

UAH Propulsion Research Center

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*Solar Thermal Propulsion Optical Figure
Measuring and Rocket Engine Testing*

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Final Technical Report

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Solar Thermal Propulsion Optical Figure Measuring and Rocket Engine Testing

Final Technical Report

UAH Solar Thermal Laboratory

Solar thermal propulsion has been an important area of study for four years at the Propulsion Research Center. Significant resources have been devoted to the development of the UAH Solar Thermal Laboratory that provides unique, high temperature, test capabilities. The facility is fully operational and has successfully conducted a series of solar thruster shell experiments. Although presently dedicated to solar thermal propulsion, the facility has application to a variety of material processing, power generation, environmental clean-up, and other fundamental research studies. Additionally, the UAH Physics Department has joined the Center in support of an in-depth experimental investigation on Solar Thermal Upper Stage (STUS) concentrators. Laboratory space has been dedicated to the concentrator evaluation in the UAH Optics Building which includes a vertical light tunnel. Two, on-going, research efforts are being sponsored through NASA MSFC (Shooting Star Flight Experiment) and the McDonnell Douglas Corporation (Solar Thermal Upper Stage Technology Ground Demonstrator).

Absorber Shell Experimentation

The interaction of the solar electromagnetic spectrum and the windowless absorber cavity in a solar rocket is being investigated in the Solar Thermal Laboratory. Material samples are positioned at the focal point of a seven foot diameter, thin-film concentrator, within a vacuum chamber. The intense radiation is intended to heat the sample to near 2500 Kelvin as infrared and temperature data are taken. The testing provides material property values of absorptivity, emissivity and reflectivity at temperature, as well as material surface changes and weight loss. These data are utilized in various computer models to simulate the operation of a complete solar thruster.

Several light tubes have been tested to 1200 Kelvin in the vacuum chamber. Temperature profiles and material changes were ascertained for Alumina ceramic light tubes. Tungsten tubes have also been heated and significant formations of carbides observed where the tube was in contact with the carbon based insulation utilized in the chamber. This research will continue at a rapid rate to provide NASA important information for the design of the Shooting Star demonstration flight experiment.

The laboratory has been continually upgraded throughout the year. A secondary concentrator was added to the test chamber that increased the energy at the focal point by nearly ten percent. This secondary concentrator which is mounted in front of the quartz window, reflected much of the stray light halo onto the test articles. A larger, ten foot diameter, thin-film mirror frame is being fabricated to replace the existing seven foot concentrator. An improved quartz window and reconfigured secondary concentrator have been constructed to accommodate the new concentrator. They will increase the energy input and prevent overheating of the window seals, a problem experienced during this past summer's testing. Improvements to the heliostat motor control and closed loop, video tracking system were also made during this first year of operation. The primary faceted mirror is awaiting final polishing at MSFC. The graduate researcher is Joseph Bonometti with Dr. Clark Hawk as his faculty advisor.

Solar Concentrator Evaluations

The performance of a solar thermal thruster is highly dependent on the interaction between its solar concentrator and absorber. A wide variety of concentrator types have been studied, these include: faceted, thin-film and Fresnel lens/reflectors. Benchtop optical testing was conducted on a series of small Fresnel lenses, using both monochromatic laser and white light sources to evaluate Fresnel lens efficiency and internal structure. Similar testing is being conducted on Fresnel reflectors.

Material samples are being tested for transmissibility in preparation for flight scale Fresnel concentrators for the NASA Shooting Star demonstration. One and three foot diameter scaled concentrators are scheduled to be tested using these same benchtop techniques. Full scale tests will be conducted early in 1997 and plans are being developed for a coupled test of the concentrator with the absorber/thruster.

Reflectivity measurements have been performed on various, commercial mylar samples for thin-film mirrors. This information was used for the construction of the new, ten foot, concentrator. Laser mapping of both four and seven foot, thin-film, vacuum formed mirrors produced laser traced images of the focal point. These contour line images indicated the shape and intensity of the concentrator's focal plane. Correction to the mirror's inner surface was accomplished by inducing pressure about a ring near the mirror center. A similar ring correction is proposed for the ten foot concentrator. Other concentrator tests were performed including tracking the moon at night and particle scattering to view the focal light rays. The student researchers are Denise Stark, Kelly Smith and Joseph Bonometti. The faculty advisors were Dr. Clark Hawk and Dr. Don Gregory.

