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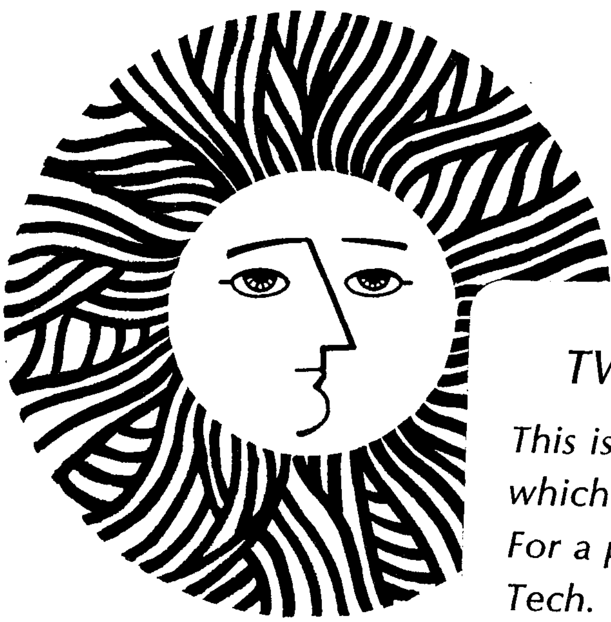

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

SOLAR ENERGY PROGRAM
FY 1980

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INTRODUCTION

Solar energy has become a major alternative for supplying a substantial fraction of the nation's future energy needs. The U.S. Department of Energy (DOE) supports activities ranging from the demonstration of existing technology to research on future possibilities. At Lawrence Berkeley Laboratory (LBL), projects are in progress that span a wide range of activities, with the emphasis on research to extend the scientific basis for solar energy applications, and on preliminary development of new approaches to solar energy conversion.

To assess various solar applications, it is important to quantify the solar resource. Special instruments have been developed and are now in use to measure both direct solar radiation and circumsolar radiation, i.e., the radiation from near the sun resulting from the scattering of sunlight by small particles in the atmosphere. These measurements serve to predict the performance of solar designs that use focusing collectors employing mirrors or lenses to concentrate the sunlight.

Efforts have continued at a low level to assist DOE in demonstrating existing solar technology by providing the San Francisco Operations Office (SAN) with technical support for its management of commercial-building solar demonstration projects. Also, a hot water and space-heating system has been installed on an LBL building as part of the DOE facilities Solar Demonstration Program.

LBL continues to provide support for the DOE Appropriate Energy Technology grants program. Evaluations are made of the program's effectiveness by, for example, estimating the resulting potential energy savings. LBL also documents innovative features and improvements in economic feasibility as compared to existing conventional systems or applications.

In the near future, we expect that LBL research will have a substantial impact in the areas of solar heating and cooling. Conventional and new types of high-performance absorption air conditioners are being developed that are air-cooled and suitable for use with flat plate or higher-temperature collectors. Operation of the controls test facility and computer modeling of collector loop and building load dynamics are yielding quantitative evaluations of the performance of different control strategies for active solar-heating systems.

Research is continuing on "passive" approaches to solar heating and cooling, where careful considerations of architectural design, construction materials, and the environment are used to moderate a building's interior climate. Computer models of passive concepts are being developed and incorporated into building energy analysis computer programs which are in the public domain. The resulting passive analysis capabilities are used in systems studies leading to design tools and in the design of commercial buildings on a case study basis. The investigation of specific passive cooling methods is an ongoing project; for example, a process is being studied in which heat-storage material would be cooled by radiation to the night sky, and would then provide "coolness" to the building.

Laboratory personnel involved in the solar cooling, controls, and passive projects are also providing technical support to the Active Heating and Cooling Division and the Passive and Hybrid Division of DOE in developing program plans, evaluating proposals, and making technical reviews of projects at other institutions and in industry.

Low-grade heat is a widespread energy resource that could make a significant contribution to energy needs if economical methods can be developed for converting it to useful work. Investigations continued this year on the feasibility of using the "shape-memory" alloy, Nitinol, as a basis for constructing heat engines that could operate from energy sources, such as solar-heated water, industrial waste heat, geothermal brines, and ocean thermal gradients.

Several projects are investigating longer-term possibilities for utilizing solar energy. One project involves the development of a new type of solar thermal receiver that would be placed at the focus of a central receiver system or a parabolic dish. The conversion of the concentrated sunlight to thermal energy would be accomplished by the absorption of the light by a dispersion of very small particles suspended in a gas. Another project is exploring biological systems. In particular, we are investigating the possibility of developing a photovoltaic cell, based on a catalyst (bacteriorhodopsin) which converts light to electrical ion flow across the cell membrane of a particular bacteria.

SMALL PARTICLE SUSPENSIONS FOR SOLAR THERMAL COLLECTION *

A. Hunt, P. Hull, J. Bouchez, C. Amkraut, and N. Pope

INTRODUCTION

Concentrated sunlight provides an intense source of radiant energy that offers an alternative to fossil fuels for operating heat engines, providing high temperature industrial heat, and directly processing fuels and chemicals. Because sunlight originates from a radiating body at a considerably higher temperature than other familiar energy sources, solar radiation has quite different characteristics from those with which we gained our power conversion experience. Our work deals with a novel approach to power conversion that matches the characteristics of concentrated sunlight to the requirement of heating a gas.

The purpose of this work is to develop a new type of solar thermal receiver that is placed at the focus of a central tower or parabolic dish concentrator system. The principle of operation differs from other advanced receiver designs under development in that the radiant solar-to-thermal energy conversion is accomplished by a dispersion of ultrafine particles suspended in a gas to absorb radiant energy directly from concentrated sunlight.[1] The very large ratio of surface area to volume, which is a property of small particles, makes them ideally suited for this application.

The Small Particle Heat Exchange Receiver (SPHER) can be used to operate a gas turbine, supply industrial process heat, or provide radiant power directly to a particle suspension for thermal or photochemical reactions. SPHER's are suitable for a wide range of power applications and are easily adapted to hybrid solar/fossil operation. The advantages of this type of receiver are its simplicity, low pressure loss, light weight, high optical efficiency, lower chamber temperatures for a given output temperature, and lack of problems associated with heat exchanger lifetime.

An open-cycle heat engine utilizing SPHER operates by compressing ambient air and injecting a very small mass of carbon particles into a gas stream. The air and particle mixture enters a transparent heating chamber where the solar flux is concentrated. The particles absorb the radiation and, because of their very large surface area, quickly release the heat to the surrounding gas. After heating the gas, the particles oxidize. The heated gas then passes through an expansion turbine to provide power for the compressor and load before going to a regenerator and being exhausted.

An earlier analysis quantified the optical and physical processes of absorption and heating of the particles.[2] Related considerations investigated include particle production methods, window and chamber design, hybrid solar/fossil compatibility, as well as environmental and safety factors. Analyses confirmed that the operating parameters are flexible and suitable to a variety of solar thermal power applications. A small laboratory apparatus built earlier demonstrated the direct heating of a gas by a small particle suspension.

ACCOMPLISHMENTS DURING FY 1980

Considerable progress was made during FY 1980 to advance the SPHER concept toward the test and demonstration stage. The analytical work was expanded to study the optical properties of small particle suspensions as selective solar absorbers, to clarify the requirements for the particle generator, to study the receiver design, and to examine the operation of the system for a wide range of conditions. Investigation continued this year into a related concept, the Solar Engine (SOLGIN). This is a new design for a small, reciprocating, direct absorption engine for use with small scale point focus solar concentrators. In an effort to broaden the understanding of radiatively coupled small particle systems, an examination was started into considerations of direct radiant processing of chemical feedstocks in the form of particle suspensions.

The experimental work was concentrated on the generation and analysis of the ultrafine carbon particles that are the heart of the SPHER. A new particle generation technique utilizing the pyrolysis of hydrocarbon gas was developed and found to be superior to the flame generation technique. Laboratory measurements of the generator operation established its capability for supplying particles in the quantities and with the properties necessary to operate an experimental receiver. The receiver chamber is undergoing final design, and a solar simulator was constructed for laboratory testing.

Analytic Studies

The goal of this year's analytic studies of small-particle suspensions was to determine how the physical and optical properties of the particles affect the operation of direct absorption receivers. The efficiency of a suspension of absorbing particles in capturing sunlight and minimizing losses from radiation by the heated particles is dependent on the particle size, shape, and optical properties of the material comprising the particles.[3] The ratio of the amount of energy removed from a beam by absorption or scattering to the cross-sectional area of the particle is defined as the absorption efficiency, Q_{abs}, or scattering efficiency, Q_{sca}, respectively. To reduce the amount of light scattered back out of a receiver, the ratio Q_{sca}/Q_{abs} must be minimized. If the particles are very small and absorbing, this condition is met, and their interaction with light can be

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Advanced Solar Thermal Technology, Solar Thermal Power Division of the U.S. Department of Energy under Contract number W-7405-ENG-48.

described by Rayleigh scattering theory. Under these conditions, Q_{abs} is proportional to the particle radius and Q_{sca} is proportional to the fourth power of the radius, so that the ratio of scattering to absorption is proportional to the cube of the radius. To maximize the optical efficiency of the receiver, the particle size is chosen to be less than 0.1 microns in diameter, resulting in scattering losses of less than about one percent.

The mass of particles, M_s, required to provide the necessary absorption in the chamber is an important quantity that can be calculated using Beer's law and neglecting multiple scattering (a reasonable assumption for small particles because the ratio of scattering to absorption is small). The mass of particles of density ρ and radius r required to reduce the intensity of a beam to I from I_o in a distance d is given by

$$M_s = \frac{4r\rho \ln (I/I_o)}{3Q_{abs} d} .$$

The general behavior of M_s as a function of particle size is shown in Figure 1. This figure illustrates that the required mass of particles to produce a given absorption reaches a constant value if the radius is small (as predicted by Rayleigh scattering theory). Large particles absorb an amount of light that is proportional to their cross-sectional area, leading to a roughly linear relationship between the required mass and the radius. The behavior in the intermediate region is shown as a dashed line because it depends heavily on the shape and optical properties of the particles. In fact, the experimental data for carbon particles (discussed later) indicates a strong minimum in the dashed region indicated by a bar in the figure.

Another dominant factor in determining the performance of a small particle suspension for a solar receiver is the dielectric response function $N^2 = (n + ik)^2 = \varepsilon_1 + i\varepsilon_2$ that describes the material from which the particles are made. The goal is to maximize the absorption efficiency in the visible part of the spectrum and to minimize it in the infrared part. The absorption efficiency for Rayleigh scattering may be written

$$Q_{abs} = 4x\text{Im}\left\{\frac{N^2 - 1}{N^2 + 2}\right\}$$

where x is the ratio of the particle circumference to the wavelength of light. The absolute maximum of the function in the braces is unbounded and occurs at $\varepsilon_1 = -2$, $\varepsilon_2 = 0$. The closer the dielectric function approaches this point, the larger the Q_{abs} will become. This corresponds to a "resonant mode" for surface states in spherical particles, and materials that approach this condition can be used to maximize the absorption in the visible region of the spectrum. To minimize the value of Q_{abs} in the infrared, ε_1 and ε_2 should be as large as possible. Metals in the infrared have just this type of behavior. Carbon is an excellent choice of materials for solar absorber applications because of its high absorptance in the visible and its metal-like optical characteristics in the infrared.

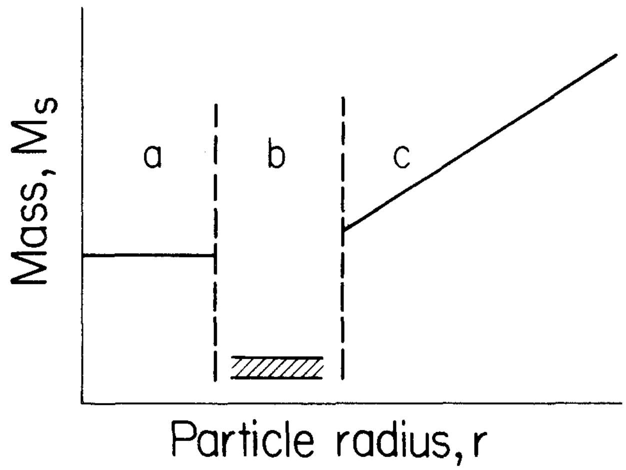

Fig. 1. Illustration of the dependence on particle size of the mass of particles required to produce a specified absorption. Region (a) is for the small particle limit (Rayleigh scattering); (b) is where the wavelength and particle size are comparable (Mie scattering); and (c) is the large particle limit (geometrical scattering). The hatched region indicates the area of the experimental results. (XBL 811-87)

The design of a realistic solar receiver must consider the confinement and flow of the particle suspension as well as the effect of the optics of the solar collection system. An important design guide for the chamber is that the overlap between the illuminated region and the particle suspension should be maximized. This overlap insures the maximum use of the particles as the absorber. Techniques were developed to analyze the required mass loading for cylindrical and conical receiver shapes. The analysis for a cylindrical shape is straightforward, but concentrating optical systems usually produce beams with considerable divergence. A conical-shaped receiver is a good approximation to this beam divergence. The analytical treatment is tractable because the decreases in beam intensity due to absorption and to geometry are separable. The results of this analysis offer the basis on which to design a chamber and to determine the requirements of the particle generator. Figure 2 illustrates the preliminary design of a receiver for laboratory testing.

The SPHER uses a transparent window to confine the suspension of absorbers. An analysis was performed to determine the efficiency of receivers using both one window and two windows in tandem.[4] To better understand the operation of windows in high-temperature environments, the analytic work was extended to study the thermodynamic stresses, sealing techniques, and cost for high-temperature windowed systems. The results confirmed that high silica materials can be used in practical, cost-effective windows for high-temperature operation.

A detailed analysis of the equilibrium properties of small particles in a radiant field was performed to investigate the effects of flux density, optical properties, and particle size. The analysis indicated that small particles can be used for radiant heat exchangers up to very high tem-

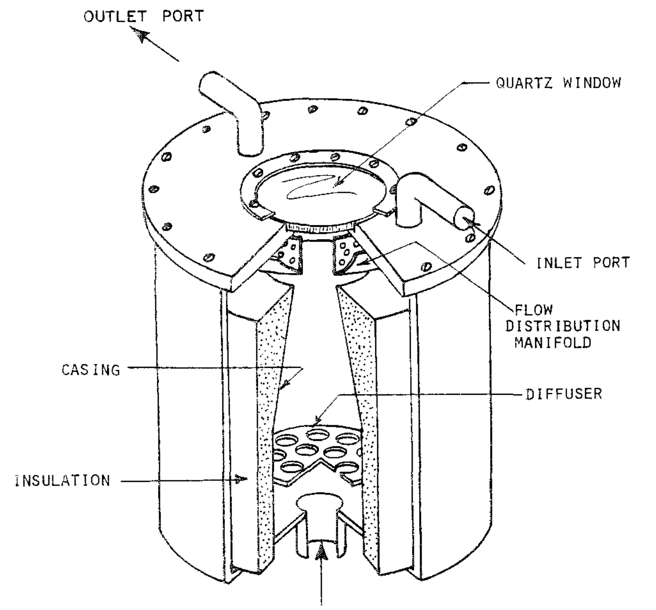

Fig. 2. Preliminary design of a small-particle heat exchange receiver.
(XBL 806-10317)

peratures (greater than 2000° C). This high-temperature capability is particularly important in processes such as the direct splitting of water into hydrogen and oxygen, the decomposition of carbon dioxide to produce carbon monoxide, and the oxidation of nitrogen to produce nitrates.

Solar Engine

Work has continued on the design and analysis of a new type of reciprocating solar engine that uses a small-particle suspension to absorb concentrated sunlight directly within the cylinders. The SOLGIN operates by drawing an air and particle mixture into the cylinder, compressing the mixture, opening an optical valve to allow concentrated sunlight to enter through a window in the top of the cylinder head, absorbing the solar flux with the particles, and converting the heat trapped by the air and particle mixture into mechanical energy with the downward stroke of the piston. SOLGIN differs from other gas-driven engines using solar energy in three main respects. First, the radiant flux is deposited directly in the working fluid inside the cylinder; second, the heat is directed to the appropriate cylinder by optically controlling the solar flux; third, the gas is heated during a significant portion of the compression stroke.

The thermodynamic efficiency of the engine was determined by use of an analytical model.[5] The efficiency depends on the compression ratio and the timing of the solar heating and is plotted in Figure 3 for a range of the parameters for a two-cylinder engine; the efficiency increases significantly for a larger number of cylinders. Efficiencies exceeding 50% can be obtained.

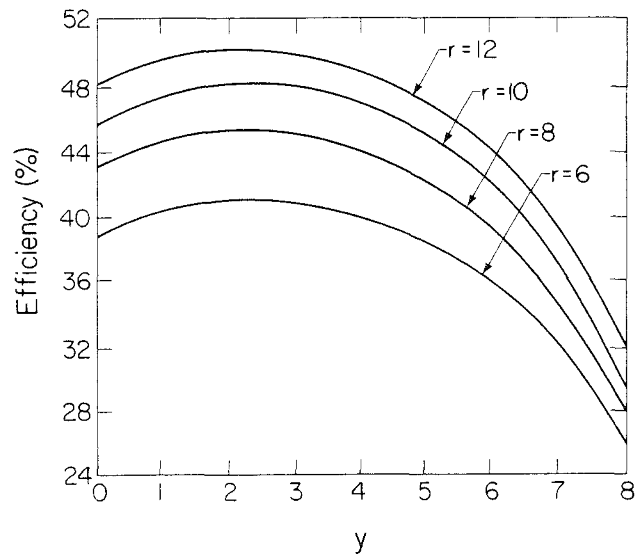

Fig. 3. The efficiency of the two-cylinder engine as a function of the timing of heat input. The variable y indicates the relative time for the onset of solar heating. When y = 0, the heating begins at the center of the compression stroke and when y = 8, the heat is added beginning at top dead center. r is the compression ratio.
(XBL 811-89)

Experimental Work

Three different methods for producing carbon particles suitable for high-temperature receiver applications were investigated experimentally. The methods included the use of a fuel-rich flame, the decomposition of carbon with a high intensity arc in argon, and the pyrolytic decomposition of acetylene gas. The optical absorption, particle density, and carbon production rates were determined experimentally. The size, shape, and state of agglomeration were studied with both scanning and transmission electron microscopy.[6]

A schematic diagram of the experimental apparatus for particle production and collection and for opacity and mass measurements is shown in Figure 4. The diagram shows the experimental setup used for producing particles from a fuel-rich flame. An extinction tube used with a He-Ne laser is used to determine the opacity of the gas-particle suspension. Nuclepore filters are used to collect the particles for weighing and scanning electron microscopy.

Opacity measurements of the particle suspensions showed consistent extinctions in excess of 95% for one-way light paths of 5 cm. The extinction and mass-loading measurements together indicated specific extinction coefficients of 15-20 m^2/gm. These results are extremely encouraging because they establish that the particles have four times greater absorption than the Rayleigh theory predicts, reducing the already very low requirement for particles. The higher absorption probably arises from two causes. An electron micrograph of a collected sample of carbon particles is shown in Figure 5. The median size of the smallest components is about 0.04 microns in diameter. Exact calculations for spherical particles this size give extinction coefficients about twice that predicted

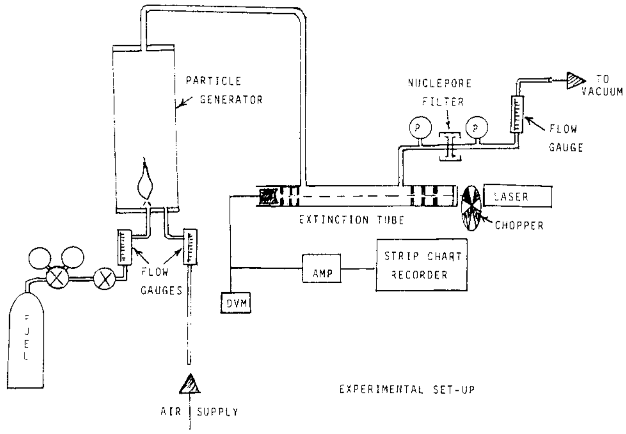

Fig. 4. Schematic diagram of the apparatus for the production and measurement of small-particle suspensions. (AMP stands for amplifier. DVM represents digital voltmeter. P's denote pressure gauges.)

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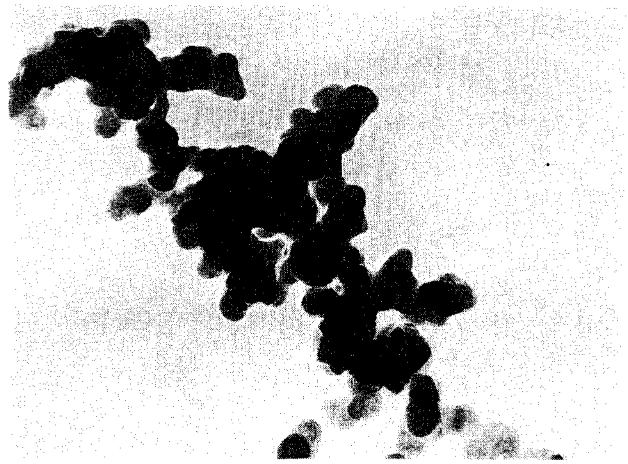

Fig. 5. Transmission electron micrograph of particles generated from the apparatus diagrammed in Fig. 4. The smallest particle diameter is approximately .05 microns.

(XBB 806-7255)

by Rayleigh theory. The second reason probably arises from the chain-like character of the agglomerates. Under some circumstances, a cylindrical particle can produce a larger mass normalized extinction than a spherical particle.

A particle generator based on the pyrolysis of acetylene was chosen for development for efficiency and stability reasons. At present a pyrolysis generator is being scaled up to operate with a 2 kW receiver chamber that is in the final design stage.

