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ARGONNE NATIONAL LABORATORY
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SOLAR ENERGY PROGRAM ANNUAL REPORT
Summary of Solar Program Activities
Fiscal Year 1978

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February 1979

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ANL SOLAR ENERGY PROGRAM ANNUAL REPORT
Summary of Solar Program Activities for FY 1978

ABSTRACT

This annual report describes the work done at Argonne National Laboratory on the Solar Energy Program during FY 1978 (July 1, 1977 to June 30, 1978). Areas included in this report are solar energy collection, heating and cooling, thermal energy storage, ocean thermal energy conversion, photovoltaics, satellite power systems, bioconversion, central receiver solar thermal power, and wind energy conversion.

INTRODUCTION

The National Energy Plan recognizes the need for strong Federal government support of research, development and demonstration of renewable energy resources, such as solar energy, as part of the overall national strategy for reducing our dependence on foreign oil imports. It is also recognized that some solar technologies are essentially state-of-the-art and are immediately commercializable, i.e., solar hot water heating and some forms of solar space heating, and that some solar technologies have potential for near term introduction, i.e., solar process heat and solar cooling. Still other solar energy sources such as solar thermal electric, photovoltaics, bioconversion, wind, ocean thermal energy conversion, and satellite power systems have potential for longer term impacts.

The National Solar Energy Development program includes solar hot water heating, solar residential and commercial building heating and cooling, solar industrial process heat, solar thermal electric conversion, photovoltaic conversion, wind energy conversion, ocean thermal energy conversion, fuels from biomass (bioconversion) and investigation of the satellite power systems concept. Activities in these programs range from active commercialization such as is being carried out for solar hot water heating through grants and tax incentives; to federally supported demonstration of commercializable or near commercializable technologies such as space heating and space cooling with solar energy and wind energy conversion; to a broad range of research, development and technology assessment activities on bioconversion, photovoltaics, solar thermal electric and ocean thermal electric conversion, and the satellite power system concept.

The current ANL solar energy program involves some aspects of all of the above solar energy research and development activities. Through a matrix management system, resources, facilities and personnel from eight ANL divisions are being utilized in the program. Expertise established in the past in other energy technologies is readily brought to bear on the solution of solar energy utilization problems. The matrix organization of ANL resources is shown in Fig. 1.

ARGONNE NATIONAL LABORATORY

MATRIX ORGANIZATION CHART

ANL ASSOCIATE LAB DIR		REACTOR DEVELOPMENT J A KYGER						BIOMEDICAL & ENVIRONMENTAL W K SINCLAIR						PHYSICAL RESEARCH BASIC ENERGY SCIENCES B ANCKER JOHNSON						PHYSICAL RESEARCH HIGH ENERGY PHYSICS G A SMITH						ENERGY & ENVIRONMENT E G PEWITT						
ANL PROGRAMS & PROJECTS		Breeder Reactor R&D	Fuel Cycle R&D	GCFR	NRC			Biomedical & Environmental Research Program	Life Sciences	NRC				Basic Energy Sciences	Nuclear Physics	IPNS Program				High Energy Physics	Internal Confinement Fusion				Alternate Energy Technology	Conservation & Selling Application	Applied Energy Conversion	Fusion Power	Chemical & Electrical Systems			
ANL DIVISIONS																																
ADMINISTRATIVE RESPONSIBILITIES	KYGER	ANL W*	A																													
		AP	A		D	C		E																		C			D			
		CT	A		E	D		E		E																(C)	(E)	D	E	E		
		EBR II	A																								(E)	E				
		ENG	D	C						E										E						D	(C)	B	E	E		
		MSD**	B	D	C	C																				(C)	(C)	D	E	E		
		RAS	A		C	C																				E			E			
		STF	B																													
	SINCLAIR	BIM						A	C	E																						
		RER						A		D				E															E			
		EIS						C		B																(E)	E	E				
	ANCKER JOHNSON	AMD				E								C													E	E				
		CHM			D			D	E					A	C	E										E		E	D	D		
		PHY												B	B														D			
		MSD**												A		E													D			
		SSS												B		E																
	SMITH	ARF														C				A	C					(D)	(E)	C	D			
		HEP																		B	E											
	PEWITT	CEN	C	B	D	E		D		E				C												B	(D)	D	D	A		
		EES			E			B		D																(C)	(B)			C		

○ - INCLUDES ACTIVE SOLAR PROGRAMS.

*Includes HFEF AL TREAT **Division has Dual Administrative Reporting Points
A = Over \$5 million D = \$150,000-\$500,000
B = \$2-\$5 million E = Less than \$150,000
C = \$500,000-\$2 million

ANL became involved in solar energy research and development in FY 1974 in a joint effort with the University of Chicago to develop a new solar concentrator concept called the Compound Parabolic Concentrator (CPC). Since that time, the level of effort applied to solar energy R&D at ANL has risen from the initial six manyears in FY 1974 to 40 manyears in FY 1978 (and an expected 80 manyear level in FY 1979).

Programmatic involvement has been expanded during this period from the initial concentrator development work to include efforts in thermal energy storage, ocean thermal energy conversion, solar heating and cooling, solar power satellite, bioconversion, solar thermal power, and photovoltaics. The principle thrusts of these programs are:

- Solar concentrator development for heating and cooling, industrial process heat, solar electric and photovoltaic applications.
- Solar heating and cooling development including thermal energy storage, demonstration program support, and reliability analyses.
- Ocean thermal energy conversion technology development.
- Materials development for photovoltaic, heating and cooling, solar thermal power, and OTEC programs.
- Environmental and technology assessment for bioconversion, OTEC and satellite power system programs.

The solar energy R&D activities at ANL during FY 1978 are described in the body of this report. Specific information regarding DOE sponsors, ANL principle investigators and contacts for further information are contained at the end of each paper.

SOLAR ENERGY COLLECTION

CPC COLLECTOR DEVELOPMENT

Kent A. Reed

Abstract

The applicability to solar energy of an important new class of nonimaging optical concentrators, known generically as compound parabolic concentrators, is under intensive investigation at Argonne National Laboratory. The large acceptance angles associated with moderate concentration nonimaging collectors eliminate the need for diurnal tracking, render the collectors relatively insensitive to errors in mirror specularity and contour, and allow the collectors to utilize a portion of the diffuse sky radiation. The development of these nonimaging collectors has progressed from proof-of-concept studies to the design and testing of engineering prototypes, and to successful commercialization. In the following this progression as well as related work is outlined.

I. Introduction

It has long been recognized that optical concentration can be employed in a solar thermal collector to reduce the necessary absorber area, leading to such important benefits as increased operating temperature, increased operating efficiency, and lower cost. Until very recently, this optical concentration was achieved using focusing optics: Fresnel lenses, parabolic mirrors, or the like, formed an image of the sun on the absorber. The beneficial properties of such focusing collectors are well understood, as are their disadvantages, which include a narrow angular field of view and the attendant need for precise optics and accurate sun tracking.

The applicability to solar energy of an important new class of nonimaging optical concentrators, known generically as compound parabolic concentrators (CPC)¹, is under intensive investigation at Argonne National Laboratory (ANL). These mirror concentrators, which funnel light without forming an image, have been called ideal because of their optical properties. They are characterized by rectangular angular acceptance functions which cut off sharply at the limiting acceptance angle, and they maximally concentrate all radiation incident within this acceptance angle. Conversely, they possess the maximum possible angular field-of-view for a given level of concentration. Due to the hindered apparent motion of the sun, moderate levels of concentration (up to 10) can be achieved in CPC-trough collectors without the need for diurnal tracking, and a concentration of 1.8 is possible in a strictly stationary collector. In addition to eliminating diurnal tracking, the characteristically large acceptance angles associated with these nonimaging concentrating collectors render them relatively insensitive to errors in mirror specularity and contour, and allow them to collect a portion of the diffuse sky radiation as well as direct solar radiation. The shape of the mirror concentrator is uniquely determined by the limiting acceptance angle and the shape of the absorber.²

The efficacy of this class of nonimaging concentrators as solar collectors was demonstrated in a series of proof-of-concept experiments.³ Early efforts coupled compound parabolic concentrators with optical concentration ratios between 3x and 10x, to nominally flat absorbers embedded in conventional insulations. Concurrent analytical and ray tracing studies provided the necessary design guidance.⁴ The experiments established that, although all the optical advantages--wide acceptance angle, insensitivity to mirror errors, and collection of diffuse sky radiation--were obtained, nevertheless, there were serious thermal problems to be solved. Better high temperature insulations behind the absorbers were needed, and it proved difficult to prevent parasitic thermal losses to the mirrors due to convection as well as conduction. It was also apparent that reduction in collector weight must be an early goal.

Recent work⁵ has been directed toward the development of higher performance, lightweight collectors incorporating nonimaging concentrators and evacuated receivers. In work for the DOE Solar Heating and Cooling Research and Development Branch, the use of cusp reflectors to concentrate radiation onto evacuated tubular absorbers was investigated. In effect, such a scheme has no "backloss," and it makes best use of commercially available all-glass evacuated receivers. This effort culminated in a laboratory-scale (0.7m^2) collector using General Electric TC-100 shrouds in 1.5x cusp concentrators. This design combines stationary operation with excellent performance--greater than 40% efficiency at 175°C . Industrial Research Magazine gave this design an IR-100 award as one of the 100 most significant new developments in 1977.

In related work for the Photothermal Electric Program, several engineering prototypes of 3x collectors were built. Roll-formed sheet aluminum reflectors and aluminized vacuum-formed plastic reflectors were used to concentrate radiation onto flat absorber plates, which were enclosed in evacuated glass tubes and which had selective surfaces. Such 3x collectors, designed to investigate process heat temperature requirements, need seasonal adjustments to their tilt.

II. Accomplishments in 1978

In-house Development

Based on the encouraging results of the laboratory-scale tests, an engineering prototype of a 1.5x cusp collector was designed and fabricated at ANL to demonstrate the feasibility of a lightweight ($18\text{kg}\cdot\text{m}^{-2}$) stationary collector employing current technology and achieving superior performance. Aluminum specular lighting sheet mirrors formed to the cusp shape and bonded to sheet aluminum cross ribs concentrate incident radiation onto tubular absorbers, which are evacuated glass shrouds. The all-glass shrouds and their all-copper serpentine manifold assemblies, supplied by General Electric Corporation, Valley Forge, PA, under a subcontract, are essentially GE TC-100 components. The ten trough collector module comprises two banks of five troughs each and a center manifold, all supported in sheet aluminum enclosures. The manifold volume is packed with conventional glass fiber insulation. The 2.6m^2 clear aperture area is covered with plexiglas for dirt protection. Heat loss tests are complete and show the overall heat loss coefficient is $0.7\text{--}0.8\text{ Wm}^{-2}\text{C}^{-1}$ at absorber temperatures in the range $80\text{--}150^\circ\text{C}$ above ambient. Operating efficiency tests have just begun and are expected to verify the performance measured in the laboratory-scale model.

A second, outwardly identical collector module is being fabricated to demonstrate the enhanced performance attainable with advanced technology. Incorporation of anti-reflection coatings, absorbers with better controlled emissivity, superior manifold insulation, and highly reflective metallized film in this 1.5x collector should boost its operating efficiency to greater than 50% at 175°C.

A high temperature fluid test loop completed last year has been made operational. Using the different fluid loops available it is now possible to test unpressurized collectors with water from ambient to 100°C, ethylene glycol from ambient to 150°C, and Therminol-66 from 50°C to 230°C.

This experimental work was supported by a continuing program of material and component assessment. Numerous candidate mirror and absorber materials were screened through measurements of their spectral hemispherical reflectances and absorptances, respectively. The effective emissivities of completed receiver assemblies were determined through electrical heating tests. Mirror assemblies were evaluated photographically and photometrically.

Concurrent with the hardware development effort, analytical and ray tracing studies of the nonimaging cusp concentrator design were undertaken to explore the effects of various parameters such as concentration, degree of truncation of the mirrors, absorber misalignment, and the like. Papers discussing the results of these extensive investigations are currently in preparation and will serve as design aids for the prospective collector builder.

Commercialization

The ANL solar energy group has a strong commitment to early commercialization of these new concentrating collector designs. Dissemination of general information to potential manufacturers has been expedited through articles in engineering magazines, exhibits in trade shows and energy fairs, talks to technical groups, and onsite visits. Subcontracts for component development and an industrial-participant program have established good bi-directional flows of technical information between ANL and particular manufacturers. In addition, ANL has stimulated and encouraged small businesses to enter the solar energy field, providing detailed concentrator and collector information and other technical support.

