Title

ENERGY & ENVIRONMENT DIVISION ANNUAL REPORT. SOLAR ENERGY PROGRAM FY 1982

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Publication Date

1983-03-01

LBL-15296
UC-59

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

FY 1982 Annual Report
SOLAR ENERGY PROGRAM CHAPTER

March 1983

ENERGY AND ENVIRONMENT DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-15296

ENERGY & ENVIRONMENT DIVISION ANNUAL REPORT

SOLAR ENERGY PROGRAM FY 1982

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

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SOLAR ENERGY PROGRAM

INTRODUCTION

During FY 1982, the Solar Energy Program at Lawrence Berkeley Laboratory (LBL) continued to focus on research that will extend the technology base for a broad range of solar energy applications, and on exploration into new approaches to solar energy conversion.

Passive approaches to heating, cooling, and lighting of buildings have been a major topic of research. In these technologies, architectural design, construction materials, and natural energy flows between the interior and exterior environment are used to control a building's interior climate and reduce the use of non-renewable energy. In FY 1982, LBL's work in passive solar included heat transfer research, systems analysis, and materials studies. In the heat transfer area, two projects were pursued. In the first, experimental and analytic studies of natural convection processes that take place within buildings and between the interior of a building and the environment were performed. The purpose was to quantify the rates for natural ventilation, interzone heat transfer, and heat transfer to and from storage masses within a building. In the second project, data from spectral infrared sky measurements taken in previous years were analyzed in order to develop correlations between sky temperature and other environmental parameters. The ultimate purpose of this work was to determine the potential for radiative cooling of buildings in various parts of the country.

In the area of systems analysis, computer models of convective and other basic heat transfer processes were developed, verified, and incorporated into building energy analysis computer programs. The resulting computer models were then used to examine the energy consumption impacts of using passive heating, cooling, and lighting design strategies in commercial buildings. A broad-based technology assessment of passive cooling strategies was completed. The purpose was to quantify the relative merits of the various cooling techniques. Daylighting was also an integral part of our building energy systems analyses. Experimental measurements of illumination levels in scale models of daylit buildings are used in conjunction with dynamic simulations to quantify the impacts of the daylighting system on the energy consumed for electric lighting and auxiliary heating and cooling. The result is a true measure of the energy benefits of daylighting designs.

Finally, a new passive research project was initiated near the end of FY 1982. Innovative materials that can replace or supplement conventional glazing materials and provide large reductions in building energy use are being identified. Laboratory samples will be prepared and evaluated in future years.

LBL is also engaged in research on the active solar cooling of buildings. Thermodynamic cycles that have the potential for increasing the efficiency of solar-fired absorption air conditioners by at least a factor of two, compared to the current state-of-the-art, are being studied. An air conditioner based on one of these advanced cycles, the double-effect regenerative absorption cycle, has been designed, fabricated, and installed in a new laboratory test facility. Lab testing will be carried out during FY 1983. In parallel with the experimental work, analysis of the performance and economics of solar cooling systems has been performed. This analysis will help to establish realistic cost and performance goals for all solar cooling systems under development in the national DOE program.

Installation of a 25-ton-capacity solar absorption air conditioning system in LBL Building 71 as part of the Solar Federal Buildings Program will afford LBL engineers the opportunity to gain first-hand experience with one of the new solar cooling units developed in the DOE solar R&D program. The installation of this system was well under way by the end of FY 1982 and will be completed by mid-FY 1983.

In both the active solar cooling area and the passive area, LBL staff are providing technical support to DOE Headquarters and the DOE San Francisco Operations Office in developing program plans, evaluating reports and proposals, and technical monitoring of R&D activities by other contractors.

A new materials-oriented research program to explore advanced processes for solar energy utilization was established this year. The program evolved from an ongoing project to develop a new concept in high-temperature gas receivers based on the use of suspensions of very small (submicron) absorbing particles as radiant heat exchangers. The three primary elements of this research program are: solar heating and chemistry of small particle suspensions, porous optical materials for insulating glazings, and solar collection and control using diffractive optics. The underlying phenomenon in each case is based on the optical effects induced by the microstructural properties of materials.

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

PASSIVE RESEARCH AND DEVELOPMENT*

R.C. Kammerud, J.W. Place, M.R. Martin, P.H. Berdahl, B. Andersson, F.S. Bauman, W.L. Carroll, A.J. Gadgil, A. Mertol, E. Ceballos, T.L. Webster, M.W. Nansteel, C.C. Conner, J.P. Coutier, M. Fontoynont, and E. F. Altmayer

The amount of conventional fuel used to heat, cool, and light buildings is determined by (1) the interaction of the building with its environment, (2) the thermal gains associated with the activities occurring within the structure, (3) the thermal storage characteristics of the building, and (4) the operating characteristics of the equipment used to convert conventional fuels to end-use energy. Traditionally, the building design process has not adequately accounted for the combined influence of these four factors on building energy consumption. To do so requires that the designer have access to techniques for properly controlling the interactions of the building with the environment and for managing the energy flows within the structure.

Passive heating, cooling, and lighting strategies integrate the energy control and management schemes into the building design. The design parameters are selected so that they enhance and control the coupling of the building to the environment, thereby reducing the requirements for auxiliary heating, cooling, and lighting energy. In this context, the Passive Program at Lawrence Berkeley Laboratory is directed at theoretical and experimental investigations of the energy performance implications of passive design strategies, with emphasis on passive and hybrid cooling and natural lighting of commercial buildings. The specific objectives of the program are the following:

1. Develop analytic descriptions of the energy processes that occur within a building and between a building and the environment.
2. Develop and evaluate advanced passive/radiative cooling systems.
3. Evaluate the effectiveness of passive systems in reducing energy consumption for space heating, space cooling, and lighting.

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

The strategy used to meet these objectives consists of coordinated experimental and theoretical tasks leading to advanced energy analysis capabilities that can be used in passive system design and evaluation. The emphasis to date has been on the development and testing of techniques for predicting (1) the "resource" for passive systems and (2) a building's response to that resource. Here, the term "resource" implies the naturally occurring potentials of the environment to provide heating, lighting, and cooling. These potentials are being investigated in projects in the following areas: convection, radiative cooling, natural lighting, and passive building energy analysis. Accomplishments and plans in each of these areas are described below.

ACCOMPLISHMENTS DURING FY 1982

Convection Research

This project consists of both experimental and analytic studies of convective heat transfer both within a building and between the building and the environment. The objective is to develop technically sound and highly generalized predictive capabilities for (1) heat transfer between room surfaces and room air, (2) heat transfer through openings between rooms or zones, and (3) natural ventilation† of buildings with outside air. The analytic work attempts to develop and apply detailed numerical models for convection phenomena in order to develop simplified descriptive algorithms to represent the heat transfer process. Detailed experimental studies have provided the data needed for validation of the numerical analysis program.

Convection research conducted in FY 1982 focused on heat transfer within rooms via natural convection. A numerical analysis technique, validated against earlier LBL experiments and analysis,[1,2] was used to develop an extensive data base on heat transfer, air temperature, and air velocities for natural convection in a two-dimensional room (shown schematically in Fig. 1). The numerical data on heat transfer between the surfaces of the enclosure and the room air were analyzed to extract a correlation between surface temperature and surface heat flux for a range of

†Natural ventilation is defined here as controlled exchange of air between the interior and exterior of a building when ambient conditions are such that energy benefits can be realized. In contrast, infiltration is defined as the uncontrolled exchange of air with the environment, which is generally not energy advantageous.

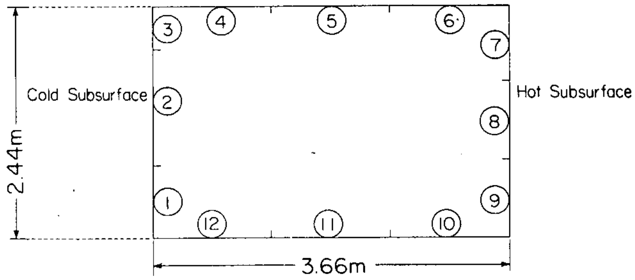


Figure 1. Schematic diagram of room used to develop convection correlation; circled numbers identify individual subsurfaces, with hot and cold subsurfaces at opposite ends of the room, as indicated. (XBL 8212-12514)

enclosure boundary conditions. These boundary conditions consisted of a hot surface on one wall, a cold surface on the opposite wall, and a constant intermediate temperature on all remaining surfaces in the room. The analysis was done for surfaces 1, 2, 7, and 8, which typically contribute on the order of 90% of the total heat transfer into or out of the room air, as described in Ref. 3. For these active surfaces, the correlation for the heat flux from the room surface to the room air, q_i, is shown below.

$$q_i = 2.40(T_i - T_i') \qquad (1)$$

with

$$T_i' = K_1 T_H \left[\frac{A_H}{A}\right]^{3/4} + K_2 T_C \left[\frac{A_C}{A}\right]^{3/4} + K_3 T_I \left[\frac{A_I}{A}\right]^{3/4} + K_4 T_H + K_5 T_C \qquad (2)$$

where T_i is the temperature (°C) of surface i; T_i' is the correlated temperature (°C) of air adjacent to surface i; T_H, T_C, and T_I are the temperatures (°C) of the hot, cold, and inactive surfaces, respectively; A_H and A_C, are the areas (m^2) of the hot and cold surfaces, respectively; A_I is the total area of all inactive surfaces; and A is the total surface area (m^2) of the room. The coefficients, K_1, K_2, K_3, K_4, and K_5 were obtained by fitting the numerically generated heat-transfer data base and are shown in Table 1. The constants shown in Table 1 are substituted into Eq. (2) and together with Eq. (1), produce a general correlation for the convective heat flux from the air to subsurface 1, 2, 7, or 8.

Table 1. Correlation constants.

Subsurface Number	K_1	K_2	K_3	K_4	K_5
1	0.372	0.285	0.449	0	0.497
2	0.740	0.567	0.893	0	0
7	0.285	0.372	0.449	0.497	0
8	0.567	0.740	0.893	0	0

This correlation predicts convective heat transfer from room surfaces much more successfully than the existing correlations recommended by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE). Comparisons of predictions from the LBL and ASHRAE correlations with the observed heat fluxes from the numerical simulations are shown in Figs. 2a and 2b.

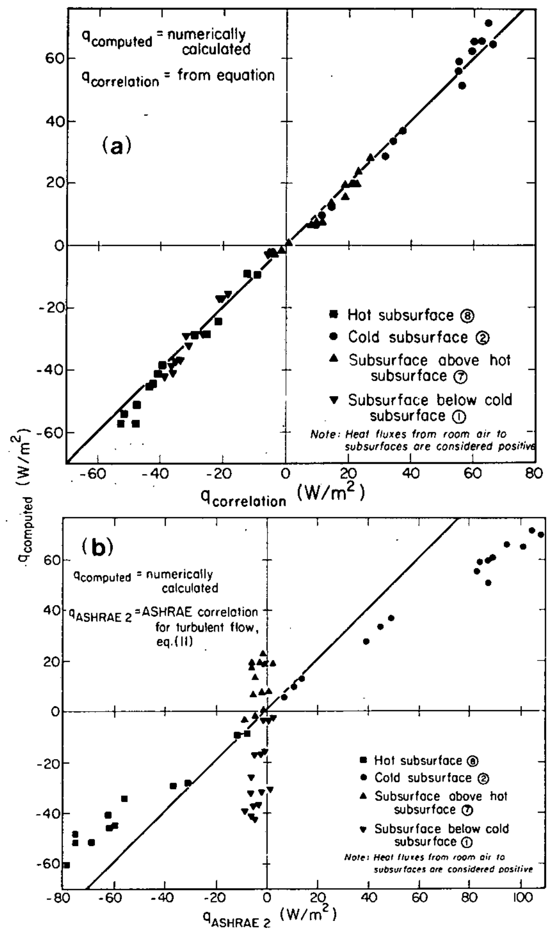


Figure 2. Heat-flux predictions from the LBL correlation (a) and the turbulent ASHRAE correlation (b) are compared with the numerically calculated results. Positions of the four subsurfaces are shown in Figure 1.
[(a) XBL 828-1081; (b) XBL 828-1085]

During FY 1982, experimental work on interzone convection in a two-dimensional enclosure separated by an adiabatic or a conducting partition was also concluded.[4] The experimental data for the two-zone configurations studied have been used to define a preliminary interzone convection heat transfer algorithm and will be used to further validate the convection numerical analysis computer program.

Radiative Cooling

Infrared radiative cooling systems consist of a radiator surface exposed to the sky and a means for transporting heat from the building's interior to the radiator surface. The objective of this project is to quantify the environmental resource for radiative cooling in order to predict cooling system performance. The resource can be characterized in terms of the apparent sky emissivity for long-wavelength infrared radiation. To obtain a useful measure of sky radiance, radiometers were deployed in 1980 to collect data at six locations in the United States. The measurements taken included the spectral composition of the sky radiance as a function of zenith angle and local climate variables, such as dry-bulb and dew point temperatures.[5]

Raw data from the six locations were subjected to a detailed screening process to produce a final set of results consisting of measured values for a total of 57 months (6 locations) during 1979 and 1980 (an average of almost 10 months for each of the six locations); these results have been analyzed and expressed in terms of average monthly sky emissivities, since these quantities do not vary strongly with daily temperature fluctuations. Radiometer measurements taken through six infrared filters having the transmission characteristics shown in Fig. 3 are expressed as equivalent sky emissivities for the respective channels.