1.0 Objective of NAS8-38609 DO 147

Provide optical quality measuring for a deployable solar concentrator and conduct fundamental test on a solar thermal rocket engine at UAH's Solar Thermal Laboratory.

2.0 Experimental Tasks

2.1 Concentrator Laser Mapping

This task was the main thrust of the investigation, but it was severely curtailed due to the fact that the faceted concentrator was never completed. The entire mounting and alignment assembly was completed and awaited the final polishing of the mirror facets. Even with UAH rough cutting the facet faces to save machine time on the NASA MSFC diamond turning lathe, the final finish was not even attempted on one of the castings. Half of the facets were rough cut and premachined for NASA in the UAH student machine shop. About a dozen or so facets were delivered to MSFC (i.e. Dave Bachelor) over a year ago, but have never been processed.

Subsequent work conducted after the second quarterly report included a rebuild of the laser rail apparatus and the substitution of thin-film, vacuum formed concentrators (a four and a seven foot diameter mirror) in place of the faceted system. Additionally, a least squares (LS) curve fit model of the reflective surface was developed based on the data. The shape predicted by the LS model accurately described the observed light pattern at the focal point. An understanding of the effect of the two seams (in the case of the 7-ft concentrator) on the film shape, was gained by mapping the mirror parallel to and across the seams. The schematic of the optical setup is presented in Figure 1 below.

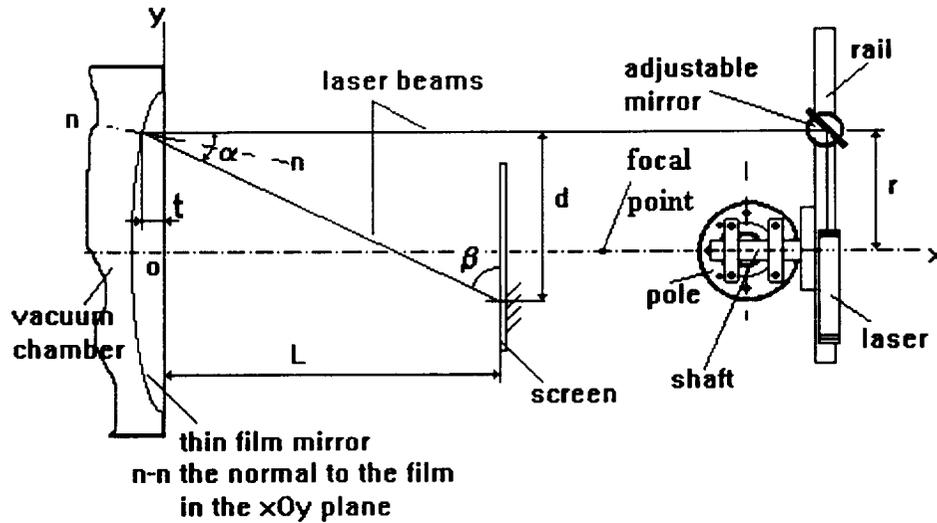


Figure 1. Surface mapping and slope measurement optical setup (top view)

The main rail, fixed on a shaft which rotated 360°, was supported by a vertical pole anchored to the laboratory floor (see Figure 1). This enabled the laser beam to describe circles, in a vertical plane, of arbitrary radius, “r”, with their centers on the concentrator axis. The flux of light at the focal plane was mapped by recording the position of the reflected laser beam on a paper (not shown in Figure 1), located at the focal plane. The incoming laser beam was aligned in two perpendicular planes -- one horizontal and one vertical - in order to ensure its parallelism to the mirror axis. Since the focal distance could not be computed prior to testing, the focal point of a parabola with a F/D = 1.5 ratio was considered as the optimum. The shape measurement in this setup reduced to the measurement of “t” in Figure 1. A data reduction equation was developed for the slope measurement:

$$x = f(y)$$

$$slope = \frac{dx}{dy} = \frac{1}{\tan\left(\frac{\pi}{4} + \frac{1}{2} \cdot \beta\right)} = \frac{1}{\tan\left(\frac{\pi}{4} + \frac{1}{2} \cdot \text{atn}\left(\frac{L+t}{d}\right)\right)}$$

(1.1)

The ATN function in the expression (1.1) represents the estimated value of the angle β from geometric considerations. The angle β is an intermediate variable, which could also be evaluated by direct measurement.

