ARGONNE SOLAR ENERGY PROGRAM
ANNUAL REPORT

Summary of Solar Program Activities
for Fiscal Year 1979

MASTER

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS
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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois  60439

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for Fiscal Year 1979

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June 1980

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Assistant Secretary for Conservation and Solar Energy
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ARGONNE SOLAR ENERGY PROGRAM ANNUAL REPORT

Summary of Solar Program Activities for FY 1979

ABSTRACT

This report describes the R&D work done at Argonne National Laboratory on solar energy technologies during the period October 1, 1978, to September 30, 1979. Technical areas included in the ANL solar program are solar energy collection, heating and cooling, thermal energy storage, ocean thermal energy conversion, photovoltaics, biomass conversion, satellite power systems, and solar liquid-metal MHD power systems.

INTRODUCTION

This is the second in a series of annual reports on the various solar energy programs at Argonne. As with the first volume, this report contains brief summaries of the current efforts at ANL to develop processes and systems for the utilization of solar energy. For the most part, these investigations have been sponsored by the U.S. Department of Energy and, as such, contribute to the DOE mission to develop and promote the commercialization of all solar technologies that can be made economically competitive with conventional energy supply technologies.

The solar energy program at ANL, though only about 2.1% of the total laboratory effort, has grown considerably from its beginning in 1974, when the program to develop the compound parabolic concentrator (CPC) was initiated. This program, which was carried out jointly with the University of Chicago, has been highly successful and is still being continued as new applications for the CPC concept have been discovered. Since that beginning some six years ago, the solar energy work at ANL has expanded to several new areas including thermal energy storage, ocean thermal energy conversion, solar heating and cooling, the solar power satellite concept, bioconversion, solar thermal power, and photovoltaics. The principal 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 (OTEC) power system development
Materials development for photovoltaics, heating and cooling systems, solar thermal power, and OTEC.

Environmental and technology assessment for the bioconversion, OTEC, and satellite power system programs.

The total effort on the programs during FY 1979 amounted to some 70 person-years, up from about 40 during FY 1978.

The following pages contain brief summaries of each of the solar energy programs undertaken at ANL during FY 1979. At the end of each program description, other relevant information about the program, including DOE sponsor and ANL principal investigator and person to contact for further information, is given.
HEATING AND COOLING
CAFETERIA SOLAR DEMONSTRATION PROJECT

R. B. Hagemann and C. J. Vachta

Abstract

A solar water heating system has been designed and installed on the cafeteria at Argonne's main site near Chicago. In operation for 10 months, this retrofit system preheats water for dishwashing and cooking. System performance is continuously monitored through the National Solar Data Network.

I. Introduction

A solar water heating system has been installed on the cafeteria building at Argonne's main site near Chicago and is providing domestic hot water for dishwashing and cooking. The project was initiated, designed and constructed by Argonne. It is funded through the Department of Energy's national program for solar heating and cooling of buildings and has been selected for continuous performance monitoring under the National Solar Data Network. IBM Corporation, under DOE contract, and Argonne installed the data acquisition system. IBM has been providing system performance analysis reports using the acquired data.

II. System Description

The cafeteria solar energy system has been designed to supply 375.2 x 10^6 Btu per year, which is 56.5% of the energy needed to heat approximately 4,000 gallons of water each day to 140°F. This retrofit system preheats water for the existing domestic hot water (DHW) system.

The collector subsystem has 72 flat-plate, single-glazed, non-selective coated collector panels manufactured by the Chamberlain Manufacturing Company. The collector array has a gross area of 1,500 square feet and faces south tilted at 45 degrees from the horizontal. The solar collector loop uses a 50% solution of ethylene glycol and water as the heat transfer fluid. Domestic hot water is isolated from the heat transfer fluid by a double heat exchanger system. This system consists of a pump and recirculation loop between two heat exchangers. The intermediate water loop provides double-wall protection between the heat transfer fluid and the domestic hot water system. Solar-heated water is stored in two 1,000-gallon insulated tanks located above ground in a tank room. Additional heating of the water, if required to maintain a 140°F temperature, is accomplished by a steam water heater.

The solar energy system, shown schematically in Figure 1, has three modes of operation, described below.

Mode 1 - Collector-to-Storage. When there is no demand for hot water and the temperature differential between the collector fluid and the water in the storage tanks exceeds the activate setting (18°F to 20°F)
of the differential temperature controller, pumps \( P_1 \), \( P_2 \) and \( P_3 \) are turned on. This mode is terminated if the temperature differential between the collector fluid and the storage tanks is below the deactivate setting (3°F to 5°F) of the differential temperature controller. The energy absorbed by the collector fluid is transferred to the storage tanks for future use.

**Mode 2 - Storage-to-Load.** When there is a hot water demand and the solar energy system (whose control logic is described above) is not operating, makeup water from the cold water supply flows under domestic water pressure to the storage tanks, replacing the preheated water used from the tank. Pumps \( P_1 \), \( P_2 \) and \( P_3 \) are off in this mode. Preheated water from the storage tanks passes through the existing DHW heater where auxiliary energy from steam is added if required to maintain the temperature at 140°F. Hot water from the DHW heater passes through tempering valve \( V_1 \), which prevents water hotter than 140°F from being delivered to the cafeteria by adding water from the domestic cold water supply if necessary.

**Mode 3 - Collector-to-Load.** When there is a hot water demand and the solar energy system is operating, pumps \( P_1 \), \( P_2 \) and \( P_3 \) are turned on. Makeup water from the domestic cold water supply flows through heat exchanger \( HX_2 \), storage tanks 1 and 2, and through the DHW heater and tempering valve \( V_1 \) to the cafeteria.

**III. Operational Status**

The system was put into operation on February 12, 1979. On February 20, 1979, operations ceased due to a freeze-up of heat exchanger #1. A thermal syphon loop within the collector loop allowed collector fluid colder than 32°F to circulate, causing the intermediate loop water to freeze and rupture the heat exchanger tubes. System fluid temperature data obtained from the data acquisition system clearly indicated that a thermal syphon occurred and caused the damage while the system pumps were off.

Therefore, the system design was modified to include a check valve on the collector pump \( P_1 \) discharge and a pneumatically operated positive closing valve on the pump suction. The valve closes whenever pump \( P_1 \) is off or a collector fluid temperature below 35°F is sensed in heat exchanger #1. A low collector fluid temperature alarm was also installed and connected to the site central surveillance system for continuous monitoring. System operations resumed on June 13, 1979, after the heat exchanger was replaced and freeze protection modifications were completed.

**IV. System Operational Problems**

Several minor operational problems have occurred. In April 1979, the IBM data indicated that a feedback loop existed in the domestic water side of the system. Energy was being fed into the storage tanks from the domestic hot water heater. The problem was traced to the building hot water recirculating pump, which was causing hot water to recirculate through storage under conditions of no demand. This was solved by installing a check valve on the discharge of the storage tanks going to the domestic water heater.
Fig. 1. Argonne National Laboratory Solar Energy Systems Schematic
A collector panel developed an internal leak while in service. A replacement panel was received under warranty from the manufacturer and installed.

On several occasions, hose leaks have developed at the collector panel connections. These leaks have occurred in constant-torque hose clamps when pressure in the system increased as fluid was added. Current operating procedures limit the pump discharge pressure to 55 psig when adding fluid to the system. This limits the pressure at the panel hose connections and appears to have solved the leak problem. Leaks are normally repaired using screw-type hose clamps. Manufacturers of the constant-torque clamp have been contacted to obtain pressure limitations for the clamp; however, they do not have this information available. No other operational problems with the system have developed to date.

V. Instrumentation and Analysis

Data reports received from IBM indicate the following amounts of energy have been collected by the collector array.

<table>
<thead>
<tr>
<th>Month</th>
<th>Incident Energy (10^6 Btu)</th>
<th>Collected Energy (10^6 Btu)</th>
<th>% of Total Incident Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>75.7</td>
<td>27.1</td>
<td>35.8</td>
</tr>
<tr>
<td>Aug.</td>
<td>69.2</td>
<td>31.0</td>
<td>44.7</td>
</tr>
<tr>
<td>Sept.</td>
<td>80.5</td>
<td>32.4</td>
<td>40.2</td>
</tr>
<tr>
<td>Oct.*</td>
<td>52.2</td>
<td>8.1</td>
<td>15.5</td>
</tr>
<tr>
<td>Nov.</td>
<td>47.0</td>
<td>7.3</td>
<td>15.5</td>
</tr>
</tbody>
</table>

These figures agree reasonably well with the collector manufacturer's published collector efficiencies. It should be noted that these figures only represent the amount of energy collected by the solar collector panels and not the overall system efficiency. IBM has not yet released a report describing overall system performance because of instrumentation problems. Preliminary evaluation of the data, after operation began again in June 1979, indicated a thermal imbalance within the system. The problem was traced to faulty flow meters in the domestic water loop. The flow meters, supplied by IBM, were specified to have galvanized steel bodies to be compatible with the system piping; however, plain steel bodies painted grey were supplied instead. The electrolysis between the dissimilar materials caused severe corrosion within the meter bodies, severely affecting their accuracy. Therefore, the corroded flow meters will be replaced with meters having stainless steel bodies and dielectric couplings. Since valved by-passes were installed around all flow meters, the solar system will not have to shut down for meter replacement.

* Of the 31 days in October, the system operated only 24 days – 7 days shutdown were required for Instrumentation Diagnostics and Maintenance.
VI. Planned Activities for 1980

System operations and performance will be observed and monitored, and actual system performance will be compared to that anticipated.

For More Information, Contact:
S. J. Vachta  
Engineering Division,  
Bldg. 214  
(312) 972-5241

Sponsor:  
DOE Assistant Secretary for Conservation and Solar Energy  
Office of Solar Applications for Buildings  
Project Officer:  W. Utt

ANL FY 1980 Program Number: 49569  
DOE FY 1980 Budget Category: EA-02
RELIABILITY AND MATERIALS PERFORMANCE OF
SOLAR HEATING AND COOLING SYSTEMS

P. S. Chopra and R. M. Wolosewicz

Abstract

The solar reliability and materials program, initiated in FY78, collects, evaluates, and disseminates reliability, maintainability, and materials performance data from DOE-sponsored solar heating and cooling demonstration systems. During FY79, the program staff reviewed 66 operational solar energy systems, developed a reliability methodology, and assessed the reliability of solar domestic hot water systems and air-heating systems. In addition, a technique to predict scaling tendencies of the water used in solar heating and cooling systems was developed.

I. Introduction

The reliability and materials (R&M) program collects, evaluates, and disseminates reliability, maintainability, and materials performance information from operating solar energy heating and cooling demonstration systems funded by the Office of Solar Applications of the Department of Energy. The purpose of the program is to improve the design and performance of solar energy systems and reduce their cost.

II. Reliability

The reliability element of the program reports and summarizes operation and maintenance experiences at the demonstration sites. A variety of channels are used to acquire technical and operational data from each site, including the National Solar Data Network (NSDN), site visits, and site operations logs. Operational data form a portion of the permanent documentation for each solar energy site; these data are logged into an R&M library. Once early system failures are eliminated through the resolution of generic problems, operational information is used to assess system reliability.

In reviewing the performance of 66 operational systems, it was found that previously identified generic problems continue to exist (see Fig. 1). These problems include freezing, interconnection leaks between collectors or between collectors and manifolds, and control system problems. However, the frequency of these problems has been reduced. Each of these problems has been investigated and several technical reports have been published that indicate how similarly designed systems have avoided a given problem or how alternate designs can help prevent it.
System Freezing

Early program results indicated that freezing affected 33% of the solar energy systems that were reviewed. The latest results, summarized in Fig. 2, indicate that only 20% of the systems froze. Although the overall freezing incidence decreased, there was a sharp increase in the number of glycol systems that froze.

This new failure mode was caused by thermosyphoning of the glycol solution between the cold collectors and the warm collector-loop heat exchanger. When thermosyphoning occurred, the water side of the heat exchanger froze and either the heat-transfer tube bundles or the end caps were damaged.

