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# Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

## ENERGY & ENVIRONMENT DIVISION

SOLAR ENERGY PROGRAM

Chapter from the Energy and Environment Annual Report 1978

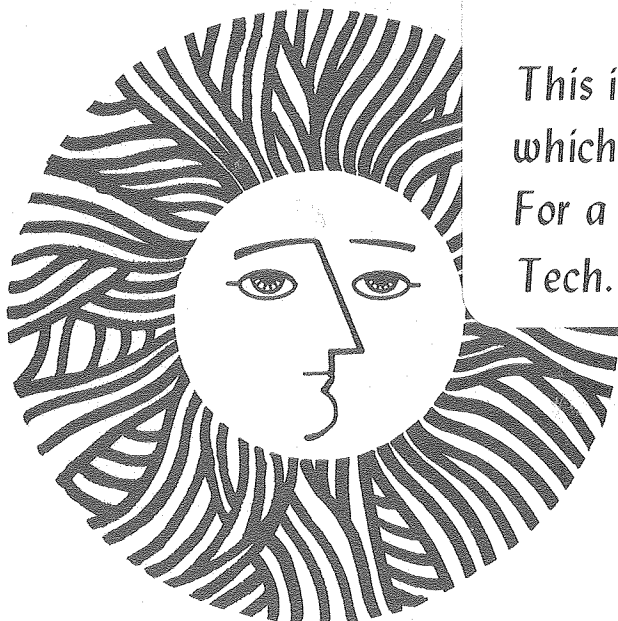
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# SOLAR ENERGY PROGRAM

chapter from  
Energy & Environment Division  
Annual Report 1978

Energy & Environment  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, California 94720



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# Solar Energy Program

## INTRODUCTION

Solar energy has emerged as a serious alternative for supplying a substantial fraction of the nation's future energy needs. To help fulfil that potential, the Department of Energy (DOE) is supporting activities ranging from the demonstration of existing technology to research on long-term possibilities. At LBL, projects spanning that range of activities are currently in progress.

An important aspect of assessing solar applications is quantifying the solar resource. In one project, LBL is cooperating with the Pacific Gas & Electric Company in the implementation and operation of a solar radiation data collection network in northern California. A continuing project has developed special instruments and is now using them to measure the solar and circum-solar (around the sun) radiation. These measurements help to predict the performance of solar designs which use focusing collectors (mirrors or lenses) to concentrate the sunlight.

Several efforts are under way to aid DOE in demonstrating existing solar technology. Technical support has been provided to DOE's San Francisco Operations Office (SAN) for its management of commercial-building solar demonstration projects. A solar hot water and space heating system was installed on an LBL building this year as part of the DOE Facilities Solar Demonstration Program. This work established model techniques and procedures, and is helping reduce fossil fuel consumption at the laboratory. Finally, technical support is being provided for SAN in a DOE small scale technology pilot program. In this program individuals and organizations are awarded grants to develop and demonstrate technologies appropriate to small scale use.

Solar heating and, especially, solar cooling are areas in which research is expected to have a substantial impact in the near-term. An absorption air conditioner is being developed that is air cooled, yet suitable for use with temperatures available from flat plate collectors. The performance of many-component solar heating and cooling systems may be improved by controlling their operation with inexpensive but sophisticated micro-electronics. A program is under way to develop and test such a controller, and to evaluate commercially available units.

Efforts continued this year on "passive" approaches to solar heating and cooling, in

which careful considerations of architectural design, construction materials, and the environment are used to moderate a building's interior climate. In a collaborative project with Los Alamos Scientific Laboratory, computer models are being developed of passive concepts. The models will be incorporated into public domain building energy analysis computer programs, and used in systems studies and in the design of commercial buildings on a case study basis. A second "passive" project is investigating specific passive cooling methods. In particular, a process is being studied whereby heat storage material would be cooled by radiation to the sky, then provide "coolness" to the building.

The laboratory personnel involved in the solar cooling, controls and passive projects are also providing technical support to the Solar Heating and Cooling Research and Development Branch of DOE in developing program plans, evaluating proposals, and making technical reviews of projects at other institutions and in industry.

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

Several projects are investigating longer-term possibilities for utilizing solar energy. One project, started this year, is addressing the development of a new type of solar thermal receiver that would be placed at the focus of a central receiver system or a parabolic dish. The conversion of the concentrated sunlight to thermal energy would be accomplished by the absorption of the light by a dispersion of very small particles suspended in a gas. Work continued this year on chemical storage processes (such as  $2\text{SO}_2 = 2\text{SO}_3 + \text{O}_2$ ) that could play an important role in providing long-term storage for high temperature power generation cycles. Another project is exploring biological systems. The possibility is being investigated of developing a photovoltaic cell, based on a catalyst (bacterio rhodopsin) which converts light to electrical ion flow across the cell membrane of a particular bacteria.

# Solar Energy

## Measurement of Circumsolar Radiation\*

*D. Evans, D. Grether, A. Hunt, and M. Wahlig*

### INTRODUCTION

Circumsolar radiation refers to light that, to an observer on the ground, appears to originate from the region around the sun. Aerosol particles cause this radiation by scattering light through small angles. The aerosol particles may be composed of ice crystals or water droplets in thin clouds, dust or sea salt particles, or photochemical pollutants. The amount and character of circumsolar radiation vary widely with geographic location, climate, season, time of day, and observed wavelength.

Focusing solar energy systems, such as parabolic troughs or the Central Receiver, typically collect the direct beam solar radiation (that coming directly from the sun) plus some fraction (usually small) of the circumsolar radiation. The exact fraction collected depends upon many factors, but primarily upon the angular size (field of view) of the receiver, the surface or cavity that absorbs the sunlight. A somewhat larger receiver will collect more of the circumsolar radiation but will experience somewhat larger radiation losses. Knowledge of circumsolar radiation can be a factor in optimizing a receiver design, or in choosing between competing designs for a particular application.

The pyrheliometer, the instrument normally used to estimate the direct beam radiation, has a  $50^{\circ}$ - $60^{\circ}$  field of view as compared to the  $1/20^{\circ}$  subtended by the sun. The pyrheliometer thus measures a substantial fraction of the circumsolar radiation as well as the direct beam radiation. For most focusing systems, the pyrheliometer will overestimate the amount of radiation that will be collected. Knowledge of the circumsolar radiation at a given location can thus be used to correct the pyrheliometer measurement.

Four instrument systems have been constructed at LBL to measure the circumsolar radiation. The basic instrument is a telescope that scans through a  $60^{\circ}$  arc of the sky with the sun at the center of the arc. The output is a digitization of the brightness of the sun and circumsolar region every 1.5 minutes of arc. Additional details of the instrument are given in previous annual reports.

### ACCOMPLISHMENTS DURING 1978

#### Operation of Telescopes

Three of the instruments continued to be operated at 1) the Solar Thermal Test Facility at Sandia Laboratories, Albuquerque, NM, 2) Barstow, California, near the future site of the 10 MWe Central-Receiver pilot plant,

and 3) Georgia Institute of Technology, the site of a 400 KW Central-Receiver test facility. The fourth telescope was located at Argonne National Laboratory until November, at which time it was returned to LBL for general maintenance and the installation of an automated sunphotometer (see below).

#### Routine Processing of Data

A major task of the project is to process the large quantities of data (240 data points/minute/15 hours each day/telescope) to a form suitable for analysis. This processing is done in two steps. In the first step, the information from the original magnetic tapes (one/telescope/week) is transferred to a mass storage system on the LBL computer. The second step is to reduce the data to a more compact form and to apply various correction and calibration factors. This "reduced data base" is then used in the analyses. During this year the data from June 1977 thru June 1978 was transferred to mass storage and a preliminary version of the reduced data base created. There is now a two year period of record for three of the telescopes, and about a year and one-half for the fourth.

#### Data Analysis

The data analysis proceeded along the lines discussed in last year's report: the analysis of instantaneous values of the circumsolar radiation, and the calculation of the average effect of circumsolar radiation on the performance of concentrating solar energy systems.

The objective of the analysis of instantaneous values is to develop correlations between circumsolar levels and other, more readily measured, solar or meteorological parameters. The circumsolar radiation could then be estimated for locations other than those covered by the limited number of telescopes. Figure 1 is presented as an example of this work. Figure 1(a) plots values of the circumsolar radiation (intensity of light from the edge of the sun out to  $\sim 30^{\circ}$ ) versus the reading of a pyrheliometer (see above) for a month's worth of data. There are three distinct regions: 1) a dense concentration of points at high pyrheliometer and low circumsolar value corresponding to clear sky conditions in the middle portion of the day, 2) a tail of roughly constant circumsolar values but rapidly decreasing pyrheliometer values corresponding to clear sky conditions towards sunrise or sunset when atmospheric absorption dominates and 3) a "crescent" of decreasing pyrheliometer values accompanied by initially increasing and then decreasing circumsolar levels, corresponding to periods when atmospheric scattering dominates.

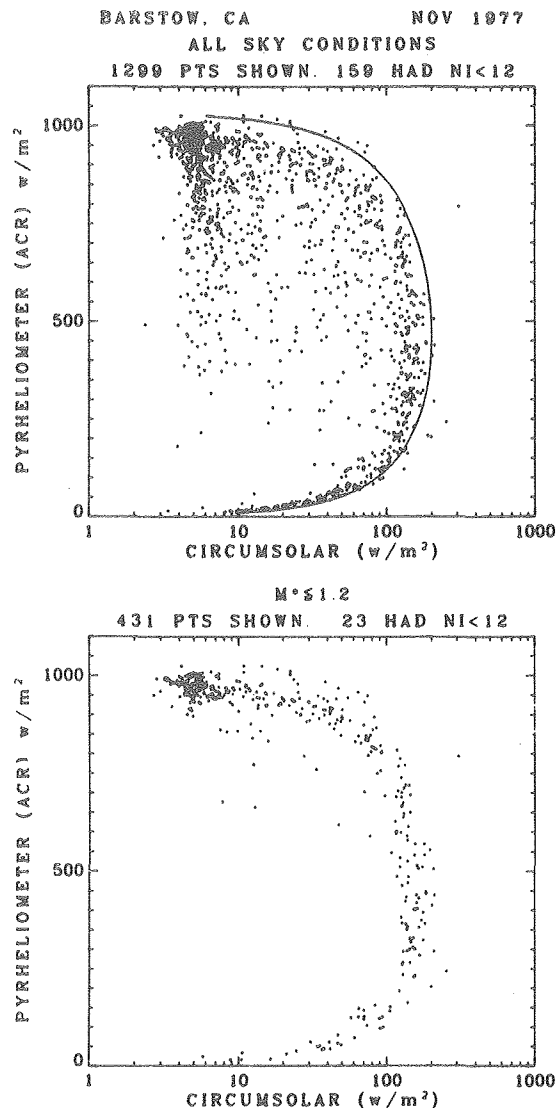


Fig. 1(a) Pyrheliometer readings versus the corresponding radiation level for each of 1299 measurements made during November 1977 at Barstow, CA. "NI 12" refers to 159 measurements (not shown) with very low pyrheliometer values. The smooth curve gives the results of a simple atmospheric scattering model.

(b) A subset of the above measurement when the effective air mass ( $m^*$ ) was less than 1.2.

The rather sharp outer limit of the crescent suggests some physical constraint.

Figure 1 illustrates two approaches to placing the above observations on a more quantitative basis. The smooth curve in Fig. 1(a), which describes reasonably well the outer limit of the crescent, is from a simple atmospheric scattering model that essentially conserves energy. Progression from the upper end to the lower end of the curve corresponds to an increasing load of scattering centers (aerosols) in the atmosphere.

A second approach has been to correlate the pyrheliometer and circumsolar values with the amount of atmosphere between the sun and the telescope. The usual characterization of this quantity is the "air mass" ( $m$ ), defined as the amount of atmosphere relative to local vertical. We have found a seasonal dependence of the correlation between pyrheliometer value, circumsolar level and air mass which is largely eliminated by using an "effective" air mass ( $m^*$ ), defined as the amount of atmosphere relative to that at solar noon. Figure 1(b) is for those measurements with  $m^* \leq 1.2$ . This selection tends to isolate the outermost points of the crescent. For moderate pyrheliometer readings (100-900 W/m<sup>2</sup>) Fig. 1b can be used to limit possible circumsolar values to a fairly narrow range. Selection on other ranges of  $m^*$  tend to isolate other regions of Fig. 1(a), although the resulting distributions are progressively smeared out with increasing  $m^*$ .

Figure 2 is presented as an example of the average effect of the circumsolar radiation on concentrating solar energy systems. The data are for the period May 1976 thru December 1977 at Albuquerque. Assume that the maximum energy available to an arbitrary concentrating system is the direct solar radiation plus the circumsolar radiation. One may then ask how much of this maximum is "lost" (falls outside the field of view) of a system with a particular operating threshold (the solar plant is in operation whenever the solar radiation exceeds this threshold) and a particular aperture radius (half the angular field-of-view) of the receiver. Figure 2 is for a threshold of 50 watts/m<sup>2</sup>. Consider a highly concentrating system with an aperture radius of .38°. The loss would range from about 2% to 5%, depending on the particular month.

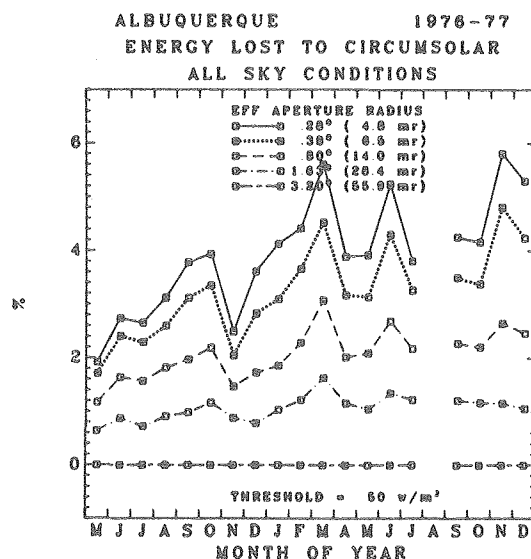


Fig. 2. The energy lost because of circumsolar radiation in a concentrating solar energy system depends on the effective aperture. The values are for a system with an operating threshold of 50 W/m<sup>2</sup> incident solar radiation.

This loss could, in principal, be recovered by using a larger receiver. However, this receiver would have higher reradiation losses and other disadvantages. An optimum design will include considerations of the circumsolar radiation as well as these other effects.

#### Other Activities

The Solar Energy Research Institute (SERI) is examining in detail the effect of circumsolar radiation on specific types of concentrating collectors. LBL has been involved in preparing the data in a form that can be readily used by SERI.

A collaborative effort with a DOE-funded engineering firm (Watt Engineering, Limited) is just underway to examine correlations of average values of circumsolar radiation with meteorological or climatological variables such as cloud cover. This work is expected to complement the correlation studies of instantaneous values discussed above.

As an ancillary use of the data, a quasi minute-by-minute pyreheliometer data base was constructed for cloud transit studies at Sandia Laboratories, Livermore. The telescopes have a ten minute cycle, each cycle consisting of a scan and pyreheliometer measurement thru each of a clear filter, eight colored filters, and an opaque filter. To construct the data base, the colored filter values were scaled to an approximate clear value. A smoothing technique was used to reduce some artificial fluctuations; the resulting time resolution is about 2-3 minutes.

A Sunphotometer, on loan from NOAA, was modified for automatic operation on one of the telescopes. The Sunphotometer is a simple, hand-held instrument used to measure the attenuation of direct solar radiation at discrete wavelengths.

The measurement is then used to calculate the "turbidity," a quantity related to the atmospheric aerosol content. A network of these instruments has been in operation for the EPA for many years to monitor air quality. The thrust of the present effort is to make simultaneous circumsolar/turbidity measurements in order to determine the extent to which the existing turbidity data base might provide estimates of circumsolar levels. To this end, the Sunphotometer has been enclosed in a temperature controlled and environmentally sealed box, and the mechanical components placed under control of the telescope electronics. The output of the instrument will be recorded on the telescope's magnetic tape.

#### PLANNED ACTIVITIES FOR 1979

The measurement program will continue. Plans are to move the telescope that is currently at LBL to SERI. Longer range plans are to take measurements in as yet unsampled areas, such as the Great Plains, eastern Oregon or Washington, and Florida.

The various analyses, including the work with SERI and Watt Engineering, will continue with the overall goal of further understanding the relationship of circumsolar radiation to other solar/meteorological variables, and to the performance of solar energy systems.

#### FOOTNOTE

\*This work has been supported by the Department of Energy through Conservation and Solar Applications (Solar Heating and Cooling - Research and Development Branch), and through Solar, Geothermal, Electric, and Storage Systems (Central Solar Technology-Solar Thermal Branch, and Distributed Solar Technology-Photovoltaics Branch).

## A Small Particle Heat Exchanger\*

A. J. Hunt

### INTRODUCTION

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

An open cycle Brayton heat engine utilizing a Small Particle Heat Exchange Receiver (SPHER)

would operate by compressing ambient air and injecting a very small mass of fine particles into the gas stream. The air-particle mixture then enters a transparent heating chamber where the solar flux is concentrated. The particles absorb the radiation and, because of their very large surface area, quickly release the heat to the surrounding gas. The air-particle mixture continues to heat until the particles vaporize. The heated gas then passes through the expansion turbine to provide power for the compressor and load before going to a recuperator and being exhausted.

A dispersion of particles distributed throughout a volume of gas is a very efficient absorber of sunlight if the particle size and optical constants are chosen properly. If the characteristic

absorption length for light passing through the material comprising the particles is greater than the particle diameter, the entire volume of the particle is active as the absorber. For this and other reasons, sub-micron particles are used.

The choice of the composition of the particles is determined by the desired optical and physical properties. Various forms of graphite and carbon are ideal choices because of their optical characteristics and the fact that the method of production affects their combustion rate. They have the additional advantage that the combustion product is carbon dioxide. The amount of CO<sub>2</sub> generated is less than one-one hundredth of that produced by a conventional plant of the same power.

The major advantage of SPHER over conventional receiver designs such as the honeycomb heat exchanger, or a cavity lined with refractory pipes, are its simplicity, efficiency, light weight and lower chamber temperatures for the same output gas temperatures. The concept has the additional advantage that it is easy to incorporate conventional fuel injectors into the system, thus enabling the plant to operate in a hybrid mode during periods of cloudiness or in the evening.