A set of graphs showing the equivalent spectral sky emissivity for several zenith angles is plotted as a function of total sky emissivity for the 8- to 14-micrometer channel under clear sky conditions in Fig. 4. Each letter plotted represents the monthly average emissivity for a single month of data taken at one of the six radiometer sites. Similar sets of graphs have been published for measurements made in each of the filter channels, and for both clear sky and all sky conditions.[6]

An empirical equation has been developed to correlate the large number of resulting data points with the

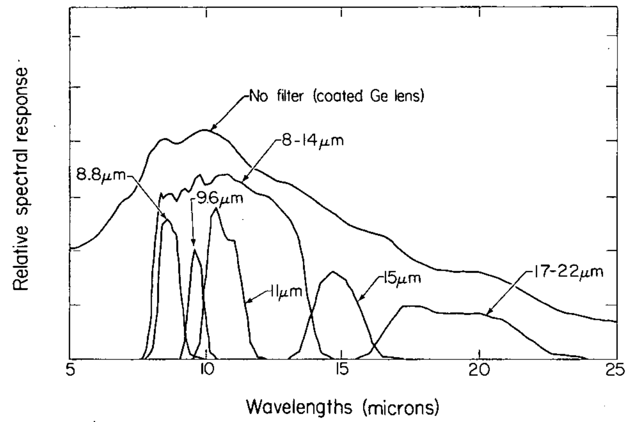


Figure 3. Radiometer spectral sensitivity with each of the six filters in place and the sensitivity with no filter.
(XBL 827-1610y)

total sky emissivity.[5,6,7] The spectral and angular component of clear sky radiation, $\epsilon_s(\lambda,\theta)$, is expressed in terms of the measured quantities $t(\lambda)/t$ and b in the equation

$$\epsilon_s(\lambda,\theta) = 1 - (1-\epsilon_s)[t(\lambda)/t]e^{b(1.7 - 1/\cos\theta)} \quad (3)$$

Here, θ is the zenith angle, ϵ_s is the total sky emissivity, and $t(\lambda)/t$ is a normalized spectral transmission function for the clear atmosphere. The curved lines drawn through the data points in Fig. 4 represent best fits to the data, using θ = °C and θ = 60° measured values. The clear sky spectral and angular emissivities obtained from the six rather diverse U.S. locations can be expressed as a function of the total sky emissivity and do not exhibit marked regional variations. Systematic but small effects can be observed when the data taken under all sky conditions are plotted in a similar manner, due to the effect of cloud cover on the apparent sky emissivity.

Commercial Building Energy Analysis

This project consists of (1) the development and experimental verification of computer programs that predict the energy consumption of passive commercial buildings and (2) the application of these programs to study the energy impacts of integrating various passive strategies with other energy systems in commercial buildings.

During FY 1982, research in this area centered on assessing the potential energy impacts of passive cooling technologies in nonresidential buildings.[8] The purpose was to identify those combinations of

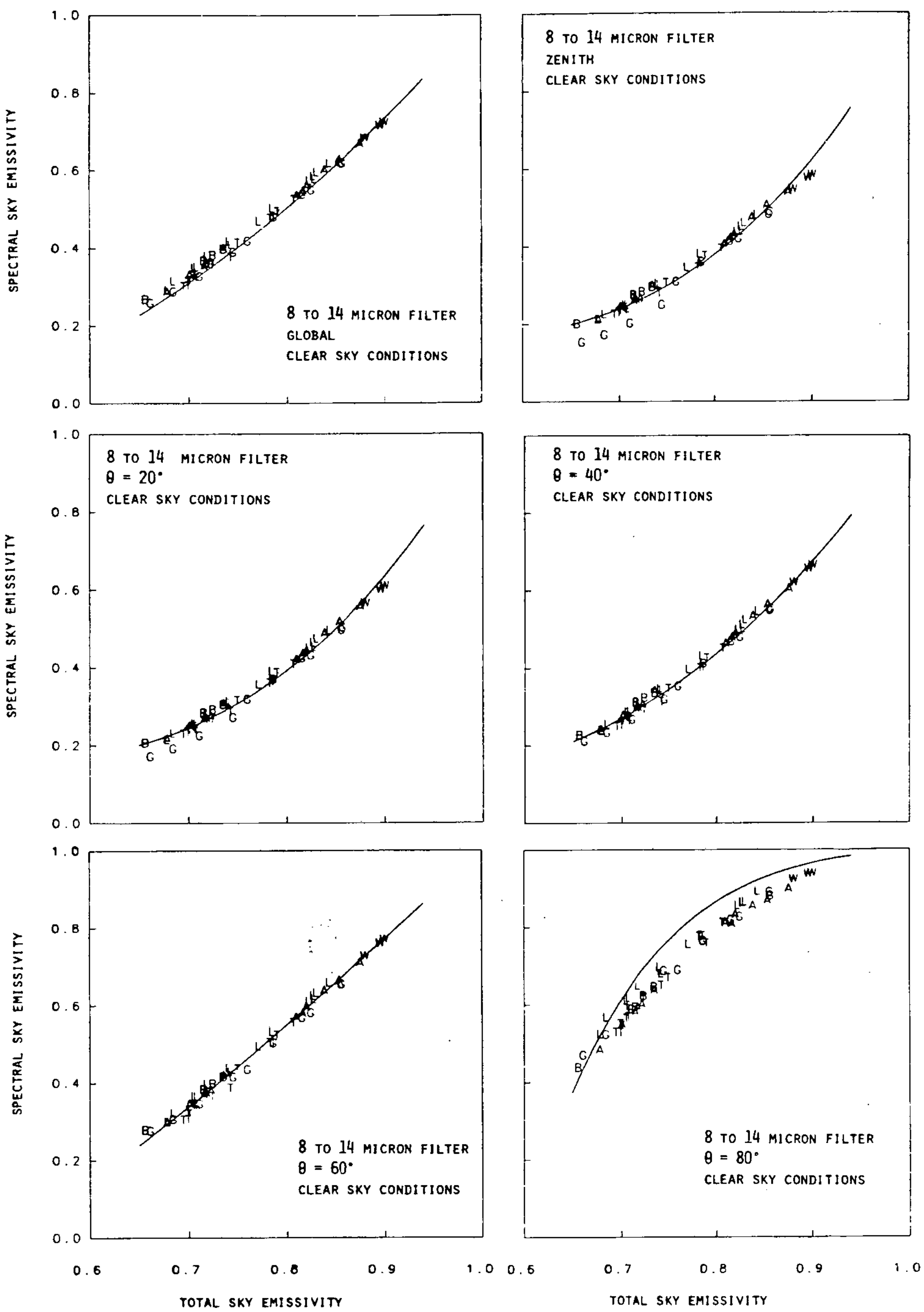


Figure 4. Measured monthly values of the 8- to 14-micron sky emissivities for clear skies, as functions of the total sky emissivity. Global values and measurements at zenith (0°), 20°, 40°, 60°, and 80° are shown. The global values are averages of the angular measurements, weighted with the cosine of the zenith angle. The 8- to 14-micron sky emissivity can be predicted from these results if the total sky emissivity is known. (XBL 831-7908)

passive cooling technologies, building types, and climates most likely to produce significant reductions in energy use; the passive technologies investigated were daylighting, ventilation, and dehumidification. This work was carried out jointly with personnel from the Los Alamos National Laboratory, who added an analysis of evaporative cooling to the assessment and who conducted economic analyses to establish preliminary indicators of economic feasibility.

Using BLAST[9] (and DOE-2 for evaporative cooling), energy consumption reductions were simulated for individual technologies as applied to specific buildings in specific climates. One-story (10,000-ft^2) and ten-story (100,000-ft^2) office buildings were selected for this assessment because they represent a large fraction of the floor area and energy consumption of the nonresidential sector and are relatively easily characterized. Eleven regions were selected to represent the range of climatic conditions for cooling in the United States. These regions were chosen using a climate aggregation methodology based on a similarity analysis of climate characteristics.[10] The energy performance of a base-case building was simulated first, then the building-simulation assumptions were changed to reflect the implementation of each passive cooling technology, and the building's energy performance was re-simulated.

Base-Case Results

The energy analyses of the base-case building provided a number of interesting results. Figure 5 shows total site energy consumption in kBtu/ft^2 yr for the one- and ten-story buildings. Requirements for both heating and cooling in such buildings are more climate-sensitive than previously thought: for the climates analyzed, the heating component varies by a factor of ten, and cooling by a factor of two. Results for the ten-story building show a similar pattern.

Lighting dominates electric consumption in all climate regions examined, ranging from roughly 60% to 75% of total electric consumption. Cooling, however, is the major source for peak power demand; significant reductions in peak power are reflected in reductions in both HVAC equipment size and utility capacity. The ratio of the peak power to total consumption tends to be higher in northern climates,

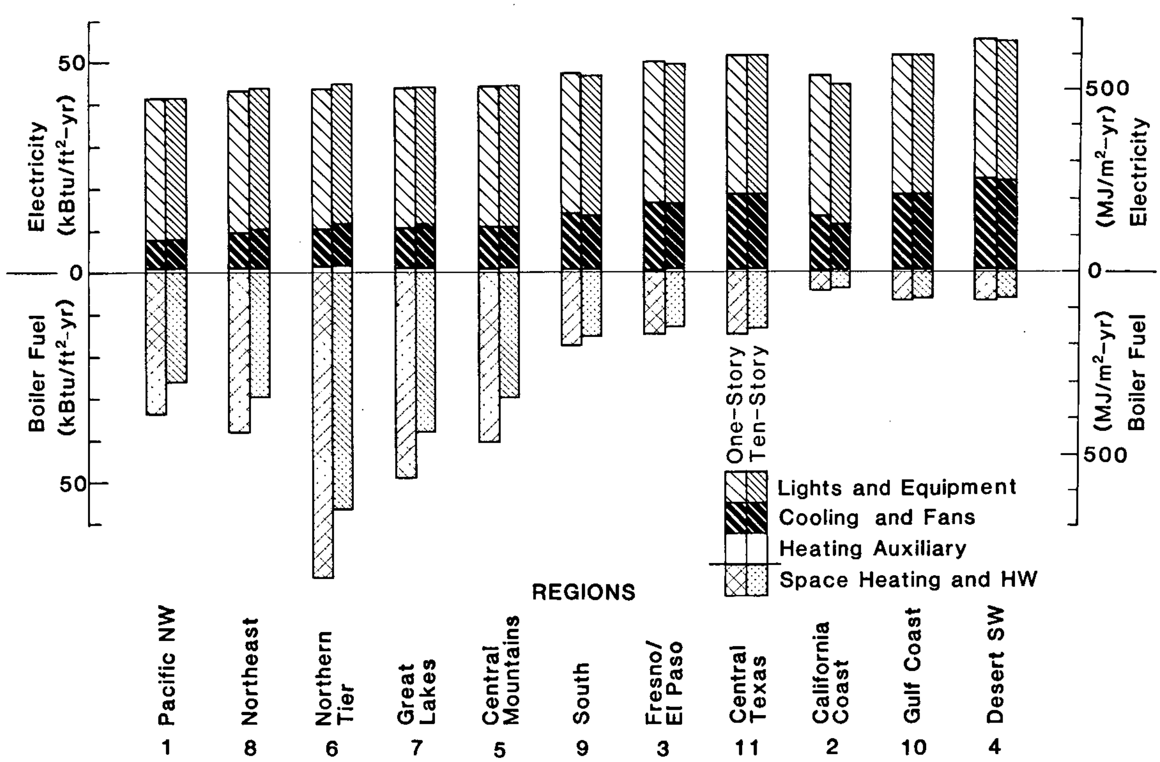


Figure 5. Annual electricity and fossil-fuel consumption of one- and ten-story office buildings, as computer-simulated for eleven regions and various end uses. These base-case designs are typical of current construction practice. The eleven regions span the range of climates in the continental U.S.

(XBL 827-7009)

suggesting that the most promising strategies there will be those having the biggest influence on peak power.

Total electricity costs for office buildings (including consumption and demand charges) far outweigh heating-fuel costs. In particular, demand charges represent a significant fraction of total electricity costs in most regions, although they vary widely. The overall importance of demand charges and their sensitivity to the application of passive cooling technologies are significant findings of the assessment. Further, the regional variation in energy costs does not correlate closely with the regional variation in energy use, showing the importance of local utility rate structures.

Passive Cooling Technology Results

Table 2 summarizes the energy and operating cost improvements for each technology. The range shown represents results for eleven climate regions representative of the continental United States. Results are for individual, newly constructed buildings. A discussion of the highlights of the results for each passive cooling technology follows.

- *Natural Lighting.* A realistically simulated natural lighting system for a one-story building produced energy consumption reductions and energy cost savings substantially greater than those of all other technologies investigated. The potential benefits of daylighting suggest that it should be one of the highest building-research priorities.
- *Evaporative Cooling.* Simulated energy performance results for the realistically designed systems showed modest savings in all climates, with the direct/indirect system showing a greater potential than the traditional direct evaporative coolers. The greatest savings occurred in the drier climates of the Southwest. Cost-savings patterns across climates were somewhat different than the energy-savings patterns due to variations in utility rate structures.
- *Nighttime Ventilation.* Simulation results for a thermodynamically ideal night ventilation system in a thermally massive building showed significant performance improvements in most climates investigated. Thermal mass was primarily responsible for substantial reduction in cooling demand and modest reductions in heating consumption. There is a strong possibility that this strategy could be effectively combined with other strategies such as day ventilation.
- *Daytime Ventilation.* Simulation of an idealized daytime ventilation system produced substantial reductions in space cooling loads, which in turn produced savings in cooling energy and total electricity consumption; the savings are similar in magnitude to those for the night ventilation strategy. The base-case building to which the daytime ventilation strategy was added in order to determine potential savings already used an economizer, so that the savings from daytime ventilation are in addition to those from economizer operation. Total energy cost-savings patterns across climates did not correlate in a simple manner with the energy-savings patterns; the relationship between energy cost savings and energy consumption savings across climates did not correlate with building size.
- *Dehumidification.* As a cooling strategy, this showed only limited potential for office buildings. Performance improvement was small in most of the climate regions analyzed and only modest in those few regions in which the best improvement was seen. The dehumidification system analyzed used the most favorable assumptions possible to characterize performance of the technology; only if occupant comfort requirements are modified will the potentials of dehumidification be enhanced over those summarized in Table 2.