There is a growing list of licensees of the DOE patents on the reflector shapes. Two licensees, Sunmaster Corporation, Corning, NY, and Energy Design Corporation, Memphis, TN, are now marketing stationary CPC cusp collectors with evacuated tubular receivers. Although similar optically, the collectors reflect strikingly different philosophies concerning design and application. A third licensee, Chamberlain Manufacturing Company, Waterloo, IA, has a DOE contract awarded under PRDA-2 to develop a higher concentration collector with evacuated receivers, and another licensee is negotiating a DOE grant for a solar heating and cooling project incorporating cusp concentrators and non-evacuated receivers.

Interlaboratory Interaction

In addition to involvement with industry, the ANL solar energy group maintains close ties with other national laboratories. Three particularly fruitful interactions occurred this year. When the thermal power systems group at Jet Propulsion Laboratory (JPL) chose the CPC collector as the first candidate to analyze in the Small Power Systems Applications Project, ANL not only supplied detailed physical and performance data, it also presented a critique of the JPL procedure. Ultimately, JPL adopted as more rigorous the ANL methodology for characterizing collector performance and improved other portions of the original JPL procedure.

In support of the Solar Thermal Test Facility (STTF) at Sandia Laboratories (Albuquerque), the ANL solar energy group designed a second-stage concentrator for the planned McDonnell-Douglas receiver panel test. After analysis of the STTF heliostat field, a segmented CPC system with a concentration of 2.5x was designed to couple the reflected solar flux to the narrow receiver panel.

One of the four circumsolar telescopes built by Lawrence Berkeley Laboratory has been in operation at ANL for the past year. Data taken by this instrument will help establish the nature and level of circumsolar radiation in the Chicago area, important knowledge for systems designers contemplating concentrating collectors.

III. Planned Activities for 1979

The performance tests of the prototype, stationary 1.5x cusp collector will be completed, and, once the advanced version is fabricated, side-by-side comparisons will be undertaken. In addition, collector modules have been purchased from Sunmaster Corporation and Energy Design Corporation, and a test plan for them has been outlined. Evaluation of these components will begin upon their receipt.

A new activity will be the design and construction of a prototype concentrating collector for process heat applications (150-300°C). Data acquired in current and previous activities will be used in an optimization procedure to identify the most desirable concentrator type and level of concentration, based on end-use requirements yet to be established. It is anticipated that developmental work in receiver design as well as reflectors will be necessary to successfully complete this higher temperature (and probably higher concentration) collector. The commercialization activity which has been so successful in the case of the stationary cusp collector will, of course, be expanded to include this process heat effort.

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Measured Performance of a 1.5x CPC

Title of Paper: Compound Parabolic Concentrator
Collector Development

ANL 189 No.: 49503

Title of 189: Development of Compound Parabolic
Concentrators for Industrial Process
Heat

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DOE Project Manager: Dr. S. L. Sargent

HEATING AND COOLING

ANL SOLAR DATA PROGRAM

P. Chopra, C. Cheng, and R. Wolosewicz

Abstract

This program is designed to collect, evaluate, and publish reliability, maintainability, and materials performance data from solar demonstration systems. The program is supported by the U. S. Department of Energy as part of the National Solar Heating and Cooling Demonstration Program.

I. Introduction

The worth or effectiveness of an energy supply system is measured by its performance (how well it does its job when working) and its reliability (how long a system is capable of working without failure). A major problem in the design and operation of an energy system arises from a conflict of the desire to render reasonably continuous service with the inherent fallibility of equipment and the cost associated with the corrective action necessary to improve system performance. Since the primary sources of cost in solar heating and cooling systems are capital costs and maintenance, the economic consequences of performance degradation and unreliability are significant impediments to successful commercialization of these systems.

The Department of Energy (DOE) is conducting a National Program for Solar Heating and Cooling of Buildings.¹ A major element of that program is data collection, evaluation, and dissemination. Information and technical data are being collected and reported on a number of residential and commercial sites. In March 1978 a program was initiated at Argonne National Laboratory (ANL) by the Solar Demonstration Branch of DOE to collect, evaluate, and disseminate reliability, maintainability, and materials performance data from these sites.

One of the key activities of the ANL program is to distinguish between reliability and materials problems normally associated with construction in the building industry and generic problems unique to solar systems. The ANL program has been planned to identify these generic problems and provide solutions. Data from solar heating and cooling systems, if collected and utilized effectively, can contribute significantly to the improved lifetime performance, life-cycle cost reductions, overall cost effectiveness and consumer acceptance of solar systems.

RELIABILITY AND MAINTAINABILITY

Objectives

The objectives of ANL reliability and maintainability (R&M) activities for the Solar Demonstration Program are: obtain solar system R&M data from

operational demonstration sites; identify problems or conditions that degrade system performance or cause early system failure and unavailability; suggest solutions for reducing or avoiding those problems or conditions; and prepare guidelines for the design, construction and operation of reliable and efficient solar systems. Specific tasks in the R&M program are: define R&M data requirements; acquire R&M data in conjunction with ongoing DOE site programs; evaluate data to identify current and potential problems; prepare an R&M critical items list and suggest solutions for generic problems that reduce system lifetime performance; and document the information obtained in this program and disseminate it in a timely manner for the use of architects, engineers, designers, component manufacturers, contractors, operation and maintenance personnel, and for potential solar system users.

Data Requirements

The Department of Energy has initiated programs to develop, demonstrate, and promote the use of solar heating and cooling systems. Considerable information is becoming available for these systems including system design descriptions, costs, and as-built details. A number of residential and commercial sites have been instrumented for collecting performance data via a Site Data Acquisition System (SDAS). The ANL program will utilize much of this data. For an R&M evaluation of existing sites and to improve the R&M performance of future systems, additional operational information on current systems is required: installation; system check-out experience; flow schematics for system operating modes; operational and site maintenance experience. Appropriate data from ANL materials assessment activities will be utilized.

Data Acquisition

All existing communication channels between DOE and its contractors will be used to acquire site specific technical data and operational information. Field engineers will monitor the demonstration sites. Other data sources that will be monitored and reviewed include: DOE sponsored conferences, government publications, technical journals, industrial publications, and component manufacturer specifications. Data will be abstracted and filed in an R&M library for subsequent use in evaluation activities.

Site Background Data

Discussions will be held between field engineers and DOE site program managers to obtain a site status update. The field engineer will review the site project files of contract office representatives (COR) and obtain copies of pertinent information including: site location; system drawings including mechanical, control system and instrumentation details; system operating mode description; component specifications; site acceptance test procedure and results; site progress reports; and operating characteristics including system downtime.

Site Visits

While site background information is valuable for a preliminary R&M assessment, some site visits must be made to evaluate the performance of various types of as-built systems. Field engineers will discuss system design, construction, test, and operation with operating and maintenance personnel and with

the architect-engineer, system designer, contractors, or component manufacturers as appropriate. A follow-up will be made on information obtained during the site background data review. New problems arising during construction, installation, start-up, and test will be identified. Data on performance of components, control systems, and instrumentation during preoperational phases will be obtained. Operation and maintenance information will be acquired by review of operating reports, and visits to operating systems and supplemented by telephone contact with site personnel. The emphasis will be on major system component failures, system downtime for extended periods or performance data indicating system degradation. Problems and corrective action will be documented. Component and system failures will be identified for possible failure analysis at ANL.

R&M Data Forms

Forms² have been prepared to record system operating problems, failures, maintenance and downtime. These forms may be completed by a field engineer, by operating and/or maintenance personnel at the site, or by telephone to the assigned field engineer to record the necessary information.

Data Evaluation

Data evaluation will be structured to permit prompt and timely dissemination of R&M information. The principal activities are: identification and resolution of generic problems; and system reliability evaluations including review of instrumented commercial solar sites, failed component analysis, failure mode analysis, and preparation of a critical items list.

Generic Problems

Operating problems at each commercial demonstration site will be documented and updated periodically using information obtained from project managers, site documents, site visits, operational data and published reports. Summary forms will be prepared to identify specific generic problem areas such as: freezing, boiling, leaking, air-locking, sensor failures, etc. Each generic problem will be evaluated to determine contributing factors. A report will be prepared to document the percentage of systems that experienced the generic problem, how similar systems avoided the problem, and other design and/or operating recommendations to ameliorate the problem.

If the problem occurs frequently or results in significant system downtime, a failure prevention bulletin will be issued for prompt dissemination of the information. Generic problem resolution should reduce the frequency of early system failures. These evaluations will be used to identify and define failure modes of solar systems and help develop component critical item lists.

System Reliability Evaluations

Operational data will be used to evaluate consequences of reduced reliability on solar systems after early problems associated with the commercial demonstration sites have been identified. These data will be supplemented by failed component analysis, failure mode analysis, and analytic studies so that system reliability can be assessed.

As the operational time of a solar system increases, various components will fail. Failure may be due to: design inherently incapable of performing its intended function; environment beyond the capability of the component or the system; faulty component or one damaged in manufacture, test or installation; and normal wear-out. Failure analyses may be performed on some components using information, where applicable, from materials assessment activities. An R&M bulletin will be issued summarizing the failure analysis results and including recommendations to reduce the frequency of failure.

Predominant solar system failure modes will be identified based on the generic problem studies, operational data and failed component analysis. Using this information in conjunction with general solar system schematics, failure modes and effects analyses will be performed in order to develop a solar system critical items list.

MATERIALS ASSESSMENT

Objectives

The degradation of heat-transfer fluid (HTF) properties and corrosion behavior in a solar system can have a significant effect on the cost and performance of the system. Materials assessment activities have been implemented at ANL to obtain data needed to interpret possible changes in system-performance efficiency caused by materials corrosion and HTF degradation. A major objective of these activities is to select durable cost-effective materials for solar systems in various climatic regions. These activities are being conducted under four tasks: (1) Atmospheric corrosion, (2) HTF corrosion, (3) HTF properties, and (4) HTF scaling.

Atmospheric Corrosion

Atmospheric corrosion of metallic supporting structures (battens/enclosures) will be measured at 15 selected SDAS sites. Site selection was based on climatic conditions, SDAS channel availability and contractor cooperation. The corrosion monitoring will be accomplished by two complementary on-site experiments: (1) Monitoring the telemetry from an atmospheric corrosion sensor, a relative humidity sensor, and an ambient temperature sensor via the SDAS; and (2) Determining the weight loss and pitting characteristics from metallic coupons housed in an atmospheric corrosion rack at each site.

The atmospheric corrosion sensor is specially designed by Rockwell International and consists of a Cu/Zn couple that registers the galvanic current which correlates with the corrosion rate. The relative humidity sensor designed by Texas Electronics, Inc., contains a movable hygroscopic element connected to a differential transformer suitable for use by the SDAS.

The atmospheric corrosion rack contains six coupons each of four materials: aluminum, galvanized steel, aluminized steel, and painted steel. These materials were selected based on current utilization in commercial collectors. Weight changes of corrosion coupons will be measured after exposure to the atmosphere for 3, 6, 9, 12 and 18 months. Weight-change data for different materials at the 15 sites will be correlated with the atmospheric corrosion relative humidity and temperature data.

HTF Corrosion

When the HTF or its corrosion inhibitors degrade with time and/or temperature to form acids, the internal surfaces of the solar collector system become susceptible to corrosion and corrosion-erosion. The damage is expected to be more severe at a collector surface that emits heat to a fluid than at a pipe surface that is heated by a fluid. The early detection of HTF or inhibitor degradation and the subsequent corrosion-erosion effect on solar collectors materials can be detected by an on-site voltage corrosivity sensor designed by Texas Instruments for use in liquid heat transfer systems. Sensors will be installed at five selected sites and tied into the SDAS. Laboratory tests will be conducted using HTF collected from the selected sites to correlate with the site measurements.

HTF Properties

Data on the specific heat and density of the HTF at operating temperatures are needed to accurately calculate the instantaneous thermal efficiency and the useful energy collected by the solar collector system. At present, nominal values are used in calculations. Heat-transfer fluid will be collected from 40 SDAS sites to determine actual specific heat and density at three operating temperatures. For aqueous non-freezing HTF, measurements will be made at 4.4, 49, and 93°C. For non-aqueous HTF, measurements will be made at 4.4, 66, and 116°C. Calculations will be made to evaluate the influence of differences between nominal and measured values on thermal efficiency and energy collection. After one year of service, measurements will be repeated to ascertain whether further changes in HTF properties affect system performance calculations.

HTF Scaling

Scaling at heat-transfer surfaces of solar collectors and heat exchangers reduces thermal efficiency and can affect operational reliability. Radian Corporation has developed a model to calculate scaling potential of aqueous HTF as functions of temperature, pH and the concentration of key scaling species. The model uses equilibrium relationships among the different dissolved species and takes into account solution nonideality and the effects of ion complexing. The generic problems associated with water chemistry and scaling of materials will be analyzed for five selected SDAS sites. These analyses will be based on water compositions at the sites. Calculations will be made of the scaling potential and the effect of the rate of scaling on thermal efficiency.