The idea for the small particle heat exchanger receiver was originated in 1976 and some basic calculations were performed at that time. The bulk of the work reported here was undertaken in 1978 as part of a project under sponsorship of LBL to investigate the feasibility of the concept.

#### ACCOMPLISHMENTS DURING 1978

The basic goal of the limited effort in 1978 was to critically evaluate the major optical, physical and chemical considerations involved in designing, building and operating a solar receiver utilizing a dispersion of fine particles in a gas. To this end, a theoretical analysis of the optical characteristics of small particles was undertaken to determine optimum particle size, density and optical properties. The thermodynamic properties of the particles were investigated to determine whether the heat fluxes and equilibrium temperatures would be suitable for solar thermal applications. Particle production techniques and gas reaction processes were surveyed to ensure compatibility with design requirements. In addition, particle confinement schemes and system considerations as well as safety and environmental factors were studied. A small laboratory apparatus was constructed that successfully demonstrated the concept. The work mentioned above validated the basic concept and helped to identify specific areas for research and development.

#### Principles of Operation

Light passing through a medium containing small particles may be scattered or absorbed. If the particles are sufficiently small and are composed of material that is intrinsically

absorbing, the extinction (the combined effect of scattering and absorption) of a beam of light passing through the medium will be dominated by absorption. The mass of particles per unit volume of gas necessary to produce a given amount of absorption for a set receiver area is constant for very small particles and begins to rise roughly linearly with size for larger particles.<sup>1</sup> The amount of light scattered back out of the receiver is also a function of particle size, with the smallest particle offering the least losses. Thus from an optical point of view very small particles (less than 0.1 micrometer diameter) are best suited to this application.

#### Energy Balance

Once the particles have absorbed the incoming radiation they begin to heat up. If the particles are small, the thermal inertia (heat capacity) of the particles is very small. This condition may be used to simplify the particle temperature analysis by considering only the in and out going fluxes. The equilibrium temperature calculated on this basis will be reached in an extremely short time compared to the residence time in the heating chamber. The condition for temperature equilibrium of a particle in a gas is given by,

$$P_A - P_E - P_C = 0$$

where  $P_A$  is the power absorbed by the particle and is a function of the integral of the product of the wavelength dependent absorption of the particle and the solar and infrared flux densities.  $P_E$  is the power emitted by the particle and is a function of size and the integral of product of the emissivity of the particle and the Planck black body function at the temperature,  $T_p$ , of the particle.  $P_C$  is the power lost by collisions and is a function of size and temperature of the particles, and the density, specific heat, and temperature,  $T_g$ , of the gas. An iterative technique is used to solve for the equilibrium temperature of the particle.

The results of the calculation are given in Table 1. They are dependent on the particle radius only through the dependence of the absorption efficiency on size. The calculations are based on a combination of graphite optical constants of Phillipp<sup>2</sup> in the infrared and Arakawa et al.<sup>3</sup> in the near infrared and visible. The incoming solar flux was assumed to be 1 kW/m<sup>2</sup> and has a concentration of 2000, typical of advanced concept solar power plants. For conditions of interest, the particle temperature never rises over 0.1°K above the gas temperature. The table also indicates that below 1500°K the heat loss process is dominated by conduction. The low ratio of emission to conduction for  $T < 1500^\circ$  also means that infrared reradiation from the particles is suppressed. The temperature difference  $T_p - T_g$  is roughly inversely proportional to the gas pressure. The ratio of  $P_E/P_C$  is independent of pressure.

The last temperature entry in Table 1 indicates that for the assumed conditions the maximum attainable temperature is 2375°K. The maximum

Table 1. Temperature differences between particles and gas and the ratio for power loss by emission and conduction for various temperatures at a pressure of 6 atm.\*

$T_p(^{\circ}\text{K})$	$T_p - T_g(^{\circ}\text{K})$	$P_E/P_C$
600	0.09	0.0004
1000	0.069	0.007
1500	0.052	0.079
2000	0.029	2.1
2375	$\sim 0$	(all emission)

\*The results of this table are based on values of absorption efficiency for particles of  $0.025\mu$  radius and the conditions given in the text.

temperature will depend on the particle size and will increase for smaller particles. This extremely high temperature capability may be relevant to solar high temperature process heat applications.

#### Particle Production

Small particles for heat exchanger applications may be produced in several ways. Dispersion of premanufactured powders is extremely difficult due to the tendency of small particles to agglomerate because of large surface forces. The best approach is to produce the particles, entrain them in a gas system, and conduct them to an injection port, thus minimizing the chances for agglomeration.

The choice of the operating parameters of the heating chamber and the gas turbine determine the desired characteristics of the particles. The most important physical characteristic of the carbon particles for the present application is the oxidation rate at a given temperature in air. Very little experimental data on this topic is available for small particles. However, measurements on bulk material show large differences in the reaction rate at a given temperature for different allotropic forms of carbon. Based on published bulk reaction rates at  $1000^{\circ}\text{C}$ , the calculated time for complete combustion of particles with a diameter of  $0.1\mu$  varies from approximately 20 microseconds for baked carbon to about 0.5 seconds for vitreous carbon. Thus the choice of particle composition offers a control of the lifetime of the particle in the chamber. An experimental program is clearly necessary to determine the best particle production technique to match to a given application.

#### Window Design

The window of the heat exchanger allows the solar flux to enter the chamber, confines the pressurized gas-particle mixture, and prevents substantial losses of heat by infrared radiation. The best candidates are pyrex and quartz.

These materials pass nearly the entire solar spectrum and are also opaque to infrared radiation with wavelengths greater than 4 micrometers.

The pressure requirements on the window are modest, on the order of two to six atmospheres for the open cycle Brayton engine. The optimum window-cavity design to confine these pressures depends on a number of factors, including the window temperature, temperature cycling, and aperture size. Pyrex has excellent strength qualities and is cheaper than quartz but does not have the high temperature capabilities of quartz. Figure 1 illustrates a receiver in which the outer window is made of pyrex and forms the pressure chamber. It is a cylindrical section facing inward to ensure the window remains in compression (the direction to provide the maximum strength for glass). The inner window is a thin sheet of quartz and acts as a heat shield. Particles are introduced only into the space behind the shield by putting the injectors below the top of the shield. Since no heating occurs in the cavity between the windows, the compressed air stream serves to cool the windows.

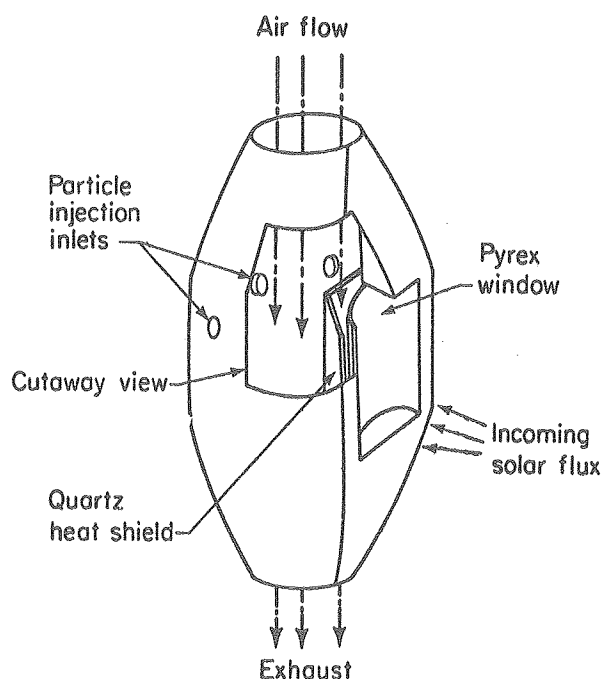


Fig. 1. Conceptual design for a small particle heat exchanger. (XBL 787-2593)

#### Power Plant Considerations

The Small Particle Heat Exchanger may be used to heat gas for use in either an open or a closed Brayton cycle. The open cycle operates by drawing in ambient air, using it as the working fluid, and discharging it again to the atmosphere. This once-through process avoids the need for the large cooling towers that are usually associated with electric power plants. The closed cycle recirculates the work-

ing fluid, and therefore requires active cooling facilities to cool the gas before recompressing.

An important question in the analysis of solar-electric production is determining the optimum size for the collector-receiver module. The optimum size for a solar-hybrid power plant utilizing small particles depends strongly on window design and has not yet been determined. However, to calculate some of the operating characteristics of a plant incorporating SPHER, the module size will be assumed to be 10 MWe. The results are based on an assumed pressure ratio of six and 80% recuperation of the exhaust heat. For a gas temperature of 980C° the plant efficiency would be about 40%. The volume of gas passing through the plant would be about 250,000 cubic meters per hour. At this flow rate the amount of carbon needed is only about 10 Kg/hr. This modest requirement for carbon can easily be met by a number of processes. The amount of CO<sub>2</sub> produced from this carbon is of the order of that generated by a single automobile. Thus, the environmental impact of this aspect of the plant is minimal.

#### PLANNED ACTIVITIES FOR 1979

The activities in the year will concentrate on deepening and broadening the examination of all major aspects of the Small Particle Heat Exchanger. The goal is to anticipate and answer fundamental and engineering questions involved in building and testing an experimental unit of moderate size at a national solar test facility. To this end there will be both an experimental and theoretical program to demon-

strate and predict the operation of the critical components of the system.

The experimental effort will be divided into two parts: A demonstration program will investigate methods of producing, controlling and heating small particles; and a more basic, parallel program will characterize the small particles and try to relate their optical and physical properties to their composition and production process.

Another effort will be to investigate the particle confinement considerations such as window materials, cooling, sealing, and chamber design. The theoretical effort will concentrate on producing modest computer programs to predict the steady state behavior of each process in a small particle heat exchanger.

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\*This work has been supported by funds from the Director's Office, Lawrence Berkeley Laboratory, Berkeley, CA.

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### Passive Systems Analysis and Design\*

*R. C. Kammerud, H. Akbari, B. Andersson, F. Bauman, C. Conner, B. Curtis, D. Fuller, A. Gadgil, F. Lenherr, D. Merritt, and W. Place*

#### INTRODUCTION

The objective of this project is to explore the application of passive solar design concepts to the non-residential building sector. Thermal models which describe the unique heat transfer characteristics of passive solar heating and cooling systems are being developed. The models will be incorporated into the public domain building energy analysis computer programs BLAST and DOE-1. The computer codes will be utilized in systems studies and in the design of commercial buildings on a case study basis. It is anticipated that these coordinated design/analysis efforts will lead to engineering field test buildings which employ a broad range of passive design features.

#### BACKGROUND

The thermal analysis portions of the LBL efforts began in early FY 1978; they resulted

from a perceived need to provide passive solar system analysis capabilities to the building design and engineering communities. Special emphasis was placed on commercial buildings where little attention had previously been given to passive design concepts. This work is a joint undertaking of the Solar Group at LBL and the WX-4 Group at Los Alamos Scientific Laboratory,<sup>1</sup> who have had responsibility for the development of the active solar simulation capabilities in DOE-1. The project is being coordinated with the conservation group at LBL which has had primary responsibility for the past and future development of the conventional building analysis capabilities of DOE-1. Some of the passive solar analysis and design projects are also related to work being done in the Windows and Lighting program at LBL. Currently, the relationship includes joint funding of one subcontract and development of a joint solar/conservation competitive solicitation.



The work also draws upon other DOE contractors including Consultants Computation Bureau and the Energy Engineering Group. The former was involved in the original development of DOE-1 and is investigating possible methodological limitations of existing analysis techniques when applied to passive solar systems. The latter contractor is expected to provide detailed data on the performance of mass storage wall thermocirculation systems which can be used in validating algorithms currently being developed at LBL.

During the latter portion of FY 1978, the LBL efforts were expanded to include design-oriented tasks. The minimal attention that has been given in the past to commercial building applications of passive solar concepts dictates that basic design concept generation and evaluations be performed. The intent, therefore, is to coordinate the thermal analysis and design tasks in order to explore the potentials for passive solar in these new areas of application.

The passive program at LBL began in November of 1977. Progress to the beginning of 1978 was limited to task definition and scheduling and to the initiation of research on thermal analysis of thermocirculation systems.

## ACCOMPLISHMENTS DURING 1978

### Algorithm Validation

Algorithms describing the thermal performance characteristics of thermocirculation systems for both laminar and turbulent flow were developed during 1978. These algorithms are based on a detailed thermal analysis of natural and forced convection of air between parallel plates at constant temperatures.<sup>2,3</sup> Efforts to incorporate these algorithms in BLAST were initiated during the final weeks of the year.

Both analytic and experimental studies of natural convection airflow patterns within room geometries and between the thermal zones in a building were initiated. The analysis work has led to a computer program which will describe the steady state circulation under arbitrary boundary conditions on surface temperatures and forced air inputs. The small-scale experimental test will attempt to obtain qualitative data on the exchange of heat between rooms. The experiment was designed and construction completed near the end of 1978.

Near the end of the year, attempts to validate BLAST for direct gain systems were also completed. The predictions of the interior temperatures of small test rooms located at LASL were successfully compared to the measured temperatures. These validation efforts included examination of the relationship between thermal performance and the distribution of the thermal mass within the cell. This has aided in identifying the alterations that must be made to BLAST in order to provide general capabilities for analyzing direct gain systems.

## Design Tasks

The design tasks were defined and initiated during the last quarter of 1978. These efforts include both conceptual designs for prototype passive solar systems and actual physical designs for DOE facilities which have been proposed for construction during 1979.

Initial efforts have been made to define ways in which natural convective thermocirculation systems might be applied to commercial buildings. These systems can produce sizable volumetric flow rates. Possible applications include: (1) preheating and delivery of ventilation air to occupied spaces during heating periods; (2) fresh air ventilation driven by opening the top of the convection channel to the environment and drawing air out of the occupied space, with make-up air provided through openings in the building envelope; and (3) space cooling by coupling the space to a pre-cooled thermal storage system such as a rockbed--thermocirculation would be used to vent the occupied space and make-up air would be supplied through the storage system. Preliminary work has begun on architectural integration of thermocirculation systems into commercial buildings.

Two DOE facilities have been identified for case study examination of passive applications. The Heavy Ion Institute at Oak Ridge National Laboratory will be an underground structure with an exposed south facade with either direct solar gain or mass storage wall elements. At the request of the Pittsburgh Energy Technology Center, LBL has performed an initial schematic design for the Energy and Conservation Building, resulting in a design that is a variation on an earlier non-passive concept.

Finally, the Passive Solar Group (PSG) was involved in a program to define and document a full range of performance indices for passive building evaluation. LBL has produced a concept paper<sup>6</sup> which identifies a procedure for quantifying the conventional energy savings which result from including passive design concepts in a structure. This work has been performed in cooperation with the National Bureau of Standards.

## PLANNED ACTIVITIES FOR 1979

Future thermal analysis efforts will focus on completion of the tasks which modify BLAST to provide analysis capabilities for direct systems, Trombe walls, and other thermocirculation systems. New modeling tasks are also being undertaken; they include:

- rockbed thermal storage systems
- roof pond systems
- salt gradient stabilized solar ponds

When completed, these models will also be added to BLAST and DOE-1. In addition, the natural convective zone coupling studies will continue. A comparative analytic evaluation of various existing and proposed passive domestic hot

water heating systems is to be completed during 1979. A promising candidate design concept will be selected, fabricated, and tested in 1980.

In cooperation with the Radiative and Passive Cooling Project in the Solar Group at LBL, a design and analysis project for a passive cooling system will be undertaken. This will be done in conjunction with a local designer/builder and will provide an engineering field test for a passive system.

The thermocirculation concepts will be further developed and entire building systems will be specified and analyzed. The systems that demonstrate significant potential will be documented in a commercial building concept manual and case study demonstrations will be sought. The LBL involvement in the case studies will continue through the design development stage and the post-occupancy evaluations of the passive structures.

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### Nitinol Engine Development\*

*R. Banks, R. Kopa, M. H. Mohamed, and M. Wahlig*

#### INTRODUCTION

Low grade heat, in the form of thermal energy at temperatures below the boiling point of water, is a widespread energy resource that could make a significant contribution to world wide energy needs if an economical technology can be developed for converting it to useful work. The Nitinol Engine Development project is investigating the feasibility of using the thermally-activated shape-change phenomenon in certain intermetallic Shape Memory Alloys, particularly the nickel-titanium compound "55-Nitinol",<sup>1</sup> as the basis for thermal-to-mechanical energy conversion at temperatures available from such sources as industrial waste heat, low-temperature geothermal brines, solar-heated water, or the moderate temperature differences that exist in the ocean thermal gradient. An important advantage in using a solid rather than a fluid working medium in such applications is the possibility of eliminating the heat exchangers required by closed-cycle fluid systems, which often constitute major cost and maintenance items in conventional low-temperature energy conversion technologies.

A prototype Nitinol heat engine has been in operation at the Lawrence Berkeley Laboratory since August 1973. Since that time, several

iterations of engine design have led to an improved understanding of the important practical considerations in applying this material to energy conversion in continuously cycling heat engines. These studies, as well as experimental and theoretical investigation of the material's thermodynamic and metallurgical properties, have confirmed the potential for developing useful and practical machines for the recovery of thermal energy from low-grade or waste heat.

#### ACCOMPLISHMENTS DURING 1978

The work of the past year has been primarily focused on detailed study of the cyclic behavior of individual Nitinol elements through a variety of theoretical and experimental approaches. Early in 1978 an instrumented cycle-simulator was constructed which enabled evaluation of the effects of repetitive stress-strain-temperature cycles under controlled conditions. A parallel study of material properties has investigated the relationship between maximum work output per unit mass of Nitinol, maximum thermodynamic conversion efficiency, and fatigue lifetime, in order to identify an ideal cycle capable of achieving an optimum combination of these parameters. As a part of the materials study, a high-resolution laser-beam dilatometer was developed by means of which very small changes

in length of a Nitinol element (on the order of 100  $\mu\text{m}$ ) may be observed as a function of stress and temperature.

### Cycle Simulator

The fabrication of the electronically controlled Cycle Simulator, which is shown in Fig. 1, was completed in March 1978. After calibration and integration with the data acquisition system, the planned experimental program was started in June 1978.

The Cycle Simulator was designed to operate fully automatically and be capable of continuous operation for millions of cycles, faithfully repeating any specific type of thermodynamic cycle selected during the research program. Test parameters that can be varied include stress levels, stress rates, percent of elongation, temperature levels, heating and cooling rates and cycling speeds.

The isothermal engine cycle was selected as the first type of thermodynamic cycle to be investigated. Although thermodynamically inferior, this cycle was investigated because most known solid state heat engines operate on the principle of an approximately isothermal cycle.

