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ANNUAL REPORT, FY 1981

September 1982

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LBL-13496

SOLAR ENERGY PROGRAM
FY 1981

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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SOLAR ENERGY PROGRAM

INTRODUCTION

During FY 1981, the Solar Energy Program at Lawrence Berkeley Laboratory (LBL) has continued to focus on applied research that will extend the technology base for a broad range of solar energy applications and on preliminary development of new approaches to solar energy conversion.

A major effort has been the research on "passive" approaches to solar heating and natural cooling, where careful considerations of architectural design, construction materials, incident solar energy, environmental energy flows, and natural daylighting are used to moderate a building's interior climate and reduce the use of non-renewable energy. Experimental and analytic studies of natural convection heat transfer processes that take place within buildings and between the interior of a building and the environment are used to determine natural ventilation rates, interzone heat transfer, and heat transfer to and from storage masses located within a building. Computer models of convective and other basic heat-transfer processes are being developed, verified, and then incorporated into building energy analysis computer programs that are in the public domain. The resulting computer models are used as a tool to examine the energy consumption impacts of using passive heating and cooling design strategies in residential and commercial buildings. To determine the potential for radiative cooling of buildings in various parts of the country, spectral infrared sky measurements were taken in previous years; the analysis of these data and the study of correlations with other sky parameters continued throughout FY 1981. In addition, a broader based technology assessment of passive cooling resources was initiated, involving other laboratories as well as LBL. Daylighting effects have become an integral part of our building energy studies. Experimental measurements of daylighting levels in scale models of buildings are used to conduct dynamic simulations of the interaction of the daylighting system with the electric lighting and auxiliary heating and cooling equipment in commercial buildings. The result is a true measure of the energy benefits of daylighting designs. A further passive task involved the design of freeze protection techniques for passive thermosiphon solar hot water systems, based on detailed thermal analysis of candidate freeze protection strategies. The analysis was followed by construction of the most promising thermosiphon system and the design and construction of a test facility for experimental verification; testing was initiated near the end of FY 1981.

LBL is also engaged in research activities for the "active" solar cooling of buildings. New advanced thermodynamic cycles being studied have the potential for increasing the efficiency of solar-fired absorption air conditioners by at least a factor of two compared to the current state of the art. An air conditioner based on one of these advanced cycles, the double-effect regenerative absorption cycle, has been designed, and fabrication was nearly completed by the end of FY 1981. The testing of an earlier model, a modified single-effect absorption air conditioner that will constitute the core of the double-effect regenerative machine, was completed in FY 1981. In parallel with the experimental work, a methodology was developed for analysis of the performance and economics of solar cooling systems, to establish realistic cost and performance goals for all solar cooling systems under development in the national DOE program.

Installation of a 25-ton solar absorption air conditioner system in LBL Building 71, as part of the Federal Buildings Demonstration Program, will enable LBL engineers to gain first-hand experience with one of the new solar cooling units developed in the DOE solar R&D program. The design of this system in FY 1981 will be followed by its construction and installation in FY 1982.

In both active and passive solar space conditioning, LBL staff members are providing technical support to DOE/Headquarters and the DOE/San Francisco Operations Office in developing program plans, evaluating reports and proposals, and technical monitoring of R&D activities by other contractors. In a closely related effort, LBL has been providing technical support for the U.S.-Saudi Arabian SOLERAS solar cooling program, which consists of field tests in Phoenix of four of the most advanced solar cooling systems developed to date by the DOE R&D program.

Measurement of solar radiation continued to be an important part of the LBL solar energy program. Special instruments (circumsolar telescopes) previously developed at LBL continued to be used in a systematic program to measure solar and circumsolar radiation (the radiation from near the sun resulting from the scattering of sunlight by small particles in the atmosphere). These measurements provide an important ingredient in predictions of the performance of solar collector systems that use mirrors or lenses to focus and concentrate the sunlight. The measurement program was accompanied by detailed analyses of the data collected over the past few years and by study of correlations between the circumsolar radiation levels and various environmental, seasonal, and location-dependent parameters.

A promising new method for converting and using concentrated solar energy is being pursued at LBL. It involves the use of very small (sub-

micron) particles suspended in a gas stream to absorb the solar energy and transfer the heat to the gas stream. A solar thermal receiver using this technique has been designed, and fabrication was underway at the end of FY 1981. Plans call for the test of this receiver during FY 1982 at one of the country's solar thermal test facilities.

Another project based on the properties of particles of small dimension was initiated at a low level of effort in FY 1981. This project is exploring the use of holographic or diffractive optical elements for solar energy conversion or control (e.g., window) systems.

One of the more basic solar research projects involves biological energy conversion techniques, using one of the simplest biological energy converters known: the pigmented protein bacteriorhodopsin. This research project is attempting to elucidate the molecular details of how this protein uses sunlight to produce an electrical current across bacterial membranes. Such understanding should ultimately lead to the production of novel photoelectric cells and solar batteries.

As part of the DOE Appropriate Energy Technology program, LBL continued to conduct energy and economics analysis to determine the effectiveness of the program. In addition, a technology assessment was carried out for the projects involving the use of wind energy.

Finally, FY 1981 constituted a peak year for the LBL solar energy R&D activities because it is anticipated that the severe DOE cutbacks in the national solar energy program for FY 1982 will adversely affect the LBL solar program. The circumsolar radiation measurement project and the appropriate energy technology project are being cancelled by DOE in FY 1982, and most of the other projects are expected to receive substantial budget reductions.

Passive Research and Development*

R. C. Kammerud, J. W. Place, M. R. Martin, P. H. Berdahl, D. Elmer, B. Andersson, F. S. Bauman, W. L. Carroll, A. J. Gadgil, A. Mertol, S. U. Choi, M. B. Curtis, E. Ceballos, M. Tavana, T. L. Webster, M. W. Nansteel, C. C. Conner, P. Coutier, M. Fontoynont, E. F. Altmayer, G. Schiller, V. Horan, H. Michaels, and N. A. Friedman

The amount of conventional fuel used to heat, cool, and light buildings is determined by (1) the interaction of the building with its environment, (2) the thermal gains associated with the activities occurring within the structure, and (3) the operating characteristics of the equipment used to convert conventional fuels to end-use energy. Traditionally, the building design process has not adequately accounted for the combined influence of these three factors on building energy consumption. By integrating these energy issues into the design process, significant reductions in the fuel used to provide a comfortable environment can be realized. This requires that the designer be sensitized to energy as an element of design; he or she must also have access to information on techniques for properly controlling the interactions of the building with the environment and managing the energy flows within the structure.

Passive heating, cooling, and lighting strategies integrate the energy control and management schemes into the building design, taking into account the design parameters of the building and the environmental conditions to which the structure is exposed. In this context, the passive program at Lawrence Berkeley Laboratory is directed at theoretical and experimental investigations of the thermal performance implications of passive design strategies, with emphasis on passive and hybrid cooling of commercial buildings. The specific objectives of the program are the following:

1. Develop analytic descriptions of the thermal processes which occur within a building or between a building and the environment. These heat transfer algorithms are based on empirical data and/or analysis from first principles.

2. Develop and test advanced passive/radiative cooling system components and evaluate other passive heating and cooling systems.

3. Evaluate the effectiveness of passive systems in reducing energy consumption for space heating, space cooling, domestic hot-water heating, and lighting in the United States and identify effective criteria for passive system design optimization. The strategy used to meet these objectives consists of coordinated experimental and theoretical tasks leading to advanced energy analysis capabilities which can be used in passive system design and evaluation.

To date, the emphasis has been on the development and testing of techniques for predicting (1) the "resource" for passive systems and (2) a building's response to that resource. In this con-

*This research was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Passive and Hybrid Solar Energy Division, of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

text, the term "resource" implies the naturally occurring potentials of the environment to provide heating and lighting (as a result of solar gains) and cooling (via radiation to the sky, conduction to the ground, and ventilation/evaporation with ambient air). These potentials are being investigated in projects in the following areas: convection and natural ventilation, radiative cooling, natural lighting, passive building energy analysis, and passive domestic hot water. Accomplishments and future plans in each of these areas are described below.

ACCOMPLISHMENTS DURING FY 1981

Convection Research

This project consists of both experimental and analytic studies of natural convection heat transfer processes which take place within buildings and between the interior of a building and the environment. The objective of the project is to develop technically sound predictive capabilities for (1) natural ventilation rates, (2) interzone heat transfer, and (3) heat transfer to/from storage masses located within a building. The analytic work attempts to develop and apply detailed numerical models for convection phenomena in order to develop simplified descriptive algorithms to represent the heat transfer process. The experiments provide guidance for the development of the numerical model and produce data for validation of the numerical model and the algorithms.

During FY 1981, the experimental work consisted of measuring the convective heat transfer between two enclosures separated by a doorway. The data were collected in a small-scale experiment for a range of Rayleigh numbers extending from 10^{10} to more than 10^{11}. It was observed that, for the same boundary conditions, the heat transfer rate is relatively insensitive to the horizontal extent of the doorway and is determined largely by the height of the opening relative to the height of the enclosure. Based on these experiments and previously published results, a correlation was developed which led to the identification of an algorithm describing the coupling between enclosures[1]:

$$h = 1.44\left(\frac{H_a}{H}\right)^{0.45} \left(\frac{\Delta T}{H}\right)^{0.25}$$

where h is the interzone heat transfer coefficient ($W/m^2\ {}^oC$), ΔT is the temperature difference between the two endwalls (^oC), H is the height of the enclosure (m), and H_a is the central aperture height (m).

A detailed numerical model which solves the governing Navier-Stokes equations describing laminar convective heat and mass transfer in enclosures was validated using data from earlier LBL experiments.[2] This computer code was then applied to examine the variability of surface convection coefficients in an enclosure as the temperature distributions on the bounding surfaces are altered. This study showed that the coefficients deviate dramatically from the constant or simple temperature-dependent values normally used in the building sciences and that the true variations have a substantial impact on the calculation of energy consumption in buildings.

The numerical model was extended to turbulent flow by addition of a model for turbulent dissipation. This new capability allows examination of wind-driven natural ventilation rates and heat transfer from surfaces under forced or natural ventilation.

Radiative Cooling

Infrared radiative cooling systems are composed of a radiator surface exposed to the sky and a means for transporting heat from the building's interior to the radiator surface. The performance of these systems may be predicted if we know the intensity of infrared radiation produced by the atmosphere as a function of both zenith angle and wavelength.

To obtain data on which estimates of cooling system performance can be based, an experimental program was carried out in 1980 to measure the sky radiance at several U.S. locations. The measurements included the spectral composition of the sky radiance as a function of zenith angle and local climate variables such as drybulb and dewpoint temperatures.[3]

During FY 1981, the spectral radiometer data were analyzed to establish a correlation between the nighttime clear-sky infrared emissivity and the weather variable to which it is most sensitive, dewpoint temperature. The results are shown in Figure 1 in comparison with earlier experimental results; the correlation is based on data obtained from Tucson, Arizona, Gaithersburg, Maryland, and St. Louis, Missouri, comprising 2,945 individual measurements. The apparent discrepancy between the LBL correlation and that of Clark and Allen at low

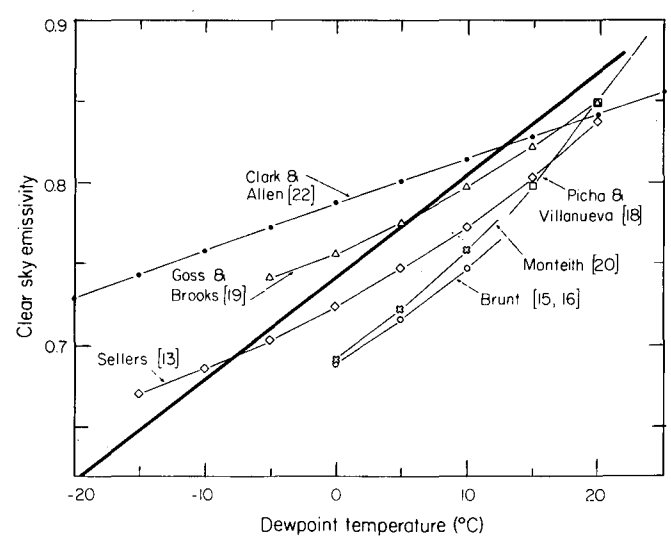

Figure 1. LBL results (heavy line) for clear-sky thermal emissivity compared with the results of previous investigators.

(XBL 813-541)

dewpoint temperatures was resolved by Clark,[4] who noted that their results closely approach the LBL values when accurate on-site temperature measurements are used. Although the sites from which the data were collected do not encompass all the climate types experienced in the United States, the fact that the observed clear-sky data from three diverse locations fall along the same straight line encouraged the belief that this may be a general result for midlatitude climates.

Under conditions of low clouds (below about 2 km), the apparent absolute sky temperature T_{sky} has been given as[5]

$$T_{sky} = (1 - f_w)\, T_{air} + f_w T_c$$

where T_{air} is the ambient air temperature, T_c is the temperature of the cloud base, and f_w represents the fraction of blackbody radiation in the 8- to 14-micron (atmospheric window) region and is equal to 0.3 ± 0.1. Data from the infrared spectral sky radiometers have been used to support this equation. The 11-micron effective sky temperature is used as a best estimate of the cloud base temperature, since the atmosphere is most highly transparent in this part of the spectrum. For the purpose of displaying this data, it is convenient to plot the sky temperature depression ($\delta T_{sky} = T_{air} - T_{sky}$) as a function of the cloud temperature depression ($\delta T_c = T_{air} - T_c$). In terms of these variables, the equation for the sky temperature reads

$$\delta T_{sky} = f_w \delta T_c$$

A plot of δT_{sky} vs. δT_c is shown in Figure 2; agreement is good for a value of $f_w = 0.32$. Based on a typical lapse rate of 5°C/km, the measured points in Figure 2 represent cloud base altitudes of zero to 4 km.

Figures 3 and 4 show the results of spectral infrared sky emissivities for clear sky conditions (558 hourly readings) and all sky conditions (879

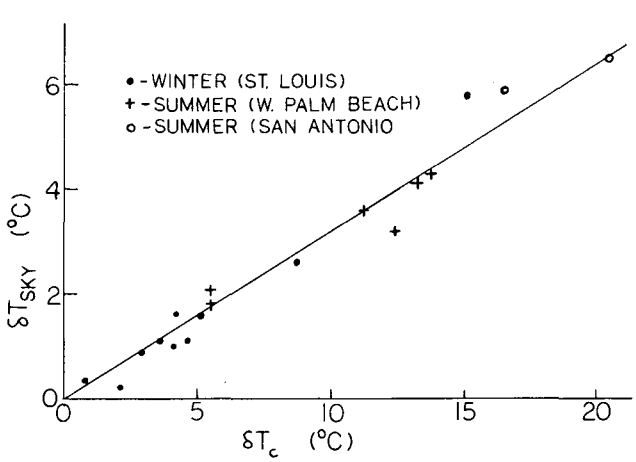

Figure 2. Sky temperature depression vs. cloud temperature depression.