II. Accomplishments During 1978

Reliability and Maintainability

The ANL R&M activities were initiated during the first quarter of 1978. Basic R&M data requirements have been established, and the initial version of R&M data forms has been completed. To enhance project visibility, a matrix was prepared showing the location and characteristics of all instrumented sites in the current commercial solar demonstration program.

The accumulation of existing background site data was initiated for commercial sites. Contacts have been established with Contracting Officer's Representatives (CORs) in the Chicago Operations Office of DOE, Marshall Space Flight Center, and PRC Energy Analysis Corporation. Initial contacts have been made with the San Francisco Operations Office of DOE. Some sites have been visited to verify the R&M data collection procedure. Operational problem descriptions have been obtained from IBM.

An interim solar critical items list was prepared from the Proceedings of the Solar Program Contractors Review.³ Based on the frequency of reported problems, the major problem areas were in collectors and piping or ducting. From the analysis of other data, the piping problems can be categorized into three generic areas: general piping leaks, leaks in the collector to manifold connections, and systems freeze-ups. These problems are being evaluated.

Materials Assessment

The on-site implementation plan to install equipment for atmospheric and HTF corrosion has been completed. Initial measurements of HTF properties are currently under way.

III. Planned Activities for 1979

A preliminary design manual based on R&M information will be prepared. This manual will contain guidelines for the prevention of system upsets caused by R&M problems. Reports will be prepared on solar site operational problems relating to freezing, interconnection leaks, and system control malfunctions.

In the materials assessment activities, atmospheric corrosion and HTF corrosion and scaling field data will be obtained and summarized in periodic reports. Comparisons will be made between design and measured HTF property values and their effect on the thermal efficiency of solar collector systems.

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Solar Applications

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THERMAL ENERGY STORAGE

DESIGN AND INSTALLATION MANUAL FOR THERMAL ENERGY STORAGE

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Abstract

For the first time a comprehensive *Design and Installation Manual for Thermal Energy Storage* has been prepared. The manual provides how-to-do-it information on storage to installers, contractors, engineers, architects, and designers. The first edition will be presented to DOE for review at the end of January.

I. Introduction

The objective of this project is to assemble and write a manual on the design and installation of thermal energy storage (TES) in solar heating and cooling systems. The audience is intended to be installers, contractors, engineers, architects, and designers who wish to enter the solar energy business. Although the manual is primarily intended for solar energy professionals, it is also capable of being used by do-it-yourselfers. Only data pertaining to state-of-the-art storage systems (water tanks and rock bins) will be presented in detail. Advanced storage systems such as phase-change or seasonal storage will not be included in the first edition, but may be included in future editions.

A considerable amount of information on TES existed prior to the beginning of this project, but the information was scattered among numerous sources including books, systems manuals, government standards, journal articles, and reports. All of these sources are either very general and lack detail or are highly detailed in only a few aspects of TES. The limited availability and scholarly style of many of the sources make it difficult for designers and installers of TES to use the information contained in the various sources. Numerous pitfalls in designing and installing TES require that a comprehensive manual be written for designers and installers.

Material was assembled, analyzed, and written from a very large number of governmental and industrial sources. This was then put into a logical structure and presented to a DOE-Industrial review panel. Based on the panel's suggestions, the manual was reorganized and revised and then once again reviewed by the panel. A second revision is currently under way.

II. Accomplishments During 1978

For the first time, a comprehensive manual on TES has been written. The manual provides how-to-do-it information to designers and installers of TES systems. This first edition is expected to be ready for DOE review by the end of January.

The contents of the *Design and Installation Manual for Thermal Energy Storage* are shown in Table I. Chapters I-IV present general information on storage without going into highly technical details that would confuse the reader. If the reader decides that he needs to know further technical details on a given subject, he can turn to the appropriate technical appendix.

TABLE 1. Contents of the Design and Installation Manual for
Thermal Energy Storage

INTRODUCTION

CHAPTER I. GENERAL CHARACTERISTICS OF THERMAL ENERGY STORAGE SYSTEMS

Introduction
Thermal Capacity
Operating Temperature Range
Temperature Stratification
Determining the Size of the Storage Device
Choosing a Location for the Storage Device
Minimizing Heat Loss from the Storage Device
Heat Exchange

CHAPTER II. ROCK-BED THERMAL ENERGY STORAGE SYSTEMS

Introduction
Special Characteristics
Performance
Design Example
Construction
Fans
Auxiliary Heating System
Operation and Maintenance

CHAPTER III. LIQUID-BASED THERMAL ENERGY STORAGE SYSTEMS

Introduction
Tank Types
Tank Costs
Pumps
Other Components
Auxiliary Heating System
Tank Installation
Operation and Maintenance

CHAPTER IV. THERMAL ENERGY STORAGE IN DOMESTIC HOT WATER SYSTEMS

Introduction
Safety
Stand-alone Domestic Hot Water Heating Systems
Domestic Hot Water Systems as Part of Space Heating Systems

TECHNICAL APPENDICES

GLOSSARY

BIBLIOGRAPHY

INDEX

The manual contains a wealth of practical how-to-do-it information on TES. Readers will learn how to size the storage system, what materials to use, where to put storage, how to design and install rock bins or how to insulate storage, and how to select and specify storage tanks and other components. In addition, operation and maintenance procedures are provided.

The material for the first edition has been prepared and is presently undergoing final editing. This first edition will be presented to DOE for review at the end of January.

III. Planned Activities for 1979

Six seminars at various locations in the United States are planned. These seminars have multiple purposes which include publicizing the manual among its potential users, disseminating the manual to users, and obtaining feedback from the users. Feedback from the users will guide the writing of the second edition in FY1979.

The project personnel will continue their activities in solar-energy standards organizations such as ASME and ASTM. Information on the new standards will be included in the second edition of the manual.

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PROGRAM SUPPORT IN THERMAL ENERGY STORAGE FOR
THE SOLAR HEATING AND COOLING R & D BRANCH, DOE

Allan I. Michaels

Abstract

This program provides technical management support in thermal energy storage and heat exchange to the Solar Heating and Cooling R&D Branch, DOE in the areas of: proposal solicitations and evaluations; monitoring of contractor performance; providing liaison and information exchange between contractors, the R&D Branch, and other government laboratories and agencies; R&D program plan monitoring and modification; and budget and schedule preparation.

The historical background and major past achievements of the program, as well as significant accomplishments in FY1978, are briefly described. An outline is presented of planned activities for FY1979.

I. Introduction

This activity officially began at ANL in April, 1976. The first task carried out was the detailed review and revision of the draft of The Solar Heating and Cooling R&D Plan, particularly in the area of thermal energy storage and heat exchange. Subsequently, ANL prepared statements of work and solicitation documents for a PRDA in four categories of innovative R&D in thermal energy storage and an RFP in six categories of system and engineering studies in thermal energy storage and heat exchange. ANL also organized and conducted the reviews of proposals received (approximately 200) in response to these two solicitations.

Other activities for which ANL has been responsible in this program include: reviews and funding recommendations for unsolicited proposals received by DOE; monitoring and evaluation of the performance of funded contractors, which involves reviews of monthly, semi-annual, and annual reports, site visits and discussions of program progress and objectives, recommendation of changes, additions, deletions to and renewals of contracts, and liaison between contractors and between contractors and other governmental and non-governmental organizations; coordination of projects with the R&D Plan and initiation of new projects as required to meet the R&D Plan schedule and objectives; and preparation of budgets and schedules to effectively carry out the planned work of The Solar Heating and Cooling R&D Branch.

II. Accomplishments During FY1978

All of the program responsibilities of ANL described above were conducted at a high level of activity throughout FY1978. A total of 26 contracts were in effect and monitored during the year.

Some specific accomplishments were as follows: 16 project review site visits were made to contractors; three additional site visits were made for the purpose of discussing new potential projects; nine project review meetings with contractors were held at ANL or in Washington, D.C.; two detailed program review and analysis reports were written and four planning meetings were held with the DOE Program Manager; 16 unsolicited proposals were reviewed and funding recommendations made; four semi-annual and annual reports were reviewed (an additional eight are in the review process); review papers describing the R&D program and related R&D projects were presented at six conferences; four R&D Branch support laboratory and/or contractor review meetings and four coordination meetings with other storage support laboratories (ORNL, NASA/MSFC) were attended; two financial operating plans were prepared; the R&D Plan was reviewed and revised twice, and the R&D Project Book was reviewed and revised; statements of work were written for nine new contracts, and eight procurement actions for contract renewals, extensions, or changes in statement of work were initiated; and several management plan and program schedule documents were prepared.

In addition to the above, information exchanges were conducted with researchers in Germany, Sweden, and Canada. ANL participated in the formation of the new ASTM Solar Energy Standards Committee E-44 and has reviewed several proposed ASTM solar standards and is chairing the Task Group on Thermal Energy Storage.

III. Planned Activities for FY1979

All of the current program responsibilities and activities will continue throughout FY 1979. With respect to R&D program content, it is expected that 14 of the currently funded contracts will be continuing in FY 1979. In addition, six to eight new contracts will be initiated based on unsolicited proposals which are currently under consideration. Four solicitations of new proposals are also planned in the areas of improved containers for phase change heat storage materials and general retrofit applications, for annual storage large scale solar systems, and for improved heat exchangers for solar heated domestic water subsystems.

A solar storage workshop is scheduled to be held in March of 1979. The structure of this workshop will be planned so as to provide guidelines for future directions and preferred emphasis in the development of improved cost effective storage systems for each of the potential solar applications.

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3-D MODELING OF THERMOCLINE STORAGE TANK

E. I. H. Lin and W. T. Sha

Abstract

A three-dimensional, transient, single-fluid computer model, COMMIX-SA, has been developed to investigate the flow stratification phenomena in thermocline storage tanks. Validation and parametric studies are in progress.

I. Introduction

The thermocline storage tank is a liquid storage device for storing solar thermal energy as sensible heat. When properly designed, stratification can be maintained in the tank so that a thermocline (i.e., a relatively thin region of steep temperature gradient) is formed which naturally separates the cold liquid at bottom from the hot liquid on top. One- and two-dimensional models [1,2] of the liquid storage tanks are available, but their usefulness is limited because the stratification phenomena in the tanks are inherently three-dimensional. Hence, our objective is to develop and validate a three-dimensional, transient, single-fluid, single-phase mathematical model to (a) investigate effects of baffles, jetting, heat capacity of walls, heat source (or sink), and geometry on flow stratification in thermocline storage tanks; (b) study effects of thermal stratification in storage tanks on solar systems performance; (c) seek ways, via parametric studies, to improve and optimize thermocline storage tank designs.

II. Accomplishments during 1978

- (a) The COMMIX-SA (COMponent MIXing - Solar Applications) computer program has been developed and made operational. The program solves numerically the conservation equations of mass, momentum, and energy, subject to boundary and initial conditions that are appropriate to storage tanks. The governing partial differential equations and their finite-difference analogs have been detailed in Ref. [3]. COMMIX-SA has been derived from the existing COMMIX-1 code [4], which was under USNRC-RSR sponsorship. The following major additions and modifications were made: water properties; integral treatment of singularities at the origin of a cylindrical-coordinate system [5]; baffle model; tank wall heat transfer model; one-dimensional computer storage and boundary conditions grouping; and several types of boundary conditions relevant to storage tank applications.
- (b) Validation of COMMIX-SA has been initiated. Predictions of thermocline and its motion in time during a demand event are in good qualitative agreement with experiments and are superior to those obtained by one of the most widely used one-dimensional models, i.e., TRNSYS (see Ref. [3]). However, three-dimensional temperature and velocity data are lacking, and assistance has been provided to DOE management in delineating test requirements for the validation of COMMIX-SA.

Fig. 1 Predicted Flow Pattern in a Vertical Section of a Cylindrical Water Tank

Fig. 2 Predicted Temperature Distribution in a Vertical Section of a Cylindrical Water Tank

- (c) Several storage-tank stratification problems have been analyzed using COMMIX-SA, and the results [3] show that (i) the code is capable of realistically predicting the flow and temperature distributions in storage tanks (see Fig. 1 for an example of flow pattern in a vertical section of a cylindrical tank); (ii) three-dimensional effects are significant (e.g., the temperature depression in the vicinity of the tank walls as shown in Fig. 2 is the result of upward motion and circumferential diversion of the incoming cold stream - see details in Ref. [3]); (iii) both inlet-outlet port locations and inlet velocity affect the degree of stratification, and the optimal conditions should be sought by systematic parametric studies.

III. Planned Activities for 1979

Validation of COMMIX-SA will continue as experimental data become available. Extensive parametric studies will be performed with emphasis placed on improvement of tank design. The computer code will be documented and released. Also, the development of a three-dimensional, transient, two-fluid (without phase change) version of COMMIX-SA will be undertaken, which will

aim at analysis of direct-contact, liquid-liquid heat exchange/storage systems.