PLANNED ACTIVITIES FOR FY 1981

The main goal of the program in FY 1981 will be to build and test a complete SPHER receiver. The success of the work will rely on the continued experimental and analytical investigation of small-particle systems. The experimental program will concentrate on the continued development of the pyrolysis particle generator, including measurements of the yield and optical characteristics of the particles. A windowed receiver chamber will be constructed and mated with the particle generator. Instrumentation will be developed to measure the performance of the system. Laboratory tests of the receiver will be conducted with a small solar simulator. After successful laboratory results, we plan to test the complete receiver at a national solar thermal test facility.

The analytical program will continue with the investigation of the important features of direct absorption systems. Emphasis will be placed on studying the geometrical aspects of the interaction between the radiant flux and the particle suspension.

REFERENCES

1. A. J. Hunt, "Radiant Energy Collection and Conversion Apparatus," U.S. Department of Energy invention number S-50, 549. Patent application filed July 18, 1979 (pending).
2. A. J. Hunt, "A New Solar Thermal Receiver Utilizing a Small Particle Heat Exchanger," Proceedings of the 14th Intersociety Energy Conversion Engineering Conference, August 5-10, 1979, Boston, Mass.; Lawrence Berkeley Laboratory report LBL-8520, April 1979.
3. A. J. Hunt, "Optical Properties of Small Particle Suspensions for Solar Thermal Collection," Proceedings of the Optical Society of America Topical Meeting on the Optical Phenomena Peculiar to Matter of Small Dimensions, March 18-20, 1980, Tucson, Ariz.; Lawrence Berkeley Laboratory report LBL-10221, February 1980.
4. W. J. Fisk, D. E. Wroblewski, Jr., and A. J. Hunt, "Performance Analysis of a Windowed High Temperature Gas Receiver Using a Suspension of Ultrafine Carbon Particles as the Solar Absorber," Proceedings of the American Section of the International Solar Energy Society Meeting, June 2-6, 1980, Phoenix, Ariz.; Lawrence Berkeley Laboratory report LBL-10100, November 1979.
5. P. Hull and A. J. Hunt, "A Reciprocating Solar Heated Engine Utilizing Direct Absorption by Small Particles," submitted to the Journal of Solar Energy Engineering; Lawrence Berkeley Laboratory report LBL-10622 (in press).
6. A. J. Hunt, "Development of a New High Temperature Gas Receiver Utilizing Small Particles," Proceedings of the International Symposium on Solar Thermal Power and Energy Systems, June 15-20, 1980, Marseille, France; Lawrence Berkeley Laboratory report LBL-10148, November 1979.

PASSIVE SOLAR ANALYSIS AND DESIGN*

R. Kammerud, W. Place, B. Andersson, F. Bauman, C. Bauer, W. Carroll, E. Ceballos, C. Conner, B. Curtis, N. Friedman, A. Gadgil, A. Mertol, M. Nansteel, D. Nawrocki, M. Tavana, J. Thornton, T. Webster, and M. Wahlig

INTRODUCTION

The quantity of conventional fuel used to create a usable environment within a building is determined by (1) the interaction of the building with its surroundings, (2) the thermal loading effects of the activities occurring within the structure, and (3) the operating characteristics of the equipment used to convert conventional fuels to end-use energy. Significant reductions in the energy consumed in order to heat, cool, and light a structure can be realized by properly controlling the thermal coupling between the building and its environment and by appropriately managing the energy flows within the structure. To fully realize the benefits derived from these passive strategies, the collection, dissipation, storage, and distribution of thermal energy within the building's boundaries must be understood in terms of the design parameters of the structure and the environmental conditions under which the building is used. In this context, the specific objectives of the Passive Solar Analysis and Design Group at LBL are:

- to develop detailed, analytic descriptions for the collection, dissipation; storage, distribution, and management of thermal energy in buildings;
- to develop, analyze, and test innovative passive design concepts for application to specific building types and energy end uses; and
- to synthesize the results of the technical and design research in order to produce architectural and engineering design tools.

The focus of the program is the commercial building sector.

Long-range program directions have been selected based on an examination of existing energy use data for commercial buildings.[1] When disaggregated by building type and end-use category, the data provide the following information:

- The comparable magnitudes of heating, cooling, and lighting energy, and their obvious interactions within a specific building, indicate the need for a balanced program which addresses the three end uses from an integrated, rather than generic, systems standpoint.
- Because there is a strong interaction between the three dominant energy end uses, energy management is a key element in the passive design process.
- Both energy use intensity and growth rate imply the need for a programmatic focus on retail, wholesale, office, public, and educational building types for both new and retrofit applications of passive design principles.
- Although the growth rate of energy use in the hotel and motel category is relatively small, the energy intensity and total energy use in buildings of this type are large. This category of buildings, therefore, is an additional target for retrofit applications of passive design concepts.

To date, the LBL program has concentrated on the development testing and verification of public domain analysis tools necessary for exploring the application of passive concepts to commercial buildings, including (1) the development of thermal models for incorporation into BLAST† and (2) the development of stand-alone analysis capabilities for convective heat transfer under natural and forced conditions. This latter analytical tool is a critical element in the examination and characterization of energy management within passive and hybrid structures. A comprehensive tool for studying the thermal behavior of passive solar hot water heating systems has also been developed. The analysis technique is appropriate for conventional thermosiphons and for innovative systems, designed at LBL, that ensure positive protection from freezing.

In addition to the technical and design research activities, projects which synthesize the results of technical research with architectural design issues have been initiated. During development of passive analysis capabilities for commercial buildings, applications of developmental versions of BLAST to direct solar-gain residential buildings have been performed. These studies have examined:

- the effect of thermal mass on the heating and cooling loads of conventional and passive solar buildings;
- the interaction between thermally massive construction and common auxiliary system control strategies; and
- the impact on cooling load of direct-gain passive heating systems.

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* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Solar Applications for Buildings, Research and Development Branch, Passive and Hybrid Division of the Office of Solar Applications for Buildings, U.S. Department of Energy under Contract No. W-7405-ENG-48.

† BLAST (Building Loads Analysis and System Thermodynamics) is copyrighted by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.

Table 1. Passive analysis capabilities of BLAST.

Direct solar gain systems.
Thermocirculation systems and Trombe walls.
Roof pond systems.
Movable insulation.
Direct ventilative cooling.
Daylighting.
Building envelope and internal thermal mass.
Shading by attached or detached devices with complex geometries.
Simultaneous dynamic analysis of multizone buildings.
Variable convective heat transfer coefficients at all surfaces.
Environmental coupling through solar radiation, thermal radiation, and wind driven convection.
Mean radiant temperature and/or air temperature thermostat control.

Applications of BLAST in commercial building design projects have been a continuing part of the program; these case studies not only produce reliable technical input for the project design teams, but also provide direct feedback to LBL regarding the types of analysis capabilities that are needed by the private sector.

ACCOMPLISHMENTS DURING FY 1980

BLAST Development and Validation

Thermal models have been developed[2-5] and are being incorporated into BLAST-3.0, which is scheduled for release in early FY 1981. The major passive analysis features added to the program are listed in Table 1. In addition, standard features of the program allow users to specify the types of internal thermal loads (heat sources), their schedules, and the strength of their couplings to the internal space through radiation to exposed surfaces and convection and by evaporation to the ambient air. The program was originally written in order to provide user-oriented analysis capabilities for commercial buildings; it therefore includes dynamic simulation of mechanical systems and central energy plants. Program input consists of an English language description of (1) the building geometry, materials and construction; (2) mechanical systems and controls; (3) the internal loads, including lighting, occupancy, and equipment; and (4) hourly weather data. Output consists of (1) building loads; (2) the energy consumed by the central plant; and (3) the energy associated with the air handling system operation.

The daylighting algorithm which has been incorporated into BLAST-3.0 provides embryonic analysis capabilities that allow examination of the energy-consumption tradeoffs among heating, cooling, and lighting design strategies. Currently, the analysis requires input from daylighting experiments. In the longer term, a more independent daylighting analysis may be desirable. To provide input to the existing analysis capability and to examine future analysis needs, a daylighting project has been initiated. The project will include (1) experimental daylighting measurements in scale models under sky conditions and in an artificial sky dome facility; (2) tradeoffs between heating, cooling, and lighting loads based on building energy analysis using the daylighting measurements; and (3) synthesis of the results into design guidelines for specific classes of daylighting systems. The experimental work has begun and will provide input data to BLAST-3.0 for tradeoff analysis. The BLAST studies will provide the technical data on which the design tool development activities will be based.

The predictions of the BLAST thermal loads program have been compared to measurements performed in a small test room located at Los Alamos Scientific Laboratory. Comparisons were made between the measured and calculated air temperatures for three distinct weather periods.[6] The results of one of these comparisons are shown in Figure 1. In all cases, the predictions from BLAST were in excellent agreement with the measured data. The deviations were well within the limits implied by uncertainties in the test room construction and the properties of its construction materials.

The validation studies have been extended[7] to a full-scale high thermal mass test building located in an environmental chamber at the National Bureau of Standards. Whereas the test cell comparisons verify the ability of the program to account properly for solar excitation of an unconditioned structure, the data from the environmental chamber allows validation of the load calculation and of the excitation of thermal storage mass by direct ventilation cooling systems. To improve on existing validation data, a fully automated air infiltration measuring system has been developed. The system will be used to supplement the standard thermal measurements normally collected and compared to computer codes. The addition of infiltration data will remove one of the largest uncertainties in the validation process.

BLAST Applications

Two types of BLAST applications have been performed. In the first type, energy analyses of prototype direct solar gain systems have been performed in order to examine the sensitivities of the building heating and cooling loads to variations in design parameters and auxiliary system control strategies. The studies examined the effect on the annual thermal loads that result from varying the south-facing glazing area on a direct-gain residential building located in each of the 26 cities for which Typical Meteorological Year (TMY) weather data is available. In some types, the results were obtained for two variations of the building design:[4] in one case, all internal wall surfaces consisted of standard low-mass gypboard construction and, in the other case, the internal partition walls were assumed to be a 4-in. concrete construc-

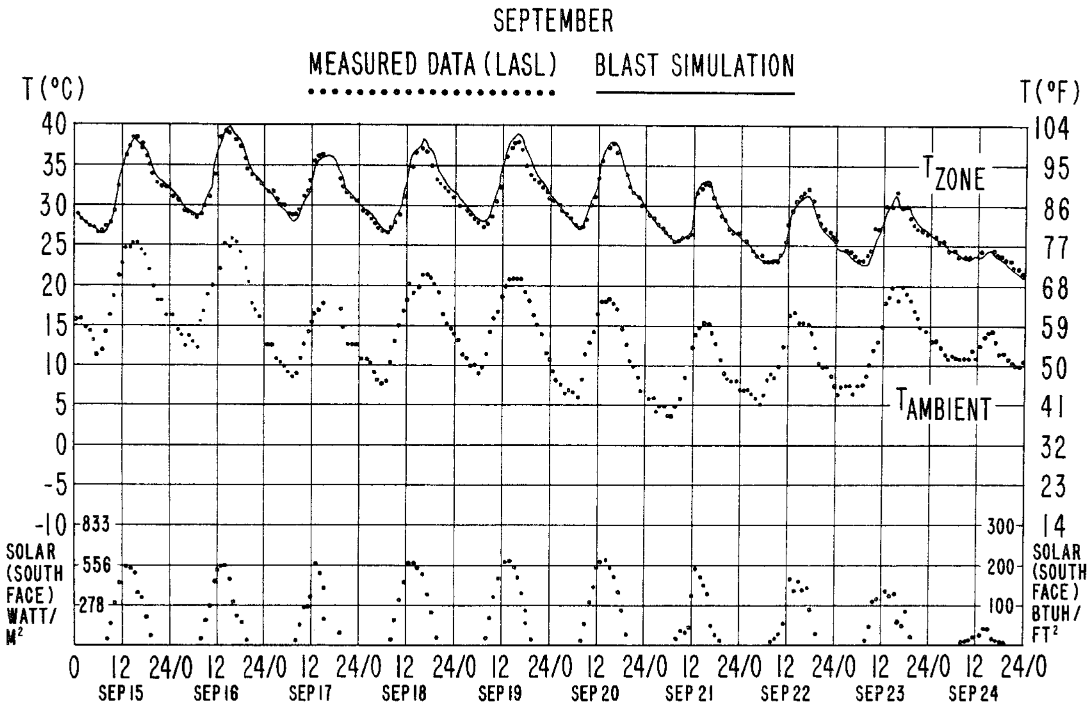

Fig. 1. Comparison of the interior air temperature predictions (F zone) of BLAST to measurement performed in a direct gain test room located in Los Alamos, N.M. The comparison is for a 10-day period in September and also shows the ambient temperature and the incident solar radiation.

(XBL 806-7121)

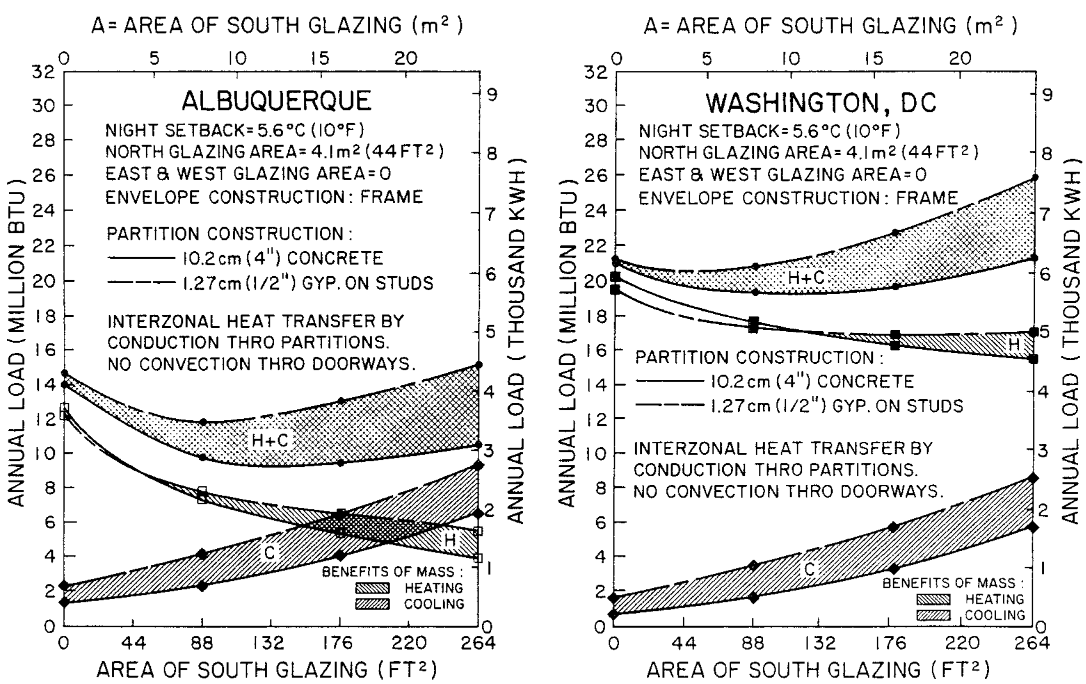

Fig. 2. Predicted annual auxiliary energy consumptions for heating and cooling a passive solar residential building located in Albuquerque, N. M. and in Washington, D. C., as a function of the area of south glazing. The calculations were performed using the building energy analysis computer program BLAST and were performed for a conventionally constructed building and for a variation which replaces the gypboard partition walls with concrete.

(XBL 804-6917A)

tion. Ventilation cooling was assumed throughout the year. Typical results from this study are shown for Washington, D.C. in Figure 2. We found that in most heating climates, as in Washington, D.C., that for south-facing glazing areas less than about 132 ft^2 (11% of the floor area) the heating benefits of south-facing glazing are dominant, but at larger glazing areas, the increase in cooling load which accompanies increased glazing area became more significant than the heating load reductions. A second striking feature of the study is also apparent in Figure 2: the importance of internal thermal mass in reducing the cooling load when forced ventilation is used. Although both building configurations included substantial mass in the insulated 4-in. concrete floor slab, the cooling performance is substantially improved by adding considerably more mass. Other important results include the observation that thermal mass can have a deleterious effect on the performance of buildings that incorporate night setback thermostat control strategies.

The second type of BLAST application has consisted of applying the program to commercial buildings during the design process. Extensive analyses have been performed on three projects during the schematic design phase. In one case, the results were used to determine the effectiveness of direct ventilation cooling and thermally massive construction on reducing cooling loads. In another case, a variety of passive heating and cooling strategies and energy conservation features were examined in order to define the scope of a retrofit project. In addition, several other DOE contractors and design firms in the private sector have been trained in the use of BLAST, and technical support has been provided for their independent applications of the program.

Natural Convection and Energy Management

A computerized numerical technique for studying natural and forced convection in room geometries has been developed.[9] The computer program has been validated[9-11] using data from the literature and from an experiment performed by LBL in conjunction with the Department of Mechanical Engineering at the University of California, Berkeley. The convection project includes the study of natural ventilation phenomena, energy management strategies, convective heat transfer coefficients, temperature stratification, and stack effect ventilation systems. Initial applications to residential scale systems have been performed in order to examine the validity of the common assumption in building energy analysis that convection coefficients are sensitive only to the direction of heat flow and not to temperature differences between building surfaces and the room air.[10,11] Initial results indicate that surface convection coefficients vary substantially from the standard assumptions and that this may be reflected in significant errors in heat transfer to and from thermal storage materials and in calculated thermal loads.

Toward the end of FY 1980, an analytic component was added to the convection research. Examinations of the numerical analysis results proved that some features of natural convection in an enclosure with a room geometry can be represented

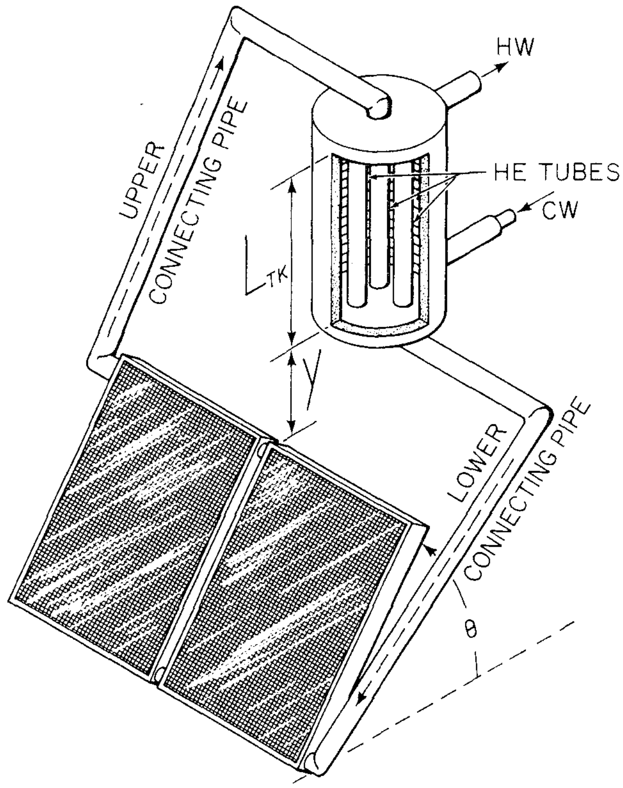

Fig. 3. Schematic representation of a thermosiphon hot water system which provides positive freeze protection. The system utilizes a primary loop filled with a nonfreezing liquid such as glycol to transfer thermal energy from the solar collector to a heat exchanger in the hot water storage tank.

(XBL 803-6909)

analytically. Efforts were therefore initiated to investigate the possibility of developing a hybrid convection analysis program which combines numerical techniques at the boundaries with analytic methods in the core, thereby providing far more efficient analysis and allows the convection studies to be extended to many more applications problems.

Domestic Hot Water and Process Heat

A passive solar hot water heating system that incorporates positive protection from freezing has been designed and thoroughly analyzed. A typical system configuration is shown schematically in Figure 3. The system utilizes a glycol-filled primary loop from the solar collector to a heat exchanger located in a conventional storage tank. This design eliminates the danger of freezing from mechanical malfunction and utilizes no parasitic power. A detailed simulation model[12,13] for the system has been developed and used to study performance as a function of climate, collector parameters, heat exchanger design, and hot water use profile.[14] The results of the analysis indicate that relatively simple heat exchangers consisting of straight tubes parallel to the axis of a cylindrical storage tank will provide system performance that is nearly equivalent to that for a standard thermosiphon. An experiment is currently being set up to validate the analysis and parametrically examine the effectiveness of various heat exchanger configurations. If the concept is experimentally verified, one of the major barriers to widespread use of thermosiphons will be eliminated, and their regional applicability will be dramatically increased.

During FY 1980, simplified performance prediction techniques were explored. Based on detailed simulations, a correlation between system performance and system design parameters was identified. Assuming the correlations hold in future analyses and experiments, the simplified method will serve as a practical design tool for the engineering community.

PLANNED ACTIVITIES FOR FY 1981

Upon release of BLAST-3.0, thermal model development activities at LBL will focus on (1) further validation of existing capabilities using data from full-scale buildings where simultaneous measurements of thermal parameters and infiltration have been carried out, and (2) on development of algorithms that describe the thermal behavior of innovative passive solar building configurations. Examples include waffled concrete ceiling structures; thermodeck structural floor and ceiling elements coupled to ventilative and/or evaporative cooling systems; infrared reflective glazing materials; and optical shutter materials. In addition, further work will be devoted to energy management systems and to improvements in the representation of convection processes in BLAST. These activities will lead to a new version of BLAST in FY 1982.

Parametric studies of commercial buildings incorporating passive heating, cooling and/or lighting systems will begin on completion of BLAST-3.0 development. These studies will be directed initially at improving the ability of the designer to select basic design directions during the early phase of the design process. The initial studies will include:

- ventilative cooling strategies;
- daylighting tradeoffs with heating and cooling loads;
- comparisons of solar control glazing, shading, and summer movable insulation in controlling cooling loads; and
- thermal mass effects.

This type of study will be an ongoing part of the LBL program.

The convection analyses and experiments will be directed at:

- characterization of the natural ventilation potentials of commercial buildings utilizing stack effect systems such as atriums; and
- examination of, and algorithm development for, convective heat transfer within and between thermal zones.