(XBL 827-880)

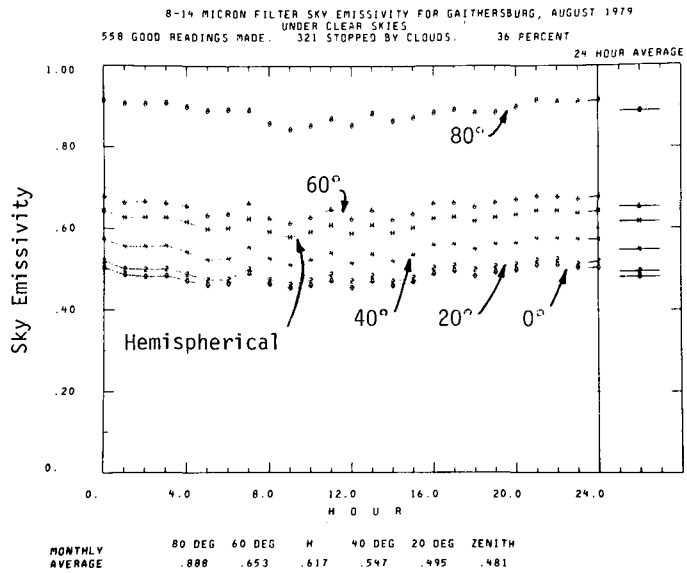

Figure 3. Measured average hourly sky emissivities in the 8- to 14-micron waveband for clear skies, for several zenith angles. The "hemispherical" curve is a weighted average of angular values.

(XBL 823-8209)

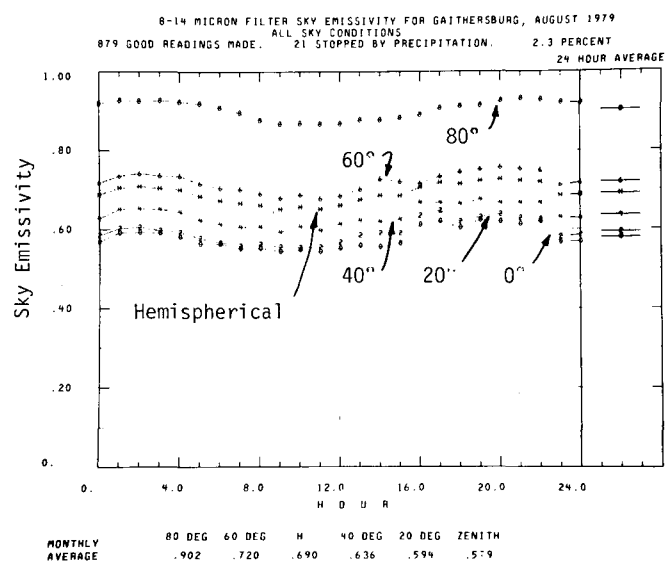

Figure 4. Measured sky emissivities in the 8- to 14-micron waveband. This figure is identical to Figure 3 except that it pertains to all sky conditions, cloudy as well as clear.

(XBL 823-8210)

hourly readings), respectively. The examples shown here are for Gaithersburg, Maryland, and represent data taken during August 1979 in the 8- to 14-micron waveband. Average hourly sky radiances expressed as emissivities are shown for zenith angles of 0, 20, 40, 60, and 80 degrees. The remaining curve is a weighted average of the angular values which represent the 8- to 14-micron emissivity seen by a horizontally exposed radiator.

For clear skies, the emissivities are nearly independent of time of day, provided the corresponding hourly average dewpoint temperatures

glazing is relatively insensitive to the glazed area in most U.S. climates. However, unmanaged east and west glazing is notably detrimental to overall performance owing to its serious impacts on cooling energy consumption. These results imply that a more integrated heating and cooling design approach is mandatory if appreciable energy benefits are to be realized.[8]

An examination of the energy consumption impacts of residential building orientation was completed.[9] It was confirmed that the location of glazing on the east and west facades of a building does not substantially alter heating season performance but can be very deleterious to cooling season energy consumption. In many climates, north orientation of glazing is not substantially inferior to south orientation; in fact, in extreme southern climates, north orientation is preferred, because (1) cooling is the dominant energy consumer and (2) north glazing receives less solar radiation than south glazing, even when the south glazing has a substantial overhang. Figure 6 shows some results from the orientation studies for a moderate U.S. climate (Nashville) and a very warm climate (Miami). In both cases, east and west orientations show the highest combined heating and cooling loads. In Nashville, south orientation shows the lowest combined loads; this advantage is more pronounced farther north. In Miami, because of dominant cooling loads, northern orientations produce the lowest loads.

Ventilative cooling of residential buildings was studied in order to examine the influence of the amount of thermal mass on cooling season performance and to determine the most desirable control strategy in a variety of climate types. It was found that relatively low air volumes (20 air changes per hour) are required to obtain nearly maximum effectiveness; it is interesting to note that this air exchange rate can frequently be accomplished with natural ventilation systems, such as cross ventilation using windows and the prevailing winds. It was also shown that, for some climates, night ventilation is a very effective cooling strategy if substantial amounts of exposed thermal mass are located in the building.[10]

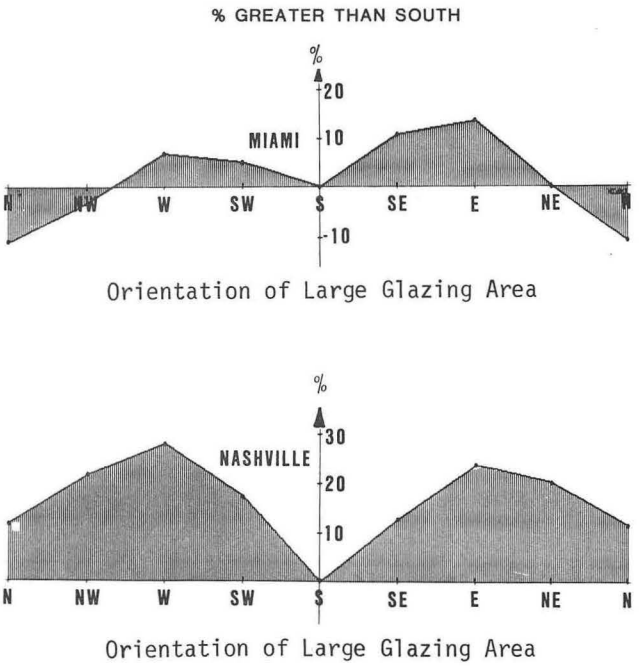

Figure 6. Combined heating and cooling loads in Miami and Nashville.

(XBL 827-879)

Commercial building studies were initiated during FY 1981. A completed study focused on the interaction between the mechanical systems in a commercial building, the environment, and the energy demands of the occupied spaces. This demonstrated that the passive design process for commercial buildings cannot be based on the substantial existing residential experience. In commercial buildings, the thermal load is only loosely coupled to the energy consumption of the mechanical systems; the dominant thermal load does not necessarily correspond to the dominant energy end use. For example, in many buildings the heating load is smaller than the cooling load, but space heating is the dominant consumer of energy at the building boundary. This substantially complicates the selection of appropriate passive heating and/or cooling approaches for commercial buildings and implies that the selection must be based on a comprehensive examination of the anticipated fuel consumption profiles for the building. It is necessary to provide the designer with a new level of technical design information regarding energy use patterns for the commercial sector.

In preparation for comprehensive studies of passive strategies in commercial buildings, a daylighting measurement facility was designed, built, and tested. The facility will be used to gather illumination data from scale models of commercial buildings; the data will be input to BLAST in order to perform total energy analyses of naturally lighted buildings. Future work on this project will provide information regarding the cooling load reductions and/or heating load increases that accompany reduced electric energy consumption for lighting.

Domestic Hot Water

The goal of the hot water project was to develop and test passive solar water heater concepts, with the focus on thermosiphons. For domestic hot water and other low-temperature applications, thermosiphons offer significant advantages over active systems in terms of simplicity, reliability, and cost. Furthermore, the widespread use of thermosiphons in other countries is evidence of the market potential of this concept. The major limitation to the use of conventional thermosiphons in the U.S. is the vulnerability in almost all climates to freezing of the potable water in the low-mass collector. Current methods of freeze-protecting thermosiphons, such as drain-down, tend to compromise the basic attributes of the thermosiphon concept, i.e., simplicity and reliability.

The major thrust of the hot water project has been to carefully quantify the performance of thermosiphons using a non-freezing collection fluid which transfers heat to the potable water through a

heat exchanger. Specific objectives of the project are to

1. Quantify the performance of thermosiphons with heat exchangers relative to systems without heat exchangers.

2. Quantify the performance differences between thermosiphons using horizontal and vertical tanks.

3. Develop and test various heat exchanger concepts and quantify the performance of each to provide the basis for optimizing heat exchanger design.

4. Investigate the significance of reverse flow in these systems and the need for using one-way valves.

5. Develop simplified design tools and application guidelines to foster implementation of these systems.

During FY 1981, a detailed computer program was written for simulating the daytime collection and nighttime reverse-flow losses of a thermosiphon water heater with a simple heat exchanger in the storage tank. Simulations were made with the computer program to determine the performance effects of heat exchanger capacity, tank stratification, tank elevation relative to collector, and system resistance (collector and connecting tube diameter and length).[10]

A simplified computer program was developed to simulate annual performance at hourly time increments using Typical Meteorological Year (TMY) weather tapes. The predictions of the simplified model agree with those of the detailed analysis to within 5 percent. Both the detailed and simplified analyses agree to within 5 percent with the data reported in the literature for non-heat-exchanger configurations.

A detailed analytical model was developed for the simple heat exchanger inside the tank. Performance was found to be sensitive to the tank temperature, collection fluid temperature, and flow rate. The detailed heat exchanger model was used to generate an algorithm which was incorporated into both the detailed and simplified system-simulation computer programs.

A residential-scale thermosiphon test facility was constructed with the following capabilities:

1. Solar collectors powered by electric resistance heaters that are controlled to simulate daily solar radiation cycles.

2. Structure capable of orienting the storage tank vertically or horizontally and at various elevations relative to the collector.

3. Experimental tank capable of accepting various heat exchanger configurations and provision for obtaining detailed tank temperature profiles.

4. Sixty-channel data acquisition system with output to magnetic tape.

A data reduction program was written that can read magnetic data tapes and generate temperature plots and performance reports.

PLANNED ACTIVITIES FOR FY 1982

Convection Research

The emphasis of the convection project during FY 1982 will be on (1) consolidation of existing analysis capabilities by thorough verification of the convection analysis and (2) applications leading to an improved characterization of surface convection coefficients in terms of the boundary conditions on surface temperatures. The zone coupling algorithm developed in FY 1981 will be further tested in order to define its limits of applicability. During the latter portions of the year, studies of wind-driven natural ventilation will be initiated; it is anticipated that this will lead to algorithms describing the ventilation rate as a function of environmental conditions and building design parameters.

Radiative Cooling

The sky radiometer data analysis will be concluded and the results published. A radiative cooling-assembly test facility will be used to examine the cooling performance of assemblies using existing radiator and glazing/wind-screen materials; both blackbody and selective radiator surfaces will be tested. Finally, advanced radiator materials will be tested to determine whether they can produce more cooling power.

Building Energy Analysis

The focus of these activities will be on the application of BLAST to study the energy consumption impacts of the various passive cooling and cooling load control options. These studies will be used to estimate the relative impacts of the individual cooling technologies in various climates across the nation. In conjunction with personnel at the Los Alamos National Laboratory, we will further analyze the thermal performance results in order to estimate the economic impacts of the cooling technologies. In the daylighting area, the illumination measurements and their analysis and the associated thermal analysis will be extended to a variety of design concepts in order to characterize system performance.

Domestic Hot Water

This project will be concluded with the publication of the results of the proof-of-concept experiments.

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Active Solar Cooling*

M. A. Wahlig, K. Dao, M. L. Warren, J. E. Rasson, R. A. Armer, H. Angerman,† and A. Heitz†

This project has three major tasks: (1) research and development (R&D) of improved absorption cycles for active solar cooling and heating, (2) performance and economic analysis of active solar cooling and heating systems to establish cost/performance goals for the R&D program, and (3) technical support activities for the active solar cooling program.

The objective of the R&D activity is to achieve a significantly higher conversion efficiency than is possible using other approaches for solar cooling and heating of buildings. Because practical temperatures range up to about 350°F for solar collectors used in residential and commercial building applications, absorption-cycle cooling systems have been selected for investigation. Being essentially heat pumps, absorption-cycle chillers can be used for heating as well as cooling if the refrigerant fluid does not freeze in the outdoor coil during heating applications. We restrict our fluid choices to those for which this heating option is available.

The R&D program consists of four phases, each successive phase leading closer to the final machine. The first phase was successfully completed some time ago.[1] By modification of a conventional gas-fired ammonia/water absorption chiller, we demonstrated the capability of our analysis techniques to predict accurately the performance of single-effect, absorption-cycle chillers under operating conditions appropriate for solar-powered cooling.

In the second phase, a completely new solar single-effect chiller[2] was fabricated, using the experience gained during the first phase. Testing of this chiller has just been completed. Evaluation and recommendations concerning this chiller are summarized later in this report.

The third phase investigates the performance improvement obtained by adding a unique second boiling effect to the single-effect chiller tested in the second phase. The basic concept of the resulting double-effect regenerative (or cycle 2R) cycle has been described previously.[3] Fabrication of the major components of the 2R chiller[4] has now

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Active Heating and Cooling Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

†Employees of Keller and Gannon, a subsidiary of Lester B. Knight and Associates, Inc.

been completed, and testing is expected to start by mid-FY 1982.

The fourth phase of the R&D activities investigates a new concept in refrigeration absorption cycles, having still higher efficiency and yet requiring less heat exchanger area and thus having a potential for lower cost. The basic concept of this single-effect regenerative cycle (which we call cycle 1R) has also been described previously.[5] The success of the cycle 1R chiller depends on our experience gained from developing the cycle 2R chiller. Locating a refrigerant-absorbent fluid pair with suitable properties at 300°F or higher should further increase the efficiency of the 1R chiller.

The objectives of the performance and economic analysis activities are to establish cost/performance goals for active solar cooling and heating systems and to identify those R&D directions that have the greatest probability of attaining these goals. The desired cost/performance goals are those that will result in significant market penetration of active solar cooling systems, starting in the late 1980's and continuing through the 1990's. A methodology has been developed to derive these goals, and preliminary solar cooling system and subsystem goals have been calculated.