Table 2. Summary of electricity consumption and cost reductions (in percents) for the passive cooling strategies examined in the technology assessment.

	Electricity Use		Electricity Cost	
Strategy	Cooling	Lighting	Consumption	Demand
Daylighting	30 to 40	40 to 50	about 40	20 to 35
Nighttime Ventilation	20 to 54	0	5 to 10	0 to 10
Daytime Ventilation	7 to 45	0	+3 to 14	0 to 35
Evaporation	9 to 44	0	1 to 7	0 to 12
Dehumidification	2 to 21	0	0 to 7	0 to 16

Natural Lighting

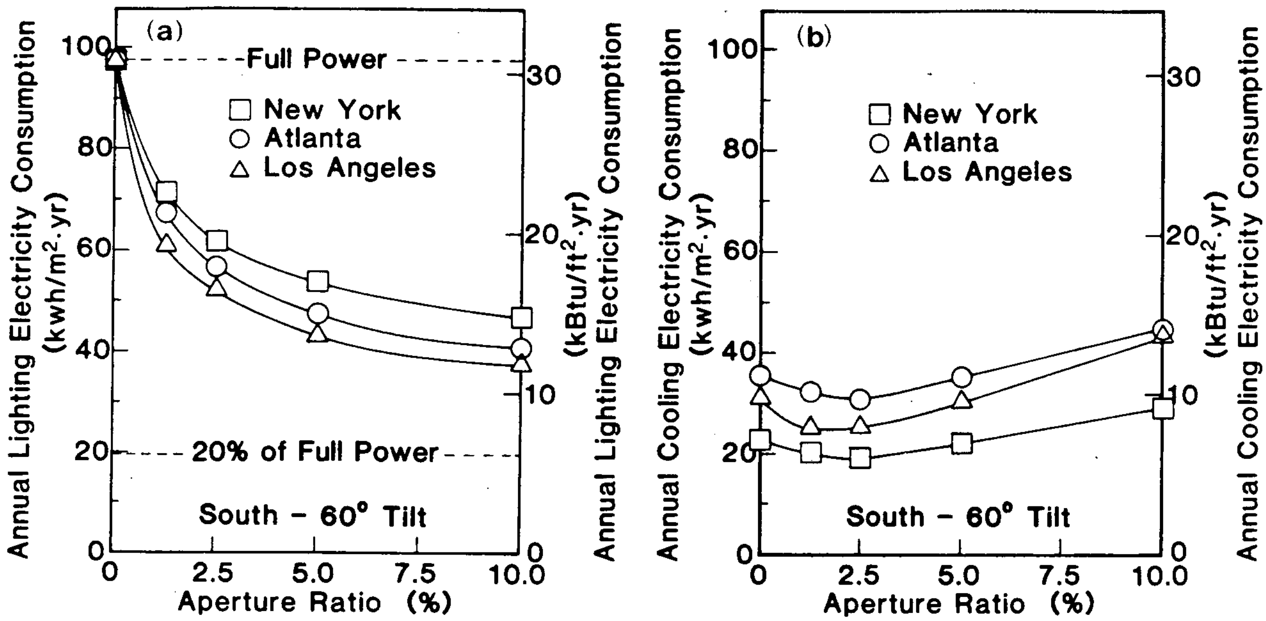
Natural lighting research within the Passive Program is closely connected to the energy analysis activities described above, but as a separate project it is more interdisciplinary in nature and addresses broader issues. The work focuses on examining the energy impacts of natural lighting within the context of the total energy requirements of the building. Experimental measurements are made on scale models to determine the radiation gains through glazing and the distribution of daylight within the building. These data are used with the energy analysis computer program BLAST to calculate the reduction in lighting electricity needed when the sunlight available is used to control electric lighting. The energy analysis program also performs a thermal analysis to predict the energy consumption for heating and cooling and the peak electric demand. The objective is to characterize the total energy impact of various solar aperture features, with an emphasis on generating design information for solar-aperture systems.[11]

An outdoor facility was set up at LBL to test the illumination behavior of a range of building configurations and daylighting apertures under actual solar conditions, using experimental scale models. During experiments, a model is mounted on a heliodon, a device that allows rapid reorientation of the model relative to the direction of beam sunlight. Within a few hours, enough data can be taken to effectively simulate clear-sky illumination effects for every possible combination of building orientation, hour of day, time of year, and geographic latitude in the United States. A pyranometer, pyrheliometer, and an array of photometers monitor radiation and illumination both external and internal to the scale model. A digital data acquisition system allows rapid scanning of the sensors to assure efficiency of measurement and simultaneity within a given set of sensor readings. The functional relationship between external-sensor data and internal-sensor data is put into BLAST to calculate the energy impacts of the daylighting system.

In FY 1982, energy analyses were performed on a prototypical single-story office building with tilted, south-facing glazing mounted in roof monitors. These simulations were performed using Typical Meteorological Year (TMY)[12] weather data for New York, Atlanta, and Los Angeles. Figure 6a shows the predicted annual lighting electricity consumption at the site vs. aperture ratio, defined as the ratio of the total area of glazing in the roof monitors to the total floor area in the building. For small aperture ratios (0 to 2.5%), the electric consumption decreases rapidly with each additional increment of aperture area. At larger aperture ratios (above 2.5%), the electric consumption is less sensitive to aperture area, indicating the diminishing number of hours during which additional sunlight can have a beneficial impact. The curves tend to asymptotically approach a lower limit, which is imposed by the electric lighting controllers and by the daily 12-hour lighting schedule, which includes many sunless hours. The reductions in lighting electricity were greater in Atlanta than New York because Atlanta has more available sunlight, particularly during the winter, when short days and cloudy conditions seriously limit the effectiveness of daylighting in New York. The greatest reductions in lighting electricity were observed in Los Angeles, which has almost exactly the same latitude as Atlanta, but clearer weather.

The annual energy consumption for cooling electricity at the site is plotted vs. aperture ratio in Fig. 6b. For small aperture ratios, cooling electricity consumption decreased with increasing aperture ratio for all three locations; this is the result of the higher luminous efficacy of sunlight in comparison to electric lighting. For larger aperture ratios, the solar gains become larger than required to provide lighting, and the cooling benefits of daylighting are negated.

The annual energy consumption of boiler fuel for heating is plotted vs. aperture ratio in Fig. 6c. For small aperture ratios, boiler fuel consumption increases with increasing aperture ratio because of the replacement of electric light with sunlight of lower heat content. This apparently negative effect is of little consequence, since the effect is small and boiler fuel is a much cheaper and more efficient source of heat than dissipating electric power in lamps. For large aperture ratios, the excess solar gains dominate the effect of the sunlight's higher luminous efficacy, and the boiler fuel consumption decreases with increasing aperture ratio. Figures 6a, b, and c suggest that movable insulation could produce significant reductions in energy consumption for lighting, cooling, and heating, if the insulation were controlled to limit summer gains to the level needed for illumination and controlled to maximize winter gains.



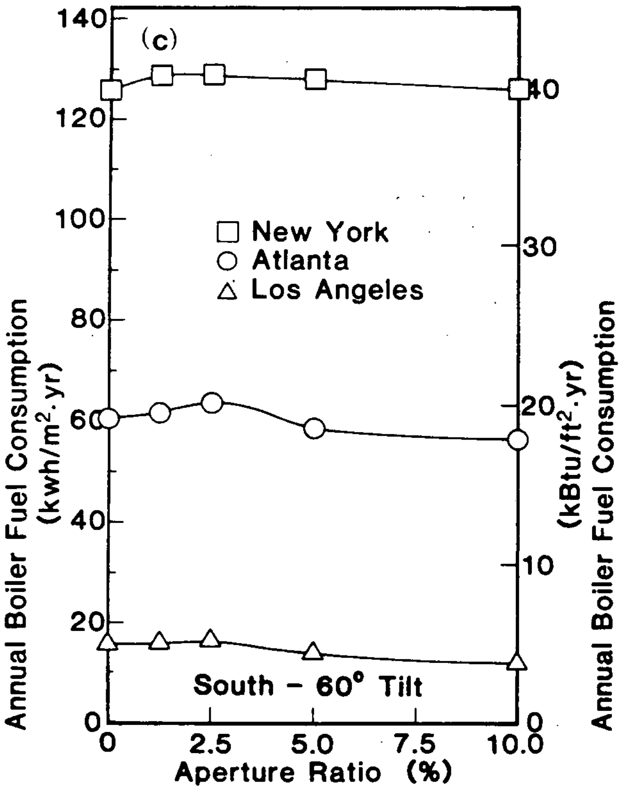


Figure 6. Simulations, for three cities, of annual energy consumption of a prototype single-story office building with tilted, south-facing roof glazing, plotted against aperture ratio (the ratio of illumination glazing area to building floor area): (a) lighting electricity; (b) cooling electricity; and (c) boiler fuel. (XBL 831-7675A)

Figure 7 shows the annual operating costs that have been computed for each location, using local billing policies for gas and electricity, including peak demand charges. For all three locations, costs decrease rapidly with increasing glazing area, up to an aperture ratio between 2% and 3%. Beyond an aperture ratio of 3%, increases in cooling electricity dominate decreases in lighting electricity, and the costs increase gradually with aperture area.

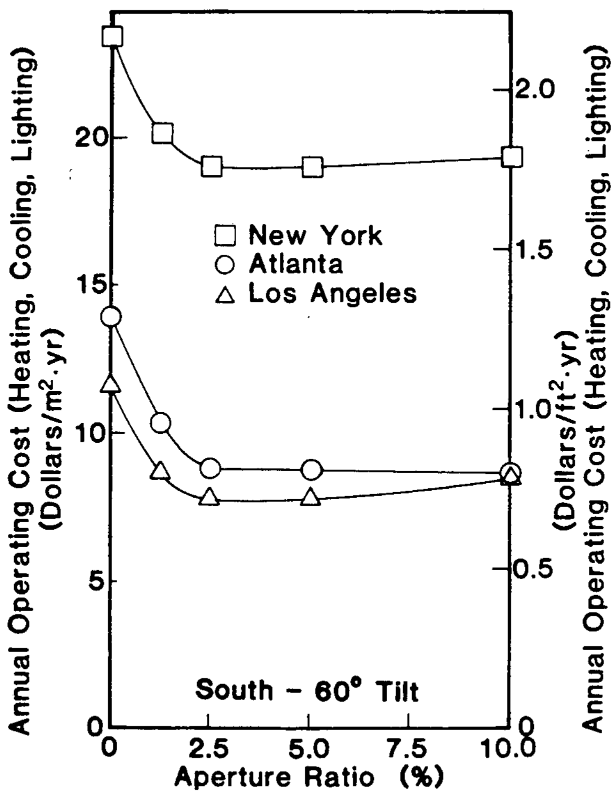


Figure 7. Annual operating costs for the prototype building of Fig. 6, computed for the same three cities and plotted against aperture ratio. (XBL 831-7675B)

PLANNED ACTIVITIES FOR FY 1983

Convection Research

The numerical simulations will be used for further studies of natural convection heat transfer from interior surfaces, and results will be used to produce correlations applicable to enclosure configurations and surface temperature distributions other than those studied in FY 1982. This work is expected to lead to a set of correlations applicable to geometric and thermal configurations of major interest, and will improve substantially the predictions of thermal loads in buildings. Turbulence model verification against data from wind tunnel tests conducted by the Florida Solar Energy Center in conjunction with Colorado State University is also expected to be completed in this period.

Construction of a full-scale, fully instrumented Multichamber Infiltration and Ventilation Efficiency (MIVE) facility is planned in FY 1983, in collaboration with two other groups in the E&E Division at LBL. Experimental research on interzone air flow driven by natural convection, wind infiltration, and/or mechanical ventilation systems will be conducted in the MIVE facility, using state-of-the-art instrumentation. Data from this facility will be used to further validate the convection analysis computer program, thereby enhancing confidence in the heat transfer correlations being developed.

Radiative Cooling

The sky emissivity measurements will be used to develop a computer algorithm for predicting the average monthly sky temperature depression below the ambient air temperature. This algorithm, including the effects of cloud emissivity, will be used with average hourly weather data from TMY weather tapes to construct contour maps of the United States showing the monthly sky temperature depression. In addition, histograms will be developed to show the distribution of this quantity over the hours of the day for each month.

Substantial effort will be devoted to the conceptualization of radiative cooling assemblies and to the evaluation of their thermal performance. In particular, the need for new materials such as wavelength selective radiators and infrared transparent glazings will be assessed and performance goals established.

Commercial Building Energy Analysis

A number of additional research pursuits are planned for FY 1983. We intend to: (1) extend the technology assessment analyses to include additional building types and passive cooling technologies (specifically, radiative-cooling and earth-contact strategies); (2) conduct parametric simulation analyses to determine the sensitivity of commercial building energy performance to selected design and use parameters and determine correlations between energy performance and climate; (3) continue investigation of daylighting, ventilation, and evaporation technology analyses with increased focus on synergistic combinations, system integration, and thermal comfort issues; (4) conduct a detailed simulation-based reanalysis of selected buildings that were designed and constructed under the DOE-sponsored passive commercial buildings program.

Natural Lighting

The natural lighting studies carried out in FY 1982 will be extended to examine the effect of variations in the input parameters, in order to determine the sensitivity of the energy consumption and cost predictions to various assumptions in the analysis. Among the factors to be examined are: thermal comfort controls, glazing characteristics, internal surface treatments, and dirt accumulation on the glazing. These studies will help define (1) the validity of the work done to date and (2) areas of emphasis in refining the design of daylighting systems. In addition to these sensitivity studies, the roof aperture work will be extended to other glazing tilts and orientations, as well as combinations of glazing orientations, and it will also consider more sophisticated techniques such as special glazing materials, reflector enhancements, and movable shading and insulation elements.

