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Basic and Applied Research Program Semiannual Report (July-December 1978)

MASTER

Barry L. Butler, Editor
Basic and Applied Research Staff

SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

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Golden, Colorado 80401

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BASIC AND APPLIED RESEARCH STAFF

DECEMBER 1979

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FOREWORD

The SERI Basic and Applied Research Program is composed of five tasks: Materials Research and Development, Photoconversion Research, Energy Resource Assessment, Fabrication and Materials Processing and Development, and Exploratory Research. The task activities provide some of the basic information necessary for the development of solar collecting and converting technologies. This report describes the status of these activities. (A table of the program structure follows.)

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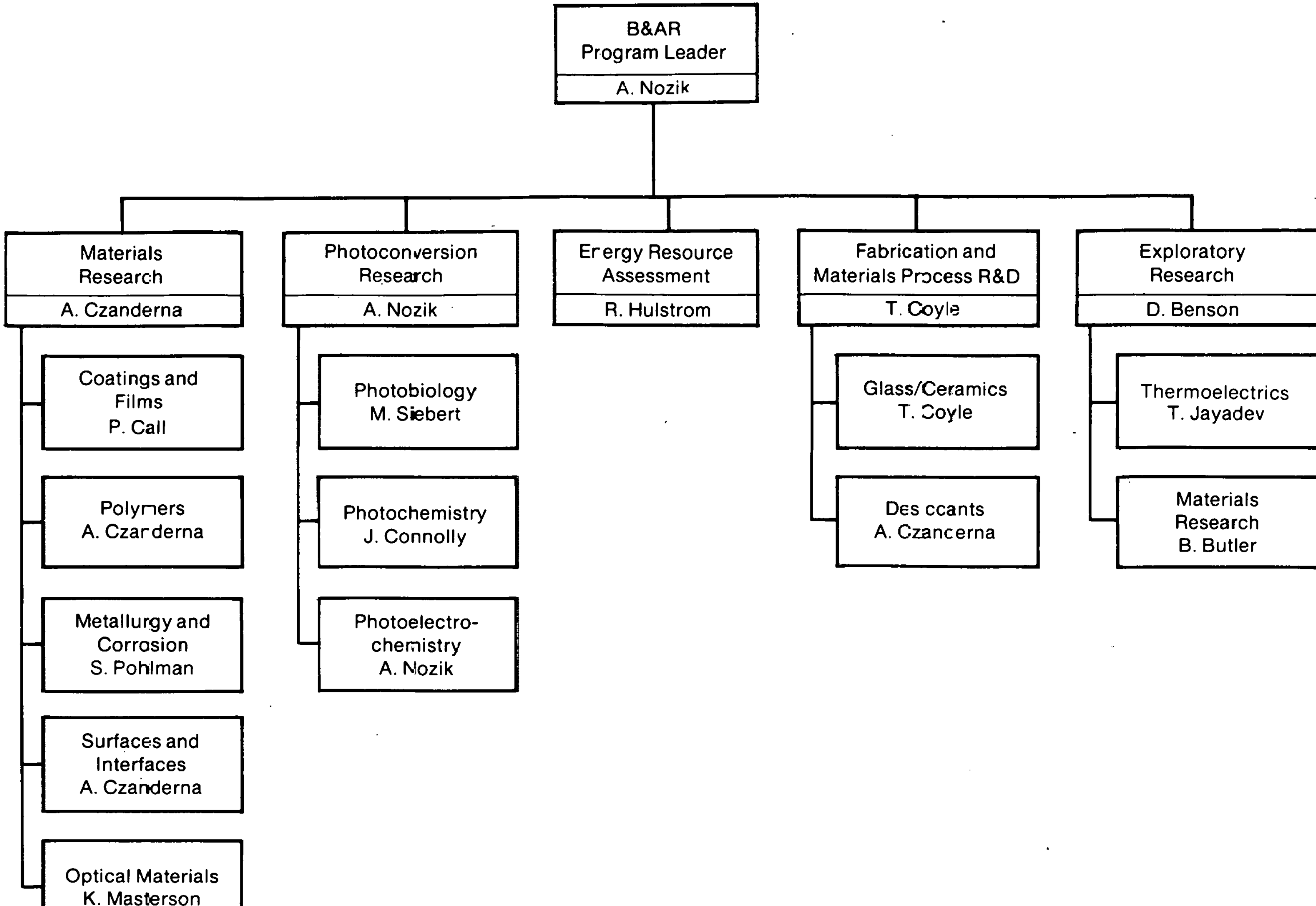

SERI Basic and Applied Research Program

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (concluded)

LIST OF TABLES

LIST OF FIGURES

SECTION 1.0

MATERIALS RESEARCH AND DEVELOPMENT

1.1 INTRODUCTORY OVERVIEW

1.1.1 Overview, Scope, Goals, and Approach

Major materials problems in solar energy conversion, such as durability, stability, cost, performance, lifetime, reliability, etc., have been identified by the DOE solar program. Resolving these will have a major impact on the technical and economic feasibility of solar technologies.

Research and development can identify new and improved materials. These can be made available to system designers through direct commercialization or process development. Improved materials have the effect of lowering life-cycle costs by reducing the initial cost, improving performance, or increasing the useful lives of solar components.

The goal of the task is to achieve optimum use of materials in solar components by developing new or improved options. The scope of the Materials R&D task includes identifying problems on a continuing basis, developing appropriate testing and characterization techniques, studying mechanisms of degradation, and performing other research necessary to understand and improve the properties of solar materials. The approach is to continue to identify problems and limitations as the national program develops. The results of this continuing study will be used to initiate, redirect, or terminate SERI research projects.

The development of characterization and testing techniques, study of degradation mechanisms, and performance of research to understand and to improve solar materials requires a long-term commitment to high-quality Materials R&D.

For FY79, Materials R&D has had subtask studies of coatings and films, polymers, corrosion monitoring, surfaces and interfaces, and optical properties. The subtasks are obviously interrelated and are structured to maximize cooperation. All are carried out by personnel in the SERI Materials Branch. The overview, goals of present research, scope, approach, apparatus, and contracts supporting these five subtasks are summarized in the following sections.

1.1.2 Apparatus and Equipment

Major pieces of equipment (more than $20K) planned for purchase as part of the B&AR program are listed below. Funds for FY79 will permit purchase of part of this equipment.

Equipment

Plasma Discharge System
RF/DC Sputtering System
High-Temperature UV-Vis-NIR Diffuse Reflectometer
Leak Detector
Adhesion Tester
Diffuse Reflectance Spectrometer
Vapor Phase Osmometer
Gas Chromatograph/Mass Spectrometer
TGA Apparatus
Solar and Environmental Simulator
Fourier Transform IR Spectrometer
AC Corrosion Facility
Electrochemical Corrosion Facility
Quadrupole Mass Spectrometers
Quartz Crystal Oscillators
ISS/SIMS Surface Analysis Facility
ESCA/AES Surface Analysis Facility
Quartz Microbalance System
Infrared Spectrometer
AES/SIMS Surface Analysis Facility
Scatter Reflectometer
Laser Ray Trace Optical Evaluator
Pulsed Dye Laser

1.2 COATINGS AND FILMS

1.2.1 Overview

The Thin Films and Coatings R&D Program supports solar technologies through the design, development, and evaluation of optical films, protective coatings, low-surface-energy films, and specialized membranes. A laboratory for thin-film research has been designed, and equipment has been identified.

Research activities have consisted of completion of the National Absorber Surfaces R&D Plan, collaborative development of electrodeposited black cobalt (with Colorado School of Mines), preparation and degradation studies of reactively evaporated black chrome (with Clarkson College), conceptual design of an inorganic membrane system for use in salinity gradient osmotic head energy systems, design of a research program for the analysis of protective coatings for silver mirrors, and conceptual design of an improved mirror production system.

National Absorber Surface R&D Plan

The R&D plan described in the first SERI Materials Branch Semiannual Report (Butler 1978) has been completed for internal and external review. A limited number of copies are available through SERI, and subsequent requests will be handled through NTIS (Call 1978; SERI/TR-31-103).

Electrodeposited Black Cobalt

A collaborative effort with the Colorado School of Mines has produced adherent black cobalt films when electrodeposited on bright nickel-plated copper substrates. A plating solution comprised of a standard Watts cobalt bath with boric acid added as a stabilizer has been used to produce a blackened cobalt film by the addition of H_2O_2, HNO_3, or $HClO_4$ as oxidizing agents. The most adherent coatings have been produced at a spinning cathode (200 rpm to 500 rpm) in a bath with HNO_3 as the oxidant and at a low current density of approximately 50 mA/cm^2. Diffuse reflectance measurements indicate that a solar absorptance greater than 0.9 at room temperature can be obtained largely independent of the bath chemistry. The films produced to date have a high thermal emittance (0.8 to 0.9) and work is underway to reduce it. Optimization of the optical properties of black cobalt films and thermal stability tests will be concluded in 1979.

International research and development on black cobalt is being reported (Sherber and Dietrich 1978; Van der Leif 1979). A collaborative effort between NASA-Lewis and Harshaw has produced black cobalt films with a room-temperature solar absorptance of 0.92 and a thermal emittance of 0.15. Preliminary experiments exhibit a long-term thermal stability at 400°C.

Degradation of Reactively Evaporated Black Chrome

Progress in this cooperative activity with Clarkson College using microbalance techniques to study changes in solar absorber films as a function of temperature and environment is described in Section 1.5, Surfaces and Interfaces.

Inorganic Membranes

Osmotic membranes used to extract energy from salinity gradients at ocean/river interfaces or from concentrated brine solutions are required to have stable physical and chemical properties in a hostile environment at high pressure (more than 15 MPa). In addition, practical applications require the refurbishment of such films (Gregor and Gregor 1978). Most membrane materials are organic polymers that are suitable for use under controlled conditions such as dialysis. A materials system has been conceptualized in an attempt to demonstrate an inorganic physical membrane. This proposed system will be fabricated using thin glass with large pores produced by etching. Physical vapor deposition of a rugged inorganic layer such as amorphous carbon, silicon nitride, or silicon oxynitride onto the pore walls will be accomplished by passing a mixture of plasma-activated gases through the thin glass substrate. Uniformity of the pore diameter, critical to proper functioning of the membrane, will be assured by the decrease in gas flow as the pore size is reduced.

Protective Coatings for Silver Mirrors

A research project to study protective coatings for silver mirrors has been designed as one part of the Materials Branch task force on the degradation of silver mirrors. The work will begin in early 1979 at a non-SERI facility with appropriate experimental apparatus. The protection of mirror materials (such as silver) will be accomplished by chemically stabilizing the surface of the material and by reducing the access of corrosive compounds to the interface. A protective layer that acts as a diffusion barrier and that forms a chemically stable compound with the mirror materials at the interface is preferred. Samples will be produced as alternatives to the commercial superstrate mirror/protective coating systems (which consist of a glass/Ag/Cu/paint system). Examples of alternative systems include glass/Ag/Cu/alternate organics and glass/Ag/(Al_2O_3, Si_3N_4, Ta_2O_5, TiO_2, SiO_2, or SiO_xN_y)/organic. The relative corrosion resistance of these systems will be evaluated in an environmental test chamber containing small partial pressures of H_2S, HCl, O_3, and/or NO_x in combination with water vapor.

Improved Mirror Production System

To achieve the environmental stability needed for solar concentrator mirrors, it may prove necessary to abandon the commercial wet processing of silver mirrors. An alternate production technique for a protected front surface mirror has been conceptualized, and an attempt will begin in mid-FY79 to evaluate the technique. An ion-plated multilayer film will be produced from the vapor phase and will consist of an Ag/inorganic protective layer on this glass. Laminating the Ag reflecting layer will also be evaluated.

1.2.2 Goals

The goal of the Thin Films and Coatings activity is to review critical requirements for thin- and thick-film materials in solar energy applications and to design, develop, and evaluate new materials or techniques to meet these requirements.

1.2.3 Scope

The scope of the current investigations is limited to intermediate temperature-selective absorbers (black cobalt and black chrome to 400°C) and protective coatings for advanced mirror systems. Research areas of potential interest include physically selective membranes, specially tailored surface energies for mitigation of dust adhesion, and encapsulant materials for photovoltaics.

1.2.4 Approach

The approach of this activity is to build in-house laboratory capability and to support the defined activities with collaborative research contracts during the buildup phase. Participation in National Solar Materials planning activities with other National Laboratory representatives has greatly aided the definition of the research phase of the thin-films activity.

1.2.5 Supporting Subcontracts

- Black Cobalt Electroplating, Colorado School of Mines (CSM), (W. Averill, Principal Investigator, CSM) $50,000; and
- High-Temperature Optical Measurements, TRW and McDonnell Douglas, Service Subcontracts, $10K each.

1.3 POLYMERS

1.3.1 Overview

The Polymeric Materials R&D Program is important to solar technologies in such areas as protective coatings, encapsulants, transmission plates, and backing for mirrors. A polymers laboratory has been designed and needed equipment identified.

Research activities have centered around producing a National Program Plan, carrying out computerized calculations of model flat-plate collector systems, and initiating a collaborative research program on the photodegradation of polymers with the University of Denver.

National Polymers Program Plan

A draft of a Polymeric Materials Program Plan has been revised, with significant input from the polymer community at large. Using this draft as a guide, the programs, personnel, and facilities needed in FY79 and beyond have been identified.

Computer Evaluation of Flat-Plate Collector Performance

A SERI report (SERI/TP-31-193; The Effects of Photo-Induced Optical Degradation of Typical Glazing Materials using Flat-Plate Solar Energy Collection Efficiency) has been completed summarizing an adaptation and improvement of computer software developed by Smith (1977) for evaluating the performance of flat-plate collectors where meteorological and insolation data are available from SOLMET tapes. In addition to the functional variations developed by Smith, the program allows for entering data for two collector covers made from different materials, or made with different thicknesses and of variable separations between themselves and the absorber materials. The software is of particular importance for evaluating the potential of different polymeric materials for use in flat-plate collectors. It has been used to calculate the loss in systems efficiency for eight different polymers resulting from the UV degradation of the optical transmission properties.

Photodegradation of Polymeric Materials

Polymeric materials planned for use as protective coatings or encapsulants for solar devices are susceptible to degradation by the UV in solar radiation. Polycarbonates that have relatively advantageous tensile strength, impact resistance, and solar transmissivity have been shown to crack and to yellow even in the presence of UV stabilizers (Smith 1977). The purpose of this study is to detect the time/temperature onset of degradation of polycarbonates using a Fourier Transform Infrared Spectrometer (FTIR). The ultimate aim is to extend lifetimes with radical quenching inhibitors and antioxidants. Coordination of this study with a similar one at JPL has been accomplished (as communicated by A. Gupta and W. Carroll of JPL).