In addition, the analysis capability will be applied to specific problems that arise in the analysis of passive systems and for which no acceptable algorithms currently exist. An example of this is the effect on thermocirculation system performance of inlet and outlet vent configurations.

Data collection from the hot water experiment will begin in early 1981. The data will be used for:

- validation of the thermosiphon simulation computer code; and
- comparison of different heat exchanger designs.

Later experiments will be oriented toward collection of a system performance data base to be used in the further identification of simplified correlative techniques for predicting system performance.

The daylighting experiments will continue during FY 1981 and daylighting designs will be examined. The results will be used to examine the tradeoffs of lighting with heating and cooling loads for various building types and climates.

REFERENCES

1. J. McMahon et al., A Review and Analysis of Commercial Building Energy Consumption Studies, Lawrence Berkeley Laboratory report LBL-10620 (to be published) 1981.
2. H. Akbari et al., Free Convective Laminar Flow Within the Trombe Wall Channel, Lawrence Berkeley Laboratory report LBL-7802, August 1978.
3. T. Borgers et al., Free Convective Turbulent Flow Within the Trombe Wall Channel, Lawrence Berkeley Laboratory report LBL-8323, April 1979.
4. M. Tavana et al., A Simulation Model for the Performance Analysis of Roof Pond Systems for Heating and Cooling, Lawrence Berkeley Laboratory report LBL-9292, June 1980.
5. M. Tavana et al., Roof Pond System Performance Sensitivities and Model Modifications, Lawrence Berkeley Laboratory report LBL-11381 (to be published), 1981.
6. B. Andersson et al., Verification of BLAST by Comparison with Direct-Gain Direct-Gain Test Cell Measurements, Lawrence Berkeley Laboratory report LBL-10619, November 1980.
7. F. Bauman, B. Andersson, W. Carroll, and R. Kammerud, Verification of BLAST by Comparison with Measurements of a Solar-Dominated Test Cell and a Thermally Massive Building, Lawrence Berkeley Laboratory report LBL-11387 (to be published) April 1981.
8. R. Kammerud et al., Human Comfort and Auxiliary Control Considerations in Passive Solar Structures, Lawrence Berkeley Laboratory report LBL-10034, April 1980.
9. A. Gadgil, On Convective Heat Transfer in Building Energy Analysis, Ph.D. dissertation, Department of Physics, University of California, Berkeley, 1980; Lawrence Berkeley Laboratory report LBL-10900, May 1980.

10. F. Bauman et al., Buoyancy Driven Convection in Rectangular Enclosures: Experimental Results and Numerical Calculations, Lawrence Berkeley Laboratory report LBL-10257, July 1980.

11. A. Gadgil et al., Natural Convection in Room Geometries, Lawrence Berkeley Laboratory report LBL-9297, October 1979 (longer version to be issued 1981).

12. A. Mertol, Heat Transfer and Fluid Flow in Thermosiphons, Ph.D. dissertation, Department of Mechanical Engineering, University of California, Berkeley, 1980; Lawrence Berkeley Laboratory report LBL-10939, April 1980.

13. A. Mertol et al., Detailed Loop Model (DLM) Analysis of Liquid Solar Thermosiphons with Heat Exchangers, Lawrence Berkeley Laboratory report LBL-10699, October 1980.

14. A. Mertol et al., Thermosiphon Water Heaters with Heat Exchangers, Lawrence Berkeley Laboratory report LBL-10033, June 1980.

NITINOL ENGINE DEVELOPMENT*

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INTRODUCTION

Low-grade heat, in the form of thermal energy at temperatures below the boiling point of water, is a widespread energy resource that could make a significant contribution to worldwide energy needs if an economical technology can be developed for converting it to useful work. The Nitinol Engine Development project is investigating the feasibility of using the thermally activated shape-change phenomenon in certain intermetallic Shape Memory Alloys, particularly in the nickel-titanium compound "55-Nitinol," as the basis for thermal-to-mechanical energy conversion at temperatures available from such sources as industrial waste heat, low-temperature geothermal brines, solar-heated water, or the moderate-temperature differences of the ocean thermal gradient. An important advantage in using a solid rather than a fluid working medium in such applications is the possibility for eliminating the heat exchangers required by closed-cycle fluid systems, which often are a major cost and require frequent maintenance in conventional low-temperature energy conversion technologies.

A prototype Nitinol heat engine has been in operation at the Lawrence Berkeley Laboratory since August 1973. Several iterations of engine design since then have led to an improved understanding of the important practical considerations in applying this material to energy conversion in continuously cycling heat engines. These studies, as well as experimental and theoretical investigation of the material's thermodynamic and metallurgical properties, have confirmed that Nitinol engines for the recovery of thermal energy from low-grade or waste heat can be constructed; however, the question of economic feasibility is still unresolved.

* This work was supported by the Assistant Secretary for Energy Technology, Fossil Fuel Utilization Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

ACCOMPLISHMENTS DURING FY 1980

During this past year, for the first time, we had available Nitinol wire specimens that had completed several million working cycles in uniaxial strain (linear tension) on the Tensile Fatigue Test Stand (shown in Fig. 1). Constructed at LBL during 1979, the stand continuously cycles Nitinol wires under controlled stress between baths of hot and cold water. Powered by the thermoelastic Shape Memory Effect (SME) response of the wires being cycled, the stand is a heat-engine. We believe this machine is the first device to exploit the SME of Nitinol wires in pure tension to achieve this many cumulative reproducible working cycles.

Single wires were taken from the power element of the Fatigue Test Stand at regular intervals, and their performance was evaluated on a high-resolution Laser-Beam Dilatometer. The dilatometer, developed during prior years of the project for characterizing the strain-temperature behavior of Nitinol wires in tension, heats and cools a specimen at slow and uniform rates so that changes in axial displacement (magnified by a factor of 200) may be precisely correlated with small changes in temperature over the material's complete thermal transformation range.

The dilatometer evaluations confirmed qualitative observations of the test stand's performance that Nitinol wires, whose properties have been stabilized by cycling in the test stand, exhibit improved thermomechanical characteristics in two important respects. The first improvement is an overall increase in potential displacement (length of "stroke") of the cycled material, as compared with that of reannealed but uncycled wire from the same stock. (Reannealing essentially restores the material to its initial condition.) The second improvement is a reduction in thermal hysteresis, the temperature difference required for the cooling and heating shape changes of the wire's thermoelastic response as a result of extended cycling on the test stand.

Dilatometer Measurements in Detail

The cyclical behavior of Nitinol wire that was reannealed but not engine-cycled can be compared with that of wires that had sustained 10^6 cycles and 5.3 x 10^6 cycles respectively on the Fatigue Test Stand in Figures 2, 3, and 4. On cooling, strain (elongation) occurs under a moderate uniform stress load of approximately 2.3 kpsi. The cooling path is shown as an unbroken line in computer-generated plots, in Figures 2-4, of data taken from the dilatometer. Shape-recovery (axial contraction), caused by reheating, is indicated by crosses.

In the uncycled wire, thermoelastic strain begins at a very moderate rate at about 25°C, with a more pronounced threshold occurring at 7.5°C.

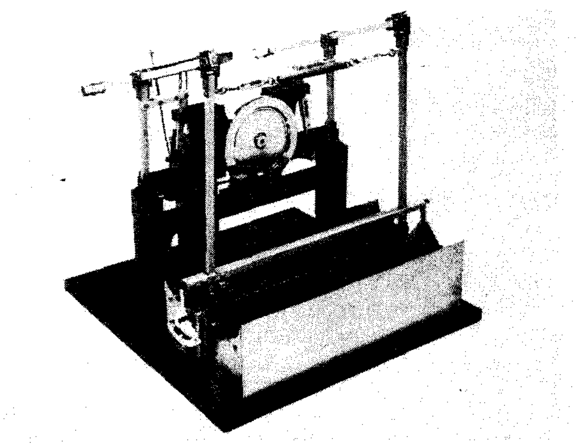

Fig. 1. Nitinol Tensile Fatigue Test Stand.
(CBB 809-11931)

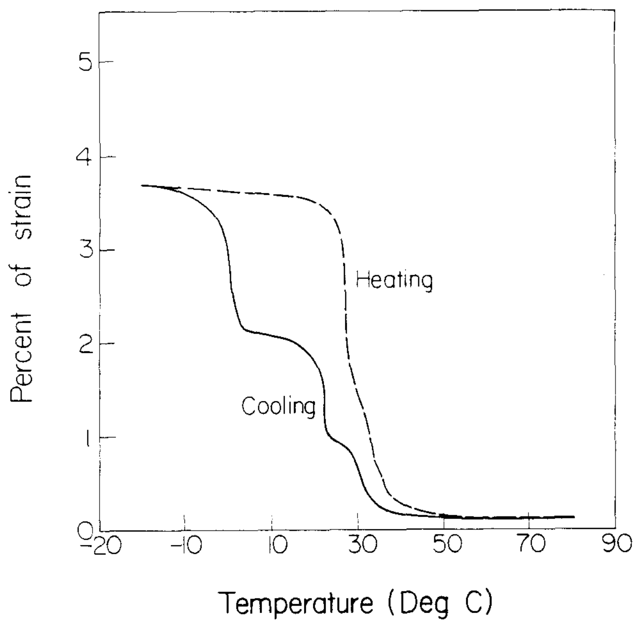

Fig. 2. Strain-Temperature Hysteresis Loop for Uncycled Nitinol Wire. Measurements were made at constant stress of 2.3 kpsi.
(XBL 811-85)

The major portion of strain in this specimen (and the maximum strain rate) occurs between the temperatures of +5° and -5°C, and displacement is essentially complete at the temperature of -20°C. On reheating, strain reversion (the shape recovery) begins at approximately 25°C and is essentially complete by 60°C. The distance between the active sections of the heating and cooling paths denotes the thermal hysteresis of the cycle, in this case about 30°C. Maximum strain in this specimen was approximately 1.3%.

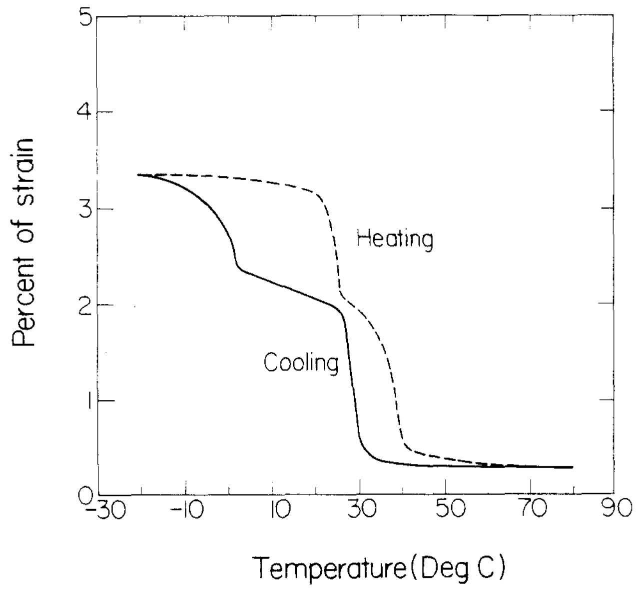

Fig. 3. Strain-Temperature Hysteresis Loop for Nitinol Wire that has undergone 1 x 10^6 cycles in the Fatigue Test Stand. Measurements were made at constant stress of 2.3 kpsi.
(XBL 811-88)

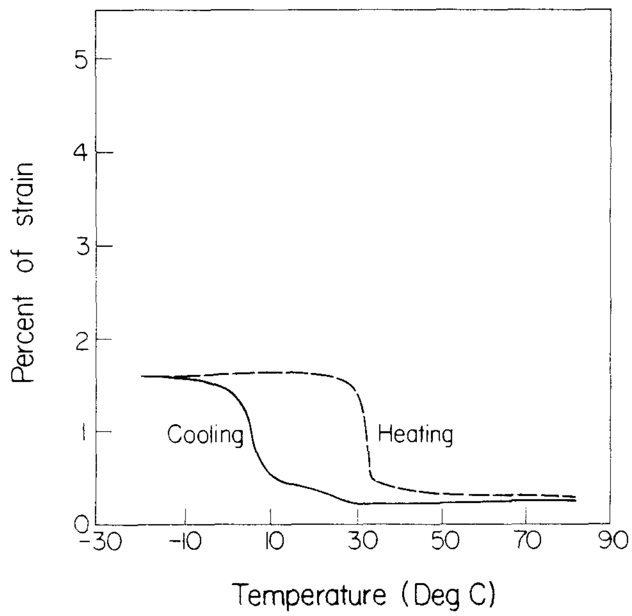

Fig. 4. Strain-Temperature Hysteresis Loop for Nitinol Wire that has undergone 5.3 x 10^6 cycles in the Fatigue Test Stand. Measurements were made at constant stress of 2.3 kpsi.
(XBL 811-91)

Wire taken from the Fatigue Test Stand after 10^6 working cycles was subjected to testing on the dilatometer (Fig. 3) under identical stress and temperature conditions as for the first sample previously described. Maximum strain in this specimen is approximately 3.5% for the complete thermal range of +80° to -20°C. However, in the thermal range defined by the operating temperatures of the test stand (+42° to -18°C), the wire had developed a novel pattern of thermoelastic behavior. Strain in this specimen begins at approximately 35°C (on cooling) followed by an elongation of about 0.75%, accomplished at the temperature of 20°C. This displacement is followed by a secondary strain threshold at ~20°C and rapidly increasing elongation to a total (local) strain of about 1.7% at the minimum (test stand) cycling temperature of 18°C. Because this subordinate or "working" strain-temperature cycle corresponds rigorously to the operating parameters of the test stand, some sort of microstructural accommodation in the material may have occurred which optimized its performance under actual working conditions. Thermal hysteresis for the working cycle was reduced to ≤10°C, according to the dilatometer measurements.

On further cooling (in the dilatometer) a third thermoelastic strain threshold appears, initiating a ternary strain-temperature cycle that preserves many of the features of the thermal hysteresis loop of the original uncycled specimen of Figure 2. This cycle occurs at temperatures never attained in the test stand's operating range of 0° to -20°C, and it is accounted for, presumably, by transformation and reversion of low-temperature crystal (martensite) variants unaffected--and therefore unoptimized--by microstructural accommodations occurring during the course of the first 10^6 working cycles.

The strain-temperature cycle for wire taken from the test stand after completion of 5.3 x 10^6 working cycles (Fig. 4) is qualitatively similar to that of the specimen tested at 10^6 cycles, although the consequences of the test conditions have become even more pronounced in the behavior of the more stabilized wire. The subordinate strain threshold observed at 20°C (on cooling) for the 10^6-cycle wire has now disappeared. Strain for the working cycle begins slightly above 30° and proceeds almost uniformly, reaching a local maximum of approximately 1.75% at 26°C, the temperature of the cold water bath at this stage of the cycle-testing schedule. The rate of elongation on cooling now exceeds the rate of contraction on heating, as indicated by the more nearly vertical slope of the unbroken line in the "working cycle" portion of the graph compared to the slope of the heating path opposite. Shape recovery on heating, for this "working cycle," also begins very close to the final (local) minimum temperature loop in this portion of the graph. At 5.3 x 10^6 cycles the area of the "unavailable" portion of the cycle--from 0° to -20°C--has become somewhat reduced, as has overall strain in the complete thermal transformation range. Displacement within the thermal extrema of the test stand operation, however, remains essentially unchanged.

Time and manpower constraints during this final period of the Nitinol Engine Development Project precluded correlating these changes in the macroscopic thermoelastic behavior of Nitinol wires from the test stand either with possible changes in the physical metallurgy of the material or with changes in the thermodynamic conversion efficiency of cycles employing these stabilized Nitinol materials. However, increased thermal sensitivity in these specimens does relate directly to systematic improvements in the observed operation of the Fatigue Test Stand (i.e., an increased cycling rate at reduced ΔT, under constant load). Therefore, it may be reasonable to assume that efficiency, as well as work output potential of the material, may be enhanced as the result of repetitive cycling under actual working conditions.

PLANNED ACTIVITIES FOR FY 1981

Support for this project was discontinued as of the end of FY 1980, and the project has been terminated.

APPROPRIATE ENERGY TECHNOLOGY*

C. Case, B. Lucarelli, J. Kessel, H. Clark, J. Kay, and J. Linse

INTRODUCTION

In 1977, the Energy Research and Development Administration (ERDA), now incorporated in 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.

To date, DOE has funded more than 1,100 projects nationwide for $19 million. The grants cover a complete spectrum of small-scale energy technolo-

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Inventions and Small Scale Technology, Appropriate Technology Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

gies, 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 1980

Since the program's start in 1977, LBL has assisted the DOE in establishing project review procedures and in evaluating the program's effectiveness. Our function has evolved from providing technical advice on a regional basis to conducting energy studies on a national level.

In the past, LBL provided DOE with technical support in three ways:

1. reviewing grant proposals for technical and economic merit;
2. monitoring projects in Arizona, Nevada, and the western Pacific; and
3. advising DOE on effective technical review procedures for the grants program.

As the program evolved, the regional DOE and state energy offices took over these functions. DOE then asked LBL to change the focus of its work and to conduct energy studies that determine the program's energy savings potential and the economic and technical feasibility of developing selected small-scale technologies and renewable energy resources. The next sections describe these studies, which are being completed in 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 for comparing 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.

For our continuing analysis, we are evaluating a sample of 57 projects funded in FY 1979.[2] The 57 projects have been 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 is being 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.

For a project to have replication potential, the project must be cost-effective and the grantee must have a plan to market the device produced or to disseminate the results of the project. From the assessment of the 60 projects, we will attempt to estimate the energy savings potential of all projects funded in FY 1979.

Technology Assessment Study

We are also assessing the technical and economic feasibility of small wind energy systems in the U.S.[3] The analysis is being conducted from a sample of wind energy projects funded by the grants program in FY 1978. 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 are assessing each project for technical performance, economic feasibility, and physical infrastructure requirements. The end product will be a report which 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.

Biomass Energy Assessment

We have completed a comprehensive assessment of California's biomass and its energy potential.[4] The study estimates the amount of biomass in the form of agricultural, municipal, and forestry wastes produced in California in 1976 and then projects these estimates to 2025. The study considers the use of biomass for producing electricity, low-Btu gas, alcohol, and methane, with an emphasis on producing alcohol and methane as fuels for the transport sector.

In terms of economic feasibility, we found that the production of ethanol from feed grains and of methane from animal and human wastes are already cost-effective if the energy is used on site. By 1990, with moderate increases in energy prices, off-site energy use should be cost-effective. Methanol produced from wood will be a cost-effective technology by 1990 for large plants which consume 3,400 tons or more of wood per day. Overall, the state's biomass can meet only 20% of the projected demand for fuels in the state's transport sector even with a reasonable conservation effort. Moreover, the feasibility of producing methanol will be limited by a fragmented biomass fuels market and by the large size of methanol synthesis plants, which will require long-distance transport of biomass.

To conclude, the state's biomass can supply a significant fraction of the state's transportation energy demand, but because of the fragmented biomass market and high costs of biomass transport, small-scale applications of biomass technologies with on-site use of the energy will probably be the dominant use of biomass for the next 50 years.

PLANNED ACTIVITIES FOR FY 1981

In FY 1981, we will complete our analysis of program energy savings. In a third and final analysis, LBL will evaluate the energy savings potential and cost-effectiveness of 30 projects funded by DOE in FY 1980. This analysis plus the prior studies should provide DOE with the data needed for evaluating the grants program. We plan to expand our assessments of specific technologies in FY 1982. The following technologies will be considered:

- small-scale alcohol fermentation plants,
- anaerobic digesters,
- active solar systems, and
- wind energy systems (an expansion of the FY 1981 study).

For each technology assessment, we will document the technical innovations and cost-effectiveness of a large sample of projects and identify projects which have exceptional energy savings potential.

REFERENCES

1. F.B. Lucarelli, J. Morris, J.M. Kay, S. Rizer, C.W. Case, and H.R. Clark, The Energy Savings Potential of the Region IX Appropriate Energy Technology Grants Program: An Assessment of Twenty Projects, Lawrence Berkeley Laboratory report LBL-9715, October 1979.
2. F.B. Lucarelli, J. Kessel, J. Kay, and J. Linse, The DOE Small Grants Program and Its Energy Savings Potential, Lawrence Berkeley Laboratory report (in progress).
3. J. Kay, A Technical and Economic Assessment of 13 Small Wind Energy Projects, Masters thesis (in progress), University of California, Berkeley.
4. F. B. Lucarelli, Jr., California's Biomass and Its Energy Potential, Lawrence Berkeley Laboratory report LBL-10058, April 1980.

ENERGY CONVERSION BY RETINAL PROTEIN, BACTERIORHODOPSIN*

L. Packer, A. Quintanilha, R. Mehlhorn, C. Carmeli, P. Sullivan, P. Scherrer, N. Kamo, S. Tristram, J. Herz, and A. Pfeiffhofer

INTRODUCTION

Light generates a pH gradient and an electrical potential across the purple membrane of Halobacterium halobium. We are investigating the time-resolved changes in protonation of the side chains of specific amino acid residues and the correlation of these changes with photon absorption and the ensuing photoreaction cycle. Our aim is to determine the precise molecular description of the photocycle and of the time-dependent steps in the uptake, translocation, and release of protons by the retinal protein catalyst in this membrane, bacteriorhodopsin.

The photocycle is initiated by absorption of visible radiation (with an absolute maximum at 570 nm) by the all-trans retinal chromophore. The initial steps of the photocycle involve the isomerization of the chromophore to the 13-cis retinal. A deprotonated Schiff base forms with a $t_{1/2}$ of about 50 μmsec. Proton release occurs in this time range (illustrated in the upper half of Figure 1). Later, the deprotonated species decays ($t_{1/2}$ about 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. This process is shown in the bottom half of Figure 1. The deprotonated photointermediate is referred to as the M_{412} species.