REFERENCES

1. Bauman, F.S., Gadgil, A.J., Kammerud, R.C., Altmayer, E.F., and Nansteel, M.W. (1983), "Convective Heat Transfer in Buildings: Recent Research Results," to be published in *ASHRAE Transactions 89,* 1, Lawrence Berkeley Laboratory Report LBL-13883.
2. Gadgil, A.J., Bauman, F.S., and Kammerud, R.C. (1982), "Natural Convection in Passive Solar Buildings: Experiments, Analysis, and Results," *Passive Solar Journal 1,* 1, Lawrence Berkeley Laboratory Report LBL-9297 Revised.
3. Altmayer, E.F., Gadgil, A.J., Bauman, F.S., and Kammerud, R.C. (1982), "Correlations for Convective Heat Transfer from Room Surfaces," submitted for presentation to ASHRAE Semiannual Meeting, Washington, D.C., 26-30 June 1983, Lawrence Berkeley Laboratory Report LBL-14893.
4. Nansteel, M.W. (1982), *Natural Convection in Enclosures,* Ph.D. Thesis, Department of Mechanical Engineering, University of California, Berkeley.
5. Martin, M.R. and Berdahl, P.H. (1982), *Summary of Results of Spectral and Angular Sky Radiation Measurement Program,* Lawrence Berkeley Laboratory Report LBL-14913.
6. Martin, M.R. and Berdahl, P.H. (1983), "Results of Spectral and Angular Sky Radiation Measurement Program," to be published.
7. Berdahl, P.H., Martin, M.R., and Sakkal, F. (1983), "Thermal Performance of Radiative Cooling Panels," to be published in *Intl. J. Heat & Mass Transfer.*
8. Carroll, W.L., Webster, T.L., Mertol, A., Andersson, B., Kammerud, R.C., Place, J.W., Martin, M.R., Peterson, J., Mangeng, C., Roach, F., Whiddon, W.I., and Hart, G.K. (1982), *Passive Cooling Technology Assessment:* Synthesis Report, Lawrence Berkeley Laboratory Report LBL-15184.
9. BLAST (Building Loads Analysis and System Thermodynamics) is trademarked by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.
10. Andersson, B.A., Carroll, W.L., and Martin, M.R. (1982), "Aggregation of U.S. Population Centers into Climate Regions," in *Proceedings,* 7th National Passive Solar Conference, 30 August - 1 September 1982, Knoxville, Tennessee, Lawrence Berkeley Laboratory Report LBL-14351.
11. Place, J.W., Fontoynont, M., Conner, C.C., Kammerud, R.C., Andersson, B.A., Bauman, F., Carroll, W.L., Howard, T.C., Mertol, A., and Webster, T.L. (1982), "Daylight Strategies," presented at Passive and Hybrid Solar Energy Update Meeting, 15-17 September 1982, Washington, D.C., Lawrence Berkeley Laboratory Report LBL-14946.
12. "Typical Meteorological Year User's Manual: Hourly Solar Radiation — Surface Meteorological Observations," TD-9734, National Climatic Center, April 1981.

ACTIVE SOLAR COOLING*

M. Wahlig, K. Dao, M. Warren, J. Rasson, R. Armer, A. Heitz,† and F. Salter

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

Absorption Chiller Research

The objective of the research activity on absorption cycles is to achieve a significantly higher conversion efficiency than is possible using other approaches for solar cooling and heating of buildings. Being essentially heat pumps, absorption-cycle chillers can be used for heating as well as cooling, if the refrigerant fluid does not freeze in the outdoor coil during heating applications. We restrict our fluid choices to those for which this heating option is available.

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

In the second phase, a completely new solar single-effect chiller[2] was designed, fabricated, and tested, using the experience gained during the first phase. This new ammonia/water chiller had several unique features for recouping thermal and mechanical energy. The report on this phase is essentially completed and should be available in March 1983.

In the third phase, we are investigating the performance improvement obtained by adding a unique second effect to the single-effect chiller tested in the second phase. The basic concept of the resulting double-effect regenerative cycle (or cycle 2R) has been described previously.[3] This 2R chiller has been designed,[4] fabricated, and assembled; the debugging and testing will be carried out during FY 1983.

During the fourth phase of the research, investigations will be carried out of a new concept in refrigeration absorption cycles, having still higher efficiency while requiring less heat-exchanger area, for a potentially lower cost. The basic concept of this single-effect regenerative cycle (which we call cycle 1R) has also been described previously.[5] The success of the cycle 1R chiller depends on our experience in developing the cycle 2R chiller. Locating a refrigerant-absorbent fluid pair with suitable properties at 300°F or higher should further increase the efficiency of the 1R chiller.

Systems and Economics Analysis

The objectives of the systems and economics analyses are: to establish cost goals for active solar cooling and heating technologies based on the present value of future energy savings; to assess the current state of solar absorption and Rankine cooling technologies; to analyze the results of computer simulations to determine where improvements can and must be made in thermal and electrical performance; and to make recommendations on research needs to develop cost-effective active solar cooling technology.

Technical Support Activities

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

ACCOMPLISHMENTS DURING FY 1982

Absorption Chiller Research

Conclusions of Research on the Single-Effect Chiller

Detailed analysis of the experimental data from the single-effect chiller tested in 1981 has been com-

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

†Head of Heitz Energy Engineering, Inc.

pleted. The evaluation of the chiller and the resulting recommendations have been incorporated in a report that should be available in March 1983.

Conclusions presented in the report include the following:

1. The amount of heat available in the hot ammonia vapor generated should be recuperated in the preheater to increase the coefficient of performance (COP) by about 15% compared to conventional chiller designs.
2. The amount of work available in the high-pressure strong absorbent returning to the absorber should be recuperated in a piston driver to reduce parasitic pumping power (for solar-driven operating conditions) from about 150 watts/ton to 50 watts/ton.
3. For ammonia-water solutions in sensible, boiling, and absorption heat-exchange processes, conventional correlations using Nusselt, Reynolds, Prandtl, and friction factors can be used to predict (with an acceptable accuracy of ±20%) the overall heat-transfer coefficients and pressure-drop characteristics of the components. For two-phase flow regimes, the Lockhart-Martinelli and Shah correlations are applicable.
4. Detailed operating characteristics of the chiller can be accurately (±5%) predicted by computer simulation. The computer simulation proposed in the report produces results that match all experimental runs to within:

   ±2°F for all absolute temperatures
   ±5% for all differential temperatures
   ±5 psi for all absolute pressures
   ±10% for all differential pressures
   ±2% for all mass flow rates
   ±5% for all amounts of heat exchanged.

   These errors are also of the same order as the experimental errors. Computer simulations can thus definitely be used as a design tool for the next generation of single-effect absorption chillers, even though heat-transfer and pressure-drop characteristics can be validated only to ±20% error.
5. Control of the chiller should be studied carefully to further improve chiller performance. In particular:
   - The condenser/absorber fan speed should be controlled to match the cooling load for reduced parasitic power.
   - The liquid-ammonia expansion valve should be modulated to match the leaving chilled-water temperature at reduced cooling load.
   - The leaving chilled-water temperature should be allowed to rise when the input hot-water temperature is low, at least partially satisfying the load and thereby assisting the back-up cooling unit.

In other words, although the proper strategy for controlling the chiller should be an integral part of the solar cooling system, it has yet to be fully thought out. An increase of about 30% in seasonal output of the chiller should be obtainable with good control strategy.

The 2R Chiller

The fabrication and installation of the 2R chiller have been completed. Figure 1 is a photograph of

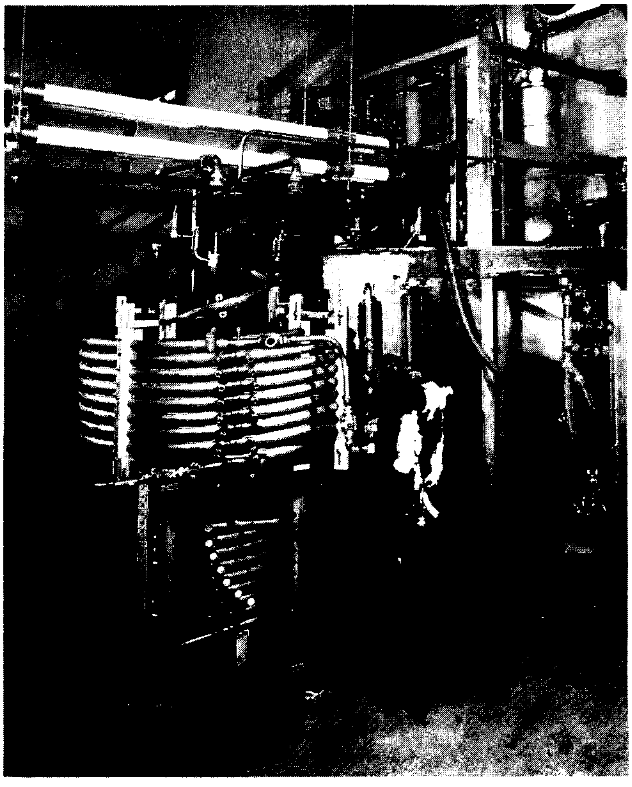


Figure 1. The cycle 2R absorption chiller being assembled in the LBL Experimental Chiller Test Facility.
(CBB 826-5078)

the installation in the laboratory test facility. Debugging was started at the end of FY 1982. The single-effect subcycle of the 2R chiller will be tested first, and modified as necessary until it runs reliably and efficiently, before the regenerative effect of the 2R cycle is tested. This should eliminate an appreciable fraction of the potential operating problems before testing the 2R chiller as a whole.

Candidate Fluids for the Cycle 1R Chiller

Under DOE contract and LBL guidance, SRI International conducted a literature search during FY 1981 and followed up with experimental measurements of the properties of absorbent and refrigerant fluids previously identified by LBL to be candidates for high-temperature (260 to 360°F) operation of a cycle 1R chiller. These measurements were completed during FY 1982, and the suitability of these fluids for cycle 1R operation will be evaluated during FY 1983.

Systems and Economics Analysis

Principal accomplishments during FY 1982 include analyzing the electrical and thermal energy performance of both commercial and residential absorption and Rankine cooling systems, establishing quantitative cost goals and estimates of advanced solar and conventional system costs, developing research recommendations for the most promising cooling technologies, and refining the cost goal methodology to include the effects of taxes and depreciation.

The thermal and electrical characteristics of absorption and Rankine solar-fired cooling systems have been evaluated[6-8] for a number of system concepts, including single- and double-effect absorption systems, and Rankine turbines driving a mechanical compressor with and without electric power generation. Three heat rejection options were considered: air cooling, evaporative cooling, and use of a wet cooling tower. Both commercial systems (25 tons of cooling for a seven-zone light commercial office building) and residential systems (3 tons of cooling for a single-story residence) were evaluated. The systems analysis is based on recent computer simulations[9] in four cities representative of different climate regions: Miami, warm and humid; Phoenix, hot and dry; Fort Worth, warm and humid with mild winters; and Washington, D.C., warm in summer and cold in winter.

If solar cooling is to become a viable technology in the marketplace, the costs of today's systems must be reduced and the electrical and thermal performance must be improved. Four measures can and must be applied:

(1) Improve the thermal performance of the systems;
(2) Improve the electrical performance by reducing the parasitic power consumption;
(3) Decrease the costs of the major system components; and
(4) Achieve system integration to reduce the number of components in the system.

Thermal Performance Improvement

The thermal performance of active solar cooling systems can be improved by increasing the thermal coefficient of performance (COP) of the absorption-cycle or Rankine-cycle chillers, thereby reducing the solar heat input, collector area, and heat-rejection requirements for meeting a given fraction of the cooling load. The efficiency of the collector system can also be improved.

Advanced evacuated tube collectors with parabolic concentrating reflectors will have improved performance at the high temperatures needed for many active solar cooling applications. The operating performance of systems can be improved by application of control strategies such as variable flow-rate control in the collector loop, chilled-water reset, capacity modulation, spin down, and applying microcomputer control techniques. The thermal performance of the system can also be improved by applying storage strategies to obtain better matching between resource and load.

Advanced absorption chillers presently under development, if successful, will operate at higher temperatures with improved performance; these include the double-effect lithium bromide-water chiller with COP = 1.1 at 260°F and the water-ammonia regenerative chillers with COP = 1.25 at 280°F ("2R") and with COP = 1.55 at 280°F ("1R").

The thermal performance of Rankine-cycle systems can be improved by operation at higher temperatures and by development of more efficient expanders (e.g., turbines) and compressors. A Rankine cooling system with minimal storage and electric power generation with utility interface can obtain better utilization of the solar resource than a system without power generation.

Electrical Performance Improvement

A crucial issue in the development of cost-effective solar-fired absorption and Rankine cooling systems is the reduction of parasitic power consumption. The electric energy consumption of the chiller system consists of energy to run the collector loop; energy to run the heat-rejection loop; energy to run the chilled-water loop; and energy to run the internal chiller pumps (e.g., the feed pump for a Rankine chiller, or the solution and refrigerant pumps for an absorption chiller). The electrical energy consumption can be reduced by proper design and sizing of pumps, piping, and heat exchangers.

For Rankine-cycle systems with electricity generation, the mechanical and electrical losses can be kept to a minimum by means of high-speed direct coupling of turbine and generator and by the use of unloading or pressure reduction to minimize windage losses (friction of the turbine or compressor spinning without power or load).

The electrical energy required to reject heat to the environment depends on the type of sink used (wet cooling tower, air-cooled dry coil, or wet-coil evaporative cooler); the amount of air movement; and the fluid pumping power required. The wet cooling tower is efficient in approaching ambient wet-bulb temperatures with minimum fan power, but fluid pumping energy is required. In many applications, an air-cooled condenser is preferred; however, the air-coil fluid cooler requires movement of a larger volume of air than does a wet cooling tower to remove the same amount of heat. The evaporatively cooled direct condenser coil achieves a good approach to the wet-bulb temperature and has the lowest combined fan and fluid pumping power requirement.