Several Nitinol wire elements obtained from different sources and with different mechanical and heat-treatment histories were subjected to tests extending over thousands of repeated cycles. The rate of wire straining, and the periods of heating and cooling (which additively determine the cycling speed), were adjusted so that the resulting cycling speeds of these tests were in the range of 5-20 cycles per minute.

This corresponds to typical operating speeds of various prototype Nitinol heat engines.

The heat input to the wire element was determined by three independent methods. The resulting stress-strain work diagram produced by the Nitinol wire was continuously monitored on an oscilloscope and, with all other pertinent test parameters, periodically recorded on a video tape.

After an initial "training" period of the wire elements (approx. 1000 thermal cycles with low strain), the strain was adjusted to the highest level which still permitted the continuation of the cycling without noticeable cumulative irreversible elongation of the wire element. The temperature of the cold bath was maintained at 20°C or at 18°C, and the temperature of the hot bath was varied until the optimum energy conversion efficiency was attained. The cycle was then repeated automatically until the failure of the wire or a noticeable deterioration of performance occurred.

It was found that at cycling speeds of 5-20 per minute a strain of approximately 1.5% was the limit beyond which a progressive irreversible elongation would occur and cause eventual failure of the wire element. The resulting efficiency of the conversion of heat to mechanical work at this strain level and  $\Delta T = 80^\circ\text{C}$  was on the order of 0.5% for a simple isothermal cycle and about 1.0% for the constant stress-isothermal cycle.

However, significantly higher efficiencies were observed for isothermal cycles in which the rates of wire straining, heating and cooling were substantially reduced. Preliminary tests showed that, for presently available Nitinol

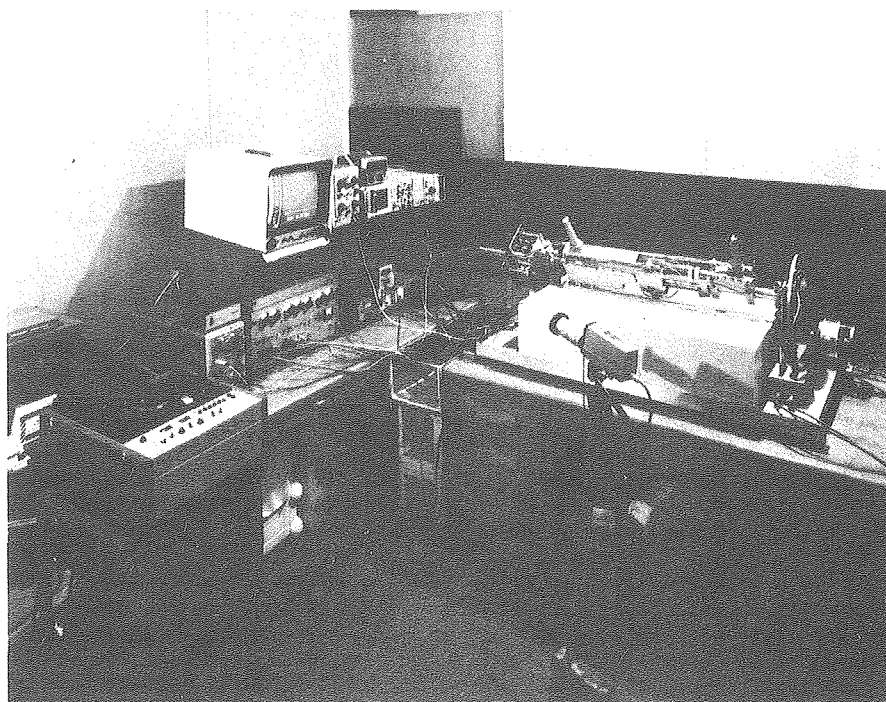


Fig. 1. Cycle simulator experimental system. (CBB 786-7380)

elements, an absolute efficiency of about 2% (equivalent to about 10% of the Carnot efficiency) was obtained in a constant stress-isothermal cycle at substantially reduced rates of straining, heating and cooling. Further investigation and corroboration of these results will be pursued.

The second type of cycle investigated was the adiabatic cycle. It is theoretically the most efficient thermodynamic cycle; however, it is also more complex and not so easily realized in a practical solid state heat engine design. Furthermore, in the adiabatic cycle the strain rates must be fast (full strain in less than 300 ms) in order to prevent excessive heat losses from the wire element during the straining period. Understanding these effects is of key importance in identifying methods of attaining higher efficiencies, and is the object of the current investigation.

### Materials Studies

We have been studying, both theoretically and experimentally, the parameters that govern conversion efficiency, work output per unit mass, and fatigue lifetime of Nitinol wire elements. An expression relating the thermal conversion efficiency of Nitinol to a set of materials properties with reference to an ideal cycle consisting of two isotherms and two isochores has been derived:

$$\eta_{\text{thermal}} =$$

$$\frac{\sigma_y^{\text{htp}} (1 - e^{-N\epsilon}) \cdot \epsilon}{\Delta H + C_p [(A_f^0 - A_s^0) + (A_s^0 - M_f^0) + (dA_f/d\sigma) \sigma_y^{\text{htp}} (1 - e^{-N\epsilon})]}$$

where:

- $\sigma_y^{\text{htp}}$  = the yield strength of the high-temperature phase;
- $\epsilon$  = strain within the recoverable range ( $\leq 8.0\%$  elongation);
- $N$  = the number of crystallographically equivalent martensite variants;
- $H$  = the latent heat of the transformation;
- $C_p$  = the average specific heat of the material over the temperature range across the cycle;
- $A_s^0, A_f^0$  = the temperature at which reversion of martensite to the high-temperature phase starts and finishes, respectively, upon heating in the absence of an external stress.
- $M_f^0$  = The temperature at which the transformation to martensite finishes upon cooling, in the absence of external stress;
- $dA_f/d$  = the rate of increase in the  $A_f$  temperature with an external stress.

The above properties have been measured for the particular Nitinol alloy under current investigation. From these measurements and the above expression, the maximum possible efficiency was calculated to be 9.0% for a  $\Delta T = 69^\circ\text{C}$  (the calculated work output is 4.3 J/gm), which amounts to 45% of the corresponding Carnot

efficiency. This 9% efficiency, however, requires 8% recoverable elongation and a stress amounting to 0.85 of the yield strength of the high temperature phase. At such a high stress level, an early fatigue failure might be expected. If the maximum stress on the material during the course of an engine cycle is reduced to 0.5 of the yield strength of the high temperature phase, a working lifetime of many millions of cycles could be anticipated, but conversion efficiency will be correspondingly reduced to a value on the order of 2.0% (13% of the Carnot limitation for these temperatures).

Our attention is now focused on the possibility of increasing the yield strength by various methods. In particular, one procedure currently being investigated holds promise (on the basis of electron microscope observations) for higher conversion efficiencies. It entails confining the thermal cycling to within the transformation temperature range. Other efficiency-limiting factors, such as the magnitude of the thermal hysteresis associated with the transformation, are also under investigation.

In the course of cycle studies performed with the laser-beam dilatometer, a method for increasing the practical efficiencies of the solid state engine cycle by means of partial heat recovery (a regenerative cycle) has been investigated. Because of the thermal hysteresis exhibited in the Nitinol cycle, there is a temperature range during both the heating and cooling processes in which negligible shape change (and therefore transformation) occurs. Heat absorbed or rejected by the material during these parts of the cycle is therefore almost exclusively sensible or specific heat, and may be stored conveniently during the cooling path (rather than rejected to the heat sink) and reabsorbed by the element on the heating path. Preliminary tests simulating such a cycle indicate that in principle cycle efficiencies in excess of 3% (absolute) may be achieved, or  $\geq 40\%$  of the corresponding Carnot efficiency.

### PLANNED ACTIVITIES FOR 1979

The Cycle Simulator studies are planned to continue principally in two important areas:

- 1) Studies aimed towards fundamental understanding of the effect of strain rates and of heating and cooling rates on the mechanism of the lattice transformation process, and subsequent investigation of methods leading to effective increase in those rates without adverse effect on the cycle conversion efficiency;
- 2) Investigation and testing of other SME materials, and of the effect of alloying on their thermodynamic performance characteristics.

The ultimate objective of the planned research is the demonstration of the practicality of an adiabatic engine cycle which could be incorporated in the design of a solid state heat engine. Since the theoretical efficiency of the adiabatic engine cycle approaches that of the Carnot cycle, it should, even given the non-ideal

behavior of SME materials, yield a substantially higher conversion efficiency than has thus far been attained in isothermal cycles.

In the materials program we will focus our attention on improving materials properties that lead to better efficiencies, while maintaining a reasonable fatigue life. In particular we plan to investigate:

1) the functional dependence of the yield strength of the high temperature phase on thermal cycling and previous heat treatments;

2) the temperature dependence of the stress required to induce martensite transformation. This relationship, and the variation of the yield strength with temperature, will determine the ranges of stresses and temperatures through which the undesirable irreversible plastic deformation during an engine cycle is minimized;

3) the dependence of fatigue life on stress, strain, and the temperature at which the strain is induced in relation to the transformation temperatures;

4) the effect of prior heat treatments on the transformation temperatures and magnitude of the thermal hysteresis;

5) the effect of cold memory on the efficiency and the relationship between this memory and the microstructure.

Further investigation of the regenerative cycle and of "incomplete" thermal cycles, during which the material is not fully transformed either on heating or cooling, is planned as part of the continuation of the dilatometric studies. The effect of these, and other cycles on the long-range working lifetime of the material will be investigated by means of a high-cycle fatigue test stand to be constructed early in 1979.

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### Radiative and Passive Cooling\*

*M. Martin, P. Berdahl and M. Wahlig*

#### INTRODUCTION

The major objective of this project is to determine the feasibility of using radiative and passive cooling systems in various parts of the country. This effort includes a determination of atmospheric infrared emission characteristics to identify geographical regions

in which selective and non-selective radiators might be effective. This will be accomplished by use of atmospheric radiation models and by an experimental program of sky radiation measurements. A computer analysis of radiative cooling will model the entire system, including the atmospheric characteristics, the blackbody or selective radiating surface, and the building

load. If the performance and economics of radiative cooling systems appear favorable, studies of infrared absorptance and emittance of candidate materials for radiating surfaces and windscreens will be carried out. Finally, convective and evaporative cooling systems will be integrated into the study so that all aspects of passive cooling will be included.

The computer simulation of the performance of passive cooling systems, a major component of this project, is to be performed in conjunction with LBL's Passive Solar Analysis Group. This group has the corresponding responsibility to perform computer simulations of passive heating systems.

In order to accurately predict the net heat exchange between the sky and a surface of known infrared characteristics, it is necessary to have a knowledge of the intensity of infrared radiation produced by the atmosphere. A knowledge of the intensity as a function of both zenith angle and wavelength is required. When this project began (March, 1977), a major effort was directed toward developing a computer model to predict this atmospheric radiation, based on the meteorological state of the atmosphere. This program is based on the public domain computer model LOWTRAN 3B<sup>1</sup>. Also during 1977 basic design of a filter spectrometer for measurement of atmospheric infrared radiance was completed.

#### ACCOMPLISHMENTS DURING 1978

A major activity in 1978 was the construction and siting of three infrared radiometer system for measurements of infrared atmospheric radiance. Since the first instrument was sited in August (Tucson), data collection has been a major activity.

#### Description of the Spectral Radiometer System

The spectrometer design incorporates a Barnes Corporation model 12-880 radiometer equipped with an eight-position filter wheel, germanium lens, and pyroelectric detector. Of the eight filter positions, one is an open hole and one is a closed hole used to determine the instrument's zero offset. The remaining 6 filter positions contain infrared interference filters with "halfpower" cuton and cutoff points given in microns ( $\mu\text{m}$ ) by (8.3, 9.1), (9.4, 9.9), (10.0, 11.4), (14.0, 15.8), and (16.6, 21.6). In addition to a stepping mechanism which allows the filter wheel to be positioned automatically, the instrument contains a rotating mirror assembly which allows the instrument's 2° field of view to be directed into the vertical direction or into a 70°C black body cavity. The entire instrument is under microprocessor control and is accessible to Lawrence Berkeley Laboratory through a MODEM telephone link. The accumulating data is transmitted over this link at intervals of one to three days.

Several measurements are made to supplement the basic radiometer data. Total infrared radiation is monitored with an Eppley pyrgeometer. Temperature and dewpoint are measured using standard techniques. The presence or absence of rain is also monitored.

Three radiometers are located in the field at the end of 1978. Systems were installed at Tucson, Arizona in August 1978; at San Antonio, Texas in September 1978; and at Gaithersburg, Maryland in November 1978.

#### Samples of the Sky Radiance Data

Figures 1-3 show samples of the radiometer data, superimposed on calculated spectra for similar meteorological conditions (identical air temperature and dewpoint). The measured radiances are assumed to be constant within each filter passband, or to be a segment of a black body curve, whichever is more appropriate. The calculated spectra (smooth curves) are obtained from a modification of the computer program LOWTRAN 3B<sup>1</sup>, described in more detail in last year's Annual Report.<sup>2</sup> Except as constrained by surface air temperature and humidity, the atmospheric constituents were assigned typical midlatitude summer values. The general agreement between the calculated and measured values of spectral sky radiance confirms that both the computer program and the radiometer produce reliable information.

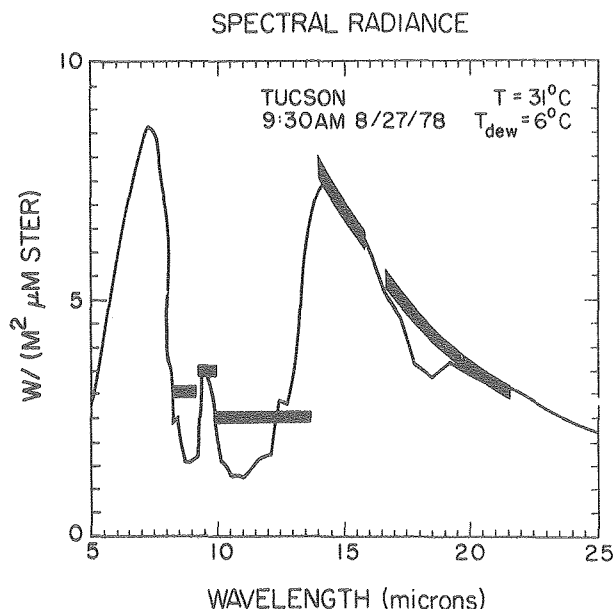


Fig. 1. Spectral radiance, both computed and measured, for clear sky conditions at Tucson, Arizona. The 10.7 micron filter is absent. Radiance in the 9.9 to 13.7 micron band is deduced from measurements through the 8.1 to 13.7 micron filter, after adjusting for the filters at 8.7 and 9.6 microns. (XBL 792-322)

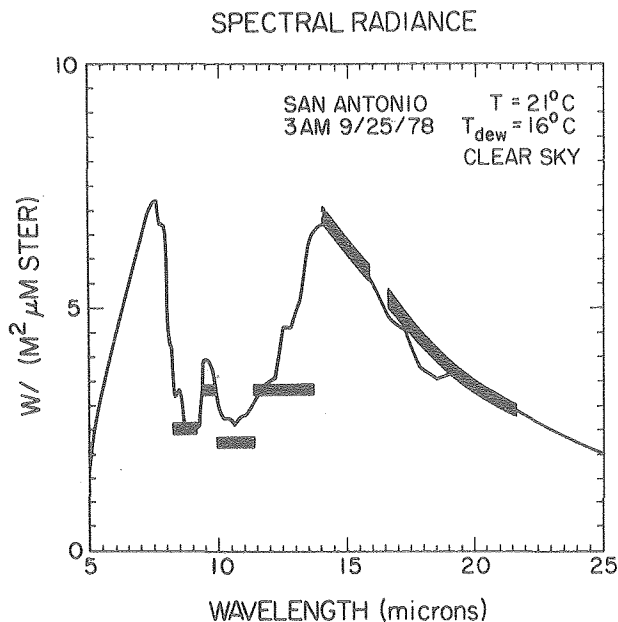


Fig. 2. Spectral radiance, computed and measured for clear sky conditions at San Antonio, Texas. Radiance in the 11.4 to 13.7 micron band is deduced from measurements through the 8.1 to 13.7 filter, after adjusting for the filters at 8.7, 9.6, and 10.7 microns. (XBL 792-323)

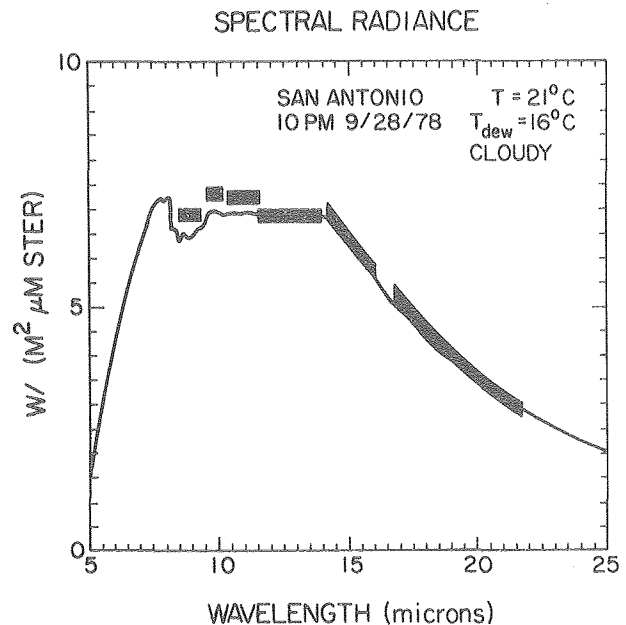


Fig. 3. Spectral radiance, computed and measured under conditions virtually identical to those of Fig. 2, but with a cloud in the field of view. In the computed spectrum, the cloud is regarded as a black body at an elevation of 4 km. (XBL 792-324)

#### PLANNED ACTIVITIES FOR 1979

During 1979 we plan to undertake a more accurate comparison between the theoretical computer model and the experimental data. This comparison will use radiosonde data (temperature and humidity profiles) as input to the computer program, and will also take into account the detailed spectral characteristics of the infrared bandpass filters.

The field radiometers will be recalled for maintenance and will be modified to make radiance measurements at several zenith angles. The instruments will then be relocated in the field for the summer of 1979, to obtain further data during periods of high air conditioning load.