To assess significant structural features of the lipid and the protein, which are important for proton movement, we have used chemical modification of amino acid side chains, spin labeling, and deuterium isotope effects on purple membranes. Purple membranes have also been reconstituted into liposomes before and after such treatment. The purpose of this step is to derive information relevant to the occurrence of proton movement at the cytoplasmic surface of the purple membrane. This information will help us understand the importance of the electrochemical potential developed across the closed vesicle membrane in the regulation of light energy conversion.

ACCOMPLISHMENTS DURING FY 1980

Chemical Modification Studies

Modification of Positively Charged Amino Acids

*This work was supported by the Assistant Secretary for Energy Research, Office of Basic Energy Sciences, Chemical Sciences Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

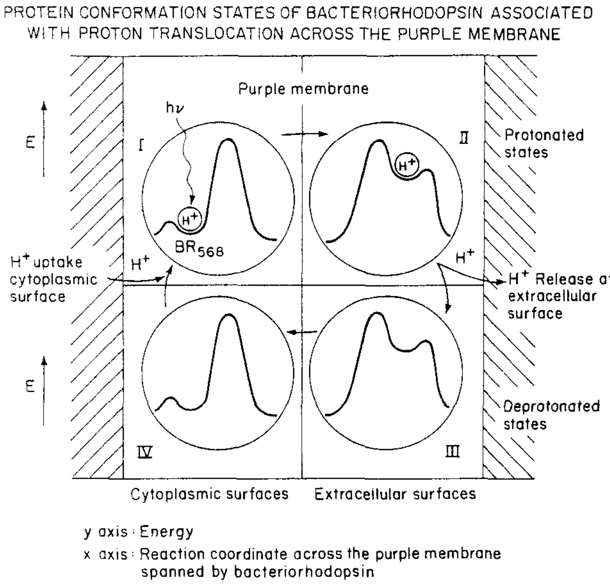

Fig. 1. Protein conformation states of bacteriorhodopsin associated with photon translocation across the purple membrane.

(XBL 8011-2373)

Lysine. Modification of up to 80% of the ε-amino groups of lysine, that is five of the six available lysine residues,[1] with imidoesters (methyl acetimidate, ethyl acetimidate and methyl butyrimidate) which introduce progressively more bulky groups onto the lysyl residues but leave the charge substantially unaltered, showed little effect on the rate of M_{412} formation and decay.[2] Similar results were obtained when the charge of the amino group was changed by the use of succinic or acetic anhydride, or pyridoxyl phosphate. These studies demonstrate that the ε-amino groups of lysine are probably not involved in a coordinated pathway of proton translocation by the protein.

However, lysine groups do play a structural role essential for activity. Using either dimethyl adipimidate (DMA) (8.3 Å) or glutaraldehyde (7.5 Å), bifunctional reagents which chemically cross-link lysyl residues, we found a very strong inhibition of M_{412} decay[3] and a decreased proton uptake in reconstituted liposomes. Cross-linking with longer chain bifunctional reagents (like dimethyl suberimidate (11.3 Å) of individual bacteriorhodopsin molecules to each other had no effect on activity. These effects suggest that intramolecular conformational changes and not protein-protein interactions in the membrane are essential for activity.

Arginine. With both 2,3-butanedione (BD) and phenylglyoxyl (PGO) treatments, similar effects were obtained for the modified purple membranes.[4] Modification of three of the seven arginine residues resulted in a 33- and 18-fold inhibition of the $t_{1/2}$ of the first and second phases of M_{412} decay, respectively, and a 19-fold increase in the amount of M_{412} stationary state when assayed at pH 8. These results indicate that the positive charges of the guanidinium groups of unmodified residues are essential for photocycling activity.

Modification of Negatively Charged Amino Acids

Glutamate and Aspartate. Water soluble carbodiimides cause the carboxyl groups of these amino acids to become either neutral or positive. These modifications slowed down the M_{412} decay; had no effect on its formation; and caused a large increase in its photostationary state.

In the presence of the added nucleophile, glycine methyl ester (GME), carbodiimide [1-ethyl-3-(3-dimethylaminopropyl) carbodiimide--EDC] treatment is expected to yield the amide adduct. With increasing concentrations of GME (1-250 m<u>M</u>), and in the presence of EDC, the degree of inhibition of M_{412} decay was partially decreased, suggesting that GME may be competing with a nucleophilic group on the protein. Evidence supporting this idea has come from double modification experiments. EDC-treated samples previously modified by ethyl acetimidate showed M_{412} decay kinetics similar to that observed in samples modified by EDC in the presence of high GME concentrations. The similarity suggests that EA-modified lysines have become unavailable for reaction with EDC, preventing the formation of intramolecular cross-links. Since EDC can only cross-link closely lying groups, we suspect that the ε-amino groups of lysine must be very close to the carboxyl groups.

Other important results of carbodiimide modification are the total disappearance of one of the photointermediates (O_{640}) in the photocycle and the inability to generate the acid stable form of the protein (with an absolute maximum at 605 nm). These results suggest that the protonation of one (or more) carboxyl residues is necessary for the generation of that photointermediate as well as for the acid stabilization of the protein.

Tyrosine. By investigating the time course of lactoperoxidase catalyzed iodination of purple membranes, we have been able to obtain evidence of an involvement of at least one tyrosyl residue in proton release and one or several tyrosyl residues involved in reprotonation.[5,6] Modification of one type of tyrosyl residue (localized on the cytoplasmic surface, according to modification studies done on intact cell envelope vesicles) markedly slows M_{412} decay but does not alter the optical and Raman spectral characteristics of the chromophore. Iodination of another tyrosyl residue alters the optical and Raman spectra of the chromophore and markedly stimulates M_{412} formation.

The modifications exhibit a strong effect on the pH-dependence of the photocycle, shifting the curve to lower pH values. This shifting suggests that the introduction of rather bulky groups onto the tyrosyl residues may alter the pK's and sterically effect their ability to take part in proton movements. What follows provides evidence for this explanation.

<u>Deuterium Isotope Effects</u>

In agreement with previous reports,[7] we find that the rise time of M_{412} is slowed by a factor of 4.7 in D_2O whereas the decay time is slowed by a factor of only 2.1. We have measured similar isotope effects for a number of chemically modified

Table 1. Kinetic parameters and isotope ratios for rise and decay of M_{412}.

Sample[c]	Rise[a] $t^H_{1/2}$	Rise[a] $t^D_{1/2}$	Rise[a] k^H_1/k^D_1	Decay[a] $t^H_{1/2}$	Decay[a] $t^D_{1/2}$	Decay[a] k^H_2/k^D_2
Control	0.069	0.33	4.76	3.65	7.7	2.11
EAC (Carboxyl)	0.099	0.42	4.24	90[b]	131[b]	1.45
I_2 (Tyrosine)	0.026	0.11	4.15	420[b]	1042	2.48
NBS (Tryptophan)	0.043	0.147	3.40	19.2	67.3[b]	3.5
DMA (Lysine)	0.072	0.35	4.86	33.0	46.2[b]	1.4
EA (Lysine)	0.062	0.32	4.9	10.8	27.4[b]	2.5
BD (Arginine)	0.096	0.49	5.1	359[b]	1055	2.9
PGO (Arginine)	0.142	0.71	5.0	355[b]	724[b]	2.0

[a]Half lives in milliseconds.

[b]Decay kinetics are biphasic, only slow phase given.

[c]Assay conditions: protein 0.15-0.30 mg/ml in 100 mM KCl and 5 mM phosphate; pH 7.5-8.0.

purple membranes. The similarity indicates that the basic mechanism remains similar in the modified samples (see Table 1). The activation parameters for the rates of rise and decay of M_{412} were determined from their temperature dependence.[8] For tyrosine modified samples, for example, the activation parameters are consistent with a decreased pK for a tyrosine residue (lowered E_a), an increased steric effect caused by iodine substitution (negative $S^{\dagger}$), and an overall decrease in the rate of reprotonation (increased $G^{\dagger}$) of the Schiff base. If the tyrosine residue is directly involved in the reprotonation of the Schiff base, the effect of its modification on the activation parameters is not surprising.

Light-Induced Surface Potential Changes of Purple Membranes

The positively charged paramagnetic amphiphile 4-(dodecyl dimethyl ammonium)-1-oxyl-2,2,6,6-tetramethyl piperidine bromide (CAT_{12}) partitions between the membrane and the aqueous phase. Therefore, CAT_{12} was useful in monitoring changes in surface potential associated with the release and uptake of protons from the purple membrane.[9] Using laser flash EPR and photolysis, we showed that the uptake and release of the CAT_{12} probe closely follows the kinetics of the rise and decay of the M_{412} intermediate.[10] This correlation indicated that the probe senses exposed negative charges at the surface from which protons are released. The number of light-induced surface charges per M_{412} in the photostationary state was calculated to be approximately 1. The value is more than 50% decreased for carboxyl and guanidinium group modification and for heavily modified tyrosine samples, suggesting that some of these groups may be located at the surface of the protein and may be involved in the uptake and release of protons from the aqueous environment.

Control of the Photocycle by the Transmembrane Potential Gradient

When reconstituted into liposomes, bacteriorhodopsin will generate light-induced electrochemical gradients across the lipid bilayer. Our reconstituted systems generate pH gradients of 0.6-1.0 and transmembrane electrical potentials of 60-80 mV.[11] The photostationary state of M_{412} at the same light intensity and protein concentration was much higher in the reconstituted system than in the isolated purple membranes. Valinomycin (0.5 μM) decreased the photostationary state of M_{412} by one order of magnitude in the reconstituted system but had no effect in isolated purple membranes. Nigericin (0.5 μM) had no effect on either system. Because we observed that, at the concentration used, Valinomycin collapses the transmembrane potential and Nigericin collapses the pH gradient, we assume that the electrical gradient was probably the major controlling factor on the kinetics of the photocycle.

Steady state, light-induced electrochemical gradients across bacteriorhodopsin containing liposomes showed a substantial slowdown of the M_{412} decay kinetics with virtually no effect on the rise kinetics. Again, Valinomycin, but not Nigericin, brought the decay kinetics of M_{412} to those measured in the absence of steady state illumination.

These responses suggest that within the protein, light may generate strong electric dipoles that could be very sensitive to the transmembrane electric potential gradients, which can be established across the bacterial membrane.

DISCUSSION

The sharp pH dependence seen in controls and the downward shift of the dependence in the rise and decay of the M_{412} species in tyrosine-modified purple membrane preparations suggests a direct involvement of reversible tyrosine protonation in the pathway of proton movement through bacteriorhodopsin (Fig. 2). Reversible dissociation of protons at both the outer and inner purple membrane surface would be expected to be pH- and pK-dependent, hence regulated by the electrochemical gradient. Since the pH gradients are small ($\leqslant 1$), pK effects on the photocycle are not to be expected, and indeed, we find that the main control parameter is the transmembrane potential.

Proton Uptake. Several structural requirements appear to be important for reprotonation of bacteriorhodopsin. Our results with modification of carboxyl and guanidinium groups suggest that a charge transfer complex essential for reprotonation may exist between the two types of groups. Moreover, the large changes in the entropy of activation for the M_{412} decay provides strong supporting evidence that interaction between these two types of groups is an essential structural feature involved in proton uptake and the photocycle's reprotonation phase. Furthermore, as judged by double modification experiments, an interaction between carboxyl groups and at least one amino group of lysine also appears to be important for reprotonation. The above structural requirements together with the inhibitory effects of bifunctional cross-linking reagents which restrain motion of intramolecular amino groups of lysine located within 8.3 Å of one another suggests that protein conformational changes are essential to proton uptake and M_{412} reprotonation. Tyrosine may also act as a donor for Schiff base reprotonation.

Proton Release. The specific groups involved in release of protons at the outer surface of the purple membrane probably include tyrosine residues; this conclusion is drawn from the observed effects of iodination and nitration[12] that shift the dissociation pK of the phenolic hydroxyl group of tyrosine residues. The pK shift may accelerate proton movement from this group on the tyrosine to a nearby basic group which may be water, OH-, a group on the lipid of the purple membrane, or a buffer anion. The acceleration would be expected to occur in the range where proton release is pH dependent. Based on the pronounced deuterium isotope effect on proton release as seen before and after iodination of tyrosine, it can also be argued that the tyrosine residues are involved in the early stages of the photocycle, i.e., those associated with the proton release.

Carboxyl groups may also play a role in the movement of protons; modification of these groups has inhibited the generation of one of the intermediates in the photocycle and the formation of an acid-stable species.

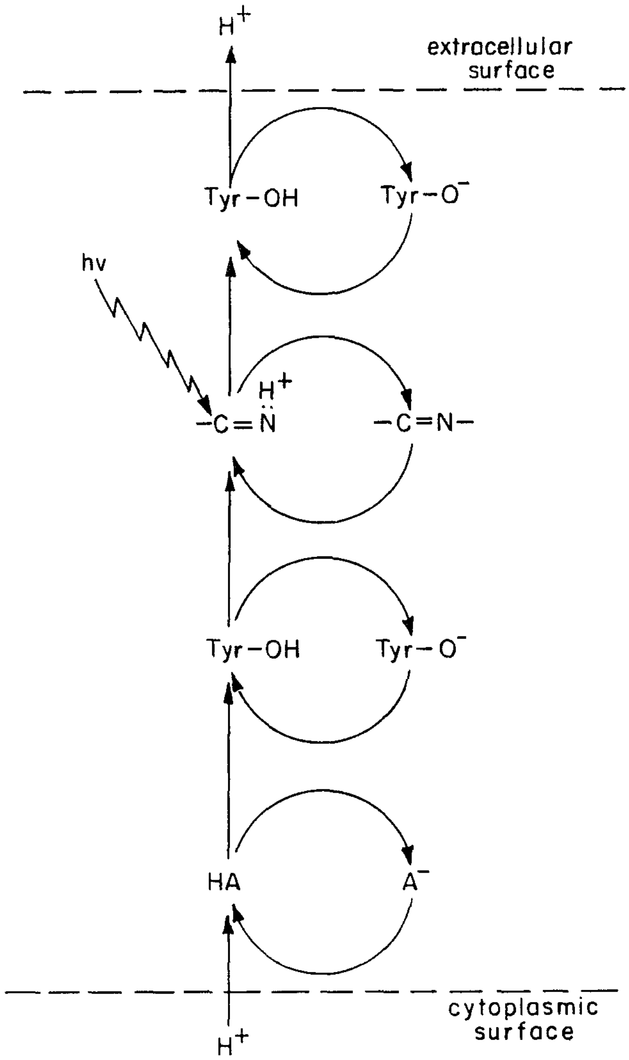

Fig. 2. A proposed pathway for uptake and release of protons by bacteriorhodopsin. We include on the pathway the reversible deprotonation of the tyrosine residues before and after the Schiff base. (XBL 805-5111)

Light-induced changes in the surface potential of the purple membrane suggest that protons are released from protonated groups at the surface, because these surface potential changes are closely coupled to the formation of the M_{412} species. Our experiments provide evidence that the groups involved may be carboxyl and tyrosyl residues.

PLANNED ACTIVITIES FOR FY 1981

Our studies of the molecular architecture of bacteriorhodopsin in relation to its energy conversion activity have been particularly fruitful in revealing that certain amino acid structural relationships and certain amino acid side chains play an essential role in the light-driven release and uptake of protons. We wish to arrive at a more fundamental understanding of the molecular basis for this activity.

Our research next year will take advantage of a spectacular new development: the discovery by Professor Y. Mukohata of Osaka, Japan of a mutant species of Halobacteria, which forms a "white membrane." The white membrane is an aggregate of protein and lipid molecules which can be recognized by electron microscopy as a patch in the plane of halobacterial membranes. This patch totally lacks retinal but apparently contains the apoprotein portion of bacteriorhodopsin, because a native purple membrane can be formed by the addition of all-trans retinal. Procedures have been developed for the isolation and purification of this patch, which is clearly the material par excellence for chemical modification studies designed to inform us about the importance of the protein structure and about different types of retinal analogues in the energy conversion process. We are the only laboratory in the U.S. that has been given this strain. Professor Mukohata, the discoverer, has spent three months on an NSF U.S.-Japan Cooperative Program, working with us to develop the methods of cultivating the organisms and preparing the white membranes. We intend to pursue studies using and comparing this material with native purple membranes.

Our research will also exploit the ability to modify groups in purple membranes in the dark and in the light. We have made some preliminary discoveries indicating that the ability to gain accessibility with external chemical modifying reagents to different groups differs in the dark and the light. Certain groups are available for reaction only in the light, such as the tyrosine groups, which are available for modification using nitration reagents. To better understand the protein conformational cycle driven by light energy absorbed by the retinal chromophore, we will perform chemical modifications in the white membrane and in regenerated purple membranes, both in the dark and during illumination, to determine the degree to which activity is affected after the specific modifications. These studies indicate the groups that become exposed and the part of the photocycle in which they will appear. Knowing the deuterium isotope effects, we ought to arrive at a better understanding of which groups play an essential role in the proton translocation, proton uptake and proton release process, all of which are aspects of the overall ability of this retinal protein system in bacterial membranes to generate a proton electrochemical gradient after absorption of a photon of 570 nm light.

REFERENCES

1. W. Stoeckenius and R. Lozier, "Light Energy Conversion in Halobacterium halobium," Journal of Supramolecular Structures, vol. 2, 1974, pp. 769-774.
2. T. Konishi, S. Tristram, and L. Packer, "The Effect of Crosslinking on Photocycling Activity of Bacteriorhodopsin," Photochemistry and Photobiology, vol. 29, 1979, pp. 353-358.
3. T. Konishi and L. Packer, "Light-Dark Conformational States in Bacteriorhodopsin," Biochemical Biophysical Research Communications, vol. 72, 1976, pp. 1437-1441.
4. L. Packer, S. Tristram, J. Herz, C. Russell, and C. Borders, "Chemical Modification of Purple Membranes: Role of Arginine and Carboxylic Acid Residues in Bacteriorhodopsin," Federation of European Biochemical Societies Letters, vol. 108, 1979, pp. 243-248.
5. P. Scherrer, C. Carmeli, P. Shieh, and L. Packer, "The Effect of Chemical Modification of Tyrosyl Residues on Proton Conductivity Mediated by Bacteriorhodopsin," Biophysical Journal, vol. 25, 1979, p. 207a.
6. P. Scherrer, L. Packer, S. Seltzer, and M. Lin, "Involvement of Tyrosine Residues in Bacteriorhodopsin Activity," submitted for publication.
7. R. Korenstein, W. Sherman, and R. Caplan, "Kinetic Isotope Effects in the Photochemical Cycle of Bacteriorhodopsin," Biophysics of Structure and Mechanism, vol. 2, 1976, pp. 267-276.
8. P. Sullivan, A. Quintanilha, S. Tristram, and L. Packer, "Isotope Effects and Activation Parameters for Chemically Modified Bacteriorhodopsin," Federation of European Biochemical Societies Letters, vol. 117, 1980, pp. 359-362.
9. C. Carmeli, A. Quintanilha, and L. Packer, "Light-Induced Surface Potential Changes in Purple Membranes and Bacteriorhodopsin Liposomes," in C. P. Lee et al., eds. Membrane Bioenergetics, (Reading, Mass: Addison Wesley Publishing Co., 1980) pp. 547-558.
10. C. Carmeli, A. Quintanilha, and L. Packer, "Surface Charge Changes in Purple Membranes and the Photoreaction Cycle of Bacteriorhodopsin," Procedures of the National Academy of Sciences (U.S.A.), vol. 77, 1980, pp. 4707-4711.
11. A. Quintanilha, "Control of the Photocycle in Bacteriorhodopsin by Electrochemical Gradients." Federation of European Biochemical Societies Letters, vol. 117, 1980, pp. 8-12.
12. M. Campos-Cavieres, T. Moore, and R. Perham, "Effect of Modification of the Tyrosine Residues of Bacteriorhodopsin with Tetranitromethane." Biochemical Journal, vol. 179, 1979, pp. 233-238.

EXPERIMENTAL AND THEORETICAL EVALUATION OF CONTROL STRATEGIES FOR ACTIVE SOLAR ENERGY SYSTEMS*

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INTRODUCTION

Improved solar energy control systems will reduce the use of nonrenewable fuel sources for heating building spaces and domestic hot water. To accelerate this reduction, an experimental test facility has been constructed at LBL to test the system efficiency and cost effectiveness of alternative control strategies for collecting solar energy and delivering it to the building load. In parallel with this experimental effort, a computer analysis capability has been developed to study the dynamics of interactions between collector, load, and control system, and an investigation has been initiated into control-related reliability problems of installed solar-heating and solar-cooling systems. LBL has also provided technical support to DOE in the controls area, including program planning and monitoring of outside contractors.

ACCOMPLISHMENTS IN FY 1980

Experimental Test Facility.

The experimental test facility was constructed to evaluate the operation and performance of active hydronic solar energy system control strategies and equipment. The facility, shown in Figure 1, consists of a collector loop heat-input simulator, a storage tank, a load loop air channel with fan coil, an auxiliary heater, and associated pumps and valves. Only the apparent temperature of the collector and the load demand thermostat condition are simulated, enabling control strategy and equipment comparisons based on identical meteorological and load conditions. The facility is described in detail elsewhere.[1,2,3]

This year the experimental test facility was operated to simulate a specific residential solar-assisted heating system for several days, using both simulated weather and typical meteorological year (TMY) weather and insolation data for Madison, Wis. in January. The residential building loads and incident insolation are calculated using TRNSYS† and are used as inputs to drive the experimental system simulation. Early in the year a number of four-hour and one-day experiments were repeated to verify operation and energy balance of the collector loop and of the load loop separately. At the end of the year, a number of two-day experiments using TMY data were run.

Test Facility Improvements

Several improvements and modifications have been made to the test facility during FY 1980.

The storage tank was drained to a level of approximately 1,000 gal to accommodate a design solar fraction of 50% for Madison. Seven equally spaced thermocouples were installed in the storage tank to measure the temperature profile. Because of the finite number of thermocouples in the storage tank, the measured energy storage can vary typically ±5 MJ from hour to hour when there is a sharp gradient in the storage tank temperature. With the reduced storage tank volume, it was found that air was drawn into the collector and load loop piping causing minimal or no flow during start-up conditions. Several valves were moved and piping rearranged to correct the problem. Similar problems have been encountered in a number of installations, stressing the importance of correct placement of pumps and valves.