Several notable ideas were generated from the research accomplished as well as the verification and confirmation of generally known or suspected optical characteristic of pressure formed concentrators. Laser mapping the entire mirror (i.e. 2-D contour lines) was shown to be effective and the use of multiple beams would have saved an considerable amount of time (as discussed in the previous quarterly reports). The trace paper also saves a great deal of testing time but required a slightly more powerful laser than was available during these tests. The most difficult issue to be addressed while conducting the mirror mapping was the initial alignment process between the laser rail and the mirror's mounting ring plane. A simple water level provided good results but the other linear

measurements were slow to perform and inaccurate. Adjustments on the rail itself were very sensitive and made final correction to the beam path difficult and frustrating. The slope error measurement was not as precise as desired even for the "gross" bulk property measurements required for solar thermal heating. However, no other low cost methodology appeared much more accurate to obtain this measurement.

The actual data obtained provided good insight to the mirrors and the focal point characteristics. The two parallel seams did not have a significant effect on the shape of the film or on the excessive halo losses. A large portion (i.e. 50%-70 %) of the concentrated energy was not directed into the expected two inch diameter spot. The outer area of the thin-film was very accurate while the inner region was flat and significantly out of focus. We concluded that a larger diameter mirror would have the same trend but the outer ring would have a proportionally larger surface area that would enter the target spot. The disadvantage would be the increase in "spilled" light energy over the outer regions where protection of surrounding equipment becomes an issue. A rigid mirror was concluded to be far superior to the thin-film type.

2.2 Concentrator Comparison Testing

This task evolved significantly from the first testing proposed. The video tests that replaced the "light box" concept were setup but not utilized. This was due to the fact that the imaging with a small light source was only useful to the faceted mirror arrangement. The thin-film substitutes were mapped with a second laser method using the method and equipment provided by SAIC. This produced poor results and was not pursued further. Video mapping of the moonlight at the focal point also proved disappointing for the vacuum formed mirror. The light is so distorted that not even a "fuzzy" image of the moon is formed at the focal point. Later testing was done on the focal image of the entire system (heliostat and concentrator) using thermal paper exposed for brief periods of time to the full concentrated solar energy. Calorimeter data was obtained as well as flux mapping and particulate (i.e. light scattering) video of the concentrated beams. These methods were great improvements and provided very good visual images of the concentrator's performance.

The benchtop laser testing of the Fresnel lens was begun under this task as a particulate substitute for the research originally planned in Tasks 1 and 3. The results described in the second quarterly report proved very useful for the NASA Shooting Star program that utilizes the Fresnel lens concept. Work is on-going in this area through other UAH programs.

2.3 Solar Thermal Rocket Engine Testing

Full scale engine testing was determined to be impractical in the UAH facility as a result of both the reduction in total power available (from 5kw to less than 2.5kw), with the smaller substitute concentrator, and the vacuum pumps procured were not large enough to maintain the desired vacuum with a continuous hydrogen gas flow. Direct thrust measurements were also discovered to be impractical in the chamber as no low cost method could be found that afforded more accurate results than calculating it from the measured bulk gas temperature. Recent work for the Shooting Star program showed the static heating of the inner absorber tube was possible. Infrared images were obtained during one test by NASA personnel in addition to the thermocouple data recorded by UAH instruments. Temperatures, however, have not reached the desired 3000 Kelvin level, with the highest values just peaking at 1400 Kelvin. Again, mirror size and quality are the reasons for the poor performance. Surprisingly, the repeatability of the vacuum formed concentrator had proved remarkably consistent.