Substantial effort will be invested in the development of computer codes which can be used to simulate the performance of passive cooling systems for existing and future conceptual designs. Computer simulations of buildings with passive cooling features must be validated against the measured performance of full-scale buildings in order to achieve an adequate level

of confidence in their predictions. Accordingly, one or more buildings will be instrumented for this purpose during 1979.

An experimental test facility will be constructed at LBL for the purpose of measuring radiative cooling rates that can be achieved by a variety of radiating surfaces and infrared-transparent glazings. Both black body radiators and selective surfaces will be studied.

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# Development of Solar-Driven Ammonia-Water Absorption Air Conditioners and Heat-Pumps\*

*K. Dao, R. Wolgast and M. Wahlig*

## INTRODUCTION

The objective of this project is the development of absorption refrigeration systems for solar heating and cooling applications. Two absorption cycles are under investigation: the basic single-effect cycle operating with low heat source temperatures compatible with flat plate collectors, and advanced multi-stage cycles operating with high heat source temperatures compatible with concentrating collectors for higher COP (coefficient of performance).

In the first phase of this project, the basic single-effect ammonia-water absorption cycle was tested experimentally to obtain answers to key technical questions concerning the use of such a cycle for solar cooling. The following constraints on the engineering and design of the test air conditioner were assumed:

- The condenser and the absorber must be air-cooled.
- The maximum heat source (hot water) temperature must be obtainable from flat plate collectors; that is below 230°F.
- The refrigerated medium (chilled water) produced must be below 50°F.

The test model was a modified ARKLA gas-fired  $\text{NH}_3/\text{H}_2\text{O}$  absorption chiller.

The first phase of this project has been concluded and has experimentally demonstrated<sup>1</sup> that the single-effect ammonia-water absorption can indeed be used for solar cooling, using an air-cooled condenser-absorber and flat plate collectors.

The second phase of the project has continued from early 1977 to the present with the main objective being to explore the commercial potential of the  $\text{NH}_3/\text{H}_2\text{O}$  single-effect absorption air conditioner. It is assumed that the following constraints must be met for a commercial unit:

- Total prime heat exchanger area: 120 ft<sup>2</sup> maximum.
- Cooling capacity: 3 tons minimum.
- Coefficient of performance: 0.65 minimum.
- Hot water temperature: 230°F maximum.
- Chilled water temperature: 45°F maximum.
- Cooling air temperature: 95°F minimum.
- Total parasitic electric power: 700 watts maximum.

A completely new 3 ton single-effect unit was engineered and designed to perform within the performance criteria stated above. The key components of this new unit are tube-in-tube heat exchangers for high effectiveness and low cost. Incorporated in this unit are

techniques for recuperation of mechanical energy from the high pressure subcooled weak solution and recuperation of heat content from the ammonia vapor produced in the generator.

The commercialization program for this type of single-effect  $\text{NH}_3/\text{H}_2\text{O}$  absorption chiller has started with the award of a subcontract to Phillips Engineering Co. for the design review of this new unit.

The success of the single-effect unit will not obviate the need for development of more advanced chillers with higher COP's compatible with high temperature collectors (above 230°F). Accordingly, this project is investigating advanced absorption cycles whose COP increases with temperature, maintaining a relatively constant fraction of the Carnot COP over a wide range of operating temperatures.

## ACCOMPLISHMENTS DURING 1978

The fabrication of the new single-effect  $\text{NH}_3/\text{H}_2\text{O}$  absorption air conditioner was mostly completed by July 1978. Its installation for testing is underway.

Figure 1 shows the major part of this chiller at the point where it was about to be connected to its condenser-absorber unit (shown in Fig. 2). The main improvements incorporated in this new unit as compared to the conventional single-effect cycle are:

- The use of a combined preheater-rectifier for the high-pressure vapor and the weak solution flow paths, instead of using separate components for these functions of heat recuperation and vapor rectification. A small 1/8 in. tube is used to collect the condensate at the middle of the vapor tube of the preheater. Since the concentration of this condensate is fairly high, it is expanded in the precooler to subcool the liquid ammonia exiting the condenser.

- The use of a newly designed pair of piston pumps. One pump uses the pressure drop of the weak solution (otherwise wasted) as the driving force to circulate about 70% of the strong solution from the absorber outlet to the generator inlet via the preheater. The remaining strong solution will be circulated by the other paired pump, which is driven by a small flow of high pressure ammonia vapor extracted from the condenser inlet. These pumps replace the usual electrically driven circulation pump.

Brief descriptions of the major components of the unit are:

1. Generator: Triaxial tube-in-tube counter-flow heat exchanger (inner coil in Fig. 1).



Hot water flows in the outermost annular channel and also inside the innermost tube. Boiling  $\text{NH}_3/\text{H}_2\text{O}$  solution flows in the middle annular channel. Outside diameters of triaxial tubes: outermost, 1.875 in.; Middle, 1.375 in.; Innermost, 0.75 in. total length: 56 ft in a 30 in. diameter coil.

2. Preheater: Triaxial tube-in-tube counter-flow heat exchanger (outer coil in Fig. 1). The weak solution leaving the generator flows in the outermost annular channel. The strong solution flows in the middle annular channel on its way to the generator. The ammonia vapor produced in the generator flows in the innermost tube as it heads towards the condenser. Outside diameters of triaxial tube preheater: outermost, 1.375 in.; middle, 1.0 in.; innermost, 0.625 in. Total length: 96 ft coiled in a 38 in. diameter coil.

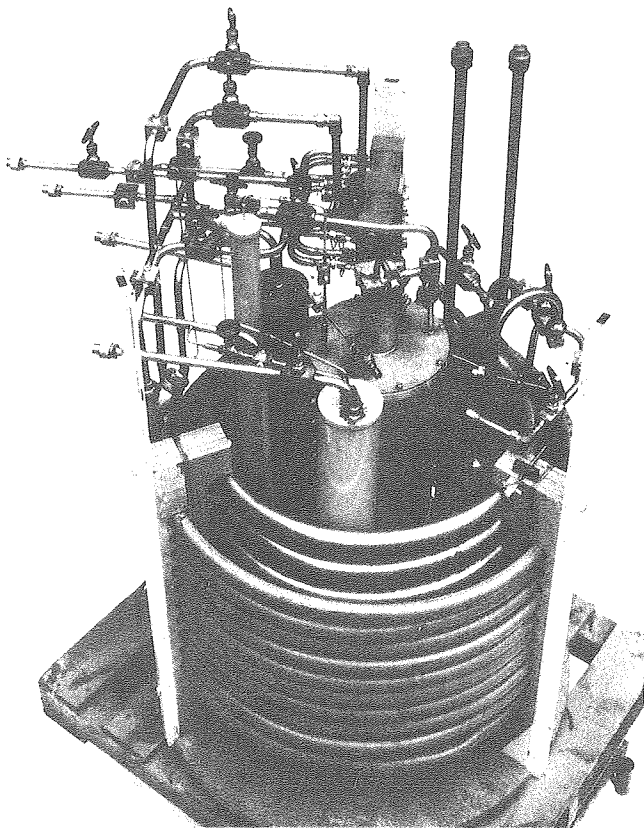


Fig. 1. Main assembly of the single-effect  $\text{NH}_3/\text{H}_2\text{O}$  absorption air conditioner. The outermost 10-turn coil is the preheater and the inner coil with larger tubing is the generator. Surrounded by the generator coil are the evaporator (short, largest-diameter tank), the pre-cooler (thin, tallest cylinder) and the two solution storage tanks. The solution pumps are located above the evaporator, slightly toward the back of the unit. (CBB 786-7686)

3. Condenser-Absorber: Finned-tube crossflow heater exchanger (Fig. 2); 8 fins per inch, 0.625 in. OD tube, 3 rows (2 rows for the absorber, 1 row for the condenser); Frontal area: 39 x 41 in.<sup>2</sup>
4. Fan Motor: 3/4 HP, 6900 cfm.
5. Evaporator: Double coils in the annular spaces of 3 cylindrical shells. Tube OD: 0.5 in., shell diameters: 10 in., 9 in., 8 in.; height: 38 in. Total tube length: 190 ft. A vapor extraction chamber and orifice were installed between the two coils to reduce the pressure drop across the evaporator.
6. Pair of circulation pumps: Cyclinder bore: 2.5 in.; stroke: 2 in. Each pump is a tandem piston pump. The use of 2 pistons per pump assures the continuity of the delivery of the strong solution. Specially designed valves are used for the intake, exhaust, suction and delivery.

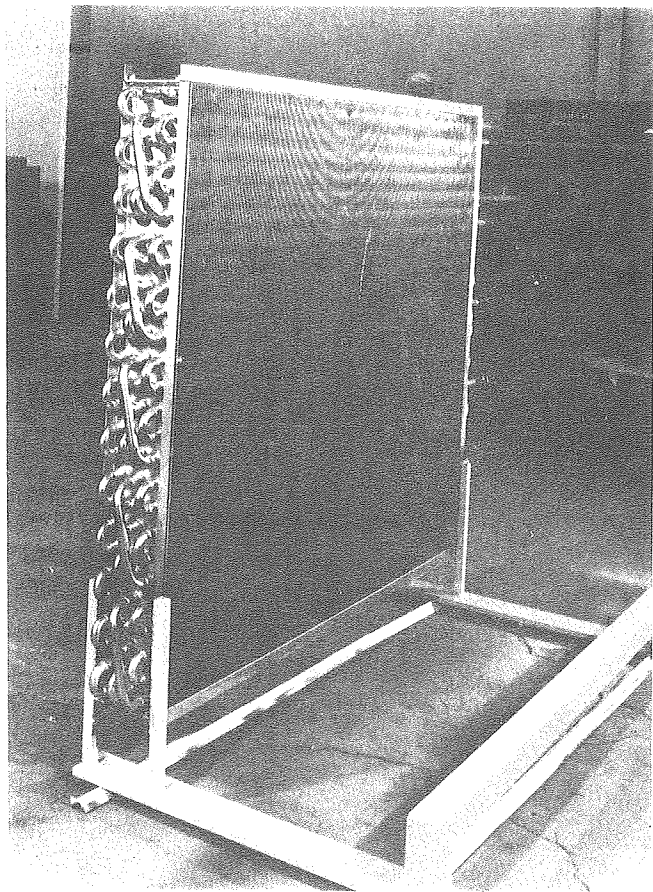


Fig. 2. Condenser-absorber unit, before connection to the air-conditioner. The first row of tubes on the left is the condenser, and the two remaining rows are the absorber. (CBB 782-2501)

The expected performance of the new chiller is summarized in the following table:

Capacity (tons)	2	3	4	5
COP	0.72	0.70	0.68	0.64
T <sub>hot water</sub> (°F)	192	216	239	263
T <sub>cond-absorber</sub> (°F)	104	108	114	119
T <sub>evaporator</sub> (°F)	43	41	38	34

Cooling air is 95°F; chilled water produced is 45°F

Electrical power: Fan  $\approx$  550 W  
Water pumps  $\approx$  150 W

Installation of this new chiller was begun in the test setup at LBL following the dismantling and removal of the previously tested chiller. Ductwork for the new condenser-absorber was installed. An SCR-controlled electric water heater was designed for use as the heat source of the new unit. This pressurized water heater has the capacity of 120,000 Btu/hr at 320°F maximum; its output temperature can be maintained constant within  $\pm 2^\circ\text{F}$ . Its fabrication was underway by the end of 1978.

The instrumentation of the test setup includes 32 thermocouples, 3 absolute and 5 differential pressure gages, and 2 turbine-type flow meters.

The initial fabrication of the pair of circulation pumps was completed, and extensive testing of the pumps continued throughout the remainder of the year. Several modifications were tried to eliminate or reduce vibrations and banging during operation at high pressure. Very smooth operation of the pumps has not yet been achieved, and additional modifications are planned.

Computer models for the components of the new chiller have been completed and debugged. The mathematical model for each component includes detailed heat transfer, pressure drop, mass and energy relationships, and takes into account specific properties of the materials used. Given the inlet conditions, the model calculates the outlet conditions for that component. The main program that connects the component subprograms is not yet completed. This computer program will be capable of optimizing the principal dimensions of any single-effect absorption chiller that is similar in design to the new LBL chiller.

The preliminary analyses and conceptual designs of two advanced absorption systems were completed and reported in Refs. 3 (Cycle 1R) and 4 (Cycle 2R). These new advanced absorption cycles are particularly compatible with solar collectors that operate in the range of 160°-350°F. The practical COP of these systems can be about 60% of the Carnot limit; i.e., given the heat source temperature  $T_s$ , the heat sink temperature  $T_0$ , and the refrigerated fluid temperature  $T_E$ , the system COP equals  $0.6[(T_s - T_0)T_E]/[T_s(T_0 - T_E)]$ .

## PLANNED ACTIVITIES FOR 1979

The installation, testing, and evaluation of the new single-effect absorption air conditioner will be completed during 1979. Reports on the testing of the chiller and of the pumps will be printed and distributed near the end of 1979.

The design, fabrication and testing of a multi-stage (8-stage) pump will be carried out. This pump will be a key component of the advanced absorption refrigeration system (Cycle 2R chiller), the design of which will also take place during 1979.

The multi-stage pump consists essentially of one double-effect piston driver linked to a group of 8 piston pumps arranged in two rows of 4 pumps each. Each pump is also double-acting with 4 check valves connected to a common intake and a common discharge pipe. For a 3-ton chiller, the piston diameters are on the order of 1.5 in. for the driver and 1.25 in. for the pumps.

Properties of refrigerant-absorbent pairs other than  $\text{H}_2\text{O}/\text{NH}_3$ , such as  $\text{R22}/\text{E181}$ , will be explored for possible use with advanced cycles. Since the concept of advance cycles, particularly cycle 1R, is completely different from that of the conventional single-effect cycles, the criteria of choosing working fluids are also different. The criteria will give less weight to pumping work and heat transfer rates in recuperators because the pumping and heat exchange rates will be smaller in the advanced cycles. Of more importance will be material compatibility and high temperature potential because the construction of advanced systems will require more complicated configuration and because the COP will increase with temperature. Working fluids are desirable that will be compatible with easily brazed materials, such as copper and copper alloys.

Analysis of the advanced cycle 1R will continue throughout 1979 in search of a good system configuration for a test model that can be fabricated in 1980.

## FOOTNOTE AND REFERENCES

\*This work has been supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U. S. Department of Energy.

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## Appropriate Energy Technology\*

*C. W. Case, H. R. Clark, and F. B. Lucarelli*

### INTRODUCTION

The Appropriate Energy Technology Program was commissioned by the U. S. Department of Energy (DOE) and established by the San Francisco Operations Office (SAN) during the summer of 1977. It began with a preliminary or pilot program (Phase I) in Federal Region IX, the Pacific Southwest, which includes Arizona, California, Hawaii, Nevada, American Samoa, Guam, the Trust Territories of the Pacific, and the Commonwealth of the Northern Marianas. Like the national program to follow in 1978, the pilot was designed to encourage the ingenuity and resourcefulness of individuals, small businesses, state and local agencies, local nonprofit groups, and Indian tribes.

DOE set aside \$500,000, exclusive of operating costs, for this initial effort and expected the grants to average \$10,000 with the ceiling placed at \$50,000. Because of the general quality of the submissions, DOE added \$850,000 to the award money (\$1,350,000 total), and the 108 grants averaged \$12,500, with a range stretching from \$328 for a beeswax melter to about \$49,000 for a hydroelectric project. The grants were awarded for development of a broad variety of small scale energy innovations and demonstration projects from wind-bouys to coffee dryers to greenhouses to geothermal residential hot water heating. All were chosen using guidelines that defined as eligible those projects which made best use of available renewable energy resources, used locally available materials, emphasized decentralized technologies, increased energy self-reliance at the community level, and/or were labor intensive and environmentally sound.

The three-step procedure for allocating the grants included the prescreening step, which ascertained whether each application was complete and whether it required special handling (e.g., referral to another agency for funding), the technical/economic review step, and the peer review step by committees set up by the governor's office of each state. These committees, aided by the technical and economic advice from the second review, made awards with final approval by DOE/SAN. In 1977 LBL prescreened all 1116 proposals received.

### ACCOMPLISHMENTS DURING 1978

For the pilot program, LBL did the technical/economic reviews of all proposals from Arizona, Nevada, Guam, and the Trust Territories of

the Pacific. Those from Hawaii were reviewed by the University of Hawaii, and most of the applications from California were reviewed by the California Office of Appropriate Technology (OAT). However, LBL reviewed about twenty of the more technically demanding proposals, which OAT could not handle.

Since the beginning of the Program, LBL has performed various program management functions such as establishing the procedures used during review processes as well as compiling and analyzing data. These functions will expand to include assistance to all other Federal Regions as Phase II gets under way. The Laboratory has been involved with DOE in the commercialization strategies for some of the more advanced projects and is presently monitoring the performances of the thirty projects funded in Arizona and Nevada. A single trip to Guam and the Trust Territories, where seven projects are dispersed among the islands, served the purposes of monitoring, advising, stimulating local interest, and setting up the machinery for self-monitoring and possibly technical and peer self-reviewing. LBL has also established an Appropriate Energy Technology Library, designed to serve people involved in this program as well as other interested Laboratory employees.

### Pilot Program--Phase I--Awards

The 108 grants made in the pilot phase of the Appropriate Energy Technology Program totalled approximately \$1,350,000, as mentioned above. Categorizing these projects cannot do justice to their individuality or variety. Generally, however, forty-two were solar-related with six concentrating on storage solutions and eleven on hot water. Four deal with waste heat recovery, twelve with energy conservation, eleven with wind projects, and one with geothermal. Of eleven biomass projects four are wood and seven are recycle. There are three hydroelectric, four aquaculture, five integrated systems and fourteen educational programs and workshops.

The number of awards distributed to each state or territory were:

Arizona	19
California	58
Hawaii	13
Nevada	11
Trust Territories and Guam	7
	<u>108</u>

## PLANNED ACTIVITIES FOR 1979

The other federal regions are now instituting Appropriate Energy Technology Programs with each region devising its own timetable. In Region IX the Phase II program began with DOE accepting applications from November 1978 to 15 January 1979. DOE has set aside \$530,000 for the awards in Region IX, and will make these awards during the summer.

LBL expects to support Phase II with the same kind of assistance that was necessary in Phase I, and to provide technical backup for any federal region that so requests, and

to conduct policy analysis/program evaluation studies for the grants program as a whole. The Laboratory will also assess the energy savings which might accrue from successful completion and commercialization of the projects and consider improvements for administering and implementing future programs.