Because almost twice the heat must be rejected by a solar-fired cooling system compared to a conventional electric-powered system for the same efficiency of heat rejection, roughly twice the fan energy will be required. Improving the thermal performance of the solar-driven chillers clearly helps to reduce the limitation that heat rejection places on the energy savings for active solar cooling systems.

Cost Reduction

For active solar cooling to be a viable technology, the costs of the major components must be reduced. Absorption- or Rankine-chiller costs can be reduced by volume production and careful packaging. System control costs can be reduced by applying integrated microcomputer control with fewer sensors. The cost of high-performance evacuated-tube or linear-trough concentrating collectors must be reduced to about $9/ft^2, if the value of solar heat collected is to be competitive with natural gas. For operation at lower temperatures, the cost of plastic-laminated-film flat-plate collectors must be reduced to about $5/ft^2.

System Integration

A high degree of integration must be achieved in active solar cooling systems to eliminate duplication of function and to minimize the number and size of components. Careful packaging of equipment can minimize the number of pumps and valves and reduce the piping runs to a minimum. Careful integration of the control of system functions can minimize the number of sensors required and maximize reliability. Using a direct-fire backup of an absorption chiller in both the cooling and heating modes will efficiently use natural gas as a backup fuel.

Incremental System Costs and Cost Goals

In FY 1982, work continued on refining the cost-goal methodology[10] based on the discounted present value of future energy savings and the assumption of a 20-year system life and 20-year, 9-year, and 5-year payback periods. Estimates were made of the energy savings, incremental cost goals, and incremental system costs. Table 1 summarizes the estimated system costs and the projected cost goals based on the Science Applications, Inc. (SAI) simulation analysis for high-temperature (300°F) second-generation Rankine turbine systems.

Table 1. Comparison of system costs and year 2000 cost goals (in 1981 $) for variations of a high-temperature (300°F), second-generation Rankine turbine system in Phoenix.

Evap. Temp./ Cond. Type	Area (m^2)	System Incremental Cost[a] ($)	Incremental Cost Goal: 20-yr payback ($)	9-yr payback ($)	5-yr payback ($)
45°F/evap	232	78 066	98 949	50 353	26 370
55°F/evap	232	78 066	109 034	55 486	29 057
55°F/water	232	78 066	94 082	47 877	25 073
55°F/air	232	78 066	78 886	39 126	20 490

[a]Costs of evaporatively cooled and air-cooled units should be comparable to those of the water-cooled units.

Evaporatively cooled condenser systems outperform both water-cooled (wet-cooling-tower) and air-cooled systems. Where possible, evaporative cooling should be used for heat rejection. Estimates of the costs of evaporatively cooled condensers should be made. The systems that operate at an evaporator temperature of 55°F save more energy than those operating at 45°F. The high-temperature advanced Rankine turbine systems should pay back in less than 20 years in the year 2000.

Technical Support Activities

Solar Cooling Program Planning

The following are among the major planning activities carried out during FY 1982:

- Prepared documents on key accomplishments, present status, and future directions of the active solar cooling research and development program.
- Participated in major program planning and review meetings for the DOE Active Heating and Cooling Division, including plans for FY 1982, FY 1983, and future years.
- Made presentations on the overall DOE solar absorption and Rankine cooling program.

Technical Monitoring

The following are some of the major FY 1982 activities by LBL in providing technical monitoring and evaluation of solar cooling projects by outside (non-LBL) contractors:

- Conducted 23 site visits and project reviews covering 14 DOE contractors.
- Reviewed six final reports and topical reports and three follow-on proposals.
- Interacted with many of the solar cooling contractors at SAN and LBL meetings with individual contractors; in addition, numerous technical discussions with contractors took place by phone and by mail.
- Prepared and sent to DOE/SAN monthly summary reports on all the DOE solar absorption and Rankine cooling projects and related projects.

Proposals for New Work

One unsolicited proposal review was conducted by LBL during FY 1982, with the resulting recommendation for action being forwarded to DOE/SAN.

Coordinating Activities

The following coordinating activities were carried out during FY 1982:

- Worked in support of DOE/SAN and ETEC (Energy Technology Engineering Center) to coordinate the technical monitoring of eight solar-cooling Operational Test Sites, including numerous meetings, site field visits, and reporting.
- Participated in the redirection of the U.S.-Mexican solar-refrigeration project, through a joint meeting in Mexico City of U.S. and Mexican technical experts, followed by first steps in the execution of the resulting joint project plan.
- Participated, as a member of the Heat Pump Integration Task Force, chaired by John Ryan of DOE/HQ, which effort culminated during FY 1982 in a report and presentation on promising future directions for an integrated program in absorption and chemical heat pumps.
- Participated in Organic Rankine-Cycle Coordination Meeting hosted by the Jet Propulsion Laboratory.
- Held frequent discussions with SERI (Solar Energy Research Institute) staff members responsible for technical support of the solar desiccant cooling program, to coordinate reports and presentations on the overall solar cooling program (including absorption, Rankine, and desiccant elements).
- Held discussions with ORNL staff for the purpose of coordinating the absorption-heat-pump activities supported by DOE/Conservation (for which ORNL has technical support responsibility) with the absorption-cooling activities supported by DOE/Solar.
- Participated in several meetings per month at SAN to coordinate LBL's technical support with SAN's program management responsibilities for the solar cooling program.

PLANNED ACTIVITIES FOR FY 1983

Absorption Chiller Research

Testing of the 2R chiller will continue throughout most or all of FY 1983. Anticipated problems include:

- Instability of operation because of unequal flow distribution into the successive absorption stages.,
- Low effective generator temperature because of fluctuating vapor flow rates into the absorption channels of the generator.
- Low effectiveness of the recuperator

because of incomplete absorption in the low-pressure channel of the recuperator.

All of these problems should be correctable using suitable flow-control devices. For the moment, it is intended to test the 2R chiller with the simplest flow-control devices, namely, simple, properly sized orifices.

If testing of the 2R chiller is successful, as predicted, design of the 1R chiller would be started late in FY 1983.

Systems and Economics Analysis

Systems and economics analysis of advanced active solar cooling systems will continue in FY 1983 in cooperation with the Active Program Research Requirements assessment. Work will focus on detailed analysis of absorption and Rankine solar cooling systems and on defining technical issues that must be addressed. We plan continued development of in-house capabilities for systems simulation and analysis of active cooling systems, including evaluation of the impact of chiller control strategies on system performance and energy savings.

Technical Support Activities

The technical support activities in FY 1983 will be similar to those carried out during FY 1982. Program planning will continue to be an important task as the respective future roles of the Administration and of Congress in setting program directions become clarified. The major documentation task of describing the accomplishments of the national solar heating and cooling program since its inception, which was to have been written during FY 1982, has been delayed and is now expected to be completed during FY 1983.

Site visits to solar cooling contractors and review of topical and final reports will continue. A number of existing projects are expected to conclude during FY 1983. At the same time, several expected program solicitations during FY 1983 should result in several new active cooling projects. LBL will be involved in helping to draft technical scope statements for these solicitations and in technical review of the proposals received. In addition, reviews of unsolicited proposals will continue to be conducted as received.

Coordination activities with other organizations involved in similar programs will continue to be pursued with high priority. The importance of this coordination increases as the total resources available to the DOE/Solar and DOE/Conservation programs decrease.

REFERENCES

1. Dao, K., Simmons, M., Wolgast, R., and Wahlig, M. (1977), *Performance of an Experimental Solar-Driven Absorption Air Conditioner,* Lawrence Berkeley Laboratory Report LBL-5911.
2. Dao, K., Wolgast, R., and Wahlig, M. (1979), *Development of Solar-Driven Absorption Air Conditioners and Heat Pumps,* Lawrence Berkeley Laboratory Report LBL-9630, p.15.
3. Kao, K. (1978), *Conceptual Design of an Advanced Absorption Cycle:* The Double-Effect Regenerative Absorption Refrigeration Cycle, Lawrence Berkeley Laboratory Report LBL-8405.
4. Dao, K., Wahlig, M., and Wali, E. (1980), *Development of Solar Driven Absorption Air Conditioners,* Lawrence Berkeley Laboratory Report LBL-11175, p.3-27.
5. Dao, K. (1978), *A New Absorption Cycle:* The Single-Effect Regenerative Absorption Refrigeration Cycle, Lawrence Berkeley Laboratory Report LBL-6879.
6. Warren, M.L. (1982), *Active Program Research Requirements for Water and Air Cooled Closed Cycle Commercial Absorption Systems,* LBID-651.
7. Warren, M.L. (1982), *Active Program Research Requirements for Commercial Solar Rankine Cooling Systems,* LBID-650.
8. Warren, M.L. (1982), *Active Program Research Requirements for Residential Solar Absorption and Rankine Cooling Systems,* LBID-652.
9. Choi, M., Morehouse, J. (1982), *Analysis of Commercial and Residential Solar Absorption and Rankine Cooling Systems,* Science Applications, Inc., Draft Final Report for Contract No. DE-AC03-81SF11573.
10. Warren, M.L., and Wahlig, M.A. (1982), *Cost and Performance Goal Methodology for Active Solar Cooling Systems,* LBL-12753.

MOLECULAR ASPECTS OF LIGHT-ENERGY CONVERSION BY BACTERIORHODOPSIN*

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Cells have developed several mechanisms for transducing and storing energy: some use them for harnessing solar energy. In the last few years, we have studied one of the simplest and most stable biological solar-energy converters known: bacteriorhodopsin (bR); Fig. 1 shows its structure. This pigmented protein catalyst can be found in the cell membrane of *Halobacterium halobium*, a bacterium that requires high concentrations of salt to survive. Our research program is attempting to determine the molecular details of how this protein utilizes light from the sun to produce an electrical current across the bacterial membranes. We anticipate that such understanding will ultimately lead to the production of novel photoelectric cells and solar batteries.

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

Light generates an electric (proton) current across the bR-containing "purple membrane" patch found in the cell membrane of these bacteria. We are attempting to elucidate how the molecular structure of bR gives this protein the capacity of converting visible-light energy into a proton current.

The purple membrane is made up exclusively of bR and lipids: the retinal chromophore in bR is attached to a lysine (amino acid) in the protein by a protonated Schiff's base linkage. Following a flash of light, the chromophore undergoes a photocycle in which several intermediates have been identified by their distinct absorption bands. Resonance Raman studies have shown that the appearance of one of these intermediates (designated M_{412}) is accompanied by the deprotonation of the retinal's Schiff's base linkage to the protein. Since, in the presence of light, bR functions as a proton (H^+) pump, it is commonly believed that the chromophore could be directly involved in the proton-pumping activity.

Whether or not other protonatable amino acid residues found in bR are involved in the mechanism of proton pumping across this protein is currently being investigated by a few groups around the world,

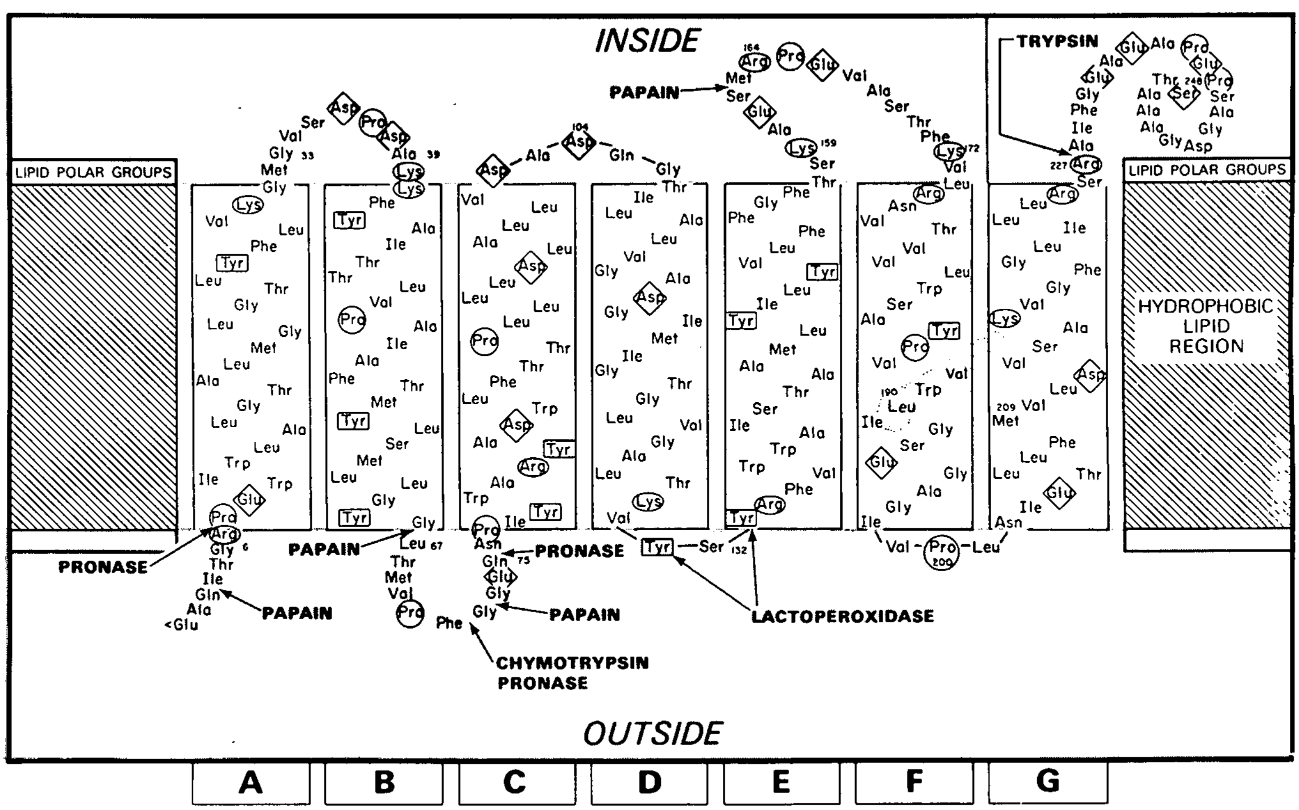

Figure 1. Amino acid sequence and membrane localization of bacteriorhodopsin.
(CBB 831-149)

including ours. Such information would be extremely important in any attempt to correlate the molecular events that occur during the photocycle, and would in fact be essential in the development of molecular models of photochemical conversion.