To prevent a recurrence of this failure mode, the contractors installed check valves or motorized valves to isolate the collector-loop heat exchanger when insolation is not available. The approach will be monitored to determine its effectiveness.
Problem Incidences through June 1978

Problem Incidences from July 1978 through April 1979

Fig. 2. Incidences of Freezing Problems for Solar Heating and Cooling Systems

Control Systems

Control-system problems degraded the performance of three more systems in 1979 than were affected through June 1978, as shown in Fig. 1. However, because of the increased number of operational systems, the percentage of control-system problems decreased from 38% to 28%.

The two major control-system problems involved design and sensor calibration. Design problems arise because solar instrumentation and control systems have to be more complex than those needed in conventional systems in order to accommodate a variable energy source. Sensor calibration is important in solar energy systems because of the small temperature differences that actuate the control systems.
Interconnections

The major interconnection problems at the demonstration sites were hose leaks, system corrosion, and thermal expansion. Field data indicate that hose leakage can be attributed to improper specification of materials and to the use of clamps that loosen under service conditions. Recommendations for avoiding these problems have been issued. When the systems are operating, the temperatures of the various pipelines increase. Unless the designer accounts for thermally-induced movements, failure will occur. Field data suggest that thermal expansion problems are caused by lack of attention to engineering details.

Solar Collectors

Twenty-five of the 66 systems that were reviewed experienced 47 collector problems. Preliminary field data indicate that 35 of the 47 recorded collector problems can be placed in five major categories, as shown in Fig. 3. The remaining problems include: buckling, condensation, lack of clearance, and dust collection on the collector glazing.

The five major types of collector problems appear to be the result of poor design, thermal stress, failure of seals, and stagnation. Preliminary information suggests that the causes are not independent. For example, sealing failures can be caused by thermal stress or design deficiencies.

Data Acquisition

Reliability data continue to be acquired from the operational, DOE-sponsored, solar heating and cooling systems. This information is stored in the solar reliability and materials library and is used to identify failure
modes and components that cause operating difficulties. Some preliminary failure rate data are available and will be used to generate a solar-energy-system critical items list. As additional systems begin to operate, the preliminary data will be refined, and the actual failure rates of the components of solar energy systems will then be used to develop improved reliability assessments.

**Solar Energy System Reliability Assessments**

Reliability assessments of two solar energy systems were performed by using reliability block diagrams. The failure rate data for these assessments were obtained from the non-nuclear portion of WASH 1400. The failure rate of a single collector panel was estimated at one failure in 10 years.

The results of the reliability assessments for a solar domestic hot-water system and for a conventional system are presented in Fig. 4. For a solar energy system having a pump with a median failure rate, the mean life is estimated at 12,300 operating hours or approximately 5.6 years. If the system has a pump with a low failure rate, the mean life increases to 19,700 hours or 9 years. In contrast, the conventional system has a mean life of 67,000 hours or approximately 13 years.

The reliability of solar domestic hot-water systems can be increased by using redundant pump configurations; however, it is still less than that of conventional systems. A solar energy system using two pumps with median failure rates is more reliable than a system using one such pump. However, a system using one pump with a low failure rate has the same reliability as a system using redundant pumps with median failure rates (one failure every 3.4 years). Thus, choosing between these pump configurations is a matter of design preference or economics.

The results of a reliability assessment for a solar air-heating system and for a conventional, gas-fired, forced-air system are shown in Fig. 5. The overall reliability of the air system is approximately 0.5 at 5000 hours (one operating year). Even if the collector array were perfectly reliable at 5000 hours, the reliability of the air-heating system would be approximately 0.53. This low reliability estimate is the result of the control system and the damper configuration.

If the failure rate of the damper could be reduced from one failure in 75,000 hours to one failure in 750,000 hours, then the reliability of the system would begin to approach that of conventional systems. Overall system reliability would then be governed by the control system and would approach 0.75 at 5000 hours. The reliability of a conventional, gas-fired, forced-air system at 5000 hours is 0.85.

### III. Materials Performance

The economic consequences of materials corrosion and solar fluid degradation impede the commercialization of solar heating and cooling systems. The materials assessment element of the solar reliability and materials program evaluates the effects of changes in the behavior of materials on the
1.0

CONVENTIONAL DOMESTIC HOT WATER SYSTEM

SOLAR SYSTEM WITH LOW FAILURE RATE PUMP
\( \lambda = 3.0 \times 10^{-6} / \text{HR} \)

SOLAR SYSTEM WITH MEDIAN FAILURE RATE PUMP
\( \lambda = 3.35 \times 10^{-6} / \text{HR} \)

SOLAR SYSTEM WITH HIGH FAILURE RATE PUMP
\( \lambda = 30 \times 10^{-5} / \text{HR} \)

Fig. 4. Reliability Assessments for a Solar Domestic Hot Water System and a Conventional System

1.0

CONVENTIONAL GAS FORCED-AIR FURNACE

\( R_{CA} = 0.90 \)
\( R_{CA} = 0.72 \)
\( R_{CA} = 0.43 \)

\( R_{CA} = \) COLLECTOR ARRAY RELIABILITY AT 5000 HOURS

Fig. 5. Reliability Assessments for a Solar Air-Heating System and a Gas-Fired, Forced-Air System
efficiency of system performance and selects durable, cost-effective materials for solar energy systems in various climatic regions.

**Atmospheric Corrosion**

Atmospheric corrosion studies examine the degradation of materials used in solar collectors and supports. Current emphasis is on the metallic components of battens and enclosures. The synergistic effects of climatic conditions (temperature, relative humidity, and atmospheric constituents) are evaluated through two complementary on-site experiments: (1) monitoring the telemetry of an atmospheric corrosion meter, a relative humidity sensor, and an ambient temperature sensor via the National Solar Data Network (NSDN) and (2) determining the weight loss and pitting characteristics of metallic coupons housed in an atmospheric corrosion rack at each site.

Results will indicate how rapidly various materials (aluminum, galvanized steel, aluminized steel, and particle steel) will corrode under different climatic conditions. Data collection has started at nine NSDN sites, and six more are being instrumented.

**Corrosion Behavior of Heat-Transfer Fluids**

The internal corrosion-erosion behavior of solar heat-transfer fluids is being investigated by correlating laboratory experiments with in-situ measurements on operating systems. The fluid breakdown is monitored by voltage-corrosivity sensors immersed in the collector coolants. Nine of these sensors have been installed and are transmitting data via the NSDN, and six more sensors are scheduled for installation during 1980.

Accelerated-corrosion experiments complement and extend the range of the in-situ data and provide a convenient means for evaluating additional materials. Experiments simulating the operating conditions of solar energy systems with uninhibited 50% ethylene glycol solutions indicate extensive corrosion of galvanized steel and black iron. Aluminum also shows evidence of pitting corrosion; copper experiences the least corrosion damage. Testing in inhibited ethylene glycol and propylene solutions has been initiated, and preliminary results should be available by August 1980.

**Properties of Heat-Transfer Fluids**

Specific-heat and density data on heat-transfer fluids at the operating temperatures of solar energy systems are required for calculation of instantaneous thermal efficiency and useful energy collected by the solar array. At present, nominal or design-specified values are used in the thermal calculations performed by the NSDN contractor. To obtain actual values, samples of the heat-transfer fluid were collected from 29 systems when they began to operate. The samples were analyzed by Brigham Young University to determine the specific heat and density as functions of operating temperature.

Using the temperature-dependent properties of the actual heat-transfer fluids and performance data from seven instrumented systems for the month of
November 1978, the NSDN contractor calculated the effect of a change in antifreeze concentration on thermal performance. A 20% increase in antifreeze concentration resulted in a 7% decrease in collected energy and a similar decrease in thermal efficiency. A 15% decrease in antifreeze concentration increased collected energy and thermal efficiency by 8%. Thermal performance improved consistently when the measured concentrations of glycol in water were lower than the design-specified concentrations, and performance declined when the glycol concentrations were higher than specified. However, a lower water/glycol concentration increases the danger of freezing. A safe minimum antifreeze concentration depends not only on the lowest expected temperature but also on the degree of corrosion protection desired.

**Fluid Scaling**

Scaling is the process by which deposits are left by the heat-transfer fluids on the internal surfaces of collector arrays and heat exchangers. These deposits reduce thermal efficiency and increase maintenance costs.

The Radian Corporation, under contract to ANL, has analyzed water samples from five DOE-sponsored solar installations. Using data in Ref. 9, a more comprehensive scaling model has been developed. This model is based on the water chemistry of the individual site and can be used by the system designer to determine whether or not scaling will be a problem and to suggest the appropriate demineralization treatment.

**IV. Future Activities**

The major activity of the solar reliability and materials program for 1980 will be to issue a set of design guidelines for solar domestic hot water systems. In addition, data acquisition activities will continue and a solar-energy-system critical items list, two materials performance reports, and a library user's manual will be issued.

**V. References**


VI. Reference Not Cited


For More Information, Contact: R. M. Wolosewicz
Energy and Environmental Systems Division, Bldg. 362
(312) 972-7706

Sponsor: DOE Assistant Secretary for Conservation and Solar Energy
Office of Solar Applications for Buildings
Project Officer: R. Hassett

ANL FY 1980 Program Number: 49580
DOE FY 1980 Budget Category: EA-02-01
NATIONAL SOLAR DATA NETWORK

P. S. Chopra and A. A. Longnecker

Abstract

Management of the National Solar Data Network (NSDN) was established at Argonne National Laboratory in 1978. This network is part of a national program to demonstrate the economic viability of solar energy for the heating and cooling of residential and commercial buildings.

Argonne responsibilities for the NSDN program include technical management of the NSDN contractor and technical support to evaluate instrumentation, data processing and performance reporting of more than one hundred solar energy systems. In this effort Argonne studied procedures to assess the accuracy of the instrumentation, and is conducting tests to evaluate the accuracy and stability of the site data acquisition system.

I. Introduction

The Department of Energy has initiated a national program to demonstrate the economic viability of solar energy for the heating and cooling of residential and commercial buildings. The major elements of the program are research, development, and demonstration. In the demonstration phase of this program, DOE has sponsored the installation of a variety of solar energy systems for residential and commercial buildings located in different climatic regions throughout the U.S. These systems provide information about solar energy equipment in actual operation.

The National Solar Data Network (NSDN) is composed of more than 100 solar energy systems instrumented for automated data collection to provide representative performance data for analysis (see Fig. 1). Equipment located at each site records data automatically every five minutes and transmits it daily over telephone lines to a central data processing system where the data are analyzed. Results of this analysis are published to demonstrate performance and to provide a basis for needed improvements to solar energy systems.

II. Accomplishments in FY 1979

Argonne provides the technical management of the NSDN for DOE and also furnishes technical support. For example, Argonne staff members evaluate network instrumentation, data collection, processing, and reporting methods and recommend improvements where needed.

Efforts to date have focused on instrument calibration and on assessing the accuracy of the collected data. To establish accuracy ranges for measured solar energy system performance, studies are underway to quantify instrumentation and software errors. For example, a stable, reference voltage-supply
module was built and installed at the solar hot water demonstration site at the Argonne cafeteria. The voltages are monitored routinely, recorded every five minutes by the site data acquisition system, and transmitted daily to the NSDN central data processing system. A printout of these data is compared with data logged at the site to check the accuracy and stability of the data acquisition system under field conditions.

Staff members may visit the sites to detect problems that degrade the performance of the solar energy system or the instrumentation. It was recently determined that the present practice for measuring air flow in ducts needs improvement. In this instance Argonne recommended that pitot tubes replace the hot-wire anemometers in current use. Based on a review of monthly site performance reports and collected data, recommendations for improving the techniques and procedures used to analyze the performance of solar systems are prepared.

III. Planned Activities for FY 1980

The work of data collection, analysis and reporting was originally under contract to IBM. Beginning October 1, 1979, this effort will be transferred to the Vitro Laboratories division of Automation Industries. Argonne has developed the plan to transfer all technical activities to Vitro Laboratories in a four-month period. The Argonne goal is to accomplish a smooth transition in the scheduled time without loss of data collection from the instrumented
sites. ANL will continue to manage the NSDN contract, reviewing and evaluating contractor performance in the areas of instrumentation, data acquisition, data analysis and reporting to assure accurate and timely information is generated.

