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B. P. Gupta
M. Carasso
R. G. Nix

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12th ENERGY TECHNOLOGY CONFERENCE

THE SOLAR THERMAL RESEARCH PROGRAM

B.P. Gupta
M. Carasso
R.G. Nix

Solar Energy Research Institute (SERI)
Golden, Colorado

Solar thermal energy systems use concentrated radiation to provide thermal or electrical energy from a few kilowatts to hundreds of megawatts, to produce high temperatures without combustion or mechanical conversion, to supplement or supplant basic heat sources in existing industrial and utility plants. They can also be integrated with thermal energy storage systems to deliver energy after daylight hours. The concentrated solar flux can be beneficially used for materials treatment or to affect chemical reactions directly.

Present solar thermal technology concentrates the solar flux by means of tracking mirrors or lenses onto a receiver, where the solar energy is absorbed as heat in a working fluid and converted into electricity or incorporated into products as process heat. Receiver temperature can range from 100°C in low temperature troughs to over 1500°C in dish and central receiver systems, although present-day experience is largely in the 100°-600°C temperature range. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line focus optics to concentrate sunlight. Current central receiver systems use a field of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a receiver. Trough and bowl are reflectors that concentrate sunlight onto linear receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system.

RESEARCH PROGRAM SCOPE AND OBJECTIVES

The full potential of the solar resource can be realized by understanding and utilizing the unique aspects of the resource. Properties that make solar a useful source of energy are: (a) it is renewable and non-polluting, (b) it can provide usable temperatures up to 1500°C, (c) it can provide high fluxes and high heating rates, and (d) it is a source of photons over a wide spectrum (300-2100 nm) that can be used as a whole or in parts by spectral splitting or shifting. These solar attributes are not directly available through the conventional fossil and nuclear sources of energy.

The research program is based on characterizing the best processes of combining the solar resource with available material resources to produce useful energy products, such as electricity, heat, fuels, and chemicals.

The principal objective of the Solar Thermal Research Program is to conduct research leading to assessments of the feasibility of new concepts that can be cost-competitive over the entire temperature range. Research opportunities are identified by determining cost and performance targets and by conducting exploratory research on innovative concepts that use concentrated solar flux. Specifically, the scope of the research program includes:

a. Identifying and assessing the technical feasibility of new concepts and concepts not sufficiently advanced to require engineering development for converting solar thermal energy to useful end products. Newly identified concepts will normally be followed by sufficient research to gain proof-of-concept and to define key issues for further research or engineering development.

b. Obtaining additional fundamental data on materials, mechanisms, operation, and performance of the concepts identified in (a), such that systems and other analyses can be performed to determine the potential for future uses of the concepts.

c. Characterization of components, materials and subsystems required for new or existing concepts that have not yet reached the engineering development stage.

d. Supporting the work of engineering development with necessary data and instrumentation required to continue engineering development work.

e. Developing general measurement technology, including evaluation and measurement of the basic solar resource and concentrated solar flux measurements.

RESEARCH ACTIVITIES

The Solar Thermal Research Program, managed by the Solar Energy Research Institute, has conducted basic and applied research in materials, thermal sciences, chemical sciences, and engineering analysis needed to provide the knowledge base for new technology. In the materials research area, notable among the results are the progress toward development of polymer-based mirrors for solar application, understanding of the mechanisms that affect silver/glass mirror lifetime, development of high temperature fluids, and development of high temperature optical and containment materials for solar receivers. Thermal sciences research has included high temperature heat transfer research, air and liquid receiver concept studies, and storage research. In the engineering analysis and research, concepts for low-cost heliostats were evaluated and definitive recommendations were made to pursue the stretched membrane heliostat concepts based on scaled membrane evaluation in the laboratory. These activities are discussed futher under three categories: Collection, Energy Conversion, and Systems and Applications.

COLLECTION TECHNOLOGY RESEARCH

Central to the operation of Solar Thermal systems are the functions of concentrating and then collecting the concentrated solar flux into a working fluid for further conversion and utilization. Thus, collection technology research emphasizes development of effective means of concentrating the solar flux and absorbing the concentrated flux in an efficient receiver. Specific research is targeted at improving the performance, increasing the durability, and reducing the cost of components. Specific research activities described below are divided in three categories; namely, Optical Materials, Concentrators, and Receivers.

a. Optical Materials

Research in this area is focused on polymer-based silver mirrors with the best optical quality possible in order to concentrate the solar flux on the smallest possible aperture at the receiver. For central receiver applications, this typically means that the mirror surface should reflect at least 90% of the incident radiation into a 2 milliradian target. The availability of a silver/polymer mirror of this quality would enable the design of lightweight and cost effective concentrators. In addition to this performance oriented target, a silver/polymer mirror film should have a sufficient durability to maintain its performance over an economic life of at least five years. Research, therefore, is directed at understanding the effects of the solar application environment, the degradation mechanisms involved, and means to overcome them.

