High heat flux engineering in solar energy applications[1]

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ABSTRACT

Solar thermal energy systems can produce heat fluxes in excess of 10,000 kW/m^2. This paper will provide an introduction to the solar concentrators that produce high heat flux, the receivers that convert the flux into usable thermal energy, and the instrumentation systems used to measure flux in the solar environment. References are incorporated to direct the reader to detailed technical information.

1. INTRODUCTION

Solar thermal energy systems collect the thermal energy of the sun for direct use, to drive a chemical process, or for conversion to mechanical or electrical energy. The systems of interest for the purpose of this paper are those which use mirrors to concentrate the sunlight to high levels. The United States Department of Energy supports research in concentrated solar thermal energy through two programs. The Solar Thermal Electric program emphasizes conversion of the solar thermal energy to electricity and also includes applications that displace use of electricity. Sandia National Laboratories in Albuquerque is the lead laboratory for the electric program. The Solar Industrial Program deals both with processes that use the thermal energy directly and with processes that use the thermal or photolytic energy of the sun to drive chemical processes. The National Renewable Energy Laboratory in Golden, Colorado, is the lead laboratory for the industrial program; however, both laboratories support both programs.

2. SOLAR THERMAL ENERGY SYSTEMS

Sunlight is divided into two components: direct and diffuse. The nominal strength of direct component, measured in a plane normal to the sun's rays, is 1 kW/m^2. To achieve higher flux levels for solar energy applications, three types of solar concentrators are commonly used, as shown in figure 1. Each uses an automatic tracking system to follow the sun's position.

Parabolic troughs typically track the sun in one axis, and focus the sunlight on a linear receiver. Maximum flux levels for parabolic troughs are ~100 kW/m^2. Heliostats are nearly-flat, two-axis tracking mirrors used in groups to concentrate sunlight onto a stationary receiver located on top of a tower. Peak flux levels achieved for heliostat fields are as high as 3,000 kW/m^2. Parabolic dishes also track the sun in two axes; however, the receiver is attached to and moves with the concentrator. As a result these systems achieve the highest flux levels, up to 15,000 kW/m^2. A fourth system type, the solar furnace, is primarily used for research. Solar furnaces use a flat, tracking heliostat to reflect the incident sunlight into a stationary dish.

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The performance of a solar furnace will be slightly less than its parabolic dish, but the furnace has other advantages as discussed below.

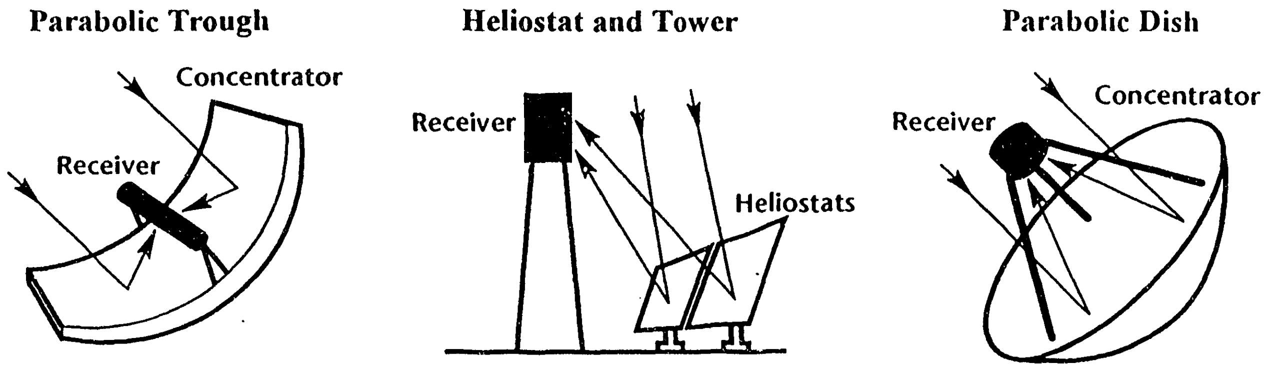

Figure 1. Common types of solar concentrators

The peak flux capability of a concentrator can be increased through the use of a secondary concentrator. Assuming a nearly-perfect primary concentrator, a reflective secondary concentrator can concentrate the sunlight 46,000 times to a nominal value of 46,000 kW/m^2. A refractive (n=1.5) secondary concentrator can achieve a theoretical concentration of 110,000.[1]

In the following sections each concentrator type and related applications are discussed, with an emphasis on the highest flux applications.