A collaborative research effort has been initiated with the University of Denver, which now possesses a Digilab FTS-14 infrared interferometer, for FTIR studies of polymeric materials. The design of an environmental test chamber (ETC) that is compatible with the FTS-14 interferometer has been finalized and the ETC is under construction. The chamber permits simultaneous exposure of the polymer to simulated solar radiation and atmospheric environments and measurement of the IR spectrum from the polymer. The sample test chamber and solar simulator are shown in Fig. 1-1. Specifications of the solar simulator for use with the ETC were also completed. Additional similar samples will be exposed to outdoor weathering on Harrison racks (Call 1978) to correlate accelerated and real-time testings.

1.3.2 Goal

The objective of the polymers program is to define the criteria for selecting polymeric materials for use as components in solar energy conversion systems. For this, an understanding is needed of the interplay of the environmental factors that limit the lifetime of polymeric materials. By modifying existing polymers or developing new materials, the lifetime of solar devices will be extended by eliminating or drastically reducing the rate of degradative reactions.

1.3.3 Scope

Lifetime limiting factors include solar flux, temperature range, humidity, atmospheric contaminants, chemical exposure, particulates, and mechanical stress; and the interplay of these degradative reaction mechanisms must be elucidated.

1.3.4 Approach

Long-term program and facilities development plans are being prepared. Specific research problems will be initiated that fit within the long-term program plan. The technical approach of each specific project is covered in Section 1.0.

1.3.5 Contracts

- Accelerated Degradation of Polymeric Materials for Solar Applications, University of Denver (D. Smith, Principal Investigator, UD), $24,900.
- Polymeric Materials R&D Program Development, Jet Propulsion Laboratory (W. Carrol, PI, JPL), $125K.

1.4 METALLURGY AND CORROSION

1.4.1 Overview

The corrosion monitoring program supports solar technologies by modifying and developing techniques for solar systems. A laboratory for corrosion monitoring research has been designed, and the needed equipment has been identified.

Research activities during the period have included studies of reference electrodes suitable for corrosion monitoring in moderate- to high-temperature solar energy systems;

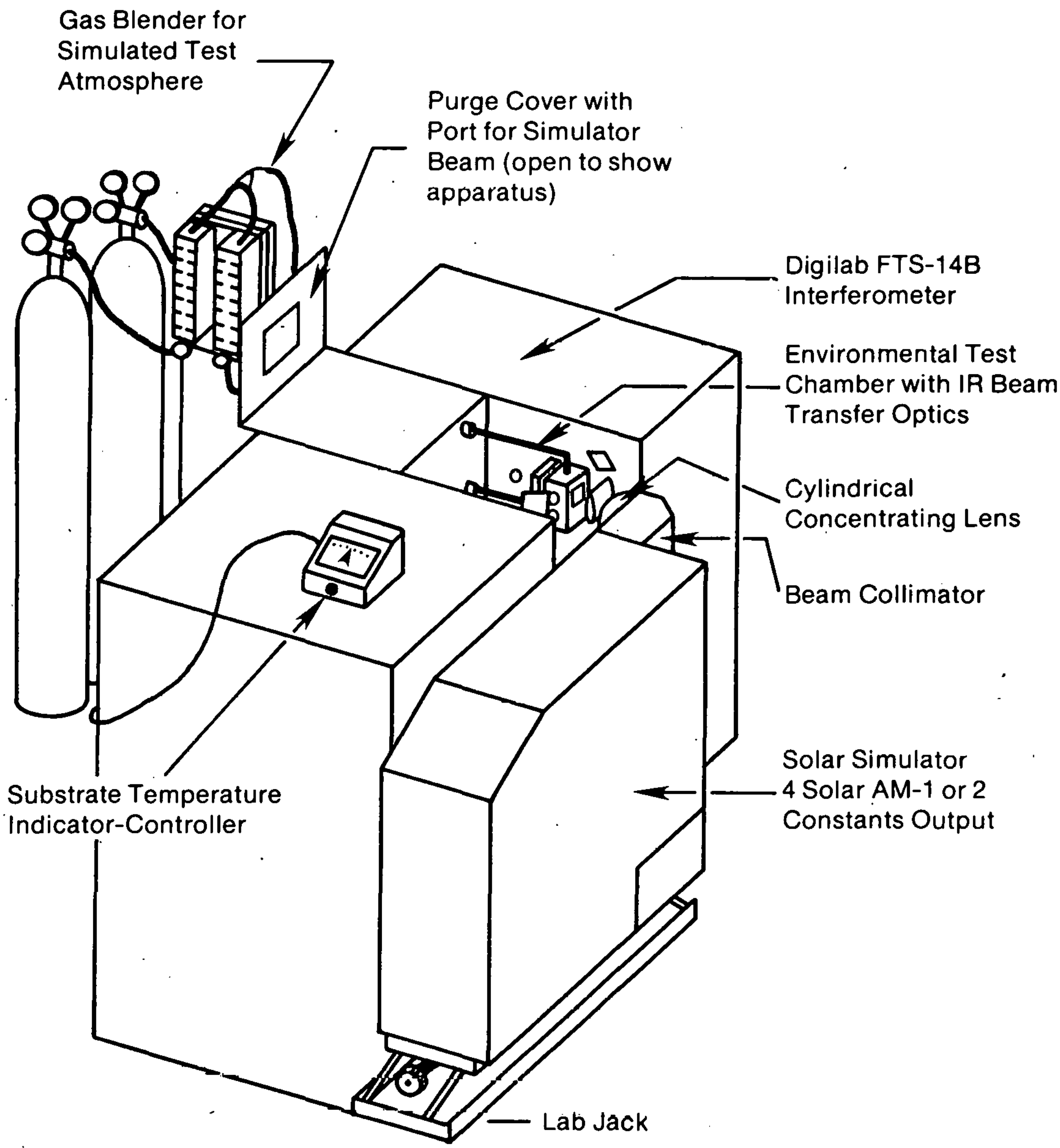

Figure 1-1. Proposed Experimental Set-Up Polymer Film Accelerated Degradation Study

evaluation of materials performance in sodium heat-transport systems; conducting a workshop on the reliability of materials for solar energy systems; organizing a structural materials coordinating committee for thermal conversion systems; and planning a program to study mirror degradation.

A Study of Reference Electrodes Suitable for Corrosion Monitoring in High-Temperature Solar Conversion Systems

The study will screen known reference electrode systems to ascertain the suitability of each system in high-temperature and high-pressure applications and to determine the limits of each electrode candidate within the limits of applicability. Additionally, this study will explore promising new half-cells to demonstrate usefulness in solar applications.

Several reference electrodes will be tested in environments ranging from -20° C to 400° C and from ambient pressures to 200 atmospheres. Among the electrodes to be tested are the Ag/AgCl system and the Hg · Tl/$TlCl_2$ systems. A literature survey has been completed, and detailed study of the references should indicate which other systems are promising.

Electrodes will be constructed using materials suitable for the temperature and pressure environments indicated. The electrodes will then be tested in autoclaves at various combinations of temperatures and pressures. The tests will determine what the signal outputs will be, compared to a standard hydrogen electrode in the autoclave. The output potentials of these electrodes will be measured and tested for stability with time at each temperature-pressure combination, and repeatability will be tested as the electrode is cycled to the elevated temperature and pressure from ambient conditions. For carrying out the high-pressure work, a blast shield has been constructed and an autoclave system installed.

The outcome of the research will be data on the applicability of reference electrodes to monitoring corrosion in solar heat-exchange systems; and the limit of each electrode tested will be determined. The net result will be the determination of electrodes technically evaluated with respect to solar applications. The logical extension of this work is to test the electrodes in a heat-exchange loop subject to the same operating conditions as an operating solar energy converter (Colorado School of Mines is performing this work).

Materials Performance in Sodium Heat Transport Systems for Solar Energy Applications

Components of advanced receivers employing liquid metal as the primary heat transfer fluid will be subject to severe thermal shock conditions. Transients reaching 200° C in a few minutes are projected. The most susceptible component will be the receiver itself, but components downstream of the receiver, such as the hot and cold leg of piping and the intermediate heat exchanger, will also see rapid temperature changes. The transient response of the system will affect the materials exposed at sodium surfaces. The reaction of these corroded surfaces and the influence of surface chemistry modification and structural phase change on resistance to thermal shock will have to be examined. In the Westinghouse-owned contract, a Westinghouse-owned sodium facility, specifically designed for corrosion and thermal transient studies under prototype thermal conditions, is being used to determine the effect of thermal striping on surface chemistry and structural phase changes that could lead to spallation and system failure.

Thermal transient tests of as-received Types 304 and 316 stainless steel materials, and preexposed Type 304 stainless steel, will be performed between 204°C and 371°C (400°F to 700°F) and between 371°C and 593°C (700°F to 1100°F), respectively. Each test will cycle at the rate of one cycle every five minutes for eight hours and then be maintained at the maximum batch temperature for 16 hours. An estimated 1600 cycles will be completed for each batch test.

Type 304 stainless steel tubing, with a surface deposit acquired during prior sodium exposure, and annealed Type 304 and Type 316 stainless steel machined into 0.25 x 0.50 x 0.75 inch blocks will be used in the sodium exposure tests. The effects of an imposed prestress will be evaluated by means of a premachined hatch (0.005-inch radius) located on selected samples (Westinghouse).

Reliability Workshop

A reliability workshop was planned and held during this period. The proceedings summarizing the input from over 200 national participants will be published in mid-1979.

Structural Materials Coordinating Committee

Precipitated by the urgent need to coordinate materials research and development in the area of corrosion and mechanical failure, a National Solar Structural Metals and Ceramics Coordinating Committee for Thermal Conversion Systems was created. The goal of the committee is to coordinate and plan structural metals and ceramics research and development for solar thermal conversion systems to assure that the goals of the National Program are achieved.

The objectives of the committee are to:

- Review research and development needs;
- Prioritize needs so that critical areas are addressed;
- Coordinate research and development to minimize duplication between the various laboratories;
- Facilitate timely and complete information exchange;
- Initiate research and development to satisfy needs;
- Maintain feedback between research and development and the technology development program; and
- Create ad hoc subcommittees to assist the coordinating committee in focusing on specific issues.

The committee consists of Steve Pohlman, SERI (Chairman); Tom Coyle, SERI; Charles Savage, JPL; William Edmunson, JPL; Richard Rohde, SLA; Jack Swearengen, SLL (Vice-Chairman); and Barry Butler, SERI (ex officio).

1.4.2 Goals

The overall objectives of this program are to increase the understanding of container materials and fluids subject to moderate- and high-temperature environments and thermal and machanical stresses; and to develop an understanding of mirror degradation phenomena and use this information to increase mirror reliability and durability.

The specific goals are to identify and to characterize the accelerated degradation of container materials due to complex load histories such as high cycling rates superimposed on static loads, or large load variations at relatively low frequencies; to determine the chemical kinetics of the initial stages of passive film formation on metals exposed to cyclic conditions and to monitor in situ reactions; to determine high-temperature fluid stability and container material compatibility under simulated thermal cycling conditions; to develop on-line monitoring devices capable of withstanding severe solar environments and producing sensitive, reliable information with an emphasis on innovative dc and ac techniques; and to determine the important parameters that affect the chemical kinetics of mirror corrosion.

1.4.3 Scope

The scope of this task is to identify critical material needs with respect to container and structural materials for the various solar technologies, to prioritize the needs to assure that the critical areas are addressed by both in-house and out-of-house activities, and to identify the corrosion mechanism associated with mirror degradation.

1.4.4 Contracts

- A study of Reference Electrodes Suitable for Corrosion Monitoring in Solar Conversion Systems, Colorado School of Mines (W. Averill, PI, CSM), $24,475.
- Materials Performance in Sodium Heat Transport Systems for Solar Energy Applications, Westinghouse ARD (G. A. Whitlow, PI, WARD), $24,690.

1.5 SURFACES AND INTERFACES

1.5.1 Overview

The long-range goals of the Surface and Interface Program have been identified for FY79 and beyond, including the personnel and facilities needed. The central role of surface and interface analysis within the Materials Branch and that analysis' extensive interactive role with solar thermal, photovoltaic, biological/chemical conversion, and storage technologies is vividly evident. For example, ESCA, ISS, AES, and SIMS were used to identify degradation products on first surface and coated silver mirrors from the MDAC project. The elements S, Cl, and O were found throughout a 20-nm depth of a visually "clear" region in the degraded mirrors. Thus, the information from surface analysis is absolutely essential for deducing degradation mechanisms, not only of mirrors but also for absorber coatings, polymer and glass protective coatings, photovoltaic surfaces and interfaces, and in catalytic and membrane materials used in biological/chemical conversion systems. Surface and interface laboratories have been designed and equipment needs identified.

Collaborative research programs for studying black chrome, copper sulfide, and desiccant materials using external facilities are detailed below.

Preparation and Degradation of Black Chrome

Black chrome has the most desirable optical properties as a selective absorber coating for flat-plate and linear concentrator collectors, but it degrades in terrestrial environments in excess of 250°C to 300°C (Call 1978). Reactively evaporated black chrome films have been prepared for elucidating the degradation mechanism using ESCA, ISS, SIMS, SEM, optical, and microgravimetric techniques. The ISS data show the surface and interface of the first films prepared are richer in chromium oxide than the intervening thickness. The ESCA data confirms the presence of both $Cr^{+3}(Cr_2O_3)$ and Cr^0 metal near the surface; an excellent possibility exists for semiquantitative analysis of the relative amounts of Cr in a Cr_2O_3 matrix. The SEM photographs show the films are smooth, but the question of possibly extensive internal porosity has not yet been resolved. Substrates that permit the microgravimetric study of further oxidation of black chrome have been obtained. The reactive evaporation of black chrome in a standard bell-jar vacuum station, successfully demonstrated with oxygen-16, has been extended to oxygen-18 for isotopic labelling. The program has been designed to compliment the process development work being carried out by Honeywell and Sandia. The collaborative effort is between Clarkson College (H. Helbig and E. Prince) and SERI.

Preparation and Degradation of Cuprous Sulfide

Cuprous sulfide, which is the principle material used for the thin-film CdS/p-type material heterojunction, degrades in terrestrial environments. For the in situ study of the degradation in simulated atmospheres, an attempt is being made to prepare Cu_2S films on a substrate suspended from a microbalance. A complete description of the apparatus is now available (Czanderna et al. 1978). Vacuum-deposited copper films are sulfided in H_2/H_2S mixtures while monitoring the mass grain, optical transmittance, and front surface reflectance. After reaching Cu_2S, the sulfiding gases can be evacuated and replaced with the desired simulated terrestrial atmosphere for degradation studies.

Cu_xS films with x = 1.87, 1.93, 2.00, and 2.07 have been successfully prepared between 70°C and 80°C with sulfiding times of 15 to 60 hours on sapphire and rock salt substrates. Results of SEM analysis show the films are sufficiently uniform to provide interpretable optical data; the granularity ranges from 50 nm to 200 nm. Results of ISS, AES, and ESCA depth profiles show no detectable contamination in the bulk of the films, although several surface impurities are present because of the required transfer in air. Diffraction data are not yet available but should demonstrate that the films have a low chalcocite structure. The progress during this period has been most encouraging for elucidating the conditions for preparing stoichiometric Cu_2S for further in situ study. The collaborative effort is with Clarkson College (H. Helbig and E. Prince) and SERI, which includes ESCA, AES, ISS, and SIMS contracts.