A number of polymers, silver deposition methods, adhesives, and stabilizers have been identified that show considerable improvement in both mirror performance and durability in the solar application environment, including ultraviolet radiation. Among the best performers is a PMMA/silver polymer stabilized by Tinuvin-P to reduce the adverse effects of ultraviolet radiation over its useful lifetime. It shows the best promise of meeting both the performance and durability needs of this exacting application. Exploratory effort is also underway to improve the surface quality of metallic substrates so as to enable the deposition of the reflecting surface directly on the substrate, so that with front surface protection, a durable reflector with inherent structural stiffness can be obtained.

b. Concentrators

Current Solar Thermal concentrators use silver/glass mirrors mounted on a variety of supporting structural configurations to reflect and focus the solar flux. Wind loads and the structural stiffness required to support the brittle glass result in heavy steel structures, and therefore expensive concentrators. The availability of silver/polymer mirrors enables the use of new structural concepts that show promise for lightweight design and considerably lower cost. Prominent among current research topics are a number of configurations using metallic stretched membranes. Figure 1 depicts such a combination of membrane concentrator and polymeric mirror. In the future, structural polymers may substitute for the metallic membranes. This research aims at understanding the major technical issues, including the structural and optical performance of promising stretched membrane reflectors. In particular, this activity focuses on the response of the stretched membrane heliostat modules to static and dynamic loading, eventually leading to the definition of design requirements, and the anticipated levels of collector field performance corresponding to different applications.

Initial analyses and testing of the stretched membrane reflector concept have shown that major improvements in the cost and performance characteristics relative to existing glass/metal heliostats may be attainable.

In addition to extensive research into structures using stretched membranes, both metallic and polymeric, research efforts include the characterization of wind

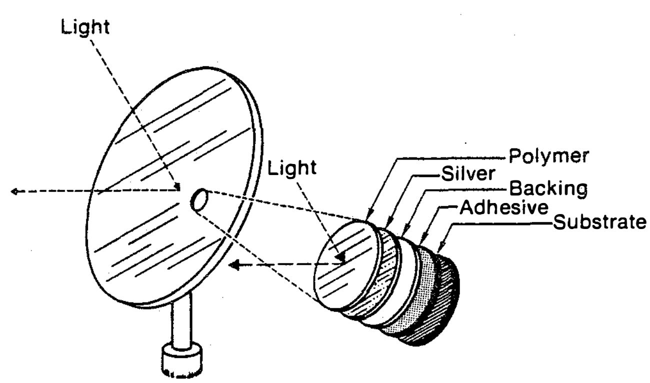

Figure 1: Membrane Heliostat

loading on heliostats in typical heliostat field configurations. The aim of this research is to devise strategies for reducing wind loads and thus relax their structural requirements and to reduce the cost of heliostats.

An advanced research effort aims at the possibility of holographic concentration. The technical feasibility of developing holographic concentrators for the entire solar spectrum with limited or no tracking requirement is being investigated. Other parallel efforts aim at assessing the performance and estimating the benefits of Fresnel lens concentrators for point focus dish and line focus trough technologies, and at splitting the solar flux into usable frequency bands for multiple usage and other novel optical approaches.

c. Receivers

The receiver is that element of a solar thermal system where the concentrated solar flux is absorbed and transferred to a working fluid for conversion. Typically, the higher the flux, the higher the attainable operating temperature. The research challenges include efficient absorption of a concentrated flux in the receiver, durability of materials, and reduction of heat losses to result in a cost-effective component. Receiver research is primarily directed at defining configurations using metal and ceramic tubes as well as those which directly absorb the concentrated flux in the working fluid. Analytical and experimental studies are being conducted to define the performance parameters corresponding to various receiver concepts, to develop approaches to enhance their performance, and to reach the proof-of-concept stage by scale model tests in solar environment.

Specific research is directed toward the evaluation of the technical feasibility of a direct absorption receiver concept, and the understanding of receiver thermal loss mechanisms in general. Both theoretical studies of the heat transfer mechanisms and fluid flow phenomena associated with a flowing film, and experimental verification of theoretical predictions form the basis for evaluating the technical feasibility of this concept. Figure 2 is an artist's rendering of the proof-of-concept experiment planned in FY1985. Separately, a research effort aims at characterizing high efficiency receivers by developing an understanding of convective losses and formulating design concepts that reduce these losses, particularly at the higher operating temperatures. Related research by a Georgia Institute of Technology research team addresses the development of glass windows for cavity type receivers. The availability of a transparent, durable window holds the promise of virtually eliminating convective losses while providing for the containment of reactants inside the receiver cavity.