ACCOMPLISHMENTS DURING FY 1982

White Membrane Studies

Last year, we reported[1] that we were initiating studies with a mutant species of halobacteria which forms a membrane patch that apparently contains the apoprotein portion of bR but totally lacks retinal. Upon addition of all-*trans* retinal, this white mutant (R_1mW) of *H. Halobium* can reconstitute the functions of bR in intact cells.[2] The "white membrane patch" isolated from these cells forms a chromophore with λ_{max} of about 568 nm after reconstitution with stoichiometric amounts of retinal.

Under acid conditions, bacteriorhodopsin is known to undergo a transformation to a species absorbing with a λ_{max} of about 600 nm. This may involve carboxyl groups of amino acids. Difference spectra of the formation of this species show a positive maximum at 640 nm. The formation of this acid species is favored by low ionic strength, low pH, and high temperature. One of the intermediates of the photocycle (O_{640}) has been proposed to be similar, if not identical, to the acid-induced species, since it displays the same dependence on pH and temperature. Our recent studies suggest that the acid-induced species observed in reconstituted white membranes is similar, if not identical, to that of purple membranes; however, they also indicate that the pK of the transition is significantly higher in the reconstituted white membranes.[3]

The flash-induced absorbance increase at 640 nm in both purple and reconstituted white membranes was compared at different temperatures. Both preparations show stabilization of the O intermediate at higher temperature, thus confirming that the O intermediate of the reconstituted white membranes is similar to that of purple membranes. However, the 640 nm absorbance increase is larger in the reconstituted white membranes under the various temperatures studied, suggesting that the O intermediate is stabilized in the reconstituted white membranes.

It is known that the acid-stabilized species contains a higher percentage of 13-*cis* retinal and that low pH facilitates the light-dark adaptation rate of bR in native purple membranes. The dark-adapted form contains a much greater percentage of 13-*cis* retinal compared to the light-adapted form. Our results, however, show[3] that the rate of dark adaptation is considerably enhanced in reconstituted white membranes with a $t_{1/2}$ of about 2 minutes compared to 60 minutes for native purple membranes.

Thus, the results of these investigations show that certain properties of reconstituted white membrane patches differ from those of native purple membranes. These differences might be caused by stabilization of the 13-*cis* conformation of retinal in the reconstituted white membranes. In any case, it seems unlikely that they arise from differences in amino acid composition of bacteriorhodopsin in the mutant since the R_1mW strain of *H. halobium* is a spontaneous mutation that involves synthesis of retinal. In agreement with our suggestions at the time,[3] the studies described below provide further evidence that the differences might be due to changes in the lipid-protein interactions in the two systems.

Protein Chemistry Studies†

Using the technique of SDS polyachrylamide gel electrophoresis, we compared native purple membrane preparations with white membrane preparations. When the gels were run for white membrane patches, we found that only one major protein peak was obtained whose speed of migration on the gel coincided with that of the single band found in the native purple membranes.

To determine if this apoprotein in white membrane closely resembled the bR protein molecule, we resorted to the technique of peptide mapping, previously used by the Cambridge group. Delipidated white membrane and purple membrane proteins were succinylated with ^{14}C-succinic anhydride before specific enzymic cleavage. The peptides were chromatographed, and the characteristic patterns were analyzed by radioautography. Bacteriorhodopsin's characteristic pattern showed a close resemblance to the radioautographs obtained for similarly treated white membrane preparations. These results strongly suggest that the apoprotein in the white membrane patches is not substantially altered from the native protein.

†Collaboration with Prof. R. Perham, Department of Biochemistry, University of Cambridge, United Kingdom.

Lipid and Lipid-Protein Interactions‡

We were able to show that the ^{31}P nuclear magnetic resonance pattern of white patches is similar at pH 7.0 to purple membrane patches, but differs from them at low and high pH. A lamellar hexagonal transition occurs in both membrane preparations at pH 2.0 in purple membranes and at pH 4.0 in white membranes. This correlates well with functional photocycle studies of white and purple membranes observed earlier, where the pHs of the O_{640} photocycle intermediates differ by some 2 pH units in the acid range.[3] In the high pH range (pH $>$ 8.5), the ^{31}P NMR spectrum exhibited a transition not observed in purple membranes. Again, this correlates well with changes in the visible spectrum of the chromoprotein of reconstituted white membrane patches at high pH not seen in purple membranes.

Infrared studies were made by means of a special technique for the preparation of wet thin-film specimens. The IR spectrum of the white membrane preparations is a function of temperature and pH. Again, the pattern found in white membranes was different from the native purple membrane in the region of the IR spectrum where phospholipid structural features should be observed. Preliminary infrared results of white membranes also show a change in the amide band below pH 5.0, indicating a lipid-protein transition at higher pH than in purple membrane patches.

Extraction of the lipids of the white membrane patches with organic solvents and spotting them on thin layer chromatographic plates further revealed that the pattern of the lipid composition in the white membranes substantially differs from that in the purple membranes.

We conclude from these studies that the differences observed in reconstituted white membranes from native purple membranes under different conditions of temperature and pH probably arise as a result of differences in lipids and lipid-protein interactions.

Circular Dichroism and Optical Absorption Spectral Studies§

White membranes show no optical activity in areas of the circular dichroism (CD) spectrum where contributions from retinyl-protein and chromoprotein-chromoprotein interactions would be expected. After reconstitution of white membranes, however, many of the distinctive features of the CD pattern due to retinyl-protein and chromoprotein-chromoprotein interactions developed. These included the formation of a negative exciton coupling band ascribed to chromophore interactions in the visible region. In the ultraviolet region, a sharp CD band at 265 nm was induced upon reconstitution of the white membrane.[4,5] This band was present only as a small shoulder in unreconstituted white membranes. The optical activity in this region is likely due to interaction of retinal with aromatic amino acid bands in the protein. The generation of this CD band in bleached purple membrane was not conclusively shown previously because of poorer resolution of this feature.

Chemical Modification Studies

Tyrosine

Last year,[1] we reported studies carried out at low temperatures[6] which showed that at least two (and perhaps more) tyrosine residues have some role in the blue shift in λ_{max} for iodinated bR. We concluded that a few tyrosine residues may be important in determining the color of native bR.

We have continued studies in the modification of tyrosines by using tetranitromethane (TNM).

Bacteriorhodopsin was modified by TNM at pH 8.0 by the method of Lemke and Oesterhelt. This results in a nitrotyrosine peak at about 360 nm and a blue shift in the chromophore. Under these conditions, the only nitrotyrosine residue that could not be reduced by dithionite was tyrosine-26, even though the blue shift remained, and we concluded that nitration of tyrosine-26 probably causes the blue shift. We found that the blue shift occurred only when light is present during modification.[7,8] Our results also suggest that modification of another tyrosine residue requires the presence of light at pH 5.5. Since normal nitration by TNM proceeds with the tyrosinate form of tyrosine, and since low pH did not inhibit this blue shift, the tyrosine residue modified must have an unusual pKa or else a different mechanism of reaction may be involved. That this reaction is totally light-dependent at pH 5.5, however, suggests that a complex of TNM with this special tyrosine might be a cause of this

‡Collaboration with Prof. D. Chapman, Biophysical Chemistry Department, Royal Free Hospital School of Medicine, University of London.

§Collaboration with Drs. N. Dencher and M. Heyn, Biophysical Chemistry Department, Biozentrum, University of Basel, Basel, Switzerland.

light-dependency: model system studies[9,10] show that, in the presence of light, TNM reacts with undissociated phenols. Chymotrypsin cleavage of the protein indicated that the residue modified was on the C_1 fragment (residues 72-248). Our method therefore allows a more specific modification of tyrosine using low pH and light.

Carboxyl

Two years ago[11] we reported results on the modification of the carboxyl group using carbodiimide. These studies have been extended.

Carboxyl groups on bR, in purple membranes, were covalently spin-labeled with Tempamine, using N-(ethoxycarbonyl)-2-ethoxy-1,2-dihydroquinoline as a highly specific coupling agent.[11,13] Spin-labeled bR (2 spins/mole) retained photocycling and proton pumping functions. Accessibility to paramagnetic broadening agents, $Fe(CN)_6^{-3}$ and Ni^{+2}, demonstrated the existence of two distinct spin populations in purple membranes: a highly mobile surface group quenched at low concentrations of these agents and buried immobilized groups whose ESR (electron spin resonance) signal remained at high quencher concentration. Treatment with denaturing agents greatly increased the mobility and quenching of these buried residues. A series of stearic acid spin labels bound to purple membranes was used to define the depth of paramagnetic interactions. $Fe(CN)_6^{-3}$ interactions were limited to surfaces whereas Ni^{+2} and Cu^{+2} effects extended into hydrophobic domains. A double modification procedure in which surface groups were first blocked selectively spin-labeled only a buried carboxyl group having a strongly immobilized signal. Comparison of the quenching behavior of stearic acids with this doubly modified sample indicated that one carboxyl residue is buried about 20 Å from the membrane surface. Cleavage of the carboxyl-terminal tail with trypsin increased the mobility of the spectrum, showing that this tail is moderately immobilized in the native structure. These data are consistent with tertiary-structure bR models that place carboxyls within hydrophobic domains of the protein-membrane matrix.

Secondary Structure Modeling of Bacteriorhodopsin**

**Collaboration with Dr. R. MacElroy, NASA-Ames Research Center, Moffitt Field, California.

Computer models for possible helix and β-pleated sheet secondary structures for the membrane-bound portions of the primary amino acid sequence of bR were constructed on the NASA-Ames molecular modeling system.[13,14] Models were analyzed to determine the positions of charged groups and identify the structures which cause these groups to extend in a common direction. The complete bR monomer was constructed by assigning secondary structures to the seven rods of the three-dimensional data according to the several schemes favored by current experimental evidence. For each model, secondary structures were chosen that could be rotationally oriented to exclude the projection of charged side chains into the lipid environment and pair opposing charges internally.

Diffraction amplitudes for two-dimensional projections of these models were calculated and compared with the 3.7 Å projection found experimentally to see whether the theoretically preferred orientations gave a better fit than other orientations and whether models with our choice of secondary structures gave a better fit than models composed only of α-II helices.

Further refinement of helix position was carried out using the interactive structural refinement procedure, and the best model has been selected. One of the favored models is shown in Fig. 2. Energy minimiza-

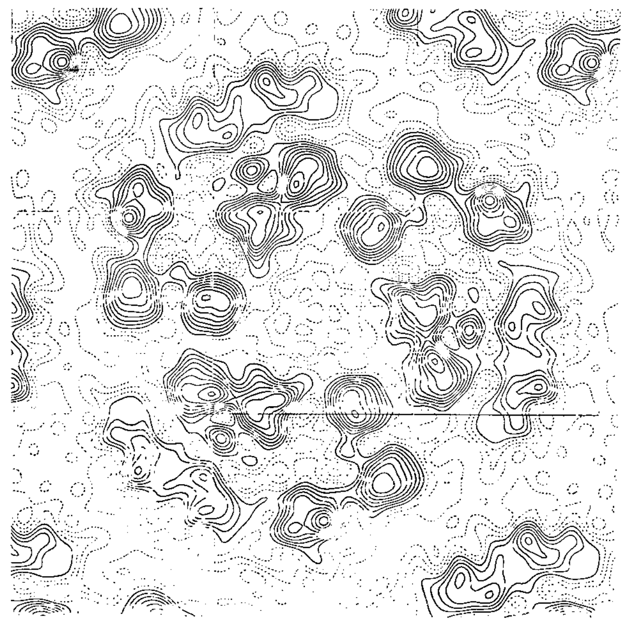

Figure 2. Computer simulated model of part of the bR molecule. (XBL 824-9354)

tion techniques will subsequently be used to explore the details of helix packing and side-chain positioning.

PLANNED ACTIVITIES FOR FY 1983

Collaborative work with Dr. Perham's group in Cambridge and Dr. Chapman's group in London will continue to focus on basic aspects of lipid composition and structure as well as lipid-protein and protein-protein interactions. These studies may help us to elucidate the differences between the reconstituted white membrane and the purple membrane.

White membranes will be used for chemical modification studies in attempts to identify those amino groups that are important for reconstituting the photo-cycling and H^+ pumping activity of the protein. These studies, in conjunction with spin labeling, will provide us with a deeper understanding of the general topography of the protein, which of course will be extremely important for any attempts at theoretical structural modeling of the system.

We will extend our flash photolysis system into the ultraviolet range in order to look at some of the reactions that involve protonation and deprotonation of aromatic residues in the protein. Our time resolution will also be improved so that earlier events in the photocycle become accessible to study.

Computer simulation studies will be pursued in collaboration with Dr. R. MacElroy. These studies will make use of the results obtained by chemical modification of the protein in terms of defining the overall topography of the system.

Our well-characterized chemically modified samples will be used for FTIR studies that will be conducted in collaboration with Drs. K. Rothschild and D. Chapman. These studies will concentrate on the overall conformational changes that accompany the photocycle as they may be resolved in time.

Photoelectric properties of both native and chemically modified samples will be explored in collaboration with the laboratories of Dr. Keszthelyi in Szeged, Hungary,[16] and Dr. Fahr in Berlin. We hope to be able to clarify the electrical events that accompany the translocation of protons across these proteins.