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OCEAN THERMAL ENERGY CONVERSION

OTEC HEAT EXCHANGER PROGRAM

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ABSTRACT

The ANL ocean thermal energy conversion (OTEC) program includes the testing of advanced heat exchangers for OTEC power plants and the provision of technical support to DOE. A horizontal pool boiler and a vertical falling film condenser were tested in Argonne's new heat exchanger test facility during FY 1978; at least six heat exchanger units will be tested in FY 1979. Technical support efforts have included the development of a model of combined boiling and evaporation of liquid films on horizontal tubes. Vapor/liquid interaction and entrainment in horizontal tubes as well as flow-induced vibration in shell-and-tube heat exchangers also were studied. Expanded technical support work is planned for FY 1979.

I. Introduction

Ocean thermal energy conversion (OTEC) is the process of producing electricity from the temperature gradients in tropical oceans. The principle of OTEC was first proposed by the French physicist D'Arsonval in 1881. A small OTEC plant, about 22 kWe, was constructed on the coast of Cuba in 1929. While this plant was plagued with technical difficulties and soon abandoned, its operation proved that the concept was feasible.

Because OTEC plants operate using small temperature differences, the thermal efficiency is comparatively small. Therefore, the amount of heat transferred to produce a given amount of power is very large, or equivalently, the heat exchanger must be very large. Studies have indicated that the heat exchangers account for more than one-half the cost of a complete OTEC system. Therefore, the economic feasibility of OTEC power plants depends heavily on the extent to which heat exchanger costs can be reduced. Recent work at ANL and elsewhere has shown that significant improvements in heat exchanger performance, and therefore sizeable reductions in total plant investment, can be achieved by use of advanced heat exchanger designs that incorporate new concepts for promoting high heat fluxes. Several concepts have been studied recently in bench-scale experimental programs at various industrial, university, and government laboratories. The more promising of these concepts have been selected for testing at the 1 Mwt size (approximately 3.2×10^6 Btu/hr).

In order to evaluate these concepts, a heat exchanger test facility has been constructed at ANL. The facility is designed to test a variety of heat exchanger designs, including:

- Evaporators: Horizontal pool boiler with Linde High Flux tubes
Vertical falling film fluted tube
Horizontal spray evaporator with Linde High Flux tubes
Parallel-flow panel type
Concentric-tube evaporator
Horizontal tubes with in-tube boiling
- Condensers: Vertical falling film fluted tube
Horizontal internally finned, externally wire-wrapped tubes
Parallel-flow panel type
Concentric-tube condenser

In addition to the heat exchanger testing work, which is a major portion of Argonne's OTEC program, technical support is provided to the DOE-OTEC program office.

II. Accomplishments During 1978

Test Facility

During FY 1978, the construction of the loop was completed, and testing was commenced. Figure 1 is a schematic of the test facility; Fig. 2 shows some of the major components in the completed facility [see Ref. 1].

The first unit tested was the horizontal pool boiler with Linde High Flux tubes (see Fig. 3). The High Flux tubes are covered with a proprietary coating designed to improve the heat transfer properties of the surface by promoting the nucleation of bubbles.

Fig. 1. Schematic of Argonne's OTEC Heat Exchanger Test Facility

Fig. 2. Major Components of OTEC Test Facility

Fig. 3. Horizontal Pool Boiler

The testing of the pool boiler was complicated by the observation that the performance of the unit was not repeatable from day to day. It was inferred that the performance of the surface changed with the past history of the surface. In order to verify this hypothesis, the unit was tested around the clock for several days. The testing confirmed that the performance of the unit changed with time. At the start of the test, the surface was deactivated. That is, the cavities that cause the nucleation were filled with liquid, resulting in low performance. With time, the performance increased until an asymptotic value of the overall heat transfer coefficient of $785 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$ was obtained. The steady-state measured performance of this unit matched very well with the analytical predictions made by Linde.

The next unit tested was the vertical falling film condenser designed

Fig. 4. Vertical Falling Film Condenser and Evaporator

by Carnegie-Mellon University (Fig.4). This condenser employs doubly fluted tubes that enhance the heat transfer on both the inside (water side) and the outside (ammonia side). The testing of this unit proceeded comparatively smoothly. The value of the overall heat transfer coefficient measured at nominal conditions was approximately $1,375 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$, based on the equivalent inside area. Choosing a larger area would of course result in a lower coefficient. As in the case of the pool boiler, the performance of the unit matched the prediction very well.

Three other units also were installed: a horizontal tube enhanced condenser (Fig. 5), a vertical falling film evaporator (Fig. 4), and an enhanced spray evaporator. Some preliminary testing has been done on the latter two units. In addition, two

Fig. 5. Horizontal Tube Enhanced Condenser

units--a small test apparatus for panel (plate-plate) heat exchangers and an in-tube unit--have been delivered to ANL for testing next year. ANL also has a procurement underway to obtain a concentric tube heat exchanger.

Technical Support

The technical support effort thus far has consisted primarily of analyzing heat transfer problems in OTEC heat exchangers. A model of combined boiling and evaporation of liquid films on horizontal tubes was developed [2,3]. This effort was directed toward developing a heat transfer model applicable to the design of horizontal tube falling film evaporators for OTEC. The heat transfer process was modeled as combined boiling and evaporation of the thin liquid film. Special account was taken of heat transfer in the initial thermal developing region of the film. Predictions were found to be in good agreement with water data and recently published ammonia data. In view of the good agreement with experimental data, this model is expected to be a useful thermal design tool.

Another problem considered was that of vapor/liquid interaction and entrainment [4]. In the horizontal tube design, liquid falls from one tube to the next in either a droplet or column mode. A criterion was developed for predicting the deflection of droplets and columns due to vapor crossflow. Based on an experimental study of drop detachment and breakup, a correlation was established for determining the resulting droplet sizes. For high vapor crossflow velocities, a criterion was developed for predicting the inception of liquid entrainment by a process known as stripping. Based on the foregoing models, conditions were defined under which vapor/liquid interaction and entrainment are important for OTEC evaporators.

A study of flow-induced vibration in shell-and-tube heat exchangers for OTEC was recently completed [5]. The dominant excitation mechanisms were considered: vortex shedding, turbulent buffeting, fluidelastic instability, and acoustic excitation. Equations were derived for predicting the maximum allowable tube span length as a function of crossflow velocity and other system variables. Regions of acoustic resonance and noise also were defined. Among the system variables studied were tube diameter and material, tube-field layout, and pitch-to-diameter ratio. All models were expressed in a form that can readily be applied to the mechanical design of OTEC heat exchangers.

Additional activities included a working fluid study and reviews of proposals and reports at the request of DOE.

III. Planned Activities for 1979

Test Facility

During FY 1979 the three recently installed units--the enhanced condenser, the vertical falling-film evaporator, and the spray evaporator--will be fully tested. At least three more heat exchanger types also will be

tested: the panel exchanger with various panel configurations in both an evaporating and condensing mode; the in-tube heat exchanger as an evaporator, and possibly as a condenser; and the concentric tube heat exchanger as both an evaporator and condenser. Other types of heat exchanger such as plate-fin or compact pool boiler also may be tested.

Technical Support

The planned areas of technical support for 1979 include:

- Support of the testing activity, including test planning, interpretation of results, evaluation of heat exchangers, and preparation of reports.
- Heat transfer and fluid mechanism studies, including further work in working fluid analysis, studies relating to the performance of compact heat exchangers, and analysis of two-phase flow instabilities.
- Power system modeling and analysis.

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DOE Project Manager:	Dr. S. Gronich

OTEC PROGRAM MANAGEMENT SUPPORT: PHYSICAL AND
CLIMATIC ENVIRONMENTAL IMPACTS

J. D. Ditmars, R. A. Paddock, J. H. Allender, and K. D. Saunders

Abstract

The area of physical and climatic environmental impacts for the Ocean Thermal Energy Conversion (OTEC) program is part of a larger program for the assessment of the potential environmental impacts of that solar technology. Predictions of potential modifications to the physical environment due to the large amounts of seawater circulated by OTEC plants require the development of physical and numerical models for several scales of motion. Argonne has provided technical oversight for the modeling efforts by others and undertaken supportive studies including the synthesis of model results for OTEC environmental impact assessment.

I. Introduction

The purpose of this project is to provide program management support to the Environmental and Resource Assessment Branch, Assistant Secretary for Energy Technology, Department of Energy with regard to physical and climatic environmental impacts of Ocean Thermal Energy Conversion (OTEC). The work at Argonne interfaces with support programs at the Lawrence Berkeley Laboratory and the Atlantic Oceanographic and Meteorologic Laboratory of NOAA that deal with potential ecological impacts of OTEC and physical oceanographic data acquisition, respectively.

The OTEC concept involves the extraction of energy from the subtropical and tropical oceans by utilizing the difference in temperature (typically on the order of 20°C) between the surface waters and waters at depth (as much as 1000 m). Circulation of large amounts of warm surface and cold, deep water through the plant heat exchangers is required. Rates of flow of seawater through the evaporator and condensor heat exchangers may be on the order of 500 m³/s for each system for an OTEC plant with net power output of 100 MW. The intake and discharge of the seawater by the OTEC plant will perturb the ambient ocean environment, and the degree to which those perturbations impact the ocean and OTEC plant operations are of concern for the environmental impact assessment of OTEC and the design of OTEC systems.

Argonne's role in this project is to undertake studies of and to provide technical monitoring of studies for DOE by others regarding the physical aspects of potential OTEC impacts on the oceans. Problems concern siting and thermal resource exploitation for OTEC include prediction of the potential for recirculation of plant discharges and subsequent degradation of the

thermal resource and prediction of the renewal of thermal resource both at the ocean surface and in deep waters. Potential environmental impacts, the assessment of which requires prediction of the physical perturbations, are the redistribution of temperature, salinity, and other water constituents of the ocean due to OTEC plant operation and the fate of working fluid leaks, biocides, and the products of corrosion in the plant effluents. Scales of interest for impact assessment range from a few kilometers for near-plant impacts and single-plant recirculation to tens of kilometers for planting spacing considerations to hundreds of kilometers for potential basin-wide impacts due to large-scale OTEC plant deployment in the Gulf of Mexico. Extraction of heat from the surface waters of the ocean may result in sea surface temperature depressions. Effects of CO₂ enhancement in the surface waters and possible CO₂ release to the atmosphere due to the discharge of the cold, deep waters near the surface are additional problems requiring consideration.

II. Accomplishments During 1978

Argonne provided technical monitoring of several studies by others under contract to DOE related to the modeling of physical environmental modifications to the ocean due to OTEC plant operations. Physical (hydraulic) model studies of the near-plant effects of the discharge plumes and the potential for recirculation at a single plant were carried out at Hydronautics, Inc. and the Department of Civil Engineering at the Massachusetts Institute of Technology. The purpose of these physical model studies was the determination of the effluent behavior and recirculation potential for generic OTEC plant designs for separate and mixed discharges under various conditions of intake and discharge port separation, discharge orientation, ambient stratification, and ambient current. Numerical model computations by Science Applications, Inc. (SAI) of near-plant effluent behavior were carried out by means of two-dimensional and axisymmetric models. Analytical and numerical studies of mixing in the intermediate fields of effluent plumes were initiated at the Department of Environmental Engineering, Cornell University. The effects the operation of 100 and 1000 100-MW OTEC plants in the Gulf of Mexico have on the vertical temperature structure were investigated by SAI and the Navy Ocean Research and Development Activity (NORDA) by means of a laterally-averaged model. A two-layer, baroclinic numerical model of the Gulf of Mexico was developed by NORDA to provide information on the circulation in the Gulf for environmental impact assessment.

Review by Argonne of the plans for and the results of these studies and a workshop¹ with others concerned with the environmental and resource aspects of OTEC led to revised plans and redirected efforts to address physical environmental problems within the scope of OTEC needs and timetables. Investigation of several early baseline OTEC designs indicates that the fractional net power losses are equal to about 2.4 times the fractional loss in thermal resource. Power cycle optimization appears to require the probability distribution of the thermal resource at a site. Preliminary studies of recirculation show that some design concepts may suffer 5-10% loss in net power output, but that design modifications may eliminate recirculation as a serious problem. Additional physical (hydraulic) model studies are required to put bounds on the recirculation potential of several generic designs in the near future. Review of model capabilities and limitations suggests that physical model studies also are needed to meet near-term OTEC needs for predictions of the complex near-field (1-3 km) effects of a single OTEC plant.