The test facility control software was rewritten to utilize hourly weather and building load data and quarter-hour insolation values, which can be inputed before an experiment. Another routine was written, in conjunction with the addition of some electronic hardware, to record the energy consumption from the electricity and gas meters. To predict more accurately the collector temperature, a simple one-node collector capacitance model was implemented for the stagnating collector simulation, thereby modeling more realistically the on/off cycling of the collector loop.

Experiments were conducted to determine system energy losses and the collector and load loop energy balances. Energy losses for each subsystem (storage tank, collector loop, and load loop) were determined observing the decay in storage tank temperature over several days with zero load or energy input.

Residential System Description

The building chosen for simulation, the weather data, and the residential heating load model are taken from the "Standard Assumptions and Methods" recommended by the Solar Energy Research Institute (SERI).[4] A typical, well-insulated 1,700 ft^2 single-story home located in Madison, Wis. was chosen for study. Meteorological data from TMY tapes combined with detailed building description determined the hourly heating requirements for the building for use in the test facility load loop. Hourly heating loads were calculated using the TRNSYS residential load model, TYPE 29. Quarter-

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† TRNSYS is a transient system simulation computer program developed at the University of Wisconsin and consists of a central algebraic and differential equation solver, a library of component models and associated input and output routines.

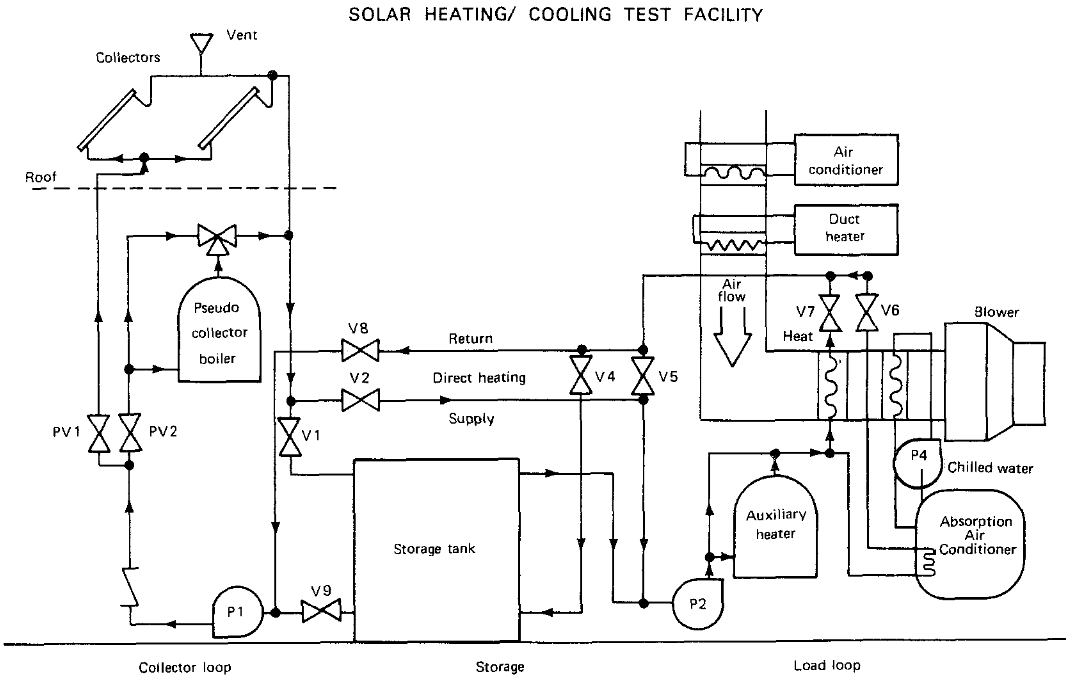

Fig. 1. Solar heating and cooling test facility. (XBL 794-1511)

hour insolation values incident in the plane of the collectors were calculated from TMY January data for Madison, Wis. using the TRNSYS solar radiation processor.

The components of the active solar system were sized using F-Chart 3.0. To provide a 50% annual solar heating fraction required a collector array of 50 m^2 and a water storage volume of about 3,800 liters (1000 gal).

The experimental procedure using the test facility is to test a particular control strategy during several "typical days" and then extrapolate results to determine long-term performance characteristics. The performance of a solar system during a particular day is dependent on the insolation, ambient temperature (which determines collector losses and building load), and the system's performance during the previous day. To evaluate the utilization of energy collected on a particular day, it is important to consider what the energy use is on the day following as well. Thus the minimum time required for a proper evaluation is two days, with the temperature of the storage tank on the first day indicative of the past day's operation.

The weather and insolation patterns for January in Madison were examined along with hourly storage tank temperatures predicted by TRNSYS for January to determine which days were appropriate for simulation. Based on the quantification of January days into categories, such as high amount of insolation, low ambient temperatures, and poor previous day, two pairs of days were chosen for detailed test facility simulation: a "bad-good" series (January 26-27) and a "good-bad" series (January 18-19).

Performance indicators recommended by Ward[5] are used for evaluating solar systems. These include collection efficiency, system thermal efficiency, solar coefficient of performance, system overall efficiency, and solar fraction. An additional performance indicator, storage tank temperature change, indicates the extent to which available solar energy is taken from, or added to, the storage tank over a given period.

Test Facility Results

Experiments were run using simulated meteorological and load inputs to evaluate experimental repeatability and to verify system energy balances. Experiments also compared two control strategies: a storage-coupled heating mode and a direct collector-to-load heating mode. In the more typical mode of operation, storage-coupled heating, collectors heat the storage tank and energy is drawn from storage to heat the load when energy is available and needed. With the direct-heating mode, the collectors can supply heat to the load without going through the storage tank. The direct-heat mode requires additional piping, valves, and control.

Tables 1 and 2 show results from test facility experiments. The quantities used in the tables are defined as follows: building load (QLOAD), auxiliary energy for load (QAUX), the natural gas usage (GAS), solar energy delivered to the load (QSOLARLOAD), insolation of the collector (QI), collected energy (QC), storage tank losses (SLOSS), load loop piping losses (LLOSS), collector loop piping losses (CLOSS), parasitic energy used (PARA), average storage tank temperature (T_{tank}), stored energy (QS), and change in stored energy (DQS).

Table 1 shows typical four-hour summaries of a 24-hour experiment for a cold January day in Madison with good insolation. The 24-hour system

Table 1. Typical four-hour summary results from a Direct Heating Test Facility Run. Simulation is of 18 January (TMY) in Madison, Wisc., a cold weather day with good insolation.

Time (hr)	T_{amb} (°C)	T_{tank}[QS] (°C) (MJ)	QLOAD (MJ)	SLOSS (MJ)	LLOSS (MJ)	QAUX (MJ)	QI (MJ)	QC (MJ)	CLOSS (MJ)	PARA (MJ)	GAS (MJ)
0	-5.4	31.5[209.6]	-	-	-	-	-	-	-	-	-
4	-8.8	30.7	86.9	2.9	4.7	72.2	0	0	0	4.5	176
8	-11.7	29.6	95.8	2.3	3.7	75.9	2.7	0	0	4.9	216
12	-9.8	36.6	83.1	3.6	5.8	45.5	416.0	191.1	4.6	7.8	89
16	-9.7	42.3	66.9	7.1	9.1	8.6	405.7	197.6	7.2	6.7	16
20	-14.1	37.5	85.8	6.7	8.7	11.7	6.6	0	0	3.0	16
24	-13.1	33.3[242.4]	99.4	4.8	6.5	34.1	0	0	0	4.0	81
Totals	-	+1.8[32.8]	517.9	27.4	38.5	248.0	831.0	388.7	11.8	30.9	594

Notes:

Qin = QC + QAUX - DQS = 388.7 + 248 - 32.8 = 603.9 MJ

Qout = CLOSS + LLOSS + SLOSS + QLOAD = 11.8 + 38.5 + 27.4 + 517.9 = 595.6 MJ

24-hour balance 2(Qin - Qout)/(Qin+Qout) = 8.3 MJ/599.8 MJ = 0.0138

QSOLAR-LOAD = QLOAD + LLOSS - QAUX = 517.9 + 38.5 - 248.0 = 308.4 MJ

Quantities in brackets represent storage energy QS and change in storage energy DQS.

energy balance is within 2%, indicating good accounting of energy flows in the collector and load loops and in the storage tank. This energy accounting is done minute by minute as the experiment progresses and is summarized on a floppy disk file after each thermostat cycle and at one- and four-hour intervals. A detailed record of the experiment is also printed out. Energy flow quantities are calculated from measured temperatures and flow rates. Energy losses are calculated from measured fluid and room temperatures and experimentally estimated loss coefficients. The parasitic and auxiliary gas consumption are measured with standard utility meters interfaced to the experiment instrumentation. The solar energy delivered to the load, QSOLAR-LOAD, includes the heat from the fan coil, QLOAD, less the auxiliary input, QAUX, and takes credit for heat lost from the load loop piping, LLOSS. The allocation of useful heating from the storage and load loop losses depends on the specific system layout.

Test days were run twice for each of two different control strategies: direct heating and storage-coupled heating. Table 2 shows the one-day energy balance totals for the different runs of the same day. The different runs show excellent agreement in the load demand, QLOAD, the total energy inputs to the system, Q_{in}, the total energy output from the system, Q_{out}, and the energy balance, ΔQ. The energy loss terms, SLOSS, LLOSS, and CLOSS also agree well from run to run. However, there is some variation from run to run in the auxiliary energy usage, QAUX, in the change in stored energy, DQS, and in the contribution to the load from solar, QSOLAR-LOAD. This variation is of the order of 25 MJ over the day and represents less than 5% of the total energy flow during the day, which was the accuracy goal for measuring energy flows in the test facility.

Comparison of Test Facility Results with TRNSYS

To assist in evaluating the results obtained from the test facility, TRNSYS simulations are conducted for the same test days. Typical simulation results are also shown on Table 2. The TRNSYS program's format allows the simulation of the test facility system using identical meteorological and load inputs as well as approximately the same component parameters and interconnections. The TRNSYS simulation was started on January 1 at 1 a.m., using TMY weather data, with a storage tank temperature of 20°C, and run continuously for the entire month. Initial average storage tank temperatures and time-dependent building loads, as determined by TRNSYS for a given period, were then used for the experiments.

The test facility operating strategy has an auxiliary boost mode where the auxiliary heater increases the temperature of the water to the fan coil as long as the return water temperature is not greater than the storage tank bottom temperature. Existing TRNSYS parallel and series auxiliary heating modes do not model this operation. The parallel mode draws the storage tank down to room temperature unrealistically, thus underestimating the auxiliary energy consumption. The series auxiliary heating mode of TRNSYS draws the storage tank temperature down until the storage can no longer satisfy the building heating requirements. It then switches to an auxiliary only mode. This more nearly approximates typical control action and is used to model the test facility. For identical conditions in Madison, the TRNSYS parallel auxiliary mode used only 9,424 MJ of auxiliary energy while the TRNSYS series auxiliary mode required 11,060 MJ of auxiliary energy to meet the January heating load.

Table 2. Comparison of Test Facility Runs with TRNSYS Simulation for January 18 in Madison, Wisc., a cold weather day with good insolation.

Quantity	Units	Run 7	Run 11	Run 8	Run 12	TRNSYS
Strategy	-	Direct	Direct	Storage	Storage	Series
Time	hr	0-24	0-24	0-24	0-24	408-432
$Tamb_{avg}$	^oC	-10	-10	-10	-10	-10
Initial T_{tank}	^oC	31.1	31.5	31.1	31.6	31.2
Final T_{tank}	^oC	32.5	33.3	32.3	32.4	36.4
Change T_{tank}	^oC	1.4	1.8	1.2	0.8	5.2
DQStank	MJ	24.7	32.8	21.0	14.6	94.7
SLOSS	MJ	27.6	27.4	27.4	25.6	35.4
QLOAD	MJ	517.8	517.9	517.9	517.3	514.6
LLOSS	MJ	38.6	38.5	36.0	32.1	24.2
QAUX	MJ	234.5	248.0	230.5	204.9	268.3
QI	MJ	831.0	831.0	832.1	831.5	831.4
QC_{th}	MJ	410.7	401.1	424.0	428.5	421.8
QC	MJ	390.7	388.7	386.8	412.5	421.9
CLOSS	MJ	12.4	11.8	11.8	11.2	15.6
PARA	MJ	32.7	30.9	33.4	31.9	-
Qin	MJ	600.5	603.9	596.3	602.8	595.5
Qout	MJ	596.4	595.6	593.1	586.2	589.8
Balance (ΔQ)	MJ	4.1	8.3	3.2	16.6	5.7
Balance (%)	-	0.7	1.4	0.5	2.8	0.97
QSOLAR-LOAD	MJ	321.9	308.4	323.4	344.5	270.5
Solar to load	%	62	60	62	67	53

Table 2 compares energy flows predicted by TRNSYS with the direct-heating and the storage-coupled heating modes run on the test facility. The solar energy collected, (QCth), as predicted by the test facility simulation Hottel-Whillier-Bliss collector model, agrees well with the TRNSYS simulation for clear days with good insolation, although in the direct-heating mode the collector loop tends to be on for a slightly shorter time. For both modes, the pseudocollector boiler system delivers slightly less energy (QC) than predicted. This may be due to a limitation in the boiler output control.

Differences between the TRNSYS simulation and the test facility direct and storage strategies are also indicated in Table 2 by the change in stored energy, the load loop piping losses, and the load handled by either solar or auxiliary energy. As expected, the test facility boost mode of operation increases the system performance slightly by using the stored solar energy at slightly lower temperatures.

The energy input to the system for the TRNSYS and test facility runs, Q_{in}, (energy from the collectors, from auxiliary, and from storage) agrees very well, as does the energy output, Q_{out} (energy to the load and all losses). The overall energy balance is quite good for all of the 24-hour runs.

Table 3. Comparison of two-day runs on test facility for direct heating and storage coupled heating modes for identical building load and meteorological conditions (January 18-19 in Madison, Wisc.). TRNSYS simulation results are also shown for comparison.

	Quantity	Direct Run 7	Direct Run 11	Storage Run 8	Storage Run 12	TRNSYS System 3
QC/QI	Collection efficiency	35.5	36.3	37.7	40.3	43.4
$\frac{QSOLAR-LOAD}{QI}$	Thermal efficiency	39.0	42.0	42.0	46.1	37.6
$\frac{QSOLAR-LOAD}{PARA}$	SCOP	7.3	8.3	7.4	8.8	-
$\frac{QSOLAR-LOAD}{QLOAD}$	Solar fraction	45.3	48.7	48.8	53.5	43.4
ΔT_{tank}	Storage temperature change (°C)	-4.8	-6.4	-5.4	-7.2	-1.0

The only significant discrepancy is the solar contribution to the load, which varied an average of about 10%. Parasitic energy for the control valves, pumps, and fans is not accounted for in the TRNSYS simulation.

Comparison of Storage Coupled and Direct Heating

A series of experiments were conducted using both direct heating and storage-coupled heating modes using real weather and insolation data for two January days in Madison. Table 3 indicates the difference in the performance between the two strategies for these two days through some performance indicators. Collection efficiency is the ratio of the energy collected by the collectors to the insolation on the collectors. Thermal efficiency is the ratio of solar energy utilized by the load to insolation incident on the collectors. Solar coefficient of performance is the ratio of the solar energy utilized by the load to the parasitic energy required to run the solar system. Solar fraction is the ratio of the solar energy utilized by the load to the total load. As indicated in the table, no significant difference exists between the control strategies for these days although the direct heating loop strategy does seem slightly better. Both modes of test facility operation utilize greater energy from storage than predicted by the TRNSYS simulation, as indicated by the storage tank temperature change. To determine long-term comparisons, more testing would be required.

Theoretical Studies to Support Experimental Program

Study Of Collector Loop Dynamics

During FY 1980, work was completed on modeling of collector loop dynamics,[6,7] and a report was prepared for publication.[8] Since the temperature drop encountered in the collector loop piping could affect the control set points, a set of curves were developed describing the predicted temperature drops to be expected in piping runs, as shown in Figure 2. These curves indicate that typical systems with properly insulated piping will have a minimal temperature drop across the piping runs and thus should not affect the control set points.

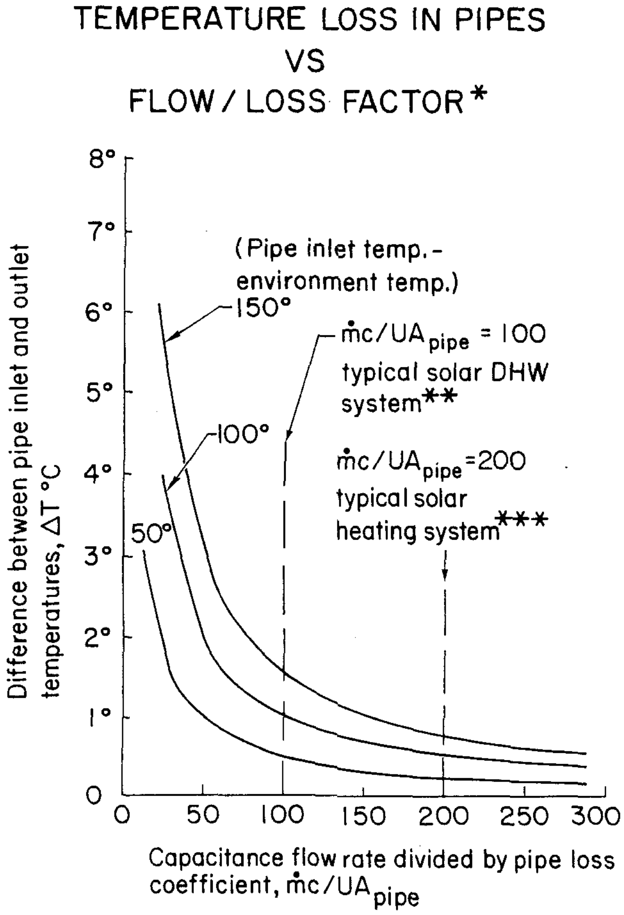

Fig. 2. Temperature loss in pipes versus flow/loss factor. * Temperature loss based on: $\dot{m}c\,(T_{in} - T_{out}) = U_{pipe}L_{pipe}[(T_{in} + T_{out})/2 - T_a]$, where U_{pipe} is the heat loss per unit length. $U_{pipe} = 0.6$ W/m-°C. $\dot{m}c/A_c \approx 90$ W/m²-°C where A_c is the collector area.
** Typical hot water system:
$A_c = 5$ m²; $L_{pipe} = 7.5$ m. $\dot{m}c/U_{pipe}L_{pipe} = 100$.
*** Typical heating system:
$A_c = 50$ m²; $L_{pipe} = 37.5$ m. $\dot{m}c/U_{pipe}L_{pipe} = 200$.
(XBL 806-7161)

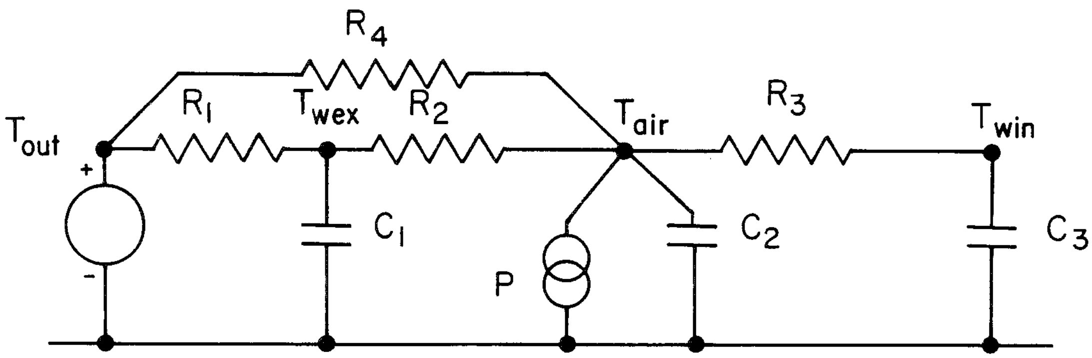

Fig. 3. The dynamic building model uses three resistance-capacitance nodes to represent the temperatures of the interior and exterior walls and room air. The heat input to the air is represented as a thermal current source, P.

(XBL 8011-2406)

Study Of Building Load Dynamics

A model of a residential building, a fan coil heat-delivery system, and a bimetal thermostat, developed previously[9] (to simulate the effects of heat input on room air dynamics) has been applied to examine the building thermal behavior in response to heat input from an active solar space-heating system.[10] The effects of the variable storage tank temperature, of outdoor temperatures, and of fan coil sizes on the cycling rate, on the on-time and off-time of a heating cycle, on room air temperature swing, and on offset of the average air temperature from the setpoint (droop) are determined by computer simulation. Heat input is provided directly to the air as, for example, when a heating fan coil is turned on. The three nodes shown in Figure 3 represent the temperature of the interior surface of the exterior wall, Twex(t); the temperature of the air in the space, Tair(t); and the temperature of the interior wall, Twin(t). The equations for the temperatures are determined from the resistance-capacitance network, using Kirchhoff analysis. The values of the thermal resistances R_1, R_2, R_3, and R_4 and the thermal capacitances C_1, C_2, and C_3 are typical of a well-insulated, single-zone building.

For given conditions of outdoor temperature, anticipation, and thermostat setpoints, the storage tank temperature has a direct effect on swing as shown in Figure 4. The droop, the offset of average room temperature from the setpoint, also depends on the amount of thermostat anticipation and on the heat-delivery duty cycle. The higher the storage tank temperature, the larger is the swing in room temperature and the smaller is the offset of the average air temperature from the setpoint (droop). Results indicate that to maintain room temperatures within comfort limits by minimizing both swing and droop, a hydronic solar space-heating system requires a control system that adjusts anticipation and setpoints in relation to the outdoor and the storage tank temperatures. This will require more than a simple on-off bimetal thermostat.