Improvements are planned in the area of installation, maintenance and calibration of site instrumentation. The contractor will develop a data accuracy plan under ANL direction. The data accuracy plan will be used as a guide to assure instruments and sensors meet accuracy requirements.

ANL also plans to complete in-situ testing of two site data acquisition systems and report on their accuracy and stability.

For More Information, Contact: A. A. Longnecker
Electronics Division, Bldg. 362
(312) 972-8065

Sponsor: DOE Assistant Secretary for Conservation and Solar Energy
Office of Solar Applications for Buildings
Project Officer: R. Hassett

ANL FY 1980 Program Number: 49558
DOE FY 1980 Budget Category: EA-02-01
LONG-TERM ICE STORAGE FOR COOLING APPLICATIONS
USING PASSIVE FREEZING TECHNIQUES

A. J. Gorski

Abstract

This program is developing a cost-effective method of solar cooling using ice passively grown and stored during the winter. The cooling system will generate large volumes of ice without any expenditure of external energy or labor. This passive method of freezing ice has the potential to provide cost-effective summer cooling.

I. Introduction

The concept of freezing ice in the winter and using it to provide cooling in the summer is not a new idea. This method has been used for food refrigeration for many years, and is still used in remote parts of the country. The major disadvantage of conventional ice storage techniques is the prohibitively high labor costs involved in cutting, moving, and insulating ice in an "ice house." However, if ice can be frozen in large volumes in the same container in which it will be stored, without any expenditure of energy or labor, long-term ice storage has the potential to provide cost-effective cooling.

The basic elements of the passive cooling system proposed here are shown in Figure 1. A large insulated tank of water is buried underground near (or under) the building to be cooled. Specially designed heat pipes extend from the bottom of the tank to the soil surface and project above the ground. These heat pipes act as one-way conductors of heat. Along the underwater length, heat from the water causes thin film evaporation of the working fluid within the unit. The resulting vapor travels upward and condenses in the above-ground radiator section, releasing the transported heat to the air. During the winter months extraction heat freezes ice along the submerged portion of the heat pipes. When the air is warmer than the water in the tank, the evaporation-condensation cycle stops automatically. Thus heat can be easily removed from the water, but it cannot be readily transferred from the environment to the water. The heat pipes used in this system are designed so that the ice will break off
periodically and rise to the top of the storage tank. In this manner, the tank is slowly filled with ice from the top down. The ice is thus formed and stored in the same container, ready for further use, without any expenditure of energy or labor.

II. Accomplishments in FY 1979

Using an indoor ice growing apparatus, we have grown and released ice automatically for approximately three months. In addition to these experimental efforts, we have developed computer codes to determine ice production rates for various ambient conditions, and have designed a new heat pipe configuration that will go automatically through a freeze-defrost mode independently of variations in outdoor temperature during the winter. Construction on a full-scale outdoor test tank was also started.

III. Planned Activities for FY 1980

During this year, we intend to complete the construction of our outdoor test tank and make it operational. Full-scale heat pipes will be used to produce ice during the 1980-81 winter and experimental measurements taken to determine system performance and optimum configuration. We also plan to design a field test installation that will be cost-effective and acceptable to both builder and user. A market analysis will be performed in relationship to the residential, commercial and industrial sectors.

IV. References


V. Reference Not Cited

DESIGN AND INSTALLATION MANUAL FOR THERMAL ENERGY STORAGE

F. Cole, K. Nield, R. Rohde, and R. Wolosewicz

Abstract

The second edition of the Design and Installation Manual for Thermal Energy Storage, ANL 79-15, has been prepared. The manual provides how-to-do-it information on storage to installers, contractors, engineers, architects, and designers. It will be available from the National Technical Information Service.

I. Introduction

The objective of this project is to assemble and write a manual on the design and installation of thermal energy storage (TES) systems. The audience is intended to be installers, contractors, engineers, architects, and designers who wish to enter the solar business, although do-it-yourselfers will also find the manual useful. Only data pertaining to state-of-the-art storage systems (water tanks, rock bed, and latent heat storage) are presented in detail. Applications are for domestic water heating, space heating, and space cooling. Advanced systems such as seasonal storage or high-temperature storage are not considered.

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 made it difficult for designers and installers of TES to use the information contained in the various sources. Numerous pitfalls in designing and installing TES required 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. Their recommendations were incorporated into the first edition of the Design and Installation Manual for Thermal Energy Storage.

II. Accomplishments During FY 1979

In March, 1979, the first edition of the Design and Installation Manual for Thermal Energy Storage was published as Argonne report ANL-79-15. The manual was discussed at four seminars held in the Northeastern, Southern, Midwestern, and Western regions of the United States. The purposes of the seminars were 1) to disseminate information on storage to designers and installers of solar systems and 2) to solicit constructive criticisms on the manual.

The seminar participants provided many useful suggestions for the second edition. In addition, latent heat storage became commercially
available, building codes were changed to recognize solar energy, and new information on the state of the art became available since the first edition was published. These items were incorporated into the second edition which is now available from the National Technical Information Service.

The contents of the Design and Installation Manual for Thermal Energy Storage are shown in Table 1. Chapters 1 through 5 present general information on storage without going into highly technical details. Mathematical equations in these chapters are simple and few in number. If readers require further technical details on a given subject, they can turn to the appropriate technical appendix.


INTRODUCTION

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   Heat Exchangers
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Domestic Hot Water with Liquid-Based Space Heating
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APPENDIX B. Heat Transfer Fluids
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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.

III. Planned Activities for FY 1980

There are no planned activities for FY 1980. The project goals have been accomplished and funding has ended. However, project personnel will continue their activities in solar standards organizations such as ASME, ASTM, and ASHRAE. ASHRAE has asked for and will receive written contributions on TES for its new edition of the ASHRAE Handbook of Fundamentals.
For More Information, Contact: R. L. Cole
Engineering Division, Bldg. 362
(312)972-6245

Sponsor: DOE Assistant Secretary for
Conservation and Solar Energy
Office of Solar Energy
Project Officer: J. M. Davis

ANL FY 1979 Program Number: 49565
DOE FY 1979 Budget Category: AD-01-01
PROGRAM SUPPORT IN THERMAL ENERGY STORAGE FOR DOE OFFICE OF SOLAR APPLICATIONS

A. I. Michaels

Abstract

This program provides technical management support in thermal energy storage and heat exchange for the Systems Development Division of the DOE Office of Solar Applications (OSA) in the areas of: proposal solicitations and evaluations; monitoring of contractor performance; 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.

I. Introduction

This activity began at ANL in April 1976. The first task carried out was the detailed review and revision of the draft of DOE's 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 Program Research and Development Announcement (PRDA) in four categories of innovative R&D in thermal energy storage and a request for proposals (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 include reviews and funding recommendations for unsolicited proposals received by DOE as well as 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 other governmental and nongovernmental organizations. Argonne also coordinates projects with the DOE Office of Solar Applications (OSA), initiates new projects as required to meet the OSA schedule and objectives; and prepares budgets and schedules to effectively carry out the planned work of the OSA's Systems Development Division.

II. Accomplishments During FY 1979

All of the program responsibilities of ANL described above were conducted at a high level of activity throughout FY 1979. A total of 30 contracts were in effect and monitored during the year.
Some specific accomplishments were as follows: seven project review site visits were made to contractors, one additional site visit was made for the purpose of discussing new potential projects, five project review meetings with contractors were held at ANL, two detailed program review and analysis reports were written, and three planning meetings were held with the DOE program manager. In addition, ANL personnel reviewed 14 unsolicited proposals and made funding recommendations; reviewed 18 semi-annual and annual reports (an additional two are in the review process); presented review papers describing the OSA program and related OSA projects at two conferences; and attended four OSA branch, support laboratory, and contractor review meetings and two coordination meetings with other storage support laboratories (ORNL, SERI). Argonne staff also prepared two financial operating plans; wrote statements of work for six new contracts; initiated ten procurement actions for contract renewals, extensions, or changes in statement of work; and prepared several management plan and program schedule documents.

In addition to the above, ANL participated in the International Energy Agency Solar Heating and Cooling of Buildings Committee meeting in Stockholm, Sweden, in January 1979 with representatives from France, Sweden, Canada, West Germany, Belgium, Switzerland and Denmark. The objectives of the task were to determine the performance and cost-effectiveness of large-scale, seasonal-storage solar energy systems for the heating of buildings and to realistically evaluate the relative merits of competing seasonal-storage concepts. ANL participated in the formation of the new ASTM Solar Energy Standards Committee E-44, has reviewed several proposed ASTM solar standards, and is chairing the Task Group on Thermal Energy Storage.

A solar storage workshop was held in March 1979 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.

III. Planned Activities for FY 1980

All of the current program responsibilities and activities will continue throughout FY 1980. With respect to R&D program content, it is expected that 17 of the currently funded contracts will continue. In addition, six to eight new contracts will be initiated based on unsolicited proposals that are currently under consideration. Two solicitations of new proposals are also planned in the areas of improved containers for phase-change heat-storage materials and membrane-lined storage containers for general retrofit applications, and for annual-storage, large-scale solar energy systems.
For More Information, Contact:  A. I. Michaels  
Materials Science Division,  
Bldg. 362  
(312) 972-7785

Sponsor:  
DOE Assistant Secretary for Conservation and Solar Energy  
Project Officer: J. Hale (Acting)

ANL FY 1980 Program Number:  49500  
DOE FY 1980 Budget Category:  AD-01-01
MODELING AND DEVELOPMENT OF THERMOCLINE AND HALOTHERMOCLINE STORAGE SYSTEMS

E. I. H. Lin, K. V. Liu and W. T. Sha

Abstract

The three-dimensional thermohydrodynamic code COMMIX-SA, developed in the previous fiscal year, was validated and utilized to simulate the heat discharge and charge responses of stratified water tanks of various designs. Effects of tank geometry, flow rate, jetting, baffles and flow distributors on tank performance were determined. Design features enhancing stratification and performance were identified. A cylindrical tank with height-to-diameter ratio equal to 4, equipped with vertical concentric cylindrical baffles and an inlet ring distributor, was shown to achieve discharge and charge efficiencies greater than 90%. Plans were outlined to develop a COMMIX-SA porous-media model for rock beds and a double-diffusive-convection model for salt-gradient solar ponds. These models are intended to address the flow-channeling problem in rock beds and stability problem in solar ponds, respectively. The construction of an ANL research solar pond was planned and an effort was made to launch a large-scale demonstration of solar ponds in agricultural applications.

I. Introduction

Thermocline and halothermocline storage systems utilize temperature and salinity-temperature gradient zones, respectively, to enhance and to achieve their solar thermal energy storage functions. Stratified water tanks and rock beds, in which thermoclines separate the hot and cold regions, are suitable short- or long-term storage units for building heating and cooling; whereas solar ponds, which rely on halothermoclines for heat retention, are appropriate for numerous agricultural and industrial process heat applications and space conditioning. The three-dimensional thermohydrodynamic computer code COMMIX-SA, which was developed in FY 1978, has proven to be a very versatile and useful analytical tool, capable of elucidating fluid flow and heat transfer processes in stratified water tanks. Furthermore, it has proven to be valuable for identifying and evaluating improved tank designs and has thus brought about expansion of the work scope to include modeling of rock beds and salt-gradient solar ponds. The current objectives of this project are: (i) Develop and validate a three-dimensional porous-media model and a double-diffusive-convection model within the COMMIX-SA framework for the investigation of heat, mass and momentum transport phenomena in, and stability characteristics of, thermocline and halothermocline storage systems; (ii) Utilize the models developed to perform parametric studies on stratified water tanks, rock beds, and salt-gradient solar ponds so as to optimize design and improve performance of these solar energy system
components; (iii) Interface with ongoing experimental programs and provide input to forthcoming ones concerning the aforementioned components to facilitate attainment of useful and practical information.