Analytical and numerical models seem best-suited for predictions of the intermediate field (2-10 km) effects. Evaluation of several generic designs in various possible sites requires the establishment of worst-case scenarios consistent with site data and with the needs of those assessing biological and ecological impacts. An estimate for the aggregate effect of many OTEC plants on the horizontal thermohaline structure of the ocean was made in terms of the power density that would be required to sustain an induced, mesoscale anomaly against natural dissipation (as measured in a Gulf Stream eddy). Rough calculations for a 160 MW OTEC plant indicate that plant-plant spacing of 12 km or more may preclude the formation of mesoscale, OTEC-induced anomalies. It is suggested that a multilevel, baroclinic numerical model of a limited ocean region (perhaps, 100 x 100 km) could be a useful tool to sharpen estimates of plant-plant interactions and spacing. Careful synthesis of the results of several models, in a spatial hierarchy from near-field to basin-wide scales, is required to provide reliable estimates of physical environmental impacts for OTEC purposes.

III. Planned Activities for 1979

Technical management activities will continue for near-plant physical modeling efforts and for an effort by Dynalysis, Inc. on a multilayer numerical model for circulation and temperature structure in the Gulf of Mexico. Additionally, Argonne will undertake studies in areas supportive of the physical impact assessment. A study of the feasibility of limited-area ocean modeling for OTEC purposes will be initiated. The capabilities available for prediction of the potential climatic impacts of OTEC will be examined and recommendations made for future research in that area. Synthesis of the essential descriptive physical oceanographic data necessary for environmental impact assessment with particular emphasis on the data required for model verification and application will be undertaken. Appropriate models developed for OTEC will be exercised and applied to specific OTEC generic designs and potential sites. Plans will be formulated for experiments to be carried out from and around the OTEC-1 platform in support of physical environmental impact assessment.

IV. References

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Title of Paper: OTEC Program Management Support:
Physical and Climatic Environmental
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Title of 189: OTEC Program Management Support:
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BIOFOULING, CORROSION, AND MATERIALS

J. E. Draley

Abstract

Management of the OTEC Biofouling, Corrosion, and Materials (BCM) project was established at Argonne National Laboratory on March 1, 1978. The responsibilities of the Argonne BCM project include writing research and development contracts, management of continuing programs on measurement of biofouling in seawater, and corrosion and materials studies. The BCM project will also issue the request for proposals and the contract for the design of the Seacoast Test Facility and participate in the design of OTEC-1.

I. Introduction

The goal of Ocean Thermal Energy Conversion (OTEC) is to stimulate the development of a commercially competitive and environmentally acceptable energy producing system that will contribute significantly to the long-range energy needs of the United States. The biofouling, corrosion, and materials program is part of the advanced research and technology effort of the Department of Energy, which is focused on the development of components and subsystems that require extensive scientific evaluation and testing for conceptualization.

Management of the interdivisional OTEC Biofouling, Corrosion and Materials (BCM) Project was established at Argonne National Laboratory (ANL) on March 1, 1978. This project establishes detailed programmatic activities in biofouling, corrosion and materials appropriate to the overall OTEC objectives. It is responsible for management of an R&D program carried out through fifteen subcontracts or interagency agreements to develop the sound technical information and understanding that will be required to meet OTEC objectives.

II. Accomplishments During 1978

Of the ten contracts originally associated with this program, nine are ongoing and one has been completed. The work in these projects includes ocean testing, data analysis, laboratory testing, and qualification of materials for potential use in OTEC heat exchangers.

The ANL BCM Project has issued the following contracts: Assays of Microfouling Community in an OTEC Simulation, Florida State University, David C. White, Principal Investigator; Investigation of the Chemistry of Calcium Carbonate Scale Nucleation and Growth from Seawater on OTEC Heat Exchangers, University of Miami, Rosenstiel School of Marine and Atmospheric Science, John W. Morse, Principal Investigator; Assay of Polysaccharide Biofouling Deposits Preserved on Pipes Exposed to Seawater near St. Croix, V.I., Miami, FL., or the Gulf of Mexico, University of Miami, Barrie F. Taylor, Principal Investigator; Evaluation Study on Design of Intake Screens for an OTEC Plant, Ichthyological Associates, Inc., David L. Thomas, Principal Investigator; and Extension of the Biology Program for OTEC Biofouling Experiment at Keahole Point, Hawaii, University of Hawaii at Manoa, Frederick Munchmeyer, Principal Investigator.

Drafts of reports on the potential qualification of stainless steel, aluminum, and copper-nickel alloys in OTEC heat exchangers have been received. As soon as final reviews have been completed, these reports will be issued as DOE documents. A draft of the Biofouling, Corrosion and Materials Program Plan has been written and sent to DOE Headquarters for comments and approval.

In order to assess the biofouling and corrosion potential in OTEC heat exchangers, a model system was mounted on a National Oceanographic and Atmospheric Administration (NOAA) 40-foot discus buoy and deployed in the Gulf of Mexico. Seawater from an 80-foot depth was pumped at a velocity of 6 ft/sec through two 5052 aluminum pipes and one titanium pipe; heat transfer efficiencies, biofouling rates and corrosion behavior were determined as a function of time and pipe composition. The biofouling films were characterized by scanning electron microscopy, epifluorescence microscopy, film thickness measurements, and by biochemical analyses, including adenosine triphosphate (ATP), chlorophyll a, and total organic carbon. One of the interesting observations has been that downstream replacement sections foul faster than samples in the original flow loop.

The buoy deployed near Keahole Point, Hawaii, which is acquiring OTEC biofouling, corrosion and fouling resistance data has had the longest (7 months) exposure to seawater. Measurements similar to those in the Gulf of Mexico have been made.

From the slow but consistent biofouling observed at all sites, it is evident that cleaning of condenser tubes is the most important element in the BCM program. For this reason, emphasis is being added to this part of the program. Corrosion/scaling data obtained this year indicate that as little as 8 ppm ammonia in seawater caused deposition of a calcareous scale. Further study of this phenomenon is under way to examine the seriousness of the potential for scaling in OTEC heat exchangers operating between seawater and ammonia.

A request for proposals was issued, and a contract was signed for the design of a Seacoast Test Facility, at which a major fraction of the BCM program is expected to be carried out in FY 1980 and beyond.

III. Planned Activities for 1979

1. New crevice corrosion and corrosion fatigue experiments in seawater will be initiated.
2. Additional cleaning procedures, involving the use of chlorine and scrubbing with brushes and balls, will be investigated.
3. A contract with the Johns Hopkins Applied Physics Laboratory (APL) is being prepared. The work will consist primarily of the measurement of heat transfer coefficients of tubes biofouled on the outside and determination of the effectiveness of using ultrasonic cleaning techniques on biofouled surfaces.
4. Work on the final design for a heat transfer monitor will continue. The objective of this work is to establish a universally acceptable monitor that can be produced commercially and used by all OTEC test facilities to study changes in heat-transfer rates due to biofouling, corrosion, and scaling.

5. It is anticipated that work on Phase I (Design Studies) of a three-phase program by the University of Puerto Rico (Donald S. Sasscer, Principal Investigator) will begin in 1979. The overall objective of this program is to study, through replicated, multiseasonal tests, the relationship between bio-growth, corrosion, materials, cleaning procedures and heat transfer in simulated OTEC flow-through experimental systems.

6. The plans for biofouling, corrosion, and materials monitoring of OTEC-1 experiments are expected to be complete in 1979. The 1-MWe OTEC-1 facility, which is expected to be located near Hawaii, will serve as a major experiment to evaluate the ability of the entire system to produce power.

7. It is intended that the Seacoast Test Facility will be designed, constructed and in operation in 1979.

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PHOTOVOLTAICS

OPTICAL PROPERTIES AND THERMODYNAMIC STABILITY
OF AMORPHOUS HYDROGENATED SILICON

J. A. McMillan and E. M. Peterson

Abstract

A study of the thermal evolution of hydrogen from amorphous hydrogenated silicon films confirms the single presence of $\equiv(\text{Si},\text{H})$ centers in good photovoltaic material prepared by glow-discharge chemical vapor deposition. The spectral selectivity of solar cells prepared with this material can be enhanced probably up to a ratio of solar absorptance to total hemispherical emittance close to ten. Such cells could be advantageously used in hybrid photovoltaic-photothermal conversion systems, thus optimizing the overall conversion efficiency.

I. Introduction

Amorphous hydrogenated silicon $a\text{-(Si,H)}$ is a potential candidate for thin-film photovoltaic devices. Its structure is not well understood although the material is known to contain from IR evidence one- and two-hydrogen centers when prepared at room temperature. The material that has good photovoltaic properties, being prepared near 350°C , contains, however, only one-hydrogen centers. If the conversion efficiency can be improved, the present investment per peak watt could be considerably reduced. Unlike single-crystal silicon cells, cells of $a\text{-(Si,H)}$ have a rather small temperature coefficient and could then be used at higher temperatures, within their range of thermodynamic stability. Since the operating temperature is determined, in the absence of cooling, by the spectral sensitivity of the cells, a knowledge of their total hemispherical emittance in the infrared would prove useful for the design of the converter units. In the case of hybrid systems - in which the cells are actively cooled and the heat used - cells with enhanced spectral selectivity would increase the thermal conversion efficiency at the same operating temperature, thus optimizing the overall system.¹ With this possibility in mind, we are developing a program in four steps, namely:

1. Study of the methods of preparation of $a\text{-(Si,H)}$ thin films,
2. Optical properties of $a\text{-(Si,H)}$ films,
3. Thermodynamic stability of $a\text{-(Si,H)}$ films, and
4. Transport properties and photoresponse of $a\text{-(Si,H)}$ films.

We report progress in steps 1 to 3; step 4 will be undertaken in the near future.

II. Accomplishments During 1978

In order to prepare and characterize thin films of $a\text{-(Si,H)}$, the following equipment was designed and built, being presently in operation.

A. Glow-Discharge Chemical Vapor Decomposition Unit. A reactor has been designed and built to produce amorphous silicon films with variable hydrogen content by RF and DC plasma decomposition of silane. The system allows independent control of gas pressure and composition, plasma discharge power, and sub-

strate temperature between ambient and 400°C. Provisions have been taken in the design for expansion to doping with boron and phosphorus when the need arises.

Deposition rates between 1 and 10 Å/s are achieved by varying the total pressure of deposition, the gas flow, the temperature of the substrate, and the power of the discharge. (The reactor has a resonance frequency close to 8 MHz.)

Typically, the reactor holds up to six 22.4 mm diameter disks, and one 12x12 mm square thin substrate of molten silica, this latter used for hydrogen analysis. One micrometer films are usually prepared under steady, reproducible conditions.

B. Hydrogen Analysis. The thermal decomposition of a-(Si,H) films is studied by heating as-deposited films on their substrates (ca. 0.2 mg of material) at constant warmup rate in an evacuated system of known volume, and measuring the pressure as a function of time. The choice of heating at constant warmup rate with a temperature programmer and a proportional controller was made because an analytical study of the curve leads to the thermodynamic parameters governing the reaction rates, as seen in Section D.

C. Spectral Selectivity Calorimeter. Equipment was designed and built for measuring total absorptance α_s under simulated insolation, and total hemispherical emittance ϵ_{th} in the black-body spectrum of the sample between room temperature and the temperature of stagnation. Figure 1 shows a schematic diagram of the calorimeter. A sun simulator was developed for this purpose.² It consists of a 3200K tungsten-halogen lamp filtered with a Corning glass CS1-75 filter reduced to one-third the stock thickness and a quartz window. Its output is shown in Figure 2 (b) together with other tungsten simulators, normalized to the AM2 spectrum (a). Figure 3 shows the spectral response of an OCLI standard silicon cell under several insulations including that of our simulator (b).

Fig. 1

Schematic diagram of the spectral selectivity calorimeter.

Fig. 2

Solar AM2 spectrum and spectra of tungsten-halogen lamp simulators.

The sample is heated in the calorimeter by the sun simulator, and its temperature recorded as a function of time. It is then cooled in the dark and the recording repeated. The heating rate is given by

$$\frac{dT}{dt} = \left(\frac{\partial T}{\partial t} \right)_{\epsilon=0} + \left(\frac{\partial T}{\partial t} \right)_{\alpha=0},$$

where

Fig. 3

Optical response of a silicon solar cell under AM2 and tungsten-halogen lamp simulators.

$$\left(\frac{\partial T}{\partial t}\right)_{\epsilon=0} = \alpha_S^* \frac{A_1}{mC_p} S^*, \text{ and } \left(\frac{\partial T}{\partial t}\right)_{\alpha=0} = -\epsilon_{th} \frac{\sigma A_2}{mC_p} (T^4 - T_o^4),$$

with A_1 = insulated area, A_2 = reradiation area, mC_p = heat capacity of the sample, $S^* = 740 \text{ Wm}^{-2}$, σ = Stefan-Boltzmann constant, T = temperature of the sample, and T_o = temperature of the calorimeter chamber. A typical recording is illustrated in Figure 4. The heating and cooling rates are solved for α_S^* and ϵ_{th} .