Reliability and Maintainability of Controls for Active Solar Energy Systems

Although a majority of the systems installed in this country effectively collect the sun's energy, systems that fail because of faulty controls have damaged the reputation of active solar energy systems. Low efficiency, improper operating modes, high auxiliary energy usage, and equipment damage can result from control or system failures caused by poor design and installation practices, defective components, and improper strategies. An

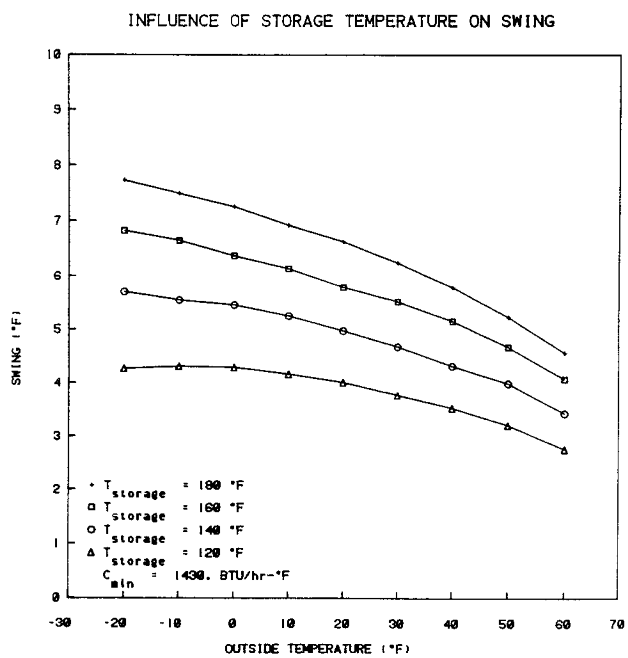

Fig. 4. Storage tank temperature influences room air temperature swing. As the storage tank temperature decreases, the swing decreases for a given outside temperature.

(XBL 8011-7564)

investigation of these failures has been initiated to determine what is needed to improve the effectiveness and reliability of solar control systems.

A preliminary review of the literature on the performance of solar control systems indicated several areas where further investigation can be very beneficial: freeze protection, fault-detection systems, effects of flow rates and set points on system performance, and the interaction of components as a system. Since failures of the freeze protection system can be both costly and destructive, an evaluation of freeze protection techniques is given the highest priority.

Technical Support Activities

This past year the laboratory has been actively involved in proposal review and contract monitoring for the Controls Element of the DOE solar heating and cooling Research and Development program. Activities have included coordination with the Solar Energy Research Institute, conducting project reviews, and reviewing the reports of DOE controls contractors. LBL served as host to a project review for the solar controls work at Drexel University and Middlebury College. We also prepared an overview of the controls program in collaboration with SERI.[11]

PLANNED ACTIVITIES FOR FY 1981

The experimental test facility work is being interrupted and probably terminated. The analysis capabilities are being transferred to provide needed assistance to the Active Solar Cooling program. The emphasis of the remaining controls work is on investigating and solving reliability and maintainability problems.

REFERENCES

1. M. L. Warren, S. R. Schiller, and M. Wahlig, "Experimental Test Facility for Evaluation of Controls and Control Strategies," Second Annual Systems Simulation and Economic Analysis Conference, January 23-25, 1980, San Diego, Calif.; Lawrence Berkeley Laboratory report LBL-10352, January 1980.

2. M. L. Warren, S. R. Schiller, and M. Wahlig, "Evaluation of Proportional and On/Off Control for Solar Collector Loops," Paper 162 (EM-2-3), Proceedings of the American Section of the International Solar Energy Society Annual Meeting, June 2-6, 1980, Phoenix, Ariz.; Lawrence Berkeley Laboratory report LBL-10716, June 1980.

3. M. L. Warren, S. R. Schiller, and M. Wahlig, "Controls for Solar Heating and Cooling," Proceedings of the Annual Department of Energy Active Solar Heating and Cooling Contractors' Meeting, March 26-28, 1980; Lawrence Berkeley Laboratory report LBL-10779. April 1980.

4. C. Leboeuf, "Standard Assumptions and Methods for Solar Heating and Cooling Systems Analysis," Solar Energy Research Institute Report SERI/TR-351-402, Golden, Colo., January 1980.

5. D. S. Ward, "Performance Evaluation Criteria," Proceedings of Operational Results Conference, November 27-30, 1979, Colorado Springs, Colo.

6. S. R. Schiller, M. L. Warren, and D. M. Auslander, "Comparison of Proportional and On/Off Collector Loop Control Strategies Using a Dynamic Collector Model," Second Annual Systems Simulation and Economics Analysis Conference, January 23-25, 1980, San Diego, Calif.; Lawrence Berkeley Laboratory report LBL-10347, January 1980.

7. S. R. Schiller, M. L. Warren, and M. Wahlig, Dynamic Modeling and Experimental Simulation of Active Solar Energy Systems, American Society of Mechanical Engineers report ASME-80-WA/Sol-14; Lawrence Berkeley Laboratory report LBL-10825, July 1980.

8. S. R. Schiller, M. L. Warren and D. M. Auslander, "Comparison of Proportional and On/off Solar Collector Loop Control Strategies Using a Dynamic Collector Model," Transactions of the American Society of Mechanical Engineers, Journal of Solar Energy Engineering, vol. 102, no. 4, November 1980, pp. 256-262; Lawrence Berkeley Laboratory report LBL-10315R, July 1980.

9. M. L. Warren, A. F. Sakkal, and S. R. Schiller, Predicting the Time Response of a Building Under Heat Input Conditions for Active Solar Heating Systems, Lawrence Berkeley Laboratory report LBL-10360, January 1980.

10. C. Vilmer, M. L. Warren, and D. Auslander, Interaction of Solar Space Heating System with the Thermal Behavior of a Building, Lawrence Berkeley Laboratory report LBL-11673, October 1980.

11. L. Groome and M. L. Warren, "Overview of the Solar Controls Program," Proceedings of the Annual Department of Energy (DOE) Active Solar Heating and Cooling Contractors' Meeting, March 26-28, 1980; Lawrence Berkeley Laboratory report LBL-10780. April 1980.

ACTIVE SOLAR COOLING*

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INTRODUCTION

This project includes both inhouse research and development (R&D) activities and technical support activities for the active cooling program. The inhouse R&D activity includes the development of improved absorption-cycle systems for active solar cooling and heating applications. The objective is to achieve a significantly higher conversion efficiency than is possible using other cooling approaches. A secondary objective is to avoid the necessity for water cooling towers by using air-cooled condensers and absorbers.

The quest for higher conversion efficiencies is consistent with the overall national solar cooling program goal of achieving cost-effective solar cooling systems. The major cost component of a solar cooling system is the collectors; the collector area required to satisfy a given load can be reduced (lowering costs) as the efficiency of the chiller component is increased.

An absorption-cycle chiller is essentially a heat pump and, accordingly, can be used for heating as well as cooling as long as the refrigerant fluid does not freeze in the outdoor coil during heating applications. Thus an absorption chiller using the ammonia/water pair (ammonia as the refrigerant, water as the absorbent) can be used for heating as well as cooling, but one using the water/lithium bromide pair can be used only for cooling because the water in the outdoor coils would freeze in heating applications.

In accordance with these considerations, a phased plan has been devised to develop an advanced high-efficiency absorption chiller that is far beyond today's state-of-the-art. This is to be achieved through the design, fabrication, testing, and evaluation of a series of incrementally improved absorption chillers.

The first phase of this project consisted of the partial reconstruction for solar-powered operation of a conventional gas-fired ammonia/water absorption chiller. This phase was successfully completed some time ago,[1] and it 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 operation. (Single-effect cycles employ only one boiler.)

The second phase includes the design and fabrication of a single-effect ammonia/water absorption chiller that incorporates several unique design features: tube-in-tube heat exchangers for high effectiveness at reasonable cost and a pair of internally powered solution pumps for reduced parasitic power use. This chiller, which represents the starting point for the development of the higher efficiency units in subsequent phases, is currently in the test and evaluation stage.

The third phase of the project is the development of an advanced higher efficiency cycle, a double-effect regenerative cycle (which we call cycle 2R) that adds a unique second stage to the chiller developed in phase two. With the addition of this second stage, the overall chiller efficiency increases continuously as a function of the inlet temperature from the solar collectors. The basic concept of this 2R cycle was described some time ago.[2] Since then the design has been completed, and fabrication has started.

The fourth phase takes advantage of the experience gained in previous phases to develop a still higher efficiency chiller, yet one with less hardware and thus with the potential for lower cost. This chiller is based on a single-effect regenerative cycle (which we call cycle 1R). Although the basic concept has been described by our group previously,[3] this chiller is still in an early design stage. The success of the cycle 1R chiller depends on our experience gained from developing the cycle 2R chiller and on locating a refrigerant/absorbent fluid pair with suitable properties at the higher boiling temperatures where ammonia/water performance drops off.

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 Applications for Buildings. 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.

ACCOMPLISHMENTS DURING FY 1980

Absorption Air Conditioner Development

A major effort during FY 1980 has been the testing of the single-effect absorption chiller. Most of this effort has been expended on a single component: the solution circulation pump.

The development of the pump is critical to the viability of the single-effect chiller as a solar cooling machine. Conceived to operate at fairly low input temperatures (about 215°F), the single-effect chiller requires large circulation flow rates (of the order of two and one-half gallons of

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Solar Applications for Buildings, Active Heating and Cooling Division of the U.S. Department of Energy under Contract W-7405-ENG-48.

ammonia-water solution per minute for a three-ton chiller). If a conventional electric diaphragm pump were used, the electric power required (about 3/4 hp) would render the chiller economically unacceptable. A piston circulation pump (called the recuperative pump) was therefore designed to recuperate 70% of the pumping power from the weak solution stream, thus reducing to 1/4 hp the external power required. A second piston pump (called the makeup pump), driven by high-pressure vapor, was designed to run in parallel with the first pump, thus eliminating altogether the requirement for any external electric power for pumping the strong solution.

We have had only limited success in developing these pumps during FY 1980. Extensive testing of the pumps using high-pressure air or nitrogen and water has shown that the pumps performed very well on the test bench. But when the pumps were connected to the chiller, mutual interactions prevented proper pump operation. The nature of the interactions is only partially understood. Pressure drops and water-hammer effects in the long lines of the chiller were some of the causes for interference with the switching of the pump valves. Valve redesign and proper choice for the location of the pilot pressure taps have eliminated these problems. Dirt in the chiller was another problem that caused valve sticking. This problem has not been eliminated yet because of difficulty in cleaning the chiller. Valve redesign using bellows may be the answer. Ammonia vapor absorption by the liquid ever present in the makeup pump switching lines may be the most difficult problem to overcome.

The status of the pumps' development as of the end of FY 1980 is: (1) the recuperative pump can be made to operate very reliably with the chiller; and (2) the success of the vapor makeup pump is in doubt, and a small electric makeup pump may be needed after all.

Considerable effort has also been spent during FY 1980 on continuing the development of the advanced cycle 2R and cycle 1R absorption chillers. For both of these cycles, higher efficiency (than the usual single-effect cycle) is predicated on a closer approach to the Carnot cycle by using the available heat input at the highest possible temperature and by rejecting heat at the lowest possible temperature. This requires that the design incorporate multipressure staged processes for boiling and for heat rejection. Since the absorption cycle must be a closed-loop flow circuit, the transition of a fluid element from the heat-input process to the heat-rejection process must be regenerative (or recuperative): i.e., the heat from a high-temperature fluid element going from the boiler to the absorber must be transferable to a fluid element going in the opposite direction.

The choice of the regenerative paths is what differentiates the cycle 2R from the cycle 1R design. Cycle 2R is simpler than cycle 1R (which is the reason 2R is being designed and fabricated first) but cycle 2R requires more heat-exchanger area. Thus the cycle 2R chiller will allow the basic multistage boiling and absorption processes to be studied without the complication of the complex regenerative path connections of the cycle 1R design.

The detailed design and all drawings for the cycle 2R chiller have been completed during FY 1980. Fabrication of parts has begun, and fabrication and assembly are expected to be completed by the end of FY 1981.

Work on the cycle 1R chiller during FY 1980 consisted of a first attempt to learn how to model the cycle and a detailed investigation of a method for selecting appropriate fluid pairs for a practical cycle 1R machine.

Detailed computer modeling of the 1R absorption cycle proved to be a formidable task. A straightforward approach was attempted during FY 1980; it consisted of writing out the equations (about 100) expressing conservation of mass, conservation of energy, thermodynamic properties (for ammonia/water mixtures), and heat-exchanger relationships, and then trying to solve this set of highly nonlinear equations. No solutions were found as the iterative scheme did not converge, even for a simpler version of this model.

A decision was made to learn techniques for solving these equations by first modeling the single-effect absorption chiller by this method. The solution technique led to a successful computer model for the single-effect chiller. The method for adopting this model to the 1R chiller remains for future investigation.

The other cycle 1R task during FY 1980--investigation of a method for selecting fluid pairs--has been quite fruitful. A solid foundation for a method for approximating the properties of binary mixtures has been achieved. The traditional method for calculation of mixture properties is based on setting up and solving an equilibrium equation for the fugacities of each of the components in the vapor and liquid states. However, the direct solution of the fugacity equation is impractical here because it requires complete and accurate knowledge of volumetric properties of vapor and liquid phases--information that is not generally available and is difficult to obtain experimentally.

A decision was made to devise an independent approach to approximate with sufficient accuracy the necessary properties of the binary fluid mixtures. An appropriate equation for this purpose turned out to be one that calculates the thermal efficiency of an ideal absorption power cycle. This cycle can be constructed by replacing the condenser and evaporator of a conventional single-effect absorption refrigeration cycle with an ideal isothermal turbine and by taking into account every possible heat and work recuperation.

The resulting basic equation for binary fluid mixtures is:

$$\left\{ (v_v - v_s)t - (X_v - X_s)\left[\frac{\partial(tv_s)}{\partial X_s}\right]_p \right\} \left(\frac{\partial p}{\partial t}\right)_{X_s}$$

$$= -h_v + h_s + (X_v - X_s)\left(\frac{\partial h_s}{\partial X_s}\right)_t \qquad (1)$$

where

$t = 1/T$ = reciprocal of absolute temperature T

v = specific volume

h = specific enthalpies

p = system pressure

X = weight fraction of the more volatile component

All properties are saturated properties and the subscripts have the following referents:

v refers to the vapor phase, and

s refers to the liquid phase or the solution.

Note that the solution's heat of mixing is included in the enthalpy h_s.

There are many ways of approximating the individual terms of Equation (1). The choices depend on the available experimental data, on the accuracy required, and on judgment. A specific method for solving Equation (1) has been developed and adopted and will be reported in the near future.

Accordingly, a basic set of experimental data needed to determine the binary fluid properties [by using Equation (1)] for performance calculations of the 1R absorption cycle have been specified, along with the accuracy required for each parameter. A statement of work was written in FY 1980 to enable DOE to issue a Request for Proposal (RFP) soliciting the measurement of this basic set of data for a number of candidate fluid pairs. After review of the proposals received, DOE negotiated a contract with SRI International at the end of FY 1980. SRI will conduct a literature search and follow up with measurements of the as yet unmeasured parameters during FY 1981.

Technical Support Activities

The following program planning activities took place during FY 1980:

- Preparation of the first and second drafts of multiyear Program Element Plans for Rankine and Absorption Solar Cooling Systems.
- Writing of a "white paper" on solar cooling technologies, as input to the DOE's five-year planning exercise.
- Preparation of documents for DOE/HQ on solar cooling's potential to achieve eventual market penetration and on the DOE solar cooling program's role in accomplishing this.
- Participation in major planning meetings for the Active Solar Heating and Cooling Program at DOE/HQ and DOE/SAN.
- Organization of a meeting at LBL at which U.S. and Mexican participants prepared a draft proposal for a joint U.S.-Mexican project in solar refrigeration; discussions later with SERI, DOE/HQ, DOE/SAN and other organizations on implementation of this joint project.

The following are some of the major FY 1980 activities in technical monitoring and evaluation of solar cooling projects by outside (nonLBL) contractors:

- Conduction of, and participation in, 21 site visits and project reviews covering 14 different DOE contractors; review of seven final reports and phase reports; assistance to DOE/SAN in specifying the Statements of Work for follow-on efforts by several of these contractors.
- Initiation of a contract with SERI for LBL to provide technical monitoring of the five U.S.-Saudi (SOLERAS) solar cooling projects. During FY 1980, LBL staff participated in the project startup meetings, preliminary design reviews, and critical design reviews, in addition to continuing interactions with SERI and with the project contractors.
- Preparation and sending to DOE/SAN of monthly summary reports on all the DOE solar cooling projects; preparation and sending to DOE/HQ of several reports on solar cooling R&D program accomplishments and status.
- Accomplishment of preliminary activities in developing a methodology for comparative assessment of solar cooling technologies (e.g., absorption vs Rankine cooling) and projects.

During FY 1980 LBL carried out the review of nine unsolicited proposals. For each proposal, the comments of all the reviewers were summarized and sent to DOE along with a recommendation for action.

LBL assisted DOE/SAN in preparing and evaluating responses to an RFP on the Determination of Properties of Fluids for Solar Cooling Applications. LBL prepared the draft statement of work, secured reviewers for the technical evaluation committee, and conducted that committee's review of the proposals received in response to the RFP.

LBL staff were engaged in a number of coordination activities related to the solar cooling program during FY 1980:

- Participation in DOE Program Reviews, including
  - -Systems Development Division Review, in Reston, Va.
  - -Commercial Demonstration Program Review, in Norfolk, Va.
  - -Active Solar Heating and Cooling Contractors Meeting, in Nevada
  - -Passive Update Meeting, in Washington, D.C.
- Attendance at solar conferences:
  - -Operational Results Conference, in Colorado Springs, Colo.
  - -Systems Simulation and Economics Analysis

Conference, in San Diego, Calif.

-Annual International Solar Energy Society Meeting, in Phoenix, Ariz.

- Participation in the DOE active solar heating and cooling technical managers' coordination meeting in Nevada.
- Participation in the bimonthly review and coordination meetings associated with the cooling marketing study projects funded by DOE.
- Coordination with NASA/MSFC (Manned Space Flight Center in Huntsville, Ala.) on the status and future priorities of the solar cooling projects that they are managing for DOE.
- Coordination with Oak Ridge National Laboratory concerning the cooling projects (for which they are technical monitors) that make use of waste heat sources.
- Coordination with the Gas Research Institute on cooling and heat pump programs and projects of mutual interest, especially solar-powered cooling applications using gas auxiliary energy.
- Assistance to the American Samoa Energy Office with their plans for using large-scale solar cooling systems as a solution to one of their major energy problems, the scarcity and high-cost of diesel fuel.
- Coordination of the utilization of the LBL Building 71 Federal Buildings Solar Demonstration Project as a field test installation for a new 25-ton packaged absorption chiller recently developed as part of the DOE solar cooling R&D program.

PLANNED ACTIVITIES FOR FY 1981

Absorption Air Conditioner Development

The testing of the single-effect chiller will continue. Further improvement of the vapor pump will not be pursued; the chiller will be operated using an electric makeup pump for the remaining chiller tests. The testing is expected to be completed and the results published during FY 1981.

By September 1981, the fabrication of the 2R chiller should be completed. Testing is expected to begin by about December 1981, followed by testing and evaluation throughout the remainder of FY 1982.

The cycle analysis work on the cycle 1R chiller will continue during FY 1981 as we continue to reduce the theoretical cycle to a practical design. The required measurements of the properties of candidate fluids for the 1R cycle should be completed by SRI International by the end of FY 1981; we will work closely with them to insure the maximum utilization of the data measured during that project. The final 1R design and working drawings are expected to follow during FY 1982.

Technical Support Activities

Activities in FY 1981 will be similar to those carried out in FY 1980. Implementation of the new multiyear solar cooling program plan will be one of the major activities. Appreciable effort will be expended in developing the Statement of Work for a major program solicitation that will serve as the main vehicle for implementing the plan. We should progress a long way toward establishing realistic cost and performance goals for solar cooling systems, making use of new marketing analyses and system simulation capabilities. The joint U.S.-Mexican project should get underway, and preliminary negotiations will be conducted for a possible U.S.-Greek program in solar cooling. Technical monitoring and review of the DOE and SOLERAS solar cooling projects will continue. Unsolicited proposal reviews will be undertaken as received. LBL will continue to participate in DOE program reviews, in solar energy conferences, and in coordination activities with other organizations carrying out related programs.

REFERENCES

1. K. Dao, M. Simmons, R. Wolgast, M. Wahlig, Performance of an Experimental Solar-Driven Absorption Air Conditioner, Lawrence Berkeley Laboratory report LBL-5911, January 1977.
2. K. Dao, Conceptual Design of an Advanced Absorption Cycle: The Double-Effect Regenerative Absorption Refrigeration Cycle, Lawrence Berkeley Laboratory report LBL-8405, September 1978.
3. K. Dao, A New Absorption Cycle: The Single-Effect Regenerative Absorption Refrigeration Cycle, Lawrence Berkeley Laboratory report LBL-6879, February 1978.

PASSIVE COOLING*

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INTRODUCTION

Passive or hybrid cooling occurs when thermal energy is rejected from a building to natural heat sinks in the environment. Such heat sinks include the atmosphere, the sky, and the ground. Cooling to the atmosphere occurs through ventilation and evaporative cooling; to the sky by infrared radiative cooling; and to the ground by conduction to the earth. Although air temperature reduction is the most obvious means for achieving comfort under overheated conditions, the comparable importance of humidity levels, mean radiant temperatures, and amount of air motion is well established. The primary objectives of this project are to evaluate the effectiveness of passive and hybrid cooling systems for displacing conventional fuels now used to power air conditioning and to develop systems that do this in an optimal manner.