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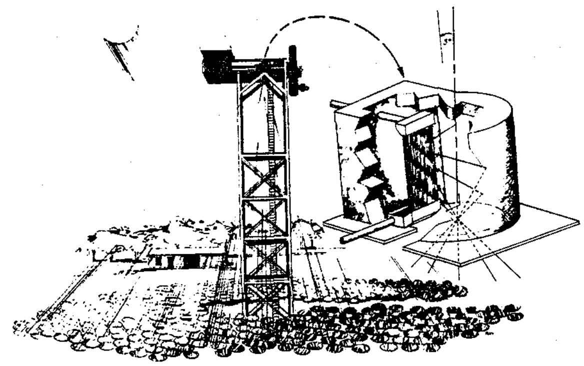

Figure 2: Schematic of the SERI 900°C Molten Salt Loop to be installed and tested at the Advanced Components Test Facility. Georgia Institute of Technology.

Materials used in solar receivers are typically subjected to a solar specific severe combination of stresses. They are exposed to a concentrated solar flux (up to approximately 3 MW/m^2 in dish configurations). They may cycle in temperature, ranging between the peak outlet temperature and ambient temperature, on a daily basis. They are exposed to mechanical stresses, and are often exposed to corrosive fluids. For these reasons, research on receiver concepts inevitably involves research on both containment materials and working fluids.

Materials research aims primarily at understanding the response of structural materials to the challenging working environment encountered in solar thermal receivers, identifying working fluids with desirable heat transfer and storage properties, and improving the durability of receiver absorber coatings. Improving the compatibility of receiver containment materials with the working fluids, and obtaining the radiation properties of materials under solar conditions are important for durable receiver designs.

ENERGY CONVERSION RESEARCH

This research aims at developing new and innovative ways of converting the concentrated solar flux into usable forms of energy. Research is divided into two specific areas, efficient conversion to electricity, and direct photo/thermochemical conversion.

a. Efficient Conversion to Electricity

Thermally regenerative electrochemical systems constitute a promising concept for conversion of solar derived heat to electricity. An experimental approach to investigate and evaluate a thermoelectrochemical (TECH) converter for direct production of electricity from heat is being pursued. The basic cycle is to use the solar thermal energy as heat input to a regenerator where the working fluids are reconstituted. Figure 3 is a schematic of the system components and the thermodynamic cycle. These energy rich working fluids are reacted in a cell to produce electricity. The TECH system contains a high energy density storage element and is potentially applicable to either dish or central receiver solar systems. Additional conversion methods are being evaluated for their potential use in solar thermal systems.

b. Photo/Thermochemical Research

Solar radiation contains a relatively wide range of photon energies. Many processes can utilize only portions of the solar spectrum effectively. Research strives to match various conversion processes and the solar spectrum to provide the most efficient solar thermal energy utilization.

Research is aimed at defining and understanding both new and existing phenomena to provide the basis for efficient conversion processes. The fraction of the solar spectrum suitable for driving pure photoconversion processes is relatively limited; i.e., less that 4% of the spectrum is ultraviolet or higher in energy. It is important, then, that processes using direct absorption of photons be coupled with thermal processes so that the entire solar spectrum can be efficiently converted.

Research is in progress on the use of the solar thermal technologies to aid in the conversion of fossil and other carbonaceous energy sources to clean fuels and chemicals. The high-temperature capability of solar technology

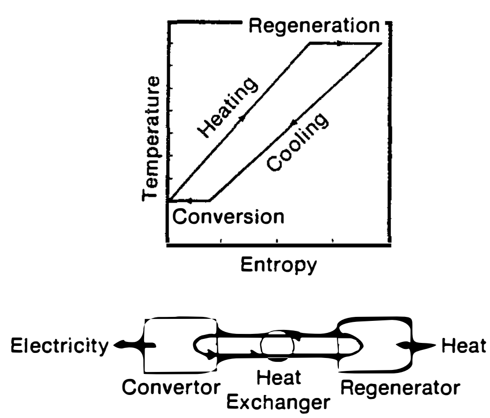

Figure 3: Thermoelectrochemical (TECH) Conversion scheme using solar thermal energy.

combined with the storability of fossil fuels has the potential for improved processes and costs for each energy source.