## FOOTNOTE

\*This work has been supported by the Buildings and Community Systems Division, Office of Conservation and Solar Applications, U. S. Department of Energy.

## Support Activities for DOE Solar Heating and Cooling Research and Development Program\*

*M. Wahlig, M. Martin, R. Kammerud, W. Place,  
E. Wali, and B. Boyce*

## INTRODUCTION

This project consists of technical support activities for the Solar Heating and Cooling Research and Development Branch of the DOE Office of Solar Applications. Areas in which LBL provides program support are controls for solar heating and cooling systems, passive cooling, active solar cooling, and passive solar analysis and design. These activities include the following: (a) peer review of unsolicited proposals; (b) preparation and evaluation of Program Research and Development Announcement (PRDA) and Request for Proposal (RFP) solicitations; (c) technical monitoring of projects performed both by other DOE contractors and by LBL subcontractors; (d) program planning, reviews and summaries; and (e) inter-laboratory coordination of support activities. Program responsibilities of the Laboratory have increased due to implementation of a program decentralization plan approved in the fall of 1978. Under this plan LBL and SAN (San Francisco Operations Office of DOE) work together to manage the national R&D program in these assigned areas, with SAN providing the project management and LBL the technical support. DOE headquarters transfers block funds to the DOE/SAN office to support the outside research and development contracts being performed under these program elements. Most of the staff members of the Solar Energy Group have participated to some extent in this effort during 1978.

## ACCOMPLISHMENTS DURING 1978

### Review of Unsolicited Proposals

LBL solar energy group members participated in formal review sessions for unsolicited solar energy proposals in the areas of active cooling, passive systems, and active systems. In addition,

approximately eleven controls and passive cooling proposals were reviewed individually, as received. Input was provided to headquarters for the preparation of guidelines for reviewing unsolicited proposals.

### Preparation and Evaluation of Program Solicitations

No new solicitations were released during 1978 in the program areas where LBL has responsibility. Recommendations were drawn up outlining desirable solicitations for the passive cooling and controls program elements for 1979. Work proceeded on the preparation of several solicitations in the active cooling area, to be released during 1979; these are concerned with advanced components and systems, marketing studies, and field testing. In the passive area, work started on the development of a solicitation for marketable products.

In response to a related DOE request for technical assistance, three LBL staff members participated in a review of proposals submitted in response to a Program Opportunity Notice (PON) issued by the Commercial Demonstration Branch.

### Technical Monitoring of Projects

Project monitoring consists of the continuous technical evaluation of projects being performed by other contractors, including site visits, review of progress reports, and organization of contractor meetings as appropriate. Site visits were made to all contractors performing passive cooling or solar controls work under LBL jurisdiction, and individual project review meetings were held with three contractors during the summer. A controls contractor meeting was held at the end of February to review early

results of the 12 newly initiated projects and two continuing projects.

During the final quarter of 1978 LBL took on the additional task of program responsibility for the active solar cooling program element. Personnel were added to handle contract monitoring tasks for this expanded program, and transfer was initiated of the back files on the active cooling projects from Brookhaven National Laboratory to LBL. Status reviews of the active cooling contracts were held during September and December.

In addition, two contracts have been issued by LBL; one contractor is preparing a passive solar design workbook. The second contractor is performing a review and evaluation of information, data and materials properties of relevance to passive solar applications. This contractor is surveying both the open and classified DOD and NASA literature. These contracts are likewise being monitored by LBL staff members.

#### Program Planning, Reviews and Summaries

Several program summaries were prepared for DOE regarding the status of controls and passive cooling projects, and presentations were made at the annual contractors' meeting to review progress in these projects for which invited papers were not submitted. Assistance was provided in writing the annual DOE "Solar Heating and Cooling Research and Development Summaries" publication.

Overview presentations of the Controls Program and of the Passive Cooling Program were given during the Cooling Workshop held in early 1979. LBL participated actively in planning and conducting the Solar Controls Workshop held in Hyannis, Massachusetts in May 1978.

Program planning activities by LBL included participation in a meeting to update and review the National Program Plan for Research and Development in Solar Heating and Cooling, as well as involvement in planning for specific program elements. The latter includes assistance in developing the National Program Plan for Passive and Hybrid Solar Heating and Cooling, Retrofit Program Plan, Joint U. S.-Saudi Arabian Passive Cooling and Active Cooling Plans, and the Systems Plan. In addition, LBL had the major responsibilities for writing the Commercialization Plan for Passive Solar Heating as well as the Solar Controls Plan.

#### Interlaboratory Coordination

LBL has participated in the two 1978 meetings of the Support Laboratories Coordinating Committee, which meets regularly to discuss the state of implementation of the R&D program, and to insure that the various laboratories are acting harmoniously in performing their many tasks. A coordinated effort took place with NBS, LASL and PRC to develop performance evaluation factors and data acquisition requirements for passive solar systems. Coordinated activities between LBL and SERI included joint work on the national passive solar program plan, preliminary work on meshing the Controls Plan and the Systems Plan, and shared responsibilities for technical monitoring of active cooling projects.

#### PLANNED ACTIVITIES FOR 1979

Activities in all the above areas will continue throughout 1979. Unsolicited proposals will be reviewed and evaluated as they are received. The Solar Controls plan is scheduled for completion and implementation early in the year. Solicitations are anticipated for the Passive Solar Technology, Controls, and Active Cooling program elements. Monitoring of outside contracts is expanding rapidly in the active solar cooling area, whereas the first set of contracts for Passive Cooling and Solar Controls will have been completed by early 1979. Several follow-on and unsolicited proposals are likely to be approved for funding during 1979. A Controls Workshop and a Cooling Workshop are scheduled for Fall 1979 and topical workshops on Rankine cycle fluids and absorption cycle fluids are planned for mid-1979. Additional meetings of the Support Laboratories Coordinating Committee will be held during the year. Finally, it is certain that numerous LBL staff members will be called upon to assist in the review and evaluation of proposals submitted to DOE solar energy PRDA, RFP and PON solicitations issued during 1979.

#### FOOTNOTE

\*This work has been supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U. S. Department of Energy.

# Experimental Test Facility for Evaluation of Solar Control Strategies\*

M.L. Warren and M. Wahlig

## INTRODUCTION

An experimental test facility for solar heating and cooling has been constructed to evaluate the operation and performance of an LBL-developed solar controller that has promising commercial potential. The LBL controller was designed to be intermediate in performance between a simple differential thermostat and an on-line microprocessor. A schematic of the solar controller is shown in Fig. 1. Electrical signals from up to eight solid state temperature sensors are standardized. By use of a pin matrix board, PPM, pairs of temperature sensors can be selected for comparison. The logic signal outputs from the comparators are used to drive Programmable Read-Only Memory (PROM) chips which in turn drive relay outputs. The controller operates the solar system according to a preprogrammed algorithm that translates operating state conditions (fluid temperatures, switch positions, comparator outputs) into a set of operating instructions (open or close valves, turn pumps on or off). The operating algorithm can be changed by reprogramming or exchanging this plug-in integrated circuit component.

The experimental solar heating and cooling system serves to test the relative performance of different controllers and alternative control algorithms for a variety of input meteorological conditions and output load demands. The measure of performance is the amount (and cost) of the auxiliary back-up energy saved by different

control strategies. The experimental evaluation of the cost effectiveness of controllers and control strategies is expected to be the primary output of this project. The development of the LBL controller and the experimental facility have been described in detail elsewhere.<sup>1,2</sup>

## ACCOMPLISHMENTS IN 1978

The major activities during 1978 involved improvements to the experimental test facility. The facility has a simulator for the solar heat input (the pseudo-collector) and a simulator for the building load. Instrumentation has been added to the facility for data acquisition and analysis. Heat balance tests using solar collector and simulator heat input have been carried out. In addition, storage heat loss experiments have been conducted without heat input or load. The TRNSYS computer program was employed to predict system performance and the results were compared with experimental measurements. Recent work is described in Refs. 3 and 4.

## Instrumentation

A major development in 1978 was the implementation of the system for data acquisition and experiment control. An HP-9825A microcomputer arrived in November 1977 and has been interfaced with the 100 channel DORIC data-logger, with the multiprogrammer, and with the solar controller. Additional memory for a total of 24 kbytes was installed in August 1978. The

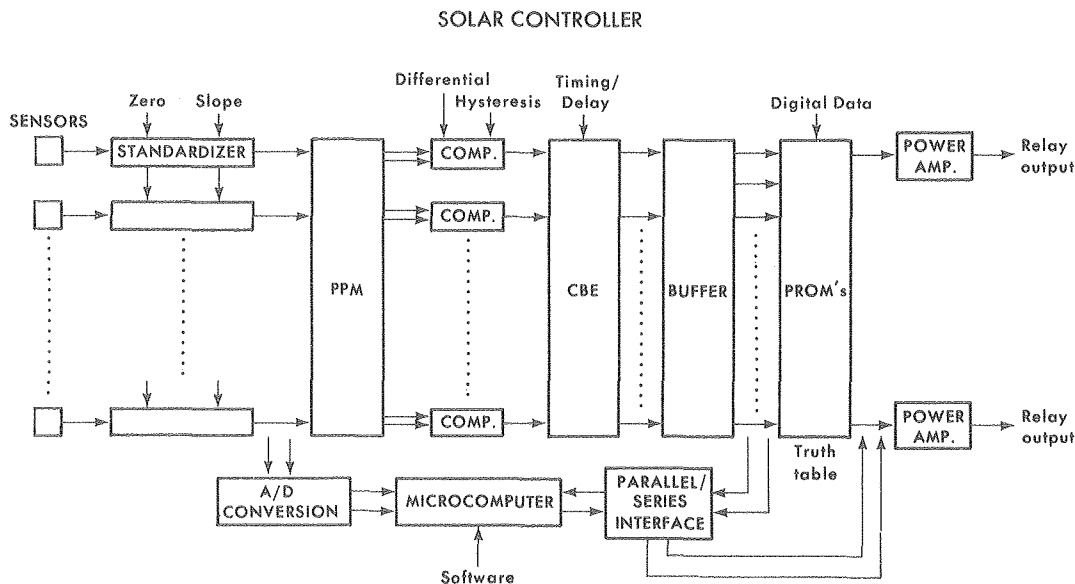


Fig. 1. Schematic of the LBL-developed Solar Controller. The inputs from 8 sensors are standardized and compared. The comparator outputs and other digital data drive the Programmable Read Only Memory (PROM) that generates relay output signals to control the solar energy system. (XBL 785-886)



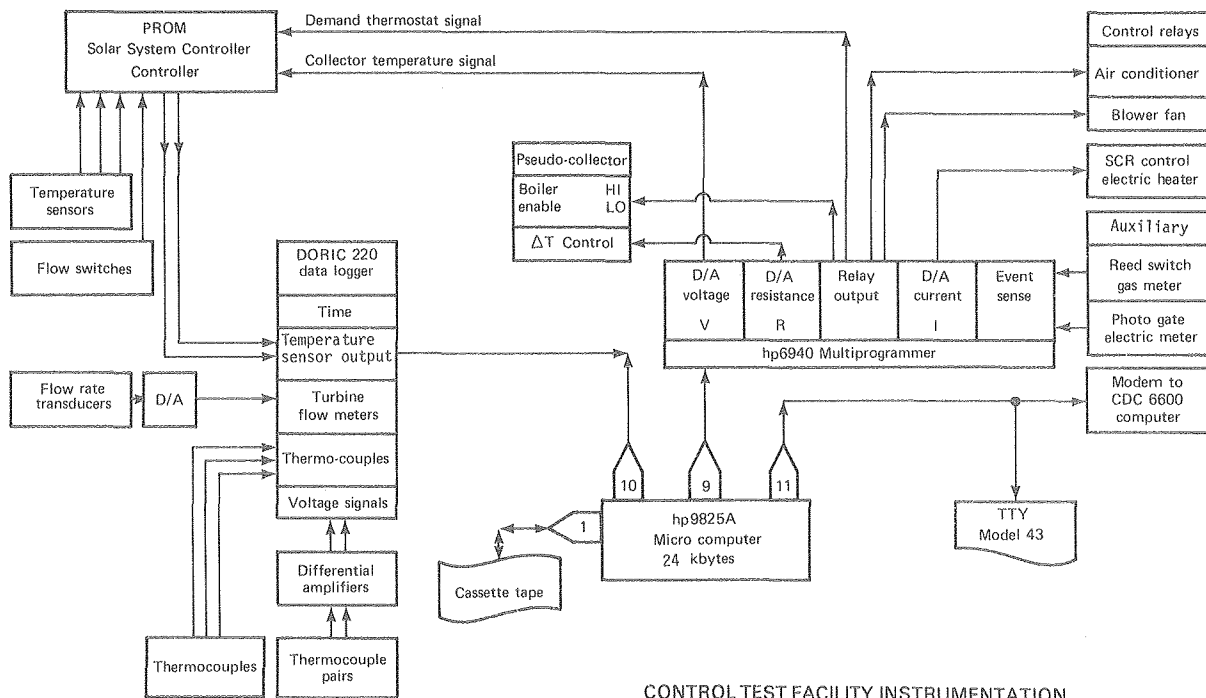
microcomputer will perform four major functions in future experiments: 1) data acquisition and on-line data reduction; 2) building load and response simulation; 3) solar collector response simulation; and 4) controller status monitoring and microcomputer override. A schematic of the instrumentation and data acquisition system is shown in Fig. 2. The temperature sensors used to generate input signals for the solar controller and about 30 copper-constantan thermocouples used to monitor solar system performance, are wired into the DORIC data acquisition system, and are available to the microcomputer for on-line data analysis and experiment control. The microcomputer incorporates building and collector response models and generates control signals through the multiprogrammer to control the load simulator and the pseudo-collector. Meteorological and insolation data from standard DOE weather tapes for various geographic regions are used to drive the load and collector model equations. Thus, the experimental facility can be operated under diverse simulated weather and load conditions to test solar control strategies. The microcomputer is also interfaced to the main LBL computer system for off-line data analysis and storage.

#### Heat Input and Load Output Simulators

To make meaningful comparisons between alternate control algorithms, the heat input and the load conditions must be reproducible. Therefore, it was decided that the solar energy input to the system and the building output load should be supplied by simulation devices that permit repeated runs under

the same external conditions. The heat input simulator, the pseudo-collector, is a boiler with a controlled mixing valve that allows precise adjustment of the input-output temperature difference,  $\Delta T$ . A resistance proportional to  $\Delta T$  is generated and used to control the pseudo-collector. In future experiments the microcomputer will generate collector temperature increase information using solar insolation data, weather data, measured system parameters, and a collector response model. An output resistance of about 2 ohm/°C, proportional to the temperature increase, generated by the multiprogrammer D/A converter, controls the pseudo-collector. Another voltage output signal generated by the multiprogrammer D/A converter is used to simulate the output of the solar collector temperature sensor and is based on the collector model calculation. The main controller for the solar heating and cooling system cannot distinguish whether the system is operated from solar collector panels or from the pseudo-boiler.

An automated air flow load channel has been designed and fabricated to simulate the building return air flow across the heating or cooling coil in the furnace ductwork of a residential system. The load simulator provides a controlled and reproducible residential building load isolated from the inappropriate laboratory environment in which the solar system is actually located. Both heating and cooling loads can be simulated. The temperature within the ductwork is carefully controlled by an electric resistance heater and an air conditioner. The microcomputer gives on/off control to the air conditioner if the inlet air temperature is too high, and gives proportional control to the duct heater



CONTROL TEST FACILITY INSTRUMENTATION

Fig. 2. Schematic of the instrumentation and data acquisition system. All experimental measurements are available to the microcomputer for online data analysis and experiment control through the DORIC data-logger. (XBL 794-1149)

if the air temperature is too low. The micro-computer also models the building heat loss in response to weather conditions, and monitors the rate at which energy is being delivered to the load by the heating or cooling coil. This information enables the microcomputer to determine when the building load has been satisfied, thus serving as the building demand thermostat for the solar system controller.

#### Heat Balance Tests

The energy flows from the collector loop and from storage should exactly balance the energy flows to the load, to storage and to ambient air. The heat input and load output, as well as all heat flows within the system, are carefully monitored. Precision flow rate and temperature measurements are recorded over time intervals of typically 5 to 15 minutes and used to calculate these heat quantities.

The heat balance error is defined as the unaccounted energy flow divided by the incoming energy flow:

$$\text{Heat balance} = \text{Heat In} - \text{Heat to Load} - \text{Heat Loss} - \text{Storage}$$

where  $\Delta\text{Storage}$  is the net heat delivered to storage.

$$\% \text{ Error} = 100 \times \frac{\text{Heat Balance}}{\text{Heat in} - \Delta S}$$

where  $\Delta S = \Delta\text{Storage}$  if  $\Delta\text{Storage} < 0$ ; and  
 $\Delta S = 0$  if  $\Delta\text{Storage} \geq 0$ .

The heat balance error depends critically on the accuracy of the fluid flow and the temperature measurements. The digital flow rate measurement is accurate to within 1%. The calibrated temperature sensors are accurate to  $\pm 0.1^\circ\text{C}$ . The copper-constantan thermocouples were found to be accurate to within  $\pm 0.5^\circ\text{C}$ . Wiring the thermocouples in pairs produced temperature difference measurements accurate to about  $\pm 0.2^\circ\text{C}$ . The heat balance error for the initial day-long experimental runs varied from 1% to 12% with the average about 7%.

For assessment of the reduction in auxiliary energy consumption associated with various control strategies, a measurement of the energy balance to an accuracy of  $\leq 5\%$  appears to be necessary. Error analysis indicates that this can be achieved if the temperature difference measurements can be made to within  $0.1^\circ\text{C}$ . Better measurements of the temperature distribution within the storage tank, plus use of amplifiers for the thermocouple difference signals have significantly reduced temperature measurement errors. Heat balance experiments are underway to determine how successful these improvements have been. A more recent experimental run shown in Table 1 indicates a heat balance error of 3.7%, which is within our goal of 5% heat balance accuracy.