The technical support activities provide assistance in the active solar cooling program area to the DOE San Francisco Operations Office (SAN) Conservation and Solar Division and to the DOE Headquarters (HQ) Active Heating and Cooling Division, Office of Solar Heat Technologies. These activities include program planning, technical monitoring and evaluation of ongoing projects, including site visits and review of progress reports, coordination of review of unsolicited proposals, assistance in the preparation and evaluation of responses to program solicitations, and coordination of related activities by other organizations.

Finally, a related activity, the LBL solar controls program, had as its objective the use of the LBL solar controls test facility to evaluate experimentally the relative performance of different solar heating control strategies for a variety of input meteorological conditions and output load demands, and the carrying out of theoretical studies of collector and load loop performance in support of the experimental work. Work on the LBL controls test facility was concluded early in FY 1981, and the results of theoretical analysis have been presented.

ACCOMPLISHMENTS DURING FY 1981

Absorption Chiller R&D

Testing of the Single-Effect Chiller. The testing of the single-effect ammonia/water chiller has been successfully completed. Most of the performance goals have been achieved as summarized in Table 1.

The chiller has been tested for about 300 hours of run time, from which about 70 performance data sets have been collected. A complete report on the performance of the chiller and its components will be issued shortly.

Table 1. Single-effect chiller test results.

	Realized	Goal
Hot water input temperature, °F	220	216
Condenser/absorber inlet cooling air temperature, °F	95	95
Leaving chilled water temperature, °F	52	45
Capacity, tons	3	3
Coefficient of Performance, COP	0.67	0.70
Condenser/absorber fan power, HP	3/4	3/4
Condenser/absorber fan air flow rate, CFM	6800	6800
Make-up solution pump power, HP	1/2	0

Initial analysis of the data indicated that the absorber was the poorest performer of the chiller components. Its overall heat-transfer coefficient was only 80 Btu/hr-ft^2-°F of tube area as opposed to the expected value of 140. This led to a high absorber temperature and, therefore, a higher chilled water temperature. Other contributions to the high (52°F) chilled water temperature included:

- An unexpected pressure drop of 10 psi across the pipe fittings at the outlet of the generator (manufacturing error);
- A 20-percent lower-than-expected heat transfer coefficient of the condenser; and
- A 35-percent lower-than-expected heat transfer coefficient of the evaporator.

Evaluation of the Single-Effect Chiller. The major results of the single-effect chiller tests are as follows:

1. The concepts of heat recuperation incorporated into the chiller worked as expected, increasing the COP to the 70-percent range.
2. The concept of power recuperation from the weak solution worked reliably: the solution driven pump had no failures during any of the runs.
3. The concept of self-powered operation needed more refinement: the vapor-driven pump did not work well because of vapor absorption in its valve switching lines.
4. Heat transfer coefficients were usually 20 percent lower than design calculation predicted, possibly because of higher fouling factors. Keeping the tubes very clean and rust free might well restore the higher heat-transfer coefficients.

5. The generator outlet pressure can be eliminated by reconnections.

6. The poor heat transfer of the evaporator occurred largely at its outlet, where most of the liquid had been evaporated. By rerouting the last tubings of the evaporator, the poor overall heat-transfer coefficient should be improved.

7. The absorber needs a better design than the conventional finned tubes.

Eliminating the obvious shortcomings, such as rust, dirt, and bad connections, should reduce the chilled water temperature to 48°F. To further lower the chilled water to 45°F, a better absorber design must be used or the hot water input must be raised to 225°F.

Fabrication of the 2R Chiller. The following components of the 2R chiller have now been fabricated:

- Boiler, as shown in Figure 1
- Recuperator
- Generator
- Preheater
- Multistage pump

The installation of the testing facility for the 2R chiller and the fabrication of the remaining chiller components are underway. Testing of this chiller is scheduled to begin in mid-1982.

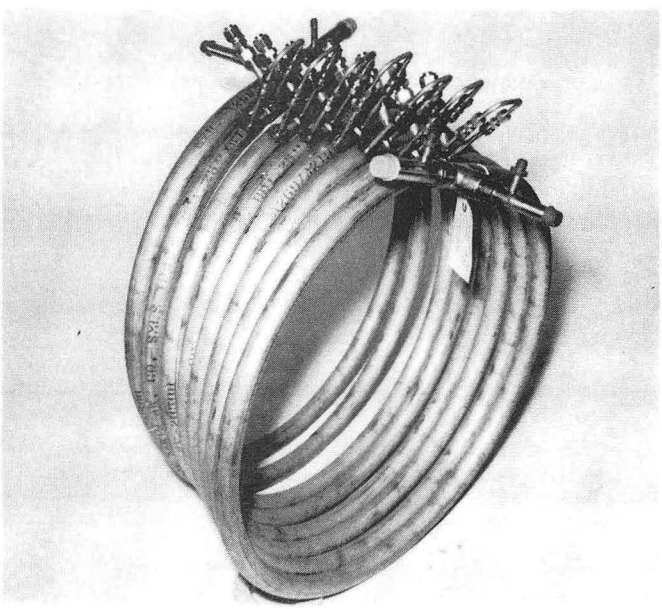

Figure 1. Multi-stage boiler of the 2R chiller. In each turn of the coil, the solution boils at a different pressure. Vapors are taken off at the larger short-tube segments welded to the coil; for further boiling, solutions are expanded to the next pressure stage through the small v-shaped tubings. Hot water from the solar collectors flows inside the inner tube of the coil.

(CBB 818-8154A)

Candidate Fluids for the Cycle 1R Chiller. Under DOE contract and LBL guidance, SRI International conducted a literature search during FY 1981 and followed up with experimental measurements of the properties of absorbent and refrigerant fluids previously identified by LBL to be candidates for high temperature (260 to 360°F) operation of a cycle 1R chiller. These measurements should be completed during the first half of FY 1982.

Performance and Economic Analysis

The principal accomplishments during FY 1981 have been development of preliminary cost/performance goals for active solar cooling/heating systems, preparation of a background report describing a methodology for developing cost/performance goals, work with other contractors performing systems analysis work to define realistic buildings and active solar cooling systems for simulation, completion of the analysis of experimental results from the controls test facility operation and reporting the results, completion of the theoretical analysis of the interaction between the solar heating system and the building response, and reporting the results.

Cost Goal Methodology. A consistent methodology has been developed by which general solar cooling market-capture goals can be and have been translated into specific cost and performance goals for solar cooling systems and subsystems.[6-9] The preliminary results indicate that realistic cost/performance goals can be established for active solar cooling systems. This methodology for establishing cost goals and developing cost and performance improvement pathways to reach those goals is not limited to active solar cooling applications; it could be used equally well for other technologies, such as passive cooling and heating.

A market-penetration scenario was postulated, beginning with commercial introduction of active solar cooling systems in 1986 and attaining a 20-percent annual market share of the entire national cooling capacity by the year 2000. The shape of this postulated market-penetration curve was based upon the actual penetration curve achieved by heat pump sales in the United States during the period 1953 to 1970. This is typical of historic early-market penetrations achieved by major HVAC products. In general, air conditioning demands are expected to grow significantly over the next 20 years, driven by population shifts to the "sun belt" regions of the country. It is estimated that over 90 percent of the new construction in this region will have central air conditioning. Energy conservation and passive cooling measures are expected to reduce significantly the sensible cooling and heating loads. However, the substantial latent (i.e., humidity) cooling loads in all buildings and internal heat gains in commercial buildings will remain and will require the use of mechanical cooling systems.

The annual energy used for cooling of buildings in the year 2000 was estimated by accounting for the expected mix of building types, regional differences in building stock and cooling loads, and residential and commercial building energy

requirements. An estimated annual energy displacement of 0.14 quad of conventional energy sources by solar in the year 2000 (for new residential, new multifamily, retrofit residential, and commercial market sectors) would result from a 20-percent penetration by solar cooling of the annual projected air conditioning market by the year 2000.

Certain cost and economic performance goals must be achieved by the solar industry before market demand will rise to a level that will produce the desired market penetration. Marketing studies[10] indicate that, for heating and air conditioning products, the relationship between market penetration and payback period is as shown in Figure 2. The payback period, the number of years for the undiscounted fuel cost savings to equal the incremental cost to produce those savings, is related to a real return on investment. Postulating market penetration goals per year necessary to achieve a 20-percent annual penetration by the year 2000, the corresponding payback and return on investment goals as a function of year of purchase have been calculated and are shown in Figure 3.

Annual system simulations of the thermal performance of active solar Rankine and absorption cooling/heating systems have been conducted using TRNSYS.[11,12] These calculations have been made for residential solar cooling/heating systems in four cities (Fort Worth, Phoenix, Miami, and Washington, D.C.) and for commercial solar cooling-only systems in three cities (Fort Worth, Phoenix, and Miami) which are representative of the cooling market. Three types of systems were evaluated: residential 3-ton absorption (ARKLA), commercial 25-ton absorption (ARKLA), and commercial 25-ton Rankine (AiResearch).

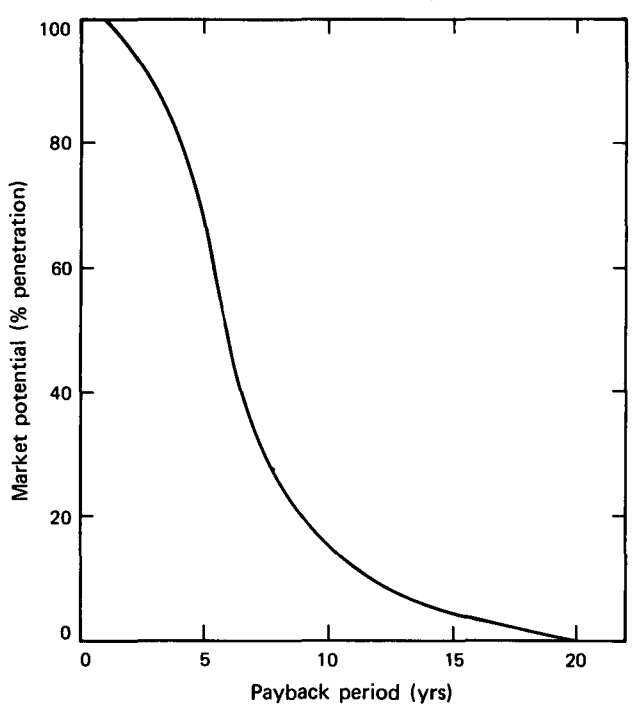

Figure 2. Market potential as a function of payback period. From Garry L. Lilian and Paul E. Johnston, "A Market Assessment for Active Solar Heating and Cooling Products," final report, OR/MS Dialogue, Inc., Cambridge, Mass., September 1980. (XBL 812-368)

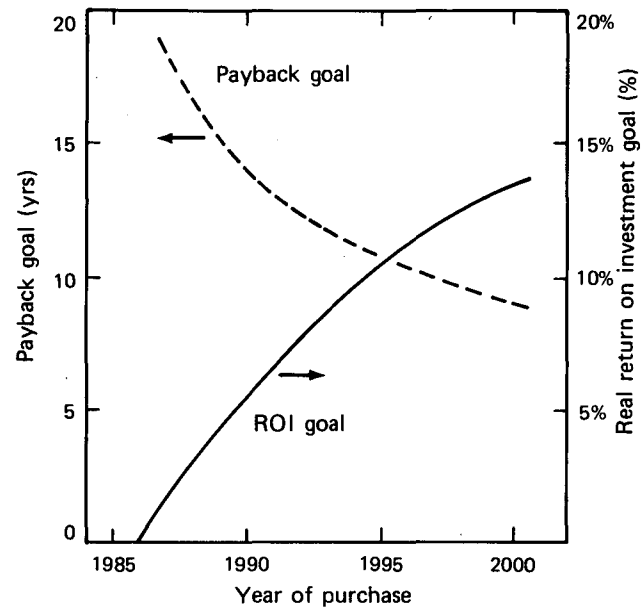

Figure 3. Payback goal and real return on investment (ROI) goal as a function of year of purchase to reach a 20% market penetration in the year 2000. (XBL 812-365)

It is assumed that a solar cooling or cooling/heating system is cost-effective when the incremental solar system cost is equal to or less than the present value of the energy savings. A standard economic analysis is used to calculate the present value of the fuel saved by an active solar system over the life of system (20 years), assuming a given internal real rate of return on the initial investment. The present value is based on the modified uniform present worth, which is a function of the fuel escalation rates and the expected real return on investment. Details of the analysis are presented elsewhere.[6,7,9]

Combining these calculations of the incremental solar-system cost as a function of real return on investment with the real return on investment goals as a function of year (as contained in Fig. 3), incremental system cost goals as a function of year have been generated for residential solar cooling systems and are displayed in Figure 4. Similar analysis has been performed for commercial cooling systems.

System and Subsystem Costs. The total solar-cooling-system cost goals for different locations can, in turn, be subdivided into subsystem cost and performance goals. It is anticipated that the major reductions in subsystem costs will be achieved by technical improvements in subsystem performance, such as increasing chiller efficiency to reduce the size of collector arrays, by volume production economies, and by development of packaged and standardized subsystems to reduce system engineering and installation costs. Preliminary system and subsystem cost estimates for a residential system are shown in Figure 5. These values are based on estimates of current subsystem costs

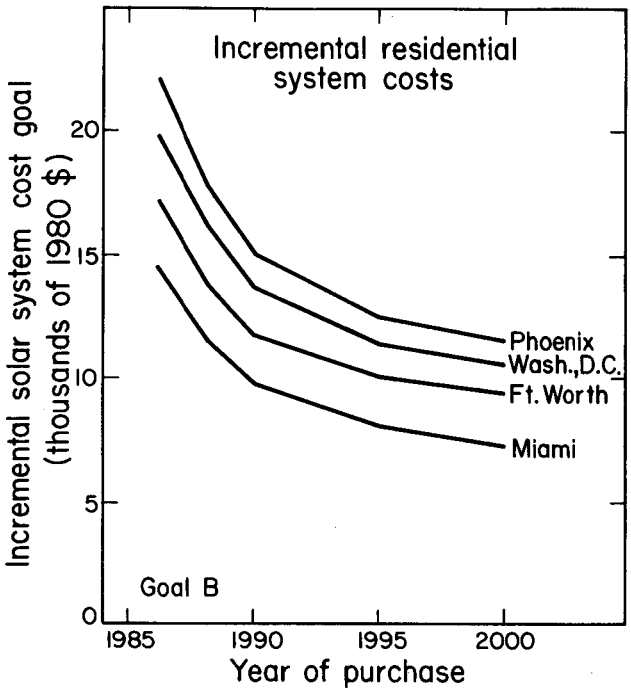

Figure 4. Residential incremental solar system cost goals for representative systems in four cities to achieve goal B, 20% penetration in the year 2000.