Sorption by Desiccants

Desiccants with desirable rates of sorption and desorption of water vapor are being sought for potential use for solar cooling of buildings. Silica gels and zeolites have been selected for the initial studies using gas chromatographic and microgravimetric facilities at the Colorado School of Mines. The components required to modify the existing equipment for water vapor sorption studies have been ordered and experience has been gained using the microbalance. Preliminary measurements began at the end of the reporting period. The collaborative effort was initiated in August with Martins of CSM.

Degradation of Silver Mirrors

This project was initiated late in 1978. Samples were cut from degraded and visually reflecting parts of first surface mirrors used on the McDonnell Douglas project. Sulfur, oxygen, and chlorine were identified as major impurities in tarnished areas to over 50-nm depth, using ESCA, ISS, AES, and SIMS. Silver, sulfur, and oxygen were found through a 20-nm depth of a visually clear region in the degraded mirrors. Copious amounts of sulfur and oxygen were also identified on a highly reflecting (visually) region of the mirror. A well-integrated plan for study was formulated with S. Pohlman, T. Coyle, and P. Call of SERI and will be formalized in early 1979.

1.5.2 Goals

The objectives of this program are to define the surface and interface requirements for studying and characterizing solar materials and to develop an understanding of the surface and interface phenomena that limit the lifetime, stability, reliability, and compatibility of materials used in solar systems. From the latter, materials will be modified to eliminate or reduce degradative reactions that limit the lifetime of materials.

1.5.3 Scope

The scope of the program is to identify the lifetime-limiting factors, such as temperature, composition, interdiffusion, contamination, pressure, and environmental exposure, that produce degradative reactions. The program has a broad impact because of the extreme sensitivity of solar devices to surface and interface effects.

1.5.4 Approach

Long-range program and facilities development plans are being made, including a list of specific problem areas. Specific degradative problems from the general areas of reflector surfaces, absorber coatings, glass interfaces, photovoltaic surfaces, and polymer/metal oxide interfaces are being studied experimentally. For each project, the technical approach is optimized as indicated in Section 1.1 to 1.4. Efforts are concentrated at studying surface and interface reactions as they occur during simulated solar-terrestrial environmental exposure.

1.5.5 Apparatus and Equipment

Three major pieces of apparatus for internal use have been ordered or specified. First, components for a microbalance system for classical use, supplemented with residual gas analyzer measurements during outgassing, desorption, or decomposition studies have been ordered. Secondly, components for a vapor chromatographic sorption system for kinetic and equilibrium studies of water vapor adsorption on high-surface-area desiccant materials have also been ordered. A report describing the design parameters for the system has been completed for internal review. Finally, research considerations were documented and requests initiated for the procurement of a complete surface analysis system, embodying as a minimum ISS, SIMS, ESCA, and a capability for adding AES and UPS.

1.5.6 Contracts

Title	Institution	Amount
Degradation of Black Chrome and Copper Sulfide	Clarkson College (H. Helbig, PI)	$24,800.
Water Vapor Sorption by Desiccants	Colorado School of Mines (G. Martins, PI)	$24,200.
ISS/SIMS Surface Analysis	3M Company (Service)	$10,200.
ESCA/ISS/SIMS Surface	Inficon L-H Analysis (Service)	$ 4,000.

1.6 OPTICAL MATERIALS

1.6.1 Overview

Optical materials are involved in the first interaction of solar energy with the conversion system. It is necessary to determine loss of system efficiency due to this interaction so that it can be minimized by use of more efficient or durable materials. An optical measurements laboratory has been designed and needed equipment identified.

Research and related activities have centered around: a solar optical materials program planning effort; development of silver/aluminum alloy mirrors; development of laboratory instrumentation for determining the optical properties of materials; designing low-cost heliostats; an attempt to develop unique flux-mapping capabilities for the point-focus concentrating collector effort; and implementation of a general-purpose computer program for ray tracing to support laboratory development, low-cost heliostats, and a point-focus concentrating collector.

Solar Optical Materials Program Planning Committee

During this period, the Solar Optical Materials Program Planning Committee was officially chartered from a previously existing ad hoc committee on optical materials, measurements, and standards. SERI has taken the lead role in the organization and activities of this committee. Although the intital areas of concern were primarily those of materials characterization and measurement standards, the emphasis of the committee now is on program planning. The present goal is to produce a unified National Solar Optical Materials Program Plan by the end of FY79. This plan will deal with four categories: absorber materials, reflector materials, transmitting materials, and standards and measurements. An interim report covering committee activities through January 1979 has been drafted and will be released in July 1979. During 1978 it was found that the solar-weighted averages of absorptance, reflectance, and transmittance of solar optical materials are not sensitive to the specific terrestrial air mass used as the weighting function. Therefore, to maintain uniformity in the solar industry, the committee advocates adoption of an air mass of 1.5, which is the same terrestrial solar air mass used by the photovoltaics program. The exact spectral irradiance associated with this air mass is still under discussion. Preliminary measurements on four different solar absorber coatings showed retroflectance contributions of less than one part in 10^5. Therefore, reflectance measurements made using integrating spheres appear to be adequate for most solar applications.

Another activity of the Optical Materials Program Planning Committee is to identify nomenclatures appropriate for solar optical materials. Interim recommendations for use by DOE contractors will be made. Committee members are active on the ASTM E44, Committee on Solar Energy, to obtain industry-wide concurrence with appropriate measurements and nomenclature.

Silver Aluminum Alloy Mirror Development

When using concentrating collectors, high specular reflectance with good durability is desirable in order to maintain high system efficiency. Thin-film plastic reflectors have high initial reflectance, but to date have shown inadequate durability against environmental degradation. A research project to seek more durable "metallized" plastic reflectors has been initiated by SERI. It is well known that fresh silver coatings have the highest obtainable reflectances but are environmentally unstable. Aluminum is more stable due to the rapid formation of an aluminum oxide film, but it has a considerably lower reflectance. In the first phase of this project, the two metals are to be co-sputtered in an attempt to produce an alloy that will have high reflectance and good durability.

A contract with Rockwell International, Rocky Flats Plant, has been negotiated to provide for the deposition and metallurgical characterization of thin films of silver/aluminum with varying alloy ratios. Trial runs have resulted in a modified sputtering geometry for the deposition of samples. SERI will measure film specular reflectance using a Perkin-Elmer Model 340 spectrophotometer that has been recently acquired. Degradation tests and subsequent film analysis should enable SERI to determine the alloy composition and preparation that exhibits the best reflectance and durability.

Laboratory Development

This activity has centered on the identification and procurement of general-purpose optical instrumentation for solar energy-related measurements and the identification of critical measurement problems that will require special instrumentation. The areas of measurement expertise that have been identified are:

- Solar absorptance of diffuse absorber surfaces;
- Thermal emittance via both calorimetry and infrared reflectance techniques;
- Solar transmittance of glazings, envelopes, receiver windows, and reflector superstrates;
- Reflectance and specularity of concentrator mirror surfaces; and
- Absorptance, emittance, and transmittance of some materials at elevated temperatures.

The equipment to perform some of these measurements has been acquired and is detailed later in this report.

Low-Cost Heliostats

An initial feasibility of a low-cost heliostat design is underway. The concept uses a central heliostat support with a universal joint mounting. The drive system is provided by cables attached to the mirror rim. It will allow for the possibility of ganged control of several heliostats and better support against wind loading forces. A preliminary model has been fabricated to assess the concept's viability. The tracking requirments for the ganged operation are being analyzed.

Point Focus Concentrating Collector

The Materials Branch is supporting the Thermal Conversion Branch in a task to characterize the optical properties of a commercially available point-focus concentrating collector. This support consists of helping to design test equipment to provide flux mapping at the focal area of the concentrator. It also includes the establishment of a laser ray-trace facility for general use in characterizing slope errors and angular acceptance functions of point-focus concentrating collectors.

Ray-Trace Program

A simple but versatile ray-trace computer program has been implemented. It will be used to analyze optical systems and to aid in instrument design. It has already been used in the design of a unique diffuse reflectance attachment for the Perkin-Elmer spectrophotometer. It will also be used to support the Thermal Conversion Branch in the analysis of concentrating collectors.

1.6.2 Goals

The objective of this program is to make available more efficient, more durable, and/or less expensive optical components for the solar and the technological data base necessary for identifying, developing, and manufacturing appropriate optical materials to be used in collector production. Lowering life-cycle costs of solar collectors will considerably improve market penetration.

1.6.3 Scope

The scope is to plan a five-year national program covering absorber, reflector, and transmitter materials. The plan will serve to define and coordinate research and development by national and commercial laboratories, universities, and manufacturers. It also sets recommended funding levels and priority areas for research and development.

1.6.4 Approach

The approach is to form a planning committee with representatives from national laboratories involved in solar energy development. This committee is assembling a recommended program plan consisting of sections on:

- Management to provide periodic review and update of the plan and for compilation and dissemination of an optical materials data base;
- Materials research and development in each of the three areas of optical interactions;
- Large-scale manufacturing technology leading to commercialization of promising materials; and
- Measurements and standards to identify appropriate optical performance prediction from weathering data and modelling based on identified degradation mechanisms.

The assembled plan will be submitted to industrial and university communities for comments and to DOE for approval and funding.

1.6.5 Apparatus and Equipment

A Perkin-Elmer Model 340 spectrophotometer has been delivered. A specially designed integrating sphere for measuring diffuse reflectance of absorber materials is under construction. The spectrophotometer will be interfaced to a recently delivered LSI II data-handling system in order to provide rapid data acquisition and determination of the solar-weighted optical properties. A Fourier Transform Infrared Spectrometer will be procured this fiscal year. Portable Fier-Dunkle instruments for determining solar absorptance and thermal emittance have also been received. Plans for next year include acquiring of optical components necessary for measuring specularity, optical constants, and high-temperature optical properties.

1.6.6 Contracts

- Silver Aluminum Alloy Mirror Development, Rockwell International (F. Fraikor, PI), $66,560.
- Development of Reflective Surface Protective Coatings, Dow-Corning (William Dennis, PI), $72,000.
- Research and Development for Solar Mirror Quality Assurance and Performance, Pacific Northwest Labs (Mike Lind, PI), $250,000.
- Solar Materials Optical Standards Development, NBS (Joe Richmond, PI), $135,000.

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SECTION 2.0

PHOTOCONVERSION

2.1 OVERVIEW

Photoconversion includes chemical and biological processes in which radiant energy is converted directly via quantum processes into other forms of energy (such as chemical feedstocks, liquid and gaseous fuels, and electricity). The SERI program includes basic research in photochemical, photoelectrochemical, and photobiological conversion of solar energy. Photochemistry deals with the effects of light in producing chemical change. The synthesis of photochemical model systems that convert light energy into chemical potential (e.g., charge separation) for processes such as CO_2-reduction or N_2-fixation is an example of a solar energy application. Photoelectrochemistry is the interface between chemistry and solid-state physics. Its solar applications include the production of chemicals or eletricity at a semiconductor-electrolyte interface. Photobiology encompasses the effects of light either in living systems or in high molecular weight complexes isolated from living systems. Understanding the primary processes of photosynthesis holds the key for potential applications in this area.

Although photoconversion mechanisms are capable of relatively high theoretical conversion efficiencies (20% to 30%), photoconversion has been largely neglected in the federal solar program. Basic research is needed in order to design and characterize new systems and to identify limitations of known systems. In all cases, a fundamental understanding of the relevant molecular processes is required to devise more efficient and controllable routes for direct production of fuels, chemicals, and electricity from available sunlight.

The long-term objective of research in photoconversion is to develop photobiological, photochemical, and photoelectrochemical conversion schemes to produce fuels, chemicals, or electricity at conversion efficiencies approaching 10% or higher. SERI's primary objective for FY79 is initiation of laboratory research on modified photosynthesis, model photochemical systems, and improved photoelectrochemical systems.

2.2 PHOTOCHEMISTRY

The Photochemistry Group consists of a senior photochemist, a senior inorganic chemist, a staff physical chemist, and an associate physical chemist. An additional associate position will be filled by a synthetic organic or inorganic chemist during the next reporting period.

Instrumentation and equipment needed for this program fall roughly into two categories: (1) kinetics, spectroscopy, and photochemistry; and (2) chemical synthesis. The major item in category (1) is a kinetic spectrophotometer. The design is modeled after a conventional laser flash photolysis system, but the capabilities of the unit will be vastly extended in terms of actinic wavelengths, data acquisition, and data processing. The major item of chemical synthesis equipment and instrumentation is a nuclear magnetic resonance (NMR) spectrometer.

SERI staff has established cooperative and collaborative arrangements at the University of Colorado for chemical synthesis and X-ray structural studies and at Brandeis University for kinetics and spectroscopy of model photosensitizers. Additional groundwork has paved the way for research on electron-transfer kinetics at the University of Texas at Austin and for picosecond laser spectroscopy and kinetics at Battelle-Columbus Laboratories.

The first priority for Inorganic Chemistry is synthesis and characterization of dinuclear organometallic complexes containing bridging organic ligands. Coordinatively unsaturated derivatives of the early transition metals will be evaluated as homogeneous catalysts and stable intermediates in photoredox systems. Basic studies will involve the interrelationships of the geometries, electronic structures, and reactivities of these systems. Coordination complexes containing electroactive ligands will also be examined.

In preparation for the kinetics and spectroscopy studies at Brandeis, SERI staff has written a software routine for the HP-9845 computer to model the kinetic behavior of transient intermediates thought to be involved in the phototchemistry of model systems such as bacteriochlorophyll.

Photochemical evolution of H_2 has been demonstrated in several laboratories. The major problem to be confronted is O_2-evolution. Accordingly, initial efforts will involve "the oxygen side" and attempts to achieve vectorial electron transfer across membrane surfaces.

Finally, the Third International Conference on Photochemical Conversion and Storage of Solar Energy will be hosted by SERI and will be held in Boulder, August 3-8, 1980. The conference chairman is also chairman of the International Organizing Committee. The local Organizing Committee consists of the entire SERI Photoconversion staff.

Utilization of solar energy to generate fuels and chemicals from abundant, renewable resources will make a significant impact on future energy supplies. The long-term goals of this task area include reduction of CO_2 to methane and fixation of molecular N_2 to ammonia. In the process, however, it is necessary to understand somewhat simpler processes, and the near-term goal of this subtask is to achieve photochemical splitting of water into molecular H_2 and O_2.

The work of this subtask encompasses photochemical research to determine optimal spectroscopic, kinetic, and redox properties of photosensitizers and organometallic model systems in heterogeneous and homogeneous media for evolution of hydrogen and oxygen from water.