II. Accomplishments during FY 1979

- Validation of COMMIX-SA with available experimental results has yielded satisfactory agreement.

- Extensive parametric studies conducted with COMMIX-SA have determined the effects of geometry, flow rate, jetting, baffles and flow distributors on the performance of heat storage tanks. Some of the design configurations investigated and the corresponding simulated heat-discharge responses are shown in Fig. 1. Design features enhancing stratification and performance have been identified. They are: (i) large height-to-diameter (H/D) ratio (3, 4, or as large as practical); (ii) ring, pipe or disk distributors; (iii) non-conducting or low-conducting materials for baffles; (iv) low flow velocity; (v) baffles (vertical baffles are better than horizontal ones). A cylindrical tank with H/D = 4.0, equipped with vertical concentric cylindrical baffles and an inlet ring distributor, has been shown to achieve discharge and charge efficiencies greater than 90%; details of this tank design and the associated heat-discharge temperature profile are illustrated in Fig. 2.

- Several color movies were produced based on COMMIX-SA simulations which display stratification and internal wave phenomena that take place in the storage tanks. These movies aid viewers, particularly analysts and designers, in gaining insight into the pertinent physical processes.

- Definitions of storage charge and discharge efficiencies and of thermal energy storage efficiency were developed. The effect of stratification on overall performance of solar heating and cooling systems was assessed by way of illustrative examples, which showed that it is usually underestimated. Also, limitations of ASHRAE devices were identified, and improved test procedures were recommended.

- A study was made, and a report written, on the basic principles, current designs, and economic advantages of salt-gradient solar ponds, and the related equation of stability in thermohaline convection. The extension of COMMIX-SA to include a double-diffusive-convection model for the study of solar ponds was outlined. Field trips made to existing ponds in Ohio (i.e., Ohio State University and Miamisburg) resulted in the following assessments: (i) salt-gradient solar ponds are technically and economically feasible; (ii) continuing R&D effort should be focused on the reliability and efficiency aspects in order to improve pond technology; and (iii) efforts on large-scale demonstrations of solar ponds in agricultural and industrial process heat and other low-temperature applications should be stepped up. A detailed proposal for the construction, demonstration and evaluation of a 1-acre pond on a 900-acre farm in Mazon, Illinois, for grain drying and hog-house heating, was
1. \( H/D = 2.5 \), No Baffle
2. \( H/D = 2.5 \), 1 Horizontal Baffle
3. \( H/D = 4.0 \), Vertical Pipe
4. \( H/D = 4.0 \), 1 Horizontal Baffle
5. \( H/D = 4.0 \), Inlet & Outlet Ring Distributor
6. \( H/D = 4.0 \), Conducting Cylindrical Baffles
7. \( H/D = 4.0 \), Nonconducting Cylindrical Baffles

Fig. 1. (a) Storage tank designs; and (b) corresponding heat-discharge responses determined from COMMIX-SA simulations.

Fig. 2. (a) Temperature profile during heat discharge from (b) storage tank with vertical concentric cylindrical baffles and ring distributor; \( Q = 2.035 \) gpm.
submitted to the State of Illinois for funding considerations. Additionally, plans were made for the construction and testing of a 1/4-acre research pond on the ANL site.

- COMMIX-SA was documented and released for public use.

III. Planned Activities for FY 1980

- Develop a porous-media model for rock beds and a double-diffusive-convection model for salt-gradient solar ponds, and incorporate the models in COMMIX-SA.

- Utilize the COMMIX-SA rock-bed model to study the flow-channeling problem, to determine effects of plenum geometry, internal partition and other design variables, and to optimize vertical and horizontal rock-bed designs. These analytical efforts will be interfaced with an experimental program (subcontracted to SOLARON Corp., Colorado) under which improved rock beds (particularly horizontal ones) are to be designed, constructed and tested.

- Utilize the COMMIX-SA solar-pond model to study behavior and stability characteristics of salt-gradient ponds, with the goal of determining methods of ensuring pond reliability and improving pond efficiency.

- Further validate COMMIX-SA as more experimental data become available. Perform further design studies with cylindrical, rectangular and irregular-shaped water tanks, annual storage units, and address fundamental questions such as scaling, stability of thermoclines, and promotion of stratification.

- Construct and operate a 1/4-acre research solar pond on ANL site. Continue to pursue large-scale demonstration of solar ponds in farming applications.

IV. Publications


| **For More Information, Contact:** | W. T. Sha or E. I. H. Lin  
Components Technology  
Division, Bldg. 308  
(312) 972-5910 |
|-----------------------------------|--------------------------------------------------|
| **Sponsor:**                      | DOE Assistant Secretary for  
Conservation and Solar Energy  
Office of Solar Applications  
Project Officer: J. M. Davis |
| **ANL FY 1980 Program Number:**  | 49572                                            |
| **DOE FY 1980 Budget Category:**  | EA-01                                            |
SOLAR ENERGY CONVERSION
DEVELOPMENT OF COMPOUND PARABOLIC CONCENTRATORS

K. A. Reed

Abstract

Compound parabolic concentrators are nonimaging optical concentrators which possess very wide angular fields of view. This paper outlines some of the recent work to develop viable solar collectors which incorporate compound parabolic concentrators or other nonimaging concentrators. Both in-house development and commercialization activities were pursued in 1979, aiming toward solar heating and cooling components. Proposed new activities are directed toward process heat applications.

1. Introduction

Compound parabolic concentrators (CPCs) use shaped reflectors to concentrate incoming radiation without forming an image of the source. By giving up the requirement for image formation, these concentrators can achieve large angular fields of view. The angular acceptance function of a CPC is the widest permitted by physical principles, with the limiting acceptance angle fixed by the level of optical concentration. Focusing concentrators fall short of this acceptance limit by a factor of three or more. The CPC-reflector curve is completely and uniquely determined by the shape of its receiver and its limiting acceptance angle.

Argonne National Laboratory has played a key role in developing compound parabolic concentrators for solar energy applications. Because of their wide angular fields of view, CPC-trough collectors can achieve moderate levels of concentration (up to 10x) without having to track the sun diurnally. Concentration by up to a factor of 1.8 is possible in a strictly stationary collector. Unlike focusing systems, these nonimaging, concentrating collectors can utilize a sizable fraction of the diffuse sky radiation and are relatively insensitive to errors in mirror specularity and contour.

All the optical advantages of CPCs—wide angular acceptance, large mirror error tolerance, and collection of diffuse sky radiation—were demonstrated in early experiments with metal reflectors coupled to bare absorbers. The thermal performance of these models was compromised, however, by parasitic heat losses from the absorbers to the reflectors due to convection as well as conduction, and the models were too heavy due to overdesign.

Recent work has been directed toward the development of higher performance, lightweight collectors based on evacuated receivers. Collectors using cusp reflectors to concentrate radiation onto cylindrical receivers were developed and demonstrated for the DOE solar heating and cooling program. A stationary collector design using General Electric (Valley Forge, PA) TC-100™ receiver
tubes in 1.5x cusp reflectors received a joint IEEE-100 award from Industrial Research magazine as one of the 100 most significant new developments in 1977. Satisfactory performance was obtained in a laboratory-scale model at temperatures up to 150°C. Similar designs evolved around the Owens-Illinois (Toledo, OH) Sunpak™ receiver tube.

In related work for DOE's photothermal electric program, engineering prototypes of 3x and 5x CPC collectors were developed. These modules used evacuated receiver tubes built by Corning Glass (Corning, NY), enclosing flat absorber strips with glass envelopes. The higher design concentrations were dictated by the higher temperature requirements, up to 250°C. The 3x collector requires seasonal tilt adjustments, and the 5x collector requires ten tilt adjustments a year.

To support the collector test and evaluation activities, a solar energy test facility (Fig. 1) was built and instrumented for testing collectors at temperatures up to 260°C. A number of test procedures have been developed to properly characterize these moderate concentration collectors.

II. Accomplishments in 1979

Development

The ANL engineering prototype of a 1.5x cusp collector was tested extensively in 1979. This lightweight (19 kg m⁻²) stationary collector was based on the laboratory-scale model discussed above, and represented the state of
the art in 1978. Reflectors formed out of aluminum specular lighting sheet and bonded to sheet aluminum ribs concentrate radiation onto GE TC-100™ evacuated receiver tubes. Two banks of five troughs each are separated by a center manifold section, and supported in a sheet aluminum enclosure. High-temperature glass fiber insulation is packed around the copper manifold piping in the center section. The 2.6-m$^2$ clear aperture area is protected by a thin acrylic plastic sheet. The heat-loss coefficient of this collector is 0.7-0.8 W m$^{-2}$°C$^{-1}$ at absorber temperatures in the range 80-150°C above ambient. Although this represents a substantial improvement over flat-plate values, almost half the heat loss is due to conduction and convection in the manifold region. There is a clear need for superior high-temperature insulation which is cost effective. The optical efficiency, often called the tau-alpha product, is about 50%, which is substantially lower than predicted. The excessive optical loss has been traced to the receivers, whose solar-averaged absorptance is 0.78, typically, compared with the 0.85 predicted by the vendor. The angular acceptance function of the collector and its thermal performance at elevated temperatures have been measured, and they support the optical efficiency measurement. Work was suspended on the advanced version of this collector.

Work proceeded on two fronts to improve the optical performance of these and similar collectors. The more conventional approach was to search for alternative absorber coatings and receiver designs, screening for high solar absorptance and low infrared emittance. The second approach stemmed from the extensive optical analyses which have been conducted using ray-tracing techniques. The computer model was validated in detailed comparisons with the data collected in the collector and material test activities. Based on the results from this computer model, alternative reflector designs have been devised which mitigate the effect of the necessary gap between absorber and reflector, and which trap some of the radiation which is reflected off the absorber surface. These new reflector designs can enhance the optical performance of the collector by 5-10%, which is comparable to the gain to be expected from superior material. These reflectors are no longer CPCs. They give up some angular acceptance in exchange for the enhancement factor.

A study was completed in 1979 which considered the requirements for a CPC collector system which generates process steam. In the conceptual design, pressurized water was heated in the collectors and then flashed to steam in an unfired pressure vessel. The study modeled the thermal performance of the individual collectors and the downstream system, including pumping requirements. A novel heat-pipe arrangement was proposed for extracting energy from the receivers and was included in the thermodynamic model.

Commercialization

The ANL solar energy group maintained its strong commitment to early commercialization of successful collector designs during 1979. In order to expedite the transfer of this technology, the group has encouraged joint design reviews and analyses with manufacturers. Using the computer ray-tracing results, commercial and tentative designs are evaluated side-by-side so that tradeoffs can be clearly identified and understood. In addition to detailed optical design guidance, the ANL group offers in-depth knowledge of today's materials and techniques.
Stationary cusp collectors with evacuated tubular receivers are now available from Energy Design (Memphis, TN) and Sunmaster (Corning, NY), two licensees of the DOE patents on the cusp reflector shape. The Sunmaster collector is intended for water systems operating at or below about 100°C. It is fully drainable and includes protection against freezing or overheating. The Energy Design collector is intended for operation at temperatures up to about 200°C using nonaqueous heat transfer fluids.

In 1979, Chamberlain Manufacturing (Waterloo, IA) completed a DOE-funded project to develop a 2.6x cusp collector for intermediate temperature applications. One each of these cusp collector models—Energy Design, Sunmaster, and Chamberlain—was obtained during the year. Evaluation began late in 1979.

The first large-scale field test of a CPC collector was turned on in 1979. A field of 972 Sunmaster collectors (about 1350 m²) is providing cooling for a hotel on St. Thomas, VI.

Standards and Ratings

The ANL solar energy group is vigorously supporting the development of solar-related standards and ratings. During 1979, group members served on the solar committee of the American Society for Testing and Materials, helping to develop testing procedures. They also participated in safety-related standards development in the American Society of Mechanical Engineers. Technical presentations were made to the Solar Energy Industries Association committee which developed the SEIA rating method for solar energy collectors, and the ANL group continues to act in a consulting capacity.