REFERENCES

1. Energy and Environment Division (1982), *Annual Report FY 1981*, Lawrence Berkeley Laboratory Report LBL-13500, p. 2-16.
2. Fry, I., et al., "Reconstitution of Light-Induced Ion Transport and Electrical Potentials by All-*Trans* Retinal in Membrane Vesicles of *Halobacterium halobium*," in preparation.
3. Lam, E., et al. (1982), "Comparison of the O_{640} Photo-Intermediate and the Acid-Induced Species in Membrane Patches from *Halobacteria halobium* S_9 and R_1mW Strains," *FEBS Lett. 146*, pp.. 106-110.
4. Fry, I., et al., "Structure of White Membrane Patches from *Halobacterium halobium* R_1mW Before and After Reconstitution of Bacteriorhodopsin with All-*Trans* Retinal Measured by Circular Dichroism," in preparation.
5. Packer, L., et al., "Circular Dichroism Studies of Tyrosine-Modified Bacteriorhodopsin," in preparation.
6. Iwawa, T., et al. (1983), "The Photoreaction of Tyrosine-Iodinated Bacteriorhodopsin at Low Temperatures," *Bioscience Reports* (in press).
7. Katsura, T., et al. (1982), "Light-Dependent Modification of Bacteriorhodopsin by Tetranitromethane. Interaction of a Tyrosine and a Tryptophan Residue with Bound Retinal," *Biochem. Internatl. 5*, pp. 445-456.
8. Katsura, T., et al. (1983), "Specific Modification of a Tyrosine Residue Involved in the Interaction Between Bacteriorhodopsin and Retinal," *FEBS Lett.*, in press.
9. Seltzer, S., Lam.E., and Packer, L. (1982), "Photonitration of Phenols by Tetranitromethane under Visible Light," *J. Amer. Chem. Soc.* (in press).
10. Lam, E., Seltzer, S., and Packer, L. (1983), "Light-Dependent Modification of Bacteriorhodopsin with Tetranitromethane," to be presented at Biophysical Society meeting, San Diego, February 13-16, 1983.
11. Energy and Environment Division (1981), *Annual Report FY 1980*, Lawrence Berkeley Laboratory Report LBL-1190, p. 2-15.
12. Herz, J.M., Mehlhorn, R.J., and Packer, L. (1983), "Topography and Mobility of Spin-Labeled Carboxyl Residues in Bacteriorhodopsin," to be presented at Biophysical Society meeting, San Diego, February 13-16, 1983.
13. Herz, J.M., Mehlhorn, R.J., and Packer, L., "Topographic Studies of Spin-Labeled Bacteriorhodopsin: Evidence for Buried Carboxyl

Residues and Immobilization of the C-Terminal Tail," submitted for publication.

14. Zwerling, H., et al. (1982), "A Computer Technique for Structural Studies of Bacteriorhodopsin," in *Methods in Enzymology* (L. Packer, ed.), Vol. 88, Academic Press, New York, pp. 772-784.
15. Baird, W., et al. (1983), "Secondary Structure Modeling of Bacteriorhodopsin," to be presented at Biophysical Society meeting, San Diego, February 13-16, 1983.
16. Packer, L., et al. (1982), "Electrical Signals in the Photocycle of Tyrosine Modified Bacteriorhodopsin," *Biochem. Intl. 5*, pp. 437-443.

LBL BUILDING 71 SOLAR COOLING PROJECT*

F. Salter

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

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

Overall administration is provided by the San Francisco Operations Office of the Department of Energy (DOE/SAN). DOE/SAN has subcontracted technical management of the project to Energy Technology Engineering Center (ETEC).

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

Table 1 summarizes the design parameters of the cooling system. In addition, the collector array will utilize Energy Design HP250 evacuated-tube solar collectors to accomplish the 250°F maximum design temperature. The collector design emphasizes simplicity and durability to minimize maintenance. This is essential, as access to the collectors will be restricted during operation of the Building 71 accelerator because of roof radiation. Fluid will be contained in continuous copper tubing so that glass-tube breakage

Table 1. Parameters of LBL Building 71 solar cooling project.

Chiller Capacity	22 tons
Chiller COP	0.73
Average Operation	6 hr/day (at 22-ton loading)
Generator Entering Water Temp.	185°F (adjustable 170°F to 200°F)
Exiting Chilled Water Temp.	45°F
Entering Condenser Water Temp.	80°F
Maximum Storage Temp.	250°F
Collector Area	5400 ft^2 (gross area)
Collector Type	evacuated tube collector
Storage Tank	2500 gallons
Thermal Ballast Tank	500 gallons
Expansion Tank	500 gallons

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

will not disrupt system operation, and tube replacement can be scheduled for periods when the accelerator is not operating. Further reliability is accomplished by using high-quality "Pyrex-type" evacuated tubes that are less prone to breakage. The collectors have no cover glass, making tube replacement easier.

ACCOMPLISHMENTS DURING FY 1982

The Final Design Review was held at LBL in December 1981. The project went to bid in early March 1982, and bids were opened on April 7, 1982. Additional funds were obtained to permit installation of the full project, and construction was started on June 7, 1982. The following construction had been accomplished by the end of FY 1982:

- The chiller package was modified, acquired, and placed in the mechanical room.
- The supporting steel framework for the solar collector was in place on the Building 71 roof.
- Most associated roofing work was complete.
- The concrete pad for the storage tanks was in place.
- Part of the electrical work was completed.

PLANNED ACTIVITIES FOR FY 1983

The solar collectors and the storage tanks are scheduled to be received in December 1982. The Building 71 accelerator will be shut down for the month of January 1983, and installation of the collectors and above-roof piping is scheduled for this period.

All project construction is scheduled for completion by March 1983. ETEC will provide acceptance testing shortly thereafter, in the latter part of March 1983. The Final Report should be completed in April 1983.

LBL will review system performance periodically thereafter, using Btu meters placed in the solar collector loop, the generator loop, and the chilled water loop.

SOLAR ENERGY SYSTEMS USING THE MICROSTRUCTURE OF MATERIALS*

A. Hunt, D. Evans, L. Hansen, L. Sariola, L. Simionesco, and D. Worth

INTRODUCTION

The goal of this program is to explore new avenues in the collection and control of sunlight and its conversion to other energy forms through the use of the microstructure of matter. The optical behavior (reflectivity, color, transmission, etc.) of bulk matter undergoes profound changes when the dimensions of the material approach that of the wavelength of light. This optical behavior may be used to advantage in systems that derive their energy from radiant sources, and in particular the sun.

A multifaceted program is in place to study optical interactions with the microstructure of materials. The three main elements of the program are: (1) the study of the direct absorption of concentrated sunlight by suspensions of small particles, (2) studies of microporous optical media, and (3) the investigation of the control and concentration of sunlight using diffractive optics based on holograms. All three elements share similar experimental and theoretical methodologies because of the central role played in each by the light scattering produced by the microstructure nature of the material. These program elements are described individually below.

I. SOLAR ABSORPTION BY SMALL PARTICLES

The concept of using a suspension of ultrafine particles to absorb concentrated sunlight has been under investigation at LBL for several years.[1] The central activity in this project has been the development of a high temperature gas receiver to utilize the energy in concentrated sunlight to heat a gas.[2] The Small Particle Heat Exchange Receiver (SPHER) operates by injecting a very small mass of fine carbon particles

*This project was supported by the Solar Thermal Test Facilities Users Association; the Solar Thermal Research and Advanced Development Program managed by the San Francisco Operations Office, the Office of Energy Systems Research, and the Passive and Hybrid Solar Division, all under the Assistant Secretary for Conservation and Renewable Energy; and the Director's Discretionary Fund though the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

into a working gas before it enters a windowed solar receiver. The particles absorb focused solar radiation and quickly transfer the heat to the surrounding gas. The mixture heats to a maximum temperature that is determined by the oxidation of the particles. The gas may be heated to medium or high temperatures suitable for operating a gas turbine for electrical power production or for supplying industrial process heat.

Last year, the first direct-absorption gas receiver, designated the SPHER, Mark I, was designed[3] and its construction started.[4] The receiver was designed to utilize 30 kW of concentrated sunlight to heat ambient air to temperatures above 700°C. To prove the concept, the receiver was to absorb 90% of the incoming sunlight in the gas-particle suspension, reducing the flux density on the receiver walls to 10% of the value it would have if no particles were present. The absorbing particles for this test were produced by the pyrolysis of acetylene.

A particle generator based on pyrolysis that was capable of supplying the necessary flow of particles for the test was developed in the laboratory.[5] After the laboratory generator was developed, it was rebuilt into a form suitable for field use.

The Mark I receiver was designed to operate using the central receiver solar concentrator at the Department of Energy Advanced Component Test Facility (ACTF) at the Georgia Institute of Technology. To design the receiver, measured data on the flux distribution of the ACTF was used to predict radiant flux on the receiver walls for various absorption chamber shapes and particle densities, using algorithms developed at LBL.[6] The receiver size and shape were varied to optimize the absorption within the chamber. The low flux loadings on the walls allowed the receiver to be constructed of stainless steel rather than the high-temperature alloys usually employed for such temperatures.

Accomplishments During FY 1982

This year, the SPHER program achieved a major goal with the completion and successful solar testing of the Mark I receiver. The design philosophy and construction of the receiver are discussed elsewhere.[7] Construction was completed in early January 1982, and the test was carried out at the ACTF during August and September. In the solar test of the Mark I, 550 one-meter-diameter mirrors concentrated sunlight by a factor of 2000 onto the 20-centimeter-diameter window of the receiver. The performance of the receiver was monitored by thermocouples, pressure transducers, and laser measurement devices to determine the absorption of the particle suspension.

Figure 1 is a schematic diagram of the experimental arrangement. The main components are the air supply system, particle generator, receiver chamber, sensors, and data acquisition system (not illustrated).

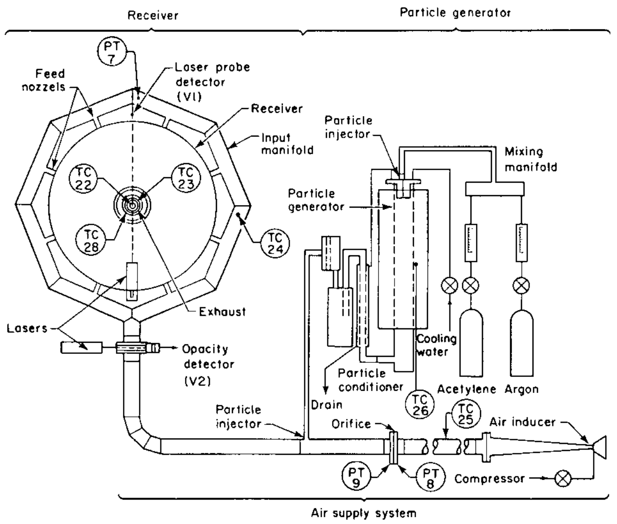

Figure 1. Schematic diagram of the experimental arrangement showing the three main components for the SPHER test. (XBL 8210-4782)

Ambient air to be heated is supplied by a Coanda-effect air inducer. This device produces a large flow of low-pressure air by using a small flow of higher-pressure air and provides an easily controllable and convenient source of air for the test. The mass flow rate of the air to the receiver was determined by measuring the pressure difference across a standard orifice plate. The particle generator produced a stream of carbon particles by the pyrolysis of acetylene in an argon carrier gas and injected them into the air supply system before it entered the receiver.

The temperature and pressure measurement points outside the receiver are also indicated in Figure 1. Temperatures inside the receiver were monitored by 26 thermocouples. A thermocouple with a four-component radiation shield determined the exhaust temperature. The receiver's power output was determined from the mass flow and the temperature rise. Solar input power was determined with a flux measuring system that was developed by the Engineering Experiment Station at the Georgia Institute of Technology. The system was designed to provide an accurate determination of the input flux by utilizing an array of water-cooled calorimeters mounted in a paddle assembly that could be slid directly in front of the receiver window. Unfortunately, because of the intense solar radiation, the operation of the calorimeters became erratic and they began to fail within the first few hours of testing. Therefore, it was not possible to obtain an accurate value for the input flux. However, the approximate power could be determined from other flux measurements taken under conditions similar to those of the test.

Test Results

Solar testing was conducted on 13 days for a total testing time of 35 hours. All the major test objectives were met. The maximum output gas temperature was 750° C, and the output thermal power exceeded 30 kW. "Burn out," or oxidation of the particles, was achieved. The test established that concentrated sunlight can be absorbed directly within a working gas by small absorbing particles. The test also established that a window can be successfully used in a high-temperature environment and that carbon build-up on the window was not a problem.

Figure 2 illustrates the test results by showing the chamber temperatures for two different carbon particle loadings. The temperature of the output gas is

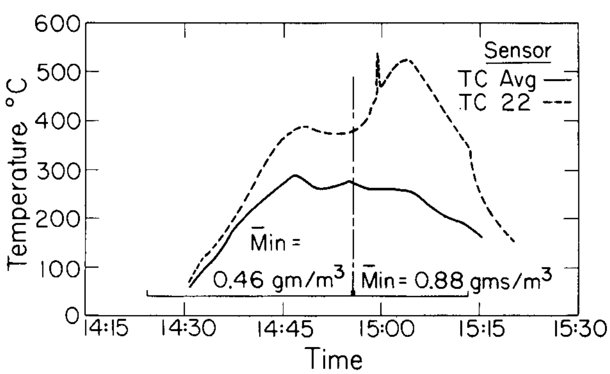

Figure 2. Exhaust gas temperature (TC 22) and average wall temperature (TC Avg) vs. time. The incoming particle density was increased from 0.46 to 0.88 gms/m^3 at 14:55. (XBL 8210-4783)

indicated by the dashed line, and the average interior-wall temperature by the solid line. It can be seen that the gas temperature exceeds the wall temperature over the entire run. In addition, the increase in density of the particle suspension (from 0.46 to 0.88 gms/m^3) at 14:55 was accompanied by a dramatic rise in the gas temperature with almost no increase in the wall temperature. The large difference in temperatures between the walls and the gas indicates that the gas particle suspension is being heated directly by sunlight and not by the walls.