#### Computer Modeling

The TRNSYS program was used to calculate system performance for comparison with experimental measurements. Simple controllers were

Table 1. Heat balance experiments

	PREVIOUS RUN	RECENT RUN
HEAT IN	210.7	205.5
HEAT TO LOAD	754.4	923.7
HEAT LOSS	55.7	61.0
STORAGE	-542.2	-744.1
HEAT BALANCE	-57.1	-35.1
% ERROR	-7.6	-3.7

Notes: Heat is given in units of megajoules ( $10^6\text{J}$ ).

studied with the computer model. As reported last year, many studies of on/off controllers and proportional controllers ran into numerical convergence problems, apparently caused by the static equations used to describe components in TRNSYS. This problem is now being addressed by researchers at Drexel University and at the present time we have no plans to pursue this computer modeling of control algorithms.

#### PLANNED ACTIVITIES FOR 1979

In 1979 work will continue to refine measurement precision and to complete microcomputer control of data acquisition and experimental operation. The LBL solar system controller evaluation studies will begin with a series of twenty-four hour runs to shake down data acquisition and on-line data reduction procedures using simulated collector heat input and building load output based on simple models. The simulation models will then be refined. A series of seven day runs will then compare system performance of different control algorithms using the LBL developed controller.

The experimental program will expand to include proportional flow modes. Modifications to the controller and to certain actuators should allow testing of proportional flow algorithms, and thus their comparison with on/off strategies. This experimental performance testing of alternative control strategies will continue throughout 1979.

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## PG&E/LBL Solar Data Network\*

*D. Anson*

### INTRODUCTION

Lawrence Berkeley Laboratory (LBL) and Pacific Gas and Electric Company (PG&E) have been cooperating in the implementation of a solar radiation data collection network in northern California. This discussion will briefly summarize the project history, characteristics of the network itself, details about data collection, instrumentation problems, and near-term accomplishments and goals.

The project objective is to provide a high quality solar radiation data base for well-located sites in northern California. This is to be accomplished through the establishment of a solar data network using accurate instruments and data analysis techniques, and will be followed by prompt data dissemination. This project is the northern California complement to the extensive solar data networks in the Los Angeles and San Diego areas of southern California.

The solar radiation measured by this project will likely provide the only data of suitable quality for solar applications available to designers, architects and engineers in much of this region. Once in full operation, the network will provide a valuable user-oriented resource.

### PROJECT HISTORY

The PG&E/LBL network originated in July 1974 as part of a larger, National Science Foundation supported solar heating and cooling project at LBL. The following year the program was transferred to ERDA, which made a policy decision not to support local solar data collection networks. However, by this time instruments had been purchased and arrangements made to implement the project. Work on the network continued at a low and discontinuous level until February 1978 when it became possible for a part-time LBL staff member to take on overall responsibility for the effort. As a result, the network is now operational, albeit with some remaining problems to be worked out.

The motivation for persevering in this effort is that there is no other comparable array of stations producing high quality solar radiation

data for northern California. The DOE supported National Weather Service Network has only two stations in California, at Fresno and Los Angeles. Neither of these locations can be considered representative of the Bay Area, the northern coast, or the interior regions to the north of Fresno.

### Network Description

The organizational relationship between PG&E and LBL is such that PG&E is primarily responsible for three tasks: routine maintenance, changing the magnetic tapes used for data collection, and raw data conversion. LBL is responsible for overall technical integrity (annual calibration, non-routine maintenance), data reduction, analysis and reporting. The current status of individual stations in the network varies considerably--from those with almost a year and a half of data (e.g., Berkeley) to the Eureka station which was established during July 1978.

Each station in the network consists of one thermopile-type pyranometer (Fig. 1) and a specially modified PG&E supplied tape recorder.

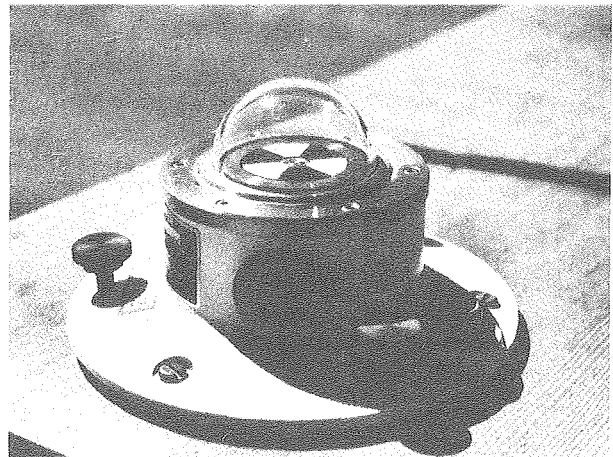


Fig. 1. A thermopile-type pyranometer used to measure solar radiation at each of the six network stations. (CBB 791-376)

The pyranometer measures the total radiation (direct sunlight plus diffuse skylight) incident upon a horizontal surface. The solar instrument used is a model 8-48 pyranometer (The Eppley Laboratory, Inc.). The network consists of six locations throughout PG&E's northern California service area: Berkeley, Red Bluff, Salinas, Santa Rosa, Auburn, and Eureka. These locations complement individual solar stations currently operated in northern California by other organizations. A contact person at each network station is responsible for routine servicing and for tape changes. A seventh instrument is maintained as a traveling calibration standard and is itself calibrated twice yearly by the NOAA Solar Radiation Facility in Boulder, Colorado.

The recorder is a modified Westinghouse WR-1C used in standard utility magnetic tape recording systems. The pyranometer is interfaced to the recorder with LBL-developed electronics that produce pulses on the tape at a rate that is proportional to the intensity of the incident solar radiation.

#### Maintenance

Unrealistic variations in the recorded data provide the primary diagnostic tools for revealing station malfunctions. The Santa Rosa station, for example, produced results for three months with all zeros. Investigation revealed a two-fold problem: one, the data pulse circuitry was not operating; and two, the inside of the instrument was saturated with moisture. The moisture inside the pyranometer dome was apparently the result of allowing the desiccant to become saturated. Thus, even if the circuitry had operated properly, the data would have been in error (too low) due to the condensation on the inside of the dome. The sensor surface was damaged by the condensate and returned to the manufacturer for resurfacing and recalibration. This incident occurred soon after network start-up and points out the necessity for preventive maintenance and rapid processing of the data. These problems with recorder malfunction and instrument moisture saturation are not expected to reoccur with the present more careful, weekly routine of checking each pyranometer.

#### ACCOMPLISHMENTS DURING 1978

The accomplishments during this past year are grouped into administrative, hardware, and data processing. Administrative tasks included: establishing a list of contact people and responsible personnel at the various station locations, setting up a calibration schedule, assembling a draft service manual for use by the network coordinator, compiling a draft maintenance manual to assist on-site trouble shooting, developing contacts with persons coordinating solar networks in other states, and visiting each of the six stations for inspection and recorder check-out.

Hardware activities were primarily related to the detection of breakdown, repair and recalibration of two pyranometers, and verification of recorder gain and zero-offset adjustments. Also, a digital voltmeter and frequency counter were acquired for pyranometer and recorder

servicing. Documentation and test methods were developed for use by other personnel if necessary. A spare pyranometer was purchased as a back-up to reduce data record gaps when instruments are inoperative or disconnected. Also, the annual calibration program was begun at the LBL station.

Each of the six solar data stations require routine and responsible attention. Adequate service procedures are the most important factor in both the short and long term success of producing high quality solar data.

The data processing is partially developed and has been used to detect hardware malfunctions in two pyranometers. More complete data analysis and data presentation methods are in progress.

Data turn-around times have been excessively long during 1978. This has been largely the result of procedural changes at PG&E's data processing center. The raw solar data reduction is not yet a routine task and is an area that needs much improvement.

Figure 2 shows a sample trace of recorded solar radiation data from the LBL pyranometer. The information available from curves such as this include hourly, daily and monthly totals of radiation on a horizontal surface, and the amount and frequency of cloudiness. In practice, the solar quantity normally used is the radiation on a tilted surface (e.g., roof-mounted solar panels or a south-facing window). Standard methods are available to estimate such quantities from the basic pyranometer measurement on a horizontal surface.

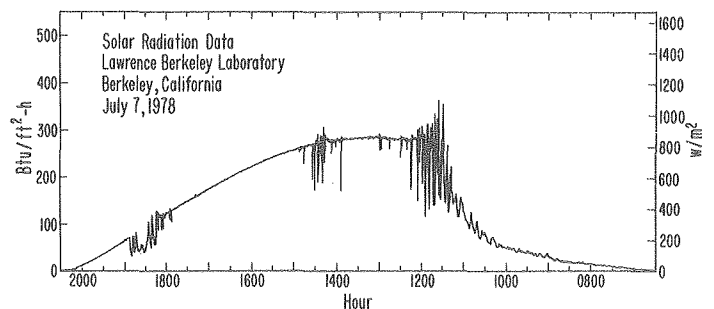


Fig. 2. Solar radiation measured at Berkeley, California on a day with morning cloudiness and scattered clouds in the early and late afternoon.  
(XBL 791-241)

#### PLANNED ACTIVITIES FOR 1979

The primary activities during this year will be 1) continued, routine operation of the network, 2) improvement of the data turn-around time from PG&E, 3) development of a more complete data analysis system, and 4) the presentation of the data in forms useful to designers, engineers, architects, and others interested in the utilization of solar energy in northern California.

Should sufficient support be available, it is planned to upgrade the instrument systems. The first priority would be the replacement of the pyranometers with a type that is now known to be more reliable and accurate. Another priority item is the replacement of the tape recorders with microprocessors that periodically report the data on cassettes or over phone lines. Systems

of this type are now in operation for several other LBL projects.

#### FOOTNOTE

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## The Role of the Proton Pump . . .Bacteriorhodopsin\*

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### INTRODUCTION

The Nobel Prize in Chemistry was awarded this year to Dr. Peter Mitchell for having developed the chemiosmotic theory, a conceptual framework for relating the development of proton gradients and electrical potentials across membranes, expressed as the protonmotive force (PMF) as  $PMF = \Delta\psi + 60mV \Delta pH$  to other energy-linked cellular processes.<sup>1</sup> An ideal experimental system for studying the relationship of ion gradients to each other is found in the halobacteria which live in concentrated salt solution and hence divert much of their energy to salt pumping. These bacteria derive their energy either from respiration of substances scavenged from their environment or

from sunlight (Fig. 1). Unlike photosynthetic membranes which contain complex structures of oxidation and reduction catalysts, the halobacteria achieve conversion of light into electrical energy by means of a photocycle operated by a single, relatively simple protein, bacteriorhodopsin, which establishes a proton gradient across the membranes which this protein spans.<sup>2</sup>

Bacteriorhodopsin molecules contain a single chromophore, retinal, and occur in clusters of trimeric units that form large purple "patches" which can be isolated in pure form. Because of its purity and crystalline arrangement, the purple membrane can be more readily studied by physical

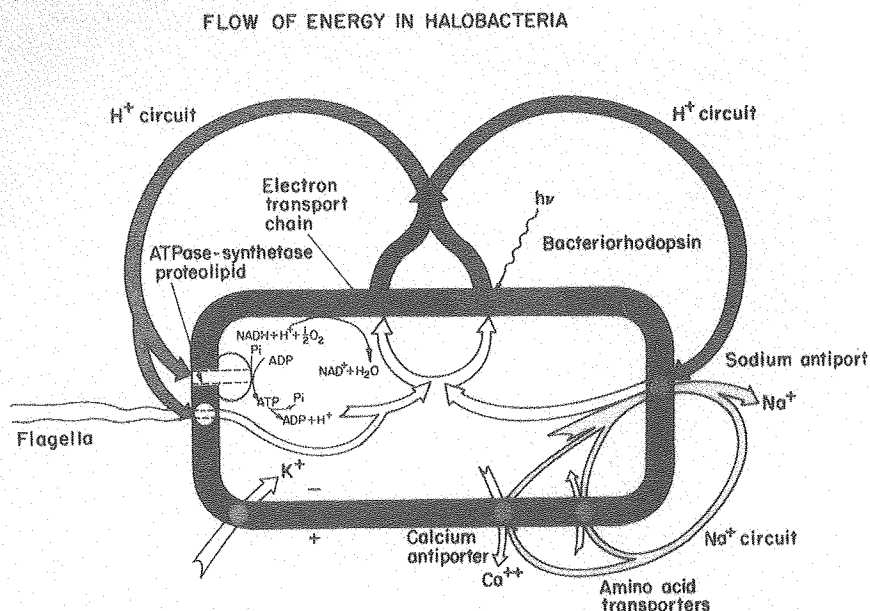


Fig. 1. Overall scheme of energy conversion by *Halobacterium halobium*. Direct conversion of sunlight into electrical current (proton movement) occurs within the "purple patches," crystalline arrays of the protein bacteriorhodopsin. Proton gradients are collapsed by being coupled to salt pumping and chemical energy synthesis in the form of adenosine triphosphate (ATP) by other catalysts in the cell envelope membrane. (BBC 7810-13460)

methods than can complex photosynthetic membranes containing more randomly dispersed components.

The small molecular size (about 26,000 Daltons) of bacteriorhodopsin has made it possible for a large team of Moscow scientists to determine its amino acid sequence. Thus molecular studies of the mechanisms of action of the protein are now facilitated.

There are compelling advantages for using chemical modification to study bacteriorhodopsin. The protein is stable to drastic alterations in the ionic strength of its environment and has proven to retain activity after extensive reaction with several chemical reagents. Certain reactive amino acids like cysteine and histidine are not found, thus minimizing cross reaction of the reagents with different amino acids. Also the retinal chromophore can be removed from the protein in a reversible manner, thus allowing the binding site environment to be probed.

Bacteriorhodopsin is probably the simplest and most stable naturally occurring light energy converter presently known. The program in the Membrane Bioenergetics Group is directed toward the elucidation of the proton conductance of this protein. Our research includes: electrical studies using planar membranes and spin probes, chemical modification studies of specific amino acid residues to obtain molecular information about the groups essential for proton conduction and light absorption, and computer assisted structural studies. A tentative hypothesis for the mechanism of proton conduction has been advanced and is now being tested and perfected.<sup>5</sup> The coupling of proton currents to salt pumping is also being investigated.

#### ACCOMPLISHMENTS DURING 1978

##### Chemical Modification Studies

To elucidate the mechanism of light driven proton movements which form an electrochemical gradient, it is important to know which amino acids in bacteriorhodopsin are involved in the proton movement. Our working hypothesis is that light-induced conformational changes and/or isomerization of the retinal chromophore causes movement of the proton attached to the Schiff base nitrogen of the chromophore and that this is the primary step in the proton pump. This proton movement probably occurs over a small distance relative to the transmembrane dimension which protons must finally traverse (which may be estimated to be overall about 45 Å based on the dimensions of molecules).<sup>8</sup> There is considerable interest in how the protein is organized to effect the remaining charge separation. One goal of our current research is to elucidate the amino acid arrangement along this proton "channel". Last year we used the tryptophan reactive reagent, N-bromosuccinimide, to demonstrate that one or two tryptophan residues were located in close proximity to the chromophore; however all four of the tryptophans in the molecule appear to be involved in photocycling activity since progressive loss of all tryptophan absorbance by N-bromosuccinimide coincided with progressive loss of activity.<sup>9</sup>

During the past year we have shown that at least one of the eleven tyrosines in the molecule was directly involved in the light dependent proton movement across the protein.<sup>5</sup> Iodination was used to alter tyrosine residues which were accessible to this reagent. In analogy with the downward  $pK_a$  shift of iodinated tyrosine molecules in water, the kinetics of photocycling of iodinated bacteriorhodopsin were observed to undergo a downward shift in their pH dependence relative to the control protein. Of particular interest is the observation that the decay of the 412 nm intermediate became significantly prolonged during iodination (Fig. 2). Since it has been established previously that the 412 nm decay is due to re-protonation of the Schiff linkage of the chromophore, we have inferred that tyrosine is a source of the protons which are donated to the chromophore. These studies indicate that aromatic hydrophobic amino acids play an important role in maintaining a proper environment in the vicinity of the chromophore and elsewhere in the molecule to afford proton conductance.

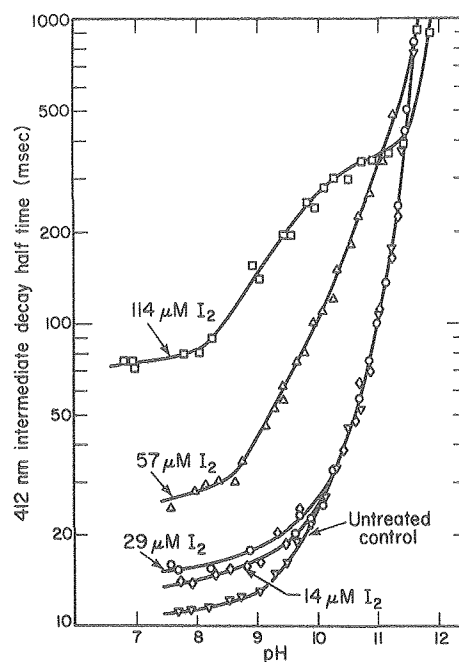


Fig. 2. Effect of iodination on the pH dependence of the decay of the 412 nm photocycle transient of bacteriorhodopsin measured by the flash photolysis technique. (XBL 782-210)

##### Studies of the Proton Channel within Bacteriorhodopsin

We have assumed that the chromophore retinal fulfills the function of pumping protons in a light driven reaction and that the protons subsequently are conducted along a proton "channel" to reach the bulk aqueous phases. Another approach towards understanding the nature of this proton "channel" is to remove the chromophore and study the residual protein for proton conductivity.

The chromophore can be removed by a bleaching process whereby the retinal is displaced from the protein by illuminating bacteriorhodopsin in the presence of a large excess of hydroxylamine.<sup>10</sup> It has been shown that this process is reversible, i.e. the light driven proton pump can be recovered upon addition of retinal to the bleached protein.

Using the above procedure bleached bacteriorhodopsin was prepared and added to lipid vesicles which were loaded with potassium and then suspended in sodium ion medium.<sup>11</sup> It is expected that negligible proton leakage will occur from these potassium-loaded vesicles since no permeability mechanism is presumed available for movement of ions other than protons. However, upon adding the potassium-specific ionophore valinomycin to the vesicles, a diffusion potential was established and resulted in electroneutral exchange of  $H^+$  for  $K^+$  ions. The addition of retinal to the bleached bacteriorhodopsin led to a substantial decrease in the proton movement. Thus the experiment suggests qualitatively that protons may be able to move through the bleached bacteriorhodopsin molecule in the dark. To obtain a measure of the capability of bacteriorhodopsin to promote proton fluxes, vesicles containing native bacteriorhodopsin were illuminated in the presence of valinomycin. The light-induced and the passive proton fluxes were comparable to one another.