D. Experimental Results. One-micrometer films of a-(Si,H) have been studied, as deposited on polished niobium substrates (good ohmic contact) with a Schottky-barrier configuration, but without the Schottky contact. Table I shows the absorptance and emittance of a typical sample, as determined in the spectral selectivity calorimeter. The selectivity, $\alpha/\epsilon = 2$, is moderate. However, addition of a quarter-wavelength AR coating would practically double it by doubling α_S^* . If the AR coating is made of ITO, which is a good IR reflector, the selectivity α/ϵ could probably be increased by another factor of two. This value would be favorable for thermal conversion.

Fig. 4

Heating and cooling curves of a sample as measured with the spectral selectivity calorimeter.

The stability of these films was studied by hydrogen evolution. Figure 5 shows a typical result. Processes A and B, peaking at 360 and 600°C, have been identified as the decomposition of $\equiv\text{SiH}_2$ and $\equiv\text{SiH}$, respectively. Table II displays the thermodynamic parameters of the kinetics of both processes. Samples prepared at 225°C only show process B, confirming the existence of only $\equiv\text{SiH}$ centers. Sputtered samples, however, show only one, broader peak when deposited at room temperature, although they contain both centers from IR evidence. This fact indicates that samples with only $\equiv\text{SiH}$

Fig. 5

Hydrogen evolution analysis of a 0.2 mg sample of a-(Si,H) with 35 atom-per-cent hydrogen.

centers are difficult to prepare by this technique. Photovoltaic research will therefore concentrate on CVD material.

III. Planned Activities for 1979

In addition to continuing with the research in progress reported here, transport and photoresponse measurements on these materials are planned for FY 1979, with the view in mind of correlating the results with the structural properties presently under investigation.

IV. References

1. J. A. McMillan, D. E. Soule, R. T. Kampwirth, and E. M. Peterson, "The Role of Spectral Selectivity in Hybrid Solar Energy Conversion", 1978 Annual Meeting of the American Section of the International Solar Energy Society, Denver Colorado, Aug. 28-31, 1978.
2. J. A. McMillan and E. M. Peterson, "Solar Simulation with Tungsten-Halogen Lamps and Optical Filters," submitted to Solar Energy.

TABLE I. Absorptance and Emittance of Typical Sample

T (°C)	α_S^*	ϵ_{th}	α/ϵ
30	0.47	0.23	2.03
50	0.47	0.23	2.03
84	0.47	0.23	2.03

TABLE II. Thermodynamic Parameters

Process	T_M (°C) ^a	Reaction Order	Frequency Factor (1/s)	Activation Energy (kJ/mole)	Assignment
I ^b	360	1	6×10^4	99	=SiH ₂
II ^c	600	1	12	83	≡SiH

^a T_M is the temperature at which the process rate is maximum at a constant warmup rate of 20 deg/min.

^bSample prepared at 20°C.

^cSample prepared at 225°C.

Title of Paper: Optical Properties and Thermodynamic
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SATELLITE POWER SYSTEM

THE SATELLITE POWER SYSTEM CONCEPT EVALUATION*

T. D. Wolsko, B. D. LaMar, S. L. Halverson

Abstract

The Satellite Power System (SPS) concept offers the potential to provide baseload electrical power through solar energy conversion at almost a continuous rate of 24 hours a day. DOE has prepared a concept development and evaluation plan designed to achieve, by the end of 1980, an initial understanding of the technical feasibility, economic practicality, and social and environmental acceptability of this concept to provide a basis for recommendations on further concept development programs. ANL, along with other organizations, is carrying out the assessment activities specified in that plan. The ANL efforts in this program are defined below.

I. Introduction

Although the sun is, in effect, an unlimited source of energy, there are two factors that inhibit extensive development of solar electric energy-generation systems on the earth. First, the sun's energy is diffuse, and second, solar energy at the earth's surface is intermittent. The sunshine reaches the earth's surface only part of each 24 hours and is often obscured by clouds. However, baseload electricity (24-hour operation) can be generated in space, where a solar energy collector is illuminated by the sun more than 99 percent of the time, regardless of weather or the day-night cycles of the earth. Such a Satellite Power System (SPS) has been under study by the National Aeronautics and Space Administration (NASA) since 1972, and by the Department of Energy since 1976.

Figure 1 shows how such a system would function. A large collector, several square miles in area, covered with photovoltaic solar cells converts solar power into electricity. The electricity is continuously converted into microwave power for transmission to large receiving, rectifying antennas (rectennas) on earth. These rectennas in turn reconvert the beamed microwave power into electricity and feed it into a utility grid. Such a satellite might weigh as much as 100,000 tons, and deliver 5,000 megawatts of power continuously to its ground-receiving station. A system of 30 to 40 or more of these satellites in geostationary orbit of 22,300 miles above the earth would provide a significant portion of the total U.S. electric power requirements.

SPS technological studies, performed by NASA since 1972, have uncovered no insurmountable scientific problems, although basic questions remain relating to the feasibility and cost of the large scale engineering tasks required. In response to the growing interest in the possibility of using space and space

* Much of the material presented here was taken from a draft copy of a DOE/ER SPS Program Summary of September 1978 prepared by the Planning Research Corporation under the direction of C. E. Bloomquist.

technology to provide significant quantities of energy for utilization on earth, a Task Group investigated this potential energy system and recommended a specific program of studies to determine the viability of the SPS concept and to identify any barriers to SPS implementation. DOE then prepared the SPS Concept Development and Evaluation Program Plan¹ and formed the SPS Project Office which is now in the Office of Energy Research and has overall management responsibility for the joint DOE/NASA program.

The objective of the joint DOE/NASA SPS concept development and evaluation program is to achieve by the end of 1980 an initial understanding of the technical feasibility, economic practicability, and the social and environmental acceptability of the SPS concept so that recommendations concerning program continuation can be made. The four major study areas that have been identified and are being undertaken during the concept development and evaluation program are:

Systems Definition

Environmental Assessment--Evaluation of Environmental Health and Safety Factors

Societal Assessment

Comparative Assessment of Alternative Energy Systems

Of these, systems definition is the responsibility of NASA, environmental and comparative assessments are being managed by Argonne, and the Planning Research Corporation is managing the societal assessment. Argonne has established an SPS Program Office and, in addition to the two study areas, is responsible for the planning and analysis function for the entire DOE effort.

II. Accomplishments in 1978

Environmental Assessment

An energy system has questionable value if its implementation sacrifices the health, safety, or welfare of the general public. The SPS Concept Development and Evaluation Program Plan therefore includes detailed study plans to determine if any of the potential environmental, health, and safety effects are so adverse as to discourage development of the SPS system.

Key environmental issues have been identified and DOE/ANL has initiated a number of specific studies to resolve some of these issues in FY 1978, with several studies continuing through FY 1979. A preliminary Environmental Assessment for the Satellite Power System was completed in September 1978.² The report summarizes the present state of knowledge and outlines the needed research yet to be done. The results of the ongoing studies and future efforts will lead to a more definitive understanding of the SPS impact on public health and safety and environmental quality, and will become inputs to the final Environmental Impact Assessment (EIA) of the SPS concept.

Comparative Assessment

Establishment of the technical, environmental, and economic feasibility of an SPS energy system does not necessarily imply that it should be built. Before

a commitment to SPS can be considered, DOE/ANL will complete a comparative assessment of the SPS and other advanced energy systems to determine if the implementation of the SPS would offer a distinct benefit. Other energy systems to be considered in this comparative evaluation include coal systems, nuclear, and solar energy systems such as central station photovoltaic, Ocean Thermal Energy Conversion (OTEC), and biomass. Work has been initiated at ANL to develop a comparative assessment methodology so that the different energy systems can be compared on a common basis. A comparative data base will be developed from which the assessments will be made. The comparative assessment will consider all the environmental, societal, economic and technical issues treated in the tasks above.

The comparative assessment activity during FY 1978 has resulted in the following products:

- Comparative methodology review and recommendation for a preliminary methodology for the comparative assessment.

- Preliminary direct energy cost comparison for SPS, light water reactor, liquid metal fast breeder reactor, ocean thermal energy conversion, combined cycle (gasification/combustion), and central station photovoltaic systems. This cost comparison includes stand-alone as well as system cost analyses.

- Analyses of the catastrophic environmental impacts of alternative technologies were begun during FY 1978. CO₂, waste heat, air pollution, nuclear safeguards, and radiation waste problems were addressed.

III. References

1. Satellite Power System (SPS) Concept Development and Evaluation Program Plan, July 1977-August 1980, DOE/ET-0034, February 1978.
2. Preliminary Environmental Assessment for the Satellite Power System, Vols. 1 and 2, SPS-EA-001, September 1978.

Fig. 1. Major Elements of a Satellite Power System (SPS)

Title of Paper: The Satellite Power System Concept
Evaluation

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BIOCONVERSION

ENVIRONMENTAL PLANNING FOR FUELS FROM BIOMASS TECHNOLOGIES

J. E. Dunwoody

Abstract

Technologies for producing clean fuels from biomass were assessed for their potential environmental side effects. Key environmental issues were identified, and a program of research was planned to address both these issues and the environmental impacts of areas of high-priority biomass development. An Environmental Assessment of the entire fuels from the biomass program was planned by Argonne National Laboratory and is being carried out by the Environmental Impact Studies Division of Oak Ridge National Laboratory. Argonne served as the technical monitor for DOE on the Environmental Impact Statement for the Wheelabrator Frye Corporation direct biomass combustion facility in Maine.

I. Introduction

The Department of Energy (DOE) conducts environmental planning and research at a number of levels. The Office of the Assistant Secretary for Environment has Department-wide authority to coordinate the environmental planning and research efforts. This coordination is achieved through the preparation and revision of annual Environmental Development Plans in each of the major technology areas. Concurrently, each technology development or applications branch in the Department is responsible for resolving the environmental issues that arise with respect to their particular technology.

To date, there has been broad recognition by environmental scientists that the key determinant to widespread adoption of biomass technologies will be the way in which the environmental impacts are handled. No other near term solar technology has the potential to have such large environmental impacts as do the family of biomass energy technologies.

Numerous recent articles and papers (^{3,4,5,6}) on the environmental impacts of biomass energy technologies have tended to reiterate the same concerns. Little original research has been performed or adapted to directly address the environmental impact of biomass technologies.

To understand the potential for environmental impact by biomass energy technologies, it is important to appreciate their potential contribution to the national energy supply.

The general consensus of these projections is that it should be quite reasonable to expect biomass sources to displace 2-4 quads of conventional

fuels by the year 2000. The recently released Solar Domestic Policy Review projects that 5.5 quads of energy could be displaced by the use of biomass by the year 2000.⁷

Table 1 summarizes the anticipated availability of primary biomass resources by various time periods (synthesis of available data by author). To comprehend the potential for environmental change it is necessary to understand the commitment necessary to produce these quantities of primary resources.

The manures and mill residues are readily available as presently generated although increasingly mill residues are being sold for commercial uses such as particle board, pulp fibre and mulch. The logging residues of 97mm DTE/yr represent the woody material left after forest harvesting for saw timber or pulp. To be used for fuel, this residue would have to be harvested and transported to its site of use. Much of the forest terrain is very steep and this residue serves a valuable (although poorly quantified) function in erosion protection, soil organic matter supply, nutrient return and protection for stand reestablishment.

Table 1. Availability of Primary Biomass Resources

Biomass Source	Quantity (mm DTE*/yr)			Delivered Cost, 1985 (\$/mm Btu)
	1978	1985	2000	
Silviculture of Biomass Farms	- -	265 265	491 491	\$1.25 - \$2.00 \$3.00
Forest Residues				
- Logging	97	97	104	\$1.50 - \$2.40
- Standing	100	100	100	\$0.75 - \$1.30
Mill Residues	28	28	28	\$0.75
Crop Residues	212	212	220	\$2.00
Manures	22	22	25	\$0.75
TOTAL	459	724	968	-

*DTE = dry ton equivalent. 100 mm DTE = 1.7 quads.

The standing forest resource of 100 mm DTE reflects the estimate of annual forest growth in excess of conventional harvest demand. Although harvest quantities are projected to increase, it is assumed that forest management practices will also improve, resulting in a fairly constant excess of forest production over demand. However, it should be noted that a large part of this 100 mm DTE is likely to be on small individual lots, thus making it difficult to assemble large quantities, or in very inaccessible areas from which greater than normal environmental damage will occur in the harvesting process.

Crop residues in excess of 200 mm DTE annually are expected to either be returned to the land or wasted by actions such as burning. These could potentially be harvested and converted into usable fuel. Considerable debate⁶ has developed over how much of this residue can be both economically and safely removed without adversely affecting the soil. A general consensus appears to be between 50% and 75%, although the impact of changed patterns of residue removal will have to be studied in detail for many different soil and crop types. Residue removal has the potential to impact the 400 million acres that are presently cropped in the U.S.