(XBL 816-1005)

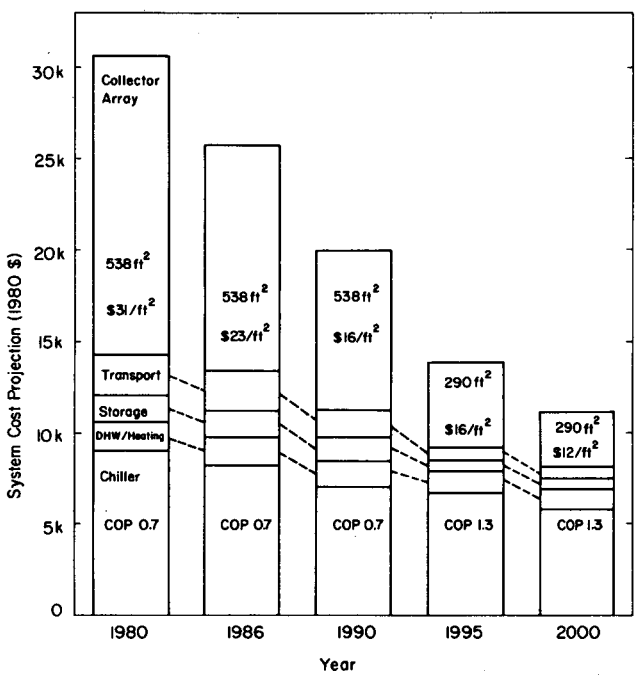

Figure 5. System cost projections for a 3-ton residential absorption cooling, heating, and hot water system showing subsystem costs.

(XBL 814-600)

plus realistic expectations for subsystem cost and performance improvements. Similar analyses have been made for commercial absorption and Rankine systems.

Technical improvements in subsystem performance are anticipated. For the residential 3-ton absorption chiller and for the commercial 25-ton absorption chiller, the current coefficient of performance of about 0.7 should stay relatively constant until the development and introduction of double-effect absorption chillers in these sizes, at which time the COP should increase to about 1.3. For the commercial 25-ton Rankine chiller, the current coefficient of performance of about 0.7 should increase gradually to about 1.5 if the operating temperature is increased to about 500°F.

The collector array is one of the major cost items of any active solar cooling system. The key to cost-effective cooling systems is reducing the collector array costs. For the high-temperature, high-COP future scenario, either evacuated tubes with reflectors or cylindrical trough collectors will likely be used. Collector manufacturing costs of $\$150/m^2$ ($\$14/ft^2$) have been projected[13] for evacuated tube concentrating collectors.

Current chiller technology, with a COP of 0.7 and the distinct advantage of operating at temperatures below 200°F, could be adequate if very low cost, good-performance collectors could be developed. As Figure 5 shows, "very low cost" can be seen to require collector costs of about $\$6/ft^2$. "Good performance" in this context means an efficiency of about 40 to 50 percent at a typical absorption chiller driving temperature of about 185°F. Work underway at Brookhaven National Laboratory[14] is directed toward the development of solar collectors that might possibly meet these types of cost and performance requirements.

Controls Test Facility and Analysis. During FY 1981, work was completed on analyzing and reporting the results of experiments run on the LBL controls test facility.[15-17] The modeling of the thermal behavior of a residential building, a fan coil heat-delivery system, and a bimetal thermostat to simulate the effects of heat input from an active solar space heating system on room air temperature dynamics has been completed.[18]

Technical Support Activities

Overall Solar Cooling Program Planning and Review. The following activities occurred during FY 1981:

- Prepared several revised versions of the Multiyear Program Plan for Rankine and absorption solar cooling systems.
- Prepared documents on the key accomplishments (and their significance) of the active solar cooling R&D program and the controls R&D program, and also on the risk/payoff aspects of the cooling program.
- Participated in major program planning and review meetings for the DOE Active Heating and Cooling Division, in Washington, D.C., and at the Belmont Conference Center.
- Made presentations and joined discussions on the solar absorption and Rankine cooling program at DOE/HQ. Had meetings with DOE/HQ program managers at HQ, at SAN, and at LBL.

- In connection with the Annual Active Solar Heating and Cooling Contractors' Meeting, LBL participated in the planning, reviewed the cooling contractors' papers for the proceedings, made the absorption and Rankine cooling overview presentation,[19] and chaired the cooling session. Similarly, LBL participated in the planning and gave an overview presentation for the May 1981 Solar Cooling Workshop and participated in some of the follow-up debriefings.

Technical Monitoring. The following are some of the major FY 1981 activities by LBL in providing technical monitoring and evaluation of solar cooling projects by outside (non-LBL) contractors:

- Conducted 18 site visits and project reviews covering 11 different DOE contractors; reviewed 25 final reports and phase reports, and 3 follow-on proposals; and assisted DOE/SAN in specifying Statements of Work for several of these contractors.

- Interacted with many of the solar cooling contractors at 13 SAN and LBL meetings with individual contractors. In addition, numerous technical discussions with contractors took place by phone and by mail.

- Prepared and sent to DOE/SAN monthly summary reports on all the DOE solar absorption and Rankine cooling projects.

- Assumed responsibility for technical monitoring of systems analysis projects related to active solar cooling.

Proposals for New Work. During FY 1981, LBL conducted the review of three unsolicited proposals and sent results to DOE/SAN with recommendations for action. LBL also reviewed proposals submitted in response to a solar cooling RFP issued by the American Samoa Energy Office.

Coordination Activities. During FY 1981, LBL staff members in the course of coordinating activities related to the solar absorption and Rankine cooling program:

- Had frequent interactions with the NASA/MSFC (Manned Space Flight Center, Huntsville, Alabama) group responsible for management of the Honeywell solar Rankine cooling project and the Operational Test Sites (OTS), including several meetings at SAN and six joint field visits to OTS by LBL and MSFC staff.

- Held a number of meetings to insure coordination of the DOE solar cooling R&D program and the SOLERAS joint U.S.-Saudi Arabian solar cooling program, which consists of four solar cooling field experiments at sites in Phoenix. The SOLERAS contractors are all also participants in the DOE cooling R&D program.

- Participated as a member of the Heat Pump Integration Task Force, chaired by John Ryan of DOE/HQ, including presentation of an overview paper on the solar cooling program at the initial meeting in June 1981 at McLean, Virginia, and participation in follow-up working group meetings at Chicago in August and at DOE/HQ in September 1981.

- Had cooperative interactions with Gas Research Institute (GRI) staff members involved with gas/solar projects.

- Participated in negotiations to establish a joint U.S.-Greek project in solar heating and cooling, held in Athens during October 1980.

- Had several discussions with members of the DOE/HQ and the SERI International Programs Offices concerning the on-again, off-again joint U.S.-Mexican project on solar refrigeration.

- Participated in reviews of the DOE solar desiccant cooling program at SAN in June and August and in Chicago in September 1981.

- Joined in meetings at SAN and LBL and other locations with staff members of ORNL and other DOE laboratories involved in activities closely related to solar cooling.

- Participated in several meetings per month at SAN to coordinate LBL's technical support with SAN's program management responsibilities for the solar cooling program.

PLANNED ACTIVITIES FOR FY 1982

Absorption Chiller R&D

The major absorption chiller R&D activity in FY 1982 will be debugging and testing the 2R chiller. Because this is the first chiller of its kind ever built, significant operational difficulties may be encountered and would have to be overcome before meaningful performance data can be obtained.

The level of effort spent on the cycle analysis and design of the 1R chiller depends on the progress of the 2R chiller testing. Ideally, work on a first practical design of the 1R chiller should be underway by the end of FY 1982.

Measurements by SRI International of properties of candidate new-fluid pairs for the 1R chiller should be completed during FY 1982.

A complete report on the testing, performance, and evaluation of the single-effect chiller will be published in FY 1982.

Performance and Economic Analysis

Activities during FY 1982 will be directed toward research into intelligent methods of controlling active solar cooling and heating systems and the documentation of the performance of different types of active cooling/heating systems and

the resulting cost/performance goals. Efforts are currently underway to obtain more realistic systems-analysis models of the thermal performance of the cooling systems and better estimates of cost and performance projections. We will continue to work during FY 1982 with other systems analysis contractors to develop realistic models of active solar cooling systems and to develop in-house capabilities for systems simulation and economic analysis for active solar cooling.[20] We will also continue to coordinate the systems-analysis activities of other organizations to determine the research requirements by which a broad spectrum of solar space conditioning systems might attain their respective cost performance goals.

Technical Support Activities

It is anticipated that the technical support activities in FY 1982 will be similar to those carried out in FY 1981. The planning activities will shift from emphasis on solar cooling system integration to a more generic long-term R&D program, consistent with new Administration guidelines. Documentation of cooling program accomplishments and research needs will be prepared because much of the existing cooling program is expected to be phased out.

Site visits to solar cooling contractors and review of progress and phase reports will continue as long as the cooling contracts are active. Unsolicited proposal reviews will continue to be conducted as received.

Finally, the critical coordination activities with other organizations involved in similar programs will continue to be pursued diligently.

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Appropriate Energy Technology*

F. B. Lucarelli, J. D. Kessel, H. R. Clark, J. M. Kay, and J. Linse

In 1977, the Energy Research and Development Administration (ERDA), since incorporated into the Department of Energy (DOE), established an appropriate technology small grants program. The purpose of the program is to fund projects that design, manufacture, and/or demonstrate small-scale energy technologies which conserve depletable fossil fuels or use renewable energy resources. DOE makes the grants available annually on a competitive basis to small businesses, individuals, nonprofit organizations, public agencies, and Indian tribes. The maximum grant award is $50,000.

The grants cover a complete spectrum of small-scale energy technologies, including solar active and passive systems, wind machines, biomass conversion systems, energy conservation devices, recycling methods, aquaculture systems, hydroelectric devices, and geothermal heating systems.

ACCOMPLISHMENTS DURING FY 1981

Energy Impact Analysis

Because of the diverse array of technologies and end-use applications of DOE-funded appropriate technology projects, DOE has been unable to assess the program's energy savings potential, an assessment that is necessary to compare the program with other DOE programs. To obtain this information, DOE asked LBL to assess the program's energy savings potential and cost-effectiveness.

We began our analysis in 1979, assessing the energy savings potential of 20 projects from Region IX.[1] We completed the analysis in 1979 and found that most of these projects could save a significant amount of energy either directly, from the original project, or indirectly, from demonstration and commercialization effects. However, the sample was small and specific only to Region IX; therefore, we could not extrapolate our findings to estimate the energy savings potential of the national grants program.

In 1981, we evaluated a sample of 57 projects funded in FY 1979.[2] The 57 projects were selected from eight of the ten Federal regions and cover the full range of technology categories funded: wind, biomass, solar, geothermal, hydro, and conservation.

The analysis was conducted in 4 steps:

1. Evaluation of project energy savings,
2. Assessment of economic feasibility,
3. Estimation of replication potential, and
4. Extrapolation of sample energy savings to estimate program energy savings.

The results of the study include the development of procedures for evaluating energy savings from appropriate technology projects, the calculation for the sample projects of energy savings, and an estimate of program energy savings.

Technology Assessment Study

We also assessed the technical and economic feasibility of small wind-energy systems in the U.S.[3] The projects apply wind systems in the agricultural, residential, and industrial sectors for pumping water, generating electricity, and heating water. Electric projects range in size from 1 to 35 kW. For this study, we assessed each project for technical performance, economic feasibility, and physical infrastructure requirements. The report discusses near-term applications of small wind systems and the physical infrastructure requirements that can make feasible a larger array of small wind-energy applications.

Development of Methods for Evaluating Small Energy Systems

Methods have been developed to evaluate the

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of State and Local Programs, Small Scale Technology Branch of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

energy impacts and cost-effectiveness of small energy systems in the following categories: wind-electric, hydroelectric, geothermal-direct utilization, active and passive solar systems, anaerobic digestion, and conservation-weatherization. A report is being issued discussing these methods of project analysis.[4]

PLANNED ACTIVITIES FOR FY 1982

The Appropriate Energy Technology Program is being phased out by DOE, and LBL will have no further involvement.

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Energy Conversion by the Retinal Protein, Bacteriorhodopsin*

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Biological energy-conversion schemes hold considerable promise for harnessing solar energy. Our research is concerned with one of the simplest biological solar-energy converters known: bacteriorhodopsin (bR). This pigmented protein is found in the cell membranes of certain salt-requiring bacteria including Halobacterium halobium. Our research program is attempting to determine the molecular details of how this protein utilizes light from the sun to produce an electrical current across the bacterial membranes. We anticipate that such understanding will ultimately lead to the production of novel photoelectric cells and solar batteries.

Bacteriorhodopsin is the only protein in the purple membrane of Halobacterium halobium. The retinal chromophore is covalently attached to a lysine amino acid side chain of the protein by a protonated Schiff base linkage. In the presence of light, bR functions as a proton (H^+) pump and generates both pH gradients and electrical potentials across the membrane. Following a flash of light, the chromophore undergoes a photocycle in which several intermediates are identified by distinct absorption bands. For the M_{412} intermediate, resonance Raman studies show that the Schiff base is not protonated. This suggests that the chromophore is directly involved in the proton pumping process.

Information on whether other protonatable amino acid residues of the protein participate in the mechanism of H^+ uptake, translocation, and release is very important in correlating the photoreaction cycle with molecular models of photochemical conversion.

The photocycle in bR is initiated after absorption of visible radiation (λ_{max} = 570 nm) by the retinal chromophore in an all-trans configuration. The initial steps of the photocycle involve the isomerization of the chromophore to 13-cis retinal. The deprotonated Schiff base forms with a half-life ($t_{1/2}$) of about 50 μsec. Proton release from the extracellular surface of the protein occurs in this time range. Later, the deprotonated species decays with a $t_{1/2}$ of 3-5 msec, restoring the original all-trans form of the chromophore. During this time, protons are taken up from the cytoplasmic surface of the protein (for a review, see Reference 1). To assess significant structural features of the protein important for the photocycle, we have used chemical modification of amino acid side chains, low temperature, and detergent effects on purple membranes. Reconstituted bR containing synthetic membranes have also been used to derive information on proton pumping activity.

ACCOMPLISHMENTS DURING FY 1981

Chemical Modification Studies

Last year, we reported[2,3] our results with modification of carboxyl and guanidinium groups, suggesting that a charge-transfer complex essential for reprotonation of the Schiff base may exist between these two types of groups. The interaction

*This work was supported by the Office of Energy Research, Office of Basic Energy Science, Division of Biological Energy Research of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

between carboxyl groups and at least one amino group of lysine also appeared to be important for H^+ movement. Tyrosines were also found to be involved as H^+ donors for Schiff base reprotonation and for the release of H^+ at the extracellular surface of the purple membrane.

