THE USE OF A STIRLING HOT-AIR ENGINE IN CONVERTING SOLAR ENERGY TO MECHANICAL POWER

by

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INTRODUCTION AND BACKGROUND

Discounting nuclear energy, all of the earth's stored and transient energy comes from one source, the sun (32:81). Furthermore, the availability of most of the stored and transient energy sources has been established, and it is seen that the demand for energy may someday surpass its supply. For instance, present consumption figures on the world's fuel reserves indicate that within a period of 50 to 90 years, fossil fuel supplies may be depleted (48:23). Even with the advent of nuclear power and the further development of hydro-power, the world will need other sources of energy to supplement its wants. Progress in the development of methods for utilizing radiation from the sun as it is received on the surface of the earth indicates that this source of energy holds much promise as one of the earth's auxiliary energy supplies. For example, while it has taken eons to produce the fossil fuels, it may become possible to store solar energy for immediate use by the process of photosynthesis (20:74).

Present-day utilization of solar energy is controlled by economics. Even though solar radiation costs nothing, it is expensive to collect. Therefore, solar mechanisms must compete with firmly established sources of power that have proven economical. However, the installation costs connected with some power plants, as well as the transportation and storage costs of its fuel, are found to be prohibitive in some areas of the world. It is in these areas where solar energy devices may compete economically with other sources of power (23:81).

Regions that experience an abundance of sunshine lie approximately between forty degrees north and south of the equator and are the only places where solar energy devices could have practical application (9:2). While many of these regions have no economical source of power, many presently see applications of solar energy as an auxiliary power source. Such a place is in the southern part of the United States, where the heating of water by solar means is commonplace, and the heating and air conditioning of residences is not only feasible but economical as well (13:5).

Remote and underdeveloped countries of the world can and do use solar energy as a means of replacing other energy sources which might otherwise be put to better use. Many of the inhabitants of India, for example, use animal dung for their cooking fires. The wide usage of some type of solar cooker could be of benefit to that country. The former fuel could then be used to fertilize the land. A solar-powered water pump could also be employed in this and similar countries to irrigate the land, thus improving the people's standard of living by increasing their economic level.

Other applications of solar energy deserve mention. Important advances are being made towards utilizing solar energy as a means of producing fresh water from the sea. Processes are being sought which will produce fresh water in this way for less than one dollar per thousand gallons (9:4). Solar energy is not destined to be used only on the earth as an energy source. It is presently being successfully used in satellites to produce electricity from photovoltaic cells. Future space travel will undoubtedly utilize solar energy in many ways.

Solar energy is not the most convenient source of power. Its shortcomings have long been recognized. Perhaps its greatest disadvantage is the form in which the sun's radiation appears on the earth. For some applications, the electro-magnetic waves, of which radiation consists, must be converted to heat; a process not so easily accomplished as the burning of fuel. Large receiving areas are sometimes required for collecting solar radiation since its intensity is relatively small per unit area. If a continuous source of power is desired, the intermittency of sunlight introduces the problem of storing energy for that purpose (20:68). However, some processes utilizing solar energy can be interrupted with only a slight inconvenience. For instance, the sun is usually shining brightest when air conditioning and refrigeration are needed most.

Continued research in the many fields connected with solar radiation yields new and better ways to meet these shortcomings. As in the past, the engineer is actively engaged in working on the development of solar energy as a power source. The meteorologist who has recorded and attempted to predict the amounts of available solar radiation, the research scientist who may be creating selective coatings to be applied to solar radiation absorbing surfaces, and the horticulturist who has attempted to correlate plant growth with available solar radiation are also making significant contributions.

Most research investigations that utilize heat sources created by solar radiation collecting devices involve either very high temperatures or comparatively low temperatures. For instance, temperatures in the thousands of degrees can be achieved by using a focusing collector to concentrate the sun's rays onto a small absorbing area. On the other hand, a heat source created by a flat-plate collector (one which absorbs direct and diffuse radiation impinging on its collecting surface) can only provide temperatures ranging from 100 to 400 F. However, many vapor and gas cycles can utilize a heat source well above the temperature ranges obtained with the flat-plate collectors and below the ranges used in high temperature work associated with focusing collectors. One example is the Stirling thermodynamic cycle. An engine employing this gas cycle can operate on any heat source which provides temperatures between 500 and 1500 F.

It was the purpose of this project to design, construct, and test an apparatus necessary to convert solar energy to mechanical power. It was proposed to do this by operating a Stirling hot-air engine with a heat source produced by a solar radiation collector. The system which converted solar energy in this manner was instrumented so that its performance and efficiency could be determined.

PREVIOUS AND FUTURE APPLICATIONS

A hot-air engine was first used as a solar power plant about a century ago. The first recorded application was made by John Ericsson, who in 1872 built a solar engine which utilized a heat source created by a parabolic mirror. The engine, shown in Figure 1, was essentially a Stirling engine even though Ericsson called it the "Caloric" engine (56:1356; 15:569).

About the same time, a new type of hot-air engine was invented by A. K. Rider of Philadelphia (15:570). In 1908, the Rider engine was used in a solar power plant which was proposed for the City of Phoenix. However, the proposal proved impractical because the collecting area of the reflecting mirrors was too small (56:1356). Figure 2 illustrates the power system.

Little work towards utilizing solar energy in this manner was performed in the following years. The principal disadvantage seemed to be the large collecting area required to operate the inefficient hot-air engines. A more efficient Stirling hot-air engine was developed by Philips Research Laboratories in Holland approximately 25 years ago. The new design included a regenerator and featured lightweight materials in its construction. A recent investigation of this modern Stirling engine as a solar power

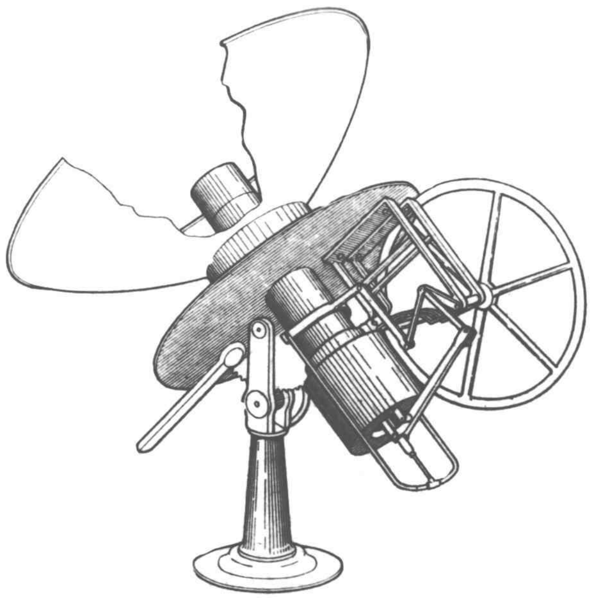

Figure 1. Ericcson's Solar Engine. (15:567)

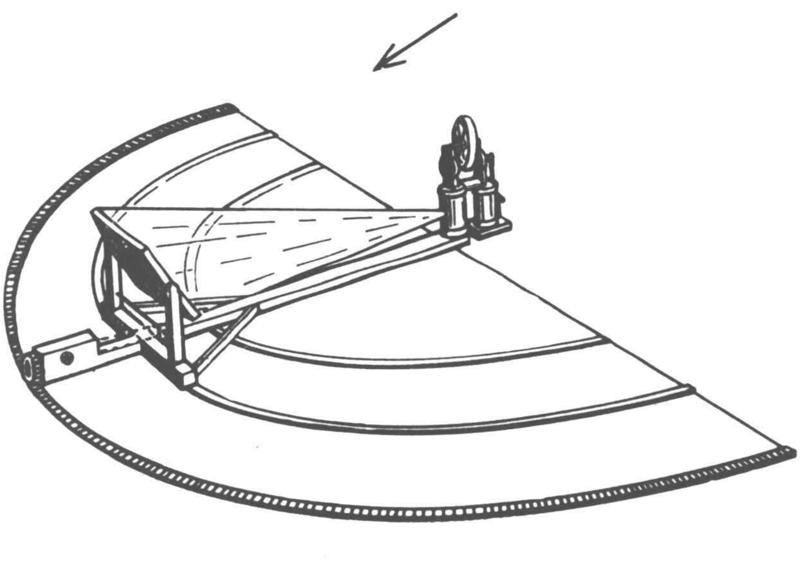

Figure 2. Proposed Solar Power Plant for Phoenix. (56:1356)

plant was conducted by India's National Physics Laboratory (56:1356).

Presently, the hot-air engine is being considered for future space applications (45:541). Needless to say, the entire proposed system is better designed than its predecessors. The engine employs the Stirling cycle and uses one of several gases for its working medium. General Motors Research Laboratories has developed the system and proposes that an all-metal Fresnel reflector be used for the solar radiation collector (29:219).

The rated power output of the entire system, including generators, is five kilowatts (6.7 hp), and its rated brake thermal efficiency is 30.5 per cent when using dry helium as a working medium. The area required for the solar collector is 283 square feet, meaning that a circular Fresnel reflector 19 feet in diameter must be used (45:557-558).

This system employing the Stirling cycle has been compared with a mercury-vapor Rankine cycle. While it is feasible to use the Rankine cycle for space applications, it is estimated that the Rankine system would weigh 42.5 per cent more than the Stirling system. In addition, the engine efficiency of the Stirling engine is supposed to be approximately three times greater than that of the engine utilizing the Rankine cycle (45:557). Therefore, from the weight and efficiency standpoint, the Stirling system may well become the first source of mechanical power in space.

Space use of the Stirling engine introduces new problems that are continuously being solved. Meanwhile, the solution to some of these problems is also enabling more practical and economical application of the solar-powered Stirling engine here on earth.

AVAILABLE SOLAR ENERGY

Solar energy is essentially the transfer of heat by thermal radiation, that is, radiation which is emitted by the sun solely due to its temperature; a temperature that is approximately 10,000 F (35:177). It is transferred to the earth by means of electro-magnetic waves which travel at the speed of light through free space.

The earth receives a more or less constant amount of solar radiation, a constant that has been estimated and observed by many people for over a century. The most recent value to be substantiated has become a standard for most people doing research work in the field of solar energy. This new value is 2.00 cal per min-sq cm (7.38 Btu per min-sq ft). (31:431). It must be remembered, however, that this value has been established in free space outside the earth's atmosphere. Furthermore, due to the earth's elliptical orbit, this constant is based upon the earth's mean distance from the sun.

The electro-magnetic waves that make up the solar spectrum contain different amounts of energy. A spectral distribution of the extraterrestrial solar energy is shown in Figure 3. The fractional accumulated energy for the spectrum is also shown. From this, it is seen that half of the radiant energy received from the sun appears in a

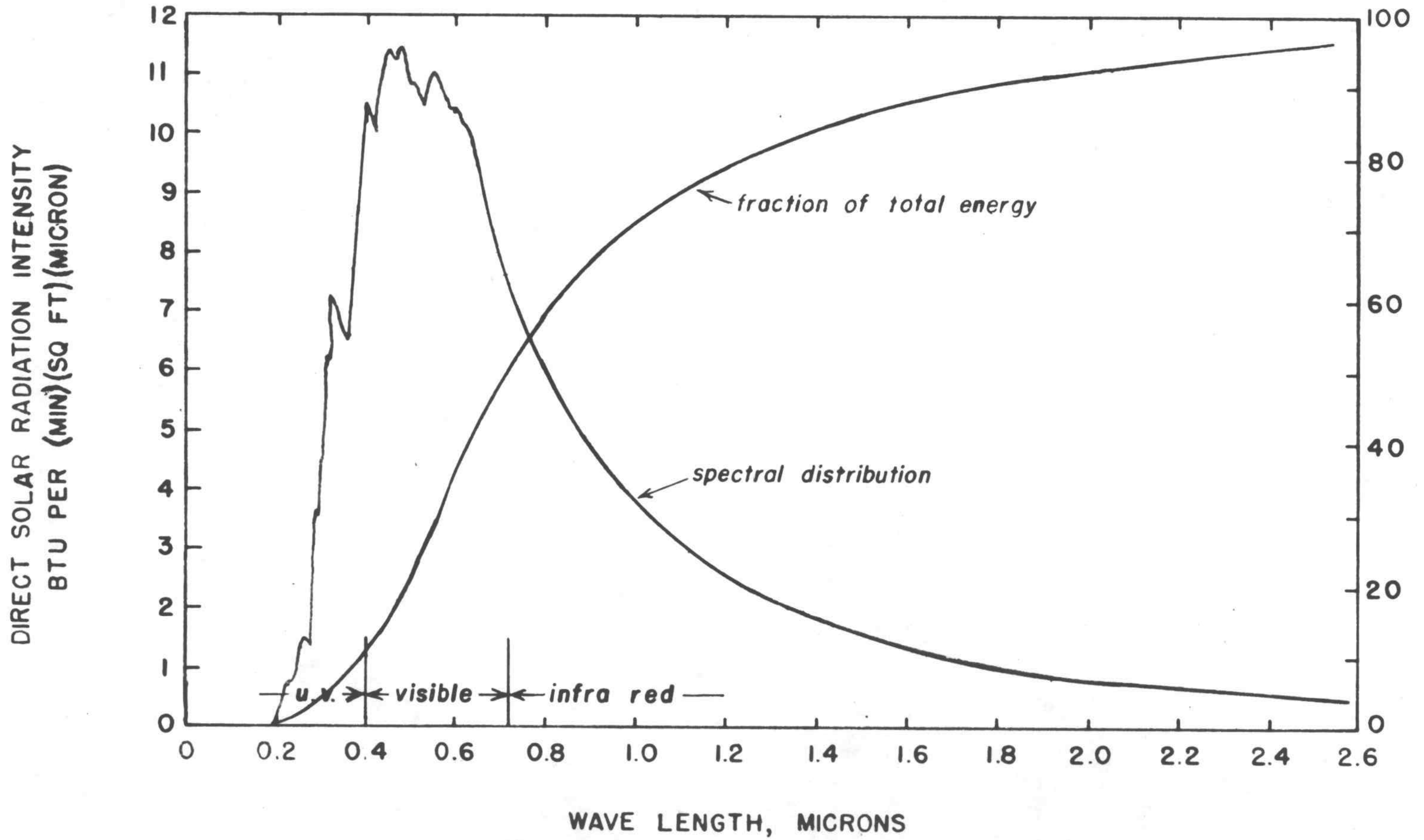

Figure 3. Extraterrestrial Solar Spectrum. (18:56)

relatively narrow wave length region. For instance, the energy in the ultraviolet and visible regions contains approximately 50 per cent of the energy. Beyond 0.7 microns, the infrared region contains the remaining amount (18:56).

Unfortunately, not all of the solar spectrum as it appears at the edge of space is transmitted to the earth's surface. In a clear atmosphere, about 80 per cent of the radiation reaches the ground at sea level (41:2). Any one of three things can happen to the energy, depending on the nature of the atmosphere, the altitude angle of the sun, and various radiation depleting factors. The energy can be reflected back into space due to clouds, it can be scattered and diffused by the constituents of the atmosphere, or it can be completely absorbed by some of these same constituents (51:135).