3. PARABOLIC TROUGHS

3.1 Concentrators

Two approaches are commonly used to achieve the parabolic shape required for a trough-type concentrator. In one approach, sheet metal is supported on contoured ribs. The sheet metal serves as a substrate for reflective surfaces that may be thin, silvered-glass mirrors or a metallized polymer film. In the second approach, thicker glass mirrors are thermally sagged to shape and attached to a metal framework.

3.2 Applications

Parabolic troughs have been used for both thermal and chemical applications. For thermal applications, the tubular receiver is a steel tube with a highly-absorptive, low emissivity coating. Such coatings include black-chrome, cermet, or black nickel, a recent development. The tube is surrounded by a glass envelope. The envelope may have an anti-reflective coating, such as solgel, and the space between is sometimes evacuated. The low emissive coating, glass envelope, and evacuated annulus work together to minimize radiative, conductive, and convective thermal losses.

Thermal applications include single- or few-collector systems to heat domestic water; systems containing thousands of square-meters of collector area to provide hot water or thermal energy to industry and institutions; and systems using hundreds of thousands of square-meters of collector area to raise the temperature of a heat transfer oil to nearly 400°C. The hot oil from these systems passes through a steam generator to produce steam that drives a turbine-generator. Nine of these plants, ranging in size from 13 MW_e to 80 MW_e, have been constructed with private funds in the Mojave desert of California. The total capacity of these plants is 354 MW_e, representing over 90% of the world's grid-connected solar electric generating capacity[2].

Chemical processes include solar detoxification of ground water via photolytic oxidation of organic contaminants. For these processes fluid flows through a transparent, glass tube.

3.3 Current Activities

Parabolic troughs have already achieved significant commercialization. Therefore, research is limited to testing of new products and joint ventures with industry to improve some components and to reduce operation and maintenance costs at operating plants.

4. SOLAR TOWER AND HELIOSTAT FIELD

4.1 Heliostat Field

Currently there are two approaches to the manufacture of heliostats[3]. Glass-metal heliostats have glass mirrors, called facets, mounted on a metal substructure. The facets are usually mechanically deformed to slightly focus the sunlight on the solar receiver. Furthermore, the facets on the heliostat are canted with respect to each other to focus the entire heliostat. Peak flux concentration from a single heliostat will typically be less than 50 kW/m^2. Much higher flux levels are obtained at the focal point of the heliostat field because multiple heliostats are aimed simultaneously at the receiver. The heliostat field at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque has 220 40-m^2 heliostats and is located to the north of a 61-m tower, as shown in figure 2. The facility can produce peak flux levels of 2500 kW/m^2 and a total power level of 5 MW_t. The heliostat field at the Solar One plant at Barstow, California, has approximately 1800 40-m^2 heliostats, producing ~40 MW_t (10 MW_e). Commercially-sized central receiver power plants will be sized to provide 100-200 MW of electrical energy. Prototype glass-metal heliostats as large as 200 m^2 have been built and tested at the NSTTF.