#### Photoelectrical Studies

It has been shown that a photovoltaic cell can be constructed from bacteriorhodopsin incorporated into Millipore filter membranes.<sup>6,7</sup> The filter membrane serves as a support for biological lipids which comprise the permeability barrier of the membrane. Bacteriorhodopsin was incorporated into the filter membranes by a multi-step absorption and fusion process. The current-voltage characteristics of the photocell were studied at high light intensity. A maximum open circuit voltage of 300 millivolts and a maximum short circuit current of 0.9 milliamp were obtained. Relative to the incident light intensity the power output of the cell was determined to be 0.07%. Under continuous high intensity illumination the activity of the cell declined, and no photovoltage could be observed after ninety minutes. One goal of future research is to improve the stability and efficiency of the photocell.

#### Conductance Studies

Planar membranes are a useful tool for discriminating between channel conductance mechanisms. Channels which are open intermittently can lead to discrete conductance jumps across lipid bilayer membranes provided that the opening and closing process is long enough to be observed. Using planar membranes painted across a small teflon orifice, we have attempted to obtain discrete conductance jumps when bleached bacteriorhodopsin was incorporated into the membranes. We incorporated bleached bacteriorhodopsin into such lipid bilayers by means of the calcium absorption and fusion technique which was developed earlier

for the Millipore filter system.<sup>6</sup> Discrete conductances are indeed observed. Alterations in the concentrations of sodium, potassium or calcium did not significantly alter the conductance magnitude.

The principal conclusion to be drawn from these experiments is that bleached bacteriorhodopsin is not an open channel for protons or other ions when an electrical potential is applied across the membrane bearing the protein. However, at infrequent intervals an occasional bacteriorhodopsin molecule seems to open up to protons. We have attempted to define the mechanism whereby this channel opening occurs by varying the composition of the planar membranes and the aqueous phase so as to induce changes in the conductance jump frequency. Thus far the parameters we have found which affect the jump frequency are the concentration of bleached bacteriorhodopsin and the temperature. Another finding of interest was that such current fluctuations in the bleached molecule were only exhibited by ions having a similar hydrated radius as  $K^+$  and  $Rb^+$ , suggesting an effective "pore" radius of about 3-4 Å.

#### Surface Charge Effects in Illuminated Purple Membrane Sheets

Recently developed spin probe techniques for measuring surface potentials<sup>12</sup> were used to measure changes in electrical potentials at surfaces of purple membrane sheets under illumination. No change was observed in native purple patches suspended in distilled water, but when beavericin and valinomycin, a mixture of two ionophoric compounds, i.e. compounds which conduct ions across membranes, was added to the sheets substantial changes in the spectra of the probe were observed suggesting that the electrical potential had decreased during illumination. The changes with the spin probe were observed under the same experimental conditions where a slowdown in the decay of the 412 nm photocycle intermediate and an increase in light induced proton release from purple membranes are observed.<sup>13</sup> This effect, however, may not be caused by the ionophoric properties of the antibiotics but by their tendency to disrupt the purple membrane as hydrophobic perturbants.

#### Computer Modeling

Knowledge of most of the amino acid sequence of bacteriorhodopsin from the work in Moscow<sup>4</sup> has made it feasible to attempt construction of a molecular model of the protein. The electron density map with seven Angstrom resolution suggests that the molecule consists of nearly cylindrical array of seven helical coils with their axes oriented almost perpendicular to the plane of the membrane. Studies with digestive enzymes have shown that the amino terminus of the sequence faces the extracellular space while the carboxyl terminus lies within the cytoplasm. These factors imply that the seven helices are connected by six nonhelical regions at the membrane interfacial region.

The overall symmetry of the protein suggests that the helical regions are of nearly equal lengths. To identify the amino acids directly involved in the bend portions several criteria should be satisfied: polar or charged groups will be stabilized at the polar aqueous interface, and certain amino acids, particularly proline residues, interrupt alpha-helical structure. In addition it is known that bacteriorhodopsin is an intrinsic membrane protein so the majority of residues in the helical regions should be hydrophobic to promote their hydrophobic interaction with the hydrocarbon chains of lipids. Because the amino acid sequence contains eleven proline residues, it appears that there must be nonhelical regions of the protein imbedded within the protein as well as within the interfacial region. Moreover, the charged amino acids are distributed in a manner that is inconsistent with their exclusive location at the polar interface of the membrane. This suggests that some ionic bridges are located within the interior of the protein and that ionic bridges may be responsible for the protein interactions which stabilize the crystalline array.

Using the above criteria a preliminary model of bacteriorhodopsin has been constructed (Fig. 3). A space filling model constructed from plastic CPK atoms was used to estimate bond angles within the peptide backbone. These angles were fed into a computer which has been programmed for molecular model building at the NASA Ames Research Center.<sup>14</sup> At present only the graphic capabilities of the Ames program are being utilized to examine some of the probable conformations of the protein. In the future we

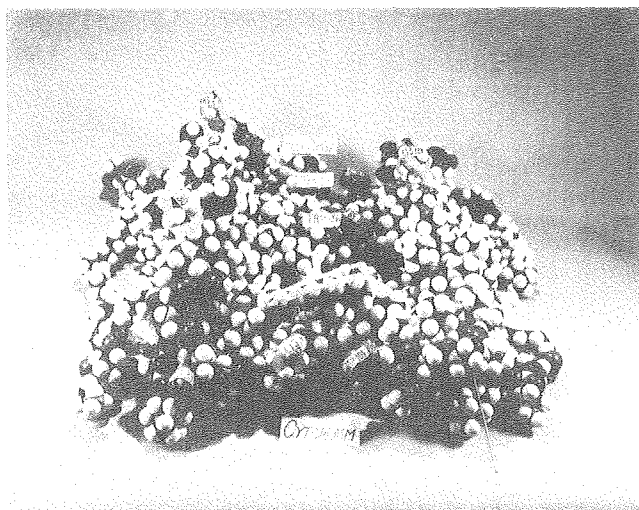


Fig. 3. Photograph of the three dimensional spacefilling model of bacteriorhodopsin assembled from the amino acid sequence of Ovchinnikov *et al.*<sup>4</sup> The model shows the distribution of aromatic tryptophan and tyrosine residues in the vicinity of the retinylidene lysine chromophore (marked with two light parallel strips of tape). The view is of the interior of the bacteriorhodopsin molecule and shows four of the seven helices. (BBC 7810-13516)

intend to carry out energy calculations for the more probable conformations so as to eliminate some of them from consideration. A particular goal of these studies is to understand protein conformational changes that can result from the possible photo-isomerizations and rotations of the chromophore. A further goal is to identify which amino acids are directly involved in protein conduction.

#### Photodesalination Studies with Cell Envelopes of Halobacterium Halobium

Ion movements across cell envelope vesicles of *H. halobium* are being assayed with a newly developed spin probe method. The method uses spin labeled amines (see Fig. 4) or carboxylic acids to monitor transmembrane pH gradients.<sup>15</sup> The basic assumption is that pH gradients are achieved rapidly due to the limited buffering capacity within the vesicles. Subsequent proton movement across the membranes in response to this gradient must be balanced by the movement of other ions (Fig. 1). The secondary ion movements result from an exchange mechanism whereby a cation moves in one direction while a proton moves in the opposite direction. The pH gradient is coupled to the development of a  $\text{Na}^+$  gradient which can be observed with the spin probes. As shown in Fig. 4, a rapid initial  $\text{H}^+$  extrusion is followed by a reversal of the proton movement when sodium ions are present within the cell envelopes. The interpretation of this experiment is that there is a proton-sodium exchange mechanism in the membranes which allows protons to move into the vesicles and sodium ions to move out, and that this mechanism is only triggered after a threshold value of the initial proton gradient has been achieved.<sup>16</sup> As depicted in Fig. 1, the extrusion of sodium ions is compensated for by potassium ion uptake (and chloride ion efflux, depending on the concentration of potassium ions added).

#### PLANNED ACTIVITIES FOR 1979

Chemical and electrical studies will be continued with the objective of detailing the mechanism of  $\text{H}^+$  conduction and the importance of localized electrical changes in improving the photovoltaic effect of bacteriorhodopsin. Photodesalination studies will also be continued.

#### Chemical Studies

The special role of one of the eleven tyrosines of bacteriorhodopsin in light dependent proton conductance will be studied further using tyrosine-specific reagents. Proton conductance by bleached preparations will also be studied. Lactoperoxidase, an enzymic method for iodination, should only label surface exposed to tyrosines. This procedure inhibits photocycle activity, and we shall explore its significance for light dependent proton conduction and conduction of protons in bleached preparations in the dark.

Modification of amino groups of lysine have previously shown that loss of 80% of these groups does not inhibit  $\text{H}^+$  conduction *per se* unless they are cross-linked together within the molecule.

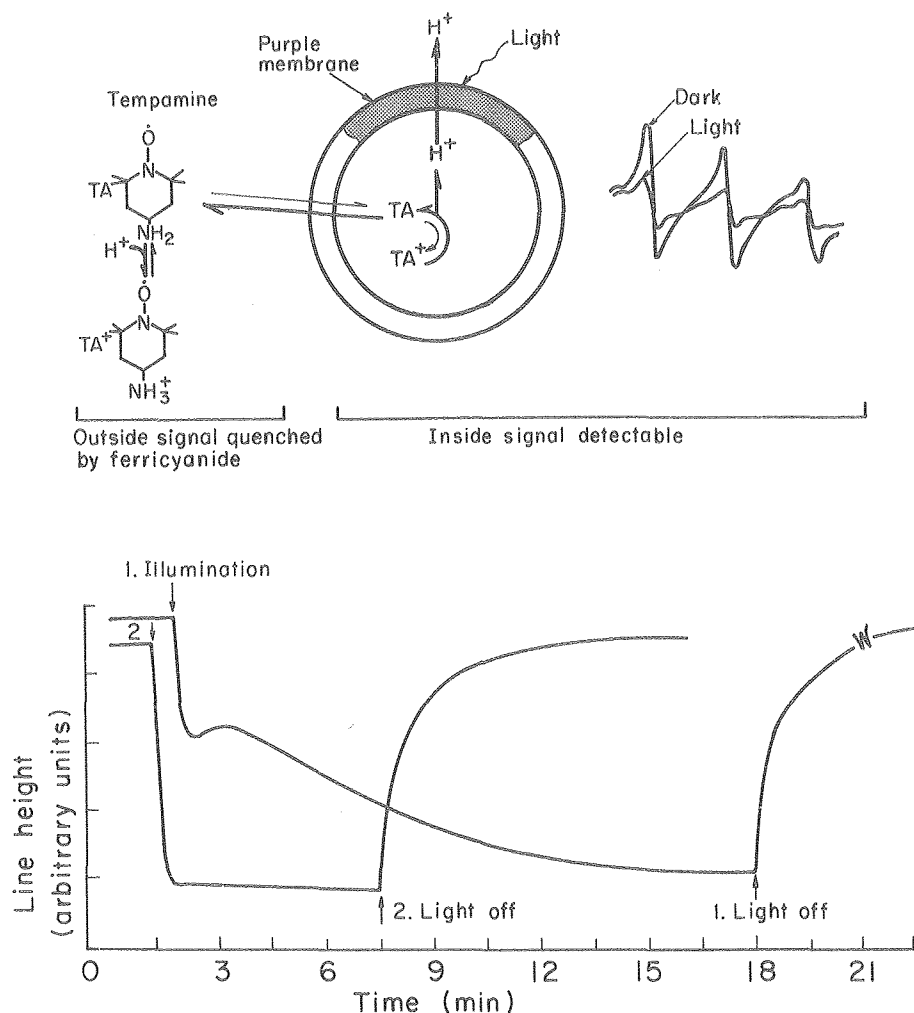


Fig. 4. Light-induced proton release from *H. halobium* cell envelopes loaded with sodium ions, assayed with the spin-labeled amine, Tempamine. The probe distributes across the membrane in direct proportion to the proton concentrations. Quenching of the signal outside the vesicles with ferricyanide allows the intra-vesicle signal to be observed. In the first trace of the line height with time, a delay in proton extrusion is observed as sodium ion movement allows protons to reenter the vesicles. On subsequent illumination rapid efflux of protons is observed since no sodium is left within the vesicles. (XBL 791-3011)

One of the amino groups in the interior has not yet been probed. Also the amino group where retinal binds can be probed. We intend to use imidoesters to attack in bleached molecules the amino groups at the retinal binding site. These studies together with spin label analogs of retinal will be used to explore the environment of the chromophore which is optimal for proton conduction.

We will subject the purple membrane fragments to the action of proteolytic enzymes. It has been shown that the protein can be fragmented when heated with papain and other proteolytic enzymes. These studies will help to determine which portions of the molecule are essential for proton conduction energized by light and for

conductance of protons through other regions of the molecule. Computer assisted modeling of the protein structure will aid the interpretation of these experiments.

#### Electrical Studies

The analysis of light dependent surface charge changes will be pursued by the use of a unique charged spin-labeled amphipathic molecule.<sup>12</sup> These studies will enable us to obtain, in purple membranes and in the native envelope vesicles of the membrane, information on a number of interesting questions, including how localized regions of charge control proton conduction; how salts affect surface charge; how localized surface charges changes on each membrane surface affect



the development of the membrane potential; and how, together with pH gradient, electrical forces provide the proton motive force for salt transport.

Construction of an improved photovoltaic device will be continued. We intend to use several membranes, including Teflon; and plan to change the manner of membrane formation to increase efficiency and reduce susceptibility to photo-degradation. Intermolecular chemical cross-linking studies will be pursued to determine if molecules after being chemically crosslinked in the purple membrane exhibit improved stability against photodestruction.

West German researchers have shown that at low light intensities the number of protons released per photon increases. This cooperativity may depend on the aggregated state of bacteriorhodopsin. Using newly developed techniques of saturation transfer EPR which gives information on the rotational mobility of spin labeled proteins, we will try to correlate the state of aggregation of bacteriorhodopsin with this cooperative effect.

#### Photodesalination Studies

We will employ the recently developed spin label Tempamine assay to further characterize the requirements for light dependent proton transients across envelopes of *H. halobium* coupled to sodium transport. We shall also develop an artificial liposome system containing the Tempamine probe, to test those fractions isolated from natural membranes with suspected sodium antiporter activity. Sodium specific and other specific artificial ion carriers will be employed as controls. These studies will enable us to develop some simple models of a photodesalination system. We hope to develop a planar membrane photodesalination device which can operate on a continuous flow basis.

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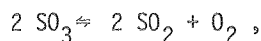


# Chemical Storage of Thermal Energy\*

A. S. Foss and S. Lynn

## INTRODUCTION

Economical energy storage is essential if solar power plants are ever to supply a significant fraction of the needs of a power grid. The purpose of this study is to develop flowsheets for technically feasible and efficient processes for the use of the sulfur oxide system,



in energy storage. The forward reaction for this system is endothermic and can be used to absorb energy. The reverse reaction is exothermic and releases the energy that has been stored.

Funding for this work was initiated in November, 1975. During calendar year 1977 the major effort in the project was in flowsheet development. The major factors affecting system efficiency were identified and the primary factors causing energy losses were made the subject of further study.

## ACCOMPLISHMENTS DURING 1978

### Chemical Storage

This year has seen the completion of the computer simulation of the storage process as shown in Fig. 1. Liquid sulfur trioxide from storage is pumped to 40 atm, vaporized and heated by the reactor effluent in the recuperator HE-1. The reactor tubes are mounted in a solar receiver. The interior tube walls are coated with a suitable catalyst such as iron oxide.

Upon exiting the reactor, the gas exchanges heat with the reactor feed and then heats the reboiler of the distillation column. The gas is further cooled to condense  $\text{SO}_2$  and unreacted  $\text{SO}_3$ , and is then stored. The  $\text{SO}_2$ - $\text{SO}_3$  liquid is distilled;  $\text{SO}_3$  is recycled to the solar reactor and the  $\text{SO}_2$  is stored as a liquid until needed.

Heat for the vaporization of  $\text{SO}_3$  is obtained from extraction steam from the parallel steam-cycle power plant. Part of the cooling of the reactor effluent, on the other hand, is used to preheat boiler feed water for the power plant. This integration is intended to maximize the energy efficiency of the system.

Energy is recovered from storage by recombining the  $\text{SO}_2$  and  $\text{O}_2$ . Liquid  $\text{SO}_2$  is vaporized, added to the  $\text{O}_2$  stream, and heated to a temperature high enough to activate the catalyst, about  $400^\circ\text{C}$ . As reaction proceeds the temperature rises until the equilibrium composition is reached. The hot gas stream then passes through heat exchangers, forming superheated steam for the power plant. Three reactor

stages are needed to convert about 97% of the  $\text{SO}_2$  and  $\text{O}_2$  back to  $\text{SO}_3$ . The  $\text{SO}_3$  vapor then exchanges heat with the feed gas, and is condensed in the  $\text{SO}_2$  vaporizer.

### High-Temperature Reactor

Figure 2 shows typical temperature and composition profiles for a single tube of the solar-heated reactor. In this example about 75% of the energy flux through the tube wall is absorbed by the endothermic reaction and the remainder increases the sensible heat of the gas stream. The bulk temperature of the gas stream closely approaches the tube wall temperature at the outlet end, whereas the outlet bulk  $\text{SO}_3$  conversion is significantly less than the conversion at the wall, which is assumed to be at equilibrium. Mass transfer is thus shown to be the limiting factor for this case.