During FY 1981, we have continued and extended studies on modification of tyrosines, lysines, and arginines (Figure 1). The results can be summarized as follows:

a. Tryosine: Tetranitromethane modification of bR shifted the absorption maximum to 530 nm; the reaction was found to be light-dependent at pH 6.0 and to probably involve only one residue.[4] The decay of the M_{412} intermediate was unaffected by nitration, whereas the $t_{1/2}$ of the rise kinetics was accelerated by more than 50 percent. Chymotrypsin digestion showed that most of the 3-nitrotyrosine eluted with the larger of the two protein fragments containing residues 72-248. Circular dichroism (CD) studies showed that the nitrated purple membranes had lost the negative band at 575 nm, characteristic of exciton coupling in native purple membranes. Extensive cross-linking of bR with glutaraldehyde prior to nitration did not prevent the blue-shift of the absorption maximum to 530 nm nor the loss of exciton coupling in the CD spectrum. These studies demonstrate that modification of a tyrosine other than tyrosine 26 (see Reference 5) also leads to a blue shift in the spectral properties of the Schiff-base-linked retinal and that this effect is not due to a disruption of the lattice structure of bR. Tyrosine 185 appears at present to be the most likely candidate. This residue may be sterically restrained because of its location next to proline 186, which may explain the large increase in the amount of 13-cis retinal induced by 3-nitrotyrosine formation of a residue in the large chymotrypsin-cleaved fragment.

b. Lysine: At pH 8.8, with a molar ratio of (the modifier) fluorescamine to bR of 170, about 6 residues of lysine were modified, whereas arginines were not affected at all. Except for the appearance of the fluorescamine peak at 394 nm and some broadening of the chromophore peak at 570 nm, the absorption spectrum of bR was not significantly changed after modification.[6] CD studies indicated a loss of exciton coupling between bR molecules, and rotational diffusion studies suggested a slight increase in the mobility of the chromophore after modification. However, the spectral changes accompanying the light-to-dark adaptation (λ_{max} changes from 570 nm to 560 nm) of purple membranes were not

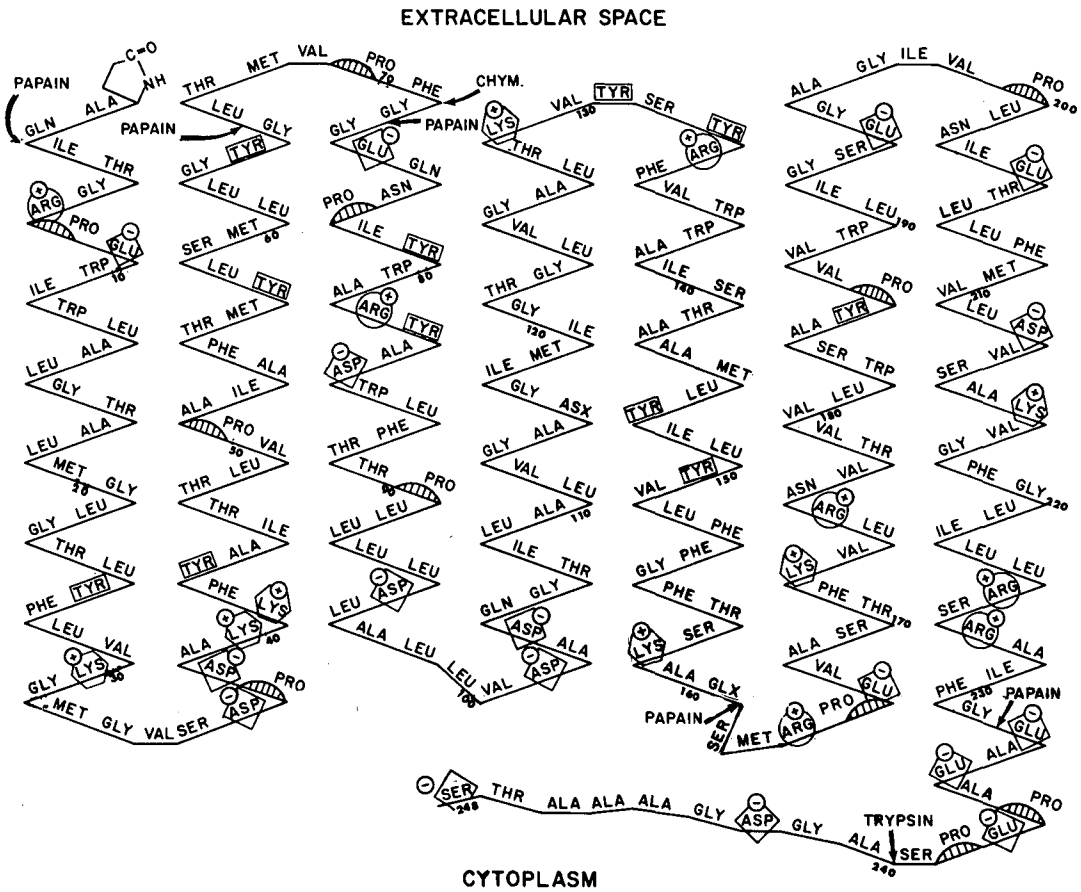

Figure 1. Schematic representation of how the amino acids of bacteriorhodopsin traverse the membrane. Specific amino acids which have been chemically modified are highlighted. The diagram also shows positions where the protein can be cleaned with papain, trpsin or chymotrypsin.

prevented by fluorescamine treatment. Our findings clearly demonstrate that, unlike what has been previously suggested,[7] exciton coupling between neighboring bR molecules in the purple membrane is not required for light-to-dark adaptation.

c. Arginine: At pH 8.2, 2,3-butanedione reacted slowly with all the arginine residues found in bR except two; there was no shift of the 570-nm chromophore λ_{max}. Scatchard and Hill plots of 2,3-butanedione treatment of bR indicated that only 7 arginines were available for modification.[8] A quantitative analysis of the inhibition of photocycling activity revealed that a specific pair of arginines must be modified to cause a marked slowdown (maximal 33-fold) of M_{412} decay and a small (1.7 x) inhibition of the M_{412} rise kinetics. The pH dependence of M_{412} decay and of the H^+ uptake kinetics suggested a direct involvement of arginines in the reprotonation of the Schiff base. We showed that the 2,3-butanedione modification, known to raise the pK of arginine, also leads to a raised pK for M_{412} decay: this is exactly what one would expect if arginine donated its proton to the Schiff base. Alternatively, as found in other enzymes,[9] the role of two specific arginines may be to regulate structural changes during cycling due to their electrostatic binding to negatively charged groups.

Low Temperature Studies

To elucidate the role of tyrosine residues in the blue-shift of λ_{max} and the light-driven proton pumping of bR, the photochemical reactions of tyrosine-iodinated bR (tyr-I-bR) were investigated by low temperature spectroscopy.[10] When bR containing all-trans retinal absorbs light, it goes through several intermediates: bath-, lumi- and meta-trans bR.[11]

After from 4 to 5 of the 11 tyrosine residues of bR were iodinated, the meta-intermediate of the photocycle of tyr-I-bR in 75 percent glycerol solution became so stable that its decay could be observed by a conventional spectrophotometer, even at room temperature. In the dark and at -65°C, it was stable for several hours.

Four different kinds of batho-intermediates were formed by irradiation with green light (500 nm) at -170°C. As in native bR, these batho-intermediates were also formed by irradiation at -60°C. Using the difference spectra between meta-intermediates and tyr-I-bR, the absorption spectra of four kinds of tyr-I-bRs, batho-intermediates, and meta-intermediates were estimated. The absorption maximum of each was at shorter wavelengths than that of its corresponding type in the native bR system.

These results indicate that at least two or more tyrosine residues have some role in the blue shift in λ_{max} for tyr-I-bR and, therefore, that tyrosine residues may be important in determining the color of native bR.

Effects of Non-Ionic Detergents

Treatment of purple membranes with the non-ionic detergents, Triton X-100 and β-octylglucoside, caused a blue shift of the chromophore absorption peak of bR. This effect was maximal at detergent concentrations where the exciton band in the CD spectrum of the chromophore was abolished or drastically reduced. The detergent-induced blue shift was also observed in glutaraldehyde-treated purple membranes, but the detergent effects on the CD spectrum were prevented by the cross-linking treatment.[12]

β-octylglucoside caused a 2- to 3-fold increase in the tryptophan fluorescence of either native or cross-linked purple membranes. Treatment of native or cross-linked purple membranes with either detergent also caused the chromophore to be susceptible to bleaching.

Photocycle kinetics of detergent-solubilized purple membranes showed that the blue-shifted form of the chromophore after solubilization was still converted to a 412-nm absorbing species after a laser flash. With native or cross-linked purple membranes, detergents caused both an acceleration in the rise and a slowing of the decay of the 412-nm intermediate. Both processes became biphasic after detergent treatment at pH 7.0. As the pH is increased from 5.5 to 9.5, the percentage of the slow phase in the decay increased linearly while the $t_{1/2}$ of decay increases logarithmically. With native purple membranes, both rise and decay of the 412-nm intermediate become biphasic as the pH increased beyond 8.5.

Our results suggest that non-ionic detergents

a. Affect retinal-apoprotein interactions, and

b. Cause changes in the protein structure that result in the alteration of pK(s) of amino acid residues which participate in photocycling.

White Membrane Studies

The discovery by Professor Y. Mukohata[13] of Osaka, Japan, of a mutant species of Halobacteria which forms a "white membrane" has enabled us to venture into an exciting and new field of bR studies. The white membrane forms a patch which apparently contains the apoprotein portion of bR but totally lacks retinal; a purple membrane can be formed by the addition of all-trans retinal. In collaboration with Professor Mukohata, we have isolated and purified "white membranes" and have initiated a series of studies on the reconstitution with several retinal analogues. Chemical modification prior to reconstitution is currently being used to identify steric and ionic constraints in the mechanisms of both reconstitution and photocycling.

Discussion

At this stage of the investigation, it seems clear that some tyrosine residues in bR not only may be involved as proton donors and acceptors to

the retinal Schiff base,[2] but also may be responsible for the red shift in the λ_{max} for absorption of retinal, when bound to bacteriorhodopsin. It appears likely that the structural location of tyrosine 26, and possibly 185, in the bR molecule may allow specific interactions with the retinal chromophore that leads to a λ_{max} = 570 nm. Our low-temperature studies confirm the idea that some of the tyrosines in bR are important in determining λ_{max} for this retinoprotein. The fact that iodination of 4 to 5 of the 11 tyrosines produces spectral evidence for four different kinds of batho- and meta-intermediates in the photocycle suggests that a few tyrosines may play a role in the blue shift of λ_{max} in the modified bR.

Whereas exciton coupling was lost after nitration of tyrosine 185 and λ_{max} was shifted to 530 nm, after fluorescamine modification of six lysines in the protein, exciton coupling was also lost, but no change was observed in λ_{max}. Since, in the latter case, the light-to-dark adaptation of bR was unaffected, we conclude that exciton coupling is not a requirement for the mechanism of light or dark adaptation of bR.

Furthermore, a specific pair of arginines may be directly involved in the reprotonation of the Schiff base or in the regulation of structural changes in bR during proton translocation.

Detergents have provided us with a mechanism for affecting retinal-apoprotein interactions without chemically modifying the protein. As in the case of certain modifications, these interactions have resulted in pK shifts of amino acid residues which seem to participate in photocycling.

The foregoing studies have clearly demonstrated the critical role that bacteriopsin and, in particular, certain specific amino acids play in both the spectral and CD characteristics as well as in the complex kinetics of photocycle intermediates and H^+ pumping activity of bR.

PLANNED ACTIVITIES FOR FY 1982

Chemical Modification Studies

White membranes are the material *par excellence* for chemical modification investigations of the role of the protein structure and different types of retinal analogues in the energy conversion process. We intend to pursue in depth the modification of tyrosine since it appears to be the most probable donor and/or acceptor of protons. Our recent discovery of the nitration of a single tyrosine[4] requires further study; the residue needs to be carefully identified and its effect on the photocycle and electrochemical activities thoroughly investigated.

Site-specific modifications of carboxyl and amino groups will be used to label the protein with nitroxide spin-probes. Since these probes provide us with information on the viscosity and polarity of their micro environment, they will be used to study conformation changes in bR during photocycling, H^+ pumping, and light-to-dark adaption. The steric effects of modification of other groups in the protein will also be investigated by measuring the changes in the local environment of the spin probe(s).

Electrical versus Electroneutral Steps in the Photocycle of Bacteriorhodopsin

The findings that transmembrane and surface electrical potential changes are associated with the photocycle in bR[14,15] raises several fundamental questions: (i) Which steps of the photocycle are related to charge movements in the protein? (ii) Where do these charge displacements occur? (iii) How do they affect the kinetics of the cycle?

To answer these questions, we will make use of several strategies:

a. Chemically modified bR will be used to identify those protein residues which are involved in charge displacements.

b. White membranes and different retinal analogues will be used to study the retinal-apoprotein interactions essential for H^+ pumping and charge displacements.

c. Absorption, resonance-Raman, and low-temperature spectral studies will be used to clarify the effects of the charge displacements on the vibrational modes of the retinal. On a molecular level, this will help to clarify where in the chromophore the electrical fields exert their strong effects.

White Membrane Vesicles Regenerated with All-trans Retinal

These vesicles exhibit full pH gradients when only 10 percent of the bR has been reconstituted, but maximum electrical gradients ($\Delta\psi$) are not observed until 100 percent reconstitution has been achieved. Enzymatic iodination of extracellular tyrosine residues caused an abolition of light-dependent $\Delta\psi$, with a significant increase in the magnitude of the pH gradient. These are very interesting findings which warrant further study.

The effects of other chemical modification protocols will be studied. Among these are treatments of vesicles with permeable and/or side-specific carboxyl, arginine, and lysine specific reagents. We wish to learn about specific structural features of bR that are required for chromophore regeneration and for the generation of Δph and/or $\Delta\psi$. Because of the low time resolution of our measurements (Δs for photocycle and ms for Δph and ($\Delta\psi$), the possible occurrence of rapid but transient signals cannot be tested. We are therefore seeking to develop more permeable ionic spin probes.

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Measurement and Analysis of Circumsolar Radiation*

D. F. Grether, D. B. Evans, A. J. Hunt, S. G. Kanzler, M. Harms, and M. A. Wahlig

This project provides measurements and analyses of the solar and circumsolar radiation for application to solar energy systems that employ lenses or mirrors to concentrate the incident sunlight. Circumsolar radiation results from the scattering of direct sunlight through small angles by atmospheric aerosols (dust, water droplets, or ice crystals in thin clouds, etc.). The solar energy system will typically collect all of the direct solar radiation (originating only from the disk of the sun) plus some fraction of the circumsolar radiation. The exact fraction depends upon many factors but primarily upon the angular size (field-of-view) of the receiver. A knowledge of the circumsolar radiation is therefore a factor in predicting or evaluating the performance of concentrating systems.