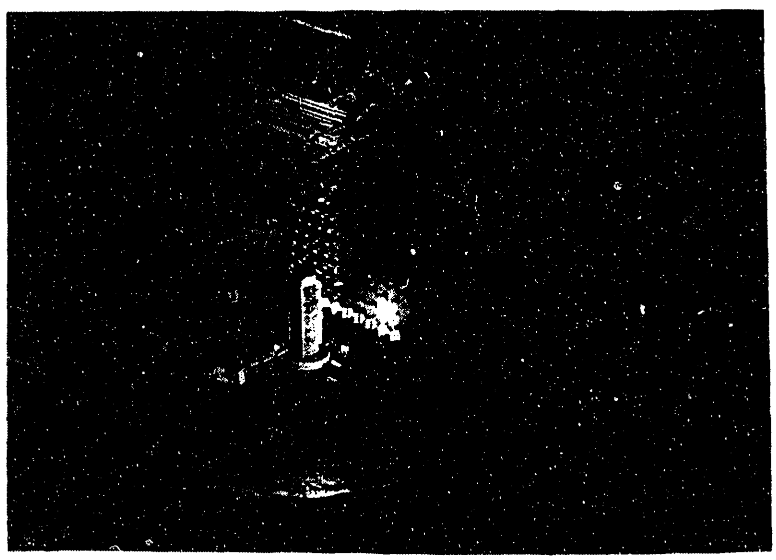

Figure 2. National Solar Thermal Test Facility

Another type of heliostat that has been developed is called the stretched-membrane heliostat. These heliostats use a thin metal film stretched across the front and back surfaces of a ring to create a vacuum plenum. A silvered-polymer film is adhesively applied to the front surface and a slight vacuum is applied to focus the heliostat. The prototypes that have been built and tested are 7-m in diameter and have one or two circular mirrors mounted on a drive pedestal, for a total area of 50 to 100 m^2.

4.2 Solar applications

The most common application of heliostat fields is to heat some type of working fluid using a solar receiver. Many receivers consist of an array of tubes though which a working fluid flows, such as water/steam, air, molten sodium, or molten nitrate salt. Receivers using all of these working fluids have been built and tested at the NSTTF[4]. The 10-MW_e Solar One demonstration plant used a water/steam receiver, while demonstration plants in Spain and France used sodium and molten nitrate salts, respectively.

The working fluid preferred in the US is molten salt, consisting of a mixture of potassium and sodium nitrates. The mixture melts at 222°C and remains molten over the 285 to 565°C operating range of the plant. As shown in figure 3, molten salt is pumped from a cold (285°C) storage tank through an array of tubes in the solar receiver where it is heated to 565°C. A black Pyromark paint is used to make the receiver surface highly absorptive. Peak flux levels typically are in the range of 400-700 kw/m^2. The heated salt from the receiver is delivered to a hot storage tank.

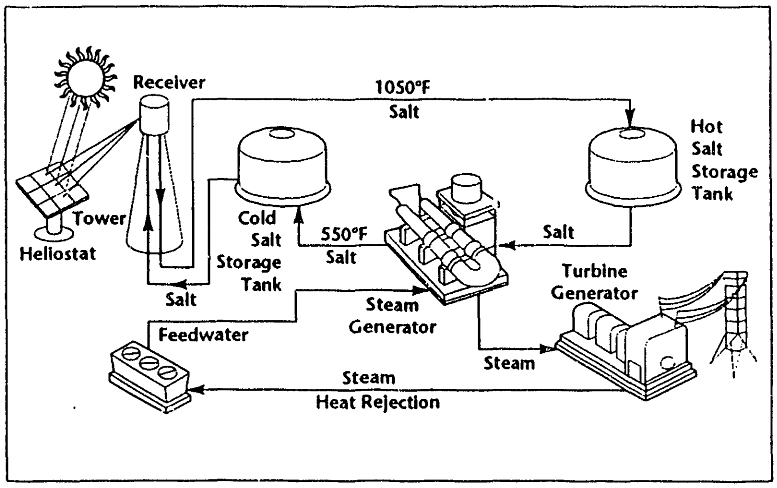

Figure 3. Schematic of electricity-generation using molten-salt technology

When electricity generation is desired, the molten salt is transferred from the hot tank through a steam generator system to the cold tank. The advantage of this approach is that storage is used to separate electricity generation from thermal energy collection. Thus, electricity generation can continue though cloud cover and for several hours after sunset, depending upon the amount of storage and the relative sizes of the solar field and turbine.

Advanced salt receivers are being developed both in the US and in Europe. In these receivers a salt film flows over the surface of a panel, rather than salt flowing though an array of tubes. On a receiver built and tested at lower power levels at the NSTTF, the salt flowed over the front-side of a panel exposed to the concentrated sunlight. A blackener is used to increase the absorptivity of the salt. In this approach, thermal losses are minimized because the maximum temperature exposed to the environment is the temperature of the salt itself rather than the higher temperature of a tube surface. In a test to be conducted in Spain, the salt will flow over the rear surface of the panel. This approach eliminates loss of salt by wind blowing it off the panel. In both approaches the advantage of the film receiver is that thermal stresses may be more easily managed in a flat panel that is free to move relative to its supports rather than in a more rigidly-mounted array of tubes. Note that in solar plants, thermal cycling occurs daily under clear skies and more often with clouds.