The United States Weather Bureau has an ever-increasing number of weather stations all over the country observing and recording solar radiation. These data have been used by many in research to correlate the amount of radiation to such things as plant growth rates and weather variations (2:3). Data have also been used to attempt to establish a yearly distribution of solar energy in the United States as shown in Figure 4. The distribution shown can only represent large areas. Some stations in the same

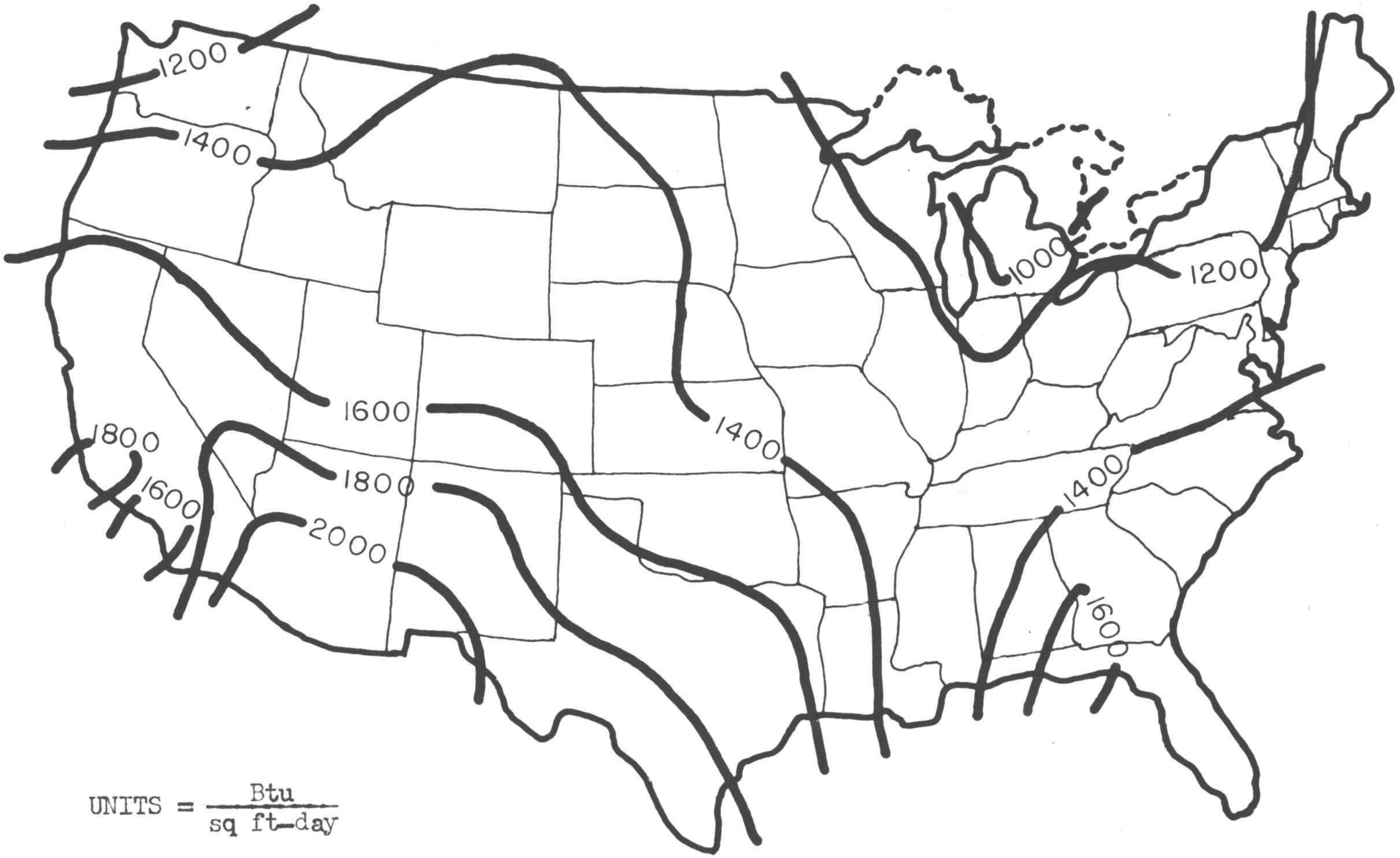

Figure 4. Solar Energy Distribution in the United States. (25:73)

general area may vary as much as 100 per cent; the chief reason being their respective locations to their surrounding topography and industrial complexes. For instance, atmospheric pollution plays an important part in the apparent radiation differences between an area located near a large industrial city and one that is located in the open country (25:75).

The instrument which has been adopted by the United States Weather Bureau for most of its solar radiation measurements is the Epply pyrheliometer. This instrument consists of a sensing element which is enclosed in a glass bulb and exposed in a horizontal position to the sky. The element is composed of a disk coated with lamp black and a concentric ring smoked with white magnesium oxide. Since the black surface absorbs most of the impinging radiation and the white oxide coating has a high coefficient of reflection, a temperature difference results (28:101). Platinum-rhodium and gold-palladium thermocouples are used to measure the produced voltage which is very nearly proportional to the intensity of the solar radiation (38:153). Generally all of the pyrheliometers in use today have a recording potentiometer to monitor them.

From the present knowledge of solar radiation and the atmosphere's effect upon it, good engineering approximations can be made of the amount of solar energy striking the earth (18:63). Perhaps in the future it will be a common occurrence to be able to accurately calculate the amount of solar radiation available at any given time of the year, day, or hour at any location on earth. To this end, people are working to correlate observed solar radiation data with theoretical attempts to establish relations between the amounts of diffuse, direct, and total solar radiation that are present during all kinds of ambient conditions.

COLLECTION CONSIDERATIONS

The higher temperatures obtained by the use of devices which concentrate the sun's rays introduce problems associated with their fabrication. For instance, focusing collectors used for solar furnaces must be made with high optical precision. A much lower degree of optical precision is adequate for the focusing collectors intended for use in conjunction with relatively lower temperature heat sources (9:4).

There are two basic types of focusing collectors in general use. These are reflectors and lenses. A disadvantage faced by both types is their cumbersome size, for large collecting areas are usually required for most solar heat sources. Another disadvantage common to these types of solar collectors is that they must be constantly positioned to face the sun if they are to effectively focus the sun's rays. These disadvantages have been minimized by constructing the collecting units of lighter materials and by making them collapsible.

Reflectors may be either circular or trough-shaped. A few basic forms are shown in Figure 5. In addition, due to the ever present attempt to make solar mechanisms more economical and portable, reflectors are made of materials ranging from plastics to foils (11:9). For instance, a

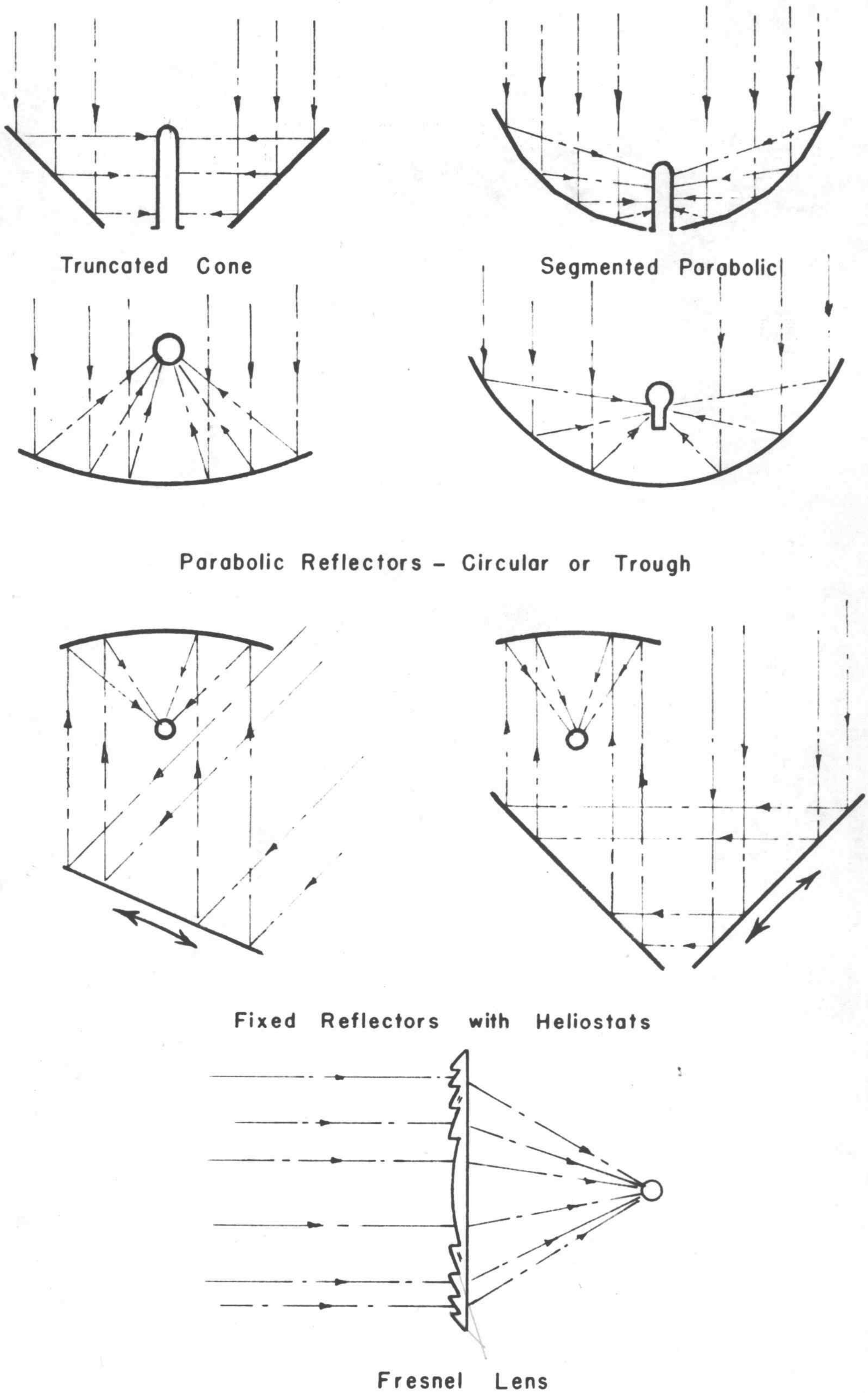

Figure 5. Various Forms of Solar Collectors. (56:1354)

material which has become available recently is a polyester film on which a thin coating of highly reflective aluminum is deposited. This material has been successfully used in several models of portable solar cookers (11:12).

The solar energy losses encountered with reflectors depend on the reflector itself. For instance, since the sun's rays have to pass through the glass of a back-surfaced mirror, more radiation is lost than from front-surfaced reflectors. However, the front-surfaced reflectors are more readily subject to weather damage (56:1355).

Lenses are also used as focusing collectors. However, most installations today which use lenses for solar radiation collecting purposes are solar furnaces. This is due principally to the limited size in which the lenses can be made. However, with the development of thin transparent plastics, it has become possible to make large, inexpensive Fresnel lenses (43:807). An illustration of the Fresnel lens is shown in Figure 5.

While most solar collectors of the focusing type in use today appear to be the reflectors, lenses also have advantages. For instance, a Fresnel lens made of plastic is inexpensive and portable. Also, a "convection shield" can be made such that the focal point is entirely enclosed and protected from heat-dissipating air currents. This is impossible with the parabolic collector.

Disadvantages may also be cited. Since the sun's rays have to pass through the material of the lens, certain wave lengths of the solar spectrum may be absorbed. In addition, the lens' surface acts as a reflector, a factor of which focusing reflectors take advantage. Finally, the size limitation placed upon the lenses serves as perhaps their biggest disadvantage.

While many focusing collectors can effectively concentrate the sun's rays, a great deal depends on the absorber at the focus of the collector which converts the concentrated radiation into usable heat. The future economical utilization of solar energy will perhaps lie with the development of good radiation absorbers having poor radiation emitting characteristics, especially if high temperatures are sought. As the temperature of an absorber increases, more and more energy is lost simply because its temperature gradient allows it to become a thermal radiator. A selective coating applied to an absorbing surface has the effect of virtually absorbing all wave lengths of solar radiation while emitting very little radiation of the infrared wave lengths (24:24).

Flat-plate collectors face the same problem, but not of equal magnitude as focusing collectors. They operate at a much lower temperature and are subject to much longer infrared radiation. Thus, choosing an appropriate selective coating, other than one that has a high solar radiation absorptivity, for the flat-plate collector is not too important. This type of solar collector usually employs a glass cover which transmits solar radiation but does not allow longer (infrared) radiation emitted by the flat-plate absorber to escape from the collecting unit. This phenomenon is commonly called the greenhouse effect, i.e., glass permits solar radiation to pass, but is opaque to radiation emitted by the interior of the greenhouse (35:177). The same principle has been applied to long parabolic trough reflectors where glass tubing surrounds a water-filled copper pipe located at the focal length (56:1355).

While many people engaged in the development of selective coatings have made some noteworthy discoveries, most of these coatings are rather complicated and costly to apply to the surfaces of radiation absorbers. Economical coatings need to be developed if widespread usage is to be expected. Coatings that can be applied by a novice might be those that come in the familiar pressurized cans.

It appears that the most effective selective coatings to date are those that are oxides deposited onto brightly polished metals. Selective coatings of cobalt-oxide deposits and chrome-nickel-vanadium deposits on polished copper and nickel have produced absorptivities of 0.93 and 0.94 and infrared emissivities of 0.24 and 0.40 respectively (24:24). Other selective surfaces have been developed by depositing manganese oxide on stainless steel and molybdenum oxide compounds on aluminum. Special coatings have been developed that involve electroplating copper, cobalt, and other suitable metals on polished metallic surfaces (34:19).

THE STIRLING THERMODYNAMIC CYCLE

The thermodynamic cycle of the Stirling engine is one which consists of four distinct processes. Figure 6 illustrates the pressure-volume and temperature-entropy diagrams for the ideal cycle.

"The first process of the Stirling cycle is an isothermal compression from point 1 to 2. Next, heat is added during a constant volume process from 2 to 3. The isothermal expansion or power stroke then takes place from 3 to 4, and the cycle is completed by the constant cooling process from 4 to 1." (16:666).

As seen from the temperature-entropy diagram, heat is also added and rejected during the respective constant volume processes. However, a regenerator included in the cycle improves the thermal efficiency. The regenerator serves the purpose of storing the heat removed during the cooling process and returning it again to the working medium during the heating process. Thus, less heat crosses the cycle boundaries and, theoretically, the cycle approaches that of a Carnot cycle (44:265; 45:544).

Engines that employ the Stirling thermodynamic cycle require the use of two separate pistons. One provides power and compression during the respective parts of the cycle. The other acts only to displace the working fluid from the hot to the cool spaces of the engine for the

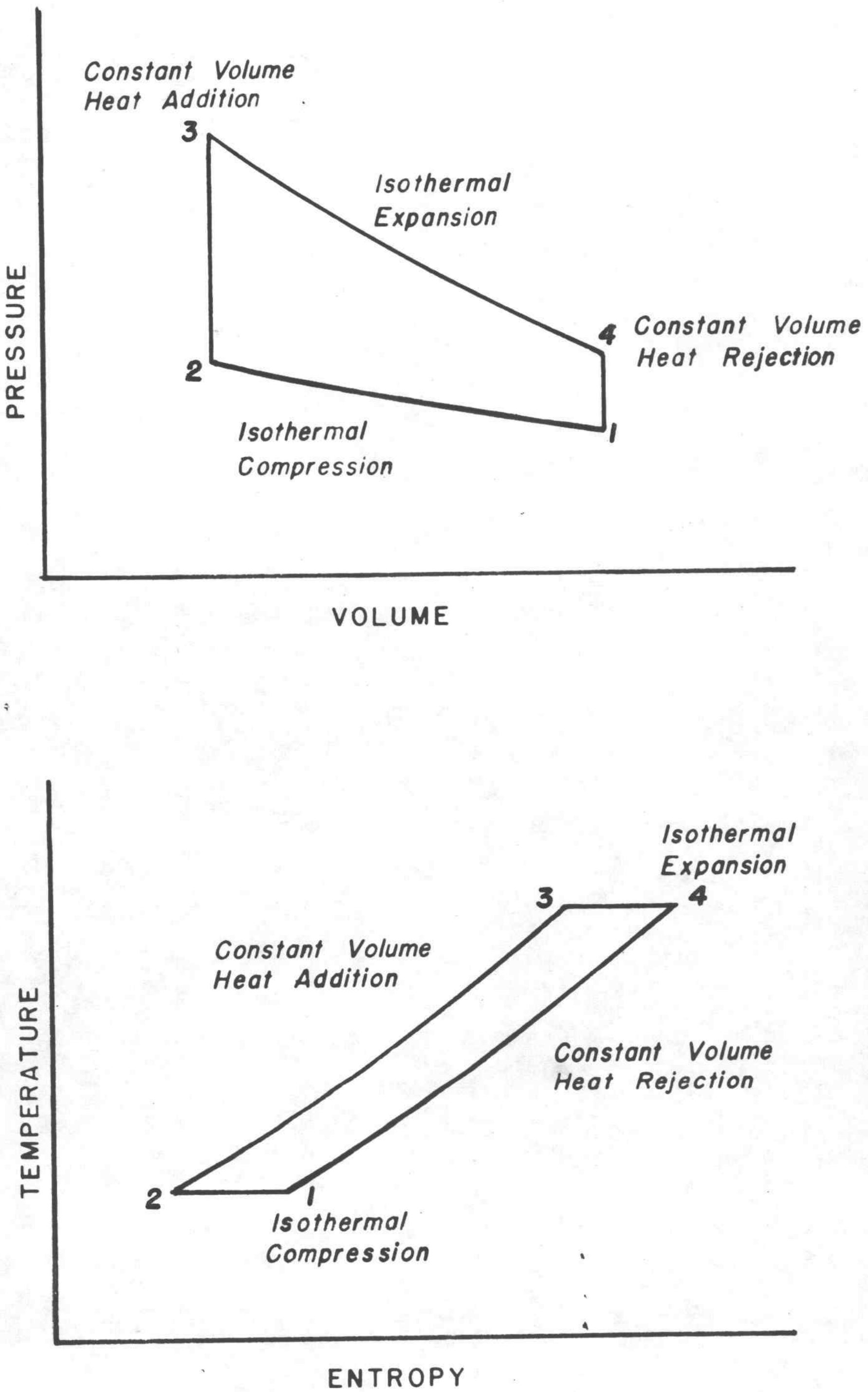

Figure 6. The Stirling Thermodynamic Cycle. (45:559)

respective constant temperature processes.