### Energy Efficiency

The overall second-law efficiency of the process is simply the sum of the net electrical outputs from operation of the daytime power plant and of storage divided by the sum of the thermal inputs to the power plant and the storage reactor:

$$E_{OA} = \frac{P_{\text{Day}} \cdot \theta_{\text{Day}} + P_{\text{Sto}} \cdot \theta_{\text{sto}}}{(Q_{\text{PR}} + Q_{\text{SR}}) \theta_{\text{Day}}}$$

where

$P_{\text{Day}}$  = Net power produced by daytime power plant ( $\text{MW}_e$ )

$P_{\text{Sto}}$  = Net power produced from storage ( $\text{MW}_e$ )

$\theta_{\text{Day}}$  = Duration of daytime operation (HR)

$\theta_{\text{Sto}}$  = Duration of storage discharge operation (HR)

$Q_{\text{PR}}$  = Rate of thermal input to power plant receiver ( $\text{MW}_t$ )

$Q_{\text{SR}}$  = Rate of thermal input to storage receiver ( $\text{MW}_t$ )

Low- and intermediate-temperature heat is exchanged between the power plant and the storage system. The power plant efficiency is defined arbitrarily as

$$E_{PP} = \frac{P_{\text{Day}} \cdot \theta_{\text{Day}}}{(Q_{\text{PP}} + Q_{\text{BFW}} - Q_{\text{VAP}}) \theta_{\text{Day}}}$$

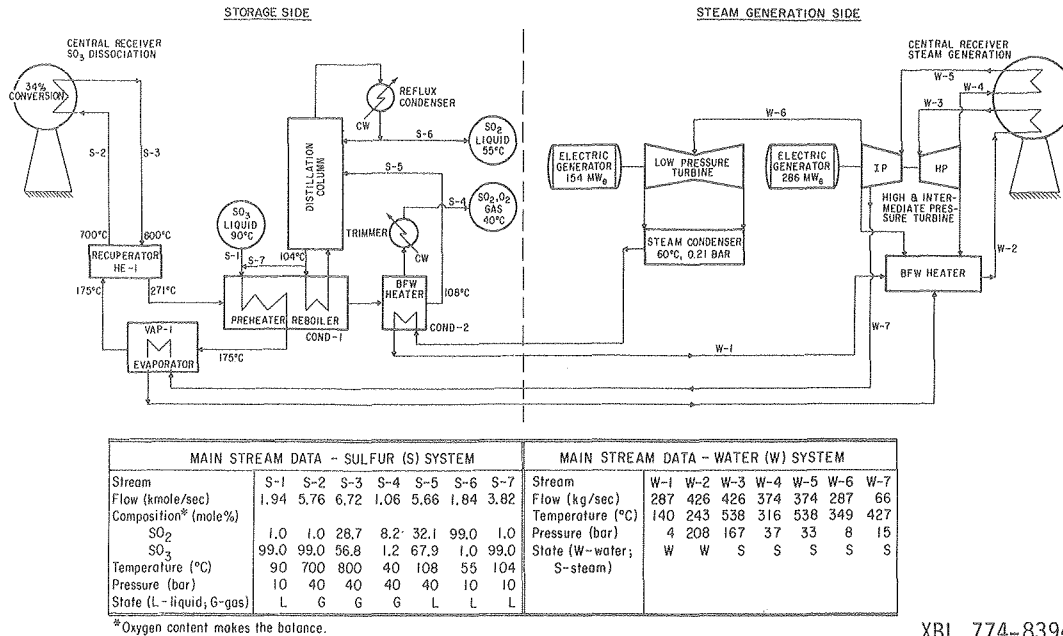
Where

$Q_{\text{BFW}}$  = Rate of heat transfer to boiler feed water ( $\text{MW}_t$ )

$Q_{\text{VAP}}$  = Rate of heat transfer to  $\text{SO}_3$  vaporizer ( $\text{MW}_t$ )

(a)

## DAYTIME OPERATION SCHEME (CHARGE MODE)



XBL 774-8394

(b)

## NIGHT TIME OPERATION SCHEME (DISCHARGE MODE)

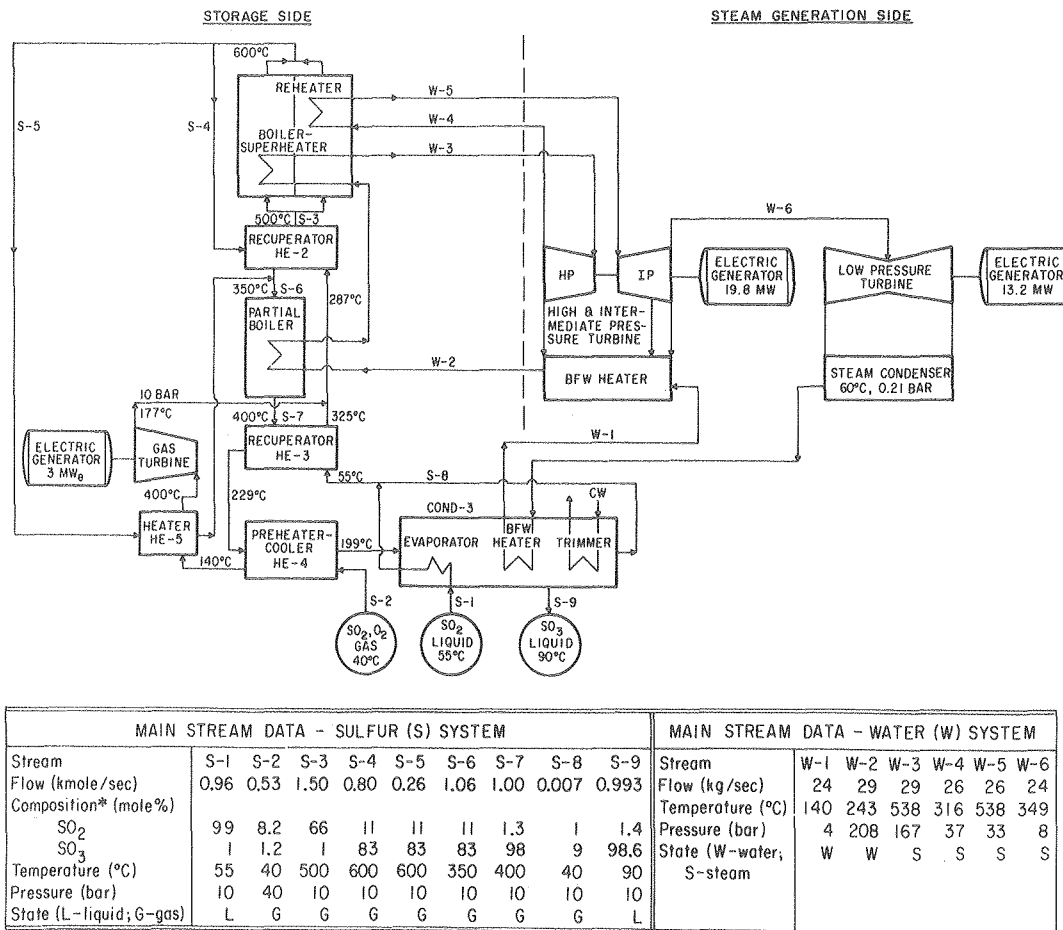


Fig. 1. Flowsheet for chemical storage of thermal energy.  
(XBL 774-8393)

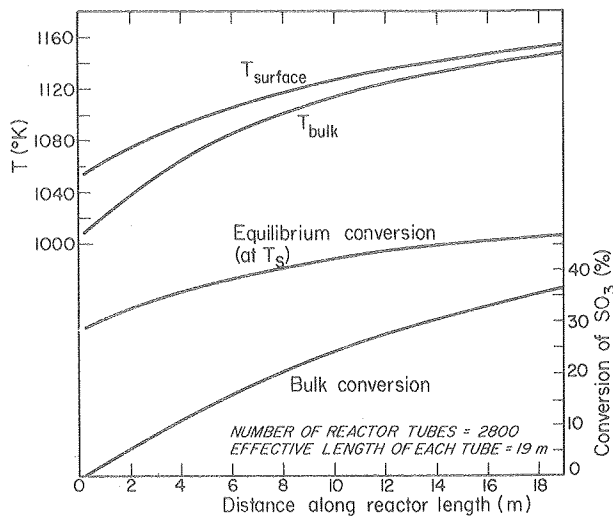


Fig. 2. Temperature and composition profiles in solar reactor. (XBL 7811-13306)

The thermal storage efficiency is defined as the ratio of usable heat delivered by the storage system to the heat input to the storage system

$$E_{TS} = \frac{\Sigma Q_{Sto} \cdot \theta_{Sto}}{(Q_{SR} + Q_{VAP} - Q_{BFW}) \theta_{Day}}$$

where

$\Sigma Q_{Sto}$  = Sum of rates of heat transfer to power plant system from storage discharge ( $MW_t$ )

#### Sensitivity Analysis

Figure 3 shows the effect on  $E_{OA}$ ,  $E_{pp}$ , and  $E_{TS}$  of the maximum allowable tube-wall temperature,  $T_{W \max}$ . As this temperature is increased a larger fraction of the  $SO_3$  can be converted to  $SO_2$  and  $O_2$ . As a result, a larger fraction of the heat absorbed by the gas stream results in chemical reaction and a smaller fraction increases the sensible heat of the gas. The ratio  $Q_{PR}/Q_{SR}$  drops with increasing  $T_{W \max}$  because a smaller stream of  $SO_3$  is needed to absorb the heat in the solar reactor and hence there is less heat to transfer to boiler feed water.  $E_{OA}$  increases slightly and  $E_{TS}$  increases substantially because there is relatively less low-temperature heat to dissipate to the environment per unit of chemical heat stored.

The maximum tube-wall temperature is only one of the system parameters being studied. The sensitivity of the system behavior has also been determined for variations in the solar reactor pressure, the temperature rise in the reactor, and the temperature at which heat can be rejected to the environment.

#### Sensible-Heat Storage

For purposes of comparison with chemical-heat storage, a sensible-heat storage system

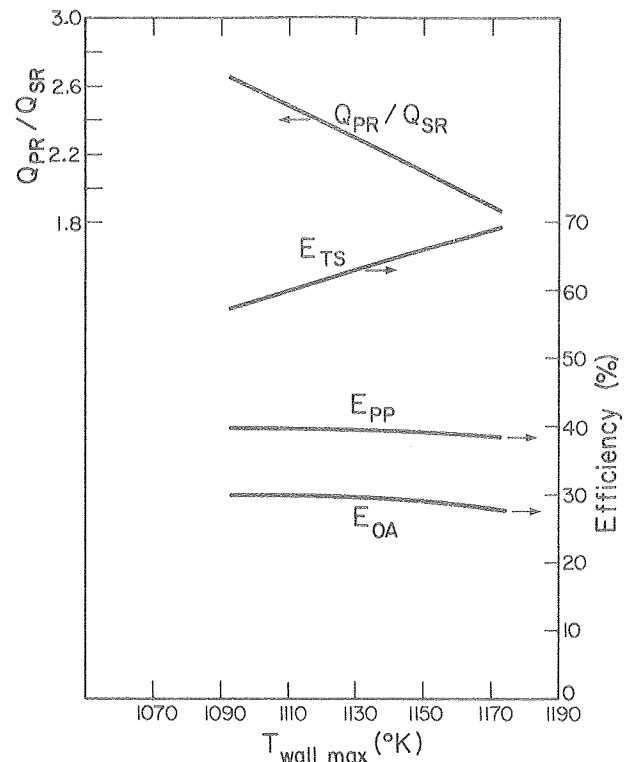


Fig. 3. Effect of maximum allowable tube wall temperature on system performance. (XBL 7811-13307)

was designed for use with a steam cycle power plant. The system utilizes a checker-work of magnesite brick. A heat-transfer medium such as helium or nitrogen is circulated through the solar receiver to bring heat to the power plant superheater, reheater, and boiler. The storage system is placed between the receiver and the power plant heat exchangers. It cycles between the temperatures of about 816° and 327°C. In this way the energy stored loses little effective thermodynamic potential since it is at all times hotter than the highest temperature in the steam cycle. The behavior of this system has been simulated by computer; the flowsheet is being compared in cost and energy efficiency to the chemical storage system. The use of pre-stressed cast iron vessels to contain the magnesite bricks appears to offer attractive cost advantages.

#### PLANNED ACTIVITIES FOR 1979

As was also recognized by Carl Hiller of Sandia Laboratories, a typical chemical energy storage system can be utilized in an unusual thermodynamic cycle.<sup>1</sup> In such systems the endothermic reaction yields an increase in the number of molecules. The hot gas from the reactor can thus be expanded through a gas turbine with a high yield of work. After the gas stream is cooled it can be recompressed. Interstage cooling causes condensation, thus reducing the work required to reach storage pressure. Discharge of storage can also be

effected with a gas turbine. The gas is preheated before entering the first-stage reactor, where it attains a temperature approaching that in the dissociation reactor. It is then expanded through the gas turbine and is thereby cooled. Passage through the second- and third-stage reactors provides the heat required to preheat the first-stage reactor feed. A flow-sheet for this energy system is being simulated by computer to allow evaluation of the system's potential. This will be the primary activity on chemical storage systems in 1979.

## Support for Commercial Solar Demonstration Program\*

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

### INTRODUCTION

The Solar Applications Group at LBL provides technical consulting and management services to support the DOE San Francisco Operation Office's (DOE/SAN) overall management of commercial-building solar demonstration projects and hotel/motel hot water solar projects located throughout the Northwestern States and Hawaii. These projects are part of the National Solar Heating and Cooling Demonstration Program,<sup>1</sup> whose primary objective is to stimulate a solar industry and to promote the use of solar energy as a means of reducing demand on conventional fuel supplies.

The group is currently involved in support for projects in this program as follows:

<u>Projects</u>	<u>Program solicitation</u>	
1	NSF-1	Cycle I
15	DSE-76-2	Cycle II <sup>2</sup>
17	PON 4200	Cycle III <sup>3</sup>
3	PON 1450	Hotel/Motel <sup>4</sup>

A detailed description of activities of this group is contained in the E&E Division Annual Report for 1977.

### ACCOMPLISHMENTS DURING 1978

During 1978 activities continued on Cycle II and Hotel/Motel projects and work commenced on seventeen additional Cycle III projects. As of the end of the year, construction was complete and operation initiated on six Cycle II projects and one Hotel/Motel project. One Cycle II and four Hotel/Motel projects were cancelled primarily due to project participant funding problems. All other projects were either near completion or still being designed or bid. Two of the Cycle III projects are currently under construction with the remainder in the design stage. In addition to other activities, LBL was requested to assist with field checkout of the IBM monitoring instrumentation system of those projects where the system

### FOOTNOTES AND REFERENCES

\*This work has been supported by the Energy Storage Division, Office of Energy Technology, U.S. Department of Energy.

1. J. Dayan, et al, "A New Power Cycle that Combines Power Generation with Energy Storage," 13th Annual IECEC. San Diego, CA Vol. 1, 285-291 (1978).

installation was completed. As of year's end, instrumentation installation and checkout is complete on only two of the Cycle II projects.

During startup and initial operation of most of the completed systems, a number of difficulties were encountered. The most frequent problem was with controls, i.e., sensor failures, erroneous wiring, and incorrect logic. Other problems encountered were storage tank over-pressurization, damaged or poorly installed piping insulation, corrosion failure, snow and ice accumulation on collectors (resulting in some damage to collector and flashing strips and shading of the array), and excessive leakage in one air system. All of these problems have been or are currently being resolved by the contractors.

### PLANNED ACTIVITIES FOR 1979

During the remainder of FY 1979, activities of this group will continue at current level of effort (3 men). However, LBL has been directed by DOE to curtail activities in this area; involvement in currently assigned projects is to be reduced to the level of one man. It is expected that all LBL activity in this program will cease after FY 1980.

### FOOTNOTE AND REFERENCES

\*This work has been supported by the Solar Heating and Cooling Demonstration Branch, Office of Conservation and Solar Applications, U.S. Department of Energy.

1. National Program for Solar Heating and Cooling of Buildings, ERDA 76-6, November 1976.
2. Commercial Integrated Projects for Use in Demonstrations of Solar Heating and Cooling, PON DSE 76-2, ERDA, 1976.
3. Commercial Integrated Projects for Use in Demonstrations of Solar Heating and Cooling, PON EG-78-N-01-4200, DOE, 1978.
4. Hot Water Initiative for Hotel/Motel Installations, PON EG-77-N-03-1450, ERDA, 1976.

# LBL Solar Demonstration Project (Building 90)\*

T. Webster

## INTRODUCTION

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

The following criteria were used to select projects for this initial program:

- Buildings should be suitable for retrofitting; i.e., possess orientation, location, and configuration amenable to solar.
- Solar space and hot-water heating should be emphasized.
- Buildings should be typical government buildings.
- Design and construction should not cost more than \$200,000.

The LBL project is funded by the DOE division of Solar Energy through the Construction, Planning, and Support Division. LBL Plant Engineering is responsible for design and construction of the project with assistance provided by the LBL Solar Group. A detailed description of the building and preliminary and final design considerations is contained in the 1977 Energy & Environment Division Annual Report.

## ACCOMPLISHMENTS DURING 1978

In order to facilitate completion of the system design the collectors were pre-bid in early 1978. A life cycle costing procedure was used to evaluate and select the collector. A Sunworks, single-glazed, black chrome collector was selected. This collector has the advantage of utilizing factory supplied, pre-sized balancing orifices in the manifolds which will allow 17 collectors in each row to be internally manifolded together. This arrangement results in significant piping savings of about \$1/sq.ft. of collector ( $SF_C$ ). After the collectors were selected the support structure was redesigned and other system details completed. Prefabricated collector supports were ruled out since they were not feasible for this application. Two pumps were included for the collector loop to provide redundancy in the event of a pump

failure. Figure 1 is a schematic of the final design.

Bids for the system installation were received in July. These bids ranged from a high of \$137,000 ( $\$110/SF_C$ ) to a low of \$79,000 ( $\$63/SF_C$ ). An alternate bid for one row of on-site constructed collectors was eliminated due to high cost, \$12/ $SF_C$  more than for the commercial collector rows. This indicates that there is no advantage in using on-site constructed collectors in this type of project. However, the extra cost for the on-site constructed collectors, as shown by the bids for this one row probably is not a realistic indication of what an entire array of these collectors would cost.

A contract was awarded to the low bidder and construction of the system commenced in August. By year's end only one major problem had occurred: the collector support structure roof penetrations did not seal well resulting in substantial leakage during a storm (occurring two months before the rainy season). The leaks were traced to an incompatibility between the roofing mastic and the elastomeric roof jacks. The roofing contractor was unaware of this problem until it occurred here and the roofing materials manufacturer is researching the problem. The problem has been temporarily corrected, but further work is anticipated.

By year's end the system installation was about 50% complete. Design of the monitoring instrumentation system was completed and instruments were ordered from IBM (the DOE instrumentation contractor). Further work on modeling system performance with the DOE-1 computer program indicates that initial estimate of annual solar performance of 33% may have been high and actual performance may be closer to 23%.

## PLANNED ACTIVITIES FOR 1979

System installation should be complete in early 1979. The instrumentation system and peripheral items such as walkways and observation platform and stairs should be complete by Spring 1979. Further analysis with the DOE-2 computer program will be made to obtain a better estimate of annual system performance.

## FOOTNOTE:

\*This work has been supported by the Solar Heating and Cooling Demonstration Branch, Office of Conservation and Solar Applications, U.S. Department of Energy.