European researchers and, to a lesser extent, American researchers are also interested in volumetric receivers that use air as a working fluid. One approach is to draw air through a ceramic mesh that is exposed to the sun. Tests on these receivers have been conducted both in the US and Spain[5]. A test will soon be conducted in Spain of a wire mesh receiver fabricated in the US by Bechtel.

4.3 Non-solar applications

The capability to provide nearly uniform flux over large areas is of interest for various thermal tests conducted at the NSTTF, including simulation of the thermal portion of a nuclear blast and simulation of aerodynamic heating[6]. A 1.5 x 1.3 m high-speed shutter is used in combination with dynamic control of the heliostat field to simulate nuclear thermal pulses. A good approximation of the characteristic nuclear pulse can be obtained, and the spectral content of sunlight more closely simulates thermal nuclear flash than other simulation techniques. Test specimens exposed have ranged in size from a complete cockpit, canopy, and mannequin in a flight suit, to flight-surface material samples placed in a windowed wind tunnel to simulate convective cooling during exposure.

Missile nose cones and radomes have been exposed to simulate aerodynamic heating from both high-speed atmospheric flight and under re-entry conditions. Such tests have included active measurement of the distortion in radar signals due to heating of the radome.

4.4 Current activities

In a joint venture with a consortium of utilities, the Solar One plant is being converted to molten salt operation through installation of a new receiver, thermal storage, and heat transport system. This project is now in the design phase and is being supported by a number of small projects at the NSTTF involving evaluation of components, instrumentation, and materials to be used in the salt system.

5. PARABOLIC DISHES

5.1 Concentrators

Because of their relatively short focal length and because the receiver and concentrator move together, the parabolic dish has the highest peak flux capability. For solar applications however, an appropriate balance must be achieved between cost and performance, so high accuracy and high flux capability are not always a priority. In fact, it is not usually desirable to have high flux on the absorber surface of the solar receiver. However, it is advantageous desirable to have the flux pass through a small opening or aperture into a cavity where the flux can expand and somewhat uniformly illuminate the receiver surface. A dish that is capable of high peak flux will generally be able to deliver its flux through a small aperture. Thus, losses via reradiation and convection from the receiver surface can be minimized.

Solar researchers use a figure of merit called slope error to describe the accuracy of a concentrator. Slope error is the amount of angular deviation from the ideal parabolic slope at any point on the surface of a concentrator. Some of the most accurate concentrators use a large number of individual mirrors or facets mounted on a parabolic substructure. For example, the two 11-m dia. parabolic dishes, called test bed concentrators, at the National Solar Thermal Test Facility, have produced peak fluxes up to 15,000 kW/m^2 at a total power level of about 65 kW_t. These high-flux levels are achieved with an array of 220 61 x 71-cm spherical facets arranged on a metal substructure. The facets have three nominal focal lengths and are arranged in three zones on the dishes. The test bed concentrators have a slope error of about 1 mrad.

A number of near-commercial designs also use facets mounted on a metal substructure, but the facets are typically larger and fewer in number. Such facets can be made of glass on a substrate or can be made from membranes stretched over a ring, much like stretched-membrane heliostats but smaller. Cummins Power Generation, for example, has developed a dish with 24 1.5 m dia. facets[7]. These facets have polymer membranes with silvered-polymer mirrors. A recently developed dish under test at the NSTTF has 12 3-m dia. facets[8,9]. In this case the membranes are metal with an adhesively-applied silvered-polymer reflective surface.

Other dish designs include single-element, stretched-membrane dishes which have been constructed in the US and Europe[10]. These dishes have a single, deeply-drawn, membrane. The membranes are plastically deformed during fabrication and are vacuum-stabilized during operation. Both polymer and glass reflective surfaces have been used with this concept. In addition, dishes have been constructed in which thicker sheet metal formed into the shape of a parabola provides both the structural support and the necessary optical contour[11]. Reflective polymer films are applied to the surface of these dishes.