III. Planned Activities for 1980

Activities relating directly to the DOE solar heating and cooling program will tail off during 1980. The evaluation of the Energy Design, Sunmaster, and Chamberlain collector modules will be completed. This evaluation will establish the collectors' optical and thermal characteristics and will assess their potential for incorporating enhancements. A topical report describing the state of the art in stationary concentrating collectors, their design and projected performance will be completed in 1980. Commercialization activities tailored to expedite the transfer of this information to the industry will continue.

The new activities planned for 1980 aim toward process heat applications. A substantial amount of the heat used in industrial processes is delivered by steam. Where steam is to be generated using solar energy, it is advantageous to boil in the collector rather than downstream, since the collector can operate at a lower temperature. One planned activity examines this proposition in detail, determining the engineering requirements and expected system performance of steam-generating, stationary, concentrating collectors.

The second new activity will develop the design principles for nonimaging secondary concentrators to be incorporated in tracking line-focus collectors. Line-focus systems show promise for applications requiring collector operation in the temperature range 250-350°C, but the mirror accuracy required for good performance keeps their cost up. The use of a nonimaging secondary concentrator at the receiver of a line-focusing primary can permit relaxation
of mirror accuracy requirements without degradation of performance, if the components are properly integrated. In developing this technology, the ANL solar energy group will continue to work closely with the collector industry to assure both good system design and timely transfer of the technology.

IV. References


For More Information, Contact: K. A. Reed
Chemical Engineering Division,
Bldg. 362
(312) 972-6234

Sponsor: DOE Assistant Secretary for Conservation and Solar Energy Office of Solar Applications for Buildings
Project Officer: J. M. Davis

ANL FY 1980 Program Number: 49503
DOE FY 1980 Budget Category: EA-01
SOLAR LIQUID-METAL MHD POWER SYSTEMS

E. S. Pierson

Abstract

The potential advantages of two-phase liquid-metal MHD power cycles coupled to solar collectors are being studied for different collector types, collector temperatures, and applications. The concept is described, and initial results are presented for a solar total energy system operating at ~590 K (~600°F) and a high-temperature (~800 K (~1000°F)) conversion system with and without cogeneration.

I. Introduction

The two-phase-generator, liquid-metal magnetohydrodynamic (LMMHD) concept was initially developed at ANL to meet the anticipated need for an energy-conversion system that would be compatible with liquid-metal-cooled heat sources such as the liquid-metal fast breeder reactor (LMFBR) and the controlled thermonuclear reactor (CTR). The use of two working fluids, a thermodynamic fluid (gas or vapor) and an electrodynamic fluid (liquid metal), gives LMMHD flexibility in coupling to different heat-source temperatures and materials constraints. Subsequent development has resulted in three versions:

1. A Rankine-cycle version best suited to low heat-source temperatures, 370 K (212°F) to ~850 K (1070°F), because there is no compression work. It can be coupled to LMFBRs, existing light-water reactors, fossil-fuel-fired combustors, and solar collectors; also, it yields calculated efficiencies several points higher than those of conventional steam cycles for the same top steam temperature.

2. A Brayton-cycle version that gives good performance at source temperatures above approximately 900 K (1160°F) with coal and at lower temperatures for other energy sources. It can be coupled to LMFBRs, coal combustors, CTRs, and high-temperature solar concentrators.

3. An open-cycle version suitable for coal or other fossil fuels.

A schematic diagram of the Brayton-cycle LMMHD concept with a gas turbine is shown in Fig. 1. An inert gas, e.g., helium, is the thermodynamic working fluid, and a liquid metal, e.g., sodium, is the electrodynamic fluid in the MHD generator. In operation, the gas and liquid are combined in the mixer and the resulting two-phase mixture enters the MHD generator. The MHD generator acts as a turbine and electric generator in one unit, in which the gas expands, drives the liquid across the magnetic field, and, thus, generates electrical power. Because the liquid has a high heat content, the expansion occurs at almost constant temperature and considerable available energy remains in the gas exiting the MHD generator. The liquid acts as an "infinite-reheat" source for the gas, thermal...
energy is continuously transferred from the liquid to the gas, and most of the enthalpy change in the generator comes from the liquid. The resulting almost-constant-temperature expansion is the source of the potentially higher thermodynamic efficiency of the two-phase LMMHD concepts. From the MHD generator, the two-phase mixture enters a nozzle, where additional gas-liquid energy is used (as in the generator) to accelerate the liquid; the resulting high-speed flow is separated in a rotating separator to minimize losses, and the liquid pressure required to return the liquid through the primary heat exchanger to the mixer is obtained in the diffuser. The nozzle-diffuser system can be replaced by a liquid-metal pump.

The gas leaving the separator still has considerable thermal energy, and this energy must be effectively utilized to obtain the highest system efficiency. It can be transferred from the hot gas to the colder gas in a regenerator, extracted with a gas turbine, or extracted with a steam boiler, which would replace the gas turbine and regenerator (see Fig. 1). The LMMHD-gas turbine and LMMHD-steam turbine systems have higher efficiencies than a gas turbine or a steam turbine without the LMMHD components.

Heat addition can be to the liquid metal, the gas, or both. Because the liquid-metal mass flow rate is much higher than the gas mass flow rate, the heat addition can be solely to the liquid metal, with the gas being heated by the liquid in the mixer, without a significant effect on cycle efficiency. This yields a simpler system, with only a liquid-liquid primary heat exchanger.

The Rankine-cycle LMMHD concept differs from the Brayton-cycle version only in the use of a condensable fluid, e.g., steam, as the thermodynamic working fluid with a compatible liquid metal, e.g., tin. Again, either a nozzle-diffuser or a liquid-metal pump is used to recirculate the liquid metal, and the energy in the (superheated) steam leaving the separator is recovered in a regenerator or a low-pressure turbine. For higher-temperature applications, the latter yields better performance. Again, heat addition can be solely to the liquid metal, and the vapor can be generated from the condensate in a direct-contact, i.e., mixing, boiler.

Liquid-metal MHD power cycles appear particularly attractive when coupled to solar collectors because: 1) the almost-constant-temperature expansion potentially means either a higher efficiency than for alternative conversion systems for the same source and sink temperatures, or the
ability to obtain both electricity and process heat (cogeneration); 2) the MHD interaction is a volume effect so that efficiency and cost are almost independent of size; and 3) the use of liquid metals in the collector and/or a direct-contact boiler or gas heater implies higher usable source temperature (thus higher conversion efficiency) and/or higher collector efficiency. Liquid-metal MHD is particularly well suited to cogeneration applications and, with the proper choice of the two working fluids, can use any heat sources of temperature above ~370 K (212°F).

II. Accomplishments During 1979

A program to evaluate LMMHD for solar applications was initiated in FY 1979, in part cooperatively with Professor Herman Branover, Ben-Gurion University of the Negev, Israel, during his temporary appointment at ANL. This may lead to a joint U.S.-Israel program to develop LMMHD. Performance results for two applications of interest to the U.S. are described below.

Sandia Cascaded Solar Total Energy System

The Sandia Cascaded Solar Total Energy System (STES) consists of a collection system with a top temperature of 311°C, a high-temperature energy storage system, a superheated toluene Rankine-cycle conversion system with a turbine-generator output of 32 kWe, and a low-temperature energy storage system that holds the heat rejected from the Rankine-cycle system's condenser for use as an energy source for heating or absorptive air conditioning.

To see the effect of replacing the toluene Rankine-cycle system with an LMMHD system, a simplified Rankine-cycle LMMHD system, i.e., with no turbine or regenerator, was analyzed with tin and steam as the fluids. The results are shown in Fig. 2, where the LMMHD cycle has a substantially higher efficiency than the STES cycle. (The latter is being operated way off...
design in this system, but the on-design performance would still be well below that for LMMHD.) The LMMHD system offers the options of: 1) providing more useful electrical power for the same condenser temperature, or 2) providing a higher condenser temperature, i.e., more useful thermal energy, for the same electrical efficiency. Note that for the LMMHD system with no regenerator, ~20% of the heat rejected is rejected at a temperature above that of the condenser, i.e., it is more valuable for process applications. (If this is not desired, a regenerator can be used to yield a higher electrical efficiency.)

High-Temperature Central Receiver

The efficiencies of the pure LMMHD (no gas or steam turbine) and the LMMHD/gas-turbine cycles are shown in Figs. 3 and 4, in that order, for mixer exit temperatures of 700 K (800°F) to 1255 K (1800°F). The efficiencies are calculated by means of a computer code that includes all major losses and the best available data for component performances. The efficiencies do not include collector efficiency, magnet power (negligible for a superconducting or a permanent magnet), and auxiliary powers. The cycle used is as shown in Fig. 1 except that only the liquid flows through the primary heat exchanger and the helium is heated by the liquid in the mixer. This eliminates one heat exchanger at the penalty of having to heat the liquid 2 to 8 K above the desired mixer exit temperature. Of course, the primary heat exchanger can be eliminated and the liquid metal circulated through the solar collectors, increasing the mixer temperature and LMMHD system efficiency for the same collector efficiency.

The efficiencies of both LMMHD systems are very attractive at ~1089 K (1500°F), i.e., approaching 0.5. At much higher temperatures the increase in LMMHD cycle efficiency with temperature becomes slight, and the efficiency may even decrease (see the curve for 1311 K in Fig. 3) because of the carryover of liquid-metal vapor with the gas from the separator. This is the reason for using lithium rather than sodium above ~867 K. Operation at higher temperatures (and efficiencies) than 1200 K is feasible with other liquid metals, e.g., aluminum or copper. The efficiency can also be increased by higher generator void fractions, multiple LMMHD stages, and/or replacing the gas turbine with a steam bottoming plant.

The LMMHD Brayton cycle can alternatively be optimized for cogeneration applications (electricity and process heat) by removing the regenerator and/or gas turbine, thus obtaining a simpler LMMHD system with a heat rejection temperature almost equal to the source temperature. Electrical efficiencies of ~0.3 for temperature drops (maximum liquid metal temperature at the exit from the solar collector or heat exchanger minus the temperature of the gas leaving the separator) of only ~10 K are attainable. Note that the gas is heated by the liquid metal in the LMMHD mixer/generator; if the gas was heated directly by the solar collectors the temperature might be lower than obtained with the LMMHD system, and the useful electrical energy would be lost.
Summary

The LMMHD cycle (engine) efficiencies presented above are compared in Fig. 5 with those for other proposed engines. The LMMHD Rankine system has either a higher efficiency or the same efficiency with process heat. The LMMHD Brayton cycle has an efficiency comparable to that of advanced Stirling engines, with potential for higher efficiency with advanced concepts, and is also very attractive for electricity and process heat.

III. Planned Activities for 1980

System performance studies will focus on operation at $\sim 600^\circ$F (590 K), as this appears to be an attractive temperature for near-term applications. LMMHD generator experiments will be made at low magnetic flux densities to evaluate permanent magnets for small conversion systems.
Fig. 5 Performance Comparison of LMMHD and Other Engines

IV. References


For More Information, Contact: E. S. Pierson
Engineering Division,
Bldg. 310
(312) 972-5966

Sponsor: DOE Assistant Secretary for Conservation and Solar Energy
Office of Solar Applications and Buildings

Project Officer: M. Gutstein

ANL FY 1980 Program Number: 49755
DOE FY 1980 Budget Category: EA-01
OTEC HEAT EXCHANGER TESTING AND ANALYSIS

A. Thomas
D. Hillis, J. Lorenz, N. Sather, H. Stevens, D. Yung

Abstract

This program, initiated in FY 1977, supports the development of high-performance, cost-effective heat exchangers for closed-cycle OTEC power plants. Argonne tests selected heat exchangers, develops design methods and algorithms for predicting the performance of full-scale units, and provides technical support to DOE.

Five 1-MWt heat exchangers were tested in FY 1979: three shell-and-tube, one folded-tube, and one compact; further tests are planned for FY 1980. In the analytical area a working fluid comparison was made; work on vapor liquid interaction in shell-and-tube exchangers was completed; a quantitative procedure for the comparison of heat exchanger tubes was initiated; and an initial computer code for two-phase flow in compact heat exchangers was written. The technical support included reviews of closed- and open-cycle power systems and of the proposed sea tests on OTEC-1. Expanded technical support is anticipated for FY 1980.