Research will be initiated in FY79 in the following areas:

Photosynthesizers—SERI will seek to characterize molecular systems exhibiting strong adsorption in the visible spectrum. Problem areas such as minimizing the quantum efficiencies of wasteful processes, promoting rapid electron transfer to suitable acceptors, and stabilizing initial charge separation states will be addressed.

Redox Catalysts—SERI will synthesize molecules (e.g., coordinatively unsaturated dinuclear organometallics) capable of serving as stable intermediates in sequential electron transfer events. These complexes must also be able to bind the substrate (e.g., H_2O) and release the desired photoproducts (e.g., H_2 and O_2).

Coupled Systems—Specifically, SERI will seek to match spectroscopic, electrochemical, catalytic, and structural properties of photosensitizers and redox catalysts.

Assemblies—SERI will seek to incorporate coupled systems into inhomogeneous media, such as polymer micelles or membrane vesicles.

2.3 PHOTOELECTROCHEMISTRY

Photoelectrochemical energy conversion is based on photoactive semiconductor electrodes that absorb visible light, thereby creating electron/hole pairs that separate in the space-charge layer produced at a semiconductor/liquid electrolyte interface. These separated electrons and holes are subsequently injected into the electrolyte to drive chemical reduction and oxidation reactions.

Photoelectrochemical cells can be configured to produce electricity or to drive chemical reactions. The emphasis of the program is on the latter systems. Chemical reactions driven uphill in energy (endoergic) produce fuels (for example, splitting of H_2O into H_2 and O_2); chemical reactions can also be driven downhill in energy (exoergic) and produce useful chemicals (for example, reduction of H_2 to NH_3). For the endoergic case, solar energy is converted into chemical energy, while for the exoergic case, solar energy provides the activation energy for the chemical reaction. The production of hydrogen by photoelectrochemical water splitting (photoelectrolysis) is a primary objective of the program.

Photoelectrochemical systems have high theoretical conversion efficiency (about 25%); they can be operated with inexpensive polycrystalline and/or amorphous electrodes without drastic loss of efficiency; and simple and inexpensive photochemical reactor systems based on photochemical diodes in a slurry or colloidal-type system can be utilized. However, the major problem preventing the implementation of these advantages is the lack of sufficient photochemical stability in those semiconductor electrode materials that have band gaps in the optimum range (1.0 eV to 2.0 eV).

The primary objective of this subtask is to explore and discover new electrode materials and electrode systems that exhibit high photoelectrochemical stability and high conversion efficiency and that operate with zero external bias. Additional objectives are to develop valid theoretical models for photoelectrochemical cells that permit a priori prediction of semiconductor efficiency, stability, and current-voltage characteristics. The significance of the recently proposed "hot carrier" injection model for photoelectrochemical cells for electrode stability and control of electrode reactions will also be examined.

For the endoergic case, emphasis will be placed on systems for H_2 production, hydrocarbon production, and carbohydrate production. For the exoergic case, emphasis will be placed on nitrogen fixation using molecular hydrogen.

The objectives will be met through research in the following areas:

- Heterojunction electrodes that contain multiple semiconductor layers with a stable outer layer semiconductor followed by decreasing band gaps in the inner layer;
- New, novel semiconductor compounds, including layered compounds with intercalated species provided to improve properties as required;
- Chemically modified electrodes that comprise organometallic complexes bonded to the semiconductor surface and that contain facile redox species to facilitate

charge transfer from the semiconductor to the electrolyte without destruction of the semiconductor or the attached metal complex;

- Hybrid bioinorganic chemical systems that combine the stable photooxidative properties of the chlorophyll-based Photosystem II with the high conversion efficiency of inorganic semiconductors;
- Theoretical analyses of charge transfer mechanisms at semiconductor-electrolyte interfaces; theoretical studies of the relationship between semiconductor band gap, stability, and flat-band potential with basic atomic and molecular properties of the semiconductor and the electrolyte;
- Photoelectrochemical systems used as photocatalysts to drive such reactions as N_2-fixation and the photo-Kolbe reaction; and
- Photoelectrochemical systems used in the form of small, colloidal particles (photochemical diodes).

2.4 PHOTOBIOLOGY

During the six-month period ending December 31, 1978, the major accomplishments of the Photobiology subtask have included the assembly of a research staff, completion of a SERI technical report, initiation of several collaborative research efforts, start-up of a rental laboratory facility, and commencement of in-house research efforts.

In addition to a photobiologist with extensive experience in the primary energetics of photosynthesis, the staff presently includes a microbial geneticist, a biochemist, and a bacterial physiologist. All have expertise in various aspects of electron transport and hydrogen metabolism in bacterial and algal photosynthetic systems.

The group completed a draft of a report entitled Photobiological Production of Hydrogen-A Solar Energy Option. The report is a literature survey of photobiological hydrogen production from its discovery in relatively uncontaminated cultures during the early 1930s to the present. The field includes hydrogen production by phototropic organisms (and their components), which occurs at the expense of light energy and electron-donating substrates. The review discusses specific technical problem areas that currently limit the yield and duration of many of the systems and research that might lead to progress in these specific areas. Future research directions necessary to develop practical photobiological hydrogen-producing systems are also discussed.

Collaborations with the laboratories of Professors Bolton (University of Western Ontario), Togasaki and San Pietro (Indiana University) have yielded some encouraging initial results. Seibert and Bolton defined the conditions under which bacterial reaction center complexes can form monolayers in a Langmuir trough and have transferred such layers to extremely hydrophobic surfaces (wax-coated substrates). This should be considered preliminary work that may lead ultimately to the fabrication of biological solar cells. The maximum in vivo photosynthetic coupling efficiency to hydrogenase in green algae (C. reinhardi) has been assessed. Using various chemical inhibitors, uncouplers, and special environmental conditions, short-term maximum hydrogen evolution rates of 174 μ moles $\cdot$ (mg Chl)$^{-1}$ $\cdot$ h^{-1} have been obtained. This represents 76% of the maximum theoretical rate (that defined by the rate of oxygen evolution) and is the highest value yet reported in this class of organism. The work is important because it demonstrates that most of the reductants generated during photosynthetic electron transport can be channeled directly to in vivo hydrogen production. Preliminary optical and EPR studies of Photosystem I (PSI) particles from the green algae, Scenedesmus, prepared in collaboration with Bolton are complete. The preparations are highly enriched in P700 (the primary electron donor of the PSI reaction center complex; 1 P700 per 26 Chl a molecules); retain the entire set of low-potential, membrane-bound iron/sulfur proteins known to be associated with PSI; and are photochemically active. They also exhibit strong radical EPR signals, which will be investigated further during future collaborative efforts. These particles may be useful in both in vitro hydrogen evolution and biological solar cell applications.

In addition to the above studies, the group set up temporary facilities in rented laboratory space at the Denver Research Institute. Weaver constructed a growth area for photosynthetic microorganisms and assembled at SERI the largest collection of photosynthetic bacterial strains in the country. He is growing ten different strains, and Schultz is stockpiling large amounts of Rps. sphaeroides for preparation of reaction center complexes. Weaver and Schultz are starting genetic and biochemical studies of electron transport carriers and dark growth modes in photosynthetic bacteria. Knowledge in these areas will aid in genetic modifications of the photosynthetic unit to enhance the photoproduction of hydrogen and other products.

The research activities to be addressed during the rest of FY79 are:

Primary Processes—The primary processes of photosynthesis are associated with specific macromolecular complexes that convert light energy into the chemical potential of charge separation. Physical, chemical, and biological properties of various preparations will be examined, with emphasis placed on determining the stability of the complexes under different conditions.

Biocatalysis—Various photosynthetic organisms are capable of evolving hydrogen using the hydrogenase and nitrogenase enzyme pathways. The relationship between the two pathways will be studied in photosynthetic bacteria, and mutant strains with enhanced hydrogenase activity will be selected.

Stabilization—Hydrogenases that are fairly stable in situ will be further stabilized using unique immobilization techniques being developed under subcontract for use in coupled systems.

Coupled Systems—Bacterial reaction centers and Photosystem I particles will be coupled to electrochemical systems to produce electricity, and ultimately will be coupled (along Photosystem II particles that supply reducing power) to stabilize hydrogenase to produce hydrogen.

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SERI

SECTION 3.0

ENERGY RESOURCE ASSESSMENT

3.1 OVERVIEW

Design of solar energy conversion devices, accurate estimates of recoverable solar energy, estimates of costs, and determinations of feasibility require a precise knowledge of the amount and characterization of the available solar energy resources. Uncertainties in the potential solar resources create uncertainties in the expected solar energy device/system performance, cost, economic feasibility, and the recoverable solar energy resources available to the United States.

The major problems in determining the amount and characterization of the solar energy resources are created by the fact that the historical, and even future, data and characterization models simply have not been gathered or developed for the specific purpose of solar energy utilization. Consequently, the historical data and previous characterization models are inadequate for direct application to solar energy requirements. Effort is required for their translation and improvement.

The major portion of this task addresses insolation—both broadband (solar thermal collectors) and spectral (solar photovoltaic collectors). The historical data base for insolation consists of generally inaccurate measurements of insolation on a horizontal surface. Recognizing such problems, the DOE Environmental and Resource Assessment Branch ERAB (now known as EPAB, Environmental Planning and Analysis Branch) initiated and essentially completed a major program that rehabilitated the historical data (to the extent possible). This program was performed by the National Oceanic and Atmospheric Administration (NOAA) and the National Climatic Center (NCC). In addition, a major program was initiated and completed that established a new insolation measuring network (38 stations) for the United States. This network was created by the DOE ERAB and NOAA, and will be operated by the National Weather Service. The network monitors the broadband horizontal insolation and the broadband direct beam insolation. All of the historical and future insolation data are archived at the National Climatic Center.

The historical and future insolation data base are not adequate for the purpose of solar energy applications. The historical data, as mentioned previously, is for the insolation on a horizontal surface; the future data is for insolation on a horizontal surface and the direct beam insolation. Solar energy applications require knowledge of the incident insolation on inclined (collectors) surfaces and of the direct solar beam into various apertures (concentrating collectors of various concentration ratios). In addition, solar photovoltaic devices, spectrally selective materials, and fuels from biomass require a knowledge of the spectral properties of the incident insolation. Such data and knowledge are almost totally lacking in the historical and future data.

The research activities contained in this task (Energy Resource Assessment) are specific elements of the DOE Insolation Resource Assessment Program Plan (IRAP), Division of Distributed Solar Technology, Photovoltaics Branch. In general, these SERI insolation resource assessment activities include the following:

- Review and improvement of models and algorithms to predict broadband and spectral insolation on inclined surfaces and into various apertures; and

- Development and operation of an Insolation Research Laboratory (IRL) for research-quality measurement of broadband and spectral insolation on inclined surfaces and into various apertures.

Both of these insolation research activities are aimed at translating the historical and future insolation data and models into a variety of inputs for solar energy applications. Detailed descriptions are given in later sections of this chapter.

Other activities that are not specific insolation research activities are as follows:

- General technical monitoring and technical support to DOE;
- A South Table Mountain Baseline Study;
- General technical support to internal SERI requirements; and
- Basic wind resource analysis and technical support to the SERI Wind Energy Systems Program and other internal SERI requirements.

The general technical monitoring and support to DOE consists of the review of proposals and support for review and planning regarding insolation resource assessment. The major activities in this area consist of the following:

- Monitoring the eight DOE Meteorological Research and Training Sites, operated by eight selected universities;
- Participation in the DOE Insolation Resource Assessment Coordinating Committee; and
- Serving as the point of contact in the American solar radiation/insolation data analysis program, for cooperative programs with other countries.

The South Table Mountain Baseline Study activity consists of establishing, by review of available and on-site collection of data, an environmental baseline data set/analysis for South Table Mountain, Colorado (the future site of SERI). In order to properly design the structure and solar collector system, a detailed meteorological and insolation data baseline is required.

The general support of internal SERI/DOE activities consists in supplying insolation and meteorological data bases, models, and consultation.

A minimal effort is maintained in basic wind resource analysis. This consists of supplying data and general analysis to internal SERI programs, such as the SERI Wind Energy Systems Program. Specific research analysis is conducted that considers the Principal Components Analysis (PCA) technique for spatial/temporal interpolation and extrapolation of wind characteristics. This is required for siting and systems analysis of wind energy systems.

3.2 RESEARCH GOALS

The long-range goal of this task is to support the use and commercialization of solar energy by removing uncertainties in system performance and cost due to uncertainties about available solar energy.

In order to accomplish this, the following research goals have been established:

- Formulate accurate algorithms for converting National Weather Service insolation data to insolation on inclined surfaces and into various apertures;
- Develop accurate models that characterize both broadband and spectral insolation on inclined surfaces and into various apertures from available meteorological data;
- Develop and operate an Insolation Research Laboratory (IRL), to accurately measure the broadband and spectral insolation on inclined surfaces and into various apertures in order to develop accurate algorithms and verify prediction models; and
- Provide technical support to DOE, SERI, industry, and the private sector.

3.3 SCOPE OF RESEARCH ACTIVITIES

The scope of this task includes model/algorithm evaluation, development, and improvement, and the taking of research data.

The model/algorithm evaluation, development, and improvement includes both analytical-computer and experimental analysis. Available models are evaluated by computer analyses that exercise each model and quantitatively compares their outputs. In general, rigorous models/solutions are employed to evaluate simplified and empirical models. New, improved models are not developed—in this manner—unless it is warranted. Rather, the most appropriate existing models are identified for use in solar energy applications.

The experimental analysis—concerning model/algorithm evaluation, development, and improvement—receive major emphasis. The taking of high-quality research data facilitates the thorough comparison of available models and algorithms. This direct comparison of model/algorithm-predicted results with measured data is the major technique for their development and improvement. The research data includes broadband and spectral insolation on inclined surfaces and into various apertures plus detailed quantification of key atmospheric parameters.

3.4 APPROACH

A major program will be conducted to measure (onsite SERI) insolation on inclined surfaces and into various apertures. This will include both broadband and spectral insolation. However, the spectral properties will be addressed after the broadband measurements are started. Measurements and observations of key atmospheric parameters (water vapor, clouds, aerosol, etc.) and mesosynoptic weather conditions will be made. These data will be used to evaluate and improve models for predicting insolation characteristics as a function of atmospheric properties and to evaluate and improve algorithms for converting the conventional NWS-network insolation data to a variety of inputs for solar conversion devices.