5.2 Applications

Parabolic dishes can be used with many different types of solar receivers, including thermal receivers to supply heat to a process, thermal receivers that drive an externally-heated engine connected to the receiver, and chemical receivers in which some type of endothermic reaction takes place in the receiver. Of these concepts, the dish/engine concept is currently undergoing the most development. Heat engines that have been tested include organic and steam Rankine-cycle engines, Brayton-cycle engines, and Stirling-cycle engines. A 25 kW_e Stirling engine on a faceted glass-metal dish holds the world record for solar-to-grid power of 29.3% net conversion efficiency[12].

The working fluid for Stirling engines is a gas, usually helium, which is expanded and cooled to drive the engine. The helium is heated by exposing an array of small tubes connected to the engine head to the heat source. These tubes are called the heater head.

Some system developers have used an array of tubes that are directly exposed to the concentrated sunlight; however, lower-cost concentrators may have variations in the flux distribution that will adversely impact the tube array. An alternative approach uses liquid-metal reflux receivers to provide uniform heat-flux at the engine heater heads. These receivers achieve near-isothermal operation by using a two-phase heat-transport system. Vapor is produced at the receiver absorber surface, condenses on the heater head, and refluxes toward the absorber by gravity.

5.3 Current activities

Sandia and various industrial researchers have been pursuing development of two types of liquid-metal refluxing receivers. One type, the heat-pipe receiver shown in figure 4, uses a small inventory of sodium and relies on the capillary forces of a wick to distribute the sodium over the receiver surface. The second type, called a pool boiler and shown in figure 5, uses a much larger inventory of sodium or sodium/potassium alloy that covers the receiver surface at all times, much like a pot of water on a stove. In both approaches the challenge is to achieve stable operation at all times while remaining within the limits of the various materials.

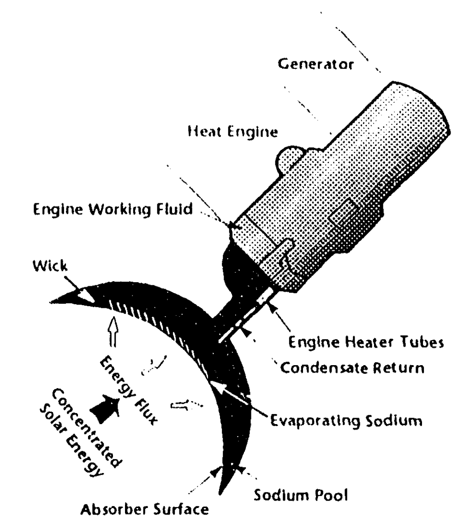

Figure 4. Heat-Pipe Receiver

Heat pipe receivers have been operated successfully for hundreds of hours at the 30 kW_t level by Cummins Power Generation[7]. These receivers, built by Thermacore, are 40 cm dia. and use a sintered nickel powder wick. Maximum flux on the receiver surface is about 350 kW/m^2; however, limit testing has been conducted to 40 kW_t at a peak flux of approximately 500 kW/m^2 at the NSTTF.

Larger Stirling engines require larger receivers. When the receiver size is increased for these higher power applications, the capillary forces must raise the sodium to greater heights. Peak fluxes may also be higher. A number of wick designs have been evaluated, including some with arteries intended to assist in distributing the sodium to the receiver surface. Tests have been conducted both in full-scale tests of a parabolic dish and in bench-scale tests using small tubular receivers heated by quartz lamps. At this point, a 75 kW_t, 51 cm-dia. Thermacore receiver, similar in design to the 30 kW_t receiver described above, has been demonstrated successfully under most operating conditions[13].

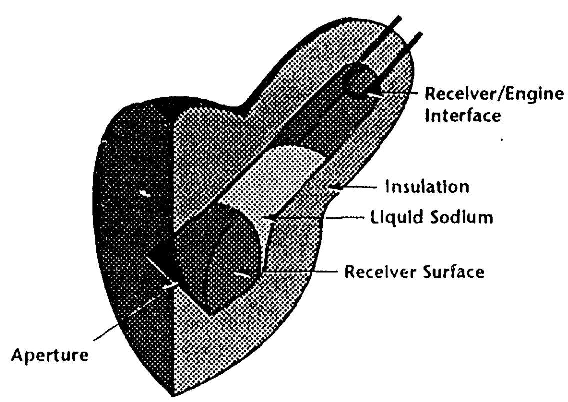

Figure 5. Pool-Boiler Receiver

Pool boilers, while appearing intrinsically simpler, have some drawbacks due to the inventory of liquid-metal required. First, the pool must be liquid when operation begins. Thus, sodium/potassium alloy (NaK 78) is preferred because it is liquid at ambient temperature; use of pure sodium requires some method of preheating, such as electric trace heating. Second, in the event of a receiver failure there is the potential for discharge of a significant amount of material (~5 kg) to the environment relative to the heat-pipe receiver.