I. Introduction

Ocean thermal energy conversion (OTEC) is the process of producing electricity from temperature gradients in tropical oceans. The principle was first proposed by the French physicist D'Arsonval in 1881, and was tried by Claude in a 22-kWe plant 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. The most recent demonstration of the ability to extract power from the ocean took place in the summer of 1979. Mini-OTEC, a small plant jointly sponsored by the State of Hawaii and Lockheed Corp., produced about 10 kW of net electrical power.

Because OTEC plants operate using small temperature differences, the thermal efficiency, i.e., the amount of heat transferred to produce a given amount of power, is large; consequently, the heat exchanger must be very large. 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 marked improvements in heat transfer performance, and, therefore, sizable reductions in total plant investment, can be achieved by using advanced heat exchanger designs that promote high heat fluxes.

In order to evaluate these designs, a heat exchanger test facility has been constructed at ANL (see Fig. 1). In addition to evaluating heat exchangers experimentally, ANL develops analytical methods for predicting
Fig. 1. Schematic of Argonne's OTEC Heat Exchanger Test Facility
the performance of full-scale heat exchangers and provides technical support to DOE on OTEC power system development.

II. Accomplishments During FY 1979

Test Facility

The construction of the loop was completed and testing began in FY 1978. Figure 2 shows some of the major components in the completed facility [1]. Table 1 summarizes results obtained to date in the test facility. All the units except the Linde flooded evaporator and the C-MU condenser were tested in FY 1979. The other two units were tested in FY 1978.

The first unit to be tested in FY 1979 was the Linde spray evaporator shown in Fig. 3. This evaporator is top fed by an ammonia spray header arrangement. The titanium evaporator tubes are coated with a proprietary nucleation promoting surface on the ammonia side. The unit was delivered to ANL with a small ammonia water leak. The leak has never been located. It is quite small and does not significantly interfere with the testing of the unit. The performance of the evaporator was in broad agreement with predictions from Linde. The tests with this unit confirmed the earlier results obtained with the Linde flooded evaporator that the past history of the High-Flux coating can have a marked effect on the nucleation ability of the surface [3]. As a
Table 1 Summary of Test Results for 1-MWt OTEC Heat Exchangers

<table>
<thead>
<tr>
<th>Heat Exchanger Type</th>
<th>Type of Enhancement</th>
<th>Tube Material</th>
<th>Tube Diameter (in.)</th>
<th>$U_0$</th>
<th>$h_{NH_3}$</th>
<th>$h_{H_2O}$</th>
<th>$H_2O$-side</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linde Flooded Evaporator (horizontal 3-pass)</td>
<td>High Flux on NH$_3$ side; no enhancement on H$_2$O side</td>
<td>Ti</td>
<td>OD = 1.5; ID = 1.43; L = 75</td>
<td>785</td>
<td>4800</td>
<td>1400</td>
<td>2.7</td>
<td>Approx. 100 hrs of continuous running required to reach steady state after full deactivation</td>
</tr>
<tr>
<td>Linde Spray Evaporator (horizontal 4-pass)</td>
<td>High Flux on NH$_3$ side; no enhancement on H$_2$O side</td>
<td>Ti</td>
<td>OD = 1.5; ID = 1.43; L = 55</td>
<td>760</td>
<td>4590</td>
<td>1295</td>
<td>4.0</td>
<td>Performance was insensitive to recirculation ratio if greater than 1.27</td>
</tr>
<tr>
<td>Linde Condenser (horizontal single-pass)</td>
<td>Proprietary enhancement on NH$_3$ side; fins on H$_2$O side</td>
<td>Al 3003</td>
<td>OD = 1.5; ID = 1.27; L = 155</td>
<td>820</td>
<td>5180</td>
<td>1125</td>
<td>1.9</td>
<td>Within ranges tested $U_0$ was independent of heat duty, and hence liquid loading</td>
</tr>
<tr>
<td>C-MU Evaporator (vertical single-pass)</td>
<td>Fluted on both sides (40/40 fins)</td>
<td>Al 6061</td>
<td>OD = 1.21; ID = 0.91; L = 172</td>
<td>825</td>
<td>1800</td>
<td>2610</td>
<td>3.2</td>
<td>$U_0$ repeatable during any continuous run, but not from one run to the next</td>
</tr>
<tr>
<td>C-MU Condenser (vertical single-pass)</td>
<td>Fluted on both sides (40/40 fins)</td>
<td>Al 6061</td>
<td>OD = 1.21; ID = 0.91; L = 172</td>
<td>1045</td>
<td>3590</td>
<td>2470</td>
<td>3.3</td>
<td>Performance insensitive to inlet vapor states ranging from 90% quality to superheated</td>
</tr>
<tr>
<td>APL/JHU Shell-less Folded-Tube Evaporator</td>
<td>No enhancement</td>
<td>Al 3003</td>
<td>OD = 3.0; ID = 2.69; L = 171 (per pass)</td>
<td>410</td>
<td>1160</td>
<td>690</td>
<td>N/A</td>
<td>Performance the same with or without inlet swirler</td>
</tr>
<tr>
<td>Trane Compact Plate-Fin Evaporator</td>
<td>Fins on NH$_3$ side; no enhancement on H$_2$O side</td>
<td>Al 3003</td>
<td>Proprietary geometry; reference area = 775 ft$^2$</td>
<td>1230</td>
<td>4540</td>
<td>1720</td>
<td>3.1</td>
<td>Fins appear to be very effective in augmenting heat transfer</td>
</tr>
</tbody>
</table>

1All results at nominal heat duty (3.2 million Btu/hr) and water flow rate (3200 gpm); $U_0$ and $h$ are in Btu/hr-ft$^2$°F.
2$U_0$ is referred to tube outer area; for C-MU units $U_0$ is based on mean outer area; for APL/JHU unit $U_0$ is based on tube inside area and for Trane unit $U_0$ is based on flat plate surface area.
3Calculated via Wilson plot with $V''''$, except for Linde condenser where $V''''$ was used in accordance with Noranda correlation, and for APL/JHU unit where $V''''$ was used in accordance with Zhukauskas correlation.
4Recirculation ratio = mass rate of liquid feed/mass rate of evaporation. $V''''$ is relatively small because the velocity is only 5 ft/sec compared to 6.5 ft/sec for the other units.
5Value given for $h_{H_2O}$ is based on mean inside area for C-MU units and smooth inside area (based on tube ID) for Linde condenser. Enhancement ratio is the ratio of the actual $h_{H_2O}$ (using Sieder-Tate) for a smooth tube; area ratio is the ratio of actual inside area to smooth tube inside area.
6Recirculation ratio = $V''''$.
7Based on nominal NH$_3$ flow rate of 12 gpm (per tube) for APL and 27 gpm for Trane.
8Wall resistance included.

Source: Ref. 2.
result, the time to reach equilibrium performance is significantly influenced by the state of the tubes prior to startup and by the process of introduction of liquid ammonia onto the tubes during startup.

The performance of the Carnegie-Mellon University (C-MU) vertical falling film evaporator (Fig. 4) was in general agreement with predictions. The measured values of the overall heat transfer coefficient ($U_0$) were found to be stable and reproducible during any continuous run; however, they were not always repeatable from run to run or even following a brief ammonia flow shutdown. These problems are attributed to poor ammonia distribution by the liquid feed channels by which ammonia is applied to the tops of the tubes. Dr. R. Rothfus of C-MU, designer of the evaporator, believes that the applicators could be redesigned and the problem alleviated.

Tests of the Linde condenser (Fig. 5) showed that its performance was a little higher than predicted by Linde. The unit is all aluminum. The tubes are enhanced by axial fins on the water side and a proprietary wire wrapping on the outside diameter. The $U_0$ was independent of the heat duty within the test range, indicating that the performance was not sensitive to liquid loading of the tubes.
Two shell-less units also were tested: a folded-tube evaporator designed by the Applied Physics Laboratory (APL) of Johns Hopkins University and a compact, brazed aluminum, plate-fin exchanger supplied by the Trane Company. The effect of design on heat exchanger compactness is strikingly illustrated in Fig. 6. The small unit is the Trane evaporator next to the APL exchanger. Both units have equal thermal duty of 3.2 million Btu/hr at a nominal 3200-gpm water flow rate.

The most significant experimental findings with the APL unit were that: a) neither mechanical swirlers to promote nucleation nor an ammonia preheater are necessary for adequate performance and b) no phase-flow instabilities were encountered under test operating conditions.

The thermal performance of the Trane compact heat exchanger exceeded the conservative predictions by Trane. This standard-design heat exchanger from the Trane Company is used extensively in the air liquefaction industry. At the present time this heat exchanger is available only in aluminum.

Other activities associated with the test facility included an ANL proposal to DOE for upgrading the test facility. The expansion would consist of tapping into the chilled water in the ring building of Argonne's zero gradient synchrotron (ZGS) accelerator. The water supply cooled by the ZGS chillers would allow testing of units up to six times larger (20 million Btu/hr) than those that can be accommodated by the present facility. The increased capacity would permit laboratory tests of units before they are installed on the OTEC-1 sea test facility. Moreover, open-cycle evaporators and condensers could be evaluated at a reasonable scale. Due to a very austere budget, DOE approved the engineering phase, which was completed, but no procurements or construction in FY 1979.
Analytical Effort

Concurrently with the data analysis from the test facility, several other tasks related to the performance of full-scale units were either initiated or completed in FY 1979. Results obtained from the ANL test facility were analyzed, the overall heat transfer coefficient of each heat exchanger was resolved into its component parts, and the test performance was compared to the predicted values. Hypothetical explanations were advanced for results differing from predictions.

Work related to vapor-liquid interaction in falling film evaporators [4,5] and flow-induced vibration in shell-and-tube heat exchangers [6] was completed. The effect of different working fluids on the OTEC heat exchanger size and system performance was studied [7]. The results showed that for high working-fluid-side enhancement the heat exchangers for different working fluids tend to approach the same size.

Fig. 6. APL Folded-Tube Exchanger, left; Trane Plate-Fin Exchanger, right.

An initial computer program was written to model two-phase diabatic flow in compact heat exchangers. The program will be debugged and refined in FY 1980. This program, when operational, will permit scaleup of units such as the Trane plate-fin heat exchanger to full size. A preliminary quantitative procedure for an initial comparison of the cost-effectiveness of shell-and-tube heat exchangers was developed. This procedure is a useful guide for selecting and recommending heat exchangers for experimental evaluation. Argonne plans to refine the procedure and extend it to the comparison of compact heat exchangers.

Technical Support

Engineering support was provided to the Ocean Systems Branch of DOE's Division of Central Solar Technology. The OTEC Technical Advisory Panel, formed in May 1978 and chaired by ANL, performed an essential function in evaluating the Power System Development projects PSD-1 and PSD-2. The panel, consisting of experts from ANL, other national laboratories, and universities, participated in design reviews, acted as technical advisor to the government source evaluation boards, and provided technical consultation on specific issues. The panel participates actively in formulating the ANL test program by reviewing proposed plans. It is anticipated that the technical support function will expand in FY 1980 as the DOE OTEC program moves to the OTEC-1 experimental tests at sea and to the conceptual design of a 10-MWe experimental pilot plant.
III. Planned Activities for 1980

Test Facility

The Trane and APL units will be tested in the condensing mode; these dual-purpose heat exchangers were tested as evaporators in FY 1979. The C-MU evaporator will be evaluated as a condenser. This unit, due to the geometry of its tubes, is expected to perform better in the condensing mode than the C-MU condenser. Experiments will be conducted with the Trane, APL and Linde spray evaporators to assess the effect of water contamination of ammonia. Information on the sensitivity of heat exchanger performance to water contamination is of high priority to OTEC system designers. It is planned to test several additional shell-and-tube heat exchangers that will offer new tube materials and geometries as well as several compact heat exchangers. The tests of these units will begin in the last quarter of FY 1980 and continue into FY 1981.