The emphasis of the project to date has been on the assessment of the "resource" for comfort conditioning based on infrared radiative cooling. Infrared radiative cooling systems are composed of a radiator surface which is exposed to the sky, an (optional) infrared-transparent windscreen to reduce convective heat gain from the air, and a means for transporting heat from the building's interior to the radiator surface. The current work includes measurement of atmospheric infrared emission characteristics in order to identify geographical regions in which selective and nonselective radiators may be effective. This effort employs both atmospheric radiation models and experimental sky radiation measurements. Promising radiator surfaces and infrared-transparent windscreens will be experimentally evaluated at an outdoor test facility at LBL.

To predict accurately the net heat exchange between the sky and a surface of known infrared characteristics, knowledge is needed of the intensity of infrared radiation produced by the atmosphere as a function of both zenith angle and wavelength. Most published measurements in the literature pertaining to the spectral radiance of the sky were obtained on one or two nights or pertain to clear skies only. Therefore, to obtain data on which estimates of cooling system performance can be based, it was necessary to make our own measurements, during the day and night, over periods of months. During 1978 and 1979, a major effort was devoted to construction of four spectral infrared sky radiometers and the siting of these instruments at various locations in the southern United States. These radiometers were set up to measure the radiance of the zenith sky at half-hour intervals in six wavelength bands ranging from 8 to 22 μm. In 1979 the instruments were modified to perform measurements at several different zenith angles. Auxiliary measurements performed consist of total infrared sky radiance (using a pyrgeometer), air temperature, and dewpoint. Further details of the measurement system may be found in the 1978 and 1979 Annual Reports[1,2] and elsewhere.[3-6]

ACCOMPLISHMENTS DURING 1980

Data collection with the four spectral infrared sky radiometer systems continued during 1980. Two of these systems were moved to different southern cities to ensure the widest possible geographical coverage of the resulting data set. The continuing analysis of the spectral sky radiance data has led to improved characterization of sky radiance during clear sky conditions. Future analysis should lead to improved information for cloudy skies as well.

The LBL experimental test facility for evaluation of radiator cooling assemblies was completed, and the first tests were performed.

The Passive Solar Cooling Group assists U.S. Department of Energy management activities in the planning and execution of the National Passive Cooling Program. This included the development and evaluation of three solicitations (e.g., Requests for Proposals) for DOE in 1980, and technical monitoring responsibilities as new projects are funded. Coordination between these activities and the work at LBL is discussed in the following paragraphs.

Spectral Infrared Sky Measurements

During the Spring of 1980, the spectral sky radiometer systems in Gaithersburg, Md. and Tucson, Ariz. were moved to West Palm Beach, Fla., and Boulder City, Nev. The systems in San Antonio, Tex. and St. Louis, Mo. remained in place. The end of the summer data-acquisition period marks the end of the sky radiance measurement portion of this project. Although a substantial amount of data analysis remains to be performed, sufficient data has been collected to produce a thorough preliminary assessment of the resource for radiative cooling in the six cities in which measurements have been made.

Analysis of the Sky Radiance Data

One component of the spectral sky radiance analysis is the comparison of numerical calculations with radiometer measurements. A modified version of LOWTRAN 3B computer model[7,8] was used to compute sky radiance based on vertical profiles of temperature, humidity, and minor atmospheric constituents. These computed radiances are compared with measured values for clear sky conditions. In general the agreement with the computer model is

* This work was supported by the Assistant Secretary for Conservation and Solar Applications, Office of Solar Applications for Buildings, Passive and Hybrid Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

very good.[9] In the center of the atmospheric window near a wavelength of 11 μm the agreement is excellent, but a measurable disagreement appears in the region of 8-10 μm. The maximum discrepancy, which corresponds to an observed radiance greater than predicted, is about 0.6 $W\cdot m^{-2}\cdot sr^{-1}\cdot \mu m^{-1}$ at a wavelength of 8.8 μm.[9] This error is about 15% of the clear sky radiance at this wavelength.

Another result of the data analysis is the development of a correlation to predict the total sky radiance for clear skies. The measurement of total (thermal) sky radiance S is made with an Eppley pyrgeometer operated in conjunction with each spectral infrared radiometer. The spectral radiometer is used to calibrate the pyrgeometer and to detect the presence of clouds. In place of the total sky radiance S, it is convenient to employ the sky emissivity defined by

$$\varepsilon_{sky} = S/(\sigma T_a^4), \tag{1}$$

where σ is the Stefan-Boltzmann constant and T_a is the absolute air temperature near the ground. A correlation of 2,945 nighttime clear sky data points for ε_{sky} and the dewpoint temperature T_{dp} in degrees Celsius yields the relation:

$$\varepsilon_{sky} = 0.741 + 0.00624\ T_{dp}\ , \tag{2}$$

$$-20^\circ C \leq T_{dp} \leq 22^\circ C.$$

The standard (random) error in the use of Equation (2) is 0.031. The experimental (systematic) error is estimated to be 0.030. Figure 1 shows the correlation for each of the months of data used to form the overall correlation, as well as the overall correlation itself. No significant systematic difference exists between data sets from the various locations. Thus, the result given by Equation (2) may have rather general applicability.

Figure 2 shows a comparison of the derived correlation with relationships recommended by other researchers[10-12] as well as with calculations based on the LOWTRAN 3B computer model. From left to right, the crosses on this figure represent the following LOWTRAN model atmospheres: midlatitude winter, U.S. standard, midlatitude summer, and tropical. Because a sky emissivity of 1.00 corresponds to a zero resource for radiative cooling, this figure indicates how well the radiative cooling resource is known for clear skies.

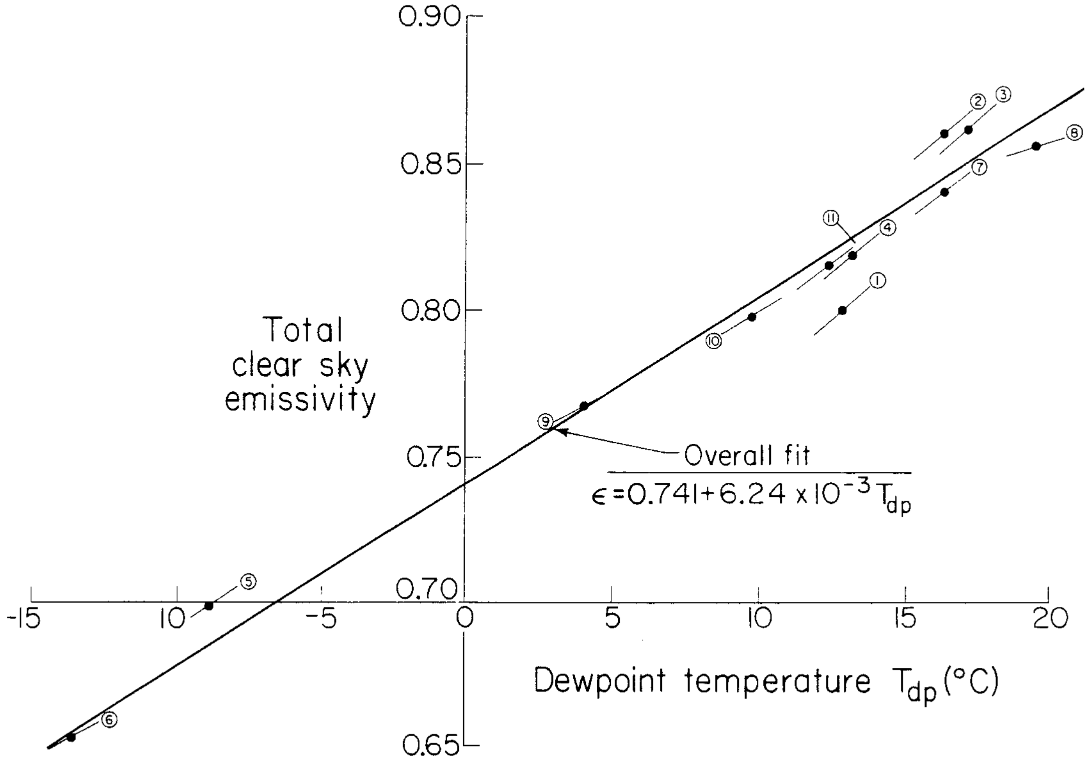

Fig 1. The measured emissivity of clear skies as a function of dewpoint temperature. The short line segments show the correlations obtained for various individual months: 1, 2, 3, and 4 represent June, July, August, and September, 1979 at Gaithersburg, Md.; 5 and 6 represent January, February, 1980 at Gaithersburg, Md.; 7 and 8 represent July, August, 1979 at St. Louis, Mo.; 9, 10 and 11 represent June, July, August, 1979 at Tucson, Ariz. The monthly fits are drawn centered at the average value of sky emissivity and dewpoint for the month concerned. The overall fit is a least-squares fit through the 2,945 individual measurements.

(XBL 8011-92)

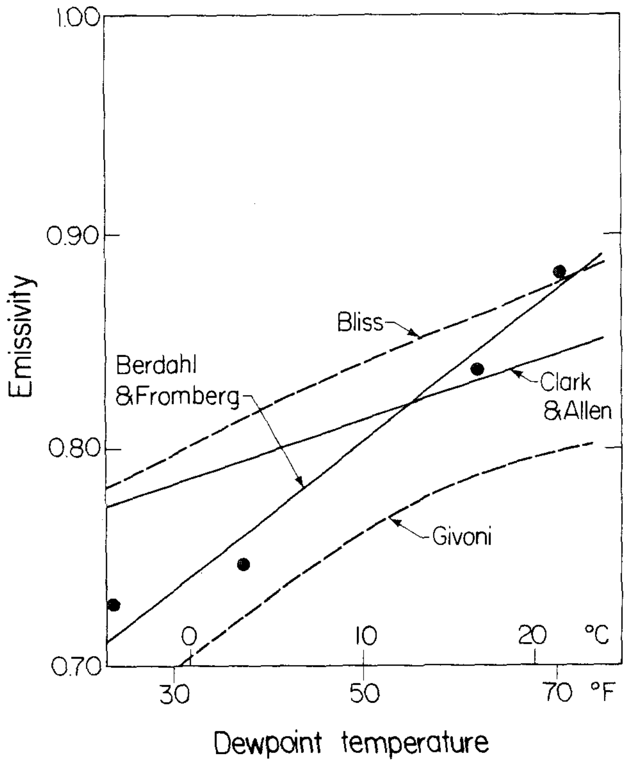

Fig 2. Relationships between the emissivity of clear skies and surface dewpoint temperatures as given by Berdahl and Fromberg and several other references.[10,11,12] The dots are results from the computer code LOWTRAN discussed in Reference 8. (XBL 8011-90)

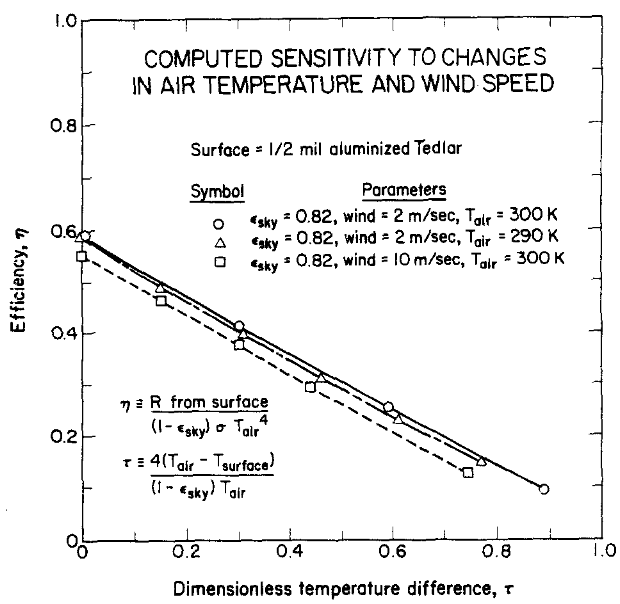

Fig 3. Computed efficiency versus dimensionless temperature difference curves for differing ambient conditions. The circles represent baseline conditions. The triangles show the effect of a decrease in air temperature. The squares show the effect of an increase in windspeed. The efficiency curve is not very sensitive to these changes. (XBL 8012-2538)

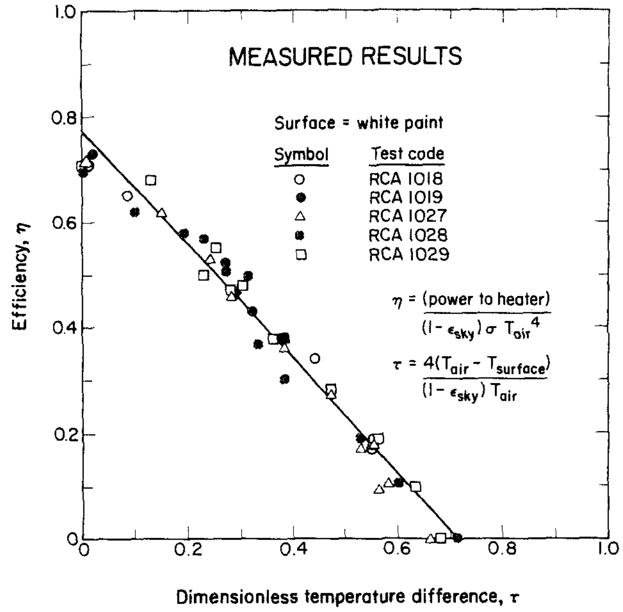

Fig 4. Measured efficiency versus dimensionless temperature difference for a white-painted radiator surface with 2 mil polyethylene glazing. Measurements were made at night with the panel facing directly upward. The solid line is a least-squares fit through the data points. (XBL 8012-2543)

Test Facility for Radiative Cooling Assemblies

Systematic performance measurements were obtained for the first time with this new facility. Further description of the facility may be found in References 13 and 14. Both nonselective (white-painted) and selective (4 mil aluminized Tedlar) surfaces were tested, each glazed with a 2 mil sheet of polyethylene. The tests were designed to determine the amount of radiative cooling which can be produced by a given surface as a function of radiator temperature.

Analytical and numerical system modeling was performed in order to evaluate various radiative cooling assemblies. For glazed radiator surfaces, these models indicated that plots of efficiency η versus a dimensionless temperature difference τ are nearly independent of the detailed conditions of the test, such as sky emissivity, wind speed, air temperature, etc. The efficiency for radiative cooling η is defined as

$$\eta \equiv R/[(1-\varepsilon_{sky})]\sigma T_a^4 \,, \qquad (3)$$

where R is the radiative cooling rate in $W \cdot m^{-2}$. The denominator in this expression represents the maximum cooling permitted by the Second Law of Thermodynamics for any radiator with temperature less than or equal to the air temperature T_a. The dimensionless temperature difference τ is defined as

$$\tau \equiv 4(T_r - T_a)/[(1-\varepsilon_{sky})T_a], \qquad (4)$$

where T_r is the absolute radiator temperature.

Figure 3 shows a computer-generated plot of η versus τ for a typical radiator panel. Performance changes caused by variations in the ambient air temperature or wind speed are small. In the experiments the wind speed was typically less than 2 m/s.

Figure 4 shows the performance results for five sets of measurements on ordinary white painted surface with a 2 mil polyethylene glazing. A least squares fit to the data points characterizes the performance of this radiator panel.

Several criteria are important for obtaining good test results. First, the presence of dew on the windscreens must be detected and the corresponding data discarded because liquid water interferes with longwave infrared transfer. Second, the wind speed should be less than about 2 m/s to prevent motion of the thin polyethylene windscreen. Finally, the sky emissivity should be less than 0.85 to produce a sufficiently large cooling rate for the calculation of accurate efficiency values using Equation (3).

Programmatic Activities

The Passive Cooling Group supports the Department of Energy's Passive Cooling Program in several areas. Personnel participate in planning activities and preparation of solicitations. DOE issued three such documents during the Spring of 1980, resulting in the selection of nine proposals for funding early in 1981. The project staff also serve as technical monitors on all current DOE Passive Cooling Projects and and are responsible for the technical review of both solicited and unsolicited proposals.

PLANNED ACTIVITIES FOR FY 1981

Analysis of the spectral infrared sky radiance data will continue with the publication of two technical papers and one report during 1981. One technical paper will develop a method for estimating the total infrared sky radiance under cloudless conditions, based on air temperature and dewpoint. The report will present statistical summaries of all data collected from measurements at six locations. The second technical paper will treat the spectral and angular components of infrared radiation from cloudless skies in some detail, including comparisons with the LOWTRAN computer model. An additional technical paper (scheduled for FY 1982) will introduce a method for estimating the daily average spectral and angular distribution of sky radiation when only the daily average sky emissivity is known. The method envisaged is applicable for cloudy as well as clear skies.

Further work with the Experimental Test Facility for Radiative Cooling will be deferred until FY 1982, in order to accommodate some of the following activities.

A major systems analysis effort is to be undertaken to perform a comparative assessment of passive cooling technologies. One component of this effort will be the construction of simplified computer models of generic passive-cooling systems for various types of residential and commercial buildings in different parts of the U.S. The models will produce estimates of the projected energy impact of various passive cooling systems. These estimates will be used to formulate a Passive Cooling Area Plan to be used by DOE in planning the National Passive Cooling Program.

The other component of the systems analysis effort will consist of detailed computer modeling of existing passively cooled buildings. Computer models based on suitably modified existing programs (such as BLAST[16]) will be formulated. These models will be validated using data collected by two Passive Cooling Experimental Facilities (at Trinity University and the University of Arizona). Each Passive Cooling Experimental Facility presently consists of two well-instrumented experimental buildings specifically constructed to test a variety of passive cooling strategies. These facilities play a central role in the National Cooling Program, and will provide data for the validation of computer simulations to other research organizations. Comparison of experimental results with model calculations will enable both the validation of the computer models and the development of improved experimental procedures. The LBL role as DOE Technical Monitor for these projects assures close coordination between LBL and the Experimental Facilities.

REFERENCES

1. M. Martin et al., Passive Cooling, Lawrence Berkeley Laboratory report LBL-11175, 1979, pp. 3-30.

2. M. Martin et al., Radiative and Passive Cooling, Lawrence Berkeley Laboratory report LBL-8619, 1978, p. 58.

3. P. Berdahl and M. Martin, "Infrared Radiative Cooling," Proceedings of the 1979 International Congress of the International Solar Energy Society (Atlanta, Ga.: American Section of ISES, 1979).

4. P. Berdahl and M. Martin, "Spectral Measurements of Infrared Sky Radiance," Proceedings of the Third National Passive Solar Conference (San Jose, Calif.: American Section of ISES, 1979), p. 443.

5. P. Berdahl, "Routine Spectral Measurements of Infrared Radiation from the Atmosphere," Proceedings of the Second International Conference on Infrared Physics (Zurich, Switzerland: Eidgenossische Technische Hochschule, 1979), p. 406.

6. M. Martin and P. Berdahl, "Description of a Spectral Atmospheric Radiation Monitoring Network," Proceedings of the Third Conference on Atmospheric Radiation, Davis, Calif., 1978, p. 148.

7. J. Selby et al., Atmospheric Transmittance from 0.25 to 28.5 microns: Supplement LOWTRAN 3B, AFGL-TR-76-0258, AD A 040 701 (Hanscom Air Force Base, Mass.: Air Force Geophysics Laboratory); available from National Technical Information Service, Springfield, Va. 22151.

8. P. Berdahl and M. Martin, "The Resource for Radiative Cooling," Proceedings of the Second

National Passive Solar Conference, Philadelphia, American Section of ISES, vol. 2, 1978, p. 684.

9. P. Berdahl and M. Martin, "Spectral Radiance of the Clear Midlatitude-Summer Atmosphere, Proceedings of the 1980 International Radiation Symposium (Fort Collins, Colo.: Radiation Commission of the International Association of Meteorology and Atmospheric Physics, 1980), p. 167.

10. G. Clark and C. Allen, "The Estimation of Atmospheric Radiation for Clear and Cloudy Skies," Proceedings of the Second National Passive Solar Conference, American Section of ISES, vol. 2, 1978, p. 675.

11. R. Bliss, "Atmospheric Radiation Near the Surface of the Ground: A Summary for Engineers," Solar Energy, vol. 5, 1961, p. 103.

12. B. Givoni, "Passive Cooling of Buildings by Natural Processes," Energy and Buildings, vol. 2, 1979, p. 279.

13. F. Sakkal et al., "Experimental Test Facility for Selective Radiative Cooling Surfaces," Proceedings of the Fourth National Passive Solar Conference, (Kansas City, Mo.: American Section of ISES, 1979).

14. M. Kruskopf et al., Radiative Cooling Test Facility and Performance Evaluation off 4 Mil Aluminized Tedlar and White Paint Surfaces, Lawrence Berkeley Laboratory report (in preparation).

15. E. Clark and P. Berdahl, "Radiative Cooling: Resource and Applications," in The Passive Cooling Applications Handbook, issued at the Passive Cooling Workshop, Fifth National Passive Solar Conference, Amherst, Mass., 1980, p. 167; Lawrence Berkeley Laboratory publication Pub-375, 1980.

16. D. Hittle, "BLAST, The Building Loads Analysis and System Thermo-Dynamics Program," Users Manual, vol. 1, U.S. Army Construction Engineering Research Laboratory technical report CERL-TR-E-153, available from National Technical Information Service, Springfield, Va. 22151.

LBL SOLAR DEMONSTRATION PROJECT*

T. Webster

INTRODUCTION

The Building 90 solar demonstration project is one of eleven projects selected to be part of the FY 1977 Department of Energy Facilities Solar Demonstration Program, a pilot program for the Solar Federal Buildings Program recently authorized by The National Energy Act. The objectives of this pilot program are to establish procedures and techniques for assessing and implementing solar systems for federal facilities and to assist in reducing energy use within DOE facilities.

The LBL project was funded by the DOE Division of Solar Energy via the Construction, Planning and Support Division. LBL Plant Engineering was responsible for design and construction of the project with assistance provided by the LBL Solar Group. A detailed description of the building, solar systems, preliminary and final design considerations, construction problems, and final costs are contained in the 1977, 1978, and 1979 Energy and Environment Division Annual Reports.