While heat-pipe receivers may suffer from dryout, boiling instability in alkali-metal pools is commonly reported because of the tendency of the pool to quench active bubble-nucleation sites. Several approaches have been taken to ensure adequate bubble-nucleation sites, including addition of inert Xenon gas and surface alterations, such as electric-discharge-machined or laser-drilled cavities and powdered-metal coatings. Extensive tests have been performed at both bench-scale and full-scale, and a full-scale device was successfully tested recently[14]. This device included both a powdered-metal coating and xenon gas. A bench-scale receiver of the same configuration is currently undergoing a 10,000-hour bench-scale test to validate long-term material compatibility. Thirty-three hundred hours of testing have been completed to date.

In bench and full-scale tests, it has been observed that boiling stability improved with increased heated-surface area, and surface treatment may not be necessary. Preliminary results from test of a 75 kW_t receiver having no surface treatment exhibited stable operation once xenon was added.

Cummins Power Generation is currently involved in a cost-shared joint-venture with Sandia National Laboratories to develop a 7.5 kW_e dish/Stirling system for remote village electrification, water-pumping, and end-of-line applications (where additional capacity is needed at the end of an existing utility line.) Additional joint-ventures will soon be in place for development of dish/engine systems for utility-scale power generation.

6.0 SOLAR FURNACES

A solar furnace uses a tracking heliostat to direct incident sunlight into a stationary parabolic dish. Typically, a venetian-blind-like attenuator is installed as part of the system to permit tailoring the power level to the needs of an experiment. While the peak flux obtained from a solar furnace will be lower than from the associated dish alone, the furnace has more flexibility because the power level can be adjusted and because the experiment at the focal point remains in a fixed position, often inside a building.

The NSTTF has two solar furnaces. The 16 kW_t solar furnace has a peak flux capability of 3000 kW/m^2 and is used mostly for receiver and process development and flux gauge calibration. The facility's 60 kW_t solar furnace uses one of the two test bed concentrators in a non-tracking mode, as shown in figure 6 during testing of a Dynatherm heat-pipe receiver.