Analytical Effort

Data analysis support will continue to be provided to the heat exchanger test program. Moreover, the model for two-phase forced convection flow in compact heat exchangers will be refined and completed. The quantitative procedure for heat exchanger cost-effectiveness evaluation will be improved and expanded to include compact heat exchangers. It is anticipated that the technical planning and scoping of OTEC-1 sea tests will require a significant analytical effort.

Technical Support

The technical support activities are expected to continue and take on added significance in FY 1980. Among the tasks will be: assistance to DOE in selecting contractors for the preliminary design of a 10-MWe pilot plant, selecting and procuring test articles for OTEC-1 second deployment, technical consultation on OTEC-1 operations, and consultation on test facilities for open-cycle component development.

IV. References


Other References Not Cited


For More Information, Contact: A. Thomas
Energy and Environmental Systems Division, Bldg. 362
(312) 972-8071

Sponsor: DOE Assistant Secretary for Conservation and Solar Energy
Office of Solar Power Applications
Project Officer: S. Gronich

ANL FY 1980 Program Number: 49552
DOE FY 1980 Budget Category: AD-03-04
Abstract

Physical and climatic environmental impacts of ocean thermal energy conversion (OTEC) are evaluated as part of a larger program that assesses the potential environmental impacts of OTEC. To predict the potential modifications to the physical environment due to the large amounts of seawater circulated by OTEC plants, physical and numerical models must be developed for several scales of motion. Argonne has provided technical oversight for modeling efforts by others and undertaken supportive studies, including the synthesis of model results for OTEC environmental impact assessment.

I. Introduction

This project provides program management support to the Division of Ocean Energy Systems, Assistant Secretary for Conservation and Solar Energy, Department of Energy, with regard to physical and climatic environmental impacts of ocean thermal energy conversion (OTEC). The Argonne project is an integral part of the overall OTEC environmental assessment program directed by the Lawrence Berkeley Laboratory and interfaces with the ocean measurements project at the Atlantic Oceanographic and Meteorologic Laboratory of NOAA.

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 condenser 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. 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 provides technical direction for the OTEC program elements concerning the physical aspects of potential OTEC impacts on the oceans. Such direction includes technical monitoring of studies for DOE by others, studies undertaken at Argonne, and integration of the results of these studies and of measurement programs for site-specific and programmatic environment assessments. Physical problems concerning siting and thermal resource utilization of OTEC include prediction of recirculation of plant discharges and subsequent degradation of the intake temperature and prediction of the regional renewal of the thermal resource. Potential environmental impacts, the assessment of which require prediction of physical transport and mixing processes, are the redistribution of temperature, salinity, and other ocean constituents due to OTEC plant operation and the
rate of working fluid leaks, biocides, and the products of corrosion in the plant effluents. Spatial scales of interest for impact assessment range from hundreds of meters for near-plant impacts and single-plant recirculation to tens of kilometers for plant spacing considerations to hundreds of kilometers for potential basin-wide impacts due to large-scale OTEC plant deployment in the Gulf of Mexico. Time horizons of interest range from early OTEC deployments, such as OTEC-1 in FY1980, to future large-scale deployments of OTEC power parks. Extraction of heat from the surface waters of the ocean may result in sea-surface temperature depressions. The effects of CO\textsubscript{2} enhancement in the ocean surface waters and possible atmospheric loading due to the upwelling of cold, deep waters also require consideration.

II. Accomplishments During 1979

Argonne provided technical monitoring of physical (laboratory) modeling and analytical modeling studies at the Department of Civil Engineering, Massachusetts Institute of Technology, and at the Environmental Engineering Department, Cornell University, and of a numerical model study for circulation in the Gulf of Mexico by Dynalysis of Princeton, Inc. Argonne reviewed the progress and results of these studies and incorporated them in its assessments of physical impacts.

The first phase of the MIT physical model studies of near-field plume behavior in stagnant ocean environments provided data on plume penetration in the water column. They also indicated that direct recirculation could be avoided by appropriate evaporator intake and discharge separation and discharge angle for plants as large as 600 MW. A towing apparatus has been installed at the MIT test facility to permit experiments that simulate the plant operation in a stratified, flowing ocean environment. It is expected that these experiments will provide the data necessary to assess the critical conditions of currents interacting with the discharge plume and to approximate the effect of the plant structure on the near-field region. The synthesis of physical model results and analyses for the near-field region is in progress at MIT and Argonne. The purpose of this study is to provide general guidelines for designers and impact assessors on near-field plume behavior and recirculation. The intermediate-field plume studies at Cornell have provided zeroth-order estimates of the spreading of the plume as a function of the ocean current and plant size. These results have been used to estimate plant spacing for multiple-plant deployments in simplified ocean environments where degradation of the thermal resource was the criterion for spacing. More detailed analyses are underway for spreading in the intermediate-field region, and better approximations of the plume behavior and of the spacing requirements are expected from a numerical model simulation. Preliminary estimates of the feasibility of limited-area ocean models have been made with the focus on environmental impacts at these scales and on resource renewal. However, increased attention to island applications of OTEC indicates the more immediate need for application of this type of model to island coastal water circulation. Work with JAYCOR, Inc., was initiated this fiscal year to develop a model for barotropic circulation around islands. Initial coding of the Dynalysis numerical model for the Gulf of Mexico has been completed, and initial computations with an 11-level model have been made. Strategies have been developed for the calibration of the model using climatological data and for sensitivity studies with particular emphasis on flows at the Straits of
Yucatan. In accord with program plans, the model was being tested with climatological forcing by the end of the fiscal year, and the simulative capabilities of the model for OTEC purposes are being investigated. Small-scale deployments may have extremely small impacts, but evolving ocean model results suggest that sea-surface temperature depressions due to large-scale deployments, while small, may perturb the air-sea exchange process. A study is underway to devise a tractable approach for OTEC purposes to this complex problem.

Throughout FY1979, technical oversight activities have included proposal reviews, reviews of the OTEC-1 Environmental Assessment, contributions to the planning of OTEC-1 environmental experiments, updating of the OTEC Environmental Development Plan, contributions to the OTEC Reference Handbook, site reviews at MIT and Dynalysis, and participation in the OTEC Gulf of Mexico Circulation Conference at Florida State University.

III. Planned Activities for 1980

The Dynalysis model will be employed to investigate the environmental and resource renewal questions associated with OTEC deployment in the Gulf of Mexico. Although the Gulf may be a site area initially of secondary importance to island sites, it is important in the general environmental and resource assessment for eventual Gulf deployment to understand now the transport pathways, residence times, and potential nutrient redistributions. The second phase of the Dynalysis effort addresses those problems directly. The results of earlier near- and intermediate-field studies will be employed by Argonne to provide input for the scenarios run with the model, with particular emphasis on 10-MWe OTEC impacts. Additional modeling efforts regarding near- and immediate-field plume behavior will be undertaken at MIT/Cornell to define plume behavior for different plant designs and ocean conditions, interactions between plants, and the linkage between transport and impact models. The modeling effort for island coastal transport will continue with emphasis on the transport of effluents. Application of the model to pertinent OTEC sites will be made. An assessment of alternative intake designs, avoidance systems, and screening options will be undertaken. The goals of this assessment are to develop recommendations for viable alternative intake design strategies compatible with OTEC operations that minimize the impacts to aquatic populations and to estimate the potential impacts for such systems. While studies are underway to determine the transport and mixing of plant effluents in the ocean, little is known about the loading of such effluents due to working fluid leaks into the seawater system of a plant. An evaluation of working fluid leaks is planned that will assess the probabilities and magnitudes of leaks to the seawater system for the range of minor routine leaks to potential major leaks. Study of approaches for quantification of climatic impacts are expected to lead to a specific study of such impacts. It is expected that the scenarios considered will include OTEC power parks, large-scale grazing, and large-scale deployment in the Gulf of Mexico. The best available estimates of sea-surface temperature depressions from the ocean models will be provided as input to this effort. Plans for specific experiments to be performed on and around the OTEC-1 platform will be developed in concert with LBL. The objective of these experiments is the acquisition of data on physical processes that will aid in the verification of modeling techniques and in the interpretation of the results of ecological studies. For example,
definition of the effluent plume is essential for the establishment of water sampling strategies. Direction and assistance in the physical aspects of the experimental program will be provided, if appropriate, in conjunction with the OTEC-1 test contractor, and data interpretation will be undertaken. In addition to the technical oversight activities, technical support will focus on the synthesis of modeling and analysis techniques for application to design and site assessment. Coordination of OTEC environmental activities with the power systems and biofouling programs at Argonne will continue.

IV. References (not cited)


OTEC BIOFOULING, CORROSION, AND MATERIALS

J. E. Draley, M. F. Adams, P. H. Benson, J. B. Darby, Jr., and A. P. Gavin

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, managing continuing programs on measurement of biofouling in seawater, and conducting corrosion and materials studies. The BCM project staff has participated in designing the Seacoast Test Facility and OTEC-1 and has been assisting in the review and development of national OTEC programs.

I. Introduction

The goal of DOE’s ocean thermal energy conversion (OTEC) program 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 DOE’s advanced research and technology effort, 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 in FY 1979 through nineteen subcontracts or interagency agreements to develop the sound technical information and understanding that will be required to meet OTEC objectives.

II. Accomplishments During 1979

Of the nineteen contracts associated with this program in FY 1979, twelve are ongoing and seven have 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.

Argonne’s BCM project issued the following contracts in FY 1979:
(1) OTEC Biofouling, Corrosion, and Materials Study from a Moored Platform at Punta Tuna, Puerto Rico, University of Puerto Rico; (2) OTEC Fouling Countermeasures Program for Heat Exchanger Tube Surfaces, International Nickel Company LaQue Center for Corrosion Technology; (3) OTEC Heat Transfer and Cleaning Tests on Biofouled External Heat Exchanger Tube Surfaces, Johns Hopkins University Applied Physics Laboratory; (4) In-situ Heat Exchanger Tube Fouling Thickness Measurements, Tracor Marine; (5) Study of the Corrosive Effects on 5052 Aluminum, CP Titanium, CA 706, and AL-6X of Mixtures of Ammonia and Seawater That May Be Encountered in OTEC Heat

Measurements of heat-flow resistance due to fouling ($R_f$) in the sea 1000 feet off Keahole Point, Hawaii, have shown that, after an initial period lasting up to several months, the four materials tested foul at roughly the same rate (see Figure 1). Immediately after periodic manual cleaning (by brushing), the value of $R_f$ increased significantly by the end of the test, which perhaps indicates the presence of a difficult-to-remove organic layer that develops slowly.

A new "Countermeasures Laboratory" has been established at the International Nickel Company LaQue Center for Corrosion Technology to select promising methods for the control of fouling in OTEC plants. Operational data for these methods will be obtained at the Seacoast Test Facility, Mini-OTEC, and OTEC-1. Programmatic and operational decisions for these facilities are now being made.

Tests of commercial methods of cleaning heat-exchanger tubes during operation have shown that at Panama City, Florida, Amertap balls on a 15-minute cycle and M.A.N. brushes on a 4-hour cycle maintained $R_f$ for titanium below 0.0001 Btu·°F·ft² for a two-month period but failed to prevent increasing values of $R_f$ for aluminum. Chlorine, at a measured residual concentration of 1 mg/liter for a 15-minute period daily, has maintained $R_f$ at essentially zero for titanium and was nearly as effective for aluminum.

A new heat-transfer monitor has been developed; preliminary testing shows reliable operation and adequate sensitivity.

On the basis of experiments completed, it is considered unlikely that objectionable amounts of calcareous deposits will form in OTEC plants unless ammonia leaks into the water. The effect of liquid ammonia leaking into seawater through small holes in experimental metal tubes has been to cause rapid enlargement of the holes in copper-nickel alloys and aluminum alloy 5052 but not in Alclad alloy 3003, titanium, or AL-6X stainless steel.

Biofouling and corrosion apparatus was mounted on a surplus landing craft, which was refurbished and modified in preparation for sailing to Puerto Rico. The craft will be moored at a potential OTEC site (2 miles off shore from Punta Tuna, Puerto Rico), and tests of fouling rate, countermeasures effectiveness, and corrosion resistance will be run.