Specifically, broadband total insolation on surfaces facing south will be measured for every 10° increment of tilt, from 90° (vertical) to 0° (horizontal). These measurements will be made with Eppley Labs precision pyranometers (PSPs). The ground that is viewed by these sensors-surfaces will be controlled so that the albedo-reflectivity is uniform; instrumentation will be used (down-looking Eppley PSP) to continuously monitor the ground albedo. The ground albedo is expected to range from about 20% (crushed lava rock surface) to 80% (snow cover). In addition to the south-facing, ground-viewing, 10°-increment tilted array, another tilted sensor-surface array will measure the total broadband insolation on surfaces of multiple azimuths: south, north, east, and west. The tilt increment on these surfaces will also be 10°, but they will be shaded from viewing the ground. Thus, they will monitor only the direct beam and diffuse sky components of the insolation on tilted surfaces. The combination of these two tilted arrays will then allow the ground-reflected component of insolation on the south-facing tilted surfaces to be measured. Because of design considerations, special, small, silicon sensor pyranometers will be used in the multiazimuth tilted array. In order to determine the direct beam component of insolation on the tilted surfaces, a pyrheliometer (Eppley Model NIP) will be used to continuously measure the direct beam insolation. This combination of instruments and configurations will allow the direct beam component, the diffuse sky component, the ground-reflected component, and the total insolation on tilted surfaces to be accurately measured. In addition, the multiple azimuth tilted array will allow the anisotropic nature of the diffuse sky component, especially cloud cover, to be investigated.

The direct solar beam insolation into various apertures will be measured by a variable field-of-view pyrheliometer. This pyrheliometer will measure the absolute direct insolation as a function of field view, ranging from about 0.60° to 6°. In this manner, the circumsolar (forward-scattered) radiation component will be determined. Depending on availability, the LBL circumsolar, telescopic scanning photometer will also be used to map the angular distribution of the circumsolar radiation.

The direct beam (conventional 5.7° F.O.V.) and horizontal insolation will also be measured for the total solar region, 0.3 μm to 3.0 μm; the visible region, 0.3 μm to 0.630 μm; and the near-infrared region, 0.630 μm to 3.0 μm. This will be done using conventional Eppley Model NIPs and PSPs. These measurements will allow the separate effects of atmospheric scattering in the visible region and absorption in the near-infrared to be established.

The spectral insolation, from 0.3 μm to 3.0 μm, will be measured with a specially designed/constructed solar spectral radiometer. This instrument will be capable of measuring the direct beam insolation (about 1° F.O.V.), the diffuse sky and ground insolation, and the total spectral insolation on inclined surfaces. The spectral resolution will be sufficient to adequately resolve all spectral properties of the insolation; the estimated spectral resolution is 0.005 μm. Measurements will be made over a variety of atmospheric conditions but not on a continuous basis.

In order to relate insolation characteristics to atmospheric and meterological conditions, detailed measurements of atmospheric properties and definitions of mesosynoptic meteorological conditions will be made. This will include the following:

- Total precipitable water vapor;
- Spectral attenuation coefficients for aerosols;
- Surface temperature;
- Surface dew point;
- Wind speed;

- Wind direction;
- Visibility, nephlometer method;
- Percent sunshine;
- Cloud cover, height;
- Cloud type, height;
- Surface pressure; and
- Air mass type.

The total precipitable water vapor will be made with both a sun photometer and the conventional radiosonde (at the nearby Denver NWS station). The sun photometer will also be used to measure the total vertical atmospheric attenuation coefficients, and the spectral aerosol attenuation coefficients. The specific wavelength channels will be (approximately) 0.380 μm, 0.500 μm, 0.600 μm, 0.700 μm, 0.880 μm, and 0.940 μm (water vapor absorption band).

An Insolation Research Laboratory (IRL) will be constructed on the SERI interim test site to perform these measurements. It will have an 11-ft by 16-ft research building and special structures that will serve as mounts for the various sensors. The IRL building will house a dedicated minicomputer that will collect, process, and store the research data. Data will be collected on a one-minute increment and used to generate standardized data tapes (SOLMET Format) that will be sent to the NCC for general distribution.

The research data will be used to evaluate existing models and algorithms and to develop improved techniques. The major emphasis will be on developing improved models and algorithms for predicting broadband and spectral insolation on inclined surfaces and into various apertures. The basic inputs to such models and algorithms will be the more commonly available meteorological parameters such as precipitable water vapor, cloud cover, percent sunshine, and the 0.380 μm and 0.500 μm attenuation/turbidity coefficients.

Rigorous radiative transfer models, such as LOWTRAN 3B and Monte Carlo techniques, will be implemented on the SERI computer facilities. These rigorous models will be used analytically to study the relationship between atmospheric conditions and insolation (through the atmosphere, on inclinced surfaces, and into various apertures). The attenuation characteristics of water vapor, ozone, oxygen, molecular scattering, aerosol scattering, carbon dioxide, and clouds will be investigated. In addition, such models will be used to evaluate existing, and develop improved, models and algorithms that use simplified, semiempirical techniques.

For the South Table Mountain Baseline Study, a remote meteorological and insolation monitoring station will be installed at what will be SERI's future site on South Table Mountain. Environmental data will be telemetered to the SERI interim laboratories to be reduced, analyzed, and archived. This continuously monitored data will consist of direct beam insolation, diffuse sky insolation, total insolation on a horizontal surface, total insolation on an inclinced surface (pointed south at an inclination equal to the latitude), wind speed, wind direction, and temperature. In addition, spot measurements will be made under the Denver "brown cloud" pollution layer to determine its impact on future SERI research data/programs. All available existing climatological data will be gathered and used to define the climatology of South Table Mountain.

General technical support of internal SERI projects, of industry, and of the private sector will be provided by maintaining current data bases and providing technical consultation. Specifically, the SOLMET insolation and meteorological data base will be maintained along with available wind data bases.

3.5 APPARATUS AND EQUIPMENT

The major apparatus and equipment required for this task is the Insolation Research Laboratory. It consists of insolation and meteorological measuring devices and the necessary data-logging computer equipment.

The insolation equipment consists of standard pyranometers for measuring the total and diffuse broadband insolation on inclined surfaces and standard pyrheliometers for measuring the direct beam insolation. Special insolation instrumentation will be developed for the following:

- Direct beam, broadband insolation into various fields of view;
- Continuous long-term (weeks/month) tracking of the solar beam;
- High-resolution, spectral measurements of the direct, diffuse, and total insolation;
- Spectral photometer measurements of atmospheric attenuation; and
- Measurements of total insolation on inclined surfaces (10° increment) at various azimuths.

For the most part, these instruments will be obtained by competitive bid, once detailed specifications and requirements are established.

The data-logging and processing equipment consists of a dedicated minicomputer system. This sytems in an LSI II minicomputer capable of recording approximately 50 channels of data, on a minute basis, at an extremely high rate of sampling.

3.6 SUPPORT CONTRACTS

- Implementation of Monte Carlo computer codes on the SERI computer facilities.
- Preliminary measurements of broadband direct beam insolation into various apertures.
- Detailed, site-specific, weather forecasts.
- Definitions of air-mass type, precipitable water vapor, and cloud cover.
- Detailed design of multiple-tilt, multiple-azimuth, sensor array system.
- Installation of South Table Mountain meteorological station.

SECTION 4.0

FABRICATION AND MATERIALS PROCESSING R&D

One approach to reducing costs in solar energy applications is to develop improved low-cost processes for manufacturing the materials that make up the hardware. Another approach is to develop improved materials, where the added cost of the improvement will be offset by better system performance and lower overall system cost. For example, by developing thinner glass for mirrors, the percent reflectance may be increased at a relatively small additional cost. This would allow a system designer to use less hardware to get the same reflected solar energy, resulting in a net reduction in system cost.

The activities in this task are focused on developing materials with lower cost and/or improved performance; they include:

- Thin Glass Mirror Development;
- Cellular Glass Development; and
- Sorption by Desiccants.

These activities are being coordinated with activities in the Materials Research and Development task, especially with regard to the development of materials testing and characterization techniques.

4.1 OVERVIEW

4.1.1 Thin Glass Mirror Development

Thin glass mirrors (≤1.5 mm) are attractive in a number of solar applications including heliostats, parabolic troughs, and parabolic dishes. The attractive features include low absorption losses, the ability to cold form a concentrating reflector, low glass cost (if handling difficulties can be overcome), and light weight.

Issues affecting the development and use of thin glass mirrors (as well as other types of mirrors) in solar energy applications were identified and discussed in Solar Glass Mirror Program: A Planning Report on Near-Term Mirror Development Activities (SERI/RR-31-145; January 1979). This report was prepared by the Solar Glass Coordinating Committee, a group initiated by SERI that has members from Sandia Laboratories, JPL, and SERI. The purpose of the committee is to guide and coordinate the activities of the government laboratories in developing glass technology to satisfy solar energy requirements. The initial report was limited to mirrors and includes discussion of current and suggested activities in nine areas:

- Thin glass processing and handling;
- Thermal forming (sagging or pressing);
- Dust and corrosion on glass surfaces;
- Glass cutting for high-strength edges;
- Physics of crack growth and impact fracture;

- Degradation of glass/silver mirror structures;
- Development of a stress measurement device;
- Nonconventional methods of fabricating mirrors; and
- Environmental interaction with the interior of glass (solarization).

4.1.2 Silver Degradation in Mirrors

One of the more pressing problems that mirrors have in solar applications is the degradation of the silver that has been observed in outdoor heliostat mirrors. It occurrs in various parts of the country and in mirrors made by various companies. The problem appears to be general; it represents a serious threat to the useful life of mirrors in the outdoor environment.

An in-house effort is underway to address this problem by developing accelerated tests to evaluate the degradation resistance of mirror structures. A Sebastion I Coating Adherence Tester (see Fig. 4-1) has been procured for measuring tensile adhesion of silver/glass mirror stacks. Adhesion testing is expected to speed the detection of mirror stack degradation, since is it expected that incipient degradation will be accompanied by a loss of interfacial strength.

A representation of the mirror structure and the adhesion testing procedure is given in Fig. 4-2. The mirror structures typically consist of glass that is coated with chemically deposited silver. A layer of chemically deposited copper is then applied, followed by a coating of paint to protect the metal from corrosion and scratching. In adhesion testing, a 2.8-mm diameter test stud is bonded to the paint with cyanoacrylate adhesive (Eastman 910). The adhesive is cured for 30 minutes at room temperature. The adherence tester in Fig. 4-1 is then used to grip the stud and apply tensile stresses up to 10,000 psi in the mirror structure.

Initial adhesion tests have shown that there are nonadherent areas at the copper/paint interface on two mirror structures that are being used in solar applications. It is suspected that this results from inadequate wetting of the copper surface by the paints. These nonadherent areas may be the entry points for an attack on the mirror metalization.

4.1.3 Hail Resistance of Thin Glass

Custom Engineering under a SERI contract evaluated Corning's Code 0211 thin glass for resistance to impact by simulated hailstones (iceballs). Three glass thicknesses were evaluated: 0.1 mm, 0.35 mm, and 0.6 mm. It was found that all thicknesses survived impact by 25-mm iceballs at velocities up to 80 m/s when backed with a steel block (a hailstone's terminal velocity is about 24 m/s). However, a thin layer of fluid under the glass is required to prevent fracture if there is waviness in the glass (which would lead to air gaps).

When a thick layer of fluid (approximately 0.1 mm) was introduced between 0.1-mm or 0.35-mm glass and the steel, fractures occurred at iceball velocities of about 10 m/s. Most of the failures had radial cracking at the point of impact as well as breaking of pieces of glass between the radial cracks near the impact.