Figure 7 shows a common arrangement of the pistons for one design of the Stirling engine; a design which employs a regenerator between the engine's heater and cooler. A pressure-volume diagram for the ideal cycle is included with a diagram illustrating the relative positions of the two pistons during the cycle. During no process does either of the pistons remain fixed while the other moves. For example, the process from 1 to 2 involves an isothermal compression of the gas by the power piston. However, the displacer piston cannot remain fixed at the top of its stroke but must rise from some lower position to provide cooling equivalent to the work of compression performed by the power piston (16:673).

The drive mechanism for an engine utilizing the Stirling cycle requires that the pistons continuously move with respect to one another. For the actual cycle, shown by the pressure-volume diagram in Figure 8, only the expansion and compression strokes remain similar to the ideal cycle (16:673).

The Stirling engines developed by Philips and General Motors employ designs which produce actual cycles as the one described. Noteworthy improvements have been made by both organizations. General Motors has found that compressed helium produced an engine efficiency 20 per cent

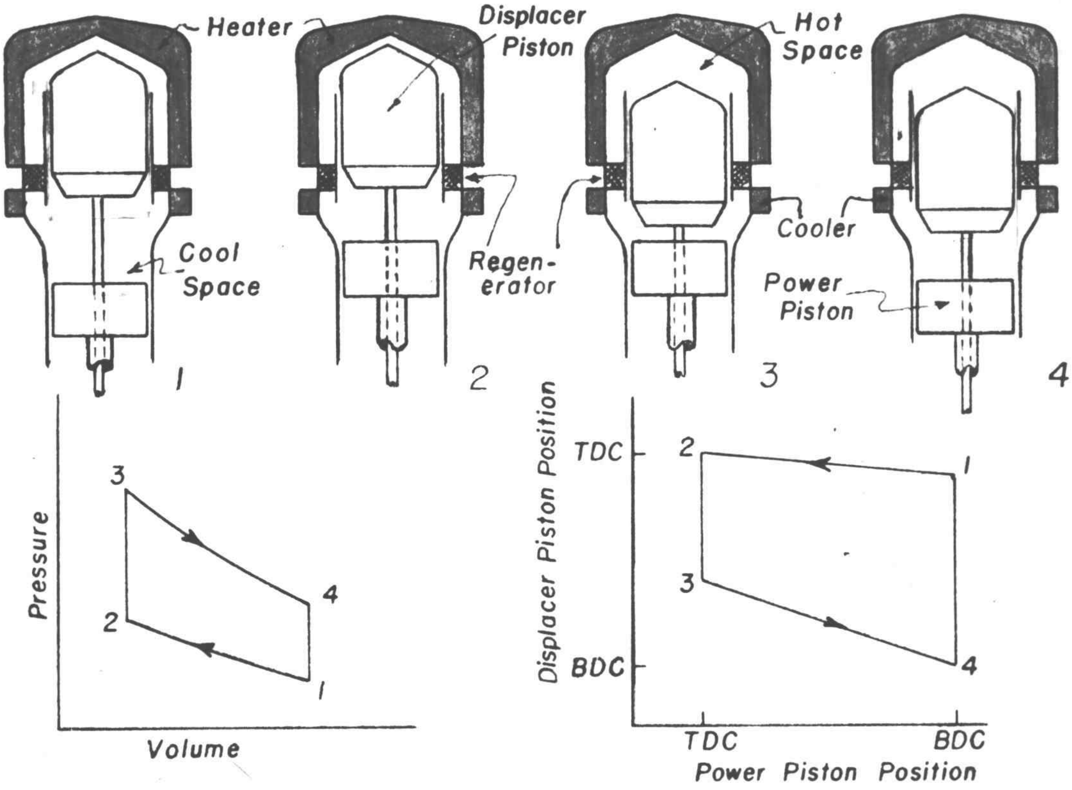

Figure 7. Ideal Stirling Cycle. (16:672)

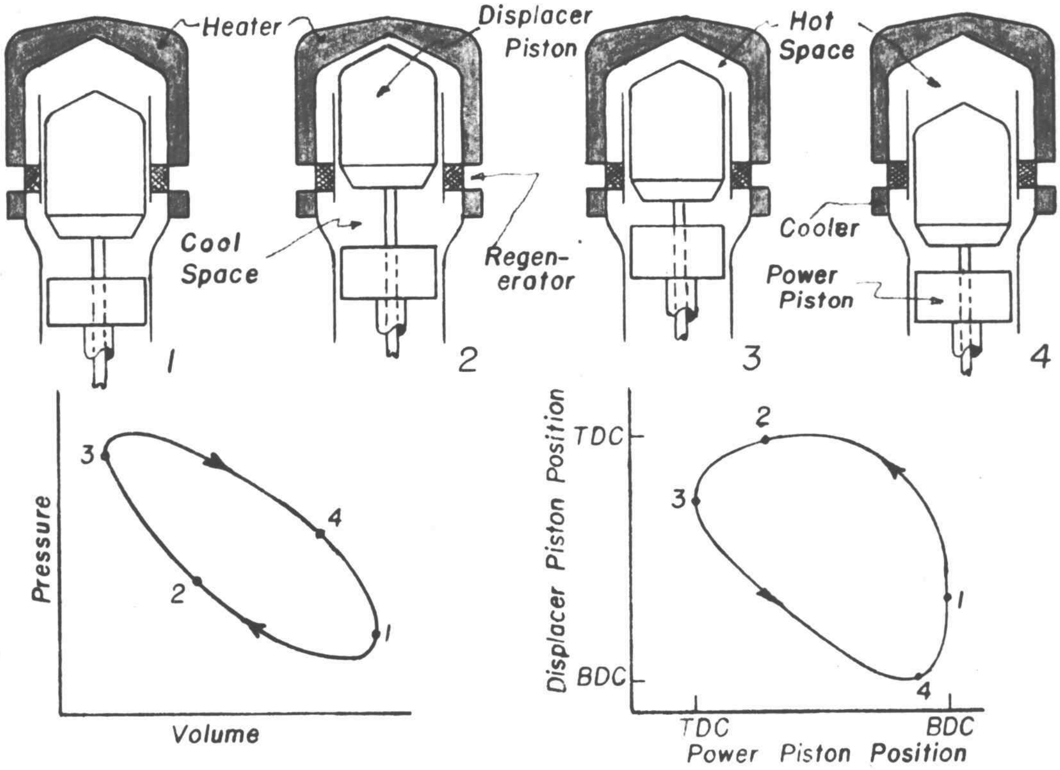

Figure 8. Actual Stirling Cycle. (16:672)

greater than that produced when air was used as the working medium. Hydrogen produced even better results; however, its use was discontinued because it diffused through metal too readily (45:550). Philips developed a regenerator composed of fine wire that could change its temperature from about 200 to 1000 F in one one-hundredth of a second and had a reported "efficiency" as high as 95 per cent (46:572).

The heat transfer problems encountered in a Stirling engine have perhaps limited its use in the present day and age. The internal combustion engine overcomes one of the main disadvantages of the Stirling engine. This is in reference to the manner in which heat is transferred to the working fluids of the two engines. For instance, a Stirling engine utilizes some type of external heat source. As a result, the transfer of heat to the Stirling engine's working fluid depends solely on a convection process between the hot parts of the engine and the gas itself. The speed of the Stirling engine seems to be limited for this reason. On the other hand, heat is instantaneously supplied to the working medium of an internal combustion engine by the ignition of a mixture of fuel and air in its combustion chamber. In addition, the metal containing the combustion process of an internal combustion engine can be externally air or water cooled. It is impossible to cool the Stirling engine in the same way.

Mechanically speaking, the Stirling engine is far simpler than a conventional internal combustion engine or an engine employing a vapor cycle. It has no valves, experiences no sudden pressure changes, requires no spark ignition, does not exhaust; nor, properly designed, does it vibrate or shake (45:544). All these factors indicate silent operation and little maintenance for a Stirling engine. Since the engine incorporates a closed cycle, it can operate on any heat source of sufficient temperature. This is perhaps its greatest advantage. Its operating temperatures and power output are only subject to metallurgical limitations and the lubrication problems encountered at high temperatures (32:95). However, advance technology is extending the temperature ranges in this respect and will continue to do so.

SYSTEM DESIGN

A solar energy conversion system which intends to utilize a heat source above 500 F to produce mechanical power consists of three things. First, solar radiation must be collected by a focusing collector. Next, an absorber serves the purpose of converting the concentrated radiation into usable heat. Finally, some type of heat engine is used to produce work from the heat source (24:24). The solar radiation collector employed in the final design of the conversion system used in this investigation was a 24 in. diameter parabolic mirror with a focal length of 9 11/16 in. The mirror's collecting area was kept normal to the sun's rays by the equatorial mounting shown in Figure 9. Its solar azimuth angle was changed by rotating the whole unit about its perpendicular axis. Its solar altitude angle was changed by the lever arrangement shown in the illustration. A description of the solar angles is included in Figure 10.

One end of the displacer piston's cylinder acted as the solar radiation absorber for the system. No attempt was made to apply any of the selective coatings described in a previous section. However, acetylene was smoked onto the end of the displacer cylinder for one of the test runs.

The heat engine used in the conversion system was the

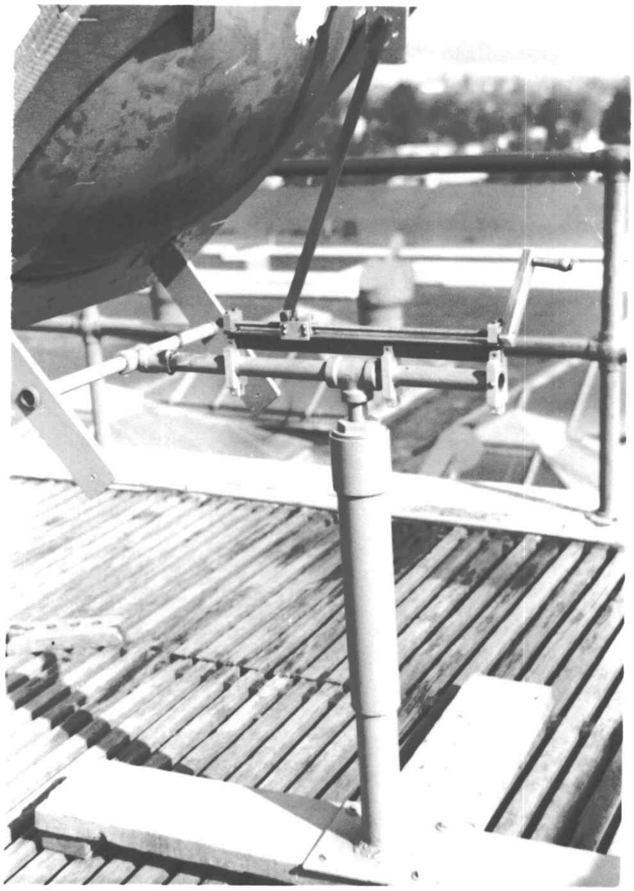

Figure 9. The Equatorial Mounting of the Mirror.

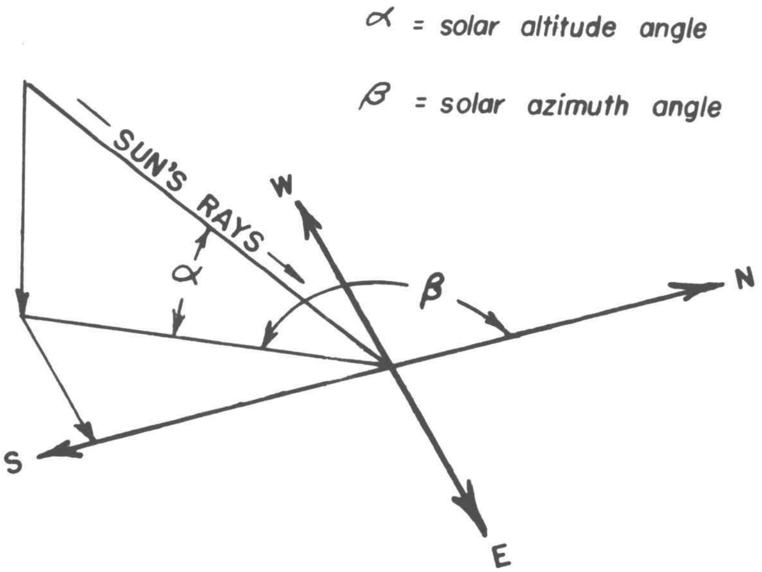

Figure 10. Solar Angles.

model Stirling hot-air engine shown in Figure 11. Figure 12 illustrates the relative positions of the displacer and power pistons during one cycle. The cyclic process occurs in the same sequence as the one illustrated in Figure 8. Clearance was provided for the displacer piston so that air could pass between it and the cylinder wall. The power piston required a tight fit since it experienced the pressure differential which provided work to the flywheel via the connecting rod. The average cycle pressure of this engine was suspected to be only slightly above atmospheric pressure since leakage occurred where the connecting rod of the displacer piston passed through its bushing.

Combining the engine with the mirror was accomplished by mounting it directly over the parabolic reflector. The engine's displacer cylinder was placed so that it could be adjusted along the mirror's axis. The combination is shown in Figure 13. Even though this arrangement allowed the engine to cast a shadow on the mirror, it proved satisfactory. The shadow obscured less than 10 per cent of the mirror's total area.

To keep the convection losses from the heated displacer cylinder to a minimum, a "convection shield" was constructed from cardboard. The shield is shown in place in Figure 14.

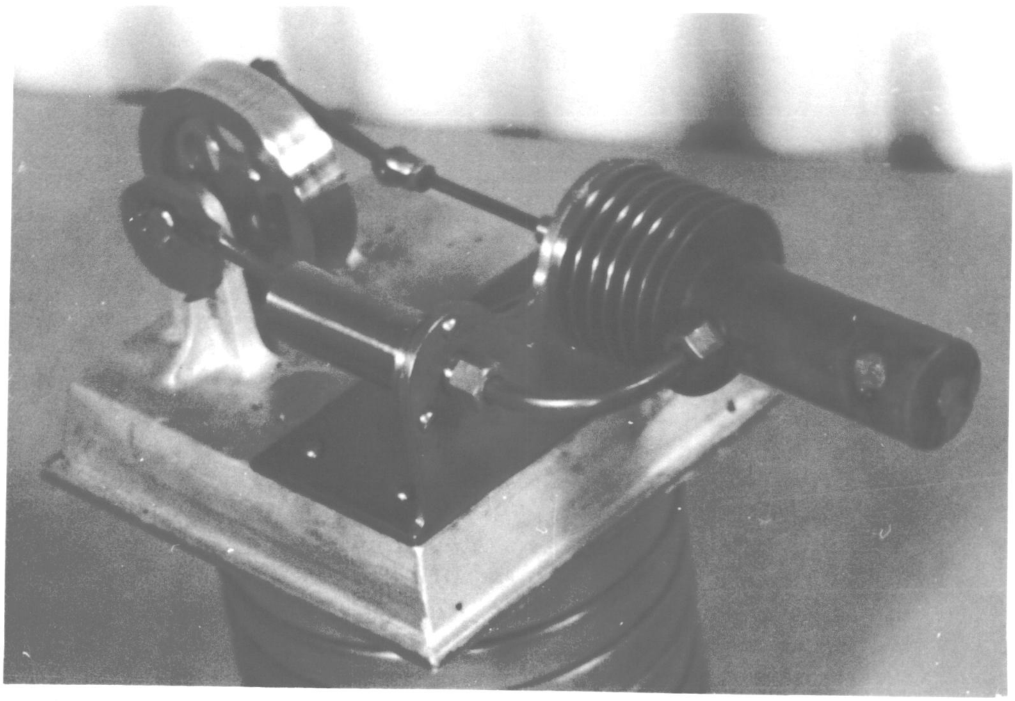

Figure 11. Model Stirling Hot-Air Engine.