The project employs unique instrument systems, called "Circumsolar Telescopes," that were designed and fabricated at LBL. Each system has a "scanning telescope" mounted on a precision solar tracker. The telescope is mechanically scanned through an arc of 6°, with the sun at the center of the arc. A digitization of the brightness of the sun or circumsolar radiation is taken every 1.5' of arc, with a complete scan taking one minute of time. One of the auxiliary instruments is a pyrheliometer, having a fixed field of view (typically 5 to 6°) and used to provide an estimate, called the "normal incidence" reading, of the direct solar radiation. The telescope and pyrheliometer have matched, ten-

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Electric Technologies, Photovoltaic Energy Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

position filter wheels: one open or "clear-filter" position, eight interference filters that divide the solar spectrum into eight intervals of roughly equal energy content, and one opaque filter to monitor detector noise. The data are recorded on magnetic tape, with one tape holding one week's data per telescope.

The telescopes have been operated primarily at locations for which the instruments can play a dual role: (1) characterization of a region or climate and (2) provision of site-specific data for proposed or actual concentrating solar energy systems. The data are used at LBL and other DOE-supported institutions, such as Sandia Laboratories and Jet Propulsion Laboratory (JPL) to evaluate the performance of concentrating systems.

A secondary purpose of the project is to relate the data to the atmospheric processes that attenuate the solar radiation available to terrestrial solar energy systems.

ACCOMPLISHMENTS DURING FY 1981

Measurement Program

Altogether, there are four circumsolar telescopes. An instrument at the JPL Parabolic Dish Test Facility at Edwards, California, was operated for the entire year. In addition to providing specific data for the test facility, this telescope also provided climate characterization data for the Mojave desert area. A second telescope, located at the Advanced Components Test Facility at Atlanta, Georgia, was supported through March. The operation of this instrument was terminated in April because of reductions in the project's budget; the telescope was returned to LBL in August. The third telescope was refurbished at LBL during the year, with plans for subsequent relocation of the instrument at Barstow, California, the site of the 10 MWe Central Receiver Pilot Plant that is currently under construction. Sandia National Laboratories, Albuquerque, continued to have the fourth instrument available for measurements in conjuction with tests at the Central Receiver Test Facility.

Systematics of Clear-Filter Data

Sufficient data are now available to investigate systematic behavior of the circumsolar radiation over a multi-year period. For present purposes, a given measurement of the telescope can be considered to consist of the circumsolar ratio, taken as a measure of the level of circumsolar radiation, and the NI reading (for Normal Incidence) of the pyrheliometer. The circumsolar ratio is defined as

$$R = C/(C + S),$$

where

C = circumsolar (from the edge of the sun out to 3°) radiation, and

S = direct solar (coming from the disk of the sun) radiation.

By the design of the telescope,

$$NI \approx C + S \quad .$$

Thus, the circumsolar ratio is approximately the same as the fractional overestimate that a pyrheliometer would make in estimating the direct solar radiation.[1] This overestimate is on the same order as, but somewhat greater than, the error made by a pyrheliometer in estimating the solar radiation available to a solar energy conversion facility that concentrates the incident solar radiation.

It had been observed previously[1] that there is a correlation between NI and R for any given month. Consider the middle of the day, defined as the period from three hours after sunrise to three hours before sunset. During this period the air mass (the amount of atmosphere between the earth and the sun), and thus the attentuation of the direct sunlight by the normal atmospheric constituents, is relatively constant. For very clear skies, NI will be about 1000 watts/m^2. As NI decreases due to increasing amounts of scattering and absorption by atmospheric aerosols or thin clouds, the circumsolar level increases in a systematic way. Any given value of NI is associated with a fairly narrow range of circumsolar ratios. The question addressed this year was whether or not the relationship changes with time and, if so, whether there is a seasonal effect.

The data for a given month were first separated into bins, each 200 watts/m^2 wide in NI. For each bin, the mean value of the circumsolar ratio was calculated. Shown in Figure 1 are the results for two of the NI bins: 700-900 w/m^2, which corresponds to moderately clear skies; and 300-500 w/m^2, which corresponds to hazy skies. In both graphs, the solid curve represents the average annual behavior; the same curve is displayed for each year. For the moderately clear sky case, a definite seasonal pattern is present, with winter peaks in the mean circumsolar ratio of 5 to 10 percent, and summer minima of about 2 to 3 percent. Any algorithm intended to predict the circumsolar ratio based on pyrheliometer readings must clearly take into account the seasonal dependence. On the other hand, the data for hazy skies show large fluctuations about an average circumsolar ratio of approximately 30 percent but no apparent seasonal dependence.

Colored Filter Data

Further progress was made this year in analyzing the colored filter pyrheliometer data for application to wave-length selective systems, such as concentrating photovoltaic devices. The first step in the analysis had been to characterize the transmission function (transmission vs. wave length and time) of each filter over an approximately three-year period of use. The filters are of the interference type (multi-layered dielectrics) and are subject to degradation. The functions were constructed from a combination of: (1) spectrophotometer measurements of the transmis-

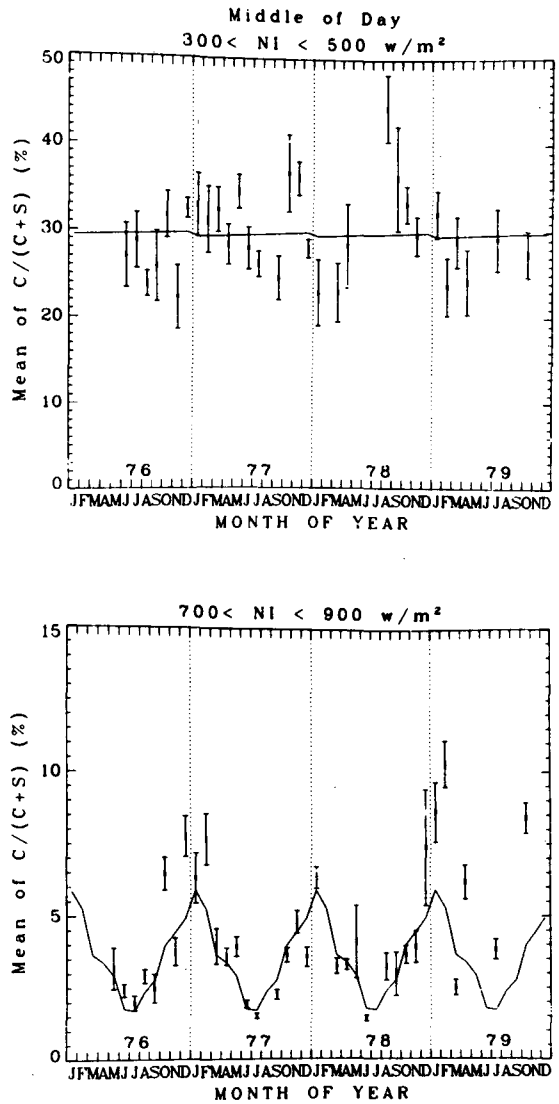

Figure 1. The mean monthly value of the circumsolar ratio, as defined in the text, plotted from May 1976 through December 1979 for Albuquerque. The data are limited by the criterion that the Normal Incidence (NI) value of the pyrheliometer be between certain values as indicated on the graphs. The solid curve represents the average annual behavior of the data points.

(XBL 814-9322)

sion of the filters made at the beginning and end of the measurement period, (2) evidence for the degradation of the filters as obtained from measurements for clear sky conditions, and (3) an atmospheric transmission computer model. Details are given elsewhere.[2,3]

Given a knowledge of the filter transmission functions, the second step was to invert the pyrheliometer readings to obtain the spectral distribution of energy in the sunlight. Because the transmission of any given filter has a complex dependence on wave length, the inversion cannot be carried out exactly, and an estimation method must be used. The method involves calculating an effective transmission over a nominal pass band for each filter.[2] The energy content of the solar spectrum within the nominal pass band is obtained (i.e., the inversion is carried out) by dividing the pyrheliometer reading by the effective transmission. Some monthly average results for two of the filter bands for the Mojave desert area (China Lake and then Barstow) are shown in Figure 2. A given data point is the ratio of the monthly total energy content for the indicated band to the monthly total for the clear ("no") filter case. Thus, the figure shows the relative amount of energy in a given part of the solar spectrum and its dependence on time. For the 0.38-0.46 μm band, there is an obvious seasonal dependence, with winter minima and summer maxima. This behavior is to be expected because, in winter, the atmospheric path is longer and relatively more of the short-wave radiation is absorbed by the atmosphere. For photovoltaic devices the plot for the 0.72-0.85 μm band is of more interest because the peak efficiency of typical (e.g., silicon) solar cells lies in this wavelength region. The data show little if any seasonal dependence (note that the graph has a

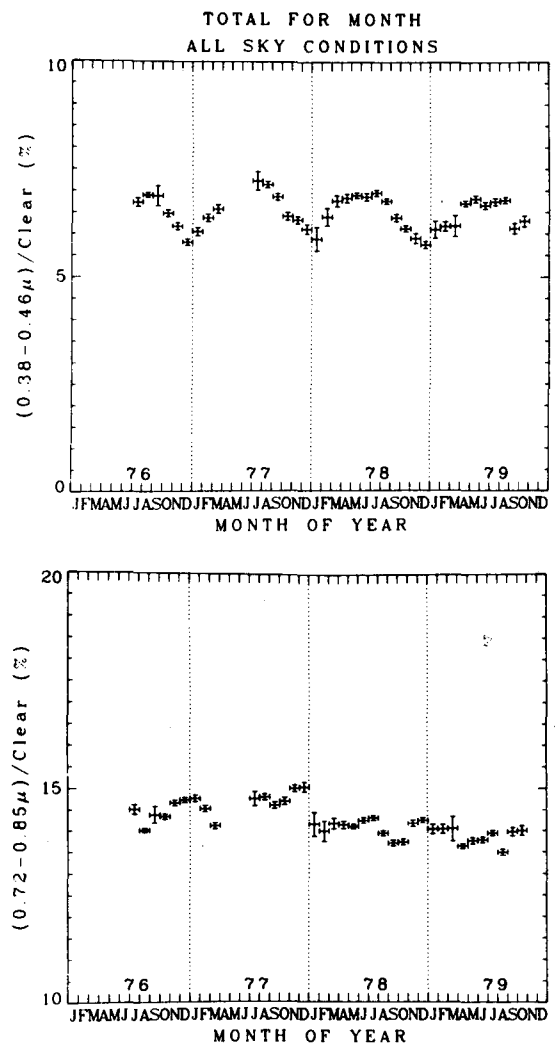

Figure 2. The relative amount of energy in the indicated portions of the solar spectrum for the Mojave Desert area (China Lake and Barstow). The data are from July 1976 through December 1979.

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suppressed zero). Thus, the preliminary indication is that it may not be necessary to have extensive wave-length-dependent measurements in order to evaluate properly the expected performance of photovoltaic devices if monthly totals, as opposed to hourly values, are being used in the evaluation.

PLANNED ACTIVITIES FOR FY 1982

As a consequence of budget reductions for the DOE Solar Program, this project is unfunded for FY 1982. Plans call for the refurbished telescope (see Measurement Program above) to be moved to Barstow and to be operated as part of the technical evaluation of the performance of the pilot plant.

If a modest level of support is available, work will continue on the analysis of the existing data.

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Support for SOLERAS Solar Cooling Engineering Field Tests*

M. A. Wahlig and F. H. Salter

LBL provides technical consulting and management services to support the Solar Energy Research Institute's overall management of the SOLERAS Solar Cooling Engineering Field Tests. These field tests are part of the Urban Solar Applications Program within the Joint United States--Saudi Arabian Program for Cooperation in the Field of Solar Energy (SOLERAS).

The objective of the Solar Cooling Engineering Field Tests is to bring solar cooling one step closer to commercialization on a competitive basis with conventional cooling systems. To meet this objective, modifications were made to systems developed under the National Solar Cooling Program to advance overall system performances, while at the same time lowering system design, installation, and maintenance costs.

The engineering field test is defined as the fabrication, installation, operation, and evaluation of a complete solar cooling system on an operational building for the purpose of verifying such predicted system parameters as thermal performance, cost effectiveness, reliability, maintainability, and installation ease. The engineering field test is expected to approximate the conditions to which a fully marketable solar cooling system would be subjected.

With the above in mind, two absorption and two Rankine solar cooling systems were installed in Phoenix, Arizona, in the winter/spring of 1981. Phoenix was selected for these installations because its climate is similar to the climate in parts of Saudi Arabia. Three of the four systems have air-cooled chillers to better adapt the system to the limited water availability in Saudi Arabia.

ACCOMPLISHMENTS DURING FY 1981

Installation designs were completed early in FY 1981, and the following systems were installed in Phoenix.

- Carrier Corporation installed a 15-ton water-cooled absorption cycle chiller at BDP-Day and Night Air Conditioning. The building is a high-bay structure of concrete block with a small office area, which is to be cooled, and a large warehouse area. Powered by about 1400 ft^2 of tracking parabolic trough collectors, the absorption unit is designed to deliver 47 kW of cooling to

*This work was supported by the Solar Energy Research Institute, through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, under an agreement with the United States-Saudi Arabian Joint Commission on Economic Cooperation.

the offices. Storage for the system consists of a large 2500-gallon tank for heat storage and a small thermal ballast tank which helps prevent excessive chiller cycling.

- Carrier Corporation's second project is a 10-ton, air-cooled absorption cycle chiller at Sigler-Faigen. The building is a high-bay, concrete-block building combining office space, showroom space, and a warehouse area. Powered by about 1000 ft^2 of tracking Fresnel-lens collectors, the absorption unit is designed to deliver 36 kW of cooling to a computer room facility. Storage for the system includes a large 4000-gallon cold-storage tank for twenty-four-hour cooling and a small thermal ballast tank.

- Honeywell, Inc. installed a 14-ton air-cooled Rankine cycle unit at an Arizona Public Service building. The building is a single-story brick structure consisting entirely of office and lab space. The system is powered by 2400 ft^2 of evacuated-tube-type collectors and is designed to deliver 46 kW of cooling, about one-half of the entire building load. Gear reduction enables the Rankine turbine to drive a conventional Trane reciprocating compressor. An induction motor with clutches on each end is mounted between the gear box and the compressor to permit the following modes of operation:

  a. Compressor driven by turbine with excess energy converted to electrical power,

  b. Compressor driven by turbine with additional power supplied by the induction motor as needed,

  c. Compressor driven by induction motor,

  d. Induction motor driven by turbine to generate electricity.

  No storage tanks are used with this system because all excess energy is converted to electrical power, utilizing the electrical grid as the storage system.