Intensive farming to raise crops specifically for their energy value might be done on the approximately 100 million acres designated as marginal crop land. Irrespective of whether this land is used for silviculture or annual energy crop production, it has the potential to increase the amount of land subject to the impacts of intensive agriculture by 25%. This must be considered a major potential environmental change.

II. Accomplishments During 1978

Following a detailed review of the research and development program of the Fuels from Biomass Branch, an Environmental Research Program⁸ was prepared. This was designed to build on the topics outlined in the 1977 biomass Environmental Development Plan⁹ and to address additional key issues where appropriate. The research suggested in this plan addressed only the most important environmental issues with potential to delay or impede the application of biomass technologies. The issues included:

Soil erosion and nutrient depletion

Impact of disease and weather

Water pollution from production and harvesting operations

Toxicity of conversion by-products

Air and water pollution from gasification and combustion

Water pollution from anaerobic digestion and fermentation

Specific experimental approaches and tasks to resolve these issues were defined.

In addition, the previous resource assessment work was reviewed and additional key resource assessment areas were defined. These included:

Assessment of "deliverable" biomass resources

Impact of limited water availability and environmental factors on terrestrial resource production

Impact of sulfur dioxide emissions and acid rainfall on plant growth

Availability of land and water areas for brackish and fresh water plant growth

Recommended approaches to resolving these assessment issues were also defined.

During 1977, the FFB branch awarded a contract to the Wheelabrator Frye Corporation to design (Phase I) a 50MWe direct biomass conversion facility. This work is progressing and during 1978 preparation of the required Environmental Impact Statement was begun. ANL has managed preparation of this EIS for DOE.

Guidelines for the programmatic Environmental Impact Statement for the FFB program were prepared. This work will be undertaken at Oak Ridge National Laboratory during FY1979 with DOE management coordination by ANL.

As part of the Department-wide (DOE) environmental planning process, the Environmental Readiness Document¹⁰ for FFB was prepared. This Document lays out the current status of information and perceived environmental research needs for each technology. It will form the basis for the new Environmental Development Plan for biomass energy technologies. In-house research on the potential impact of forest pathology¹ and biofuel genetic resource development² on biomass production was undertaken.

III. Planned Activities for 1979

As the lead laboratory for biomass environmental research, Argonne will continue to provide technical assistance to the Department of Energy as manager of the overall environmental research program for fuels from biomass. Substantial assistance will also be sought from other research facilities in this area including the Solar Energy Research Institute, Oak Ridge National Laboratory, and Pacific Northwest Laboratory. Research will be initiated in the following areas in FY 1979:

Soil erosion and nutrient depletion by residue removal

Ecosystem impacts of whole forest harvesting

Air and water pollution from biomass combustion and gasification

Fermentation sludge disposal

Region wide environmental impact assessments in three regions

The majority of these studies are planned as multiyear programs. Different procurement mechanisms will be used to obtain suitable research teams to conduct the research tasks. ANL sponsored research in the area of air and water pollution from biomass combustion and gasification will build on resources and experience developed in coal conversion research.

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CENTRAL RECEIVER SOLAR THERMAL POWER

MATERIALS TESTING FOR SOLAR CENTRAL- RECEIVER THERMAL POWER SYSTEMS

S. Majumdar

Abstract

Several features of solar central-receiver power systems present materials problems different from those normally encountered in fossil-fuel plants. The thermal loading of critical components is highly cyclic because of the basic diurnal cycle and the additional effect of intermittent cloud cover. Also, in central-receiver systems using a "once-through" boiler design, fatigue problems arise from the phenomenon of departure from nucleate boiling, which occurs in the boiler tubing.

In some advanced designs for future solar power systems, liquid sodium is proposed as the coolant for the central receiver. The Liquid Metal Fast Breeder Reactor program has provided considerable information on sodium effects on structural materials. This information, particularly with respect to material compatibility with sodium and sodium effects on elevated-temperature mechanical properties, needs to be reviewed in light of the anticipated operating conditions associated with solar central-receiver systems.

In response to these needs, a materials program has been developed. The program includes biaxial-creep fatigue testing of Incoloy 800 and Type 316H stainless steel superheater tubing, high-cycle fatigue testing of Incoloy 800 tubing, and the preparation of a literature review on sodium effects on candidate materials.

The literature review on sodium effects has been completed. A summary of available creep-fatigue data on Incoloy 800 and 800H has been compiled. Test equipment for the high-cycle fatigue tests has been procured. In the present report, the results of eight biaxial creep-fatigue tests on Type 316H stainless steel are discussed.

I. Introduction

The present program is concerned with the determination of specific elevated-temperature mechanical properties of materials used for critical components in solar central-receiver power systems. Several general features of solar central-receiver operating conditions are likely to create difficult structural design problems. The first of these is the highly cyclic nature of the thermal loading of critical components. Solar plants will undergo at least one major start-up and shut-down cycle per day, with the likelihood of additional thermal cycles being imposed by intermittent cloud cover and unscheduled maintenance and repair. Thus critical elevated-temperature components may be

expected to accumulate on the order of tens of thousands of thermal and associated strain cycles over a 30-year design life. In addition, repeated thermal cycling of superheater or boiler tubing while under internal pressure can lead to incremental growth or ratcheting. The analyst must therefore design against structural failure due to thermal fatigue and creep-fatigue interaction and must also avoid excessive deformation due to incremental growth.

A related feature of solar central receiver operation is the phenomenon of departure from nucleate boiling (DNB) that occurs in the boiler tubing. During daytime operation, coolant water from the condenser first experiences local, or nucleate, boiling as it travels through the boiler tubing. With further heating, general, or film, boiling occurs somewhat farther along the tubing. Since the efficiency of heat transfer from the inner wall of the boiler tubing to the coolant is greatly decreased with the onset of film boiling (i.e., the departure from nucleate boiling), a rather abrupt increase in inner wall temperature is present at the location where DNB occurs. The position of this boundary between film and nucleate boiling in the boiler tubing generally fluctuates in a cyclic manner with time, and the inner wall in this fluctuating region experiences rapid alternate heating and cooling. The frequency of the temperature and associated strain cycles is typically on the order of one Hz so that 10^8 or more cycles may be accumulated over the life of the tubing. Elevated-temperature high-cycle fatigue data on boiler tubing materials are therefore needed to design against possible failure associated with DNB.

The third aspect of solar-plant operating conditions likely to cause design difficulties is that, during steady-state operation, the boiler and superheater tubing will be loaded nonaxisymmetrically at elevated temperatures. In particular, critical passes of the superheater tubing will be loaded during daytime operation such that the outer tubing wall on the high-temperature side will experience a large compressive axial stress and a moderate compressive hoop stress. On the other hand, the inner wall on the high-temperature side will be subjected to a compressive axial stress and a small tensile hoop stress. Considerable constitutive relation information under compressive and mixed tensile-plus-compressive creep conditions will be required to permit structural analyses of the components. In addition, failure criteria for nonaxisymmetric multiaxial tensile-plus-compressive creep-fatigue conditions must be developed. Finally, the nonaxisymmetric loading further complicates the ratcheting analysis.

In some of the more advanced designs for future solar central receiver systems, the use of liquid sodium is proposed as the coolant in the central receiver tower. The heated sodium would flow from the tower to a steam generator at ground level, where the steam to drive the turbines would be produced. Such an arrangement offers several advantages over the direct generation of steam in the receiver tower, including (1) the benefits of the superior heat-transfer characteristics of the sodium coolant, (2) the elimination of the high internal pressure in the receiver tubing, and (3) the elimination of problems associated with stress-corrosion cracking and departure from nucleate boiling in the receiver tubing. Considerable information has been obtained on sodium effects on structural materials in the Liquid Metal Fast Breeder Reactor (LMFBR) program. However, this information, particularly with respect to material sodium compatibility and sodium effects on elevated-temperature mechanical properties, needs to be reviewed and extended to the materials and anticipated operating conditions associated with solar central-receiver systems.

The present program has been developed in response to the need outlined above and is divided into three subtasks. The first subtask is concerned with biaxial creep-fatigue testing of Type 316H stainless steel superheater tubing and the test matrix is shown in Table 1. The second subtask is concerned with a comprehensive survey of available information on sodium effects on candidate materials for solar thermal steam generators. The third subtask is concerned with biaxial creep fatigue and high-cycle fatigue testing of Incoloy 800 tubing.

II. Accomplishments During 1978

Eight tests under subtask 1 have been completed and are summarized in Table 2. The results so far tend to indicate that the application of internal pressure can induce considerable ratcheting in the tubes and a one-minute compressive hold in the axial direction may be damaging. However, more tests are required to verify this.

A literature review of sodium effects on mechanical properties has been completed under subtask 2 and a report will soon be published.

A summary of all available creep-fatigue data in Incoloy 800 and 800H has been published as an ANL report under subtask 3. Also loading frames and necessary electronics for conducting high-cycle fatigue of Incoloy 800 have been procured.

III. Planned Activities for 1979

The test matrix shown in Table 1 will be completed under subtask 1.

Biaxial creep-fatigue testing of Incoloy 800 will begin following completion of subtask 1. The test matrix will be the same as for Type 316H stainless steel under subtask 1.

High-cycle fatigue testing will also be carried out during the year. A proposed test matrix is shown in Table 3.

Table 1. Test Matrix for Subtask 1.

Temperature = 593°C

Cyclic Axial Strain Rate = 0.004 s^{-1}

Axial $\Delta\epsilon_t$ (%)	P_i (MPa)	Hold Time (min)	Expected Life	
			N_f	t_f (h)
0.5	0	0	15,000	10
	7.6	0	10,000	7
	13.8	0	10,000	7
	0	1C	10,000	175
	7.6	1C	10,000	175
	13.8	1C	10,000	175
	7.6	1T	5,000	90
	7.6	5C	10,000	840

Total Time = 1479 h

Add 100% for Duplicate Tests = 1479 h

Total Testing Time = 3000 h

Table 2. Summary of Biaxial Fatigue Data for 316H Stainless Steel.

Test. No.	Hold Time (min)	Temp. (°C)	Int. Press. (MPa)	Axial Strain Range		Diametral Strain Range (%)	Axial Stress		Average Hoop Stress (MPa)	N _f (cycles)	Mean Diametral Strain @ N _f (%)
				Total (%)	Plastic (%)		Range (MPa)	Mean (MPa)			
997	0	574	0	0.51	0.19	0.20	493	1	0	14156	-0.02
999	0	576	0	0.50	0.19	0.19	482	0	0	8110	-0.02
1001	0	568	7.58	0.50	0.17	0.19	510	19	42	16661	+1.05
1012	0	577	7.58	0.50	0.17	0.20	500	20	42	9229	+0.96
1031	0	609	13.79	0.50	0.15	0.17	535	1	76	6739	+2.50
1027*	1C	618	0	0.50	0.17	0.21	514	7	0	4047	-0.13
1024**	1C	611	7.58	0.50	0.18	0.18	498	-5	42	5369	+1.19
1033	1C	606	7.58	0.50	0.17	0.18	507	12	42	4538	+0.83

*Specimen overstrained due to power interruption.

**Specimen failed at thermocouple.

Table 3. Proposed Test Matrix for Incoloy 800 at 593°C.

Int. Pressure (MPa)	Axial Strain Range (%)	Frequency (Hz)	Strain Rate		Estimated		Maximum	
			Tens. (s ⁻¹)	Comp. (s ⁻¹)	N _f	t _f (hr)	N _f	t _f (hr)
0	0.5	10	0.1	0.1	40,000	1.1	10 ⁶	27.8
	0.4	12.5	0.1	0.1	10 ⁵	2.2	3 x 10 ⁶	66.7
	0.3	16.7	0.1	0.1	10 ⁶	16.6	5 x 10 ⁷	832
6.9	0.5	10	0.1	0.1	40,000	1.1	10 ⁶	27.8
	0.4	12.5	0.1	0.1	10 ⁵	2.2	3 x 10 ⁶	66.7
	0.3	16.7	0.1	0.1	10 ⁶	16.6	5 x 10 ⁷	832
	0.25	20	0.1	0.1	10 ⁸	1389	10 ¹⁰	138,900
0	0.5	1	0.01	0.01	40,000	11	10 ⁶	278
	0.4	1.25	0.01	0.01	10 ⁵	22	3 x 10 ⁶	667
6.9	0.5	1	0.01	0.01	40,000	11	10 ⁶	278
	0.4	1.25	0.01	0.01	10 ⁵	22	3 x 10 ⁶	667
0	0.4	2.27	0.01	0.1	30,000	3.7	8 x 10 ⁵	98
6.9	0.4	2.27	0.01	0.1	30,000	3.7	8 x 10 ⁵	98

Estimated Total Test Time = 1502 hr, $t_{\max} = 5339$ hr (Using Runout = 1400 hr)

Allowing 100% for Duplicate Tests Total Estimated Testing Time = 3000 hr, $t_{\max} = 11,000$ hr

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STTF: Proposed Second-Stage Concentrator

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Abstract

The 5MWth Solar Thermal Test Facility at Sandia Laboratories was optimized for full-scale receiver testing. However, an early test particularly important to the US-DOE Solar Thermal Program is that of a single vertical McDonnell-Douglas panel similar to those in the 24-panel receiver proposed for the 10MWe Barstow plant. The narrow panel width relative to the focussed beam spot reduces the power intercepted by the panel below the minimum acceptable for meaningful testing. This paper summarizes a design study performed at Argonne National Laboratory in which various configurations of Compound Parabolic Concentrators were investigated as a possible second-stage concentrator on the STTF tower. The recommended configuration, a two-segment CPC design, intercepts and delivers the power necessary for both acceptance and overstress testing of the McDonnell-Douglas receiver panel while minimizing the added mechanical complexity.