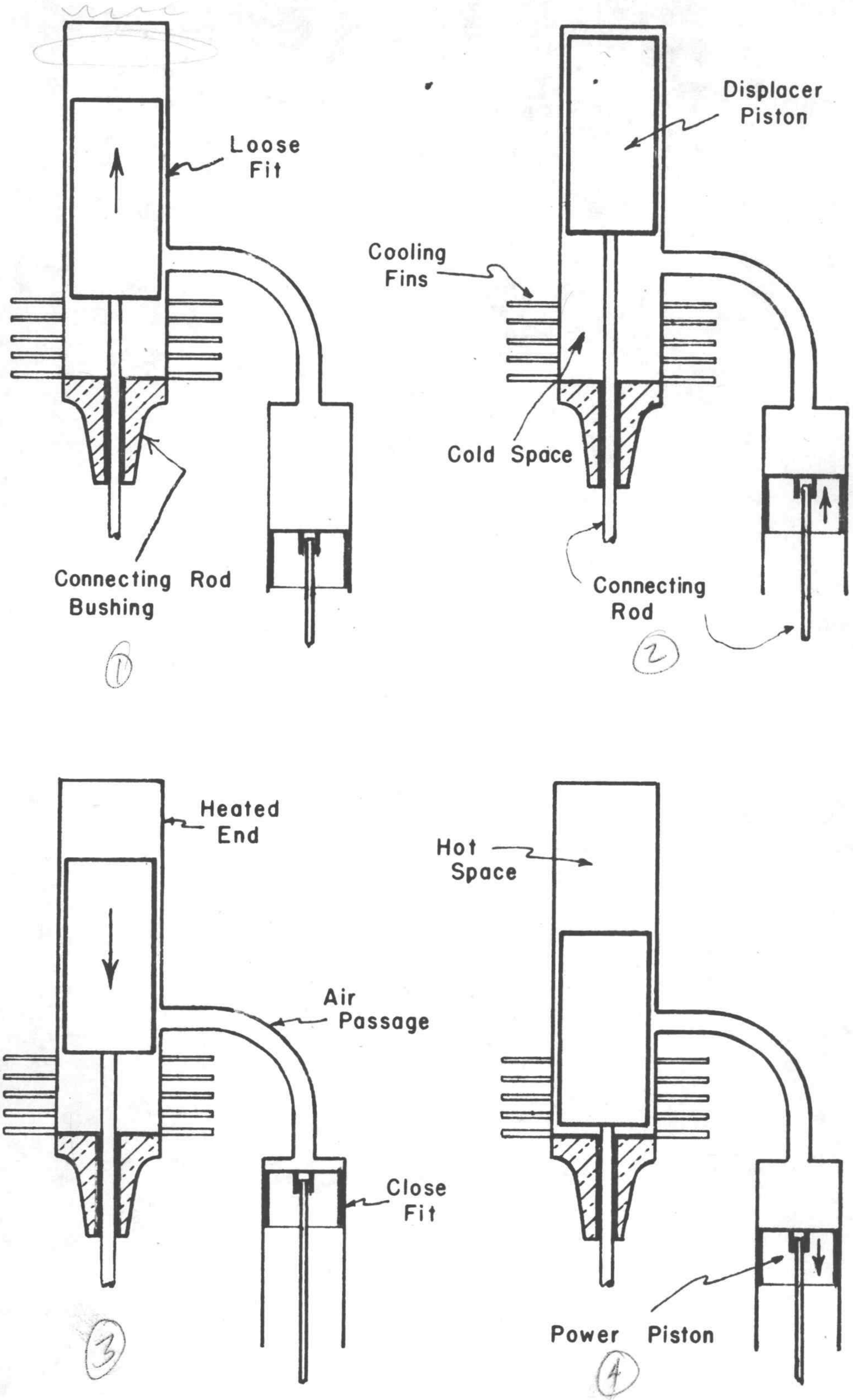

Figure 12. Relative Piston Positions.

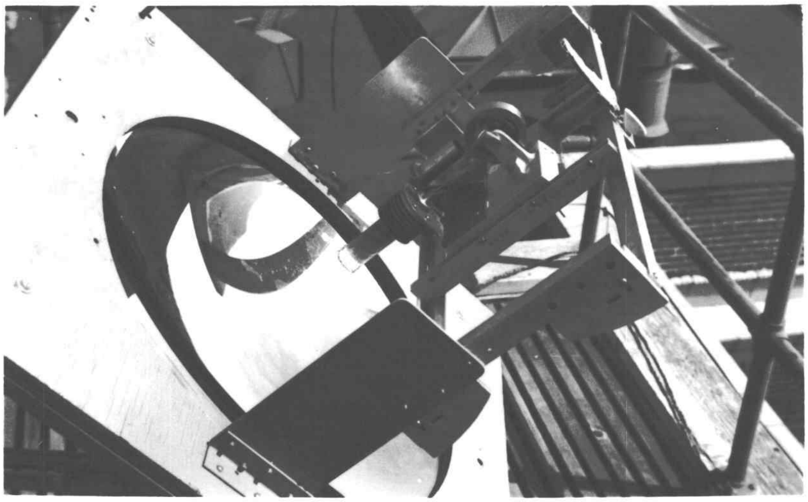

Figure 13. Engine Mounting.

Figure 14. Testing Site for the System.

The entire system and testing equipment were placed on the top of Covell Hall on the Oregon State University campus. This site, while somewhat inconvenient, was exposed to sunlight the entire day and provided a restricted testing area.

INSTRUMENTATION

The performance test on the solar energy conversion system involved the measurement of several items. For instance, instrumentation was provided to record the amount of solar radiation available on the testing days. Instruments were also designed and constructed which determined the mechanical power the engine developed. In addition, a separate test setup was provided so that the performance of the solar-powered engine would be compared with that obtained when the engine utilized a different heat source.

The parabolic mirror could only utilize direct solar radiation normal to its collecting area. Since the normal direct radiation was not measured, it was found by dividing the sine of the sun's altitude angle into the amount of direct solar radiation received on a horizontal surface (37:19). In addition, the direct radiation received on a horizontal surface was found by subtracting the diffuse (sky) radiation from the total radiation received on a horizontal surface. Fortunately, the Epply pyrheliometer described in a previous section was capable of recording the diffuse radiation simply by shielding its sensing element from the direct rays of the sun while at the same time, permitting as much of the sky as possible to be exposed to the element.

An Epply pyrheliometer and recording potentiometer were set up in the prescribed manner. A view of a pyrheliometer installation is shown in Figure 15.

Previous performance tests on the model Stirling hot-air engine measured the power output by using a prony brake arrangement in conjunction with its flywheel (22:13; 47:9). The engine itself was not adaptable to any other convenient torque measuring device. For instance, the presence of the crank on both ends of the flywheel shaft prevented the use of some type of pump or generator mechanism as the means of varying the load on the engine.

Since the power produced by the engine proved to be very small in former performance tests, the prony brake had to be designed so that minimum drag was encountered for small engine loads. A lightweight prony brake with small contact area between it and engine's flywheel would meet this criterion. Also, since the engine's prony brake would produce small torques, the design had to provide a brake whose lever arm was as short as possible so that greater brake forces could be produced. Thus, more accurate force measurements could be made. The brake design adopted by this investigation is shown in Figure 17. Figure 16 shows the prony brake installed on the flywheel of the engine.

Since the engine would assume many positions, it was

Figure 15. Pyrheliometer Installation.

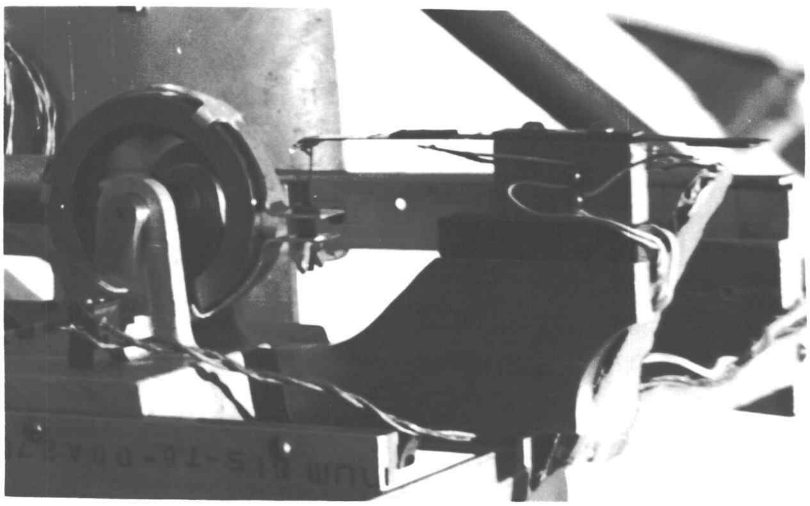

Figure 16. Power Measuring Apparatus.

paramount that the device which measured the force produced by the prony brake be capable of meeting this requirement. It was therefore decided to use the cantilever beam arrangement shown in Figure 16. The force, applied to the end of the beam, was measured by means of a strain gage attached to the surface of the beam. Figure 18 indicates the position at which the gage was fastened to the beam. A strain gage could be used satisfactorily in this manner since the strain at the outer surface of the beam was directly proportional to the force applied at its end. An Ellis bridge amplifier and meter was used to measure the resulting strain.

Measurement of a small engine's speed is perhaps most readily accomplished by using a stroboscope. However, this method proved unsuccessful for the solar-powered Stirling engine because the intensity of the sunlight on the moving parts of the engine was greater than the intensity of the stroboscope's light. Other methods were investigated, but the one that proved most accurate and easiest to use involved a Tektronix oscilloscope to measure the period of the engine revolutions.

By installing a thin leaf switch such that it came lightly into contact with the engine's crank during each revolution, it was possible to complete an electrical circuit which triggered the calibrated sweep of the

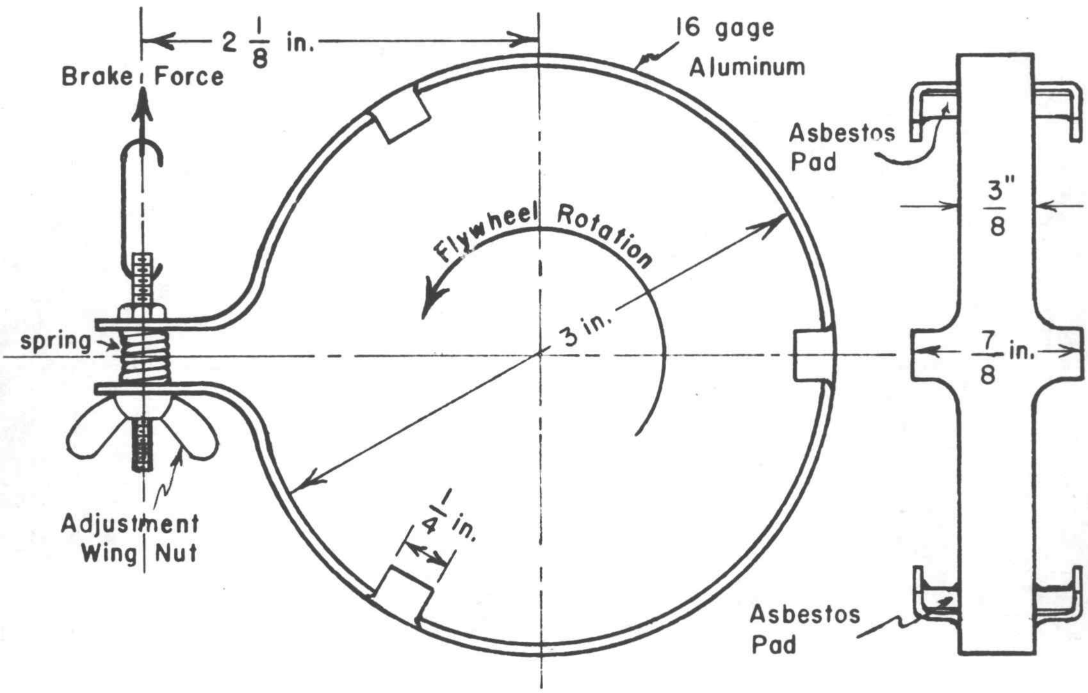

Figure 17. Prony Brake Design.

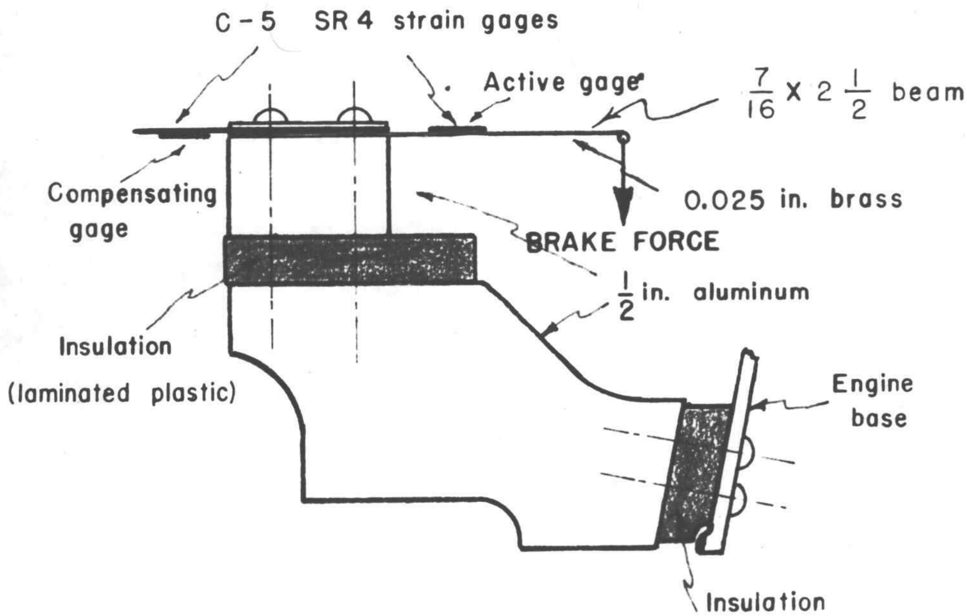

Figure 18. Cantilever Beam Design.

oscilloscope. Thus, it was possible to determine the time interval between engine revolutions. The effect of the friction between the leaf switch's contact point and the engine was negligible. The leaf switch can be seen mounted on the engine in Figure 16. The diagram for the triggering circuit is shown in Figure 19.

The temperatures achieved by the end of the displacer cylinder were determined by the installation of two thermocouples. Both were attached to the cylinder with silver solder. One of the thermocouples was fixed on the center of the cylinder's end. The other was attached on the side of the cylinder 3/4 in. from its end. Figure 20 shows the placement of the thermocouples on the displacer cylinder.

The separate performance test on the Stirling engine involved placing the engine's displacer cylinder into a small, well-insulated electrical resistance furnace. The electric power supplied to the furnace was controlled by a rheostat and Variac and was measured by a wattmeter. The mechanical power produced by the engine was obtained in the same manner as described previously with the exception that the engine's speed was measured with a stroboscope. The test setup is shown in Figure 21. The section of the furnace shown in Figure 22 illustrates the position of the displacer cylinder.

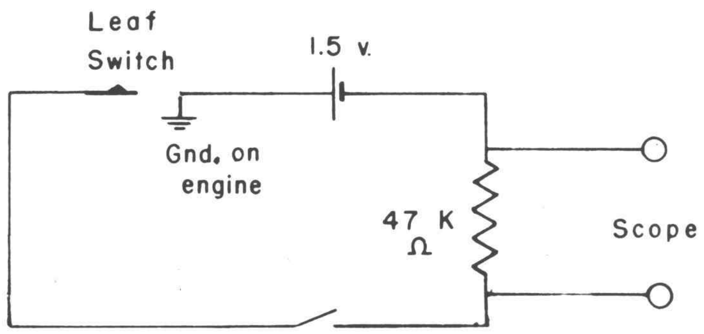

Figure 19. Oscilloscope Triggering Circuit.

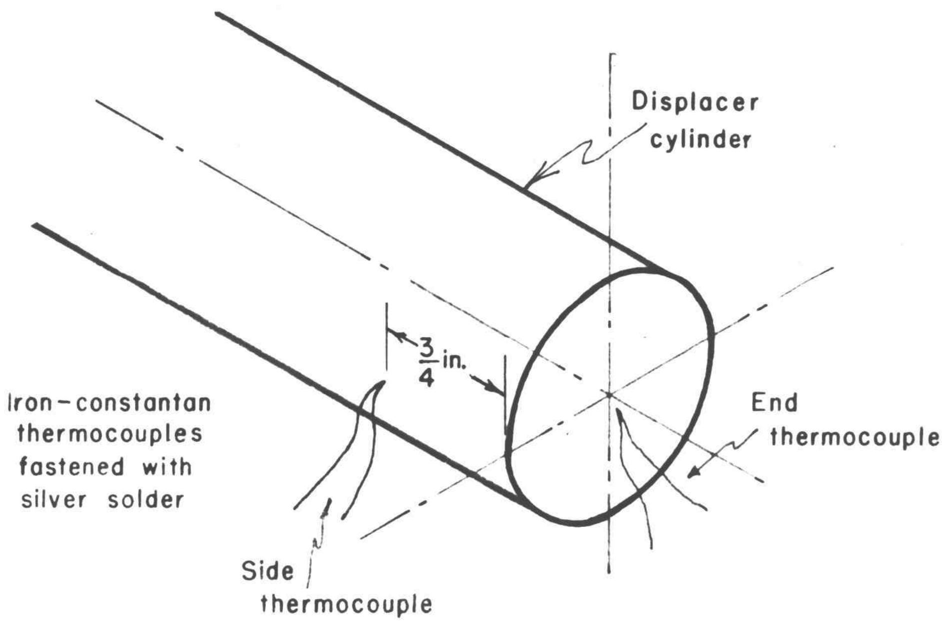

Figure 20. Thermocouple Placement.