- United Technologies Research Center installed an 18-ton air-cooled Rankine cycle unit at Hamilton Test Systems. The building is a single-story office structure with extensive external shading provided by overhangs and greenery. Powered by 1300 ft^2 of tracking parabolic-trough collectors, the system is designed to deliver 60 kW of cooling to the building. Storage for the system consists of a 2000-gallon cold tank and a 1500-gallon hot tank. In this system, a small high-speed centrifugal compressor is directly driven by the Rankine turbine.

During FY 1981, LBL's activities in support of these projects was primarily in the following areas:

- Complete critical design reviews,
- Review final construction plans and specifications,
- Factory visits to inspect equipment prior to shipment,
- Frequent site visits to follow and report on construction progress, start-ups, and acceptance tests,
- SOLERAS-DOE design review meeting,
- Dedication of projects.

PLANNED ACTIVITIES FOR FY 1982

LBL's contract expired at the end of FY 1981. However, LBL may be involved in a final series of start-ups and acceptance tests after various improvements are made to the four systems in the spring of 1982.

LBL Building 71 Solar Cooling Project*

F. H. Salter

This active solar cooling project is part of the Department of Energy (DOE) Solar in Federal Buildings Program. The purposes of this program are to demonstrate the Federal Government's confidence in the solar industry and to stimulate growth and technical improvements in solar technology through the installation and demonstration of a variety of commercially applicable solar energy systems in buildings owned or occupied by the Federal Government. The program provides technical and financial assistance through interagency agreements to Federal agencies for design, acquisition, construction, and installation of solar heating and cooling equipment projects.

LBL Plant Engineering Department is responsible for project engineering and contract administration for this project. LBL's duties include: preparing the project proposal, preliminary engineering, conceptional design, design criteria, selection of an outside A/E for final engineering and preparation of plans and specifications, engineering and administrative support for the A/E, periodic review of the final design, administration of the bid process and subcontract negotiations, construction supervision, acceptance testing, and extended field testing of the system. The LBL Active Solar Research Group provides technical assistance and review of the project.

Overall administration of this project is provided by the San Francisco Operations Office of the Department of Energy (DOE/SAN). DOE/SAN has subcontracted technical management of this project to Energy Technology Engineering Center (ETEC). Approval of the final design by DOE/SAN and ETEC is required prior to release of construction funds.

ACCOMPLISHMENTS DURING FY 1981

An intragovernmental order to proceed with the design of the project was received in January 1981. LBL developed preliminary engineering and design criteria for the project. Interactive Resources of Richmond, California, was selected in July 1981 to provide final engineering. The design was about 70 percent complete by the end of FY 1981.

Scope of Project

The Solar Cooling System will provide substitute capacity for the existing Building 71 chilled-water system by installing the new chiller next to and in parallel with the existing electric chillers, which will be retained for backup. The system will consist of roof-mounted collectors, storage tanks, and a nominal 25-ton lithium-bromide chiller package and associated pumps, piping, insulation, valves and fittings, controls, and instrumentation. The chiller package will be supplied by Arkla and will be field-tested in the Solar Cooling System. Because more than 25 tons of cooling are continuously required at Building 71, the solar chiller will operate at full load for an average 6 hours per day.

The following table summarizes design parameters:

Chiller Capacity	22 tons
Chiller COP	0.73
Average Operation	6 hr/day (at 22-ton loading)
Generator Entering Water Temp.	180°F (adjustable 170°F to 200°F)
Leaving Chilled Water Temp.	45°F
Entering Condenser Water Temp.	80°F
Maximum Storage Temp.	250°F
Collector Area	6000 ft^2 (gross area)
Collector Type	evacuated tube collector
Storage Tank	2500 gallons
Thermal Ballast Tank	500 gallons
Expansion Tank	500 gallons

The collector array will utilize stationary mount, concentrating (CPC reflector), and vacuum-tube receiver solar collectors to accomplish the 250°F maximum-design temperature. The collector design will emphasize simplicity and durability to minimize maintenance. This is essential to this project because access to the collectors will be restricted due to roof radiation during operation of the Building 71 accelerator. Because fluid will be contained in continuous copper tubing, glass tube breakage will not disrupt system operation, and tube replacement can be scheduled for periods when the accelerator is not operating. Further reliability will be accomplished by using high quality "Pyrex-type" evacuated tubes that are less prone to breakage. The collectors will have no cover glass, making tube replacement easier.

PLANNED ACTIVITIES FOR FY 82

Final approval of the plans and specifications of the Building 71 Solar Cooling System was given by ETEC and DOE in December 1981.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Active Heating and Cooling Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Remaining Project Schedule

Advertise for bids
Early February 1982

Construction contract signed by all parties
Early May 1982

Construction complete
September 1982

Acceptance test complete
October 1982

Final construction status report
November 1982

Field Tests

This project has been approved for inclusion in the National Solar Data Network and will have instrumentation installed and data processed by Automation Industries, Inc. - Vitro Laboratories Division.

Development of a 30-kW High Temperature Solar Receiver Using Small Particles as the Heat Exchanger*

A. J. Hunt, M. Deiringer, D. B. Evans, L. Hansen, P. G. Hull, and D. Paydarfar

The solar resource is distinguished from traditional energy sources by two main features. First, sunlight arrives on earth as pure radiant energy, with no conductive or convective heat transfer. Second, sunlight is characteristic of a source with much higher temperature than other present-day energy supplies. Because of these differences, we must independently evaluate the techniques of heat exchange and energy conversion used with solar energy and not simply adopt the technology developed over the last century for using conventional energy sources. The work described here utilizes a novel approach to match the unique characteristics of concentrated sunlight to the requirement of heating a gas.[1,2]

The purpose of this work is to develop a new type of solar thermal receiver that utilizes concentrated sunlight to heat a gas to high temperature to operate a turboelectric generator or to supply industrial process heat. The Small Particle Heat Exchange Receiver (SPHER) uses a very small mass of ultrafine carbon particles suspended in a gas to absorb sunlight and transfer the heat to the gas. The concentrated sunlight, provided by a parabolic dish or system of mirrors, passes through a window into a chamber containing the absorbing suspension. Because the particles are very small, they are not significantly affected by gravitational or inertial forces; they are effectively part of the gas. An extremely small mass of these particles provides a large surface area for solar energy collection and heat exchange. The particles heat until they react chemically with the gas or vaporize. The particles may be used in a once-through fashion because of the very low mass of carbon required.

*This project was supported by the Solar Thermal Test Facilities Users Association, a non-profit corporation which manages high temperature solar thermal testing for the U.S. Department of Energy, under contract DE-AC03-76SF00098.

Major advantages of this receiver are high efficiency, low pressure loss, simplicity, and light weight. Other benefits of this approach are a lower chamber temperature for a given output-gas temperature and freedom from cycling and lifetime problems experienced in other heat exchangers. The SPHER concept is suitable for a wide range of sizes and a variety of applications.

ACCOMPLISHMENTS DURING FY 1981

This year, the project moved from conceptual studies and experimental investigations to a solar proof-of-concept. In an agreement with the Solar Thermal Test Facilities Users Association, we undertook the design and construction of a receiver[3] capable of heating ambient air to approximately 800°C with a power conversion capability of 30 kW. The system consists of two major components, the particle generator and the receiver, and it also includes instrumentation and an air supply system. It is planned to test the receiver in 1982 at the Advanced Components Test Facility (ACTF) on the campus of the Georgia Institute of Technology. The development work performed in FY 1981 on the major components is summarized below.

Particle Generator

The function of the particle generator is to provide a sufficient flow of absorbing particles to insure that more than 90 percent of the radiant energy entering the receiver is absorbed directly in the gas-particle suspension. The particle generator was developed in two stages. A laboratory version of the generator was built to demonstrate that an adequate particle flow could be produced to reach the 30-kW power rating. After the laboratory generator was developed sufficiently to achieve the output required, a new generator suitable for solar testing was designed.

The generator produces particles by pyrolysis of acetylene gas injected with a carrier gas (argon) into a heated tube. A laboratory generator was constructed using a downward flow through a heated quartz tube, as is illustrated in Figure 1. Through a series of experiments and modifications, the output of the generator was increased until a problem was encountered with carbon build-up on the gas injector. The gas injection port was redesigned to provide cooling for the tip, and a further series of experiments resulted in a maximum particle production rate of about 25 mg/sec. This was in excess of the calculated requirement of 16.1 mg/sec for the 30-kW receiver.

After the successful scale-up of the laboratory generator, a new generator was designed that was capable of being transported to a remote site and of being operated on the tower of the solar receiver test facility at Georgia Institute of Technology. This field version of the generator also incorporated design changes to further increase the output and to simplify its operation. A stainless-steel reactor tube was used instead of quartz, and the reaction zone was lengthened to enhance the particle production. The field generator was constructed and underwent preliminary tests at the end of the fiscal year.

The output of the particle generator is monitored by measuring the opacity of the particle suspension with the transmissometer diagramed in Figure 1. It consists of an extinction tube equipped with a series of baffles to isolate the end windows and provide a known extinction path length. A helium-neon laser beam is passed through the tube, and the transmitted light is measured by a detector. To determine the absorption capability of the particles, the particle mass loading must also be determined. This was measured by weighing the particles deposited on a filter from a known volume of gas, as illustrated in Figure 1.

Samples of the particles, taken on Nucleopore filters at all stages of work, were examined with a scanning electron microscope to determine their average size and state of aggregation. The results of an examination of the residual gas using mass spectrometry indicated the residual gas consisted mainly of hydrogen and acetylene.

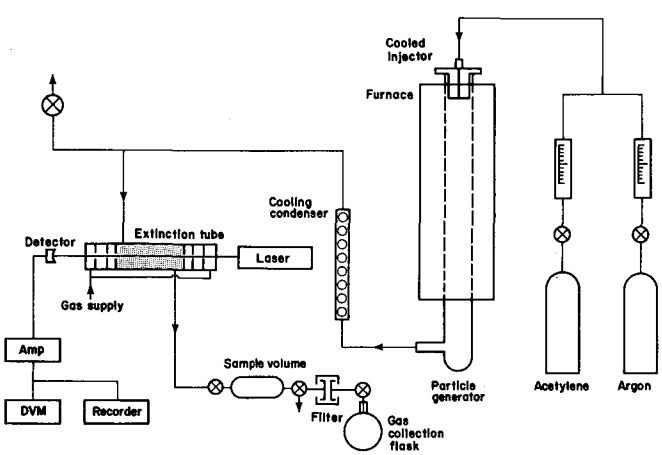

Figure 1. Schematic drawing of the particle generator and measurement apparatus.

(XBL 823-183A)

Receiver Design

The receiver provides containment for the gas-particle mixture while it is being heated. It consists of a window, an open volume in which the sunlight is absorbed, and a gas injection and exhaust system. Because the SPHER is basically different from traditional heat exchangers, a new set of criteria had to be developed to guide its design. The size of the receiver is dictated by the density of the absorbing particle suspension and the allowable flux density on the walls. Considerable effort went into the design to minimize the radiant flux density incident on the receiver walls.

The dimensions of the receiver were dictated by the beam geometry at the ACTF and the desire to maximize the power conversion ability without requiring an excessive scale-up of the particle generator. The completed receiver will be capable of operating at power levels significantly higher than 30 kW by using a particle generator with a larger capacity. The size of the receiver to obtain a specific absorption within its volume is inversely proportional to the rate of particle production. Because there is a capital cost associated with the size of the chamber and an operating cost to supply the absorbing particles, the size of future direct absorption receivers will be determined by minimizing the sum of the capital equipment and operating costs.

The shape of the receiver chamber was determined by positioning the walls at locations to minimize incident flux density. Because the flux density is a function of both the collector field geometry and the absorption occurring in the chamber, a new method to predict the flux was developed based on measurements of the collector system.[4] The measurement was made by placing a small aperture at the planned location of the receiver window. Then the flux density was determined with a scanning calorimeter bar over a plane at a distance behind the aperture that is large compared to the size of the opening. These data provide detailed information about the angular distribution of flux and are used with an analytic method to calculate the flux density on an arbitrary surface. The calculation (implemented on a large-scale computer) also determines the effect of the absorbing suspension. Figure 2 is a map of the flux density in a vertical plane above the focus of the ACTF. Figure 3 is a cross-sectional view of the receiver. The window at the bottom admits the solar flux into the inner region. Comparing Figures 2 and 3 indicates the strong influence of the flux density pattern produced by the concentrator on the shape of the absorption chamber (A in Figure 3).

Figure 3 illustrates the main features of the SPHER design. The gas-particle mixture is routed into the nozzle ring B. A total of 18 nozzles (C) direct the gas flow from the nozzle ring into the chamber to cause a significant swirling motion. This circular motion organizes the flow in the chamber and reduces the possibility of hot spots

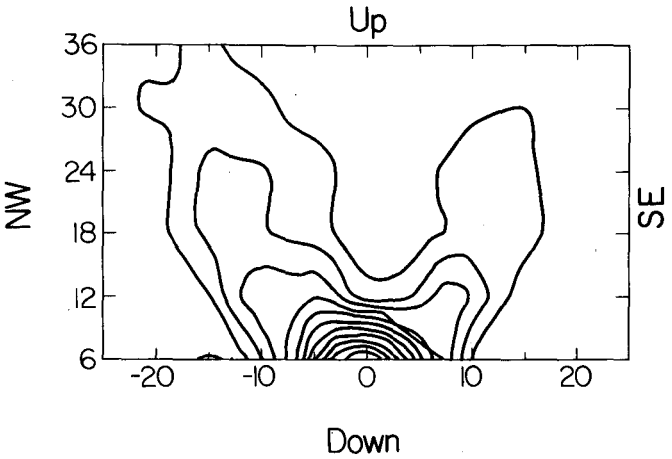

Figure 2. Measured lines of constant flux density inside the SPHER for no absorption. The distances on the axes are measured in inches from the focal point. Flux density contours run from 8 W/cm^2 to 48 W/cm^2 (nearest the focus) in intervals of 4 W/cm^2.

