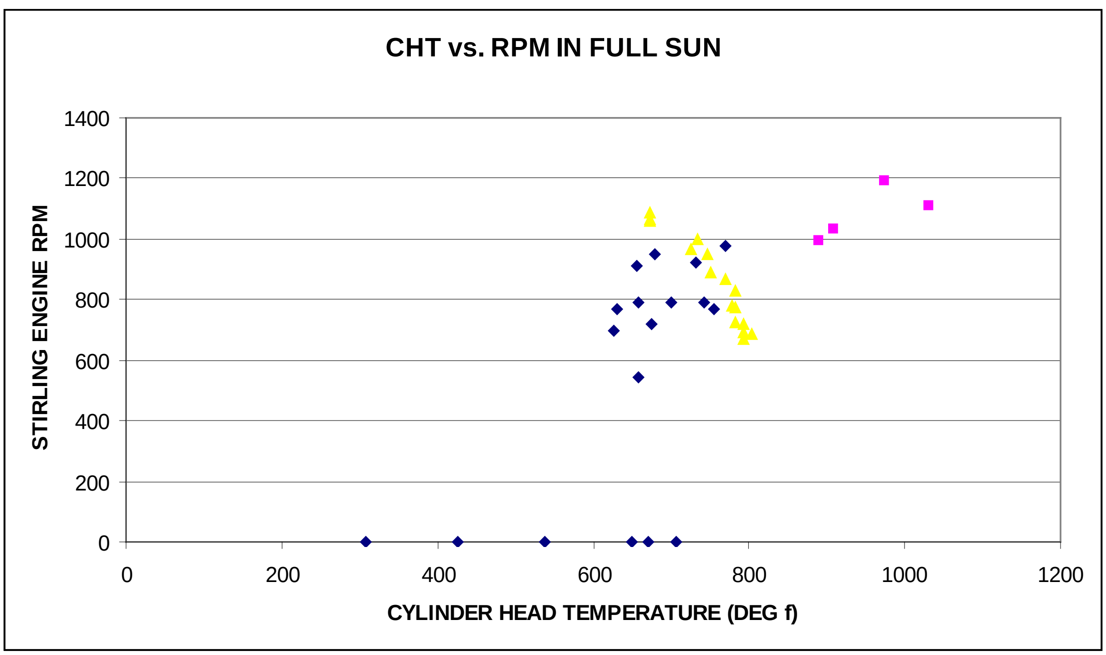


TABLE A1. *CHT VS RPM DATA*

1-OCT, 15:00 TO 15:21				6-SEP, 10:57 TO 11:56	
CHT	RPM	CHT	RPM	CHT	RPM
673	1087	742	790	975	1193
673	1067	675	718	910	1032
673	1059	754	770	890	991
725	967	670	0	1032	1107
733	999	769	980	CLOUDS	
747	948	700	790		
750	890	630	770		
770	865	707	0		
782	830	650	0		
778	781	732	924		
783	772	659	543		
782	727	627	700		
794	718	680	950		
792	670	656	910		
803	686	658	790		
794	690	538	0		
		425	0		
		308	0		