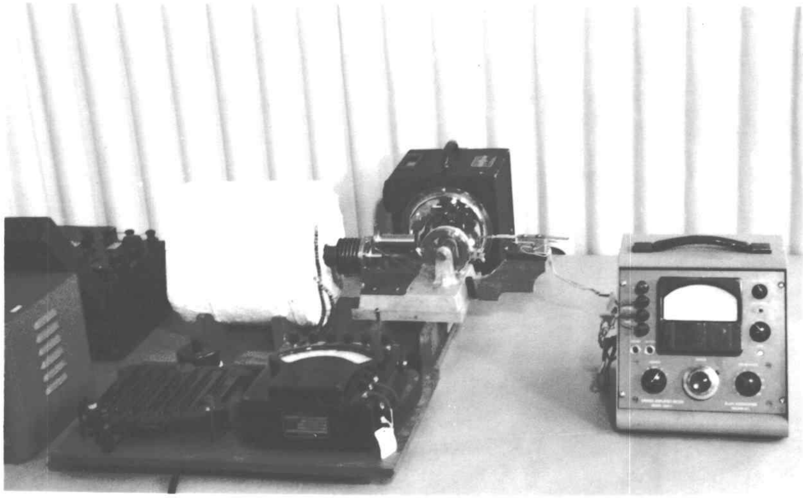

Figure 21. Performance Test Setup with Electric Furnace.

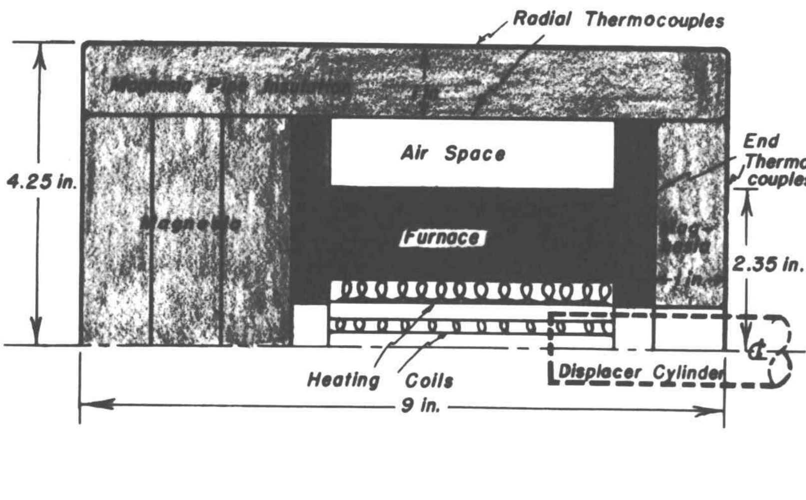

Figure 22. Section of Insulated Furnace.

DISCUSSION OF TEST RESULTS

Preliminary test runs were made on the solar-powered Stirling engine to determine the best position for its displacer cylinder along the mirror's axis. Tests performed with the end of the cylinder submerged approximately 1/2, 1, and 1-1/2 in. past the mirror's focal point seemed to indicate that the 1 in. setting produced the best performance results. Actually, with this setting, the displacer cylinder was exposed to concentrated light on its entire end and approximately 3/4 in. along its side. The manner in which the light was concentrated on the end of the cylinder is shown by the picture in Figure 13.

Data that were chosen for the preparation of the final performance results were based upon the best testing procedure devised for obtaining the necessary observations. For instance, when it was found that the strain gage meter refused to remain zeroed during a test run, it became necessary to use one of two testing procedures. One method required the removal of the force from the cantilever beam while zeroing the meter. The resulting force was then observed upon replacing the load on the beam. The second method involved observing the meter before and after removing the load from the beam. Thus, the difference was the resulting torque force produced by the prony brake. A steady operating condition of the engine could be detected more readily when employing the latter method. Therefore, the data taken by this latter method were used in the preparation of the performance results.

It was found that a difference existed in the performance of the Stirling engine each day the solar energy conversion system was tested. Therefore, the power output was represented by separate curves constructed for each day. These curves as well as one which estimates the mean power output are shown in Figure 23.

Since it was inconvenient to express the small power produced by the engine in units of hp, it was decided to use units of milli-hp instead. One milli-hp is equal to 0.001 hp. At full load, the maximum power produced by the engine varied from approximately 0.50 to 0.65 milli-hp. A value of 0.58 milli-hp (equivalent to 1.48 Btu per hr) was chosen as the mean. A speed of 320 rpm accompanied the maximum power output. The average maximum no-load speed for the engine was 540 rpm.

The overall efficiency of the solar energy conversion system followed the same general relation as the power produced by the Stirling engine. Figure 24 shows the overall efficiency of the system. Instead of constructing a curve for each testing day, a range for all tests was used to

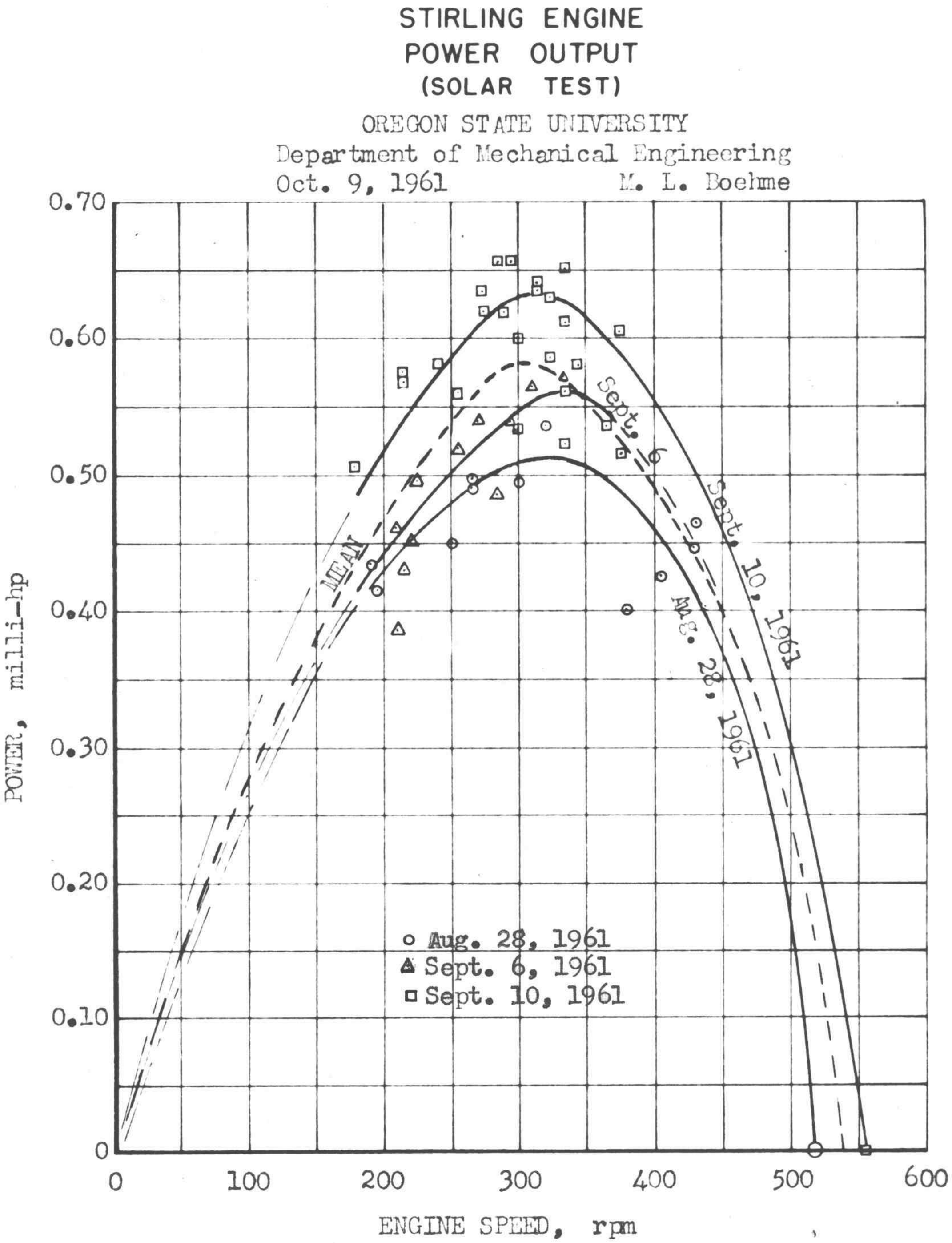

Figure 23. Power Produced by the Solar-Powered Stirling Engine.

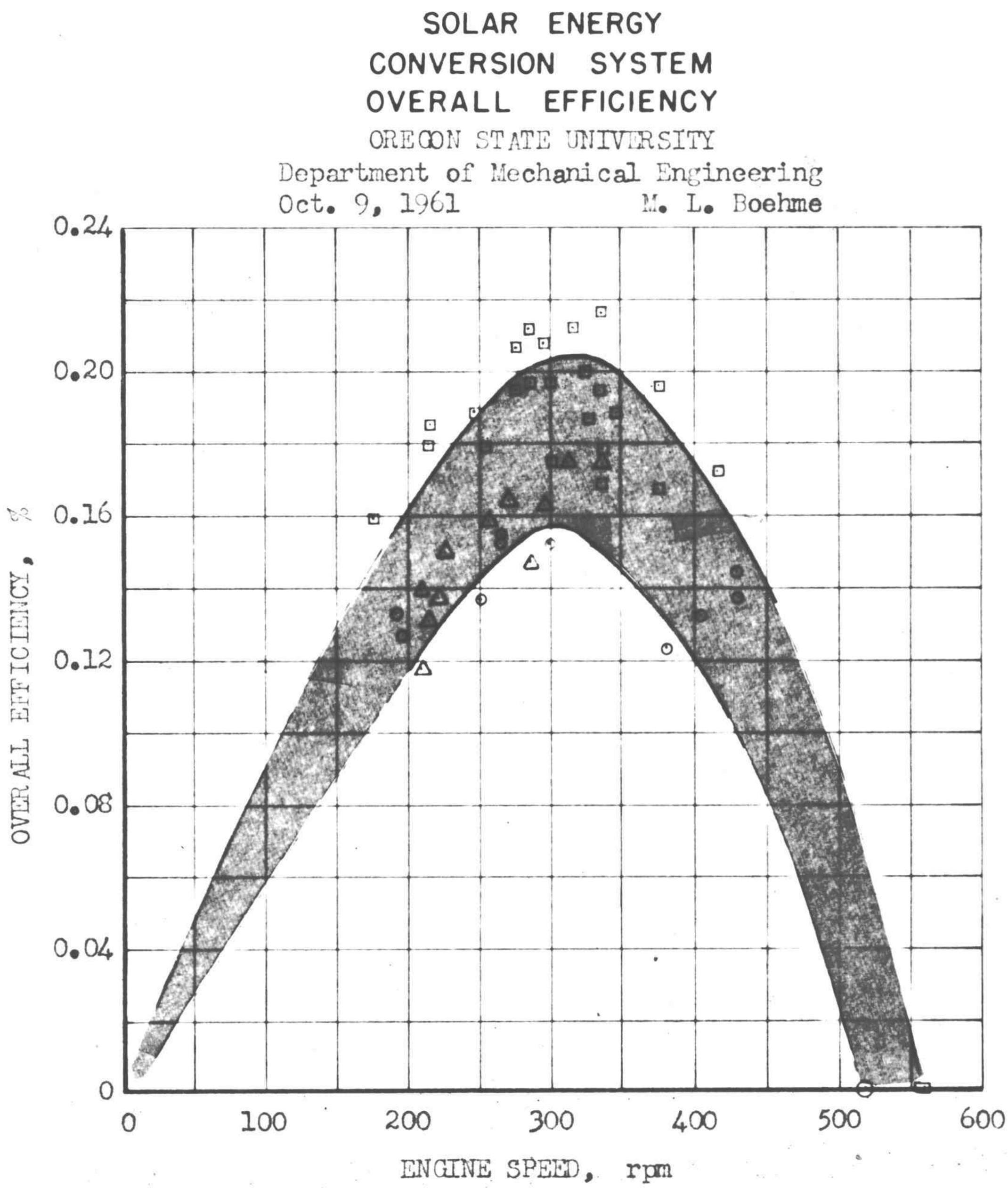

Figure 24. Overall Efficiency of the Solar Energy Conversion System.

indicate the efficiency. However, a maximum mean efficiency could be represented as being approximately 0.180 per cent. In other words, the mechanical power produced by the engine was less than one-fifth of one per cent of the available solar energy impinging upon the mirror's collecting area.

Calculations used in determining the performance of the solar power plant are found in the appendix.

The direct solar radiation which was normal to the mirror's collecting area was found by the previously described method. For the days that testing was conducted on the solar energy conversion system, the average normal incident radiation was 294 Btu per hr-sq ft. Therefore, 810 Btu per hr of solar energy was available to the effective collecting area of the 24 in. diameter parabolic mirror. Although the radiation did not remain constant during the test runs, its variation was found to be only from one to three per cent from the average. The results of the radiation observations and calculations are shown in the appendix.

The fact that the solar-powered Stirling engine was tested on separate days undoubtedly accounted for the difference existing in the performance results. Different testing conditions were created for each test, for both the engine and its testing equipment could not remain set up overnight. Thus, the apparatus had to be dismantled between tests.

Irregularities in the performance were also noted during a single testing period, for a testing procedure was adopted so that the eingine's performance could be compared at one speed. For example, at 325 rpm, the engine's power output varied from 0.585 to 0.630 milli-hp. The operating characteristics of the engine could have caused this variation. It was noted, for instance, that the engine's speed would increase momentarily when its bearings were being oiled. On the other hand, an error in the instrumentation could have caused the performance results to vary. An error of the nearest division to which the scale of the strain gage meter could be read would have accounted for the difference in power cited above.

The testing of the Stirling engine with its displacer cylinder placed in the electric furnace made it possible to compare its performance with the performance of the solar-powered engine. Therefore, to achieve similar testing results, the heat supplied to the small electric furnace was controlled until the engine achieved the same no-load speed that it had when it was used as part of the solar energy conversion system. Testing followed the same procedure as for the solar runs, except that the speed of the engine was measured with a stroboscope. The results of the electric furnace performance test are shown in Figure 25 and Figure 26. The minimum speed which could be conveniently determined with the stroboscope was approximately 200 rpm and explains the lack of data below that point.

At full load, the maximum power developed by the engine during the electric furnace performance test was 0.565 millihp at a speed of 275 rpm. The no-load speed was 530 rpm. The maximum brake thermal efficiency of the Stirling engine during the electric furnace test was approximately 0.20 per cent. These results are compared with the results of the solar-powered Stirling engine in Figure 25 and Figure 26.

Installation of the thermocouples on the displacer cylinder enabled its temperature to be observed. Unfortunately, the thermocouple on the side was of little value, for its readings were very irregular. Actually, it was installed in the wrong place, for the concentrated light on the end of the cylinder would sometimes strike the thermocouple when the mirror was not positioned correctly. At best, its temperature was estimated as being 40 to 50 F below that of the thermocouple at the very end of the cylinder. The temperature at the end of the cylinder increased as the load on the engine was increased.

Results from one of the tests are shown in Figure 27.

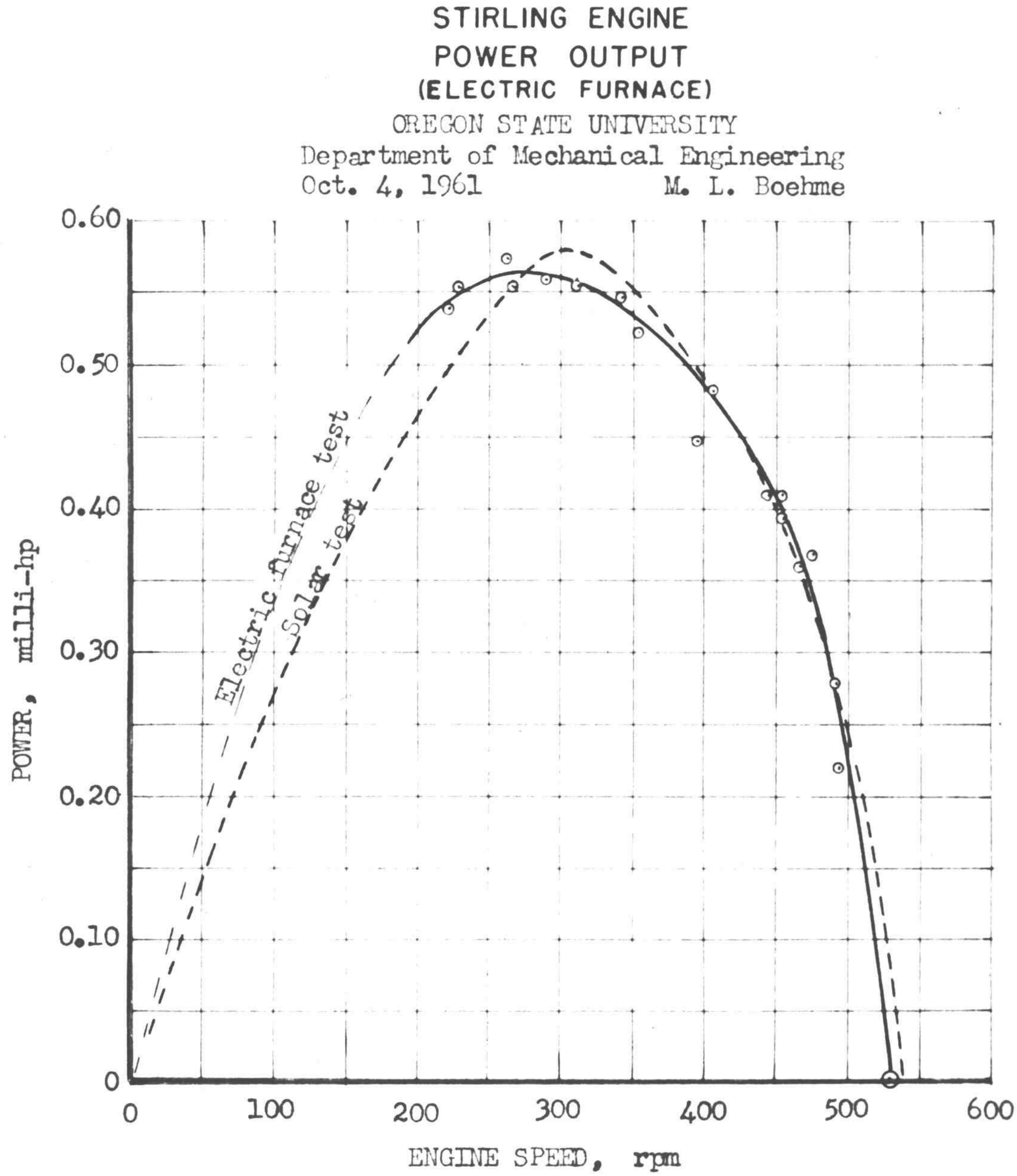

Figure 25. Stirling Engine Power Output-Electric Furnace Test.