(XBL 823-182)

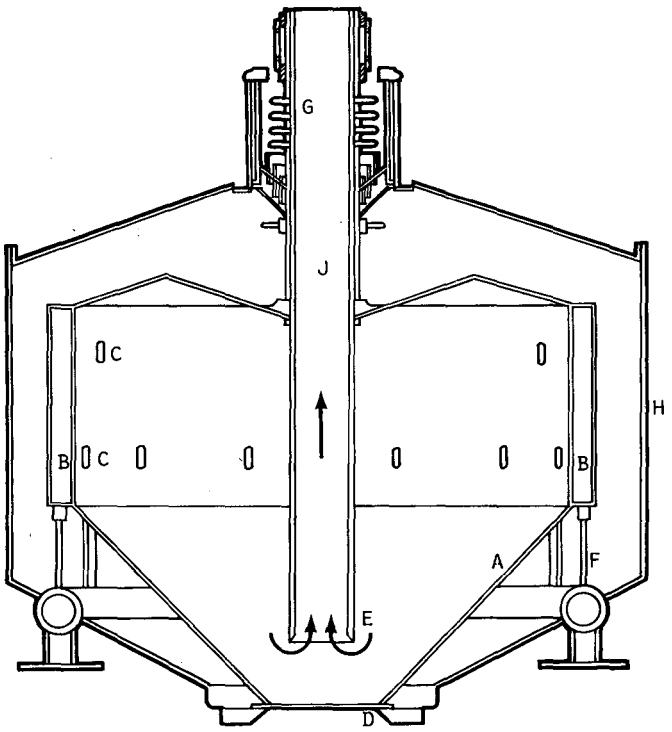

Figure 3. Sectional view of the SPHER absorption chamber: (A) absorption chamber, (B) nozzle ring, (C) gas injectors, (D) window, (E) exhaust tube, (F) spring leg supports, (G) bellows assembly, (H) outer skin, (J) location of radiation shielded thermocouple.

(XBL 823-181A)

originating from axially nonuniform flux distributions. The gas-particle mixture circulates cyclonically to the axis near the window (D), where the exit tube (E) is located. A unique aspect of the design involves the transparent quartz tube that penetrates the high-flux region. The tube acts as an exhaust port and insures that the gas-particle mixture passes through the maximum flux density region before leaving the receiver. The use of a quartz tube provides a refractory exhaust pipe that does not interfere with the flux distribution because it is transparent.

The nozzle ring and absorption chamber are supported by a set of flexible spring legs (F) mounted to a rigid toroidal tube that carries the weight of the receiver. A bellows assembly (G) near the top of the receiver reconciles the thermal expansion of the interior of the chamber with the cool outer skin (H). A thermocouple equipped with multiple heat shields is located in the exhaust tube at location J. The region between the absorption chamber (A) and the outer skin is filled with compressible high-temperature insulation to minimize the heat losses from the absorption chamber.

To minimize costs, no "super" alloys were used in the construction of the receiver or generator. The lining of the receiver is stainless steel, fabricated mostly from sheet metal stock. An air induction system based on the Coanda effect is used to produce the inlet gas flow because of its ease of control and operation.

PLANNED ACTIVITIES FOR FY 1982

The construction of the SPHER will begin in October of 1981. The receiver will be fabricated largely by the sheet metal section of the LBL mechanical shops. The construction will be completed in December and the receiver moved to laboratory facilities at LBL for initial check-out. The air supply and measurement system will be tested, the particle generator connected to the receiver, and the instrumentation completed. A 2.2-kW xenon arc lamp will be used for low-power testing and system check-out. Laboratory flow tests are scheduled for the beginning of December and will continue into 1982. The receiver will be moved to the Georgia Tech facility in the spring or summer of 1982 for solar testing and evaluation.

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Diffractive Solar Collection Systems*

D. B. Evans and A. J. Hunt

The purpose of this project is to investigate solar collector systems based on the diffraction of light. Present solar collection systems rely on reflection or refraction of sunlight. The technique proposed here is based on the use of diffractive optics, in particular Holographic Optical Elements (HOE's), to intercept sunlight and diffract it toward an energy conversion or storage device (e.g., photovoltaic cell, solar thermal receiver, or thermal mass).

HOE's can be made by exposing a dye-sensitized emulsion to the interference between two beams of coherent light.[1] The characteristics of the HOE are determined by the position and strength of the optical elements used to form the beams. A simple point focus HOE can be made by interfering a plane-parallel wave front with a coherently related spherical wave front originating from a point source. Diffractive optical elements can be used instead of conventional optics to concentrate, spectrally separate, or redirect sunlight. Because of the unique diffractive properties of HOE's, many effects occur that cannot be achieved with geometrical optical systems. For example, the diffraction characteristics may be used to focus and guide differing wavelengths of light to photocells with matching spectral responses. Theoretical efficiencies for the conversion of light to electricity can exceed 50 percent for an array of photocells with graded band-gap energies. In daylighting applications, holographic coatings may be placed on windows to guide sunlight deep within a room to provide task lighting to areas of the building that would not otherwise receive natural lighting.

Other fascinating possibilities open up when the unique properties of HOE's are applied to solar collection optics. Multiple holographic exposures can be superimposed on an emulsion or arranged side-by-side in narrow strips to successively refocus the moving image of the sun onto a stationary receiver. Using these techniques, sunlight might be focused onto a fixed receiver throughout the day without the need for moving parts. There are, however, potentially significant restrictions on the efficiencies attainable using refocusing techniques.

In addition to being technically feasible, solar HOE's have the potential for low cost, mass production procedures. Once a "master" hologram has been produced with the proper characteristics, it can be duplicated by contact-printing techniques. An even lower cost device may be made by embossing plastic films with metal masters.

*This project was supported by the Director's Discretionary Fund through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ACCOMPLISHMENTS DURING FY 1981

During the past year, the LBL Solar Group has been investigating diffractive collector concepts as part of an overall program to study the optical properties of matter of small dimensions. This diffractive work can be divided into three areas. The first area involves basic studies of the general characteristics of holographic optical elements when considered for solar applications. Topics of interest in this area include the impact of the wavelength-dependent nature of diffractive systems on solar designs and the significance of traditional concepts such as flux concentration when viewed in a diffractive context. The second area of the program has centered around more detailed analytical calculations of the performance of specific concentrating HOE's. An ultimate goal is to develop a set of computer-assisted design tools for solar holographic systems. An interesting by-product of this branch of the research has been the production of computer-generated HOE's using LBL's computer-graphics facilities. The final area of the research has been the development of a complementary experimental program. This experimental effort not only provides validation of our analytical techniques but also has been geared toward developing laboratory techniques for characterizing the true efficiency of HOE's in solar applications.

Analytical Studies

To gain an understanding of perhaps the simplest type of concentrating HOE, analytical studies during FY 1981 began with a detailed analysis of the geometry and spatial distribution of interference fringes for holograms whose image is a coherent point source of light. For this type of HOE, the position of the nth interference fringe is determined by the relation:

$$n = \frac{2}{\lambda}(\rho - z - x \sin\psi),$$

where λ is the wavelength of light, ψ is the angle (assumed to lie in the x-z plane) of the reference beam with respect to a normal to the hologram plane, z is the closest distance from the point source to the hologram plane and ρ is the distance from the point source to a point P(x,y) on the hologram plane. It follows that the fringe spatial frequency in the plane of the hologram is given by

$$f = \frac{2}{\lambda}\left[\left[\frac{x}{\rho} - \sin\psi\right]^2 + \left[\frac{y}{\rho}\right]^2\right]^{1/2} .$$

A computer analysis based on the preceding equations was performed to quantify the relationship between various geometrical factors and the

fringe spatial frequency distributions characteristic of sample concentrating HOE's. A result of particular interest from this analysis is the rapid increase in fringe spatial frequency as the reference beam angle, ψ, is increased. It was found that beam angles as small as 3° can be expected to result in fringe spatial frequencies as large as 2000 lines/mm. This result is significant in that it dictates rather stringent resolution requirements for emulsions used to produce off-axis HOE's.

Computer-Generated HOE's

As a next step in the understanding of the basic focusing HOE, the same relations given above were used to make several computer-generated HOE's. For computational purposes, the hologram plane was represented as a finely spaced grid of points. Hologram transmission values for each point on the hologram plane were then calculated and plotted on film, using a high resolution microfilm output device, the Dicomed D48. Figure 1 shows a magnified representation of a typical computer-generated HOE. Based on the fringe spatial frequency analysis, HOE's produced were limited to the on-axis ($\psi = 0$) type to keep the resulting fringe spatial frequencies within the resolution limits of the graphics device (~200 lines/mm). Despite the limited resolution capabilities of the Dicomed, the computer-generated HOE's exhibited good focusing capabilities, although diffraction efficiency was low.

An interesting feature of the HOE's produced by this technique is what appear to be spurious images on the hologram itself. A closer investigation reveals that this effect is due to quantization errors inherent in the finite mesh technique used to produce the HOE's. An analysis of this effect in terms of its Fourier-transformed image indicates that this "optical noise" is potentially separable. Based on this analysis, we are currently investigating techniques for making high-quality optical copies of these computer-generated HOE's by spatial filtering of the Fourier transform of the image.

Computer Reconstruction of Holographic Images

The techniques used in producing computer-generated HOE's have been extended to provide a simulation of the complete holographic process, including image reconstruction. As described in the previous section, the resultant interference intensity at each point on the holographic plane is represented by a value on a fine mesh grid. Using a suitable model for the hologram of interest, the intensity at each point on the mesh is related to a corresponding value of transmission for the hologram at that point. This resulting transmission is then used to calculate the interference contribution from that point on the hologram to each point on a corresponding grid mesh representing the image plane. The contributions from all points on the hologram are then summed to give the total intensity at each image plane point. Global parameters, such as spot size and efficiency, can easily be calculated by numerical integration of the intensity distribution over an appropriate area of the image plane.

Figure 2 illustrates the results of this technique for the case of an on-axis, point-source HOE. The resultant intensity in the image plane is plotted logarithmically as a function of position along a line through the focus in the HOE's image plane. The fine structure evident in this plot is a result of the finite mesh used on the hologram plane and illustrates the need to use the smallest possible mesh when detailed intensity behavior on the image plane is to be studied. These small-scale perturbations can be neglected when efficiency integrals

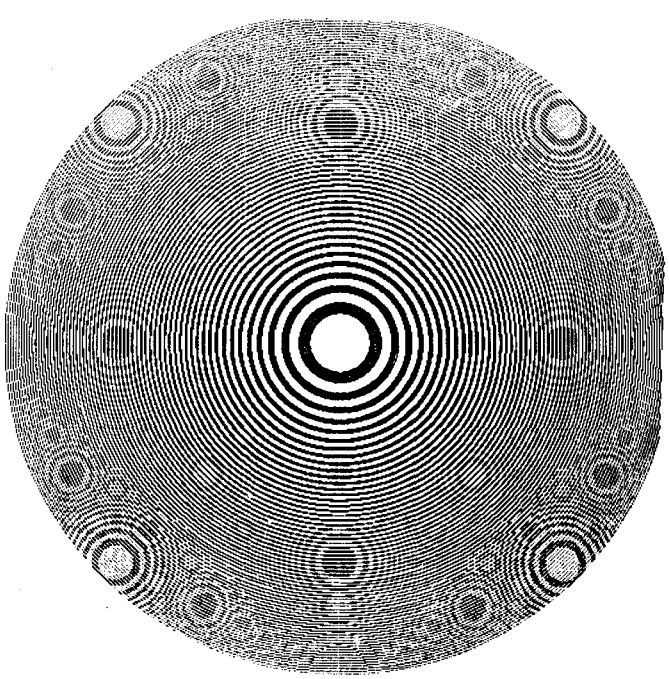

Figure 1. Magnified image of a computer-generated HOE.

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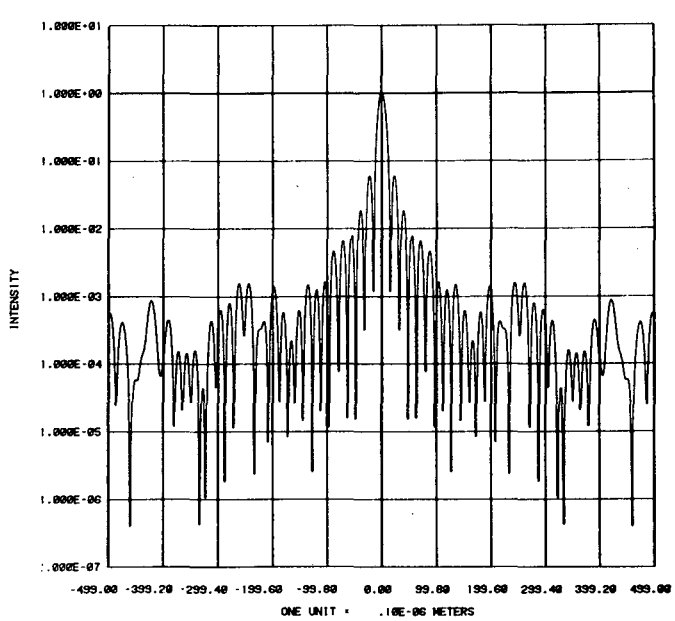

Figure 2. Intensity distribution of a computer-reconstructed image, as described in the text.

(XBL 824-9221)

are being evaluated, as long as their scale is truly small with respect to the given area of integration. This condition may be met by proper selection of the hologram mesh size.

The LBL Experimental Program

In an effort parallel to the theoretical analysis described above, an experimental program has been conducted to more fully understand the practical aspects of the utilization of HOE's for solar applications. One aspect of this experimental program involves the production and characterization of optical HOE's as validation of our analysis techniques. To date, a number of point focus HOE's have been made using high-resolution silver halide emulsions. Some of these HOE's were constructed to match as closely as possible the geometric configurations in our theoretical analyses. The reconstruction intensity distributions of these test HOE's have been measured and will be compared with computer predictions. In addition to the validation effort, efficiency measurements are being made on the test HOE's to gain a practical understanding of the dependence of HOE efficiency on various physical parameters, such as exposure and development conditions.

PLANNED ACTIVITIES FOR FY 1982

The computational techniques currently being used are strictly applicable only to the case of thin holograms and are inconvenient to modify for different construction geometries and/or holographic models. During FY 1982, these calculational techniques will be reorganized into a logically modular structure using an operator representation of the holographic process based on the theories of Nazarthy and Shamir.[2] Using this theoretical structure, each element of the holographic system can be represented as a discrete operator whose detailed specification may be changed as required. Effects due to finite beam size, apertures, and the modulation transfer function of the holographic medium can then be included as additional optical operators. The ability to include these effects is imperative for the study of HOE's illuminated by non-ideal sources such as the sun itself.

The feasibility of extending our analyses to thick or volume holograms will also be addressed. In considering the three-dimensional nature of the volume hologram, a much more complex mathematical theory is required, primarily to account for the depletion of the incident beam as it propagates through a highly efficient diffractive medium. A potential technique involves the Fourier decomposition of a focusing HOE into a series of constant-frequency gratings each of which may be described by a generalized coupled-wave theory.[3-5]

In future years, we plan to extend our experimental program to the characterization of the effects of reconstruction wave length and beam geometry and to a study of the relationship between holographic concentration and field of view in real HOE's. The plan is to develop an operational definition of solar holographic efficiency, while exploring laboratory techniques to measure that efficiency. In pursuing this goal, we plan to use the facilities of local holographics companies while we expand our own laboratory measurement capabilities at LBL.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Dr. Hla Tin of NTS Corporation, the inventor of the Holoconcentrator, for introducing us to the use of holograms for solar concentration.

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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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