* This work was supported by the the Assistant Secretary for Conservation and Solar Energy, Field Applications Branch, Office of Active Heating and Cooling, U.S. Department of Energy under Contract No. W-7405-ENG-48.

ACCOMPLISHMENTS DURING FY 1980

The solar system was designed to operate in conjunction with a new building exhaust air-return system. Because of delays of about a year in installing the system (due to funding problems), the solar system was operated independently of the building. Water was circulated between the collector and storage but was not actively connected to the building heating system during 1980. This type of unloaded operation resulted in high operation temperatures and offered an opportunity for a thorough "shakedown" of the system. The return-air system installation will be completed in early 1981.

The following problems were identified and corrected during 1980:

- The freeze protection sensor/controller allowed circulation to start at 45-50° F instead of 35° F as designed; the controller was adjusted to the final setpoint by a trial and error process.
- Whenever the pump was activated for freeze protection, a thermosiphon action in the same direction as the pump flow caused warm water to continue circulating after the pump was turned off. This resulted in very high system losses. Motor-operated ball valves were installed at the circulation pumps to correct this problem.

- The collector pump cycled excessively during morning startup; the ΔT controller was adjusted to reduce this cycling to a minimum.
- One pump relay failed and was replaced.

The instrumentation system was made fully operational in March 1980. Monthly advisory reports are being issued by Vitro Labs until the return-air system installation is complete. Data from these reports point out a number of interesting facts about the system operation. The following data are from the August report and are representative of system operating characteristics during the year.

- Average storage temperature for the month was 178° F. This high average temperature results from operating the system unloaded.
- Average collector array efficiency for the month was 19% (of total available insolation). This efficiency should improve for loaded operation.
- Because of the high operating temperature, the solar system provided 4% of the heating load in spite of not actually being activated. The system is designed so that the operating temperature is set by a three-way mixing valve (whose controls are not yet activated), and solar heat is provided whenever the heating system return water temperature is lower than the storage temperature. The storage was hot enough so that solar heat was provided even though the mixing valve was not set for a low operating temperature.
- Total system losses were 33% of collected energy. Storage and transmission losses were each about 12% with the remainder being startup, intentional heat dump, and unexplained losses.
- The maximum temperature of 190° F, necessary to activate the heat dump mode (i.e., to circulate hot fluid at night), was rarely achieved.
- The solar COP (collected energy divided by pump energy) was about 67.
- Domestic hot water use for the building was an average of only 40 gal per working day, considerably less than the expected one gal per day per person.
- Average daily incident solar radiation on the collector array was 1,721 Btu/S.F.-day versus the long-term average of 1,866 Btu/S.F.-day shown in the Solar Data Manual for Richmond, California.

PLANNED ACTIVITIES FOR FY 1981

After completion of the return-air system, the solar system will be activated, and formal monthly reports that will document the actual performance of the system will be issued by Vitro.

SUPPORT FOR COMMERCIAL SOLAR DEMONSTRATION PROGRAM*

F. Salter, S. Peters, and T. Webster

INTRODUCTION

The Solar Applications Group at LBL provides technical consulting and management services to support the Department of Energy's San Francisco Operations Office's (DOE/SAN) overall management of commercial-building solar demonstration projects and hotel/motel hot water solar projects located throughout the northwestern states and Hawaii. These projects are part of the National Solar Heating and Cooling Demonstration Program,[1] which has the primary objectives of stimulating a solar industry and promoting the use of solar energy as a means of reducing demand on conventional fuel supplies.

The group is currently involved in support for the projects in this program shown on Table 1.

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Field Applications Branch, Office of Active Heating and Cooling, U.S. Department of Energy under contract No. W-7405-ENG-48.

ACCOMPLISHMENTS DURING FY 1980:

LBL was directed by DOE to terminate participation in the solar demonstration program by the end of FY 1980 and to restrict our activity level to one full-time employee during FY 1980. To carry out these instructions, we transferred a number of projects to DOE/SAN and to the Energy Technology Engineering Center (ETEC) during the course of the year. All but essentially completed projects were transferred by the end of FY 1980.

Table 1. Projects being assisted.

Projects	Program Solicitation	
1	NSF-1	Cycle I
4	DSE-76-2	Cycle II[2]
5	PON 4200	Cycle III[3]
3	PON 1450	Hotel/motel[4]

As for the projects remaining with LBL, activities during FY 1980 included monthly reports, midconstruction and final project inspections, instrumentation checkouts on sites instrumented by Vitro Laboratories,† resolution of operation and instrumentation problems, review of participant Final Reports and Data Collection Reports, and refurbishment considerations on several projects.

PLANNED ACTIVITIES FOR FY 1981

LBL will continue technical consulting and management activities on the remaining complete or nearly complete projects until these projects are transferred to the Solar Energy Research Institute during the course of FY 1981.

† Vitro superseded IBM.

REFERENCES

1. U.S. Energy Research and Development Administration, National Program for Solar Heating and Cooling of Buildings, ERDA 76-6, Washington, D.C., November, 1976.
2. U.S. Energy Research and Development Administration, Commercial Integrated Projects for Use in Demonstrations for Solar Heating and Cooling, Program Opportunity Notice DSE-76-2, Washington, D.C., 1976.
3. U.S. Department of Energy, Commercial Integrated Projects for Use in Demonstrations of Solar Heating and Cooling, Program Opportunity Notice EG-78-N-01-4200, Washington, D.C., 1978.
4. U.S. Energy Research and Development Administration, Hot Water Initiative for Hotel/Motel Installations, Program Opportunity Notice EG-77-N-03-1450, Washington, D.C., 1976.

MEASUREMENT AND ANALYSIS OF CIRCUMSOLAR RADIATION*

D. Grether, D. Evans, A. Hunt, M. Wahlig, and S. Kanzler

INTRODUCTION

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 (i.e., 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 on many factors but primarily on the receiver's angular size (i.e., its field-of-view). A knowledge of the circumsolar radiation is a factor in predicting or evaluating the performance of concentrating systems.

The project employs unique instrument systems (known as Circumsolar Telescopes) that were designed and fabricated at LBL. Each system has a "scanning telescope" mounted on a precision solar tracker. The telescope scans mechanically through an arc of 6^{o} 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, which has a fixed field of view (typically 5-6^{o}) and is used to provide an estimate (called the "normal incidence" reading) of the direct solar radiation. The telescope and pyrheliometer have matched ten-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 worth of 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 (e.g., Sandia Laboratories and SERI) in considering the performance of concentrating systems.

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

Details of the instrument system and examples of the measurements and summarized data have been given in previous annual reports. This present report is based primarily upon References 1 and 2.

ACCOMPLISHMENTS DURING FY 1980

Measurement Program

For the past several years, LBL had supported the operation of, and analyzed the data from, all four telescopes. This year, the budget was suffi-

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Solar Applications for Buildings, Photovoltaic Energy Systems Division U.S. Department of Energy under Contract No. W-7405-ENG-48.

cient for LBL to support only two telescopes. Sandia National Laboratories in Albuquerque, N.M., agreed to operate one, but only in conjunction with tests at the Central Receiver Test Facility. LBL continued to support an instrument at the Advanced Components Test Facility at Atlanta, Ga. An instrument that had been upgraded at LBL during 1979 was installed in October, 1979 at the Jet Propulsion Laboratory Parabolic Dish Test Facility at Edwards, Calif. As well as providing specific data for the test facility, the telescope is providing climate characterization data for the Mojave desert area. The instrument that was located in nearby Barstow, Calif. for this latter purpose was returned to LBL. Barstow is the site of the 10 MWe Central Receiver Pilot Plant (Solar One) that is currently under construction.

A sunphotometer, on loan from the National Oceanographic and Atmospheric Administration, was mounted on the telescope installed at Edwards. The sunphotometer is used to estimate the turbidity of the atmosphere, a quantity that is related to the atmospheric scattering of sunlight by aerosols. The intent is to investigate possible correlations between turbidity values and circumsolar levels. The photometer, originally hand-held, was placed in an environmentally sealed and temperature-controlled housing, and the output was connected to the telescope's data-acquisition system.

Summary of Clear-Filter Data

Summaries of the clear-filter (nonwavelength selective) data through December, 1979 were prepared. The method for obtaining this type of summary is described in Reference 3. Sample results are shown in Figure 1 for the Mojave desert area. Displayed in Figure 1(a) is the monthly average circumsolar ratio, which is defined as the monthly total circumsolar radiation (from the edge of the sun out to 3°) divided by the sum of the direct solar radiation (coming from the sun's disk) plus circumsolar radiation. This quantity is approximately the same as the fractional overestimate that a pyrheliometer would make in estimating the monthly total direct solar radiation. Figure 1(b) shows the ratio of the monthly total direct solar radiation to the extraterrestrial value (outside the earth's atmosphere). This quantity (similar to the commonly used K_T of Reference 4) compensates for the seasonal changes in day length and the varying earth-sun distance, and hence can be taken as an indicator of "cloudiness." The circumsolar ratio shows a distinct seasonal dependence with a winter peak of as much as 7% and summer minima of about 2%. A noticeable correlation also occurs with the total/extraterrestrial parameter; cloudy months tend to have high circumsolar levels. Comparable data from Albuquerque (not shown) do not have any obvious seasonal dependence. Rather, the circumsolar ratio shows a trend of increasing values from 2-3% in May and June, 1976, to 4-5% in February and March, 1977, and then, with considerable fluctuations, a relatively steady value thereafter.

Colored Filter Data

This year, a considerable effort was devoted to analyzing the colored-filter pyrheliometer data for application to wavelength selective systems, such as concentrating photovoltaic devices. As a tool in the analysis, the atmospheric transmission computer program LOWTRAN[5] was combined with an extraterrestrial solar spectrum.[6] The resulting Solar Spectral Model (SSM) provides a spectrum for any specified set of atmospheric conditions.

The first step in the analysis was to characterize the transmission function (transmission

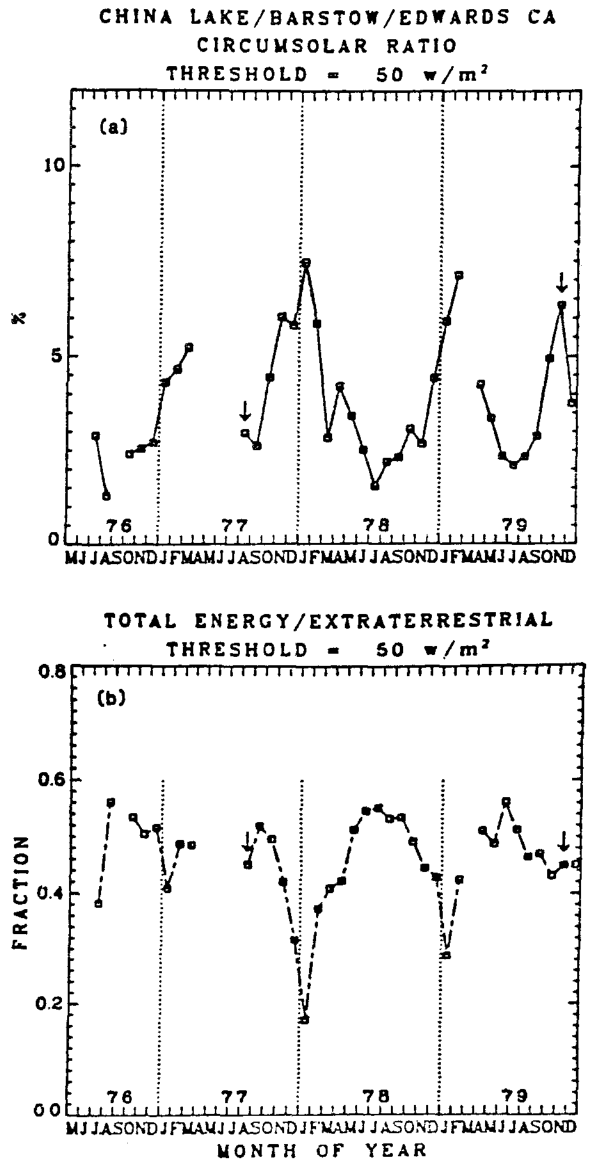

Fig. 1(a). The monthly value of the circumsolar ratio, as defined in the text, plotted from July, 1976 through December, 1979 for the Mojave desert area: China Lake, then Barstow, and finally Edwards, Calif. The small vertical arrows indicate the changes from one telescope location to the next.

Fig. 1(b). The corresponding value of the monthly total direct solar radiation divided by the extraterrestrial solar radiation.

versus wavelength and time) of each filter over an approximately three-year use period. The filters are of the interference type (multilayered dielectrics) and are known to be subject to degradation. Spectrophotometer measurements of the filters' transmission were made at LBL this year. Figure 2 displays the spectrophotometer measurement for a particular filter. Comparisons to similar measurements provided by the manufacturer when the filters were new suggested that many of the filters had changed in overall transmission. A method[1] was developed to track the change in transmission over time, using the colored-filter pyrheliometer readings for clear-sky conditions, when the atmosphere is relatively stable and the atmospheric attenuation processes are relatively well-understood. For each month of data, ratios of colored-filter to clear-filter pyrheliometer readings were extrapolated to zero air-mass, where the air-mass is a measure of the amount of atmosphere between the telescope and the sun. The extrapolated values are relatively independent of actual atmospheric conditions and the season of the year but quite sensitive to changes in filter characteristics. The analysis showed that most of the filters had undergone a slow but steady decrease in transmission over time, typically about 2%/yr. In contrast, one of the filters was observed to have experienced an abrupt reduction in transmission of about 17% during a particular month. To account for such effects, ad hoc "aging" factors were adapted, with a linear dependence being generally adequate to describe the data. The LBL spectrophotometer measurements together with the aging factors are then taken as specifying the filter transmission functions.

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. As indicated by Figure 2, the transmission of any given filter has a complex dependence on wavelength. As a consequence, the inversion cannot be carried out exactly and an estimation method must be used. The method developed for estimating, described in detail in Reference 2, involves calculating an effective transmission over a nominal pass-band for each filter. The dotted rectangle in Figure 2 shows the nominal pass-band and an effective transmission value corresponding to the displayed filter transmission curve. The calculation uses an SSM spectrum to take into account, approximately, the shape (but not the magnitude) of the actual solar spectrum over the filter's wavelength region. The resulting effective transmission values have been shown to be insensitive to the details of the model. The energy content of the solar spectrum within the nominal pass-band is obtained by (i.e., the inversion is carried out by) dividing the pyrheliometer reading by the effective transmission.

Figure 3 displays in bar graph form the inverted values for two sequences of colored-filter, clear-sky pyrhelimeter readings. Superposed on the data is an SSM-modeled spectrum for nominal clear-sky conditions. For ease in comparison, the average of the modeled spectrum over each pass-band has been plotted as a solid square at the center of the band. The two data sequences and the modeled spectrum are for the same air mass value and have nearly the same clear-filter pyrheliometer readings (about 940 W/m^2). The variation in spectral composition of the data is noteworthy. One sequence is in quite good agreement with the model, and the other has a relative depletion in the 1.0 μ wavelength region; a portion of the spectrum that is particularly sensitive to photovoltaic applications.

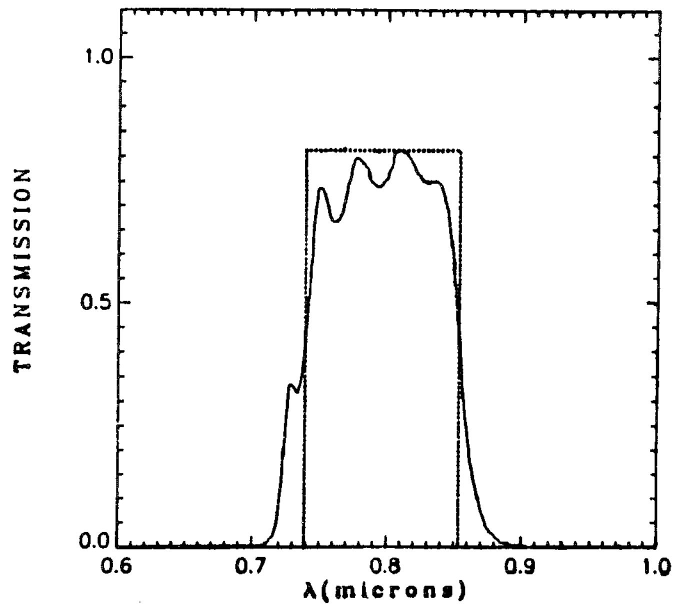

Fig. 2. The solid curve is the transmission versus wavelength, as determined on a spectrophotometer, for a particular colored filter. The dotted rectangle shows the nominal pass-band and an effective transmission for the filter.

PLANNED ACTIVITIES FOR FY 1981

For 1981, plans are to continue operating the instruments at Atlanta and in the Mojave desert area and to move a telescope to the site of Solar One by June, 1981. This latter telescope is to be interfaced to the data-acquisition system of Solar One so that the circumsolar radiation can be readily taken into account in evaluating the plant's performance. Plans call for the telescope currently at LBL to be rehabilitated, upgraded, and relocated.

Work will continue on the analysis of the clear-filter data with an increased emphasis on analyzing the systematic behavior of circumsolar radiation with respect to atmospheric conditions and their measurements. The goal is to develop a model of the circumsolar radiation so that estimates can be obtained for locations lacking actual measurements.

The effort on the colored-filter pyrheliometer data will be concluded using the data available to date, with summaries produced of the energy content of the solar spectrum for various locations, atmospheric conditions, seasons of the year, etc. Some attention will be given to the colored-filter scan data.

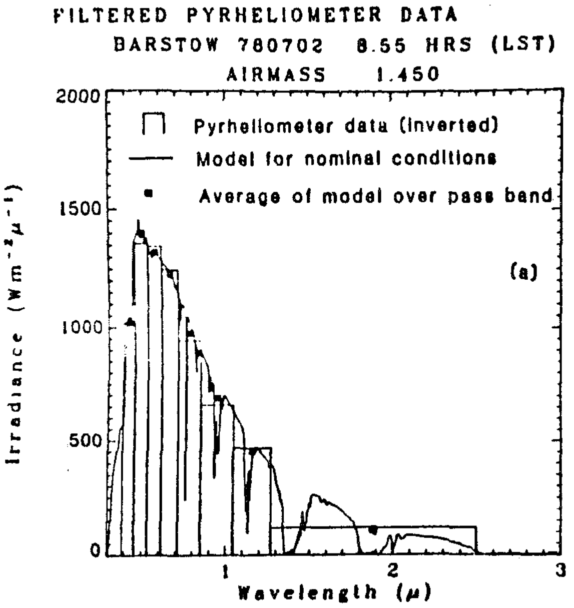

Fig. 3(a). Colored-filter pyrheliometer data for a particular date and time. The bar graph is for the actual data, inverted as described in the text. The solid curve is a modeled solar spectrum for nominal clear-sky conditions but for the same air-mass as the data. The solid squares are averages of the model over the pass-band of the filters and are included for comparison to the data.

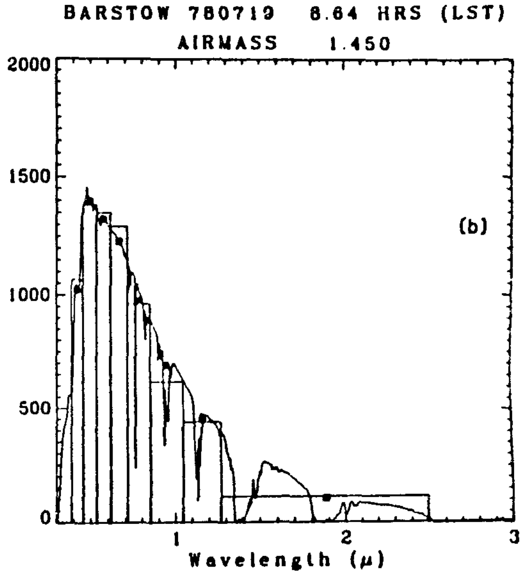

Fig. 3(b). Data for a second date but for the same air-mass value and essentially the same clear-filter pyrheliometer value as in 3(a).

If sufficient support is available, a new instrument will be designed as part of the FY 1981 program. The design would incorporate our knowledge of the character of circumsolar radiation as obtained with the current instruments and with a control system based on micro-processor devices. The instrument would be simpler to operate and maintain and would take fewer data points over a somewhat increased range of parameters. Actual construction would begin in FY 1982.

REFERENCES

1. D.F. Grether, D. Evans, A. Hunt, and M. Wahlig, "Measurement and Analysis of Circumsolar Radiation," Proceedings of the Annual DOE Insolation Resource Assessment Program Review, Davis, Calif., August 1980; Lawrence Berkeley Laboratory report LBL-11645, October 1980.
2. D.B. Evans, D.F. Grether, A.J. Hunt, and M. Wahlig, "The Spectral Character of Solar and Circumsolar Radiation," Proceedings of the Annual Meeting of the American Section of the International Solar Energy Society, Phoenix, Ariz., May 1980; Lawrence Berkeley Laboratory report LBL-10802, June 1980.
3. D. F. Grether, D. Evans, A. Hunt and M. Wahlig, "Application of Circumsolar Measurements to Concentrating Collectors," Proceedings of the 1979 International Congress of the International Solar Energy Society, Atlanta, Ga., June 1979; Lawrence Berkeley Laboratory report LBL-9412, June 1979.
4. B.Y.H. Liu and R.D. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation," Solar Energy, vol. 4, no. 3, 1960, p. 1.
5. J.E.A. Selby et al., Atmospheric Transmittance from 0.25 to 28.5 microns: Supplement Lowtran 3B, AFGL-TR-0258, AD A 040 701 (Hanscom Air Force Base, Mass.: Air Force Geophysics Laboratory, November 1976); available from National Technical Information Service.
6. M.P. Thekaekara, "The Total and Spectral Solar Irradiance and Its Possible Variations," Preprint X-912-75-155 (Greenbelt, Md.: Goddard Space Flight Center, June 1975).