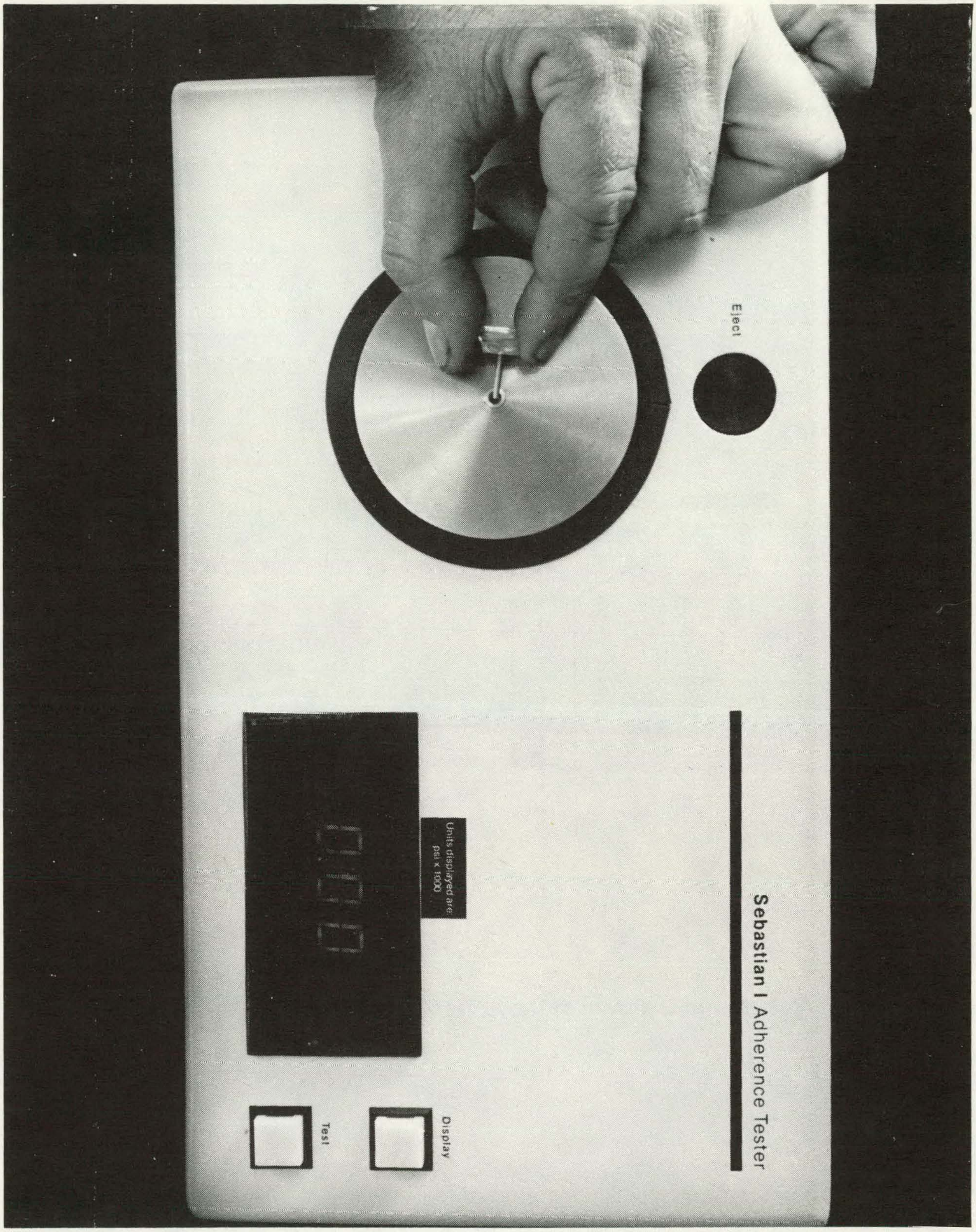


Figure 4-1. Sebastian I Coating Adherence Tester

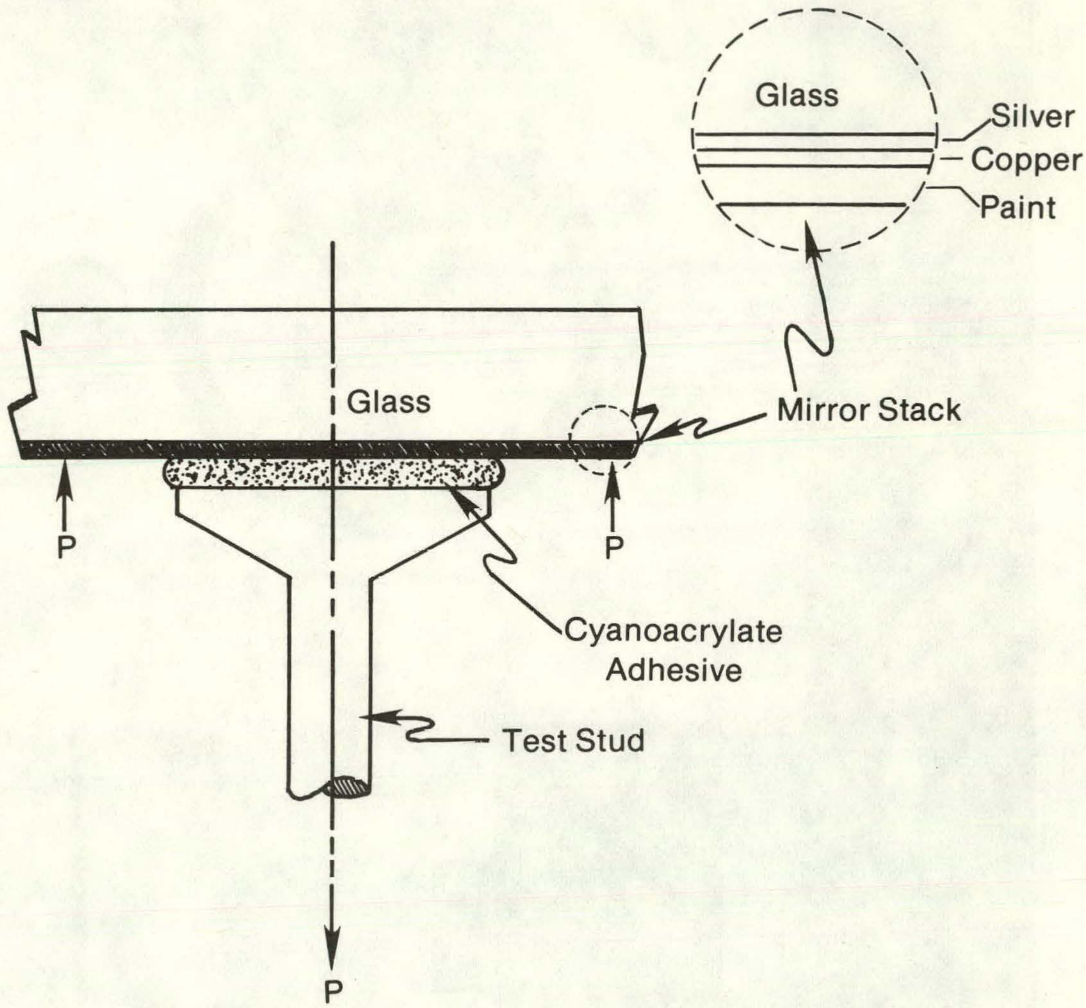


Figure 4-2. Schematic Diagram of the Adhesion Test and the Mirror Stack.

The final report (Hail Impact Tests on Microglass) on this phase of the work has been prepared by Custom Engineering. This work indicates that thin glass can withstand hailstones if it is backed by a rigid substrate.

4.1.4 Thin Glass Manufacturing

A preliminary statement of work (SOW) and a sole source justification have been prepared for the evaluation of Corning Glass Works' (CGW) patented fusion glass process as a source of high-quality thin glass. The evaluation will be done at CGW's Harrodsburg, Kentucky opthalmic glass plant. The preliminary SOW is being reviewed by the Solar Glass Coordinating Committee and by CGW prior to writing the final SOW.

4.1.5 Cellular Glass Development

Cellular glass is a low-density material formed by the evolution of gas while the glass is molten. It is normally used for thermal insulation. It is an attractive candidate as a mirror support structure in solar applications because of its low cost, its high stiffness-to-weight ratio, its thermal expansion coefficient match with sheet glass, and its chemical-dimensional stability. A statement of work has been agreed upon with JPL for development of cellular glass materials tailored to solar applications. This is an extension of JPL's current commitment to the use of cellular glass in parabolic dishes and will include assessment of this material as a mirror support structure in other applications such as heliostats and parabolic troughs.

4.1.6 Sorption by Desiccants

Desiccants with desirable rates of sorption and desorption of water vapor are being sought for potential use in the solar cooling of buildings. Silica gels and zeolites have been selected for the initial studies using gas chromatographic and microgravimetric facilities at the Colorado School of Mines (CSM). The components required to modify the existing equipment for water vapor sorption studies have been ordered and experience has been gained using the microbalance. Preliminary measurements were begun at the end of the reporting period. This collaborative effort was initiated at CSM in August.

4.2 GOAL

The goal of this task is to develop improved fabrication techniques and processes for materials that will reduce costs or improve performance and lifetime in solar systems.

4.3 SCOPE

The activities in this task include efforts to develop thin glass mirrors that promise high reflectivity and easy formation of concentrating reflectors, development of cellular glass for use as a mirror support material, and water vapor sorption research on desiccants to identify important desiccant characteristics for solar cooling applications.

4.4 APPROACH

Thin Glass Mirror Development—The Solar Glass Coordinating Committee was formed to identify important issues in solar applications for mirrors. Work at SERI to address some of these issues includes in-house work on the degradation of silver in outdoor environments and subcontracts on thin glass manufacturing and on the hail impact resistance of thin glass.

Cellular Glass Development—A subcontract with the Jet Propulsion Laboratory on cellular glass development is being negotiated to include an assessment of the use of cellular glass in a number of solar applications.

Desiccant Cooling—A collaborative effort is underway at the Colorado School of Mines to modify and use existing equipment for water vapor sorption studies on silica gels and zeolite desiccants.

4.5 APPARATUS AND EQUIPMENT

Description	Use
Sebastion I Adherence Tester	Adhesion of mirror structure
Blue M oven and timer	Elevated temperature cyclical aging
Linde gas handling equipment	Exposure of mirrors to corrosive gasses
Paasche spray guns	Mirror silvering
Bird applicator	Applying coatings
Desiccators and glassware	For environmental aging of mirrors
Jar mill and jars	Ceramic laboratory grinding
Stainless steel screens	Classification of powders
Chemical supplies	Mirror testing
Calibration stand	Calibrate adhesion tester

4.6 SUPPORTING SUBCONTRACTS

- Hail Impact Tests on Microglass; Custom Engineering, D. Crabtree ($6K).
- Cellular Glass Development; JPL, W. F. Carroll (in negotiation) (approximately $100K).
- Thin Glass Development; Corning Glass Works, A. F. Shoemaker (in negotiation) (approximately $250K).
- Sorption by Desiccants; Colorado School of Mines, Professor G. Martins ($24,147).

SECTION 5.0

EXPLORATORY RESEARCH

5.1 OVERVIEW

The six-month period covered by this report has seen the identification and initiation of several areas of research; these are closely linked with recognized opportunities for useful application of solar energy. Equipment has been assembled; interim laboratory facilities have been arranged; and collaborative research activities through subcontractors have been initiated.

Research areas that were identified and initiated encompass materials for thermoelectric conversion, materials and processes for desiccant cooling, photothermal degradation of materials, studies of optical materials and coatings, and methods of analysis of optical systems.

During this formative period, the research activities described have not produced finished results, but several preliminary results promise to lessen barriers to expanded solar energy application.

Thermoelectric conversion has been found to be an attractive alternative to other means of direct solar-electric conversion. The materials required are of low potential cost because they need not be of high purity nor of high crystalline perfection. Organic and amorphous materials have been identified as possible candidates for low-cost solar conversion devices.

The thermoelectric process is very attractive for application to OTEC and to stratified solar ponds.

Desiccant cooling, while promising effective, low-cost solar cooling, needs improvements in system design and in desiccant materials. Research tasks are being initiated in these areas. They must be completed prior to further prognostication.

Photothermal degradation of glazing and coating materials is identified as a major factor in restricting the use of many low-cost polymers in solar energy conversion. Exposure facilities that can reproduce combined thermal and radiation effects on materials have been designed, and experiments in polymer degradation are planned.

5.2 THERMOELECTRIC ENERGY CONVERSION

The Exploratory Research subtask includes an assessment of solar thermoelectric energy conversion. Table 5-1 outlines the aspects of the subject being addressed. An interdisciplinary team from the Systems Analysis Branch, the Materials Research Branch, and the Subcontracts Branch is preparing the assessment and has scheduled completion for early FY80. (Part of the assessment has been previously reported in SERI/TR-35-078, Conversion System Overview Assessment, January 1979.)

Table 5-1. OUTLINE OF THE SERI ASSESSMENT OF THERMOELECTRIC ENERGY CONVERSION

I. State-of-the-Art in Thermoelectric Energy Conversion

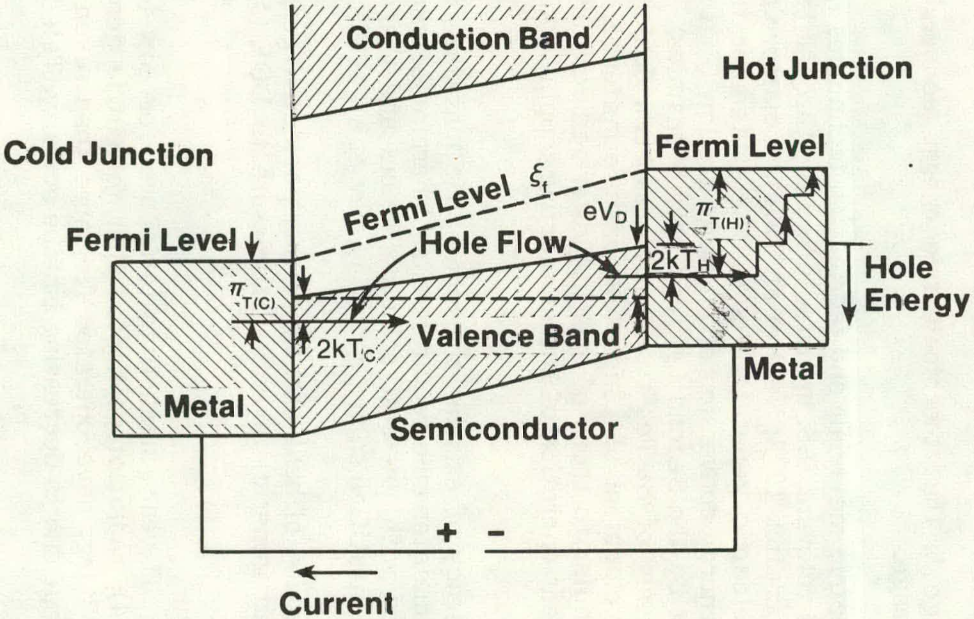
   A. Materials performance
   B. Fabrication techniques
   C. Device efficiencies
   D. Costs

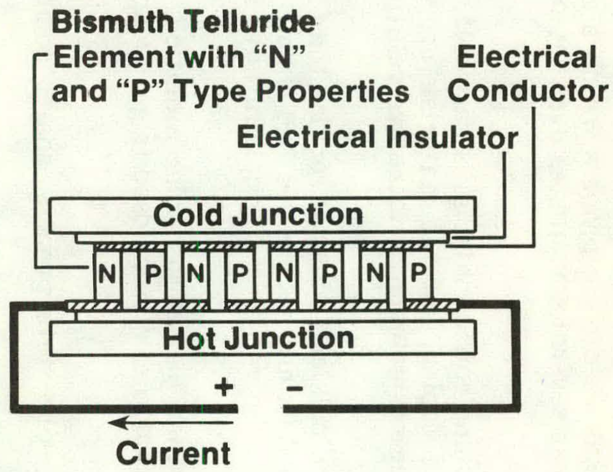
II. Status of R&D

   A. New materials
      1. Bi_2Te_3 (formed by powder metallurgy)
      2. Amorphous semiconductors
      3. Organic semiconductors
   B. New fabrication techniques

III. Potential Applications - Systems Analysis

   A. Solar
      1. OTEC
      2. Salt pond
      3. Other
   B. Nonsolar
      1. Geothermal
      2. Waste heat utilization
         a. Industry
         b. Utility
      3. Other
   C. Impact on energy market





— Typical Module Assembly. Elements Electrically in Series and Thermally in Parallel.

Figure 5-1. Energy Diagram for a Circuit Containing p-Type Semiconductor and Two Metal Contacts. The Energy of the Carriers in the Metal is the Fermi Energy, Whereas in the Semiconductor They are at the Fermi Energy Plus 2kT.

Thermoelectric energy conversion involves a bulk electronic process within a semicondustor (Fig. 5-1). The thermoelectric process has several advantages over the photovoltaic process:

- High electrical conductivity in the thermoelectric material is desirable. Consequently, the process uses high levels of doping, and the materials are not very sensitive to impurities. The semiconductor material is therefore relatively low in cost (see Table 5-2).
- The thermoelectric process occurs in the bulk and does not require the formation of a junction. Consequently, single crystals are not needed and simple fabrication techniques, similar to those used in the ceramics (porcelain ware) industry, can be used.
- The process utilizes thermal energy rather than direct solar radiation. Consequently, the thermoelectric materials can be easily enclosed (e.g., encapsulated) and protected from the environmnent.

Thermoelectric energy conversion, as another solid-state process, shares some of the best advantages of photovoltaics, viz:

- the converter has no moving parts and requires little maintenance; and
- the converters have a long life expectancy.*

An important additional advantage is that thermoelectric energy conversion can use cheap, simple, thermal energy storage.

The state-of-the-art in thermoelectric materials and fabrication techniques was addressed through direct contact with all relevant U.S. manufacturers and through two small industrial subcontracts (Syncal Corporation 1978; Neill et at. 1978). Commercial materials are available for use in thermoelectric generators operating at temperatures to and above 1000 K (Fig. 5-2). Typical energy conversion efficiencies are low (Fig. 5-3) but are not fundamentally limited (except by the Second Law of Thermodynamics). A two-fold increase in the conversion efficiency of Bi_2Te_3-type alloys has been demonstrated recently in the laboratory. The development of a high-temperature material, such as SiC with thermoelectric properties similar to those of existing lower-temperature materials ($Z \sim 10^{-3}\ K^{-1}$), would permit efficient operation of thermoelectric topping cycles for both solar and fossil power plants.