Research includes the absorption of concentrated sunlight by solids. The goal is to understand physical, chemical, and thermodynamic processes through analytical and experimental research. A technology base is being established to enable an assessment of direct flux gas-solid reactions for beneficial solar thermal conversion. Analytical tools are being developed to understand and predict the ongoing phenomena.

Experimental research is also in progress to characterize the chemical kinetics of solids decomposition using zinc sulfate as a model compound. Direct flux decomposition of zinc sulfate is applicable to several thermochemical water splitting methods. A major incentive for the solar decomposition of these sulfates is that the high heat rates available may substantially reduce the temperature of the decomposition reaction by controlling the decomposition reaction pathway and replacing the hot concentrated sulfuric acid decomposition step.

For solar thermal conversion to be cost effective, the entire solar spectrum should be effectively utilized. The UV portion of the solar spectrum, suitable for driving some typical photoreactions, accounts for less than 4% of the entire spectrum. This suggests that a photolytic reaction might be used as a "trigger" reaction to control a thermal reaction that uses the other 96+% of the solar spectrum. Research is conducted on the use of energetic photons to generate free radicals from added trace chemicals such as acetone. The free radicals are expected to cause significant improvements in the selectivity and increase in the yield of industrially important reactions, such as the cracking of ethane or naptha to ethylene. Activities underway include (a) assessing industrial chemistry to identify the most promising reactions, (b) design and fabrication of a reactor for data collection in the small arc image furnace to confirm hypothesized reaction improvements, and (c) researching the detailed mechanisms and kinetics to understand the underlying phenomena.

Another research effort is a laboratory evaluation of the solar incinerability of hazardous organic wastes. Specifically, the research separates photolytic effects from thermal effects, with emphasis on determining the beneficial effects of the high flux on solar incinerability, i.e., "trigger" reaction effects. This research is rather broad with respect to the types of hazardous wastes. The significance of this research is that it will enable an assessment of the feasibility of using solar energy for hazardous waste detoxification .

In a parallel effort by researchers at the University of Houston , solar assisted chemical bond breaking is being investigated. The idea is that thermal energy makes photoreactions more effective by reducing the photolytic energy necessary to complete the breaking of bonds already highly excited by thermal energy. Photoenhancement of catalytic processes by direct flux is also a possibility. Research has shown that nickel oxidation was enhanced by a factor of 3 to 4 when impinged with simulated solar flux of 1 to 2 MW/square meter. In many catalytic reactions of significant industrial importance, the rate limiting step is breakage of an internal bond of a chemical species absorbed on a catalyst surface. In the manufacture of NH_3, the rate limiting step is thought to be the breakage of the N-N bond in N_2. Based on the detrimental effects observed in materials oxidation, it is reasonable to hypothesize a beneficial photoenhancement of catalytic processes; for example, breakage of the N-N bond can increase. The significance of this research is to beneficially utilize phenomena that otherwise are considered detrimental, and thereby develop approaches to use the unique aspects of solar energy for industrially practical applications.

SYSTEMS AND APPLICATIONS TECHNOLOGY

Systems and applications technology research emphasizes the generation and characterization of innovative concepts and applications. Innovative concepts and applications are guided by the need to make significant improvements in solar energy cost-effectiveness by providing a much more attractive application or new concept. The approach is (1) to identify the concept or application, (2) to do sufficient research to characterize the concept or application, (3) to perform a comparative analysis of alternatives and assess cost effectiveness, and (4) if attractive, to develop targets for performance to guide future research. Systems analyses provide an early evaluation of the potential of innovative concepts and new applications relative to overall program goals, and enable the development of specific performance targets for research. Performance tradeoffs among components and sensitivity analysis allow identification of research areas that have the maximum potential for contribution towards achievement of performance and cost goals.

Studies in progress are evaluating (a) the potential to cost effectively provide solar derived heat up to 900°C using the direct absorption receiver concepts, (b) the feasibility to use the stretched membrane concentrator concept for solar systems of different sizes and temperature ranges, and (c) new conversion schemes for their potential to cost-effectively provide solar to electric conversion.

New applications are being evaluated which include the use of fossil-solar hybrids for systems requiring energy continuously and the associated concepts for different system sizes.

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SUMMARY

The research program pursues activities that will assist in the achievement of long-term targets. In addition to the long-term performance and cost targets for electricity and heat, the research program aims to explore new and innovative ideas for other applications for which definitive goals and targets can be established only after an increased understanding of the solar resource and its unique attributes. Some research is already in progress at the Solar Energy Research Institute and through academic and industrial research organizations. Effort is continuing to stimulate new ideas and explore new approaches.

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