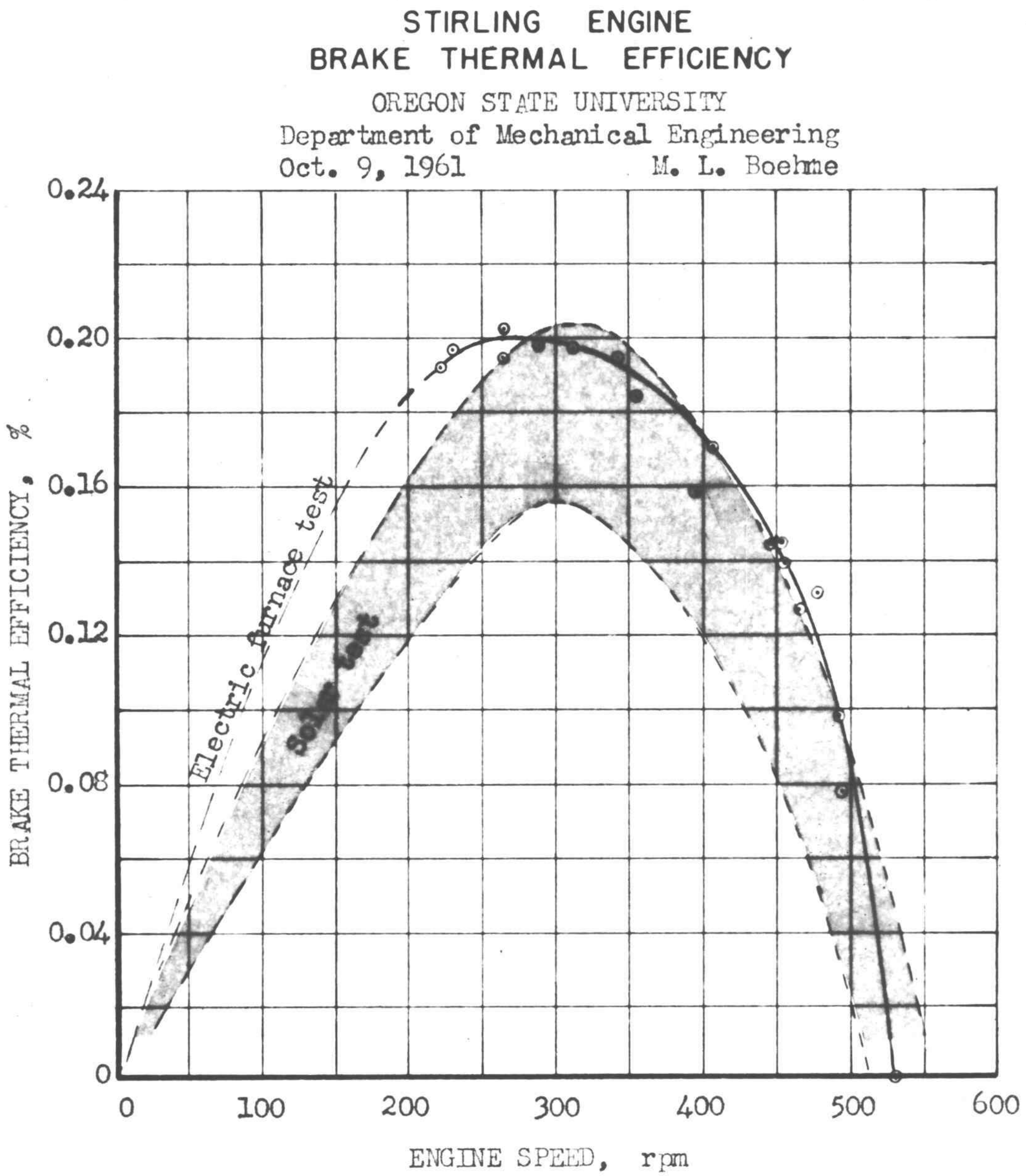

Figure 26. Stirling Engine Brake Thermal Efficiency-Electric Furnace Test.

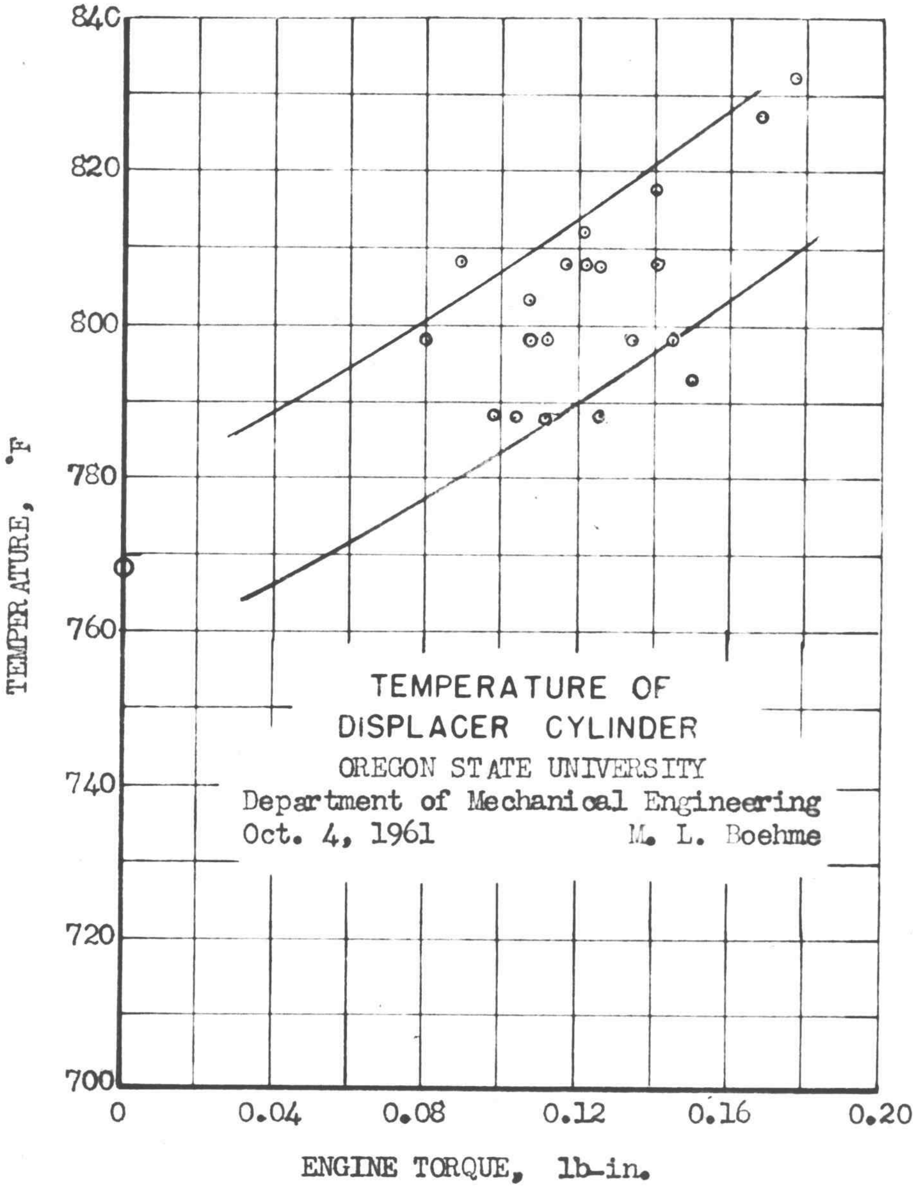

Figure 27. Displacer Cylinder Temperature.

A maximum temperature around 820 F occurred when the torque produced by the engine was 0.170 lb-in. The minimum temperature at the very end of the cylinder was approximately 770 F and was achieved during the no-load run.

A solar test run was made with the end of the cylinder coated with carbon deposited by an acetylene torch. Since the carbon was black, the absorbing surface of the displacer cylinder should have both absorbed and reradiated more solar radiation. However, no difference in the performance of the engine could be detected. In fact, during the test run, the carbon disappeared from the end of the cylinder where the sun's rays had been concentrated on it.

CONCLUSIONS

It was known at the outset of the project that the model Stirling hot-air engine incorporated in the solar energy conversion system would operate simply by heating the end of its displacer cylinder by a bunsen burner. Yet, since the temperatures obtainable in the neighborhood of the parabolic mirror's focal length were not known, it was questionable whether the heat created by the mirror with the end of the displacer cylinder positioned inside its focus would be great enough to power the engine. However, the solar-powered engine proved capable of performing in a manner comparable with the preliminary experiment conducted on it.

The engine used in the system proved to be very inefficient. Previous tests performed on the same engine resulted in the same conclusion (22:24; 47:14). However, the overall efficiency of this project's conversion system was far better than that achieved by the previously mentioned performance tests. For instance, one of the tests was performed with the displacer cylinder's end heated by a bunsen burner (22:11). When the maximum brake thermal efficiency of that test was compared with the maximum efficiency of the solar energy conversion system, it was found that the latter efficiency was three times greater.

Due to the higher temperatures involved, the power produced by the Stirling engine during this previous test was approximately three times greater than when the engine was solar-powered (22:19).

Testing the Stirling engine with its displacer cylinder placed in the electric furnace made it possible to compare its performance with the performance of the engine when it was mounted over the parabolic collector. The power produced by the engine compared very favorably as is indicated in Figure 25. However, perhaps it is of more interest to compare the engine's efficiency during the two tests (Figure 26).

The efficiency of the solar-powered engine was actually the efficiency at which the system converted the available solar energy into usable mechanical power. On the other hand, the engine's efficiency during the furnace test represented the efficiency at which the engine utilized the electric power supplied to the furnace. Therefore, since the solar tests differed from the furnace tests because of the solar radiation collector, it would appear that some idea of the solar radiation collection efficiency could be obtained from the results of the two tests.

This collection efficiency would represent the efficiency at which the mirror and absorbing surface of the displacer cylinder converted the available solar energy to heat. The definition of the collection efficiency for this case would be the ratio of the overall efficiency of the solar energy conversion system to the brake thermal efficiency achieved by the hot-air engine during the furnace test. However, since the overall efficiency of the conversion system could only be represented by a range, no attempt was made to establish a solar radiation collection efficiency in this manner.

One of the energy losses encountered by the solar-powered Stirling engine was the heat loss from the heated end of the displacer cylinder. Because of its high temperature, heat was lost by thermal radiation and convection to the surroundings. Also, heat was lost because it was conducted to other parts of the engine. The effect of this loss on the efficiency of the engine was two-fold. First, the heat was not utilized by the working fluid of the engine, but instead was lost by radiation and convection from the hot parts of the engine. Secondly, the transfer of heat from the hot end of the displacer cylinder resulted in raising the cooling fin's temperature. When this occurred, the temperature gradient necessary for the convection of heat from the engine's cooling space to its cooling fins was lowered. Thus, the ideal (Carnot) efficiency for the cycle was reduced.

The maximum power produced by the solar energy conversion system employed in this investigation indicated that a solar radiation collecting area of 4750 sq ft would be required if a similar system was to produce one horsepower. This does not compare very favorably with the 50 sq ft deemed necessary by some investigators of solar power plants (56:1356).

More research and development are needed before the method used in this project will prove to be economical and practical. Since the fuel (solar energy) costs nothing, its utilization is not too dependent on the efficiency at which it can be converted to usable sources of power. However, the installation and maintenance costs connected with a large solar collector as the one indicated above would appear to be prohibitive.

The conversion of solar energy to mechanical power by using a Stirling hot-air engine does have possibilities for providing an auxiliary power supply in the future and definitely has possibilities for being utilized in space applications. Perhaps the biggest advantage of such a system is the engine itself, for it is simple to operate and can run effectively on a heat source created by a focusing solar collector. In addition, similar solar energy conversion systems would prove to be valuable to those underdeveloped countries where sunshine is abundant and the need of a small source of power apparent.

RECOMMENDATIONS

Undoubtedly, better results would have been achieved if all the testing had been performed on the same day. Since this is not always possible, it is suggested that future testing of solar energy conversion systems be conducted on consecutive clear days. Solar radiation observations seemed to indicate that the best time to perform tests was from a half hour before noon to a half hour after noon. During this time, the solar altitude angle and the normal incident radiation experience little change. In addition, it is suggested that the testing equipment remain set up. Perhaps some type of weather-resistant cover could be employed for this purpose.

The design of the force measuring device used in this investigation could be improved. For instance, placement of the strain gages on opposite sides of the cantilever beam would have improved the force observations in two ways. First, since the strain gage on top of the beam would be in tension and the one on the bottom would be in compression, the actual change in resistance created by a force applied to the end of the beam would be doubled. Thus, more sensitive forces could be determined. Secondly, less chance of error due to temperature changes of the active gage would occur since the one gage serving as the temperature compensating gage would certainly experience the same temperature as the one installed just opposite it.

The prony brake design had two drawbacks. First, the brake tended to grab during some of the higher speeds. Second, too small an adjustment range was available with the wing nut arrangement shown in Figure 17. Since it was believed that a small contact area between the prony brake and the flywheel of the engine would produce the best results, the contact area was distributed in three places. However, it is suggested that an improved design consist of the contact area distributed continuously around the brake's periphery. Perhaps its tendency to grab would be eliminated.

A different placement of the passage that connects the displacer cylinder to the power cylinder might improve the performance of the engine. Changing the position of the passage to the end of the displacer cylinder as shown by the drawing in Figure 28 would allow the air to pass through the cold space in a manner similar to that illustrated in Figure 8. The installation of some type of regenerator sould also produce better results.

In order to achieve an idea of the collection efficiency of the mirror, the use of a heat exchanger such as shown in Figure 29 might be adopted. The design of the heat exchanger conforms to the same shape of the displacer

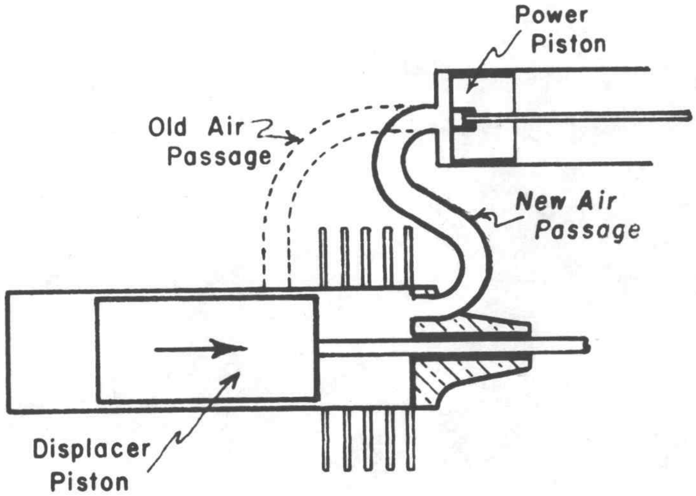

Figure 28. Air Passage Change.