The poor energy conversion efficiency of existing thermoelectric materials is offset by their low-cost, long-life, and low maintenance requirements. Thermoelectric conversion is quite competitive when coupled with low-cost solar collectors and thermal storage such as ocean thermal sources and stratified solar ponds (Jayadev et al. 1979).

SERI has designed a novel combination of heat exchanger/thermoelectric generator (Fig. 5-4) and submitted a detailed (but generic) invention disclosure to DOE (Jayadev and

*The U.S. Navy has reported a 35-year mean-time-to-failure for low-temperature thermoelectric devices (Goff 1974); radioisotope-heated thermoelectric generators for spacecraft, such as Pioneer and Viking, have operated for more than seven years with only slight decreases in power output due to decreasing isotope activity (Teledyne Energy Systems 1978).

Table 5-2. SUMMARY OF COSTS FOR THERMOELECTRIC MATERIALS

	ELEMENTS			
Pounds	Si $/lb	Ge $/lb	Bi $/lb	Te $/lb
Less than 1,000	7.20	22.80	7.45	9.45
3,000	6.00	19.00	6.30	7.80
30,000	4.32	13.70	5.67	6.71
100,000	3.89	12.33	4.54	5.37
300,000	3.50	11.10	3.41	3.87
500,000	2.70	8.60	2.73	3.10
1,000,000	1.54	4.90	1.80	2.04
2,000,000			1.13	1.29

ALLOYS

TAGS $(AgSbTe)_{0.15}(GeTe)_{0.85}$			PbTe		
Te	200,000 lb	$ 3.87/lb	Pb	200,000 lb	$ 3.87/lb
Ge & Dopant	40,000 lb	11.10/lb	Te	20,000 lb	2.80/lb
Subtotal	240,000 lb	$ 5.08/lb	Subtotal	220,000 lb	$ 3.77/lb
Labor 8%		.42	Labor 8%		.30
Price	240,000 lb	$ 5.50/lb	Price	220,000 lb	$ 4.07/lb
BiTe			SiGe (50/50 Alloy)		
Bi	400,000 lb	$ 2.73/lb	Si	400,000 lb	$ 3.10/lb
Te	250,000 lb	3.87/lb	Ge	400,000 lb	8.60/lb
Subtotal	650,000 lb	$ 3.17/lb	Subtotal	800,000 lb	$ 5.85/lb
Bi	1,000,000 lb	$ 1.80/lb	Si	1,000,000 lb	$ 1.54/lb
Te	670,000 lb	2.04/lb	Ge	1,000,000 lb	4.90/lb
Subtotal	1,670,000 lb	$ 1.90/lb	Subtotal	2,000,000 lb	$ 3.22/lb
BiTe			SiGe (65/35 Alloy)		
Bi	2,000,000	$ 1.13/lb	Si	520,000 lb	$ 2.70/lb
Te	1,340,000	1.29/lb	Ge	280,000 lb	11.10/lb
			Subtotal	800,000 lb	$ 5.64/lb
			Si	1,300,000 lb	$ 1.54/lb
			Ge	700,000 lb	6.75/lb
			Subtotal	2,000,000 lb	$ 3.36/lb

Costs are based on analyses in Neill et al. (1978). Note that conventional thermoelectric generators (such as Teledyne Telan, which is based on Pbte) require about 2.5 pounds of thermoelectric materials for a 100-W electric output. The retail cost of the device is presently $8/W in very small quantity production.

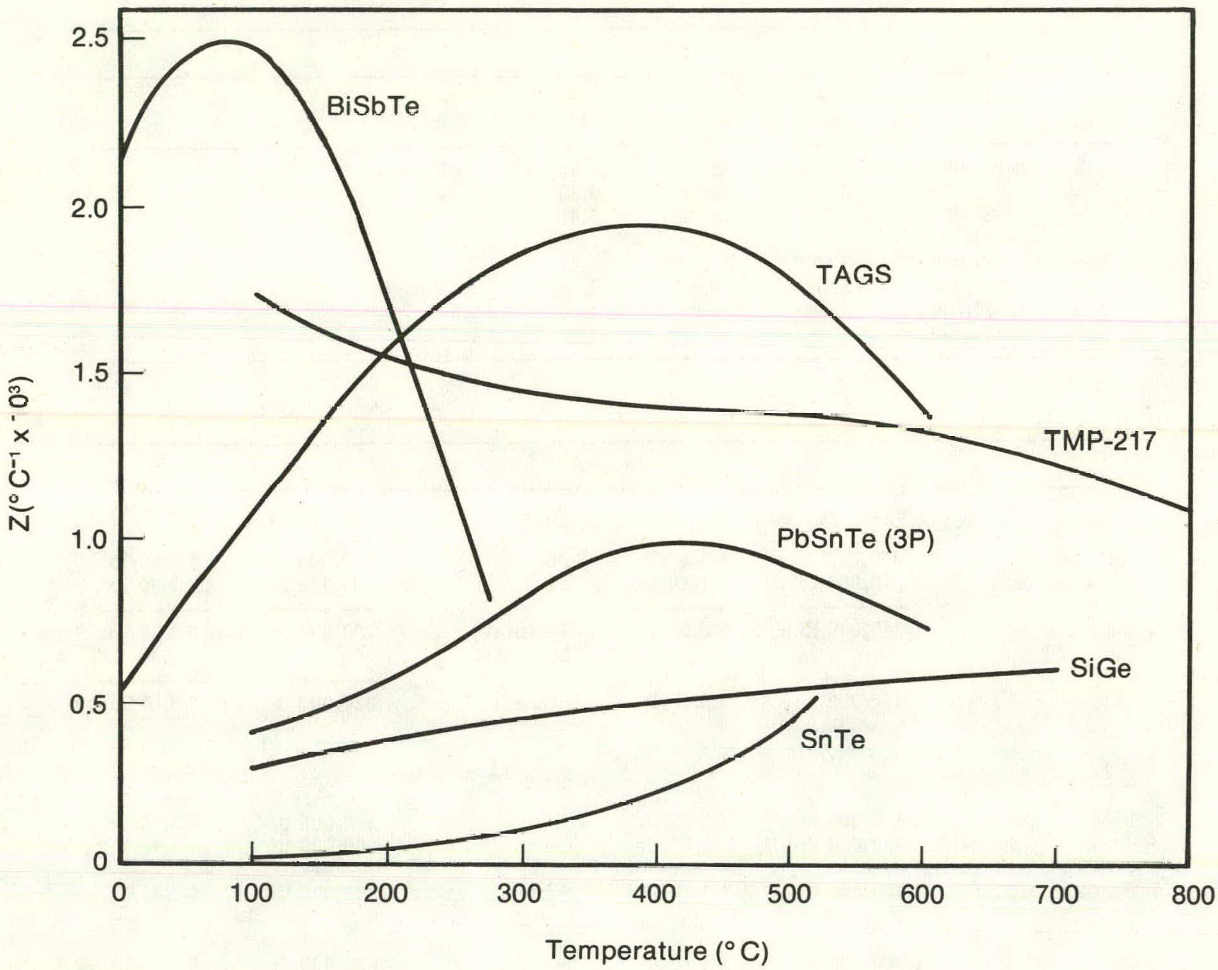


Figure 5-2. Figure of Merit of p-Type Thermoelectric Alloys. The Figure of Merit Depends on the Seebeck Coefficient $\alpha(VK^{-1})$, Electrical Conductivity σ $(\Omega^{-1}cm^{-1})$, and Thermal Conductivity k (watt $cm^{-1}k^{-1}$) as $Z = \frac{\alpha^2\sigma}{k}$ (K^{-1})

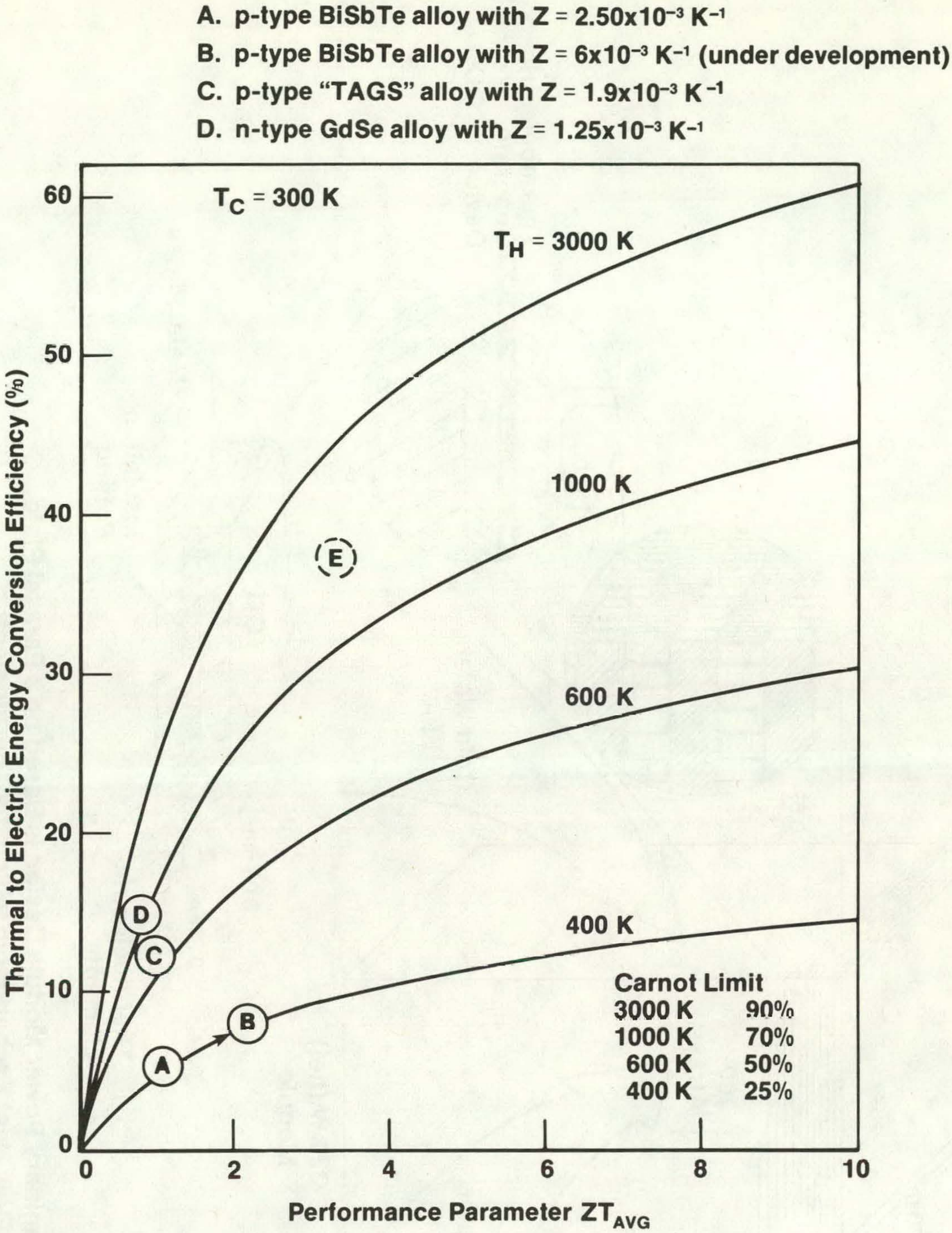


Figure 5-3. Maximum Energy Conversion Efficiency of a Thermoelectric Device as a Function of the Performance Parameter, ZT_{AVG} A is Typical of Present BiSeTb Alloys, B Has Been Demonstrated in the Laboratory, C is Typical of Available "TAGS" Alloy, and D is Typical of GeSe Materials. The Point E Indicates the Performance Possible with an Alloy Capable of Operation at 2000 K with $Z=1\times10^{-3}$ K^{-1} (Goff and Lowney 1979)

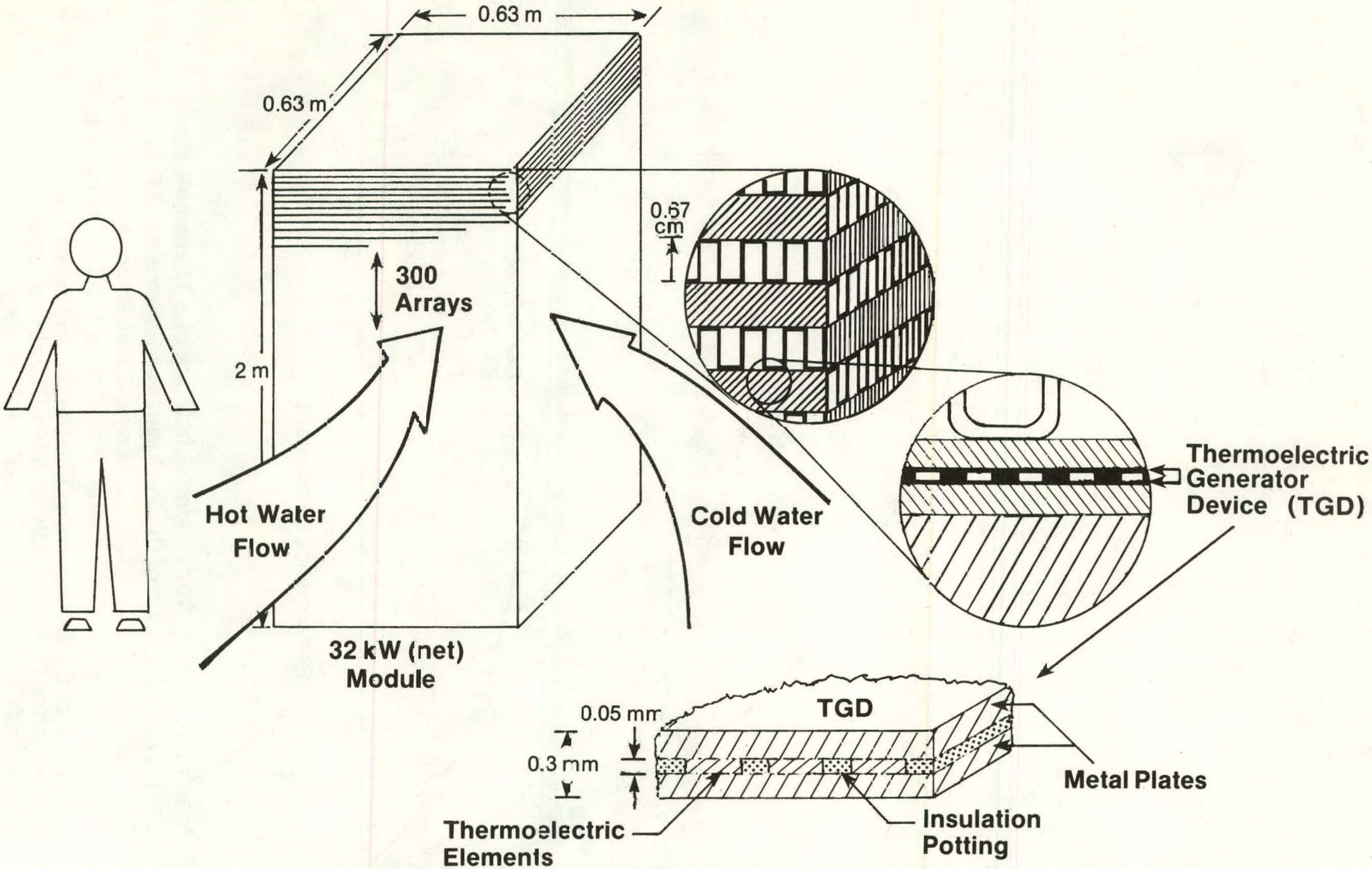


Figure 5-4. A Preliminary Power Module Design is Based on a Parallel Plate, Cross-Flow Heat Exchanger in which the Thermoelectric Generator Devices (TGD) are Sandwiched Between the Plates. The TGD and the Heat Exchanger are Well Suited to Automated Mass Production.