Planned Activities for FY 1983

As a result of the SPHER test program, several phenomena and potential applications in the area of direct radiant heating of two phase suspensions by solar thermal power were identified for further investigation. Analysis of the test data indicates that the majority of the heating can be localized in the absorbing gas-particle suspension. This phenomenon may be the key to achieving very high temperature direct-radiant processing. This localized heating could be used to isolate high-temperature chemical reactions from reactor walls, thereby reducing the demands on wall materials. If an ongoing chemical process can be separated from actively cooled walls without quenching the reaction, ultra-high-temperature solar-driven reactions may become feasible.

To investigate local heating effects, we plan a more detailed study of the coupling of concentrated radiation to absorbing suspensions. This is an interesting and complex problem because the large temperature variations cause density fluctuations in the gas that, in turn, change the optical absorption of the suspension. If time and resources permit, we plan to develop methods to predict and measure the density fluctuations in the suspension in the presence of a strong radiant flux density.

The second area we plan to investigate is the use of direct radiant heating of particle suspensions to produce chemical reactions.[8,9] We have identified several chemical processes of industrial importance that may be adapted for direct radiant solar heating. These include the detoxification of chemical wastes, the processing of phosphate rock to make elemental phosphorus, and cement processing. We plan to make a preliminary experimental investigation of direct radiant processing of suspensions of chemical feedstocks in FY 1983.

In a related but somewhat different area, we plan to investigate the capability of small particle suspensions to simultaneously capture sunlight and provide catalytic sites for gas-phase reactions. This effort will be an expansion of the direct radiant heating work.

II. MICROPOROUS OPTICAL MATERIALS

Microporous optical material consists of a rigid matrix of nonabsorbing material with a pore size considerably less than a wavelength of light. Its density may be only a few percent of the density of the bulk material of which it is made. This material differs in a remarkable way from other porous materials in that it is highly transparent and has an effective index of refraction close to unity. The material is transparent because the pores are so small that they scatter very little visible light. It has a low index of refraction because propagating electromagnetic radiation responds to the *average* properties of the solid over dimensions comparable to the wavelength of light. The reflectivity of this material may also be very low because of its refractive index. Due to the low density and small pore size of this material, it is a very good thermal insulator.

The introduction of micropores into a solid opens new vistas in the materials science of the optical properties of solids. By varying the density, the index of refraction may be varied from the bulk value of the solid to nearly that of a vacuum. This offers a new degree of freedom for optical designers because it will be possible to specify the index of refraction of an optical element rather than being limited to existing materials. Graded index optical systems are possible by varying the local pore density of the material. Other approaches and processes in optics may benefit from the freedom of choice of the refractive index and low reflectivity.

For solar and conservation applications, the combination of transparency and low thermal conductivity makes the use of microporous materials for insulating windows and solar collector glazing very attractive. Microporous materials offer an alternative to conventional glazings in that they can replace double or triple pane glass with a package of similar thickness and transparency that possesses a higher R value.

The first transparent porous materials were made some time ago by using a process based on colloidal gels.[10] Materials prepared in this way are called aerogels. In this process, a colloid of the desired material is made sufficiently dense that the individual colloidal particles begin to link together. After cooling or aging, the material changes from a liquid state to that of a gel or jelly. The material is then a semisolid matrix of linked solids permeated by a liquid. Attempts to drive off the liquid by heating or drying inevitably lead to the collapse of the matrix, and the material shrinks to a fraction of its original size. This shrinkage occurs because, during drying, both liquid and gaseous states coexist in the matrix. Because of the very small size of the pores, surface tension effects between the gas and the liquid are very large, causing the structure to collapse during drying. The distinction between liquid and gas may be eliminated by raising the temperature and pressure of the liquid above its critical point. The resulting fluid may then be released from the gel without surface tension effects that would destroy the matrix. This process is referred to as supercritical drying.

Recently, interest in silica aerogels has resurged in Europe because of their application in Cherenkov detectors,[11] and a significant amount of material has been produced in Sweden.[12] Work started in this country[13] on using silica aerogels for windows, but it was discontinued. Several problems remain to be solved before these materials are ready for the commercial marketplace. While aerogels do not significantly interfere with directly transmitted light, they are slightly scattering, resulting in some haziness and color effects. Research in two main areas is required to improve the properties of aerogels before they may be used as glazing material. First, their physical and optical properties must be improved for them to gain widespread acceptance. Second, preparation techniques that are more suitable to mass production than the present laboratory technique need to be developed.

Accomplishments During FY 1982

Work was initiated on porous optical materials in the spring of 1982 as part of the microstructure studies program. Samples of microporous material were obtained, and measurements of their scattering characteristics were performed. An angular nephelometer was borrowed for intensity and polarization measurements. Initial results indicated that the material did not have an angular scattering distribution characteristic of Rayleigh scattering. The polarization measurements were complicated by the discovery of rather striking birefringent effects. This phenomenon has not been previously reported in the literature. To explain these scattering properties, a tentative model was developed that is based on density fluctuations over distances larger than the pore size of the material.

A research effort was initiated late in FY 1982 with the support of the DOE Passive Solar Program to develop techniques to produce transparent microporous materials and investigate their properties for insulating glazing applications.

Planned Activities for FY 1983

In a joint effort with the Windows and Daylighting Group of the E & E Division, an experimental facility is being constructed to produce samples of porous silica for experiments. Production of small amounts of this material is expected to begin early in FY 1983. Facilities for producing the material are being set up, and equipment for detailed optical and scattering measurements will be assembled in FY 1983. A primary focus of the effort will be to determine the causes of the residual scattering in the aerogel and to reduce it. Alternative materials and methods for producing microporous optical material will also be explored.

III. DIFFRACTIVE SOLAR COLLECTION SYSTEMS

This program element encompasses the use of diffractive optical devices to collect, redirect, and control sunlight.[14] Traditional solar collection systems rely on reflection or refraction of sunlight. The concept investigated here is based on using Holographic Optical Elements (HOE's) to intercept and diffract sunlight toward an energy conversion device, or on using HOE's as window or skylight coatings. Suitable energy conversion devices include photovoltaic cells or thermal receivers. Alternatively, a thin HOE coating may be placed on a window to diffract sunlight to an interior area that would not otherwise receive natural lighting.

A HOE is a simple type of hologram. The most familiar types of holograms act like 3-dimensional photographs and contain detailed information about the shape and lighting of the object. A HOE used for solar collection and control is more like a lens than a photograph. A simple HOE can be made by exposing a dye-sensitized emulsion to the interference between two beams of coherent light. Figure 3 illustrates two methods of making HOE's. Figure 3(a) illustrates the setup for making a transmission HOE that acts like a lens, and Figure 3(b) shows a method to make a reflection hologram that acts more like a mirror. The HOE characteristics are determined by the strengths and positions of the optical elements used to form the beams.

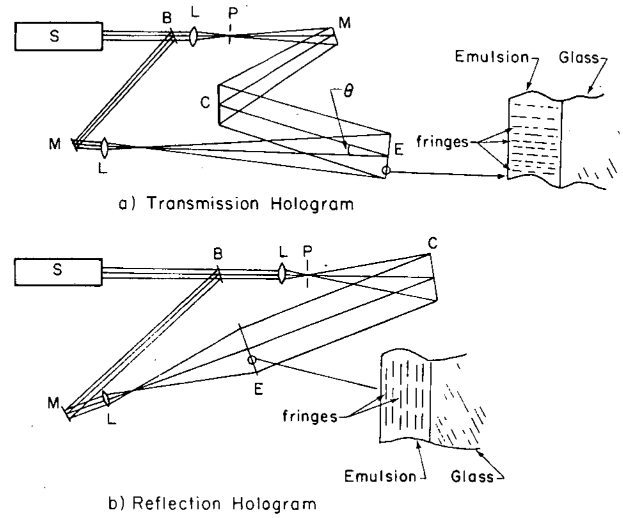

Figure 3. Typical holographic setup for (a) transmission hologram and (b) reflection hologram. Extreme enlargements of the emulsion cross sections are also shown. The components illustrated are the laser source S, beam splitter B, plane mirrors M, pinhole P, collimating mirror or lens C, emulsion E, and lenses L. (XBL 8211-7351)

Accomplishments During FY 1982

Our investigation of the properties of HOE's for solar applications falls into three main areas: basic studies of the characteristics of diffractive devices for solar applications, including their wavelength and angular dependence; analytical calculations of the performance of specific concentrating HOE's; and experimental work to measure the efficiency of HOE's for solar energy applications.

During FY 1982, the study of HOE's for solar collection focused on the properties of volume (thick) holograms. Effects on the efficiency related to the Bragg condition were found to be important in applications where wide-angle response and high efficiency were required simultaneously. The application of HOE's for window coatings for daylighting purposes was explored in more detail. Figure 4 illustrates the use of HOE's placed on windows to redirect sunlight to the ceiling of a room, to substantially reject sunlight for some incident angles, or to redirect a rather narrow band of light deeply into a room independently of the solar angle.

Planned Activities in FY 1983

The use of HOE's as window coatings will be pursued further as part of an assessment for the Office of Energy Systems Research of the DOE Conservation Program. The project will investigate the possibilities, techniques, and effort required to develop holographic window coatings into practical systems for enhancing the use of daylight inside commercial and residential structures.

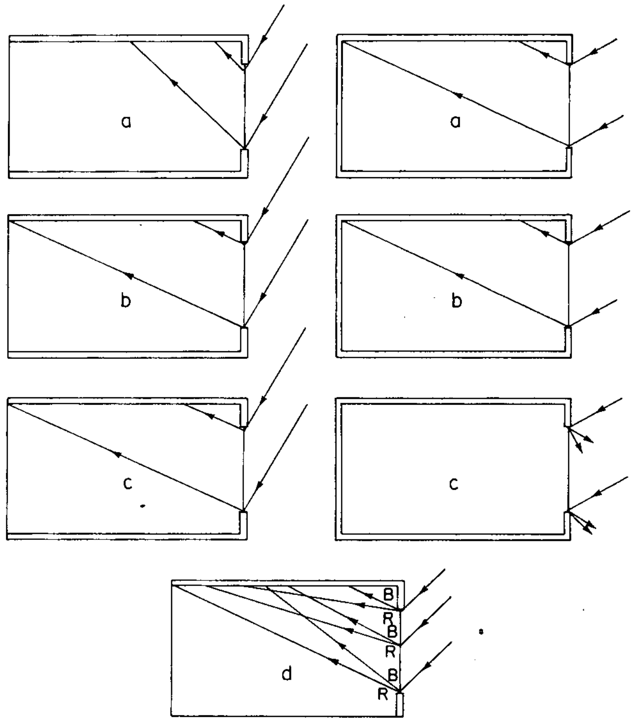

Figure 4. Holographic diffraction gratings for window coatings: (a) the action of a thin hologram with constant fringe spacing on light of one wavelength; (b) the use of a thick hologram to direct light to a portion of the room independent of the solar angle; (c) angular rejection of sunlight by a thick hologram; (d) spectral recombination with sunlight, using a thin hologram. (XBL 8211-7353)

REFERENCES

1. Hunt, A.J. (1978), *Small Particle Heat Exchangers,* Lawrence Berkeley Laboratory Report LBL-7841.
2. Hunt, A.J. (1982), "Radiant Energy Collection and Conversion Apparatus," U.S. Patent No. 4,313,304, issued February 2, 1982.
3. Hunt, A.J., Hansen, L., and Evans, D.B. (1982), "Solar Heat Receiver and Process for Using Same," patent applied for.
4. Hunt, A.J., Deringer, M., Evans, D.B., Hansen, L., Hull, P.C., and Paydarfar, D. (1982), "Development of a 30-kW High Temperature Solar Receiver Using Small Particles as the Heat Exchangers," *Energy and Environment Division Annual Report FY 1981,* Lawrence Berkeley Laboratory Report LBL-13500, pp. 2-26 to 2-28.
5. Hunt, A.J. (1982), "Particle Generator," patent applied for.
6. Evans, D.B. and Hunt, A.J. (1981), "An Empirical Method for Determining Flux Distributions in Solar Thermal Receivers," *in Proceedings of the Workshop on Solar Flux Measurements,* Solar Thermal Test Facilities Users Association, Albuquerque, NM, 26-28 Oct. 1981, Lawrence Berkeley Report LBL-13523.
7. Hunt, A.J., and Evans, D. (1982), "The Design and Construction of a High Temperature Gas Receiver Utilizing Small Particles as the Heat Exchanger — (SPHER), Phase I Report," Lawrence Berkeley Laboratory Report LBL-13755, 1982.
8. Hunt, A.J. (1982), "Solar Radiant Heating of Small Particle Suspensions," in *Fundamentals of Solar Energy,* Vol. 3, published by AIChE, also Lawrence Berkeley Laboratory Report LBL-14077.
9. Hunt, A.J. (1982), "High Temperature Heat Exchangers Using Transparent Windows," invited paper at the Workshop on High Temperature Materials for Solar Thermal Applications, Cocoa Beach, FL, Jan. 21-22, 1982.
10. Kistler, S.S. (1931), *Nature 127,* 741.
11. Bourdinaud, M., et al. (1976), "Use of Silica Aerogels for Cherenkov Radiation Counter," *Nucl. Instrum. Meth. 136,* 99.
12. von Dardell, G., Professor, Lund University, Lund, Sweden, private communication.
13. Schmitt, W.J. (1981), "The Preparation of Acid Catalyzed Silica Aerogel," Presented at the Annual Meeting of the AIChE, New Orleans.
14. Evans, D.B. and Hunt, A.J. (1982), "Diffractive Solar Collection Systems," *Energy and Environment Division Annual Report 1981,* Lawrence Berkeley Laboratory Report LBL-13500, pp. 2-29 to 2-31.

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