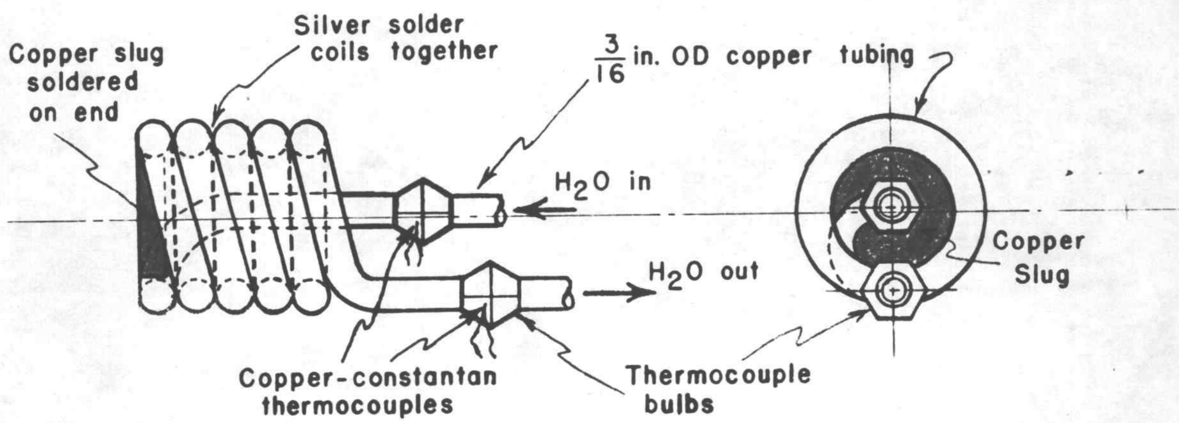

Figure 29. Heat Exchanger Design.

cylinder and is intended to be placed in the focus of the mirror in the same manner as the end of the cylinder was placed. The heat exchanger can also be used to determine the effectiveness of different selective surfaces applied to it.

Since the performance of the Stirling engine used in this investigation varied during the test runs, a method for immediate observation of these variations would have been welcome. Perhaps for future tests, it may be possible to use some type of coordinate recorder for this purpose. For example, with the abscissa recording the force measurements and the ordinate recording the engine's speed, "power output diagrams" may be created by introducing the required constants.

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A P P E N D I X

FRESNEL LENS COLLECTOR

One design of the solar energy conversion system involved the use of a Fresnel lens as the solar radiation collector. The lens was made of acetate butyrate plastic and was 13 in. in diameter with a focal length of 14 in. The manner in which the lens was mounted is shown in Figure 30.

In order for the lens to be completely effective, it had to be mounted so that its surface was absolutely flat. However, when gluing the plastic lens onto its wooden frame, its glued circumference would shrink. Thus, the thin plastic developed wrinkles in its surface. The effect of the wrinkles seemed to cause a distortion of the concentrated light at the lens' focal point.

A preliminary design of the conversion system included a radiation absorber consisting of a liquid metal bath located at the focal point of the lens. The Stirling engine would have used the bath as its heat source. However, after investigating the possibilities of melting several metals with low melting points by this method, the idea was discarded. The area of high temperature provided at the lens' focal point was too small.

Additional disadvantages of this design were also evident. For example, high solar radiation reflection losses would have occurred from the surface of the molten metal.

Figure 30. Fresnel Lens Collector.

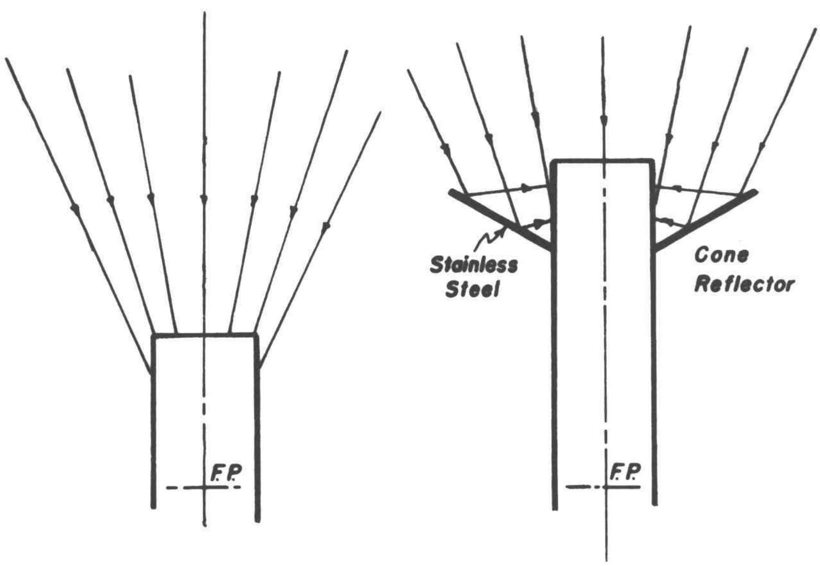


Figure 31. Truncated Cone Collector.

Also, the transfer of heat to the working fluid of the engine would have involved, first, a convection process from the liquid metal to the end of the engine's displacer cylinder, then a conduction process through the walls of the cylinder, and finally another convection process from the cylinder's walls to the gas itself. Therefore, it was evident that the heat transfer process from the absorbed radiation to the working gas of the engine would have encountered high thermal resistances.

The observation above indicated that perhaps the best manner in which to utilize the concentrated solar radiation was to place the end of the engine's displacer cylinder at the focal point. The surface of the cylinder then served as the absorber for the concentrated radiation. Thus, the previous liquid metal thermal resistance would be eliminated.

With the lens' focal length and diameter having close to a one-to-one relation, the collected rays of the sun struck the end of the displacer cylinder at a small angle with respect to the cylinder's center line. This is illustrated in Figure 31. Another method of concentrating the sun's rays on the end of the displacer cylinder could have been used. This method would have consisted of a truncated cone reflector made of stainless steel installed on the end of the displacer cylinder as illustrated in Figure 31.

The engine was not tested with the cone reflector used in this manner. However, without it, it was found that the engine would barely run under a no-load condition. Reflection losses occurring with the stainless steel reflector would have reduced the available solar radiation even further.

The Fresnel lens solar collector was abandoned because the results cited above indicated that the collecting area was not large enough.

OSCILLOSCOPE CALIBRATION

The calibrated sweep of the oscilloscope was assumed to be accurate and in adjustment for the tests performed on the solar-powered Stirling engine. However, when this instrument was checked with a stroboscope, it was found that the oscilloscope measurements of speed were as much as three per cent in error. Since the stroboscope could be adjusted by means of a vibrating reed (controlled by the 60-cycle power supply), this instrument was used as a standard by which the oscilloscope could be calibrated. Adjustments were made at 900 on the stroboscope's low range and at 3600 on its high range.

The middle of the stroboscope's low range was used to determine the speed of the engine during the calibration of the oscilloscope. This range had to be used because the speed of the engine was below that of the smallest value on the scale. Thus, the moving parts of the engine had to be viewed two or three times per revolution.

The calibration curve for the oscilloscope is included in Figure 32. The oscilloscope was adjusted and used for the last solar test. When checked against the stroboscope for the second time, it was found to compare within one per cent.

TEMPERATURE CORRECTIONS

A Hoskins Thermo-Electric Pyrometer with iron-constantan thermocouples was used to find the temperatures at the end of the displacer cylinder. However, in order to find the actual temperatures, it was necessary to calibrate this instrument.

Calibration was carried out by observing the temperatures of lead, tin, and zinc as they were melted and again while they were solidifying. The metal's latent heat of fusion allowed its melting temperature to be observed in this manner because the temperature remained steady during the phase change. Corrections were applied to the pyrometer readings according to the correction curve shown in Figure 33.

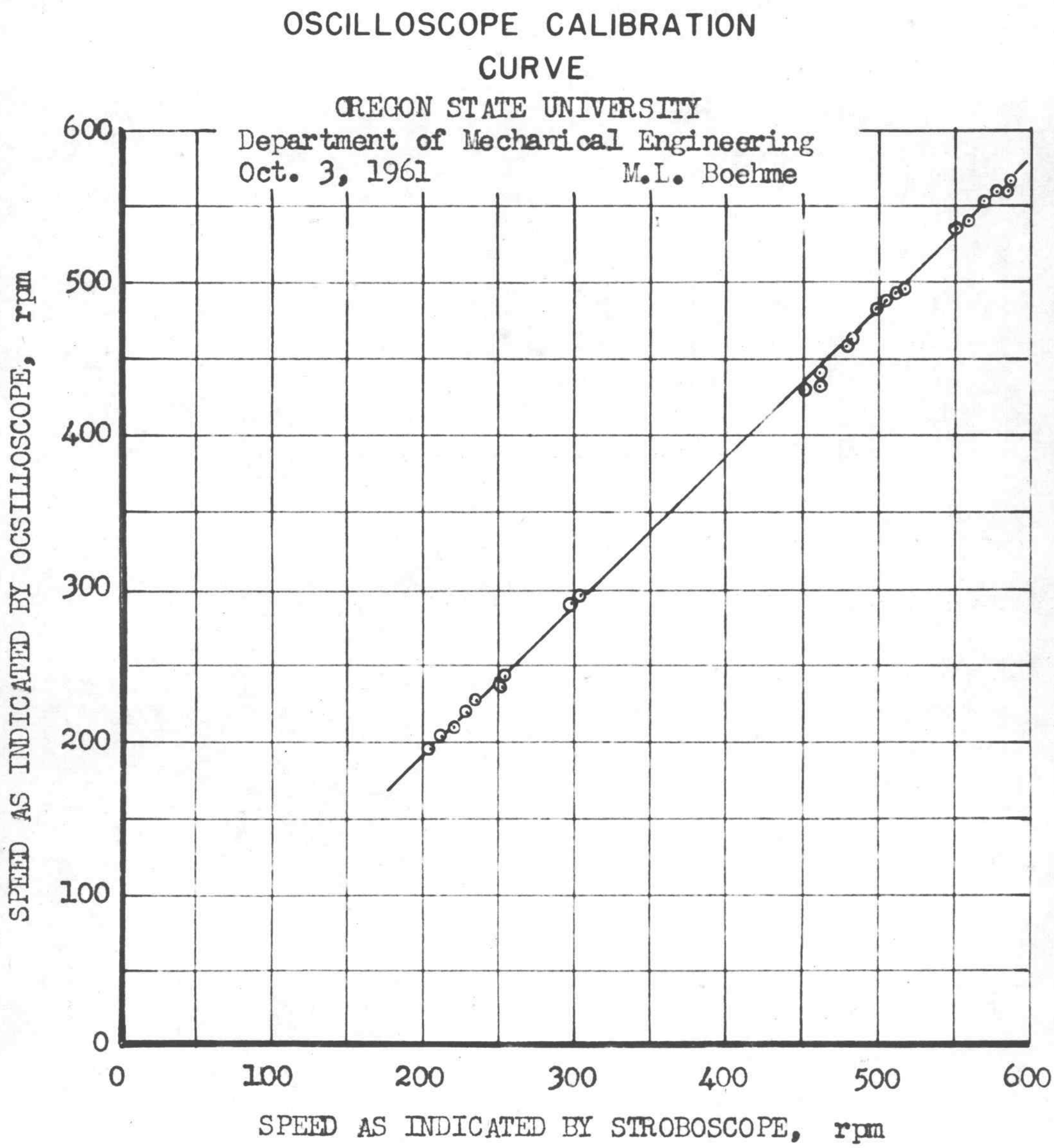


Figure 32. Oscilloscope Calibration Curve.

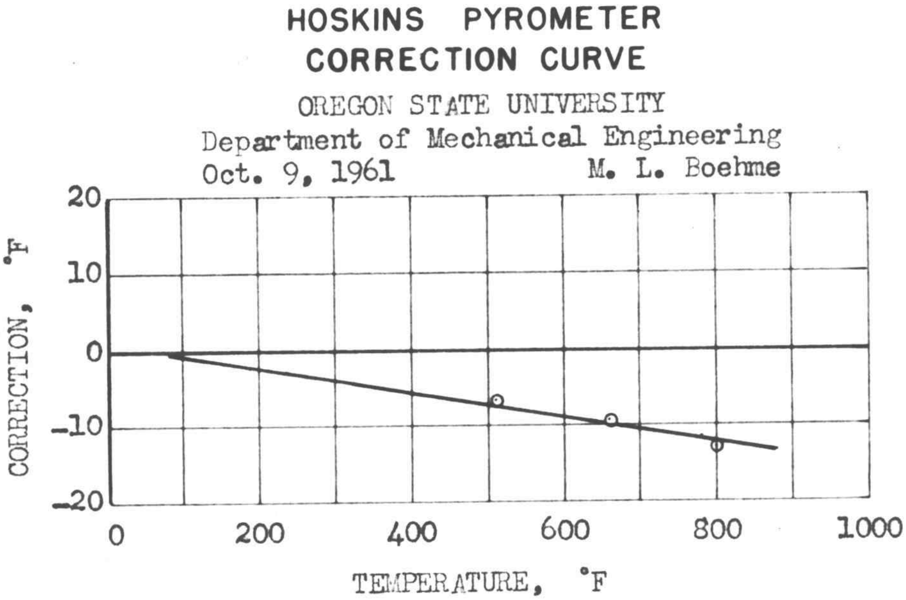


Figure 33. Pyrometer Correction Curve.

SOLAR RADIATION OBSERVATIONS

The solar radiation values received from the pyrheliometer's recording potentiometer represented the total (direct plus diffuse) radiation received on a horizontal surface. The diffuse radiation was found by shading the sensing element of the pyrheliometer every ten minutes for a period of two minutes. During this period, the recording potentiometer was able to record the resulting diffuse radiation. For the days that the solar-powered Stirling engine was tested, the diffuse radiation seemed to remain constant. This accounts for the linear relation between the direct and total radiation received on a horizontal surface shown in Figure 34. Although the observations were made only during one of the days that testing was performed on the engine, it was assumed that the same results would have occurred on other similar days of the season.

The solar altitude angles were found by using an almanac and a prepared table of altitude and azimuth angles. The method of calculating the solar altitude angles is presented in Example 1. Figure 35 illustrates the solar altitude angles for the days testing was performed on the solar powered Stirling engine.

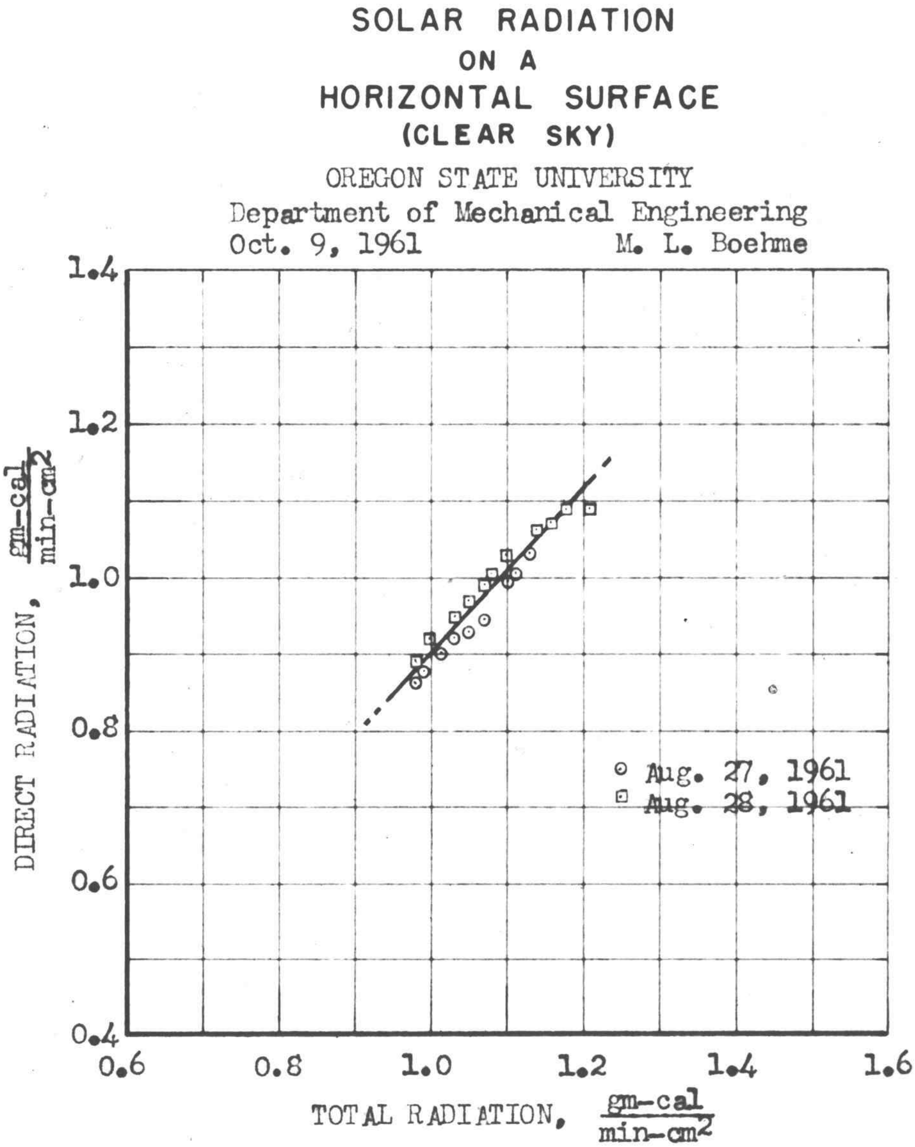


Figure 34. Radiation Received on a Horizontal Surface.