Benson 1978). More detailed designs for specific applications will be made to utilize the characteristics of advanced thermoelectric materials now being tested.

The thermoelectric concept appears to be advantageous in OTEC applications; its use eliminates the need for a working fluid, turbo-generator, and vessel for pressure containment. A preliminary analysis of the thermoelectric OTEC suggests that it could cost less than the closed-cycle, base-case design of TRW. An analysis of market penetration tested the sensitivity to cost reductions. A very substantial increase in OTEC utilization can be expected from a small decrease in OTEC capital costs (Fig. 5-5).

The only fundamental limitation to thermoelectric energy conversion efficiency is the Second Law of Thermodynamics. Recent developments that offer encouragement that substantial improvement can be made are:

- Industrial research recently has succeeded in developing a Bi_2Te_3-based alloy with a 50% greater conversion efficiency than previously available materials (private communication from W. Kincade, Teledyne Energy Systems, Feb. 1979).
- New materials, such as organic and amorphous semiconductors, that have not yet been considered seriously for their potential as thermoelectric devices have properties (high Seebeck coefficients, suitable electrical conductivity: Heeger and MacDiarmid 1979; de Neufville 1974) that indicate great potential in such application.
- Improved theoretical understanding now permits detailed computer modeling of the probable performance of thermoelectric materials. This modeling allows assessment of the importance of impurity bands and shows how to optimize the material for various lattice thermal conductivity and temperature dependencies that may be achieved by alloying (Goff and Lowney 1978).

The exploratory research on thermoelectrics will continue as outlined in Table 5-1. Ongoing and pending subcontract work includes the following:

- Teledyne Corporation is studying fabrication, characterization, and performance of advanced Bi_2Te_3-type thermoelectric materials. (Samples will be delivered to SERI for experimental verification of high-energy conversion efficiency.)
- General Atomic Company is preparing hydrided amorphous silicon alloys containing germanium, carbon, and nickel for thermoelectric measurements by SERI.
- The U.S. Naval Surface Weapons Center has used computer modeling to predict the performance of SiC and its modifications in thermoelectric energy conversion devices.
- Colorado School of Mines is providing laboratory facilities (pending completion of SERI facilities) and consulting services in the measurement of Seebeck coefficients and of electrical and thermal conductivities of samples provided by SERI.

5.3 DESICCANT COOLING

The major effort of the study of desiccant cooling has centered on completing the development and the analysis of computer simulations of solar space heating, solar desiccant coolers, and electrically driven vapor-compression air-conditioning systems for residential heating and cooling. The study provides an evaluation of the potential of residential

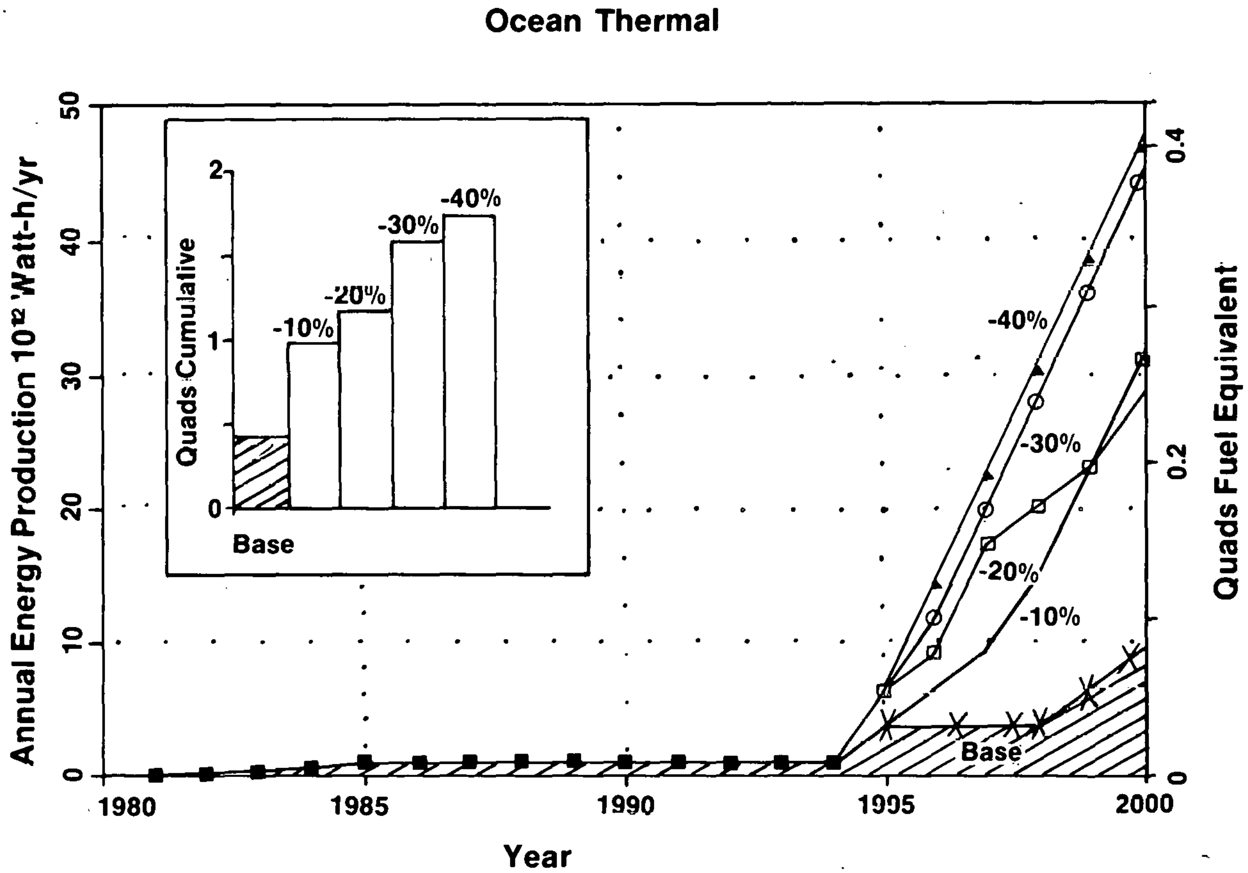


Figure 5-5. The Market Penetration of Ocean Thermal Electric Systems Based on the Results of a Simulation Model

solar desiccant cooling and seeks to identify the optimum configurations of the system, the climatic conditions, and the economic parameters. The solar cooling system chosen for study has a disc-shaped desiccant bed configuration and is used in the recirculation mode (Fig. 5-6).

SERI has conducted simulations of the heating and cooling demand in five U.S. cities wide-ranging in climate and insolation. Using this information, the optimum air conditioning system was chosen to maximuze the conservation of fossil fuels and minimize operating costs. Consumers increasingly are using residential air conditioning that employs electrically driven vapor-compression coolers. As a result, scientists studied five locations to determine if it would be beneficial (in both economics and displacement of fossil fuel) to replace vapor-compression coolers powered by fossil fuel (via electrical energy) and natural gas-fired space heaters with solar-powered heating and desiccant cooling systems. The overall conclusion was that solar heating and desiccant cooling systems operate best in climates with nearly balanced seasonal heating and cooling loads. The results are documented in a final SERI report (Shelpuk et al. 1979).

During the remainder of FY79, the activity under this task will involve the following: continuation of the analysis of desiccant cooling systems, with emphasis on the comparison of various dehumidifier beds currently under development by other DOE contractors; analysis of open-cycle cooling concepts that employ liquid desiccants; design, fabrication, and use of a laboratory facility for a program to test dehumidifier beds; and provision of program management services in support of DOE for the desiccant cooling program.

5.4 PHOTOTHERMAL DEGRADATION

A laboratory has been designed to assess the thermal and photothermal stability of solar materials; essential equipment has been acquired or is being designed for use in this laboratory.

SERI has acquired four multizone Lindbergh furnaces that can be controlled independently from 250°C to 1300°C. The sample chambers have been designed for a range of environmental conditions from high-vacuum (about 10^{-6} Torr) to mixtures of atmospheric pollutants in air (NO_x, SO_x, HCl, H_2O, O_3, etc.).

SERI also has designed a thermal-cycling facility to study the effects of cyclic fatigue on the mechanical properties of solar materials. A preliminary design consists of two banks of quartz iodine lamps on top of a vacuum chamber, a baffle that shields one-half of the samples from the opposite bank of lights, and two water-cooling loops that are activated in opposition to the light banks. Cycling times of a few minutes from room temperature to 700°C are anticipated. A commercial cycling vacuum furnace is being explored as an alternative.

Test fixtures for concentrating collectors in the SERI Subsystem Technology and Development facility are being designed to access photothermal conditions with solar fluxes in excess of 3MW/m^2 and temperatures to 800°C.

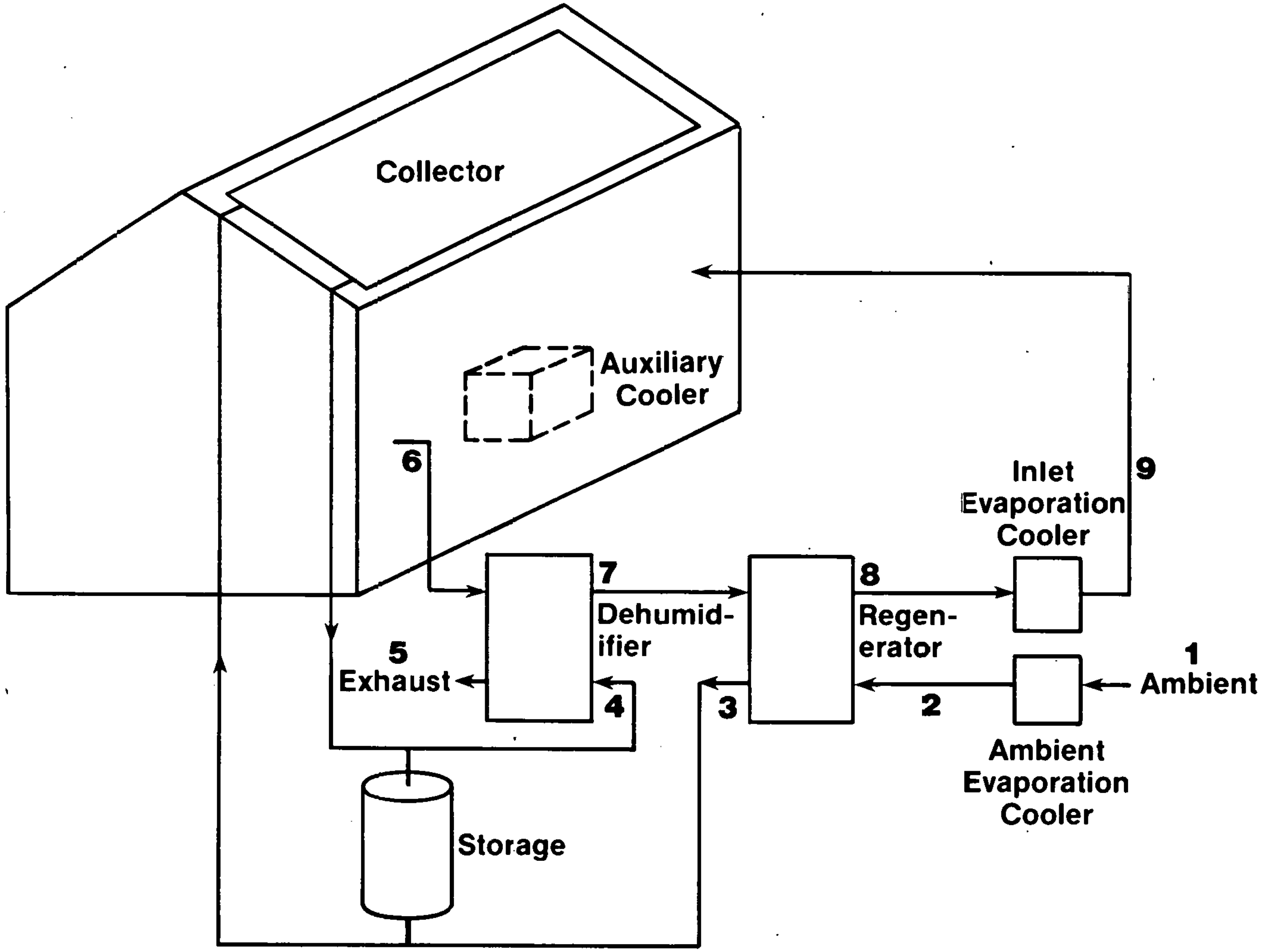


Figure 5-6. Solar Desiccant Cooler—Recirculation Mode

5.5 AMORPHOUS MATERIALS

Two essential elements of a laboratory for thin-film deposition are in the procurement process. Each is capable of producing amorphous materials from the vapor phase. An RF/DC magnetron sputtering system with RF bias and etch capabilities has been ordered and a design for a glow discharge deposition system has been produced.

5.6 REFERENCES

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16. Abstract (Limit: 200 words)

The status of research projects in the Basic and Applied Research Program at SERI is presented for the semiannual period ending December 31, 1978. The five tasks in this program are grouped into Materials Research and Development, Materials Processing and Development, Photoconversion Research, Exploratory Research, and Energy Resource and Assessment and have been carried out by personnel in the Materials, Bio/Chemical Conversion, and Energy Resource and Assessment Branches. Subtask elements in the task areas include coatings and films, polymers, metallurgy and corrosion, optical materials, surfaces and interfaces in materials research and development; photochemistry, photoelectrochemistry, and photobiology in photoconversion; thin glass mirror development, silver degradation of mirrors, hail resistance of thin glass, thin glass manufacturing, cellular glass development, and sorption by desiccants in materials processing and development; and thermoelectric energy conversion, desiccant cooling, photothermal degradation, and amorphous materials in exploratory research. For each task or subtask element, the overview, scope, goals, approach, apparatus and equipment, and supporting subcontracts are presented, as applicable, in addition to the status of the projects in each task or subtask. Listing of publications and reports authored by personnel associated with the Basic and Applied Research Program and prepared or published during 1978 are are also included.

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