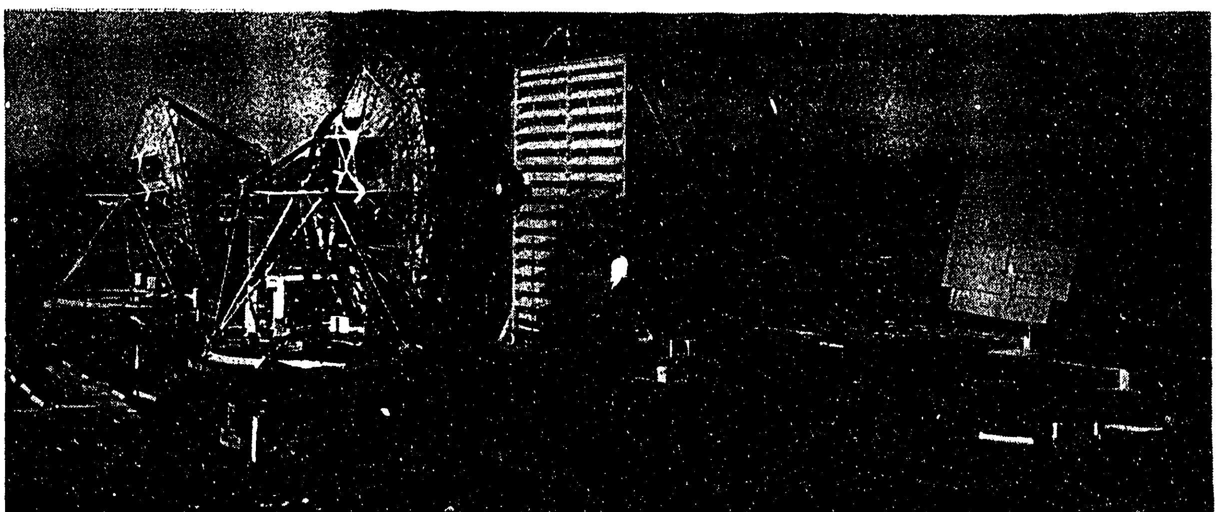

Figure 6. 60 kW_t Solar furnace during testing of Dynatherm receiver

The National Renewable Energy Laboratory also operates a small solar furnace[15]. Current research includes processing of ceramics with flux levels from 200-1000 kW/m^2. With the addition of a secondary concentrator, researchers have measured flux levels as high as 21,000 kW/m^2. A new set of experiments involves trying to form fullerenes, using a secondary concentrator, at flux levels of 10-12,000 kW/m^2.

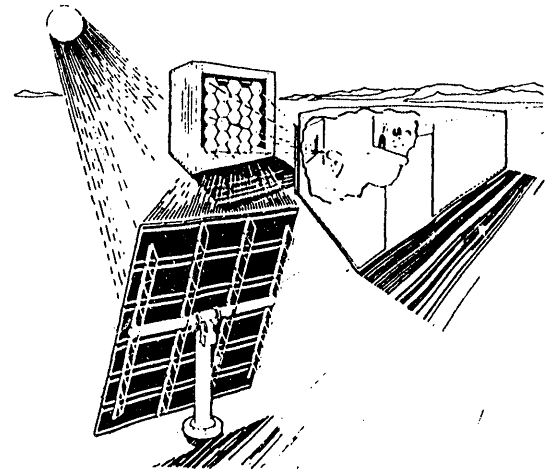

Figure 7. NREL High-Flux Solar Furnace

7.0 INSTRUMENTATION SYSTEMS

In order to test solar receivers and material processes, the concentrated flux and receiver surface temperatures must be well understood. Systems to measure both of these quantities have been developed at Sandia.

7.1 Beam characterization systems

Beam characterization systems measure the flux produced by point-focusing solar concentrators by viewing the light reflected from a lambertian target[16]. A lambertian target scatters light evenly regardless of the angle of incidence of the incoming light. The target that can be used depends upon the intensity of the flux being measured. At low flux levels a lambertian paint can be used on an uncooled surface. For example, the north wall of the solar tower is painted for use in characterizing individual heliostats. At moderate flux levels this paint may still be used, but it must be placed on a cooled substrate. At high flux levels, such as produced by the full heliostat field or by parabolic dishes, a water-cooled aluminum target is used with an alumina ceramic coating. These targets range in size from a set of three 1 x 3 m panels, for evaluation of the heliostat field, to 50 cm dia. targets used in evaluation of parabolic dishes.

The reflected light is detected by CCD video cameras and digitized by a PC-based system. The software used is from Big Sky Software, and is a modification of a product originally developed for use with laser beams. The video data provides only a relative measure of beam intensity. Circular-foil flux gauges (calorimeters) are mounted in the target to permit an absolute determination of the intensity. Flux gauges are calibrated by comparison to a Kendall radiometer in a solar environment. This method is preferred to extrapolating from manufacturer's calibrations performed with a non-solar spectrum.

The NSTTF currently has four beam characterization systems. One of the systems is installed in a portable computer so it can be taken to sites such as Solar One or the Cummins Power Generation, Inc. test site in Abilene, Texas.

We have recently begun a project to determine whether we can estimate flux distribution from observing the light reflected from a receiver surface during operation, rather than having to perform measurements separately. This would permit on-line monitoring of the incident flux on a receiver, such as the Solar Two project receiver. Panels from a central receiver experiment will be installed on the NSTTF's solar tower and flux measurements will be compared to those obtained from white, lambertian panels. While accurate, quantitative measurements may not be obtainable, qualitative measurements could be used for control purposes and to detect irregularities in the flux distribution during operation. On the Solar One project, an array of flux gauges was used to monitor incoming flux and these were a constant maintenance headache.