I. Introduction

The 5MWth Solar Thermal Test Facility (STTF) at Sandia Laboratories consists of a field of 222 Martin-Marietta heliostats redirecting and concentrating solar energy into various test bays at different elevations on a 60m tower. The heliostats are laid out on 9.7m centers in east-west rows to the north of the tower. The spacing between rows varies from 12m at the south end to 21m at the north end of the field. The rows are trimmed in length so that the field is roughly fan-shaped, with its apex at the tower, and subtending $\pm 50^\circ$ east and west of true north. Each heliostat consists of 25 mirror facets and has a total mirror area of 37m^2 . The facets can be individually aligned and focussed to minimize the size of the collective image. Under optimum sun and heliostat conditions, the total heliostat field is capable of concentrating more than 5MWth into a 2.5m diameter spot on a vertical target plane at the top of the tower.

An early test at the STTF particularly important to the US-DOE Solar Thermal Program is that of a single vertical McDonnell-Douglas (MDAC) panel similar to those in the 24-panel receiver proposed for the 10MWe Barstow plant. This panel is 0.89m wide and 17.1m high, although only 12.5m of its length will be irradiated. To meet the test objectives, the integrated flux on the receiver panel must exceed 3MWth. Due to its narrow width, however, the MDAC panel can intercept only about 2.75MWth out of the more than 5MWth delivered by the heliostat field.

During 1978, Argonne National Laboratory performed a design study for Sandia in which various configurations of Compound Parabolic Concentrators (CPC)¹ were investigated as a possible second-stage, or secondary, concentrator on the STTF tower. By making the MDAC panel appear wider, a secondary optical concentrator can increase the net power to the panel. Due to its nonimaging optics, the CPC stands out in this application, since it has the widest possible angular field-of-view for a given level of concentration, and since it does not concentrate to a mere line image. The objective of the study was to arrive at a design which minimized added mechanical complexity while delivering at least 3MWth, and preferably more, to the MDAC panel. It was concluded that these criteria can best be met with a two-segment CPC design described below.

II. Accomplishments in 1978

A preliminary investigation, based on summary data from Sandia, revealed that a single CPC-trough coupled to the MDAC panel would probably be an inadequate solution to the problem. In order to view the full 100° angular width of the 222 heliostat field, such a concentrator must be restricted to a geometrical concentration ratio less than 1.3, which results in too narrow an entrance aperture to intercept the desired power. If the concentration ratio is raised above 1.3, the wider entrance aperture does intercept more of the flux from the heliostat field, but the concomitant narrowing of the angular field-of-view results in rejection of the flux contributions from increasing numbers of heliostats on the east and west edges of the field. It appeared that the 3MWth threshold could be met only under the very best of circumstances using a single concentrator.

The above conclusion led to the multi-segment concentrator concept. The MDAC receiver panel is divided conceptually into a number of zones from top to bottom, with each zone illuminated by its own concentrator segment which, in turn, views only a restricted sector of heliostats in the field. In the case of two equal zones, the upper zone's concentrator segment could be irradiated by the 111 heliostats lying east of north, for example, while the lower zone's segment is irradiated by the 111 heliostats lying west of north. The two CPC-segments each now require only a 50° full acceptance angle, which allows a maximum geometrical concentration ratio of nearly 2.5. Even higher concentration ratios can be reached in 3-, 4-, or more segment designs. Since the entire receiver panel is fixed in orientation, facing due north, asymmetric CPC's are required¹ for viewing heliostat sectors lying east and west of north, but this has the advantage that the resulting entrance apertures are more nearly normal to the respective incident flux.

In order to study these concentrator configurations quantitatively, a computational tool was needed. Sandia possessed the elaborate HELIOS code which could compute in detail the flux contribution at a point on a target from a given subfacet of a given facet of a given heliostat, but which, at that time, had no capability for treating secondary concentrators, and which was very costly to execute repeatedly in any case. To facilitate the study at ANL a short, fast code was developed to mimic the HELIOS code, but at a greatly reduced level of detail. The short code calculates the total power normally incident on an arbitrary planar target aperture or set of apertures from some or all of

the heliostats in the field. The short code was verified for the case of a bare receiver using Sandia-supplied HELIOS results for focussed heliostats with 0.8 reflectivity and 3mrad error distribution for comparison, the short code was verified for the case of a bare receiver.

Three secondary concentrator configurations were then studied, calculating fluxes for solar noon at fall equinox with 1Kw/m^2 insolation. The MDAC panel was assumed to be flanked on either side by line flux sensors for a total receiver width of 1m. Accordingly, the exit aperture width for each CPC segment was set at 1.0m. Further, each CPC-segment was designed to limit exiting light rays to a maximum transverse exit angle² of 80° to avoid grazing angles of incidence on the absorber surface.

The one-segment concentrator configuration consists of a symmetric, untruncated CPC with a full angular acceptance of 90° and a geometrical concentration ratio of 1.39 coupled to the MDAC panel. The entrance aperture of the system is 1.39m wide by 12.5m high, and faces due north. For the conditions stated previously, this aperture intercepts 3.75MWth normally incident from the 210 heliostats within its angular field-of-view. Increasing the angular field-of-view to include the remaining 12 heliostats results in a net reduction in the intercepted power due to the narrower aperture width. With polished aluminum mirrors, the optical transmission of the concentrator would be ≈ 0.9 , resulting in a throughput of 3.38MWth. Assuming a uniform distribution of flux at the exit aperture of the concentrator, the net power delivered to the MDAC panel would be 3.00MWth.

The two-segment concentrator configuration consists of two asymmetric CPC's which are mirror images of one another. Each has a full angular acceptance of 50° , and each is truncated to an actual geometrical concentration ratio of 2.0. The entrance aperture of each is 2.0m wide by 6.25m high, the lower segment aperture facing 22.5° east of north and the upper facing 22.5° west of north. The entrance apertures collectively intercept 5.10MWth normally incident from the 218 heliostats within their angular fields-of-view. As before, the optical transmission of each concentrator segment is ≈ 0.88 , the throughput of the concentrators is 4.4MWth, and the net power intercepted by the MDAC panel is 3.99MWth.

The three-segment concentrator configuration consists of two (mirror-image) asymmetric CPC's, and one symmetric CPC, each with a full angular acceptance of 36° , and each truncated to an actual geometrical concentration ratio of 2.5. The entrance aperture of each is 2.5m wide by 4.17m high. The lowest aperture faces 30° east of north, the center aperture faces due north, and the highest aperture faces 30° west of north. These entrance apertures collectively intercept 5.46MWth normally incident from the 216 heliostats within their angular fields-of-view. Now the optical transmission is ≈ 0.87 , the throughput is 4.75MWth, and the net power intercepted by the MDAC panel is 4.23MWth.

Based on this study, and the criteria discussed in the introduction, the two-segment configuration is considered the most promising design for the STTF facility. The power delivered to the MDAC panel is sufficiently

in excess of the minimum requirements that less-than-perfect materials and test conditions can be tolerated, and the number of different mirror components and general level of mechanical complexity is the minimum required to reach this power level. This was the design recommended to Sandia.

III. Planned Activities for 1979

The most important remaining work is the consideration of the actual flux distribution along and across the MDAC panel. This would confirm that there will be no flux "hot" spots on the panel, and would also provide diagnostic information for use in the analysis of test results.

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WIND ENERGY CONVERSION

NOCTURNAL BOUNDARY-LAYER WINDS

D. L. Sisterson and B. B. Hicks

ABSTRACT

A study of the nature, frequency, and distribution of nocturnal low-level wind maxima in the central U.S. is being made by utilizing data already collected by existing instrumented towers. The uncritical use of empirical power laws in determining wind profiles does not take the nocturnal wind maxima into consideration. These phenomena present both a potential hazard and an unrealized resource to wind energy projects in the midwest and Great Plains.

I. Introduction

It is now fairly well known that layers of faster moving air can occur in the lower atmosphere once frictional drag at the surface has been sufficiently reduced by the formation of cooler layers of air near the ground (ground-based inversions) at or near sunset. Once "decoupled" in this way, winds are free to accelerate in response to existing pressure gradients; in fact, some overshooting takes place as the flow attempts to establish a new balance with inertial forces, and extreme departures from simple wind profiles occur. Strongest manifestations of this phenomenon develop over land with favorable combinations of relatively smooth terrain, light to moderate surface winds in the late afternoon, and clear evening skies that permit unrestricted radiative cooling of the surface. The mechanism outlined above follows Blackadar's 1957 explanation of the formation of the nocturnal low-level wind maxima through momentum decoupling and inertial oscillation (1). Observations of these maxima (extensive, broad layers of faster moving air rather than narrow jets) date back as far as 1938 (2), and nighttime aircraft landing accidents in the midwest and Great Plains have been attributed to the strong shears that accompany the phenomenon.

Recent serial wind-profile measurements made by atmospheric scientists of ANL's Radiological and Environmental Research Division (as a part of an ongoing DOE-sponsored study of pollutant transport in the lower atmosphere) indicate that these decoupled low-level wind maxima probably form more frequently and at significantly lower altitudes than had previously been supposed (see Figure 1). Since these maxima are associated with near-zero wind velocities near the surface and unusually strong vertical shears in the horizontal winds in the first 30-150 m above ground (3), they are of particular interest to the wind energy community. The wind speed representing the wind maxima at 150 m at night is typically twice the wind speeds at 500 m during the day.

Fig. 1. Time-height cross section of average, normalized winds observed in midsummer over Sangamon County, Illinois (3).

The uncritical use of simplified wind profile representations for wind power assessment (such as the empirical $1/7$ power law) will systematically underestimate the wind energy potential of the central U.S., since this does not take the nocturnal low-level wind maximum into consideration. Moreover, the occurrence of these wind maxima may present a potential hazard to large, central-station wind machines; the long blades of horizontal-axis machines may be subjected to excessive strains as they move in and out of faster-moving air layers aloft. On the other hand, dispersed, small wind turbines mounted on tall towers may be able to tap this elevated energy source in conditions where standard observations report little or no wind at all.

In the present study wind data already collected by large instrumented towers are being used to determine the nature, frequency, and distribution of nocturnal low-level wind maxima, with a view toward the development of objective siting criteria for wind turbines in the central U.S.

II. Accomplishments During 1978

Initial investigation of the occurrence of the nocturnal low-level wind maxima has been limited to the study of wind data from the ANL 50-m tower and the 488-m WKY-TV tower located near Norman, Oklahoma. The records from the latter tower are currently being converted to a standard format for analysis of nocturnal wind-maxima events.

Percentage frequency distributions of power law exponent (p) values based on the 19- and 75-ft wind speeds for four years of nighttime hours (1961-1964) as determined from Argonne data are shown in Figure 2. The curve $p > .14$ represents the percent occurrence of wind shears greater than predicted by the $1/7$ power law; $p \geq .45$ represents the occurrence of fully decoupled conditions when the amplitude of the low-level wind maxima is greatest. Note that on 10% of winter evenings and on 50% of summer evenings, evidence of a low-level wind maximum is found, despite the relatively irregular terrain surrounding the ANL site. Since the tower is below the peak of the wind maxima, methods of estimating this height are being studied.

Fig. 2. Percentage frequency distribution of p-values based on the 19- and 75-foot wind speeds for nighttime hours for 1961-1964 at Argonne.

III. Planned Activities for 1979

The data obtained from the ANL and WKY-TV towers will be used to define improved boundary-layer scaling procedures for generalizing empirical siting criteria. In addition, wind-shear/wind-maximum forecast nomograms will be constructed to aid the assessment of the hazard to large machines. Although developed in terms of relatively sophisticated micrometeorological measurements, these procedures would be parameterized for use with standard meteorological observations.

Wind data from additional towers available to test the nomograms are listed below:

1. Quad Cities tower (100 m) in Illinois, with data available from 1973-present;
2. Dresden tower (120 m) in Illinois, with data available from 1969-1973; and
3. Monticello tower (100 m) in Minnesota, with data available from 1973-present.

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