Given: The position of Corvallis, Oregon, is 123°18' W and 44°34' N.
Req'd: Find the solar altitude angle at 12 AM (PST) on Sept. 6, 1961.

1. Pacific Standard Time (PST) of 12 AM is equivalent to 2000 Greenwich Mean Time (GMT).

2. The Greenwich Hour Angle (GHA) for 2000 GMT was 120°26' and the Declination (Dec.) was 6°18' (52:175).

3. The Local Hour Angle (LHA) at Corvallis was found as follows:

$$\begin{aligned} LHA &= 123°18' - GHA \\ &= 123°18' - 120°26' \\ &= 2°52' \end{aligned}$$

4. For a LHA of 2°52' and a Dec. of 6°18', the solar altitude angle was approximately 52.0° at the 44° latitude and approximately 51.0° at the 45° latitude (53:108, 134).

5. The solar altitude angle was therefore estimated as being 51.5° at Corvallis (44.5° latitude).

6. Since 12 AM (PST) is based on the 120° meridian, the time had to be changed accordingly. Each degree of longitude represents a time change of 4 min. Therefore, a correction of 12 min was subtracted since the time west of a meridian is earlier than the time east of a meridian. High noon at the 120° meridian corresponds to 11:48 AM in Corvallis, Oregon (123° longitude).

7. Since the solar altitude angle changed very little at high noon, the answer of 51.5° was still used. This was not true for other times of the day. Thus, a curve of the solar altitude angles for the day of Sept. 6 was constructed and the time scale changed the required 12 min.

EXAMPLE 1. Solar Altitude Angle Calculations.

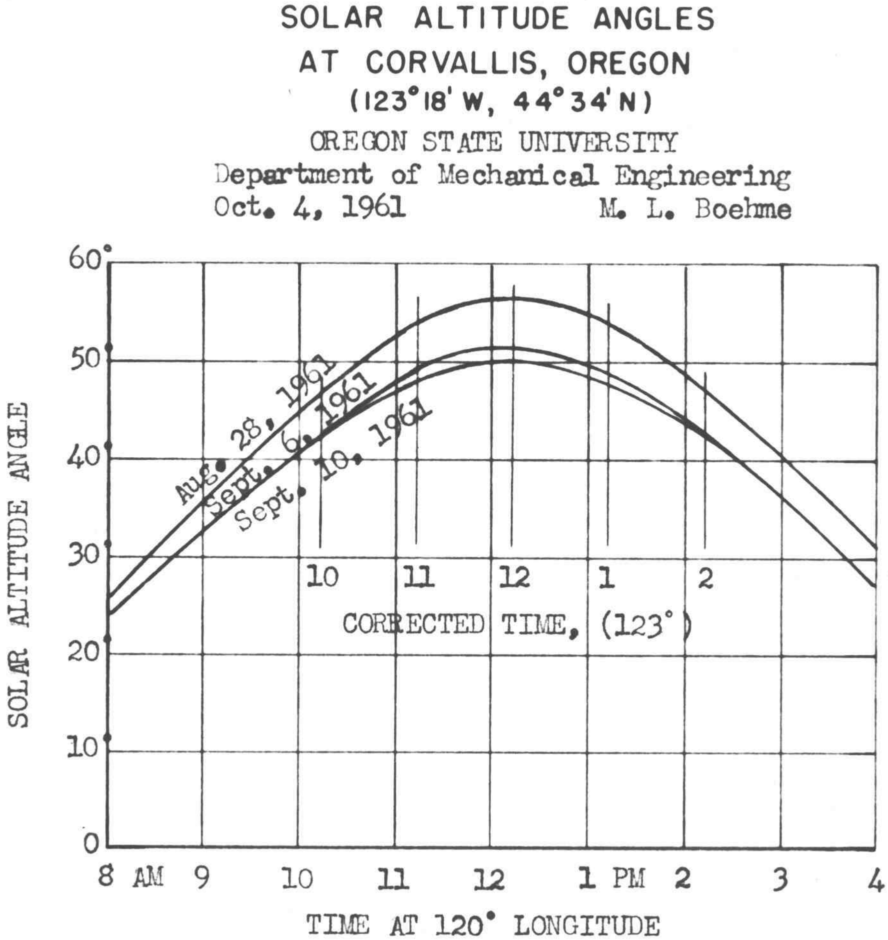


Figure 35. Solar Altitude Angles.

PERFORMANCE CALCULATIONS

The effect of the prony brake's unbalanced weight (brake tare) on the force measurements had to be taken into account. Since the engine was to assume various angles, the brake tare would also vary. Example 2 illustrates how brake tare was determined. The results of the calculations are shown by the curve in Figure 36.

Example 3 illustrates how the engine's speed was determined from the oscilloscope readings. The performance of the solar-powered Stirling engine was determined by methods presented in Example 4.

Table I presents data that were taken during one of the testing days. The results of the performance calculations are also shown in Table I. Data from the electric furnace test are included in Table II. The calculated results are also included in Table II.

Given: The unbalanced weight of the prony brake (brake tare) was 8 gm when the engine was in a horizontal position.

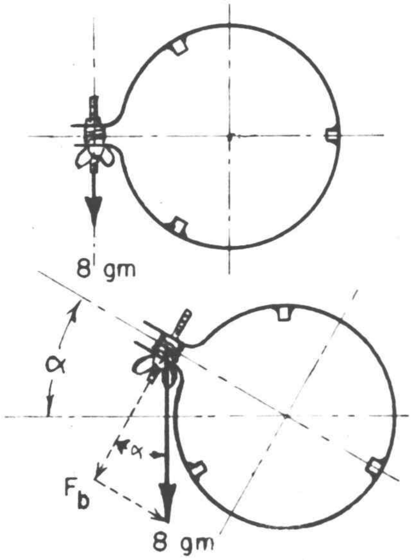
Req'd: Find the effect of the brake tare on the force measurements.

1. For convenience, the unbalanced weight of the brake was assumed to be concentrated at the point shown in the sketches.

2. At any solar altitude angle (α), the measured force consisted of the actual force produced by the engine plus the brake tare.

3. Therefore, the brake tare (F_b) was found by the relation:

$$F_b = (8 \text{ gm})(\cos \alpha)$$



EXAMPLE 2. Brake Tare Calculations.

Given: The calibrated sweep of the oscilloscope was triggered at 3.7 cm. The multiplier was 50 milli-sec per cm.

Req'd: Find the speed of the Stirling engine for this observation.

1. The period of each revolution was found as follows:

$$\begin{aligned} \text{Period} &= (\text{scope reading})(\text{multiplier}) \\ &= (3.7 \text{ cm})(50 \text{ milli-sec per cm}) \\ &= 185 \text{ milli-sec per rev} \\ &= 0.185 \text{ sec per rev} \end{aligned}$$

2. The speed of the engine was then determined from the following relation:

$$\begin{aligned} \text{Speed} &= \frac{(60 \text{ sec per min})}{\text{Period}} \\ &= \left(60 \frac{\text{sec}}{\text{min}}\right) \frac{\text{rev}}{0.185 \text{ sec}} \\ &= 325 \text{ rpm} \end{aligned}$$

EXAMPLE 3. Engine Speed Calculations

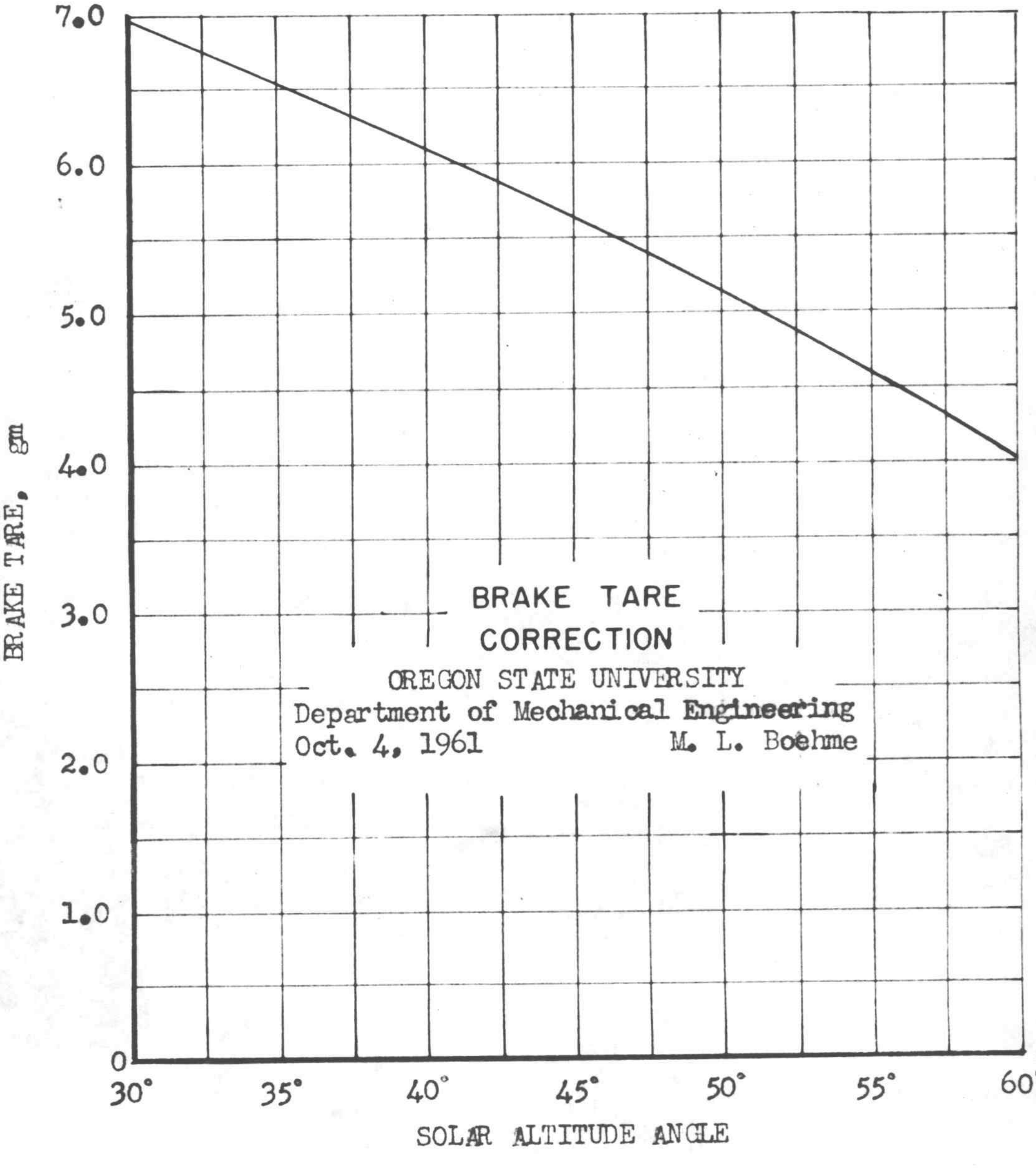


Figure 36. Brake Tare Correction.

Given: The lever arm (r) of the prony brake used to measure the power of the Stirling engine was 2.125 in.

Req'd: Determine the engine's performance from the observed force and speed measurements and the calculated values for the direct normal solar radiation (Rn_{normal}).

1. The power (P) delivered by the engine was found by applying the force (F) and speed (N) measurements and unit equivalents to the following equation:

$$
\begin{aligned}
P &= (r)(F)(N) \\
&= (2.125 \text{ in.})(F \text{ gm})(N \text{ rpm}) \\
&= (2.125 \text{ in.}) \frac{1 \text{ ft}}{12 \text{ in.}} (F \text{ gm}) \frac{1 \text{ lb}}{454 \text{ gm}} \left(N \frac{\text{rev}}{\text{min}}\right) \frac{2\pi \text{ rad}}{\text{rev}} \\
&= 0.00245 (F)(N) \frac{\text{ft-lb}}{\text{min}} (1 \text{ hp}) \frac{\text{min}}{33{,}000 \text{ ft-lb}} \\
&= 7.425 \times 10^{-8} (F)(N) \text{ hp} \\
&= 7.425 \times 10^{-5} (F)(N) \text{ milli-hp}
\end{aligned}
$$

2. The effective area (A_e) of the mirror was found by determining its effective diam and the area of the engine's shadow on its surface. The effective diam = 23 5/8 in. The shadow = 43 in^2. Therefore, A_e = 396 in^2.

3. The total solar energy collected by the mirror (E_t) was found by applying the mirror's effective area (A_e) and unit equivalents to the relation:

$$
\begin{aligned}
E_t &= (Rn_{normal})(A_e) \\
&= \left(Rn_{normal} \frac{\text{gm-cal}}{\text{min-cm}^2}\right) 3.69 \frac{\text{Btu}}{\text{ft}^2} \frac{\text{cm}^2}{\text{gm-cal}} (396 \text{ in}^2) \frac{1 \text{ ft}^2}{144 \text{ in}^2} \\
&= 10.15 (Rn_{normal}) \frac{\text{Btu}}{\text{min}} \left(60 \frac{\text{min}}{\text{hr}}\right) \frac{\text{hp-hr}}{2544 \text{ Btu}} \\
&= 0.239 (Rn_{normal}) \text{ hp} \\
&= 239 (Rn_{normal}) \text{ milli-hp}
\end{aligned}
$$

4. The overall efficiency of the conversion system (η_o) was determined as follows:

$$
\begin{aligned}
\eta_o &= \frac{P}{E_t} (100) \\
&= \frac{P}{239 (Rn_{normal})} (100)
\end{aligned}
$$

EXAMPLE 4. Performance Calculations.

TABLE I

Solar-Powered Stirling Engine Test Data and Calculation Results

Time (PST)	Solar altitude angle	Brake force (avg.) gm	Brake tare gm	True brake force gm	Scope (avg.) cm	Engine speed rpm	True speed rpm	Total radiation (hor.) $\frac{\text{gm-cal}}{\text{min-cm}^2}$	Direct radiation (hor.) $\frac{\text{gm-cal}}{\text{min-cm}^2}$	Direct radiation (normal) $\frac{\text{gm-cal}}{\text{min-cm}^2}$	Power milli-hp	Overall efficiency
1:15	52.5	28.8	4.5	24.3	5.0	240	250	1.17	1.09	1.37	0.450	0.137
1:15	52.5	33.2	4.5	28.7	6.3	190	195	1.17	1.09	1.37	0.415	0.126
1:25	51.5	35.2	4.5	30.7	6.4	185	190	1.15	1.07	1.37	0.435	0.133
1:25	51.5	27.0	4.5	22.5	3.9	310	320	1.15	1.07	1.37	0.535	0.163
1:30	51.0	26.8	4.5	22.3	4.1	290	300	1.14	1.06	1.36	0.495	0.152
1:30	51.0	18.8	4.5	14.3	3.3	365	380	1.14	1.06	1.36	0.400	0.123
1:35	51.0	19.2	5.0	14.2	3.1	390	405	1.12	1.05	1.35	0.425	0.132
1:35	51.0	19.6	5.0	14.6	2.9	415	430	1.12	1.05	1.35	0.465	0.144
1:35	51.0	19.0	5.0	14.0	2.9	415	430	1.12	1.05	1.35	0.445	0.138
1:40	50.0	30.0	5.0	25.0	4.7	255	265	1.11	1.04	1.36	0.490	0.151
1:40	50.0	30.2	5.0	25.2	4.7	255	265	1.11	1.04	1.36	0.495	0.152
2:45	45.0	NO LOAD RUN			2.4	500	520	0.97	0.89	1.26	NO LOAD RUN	

TABLE II

Stirling Engine Test Data and Calculation Results
(Electric Furnace)

Brake force (avg.) gm	Brake tare gm	True brake force gm	Engine speed rpm	Power input watts	Power milli-hp	Brake thermal efficiency
32.0	8	24.0	312	210	0.555	0.197
34.0	8	26.0	290	210	0.560	0.198
23.2	8	15.2	396	210	0.445	0.158
24.0	8	16.0	406	210	0.480	0.170
19.6	8	11.6	456	210	0.390	0.138
20.2	8	12.2	453	210	0.410	0.145
14.0	8	6.0	494	210	0.220	0.078
15.6	8	7.6	491	210	0.275	0.098
20.4	8	12.4	444	210	0.410	0.145
20.4	8	12.4	444	210	0.410	0.145
29.6	8	21.6	342	210	0.550	0.195
28.0	8	20.0	352	210	0.520	0.185
36.0	8	28.0	266	210	0.550	0.195
37.2	8	29.2	264	210	0.575	0.202
40.8	8	32.8	228	210	0.555	0.197
40.8	8	32.8	222	210	0.540	0.192
18.4	8	10.4	466	210	0.360	0.127
18.4	8	10.4	476	210	0.370	0.131
NO LOAD RUN			530		NO LOAD RUN	