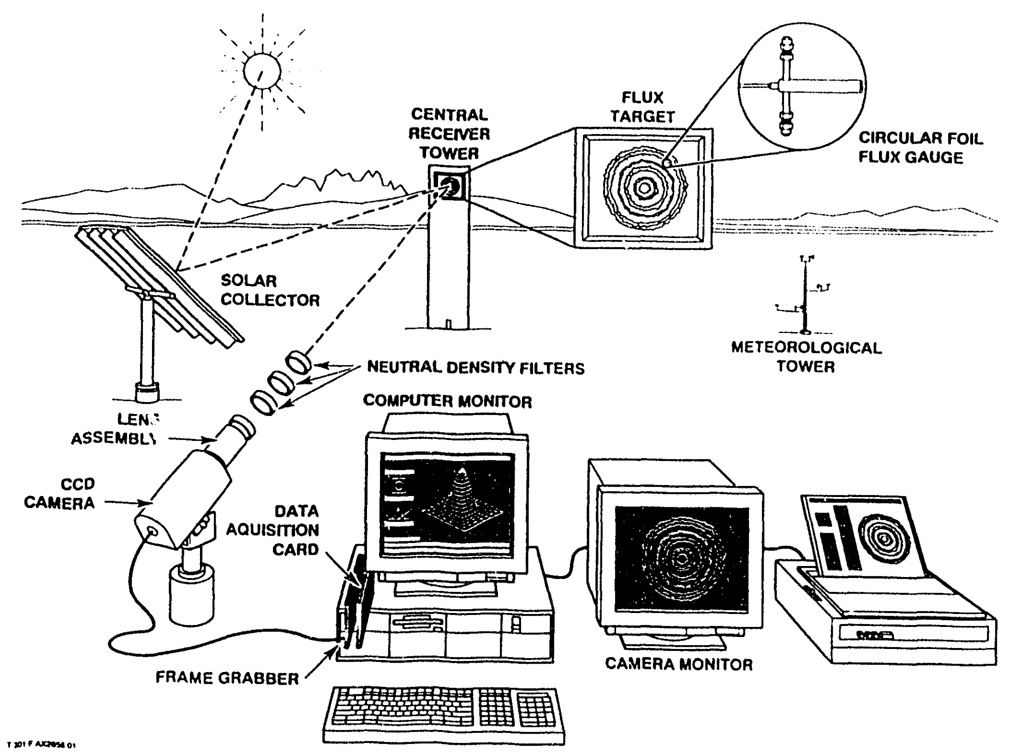

Figure 8. The Beam Characterization System for Heliostat Evaluation

7.2 Infrared measurements

For testing of solar receivers it is important to monitor surface temperatures. Surface thermocouples may be used, but temperature variations may occur between thermocouples, and with the high incident flux on the thermocouple, the temperature being measured may be that of the thermocouple rather than the surface on which it is mounted.

For testing of receivers on parabolic dishes, an infrared camera system has been developed[17]. Even though a high percentage of the solar radiation incident on the receiver surface is absorbed, a significant amount is reflected. To detect the surface temperatures, a solar blind system is required. The system selected operates near 1.9μm. It has a resolution of 3°C over its operating range of 400 to 900°C. System components include a PbO-PbS vidicon, lens, narrow-band filter, and neutral density filter wheel. The standard video output from the system is tied to a video digitizer that permits monitoring of the signal strength of each pixel. An alarm system detects the highest pixel and triggers system shutdown if the level is higher than a preset threshold. The signal is also recorded on videotape. The system has proven invaluable in monitoring the temperature distributions on both reflux receivers and the directly-illuminated heater head tubes of a Stirling engine.

Development of a similar system is under consideration for use with the Solar Two project. However, atmospheric attenuation is high in the 1.9 μm region. While acceptable relative to the short focal length of a parabolic dish, attenuation limits the applicability where locating the camera near to the receiver would be difficult.

8. SUMMARY

Solar concentrators have been developed which produce heat fluxes up to 15,000 w/m^2, and higher with a secondary concentrator. High-flux capabilities are relevant when attempting to minimize thermal losses by delivering flux through a small aperture; however, the absorber surfaces of solar receivers generally operate at much lower flux levels. The high flux capabilities of solar concentrators have also been applied to a variety of thermal simulation activities.

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