Seven reports were published by Argonne as part of the BCM project. 1-7

III. Planned Activities for 1980

1. "Stage 1" of the Seacoast Test Facility will be constructed, and countermeasures tests using warm seawater will be started.
Fig. 1. Heat-Flow Resistance Due to Fouling, Keahole Point, Hawaii
2. A second deployment of Mini-OTEC will be started featuring countermeasures tests and the operation of the 50-kWe (gross) Mini-OTEC power plant, the latter not at government expense.

3. Measurement of biofouling, the effectiveness of countermeasures, and corrosion resistance of aluminum in seawater while being cleaned with Amertap balls will be started on OTEC-1.

IV. References


COMPUTER MODELING OF AMORPHOUS MATERIALS FOR PHOTOVOLTAIC CONVERSION

L. Guttman, W.Y. Ching and J. Rath

Abstract

Random network models of amorphous silicon have been constructed and their one-electron wave functions computed. A population analysis of the filled states shows fluctuations of atomic charge amounting to 0.2 electron on the average. The charge is largely accounted for by bond length and angle deviations.

I. Introduction

Amorphous hydrogenated silicon shows promise as a material for thin film photovoltaic devices, but there is a lack of knowledge of its atomic and electronic structure. The reasons are partly the variability of the properties with the method of preparation, and partly the difficulties inherent in studying amorphous substances. The present work is intended to provide reliable theoretical information on somewhat idealized models, which may nevertheless serve as a guide to interpretation of experiments.

II. Accomplishments During 1979

Before the period of this report, methods had been developed for systematic construction of computer models of pure amorphous silicon, and the electronic structure of a single example had been computed. A number of other examples have now been made, in all of which every Si atom has just four neighbors, which are periodic in space (and therefore have no free surfaces), and whose geometric distortions are small enough that they may be regarded as realistic. The electronic states of these models show that the randomness of the structure induces appreciable fluctuations of the electronic charge density. Instead of being neutral, as in crystalline Si, individual atoms acquire static charges that amount to ±0.2 electron (out of the 4 valence electrons) on the average. The charge, q, on a particular atom can be calculated from

\[
q = a \sum_{i=1}^{4} \frac{r_i - r_0}{r_0} + b \sum_{j=1}^{12} (\phi_j - \phi_0) + c
\]

Here \(r_i\) denotes the distance to a first neighbor, which has the value \(r_0\) in the crystal. The angle \(\phi_j\) is that between two bonds, one between the atom in question and a first neighbor, the other between that neighbor and one of its first neighbors; \(\phi_0\) is the tetrahedral angle. The parameters \(a, b,\) and \(c\) have been fitted by least-squares, and this simple function accounts for nearly 2/3 of the observed charges. Furthermore, the two sums have natural interpretations in terms of the formation of \(\text{sp}^3\) hybrid directed covalent bonds.
Some computations have been carried out on examples in which isolated atoms have only three near neighbors. Such defects are believed to occur frequently during the deposition of pure amorphous Si. The defective atoms are found to be associated with highly localized electronic states which must be only singly occupied to produce electroneutrality, rather than doubly, as for all the other atoms. The states thus conform to the picture of "dangling bonds" that has been used to describe this situation. Their position in the forbidden energy region of perfect networks supports the idea that they may be important in preventing the dopability of pure Si, as has been generally believed.

III. Planned Activities for 1980

Further studies of pure Si will be carried out, with the hope of completing the interpretation of the charge localization. Models of hydrogenated Si are being constructed, which, if they can be confirmed by concurrent neutron diffraction experiments at Argonne, will permit extension of the electronic computations to this material. Other kinds of defects which have been conjectured to exist will be studied as our facilities permit.

IV. References (not cited)

SATELLITE POWER SYSTEM CONCEPT EVALUATION

B. D. LaMar, J. J. English

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% 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 MW of power continuously to its ground-receiving station. A system of 30 to 60 or more of these satellites in a geostationary orbit 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 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 Plan 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 Fall 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 are being undertaken during the concept development and evaluation program are: systems definition, environmental assessment (evaluation of environmental, health, and safety factors), societal assessment, and comparative assessment of alternative energy systems. Of these, systems definition is the responsibility of NASA, environmental and comparative assessments are being integrated 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. Activities in 1979

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 were identified and DOE and ANL initiated a number of specific studies to resolve some of these issues, with several studies continuing into FY1980. In addition to the integration role for the entire environmental assessment area, Argonne had detailed management and technical responsibility for the atmospheric and climatic effects of SPS. A preliminary environmental assessment for the satellite power system was completed in September 1978, and a completely revised edition was submitted to DOE in October 1979. 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 in 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, 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. A comparative assessment methodology has been developed so that the different energy systems can be compared on a common basis. A comparative data base has also been developed from which the assessments will be made. The comparative assessment considers all the environmental, societal, economic and technical issues treated in the tasks above. A preliminary comparative assessment will be published by mid-1980.

Planning and Analysis

Argonne provided DOE with planning and analysis support which included preparation of program execution plans; maintenance of an information and data, storage, and retrieval system; development of source material for Congressional and Executive Department briefings; maintenance of a management information system; and most importantly, preparation of plans for the future. Argonne is integrating the planning effort for the next phase which will be invoked if the decision is made that exploration of SPS should continue.
III. Accomplishments in 1979

- Developed the role and implementation of the planning and analysis work element. This includes support to the SPS Program Office in program services, ground-based exploratory development planning, technical analysis, and program management support.

- Participated in preliminary review of the SPS concept development and evaluation program, October 1978.

- Established a comparative assessment review committee.

- Developed SPS decision planning aids in conjunction with Battelle Memorial Institute.

- Completed the comparative assessment methodology report.

- Participated in the interim review of the SPS concept development and evaluation program, June 1979.

- Completed a revision to the preliminary environmental assessment.

- Completed the preliminary comparative assessment.

- Completed a draft of the SPS ground-based exploratory development (GBED) program plan.

- Completed comparative assessments on land use, climate, net energy, health and safety, and welfare effects of SPS and other energy technologies.

- Conducted and reported on workshops on the following atmospheric-effects topics: rectenna waste heat, stratospheric and mesospheric impacts, ionospheric and magnetospheric impacts, tropospheric impacts, and upper atmospheric experiments.

IV. References


For More Information, Contact: B. D. LaMar
Energy and Environmental Systems Division, Bldg. 12
(312) 972-8062

Sponsor: DOE Assistant Secretary for Energy Research
Office of Satellite Power Systems
Project Officer: F. A. Koomanoff

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DOE FY 1980 Budget Category: KD-03
Abstract

The biomass environmental research programs at Argonne cover a wide range of activities from laboratory and field research on emissions from bioconversion technologies to resource assessments and research program coordination. The overall objective of this program is to identify potential biomass environmental problems and to develop solutions to these problems before they impede or limit the utilization of the U.S. biomass resources.

I. Introduction

In the Domestic Policy Review of Solar Technology, biomass was identified as the solar technology with the greatest near-term potential for displacing petroleum and gaseous fuels. However, current utilization of this renewable resource is limited to the burning of wood wastes in the forest products industry, about 1.5 quads/yr, and producing very minor amounts of ethanol, less than 0.005 quads/yr for use in gasohol. Estimates of the biomass resource base indicate that as much as 15 quads/yr might be available on a long-term basis and that this base could be expanded by various "energy farming" concepts. The near-term goal is to double biomass usage by 1985 and then to again double this amount by the year 2000 for a total biomass utilization of about 6 quads/yr.

While this may seem to be a modest goal when compared to the 15-quad/yr resource base, many technical, economic, and environmental concerns must be resolved before even these goals can be realized. An environmental research program that emerged within DOE this past year is aimed at addressing those issues with the greatest potential for delaying or impeding the application of near-term biomass technologies. The environmental research program begun at Argonne during FY 79 is divided into three project areas: biomass combustion, biomass gasification and pyrolysis, and fermentation stillage disposal. Argonne's earlier involvement in DOE resource evaluation and environmental planning activities continued in two areas, feedstock assessments for alcohol fuels and direct technical support. Each of these five areas will be discussed in separate sections in terms of FY 1979 program activities and the planned FY 1980 activities.

II. Biomass Combustion

This portion of the program was further divided into industrial-scale combustion and residential-scale projects. In both cases, the only biomass resource considered was wood although other potential industrial resources, such as bagasse, might be addressed in the future. The industrial combustion portion of this study involved an assessment of the existing EPA data base
and published EPA emission factors for wood combustion. The residential phase of the work is a laboratory study of typical air-tight, wood burning stoves, which have become very popular in the past few years for home space heating.

The characterization of air pollutant emissions for industrial wood-burning sources proved to be more difficult than had been originally envisioned. This difficulty was attributed mainly to the lack of data relating emissions of various pollutants to the combustion parameters, types of wood-burning boilers, and types and kinds of wood available as fuel. Nevertheless, using the data and information available in the literature, emission factors were developed. These factors were based on the ultimate analysis of wood, the combustion efficiency or the carbon conversion fraction expected in various types of boilers, and, in general, the boiler type.

Since wood combustion for the generation of steam and space heat is expected to increase as other fuels become scarce and more expensive, it was recommended that a test program be undertaken to more accurately quantify emissions for these sources. This test program should develop more accurate emission rates from various types of boilers while burning different wood types. Also, combustion conditions such as excess air injection, fuel-feed rate, grate area, heat release rates, etc., should be controlled while measuring pollutant emission rates.

More data related to particulate characteristics, especially particle size distribution, is required to design better and more efficient particulate removal systems for wood-fired boilers. These systems would be required to be installed if compliance with particulate emission standards is to be achieved. For example, if a 50-MWe (approximately 500 million Btu/hr heat input) wood-fired boiler is to be built today the allowable particulate emission rate would be 0.03 lb/10^6 Btu. This would require the installation of a very efficient electrostatic precipitator or baghouse. However, design data such as particulate size distribution, resistivity, ash analysis, etc., are not yet available to calculate control equipment design parameters.

In FY 1980, the best estimates of the emission factors will be used to project local and regional air quality impacts from industrial wood-fired boilers. These impacts will be compared with ambient air quality standards to define the degree of emission control necessary, to assess potential environmental control technologies, and to determine the system sensitivities to the observed uncertainties in the emission factors.

During the past year the residential wood burning study has developed the experimental facilities and procedures for conducting controlled emission tests and developed the analytical techniques necessary to measure and assess the potential health and ecological impacts of the various stove emissions. The stove test facility was designed with two criteria in mind, first to be as representative of a home installation and operation as possible, and, secondly, to give the experimenter as much control over the combustion process as would be consistent with the first criterion. The second criterion is critical to assuring that stack samples can be related to the combustion process conditions and that representative gas samples can be withdrawn from the stack. The sampling apparatus is a modified version of an EPA method 5 sampling train. The modifications are necessary to recover organic samples for subsequent gas chromatographic and mass spectroscopic procedures for determining the biological
activity of the tars and creosotes in the smoke. This test is a variation of the well-established Ames test.

During FY 1980, the stove testing program will determine emission factors for specific stoves as functions of wood type and preparation plus stove operating conditions. The samples obtained in the emission tests will be characterized for chemical composition and biological activity.

III. Biomass Gasification and Pyrolysis

Biomass gasification systems which could be easily retrofit into existing boiler systems are probably the fastest and most economical approach for early utilization of a wide range of biomass feedstocks. During FY 1979, this program surveyed over seventy gasifiers of three basic types: fixed beds with counter-current feed, fixed beds with co-current feeds, and fluidized beds with deep-bed injection. The units have been used to gasify wood wastes, cotton gin trash, manure, apricot pits, and many more biomass materials.

Four units were selected for a joint sampling program to determine the environmentally significant emissions. Programs were established at two of these four during FY 1979 and the other two will be participating in FY 1980. The two units studied were the high-temperature, flash pyrolysis process at Arizona State University (ASU) and a low-temperature pyrolysis process developed by Garrett Energy Research.

Analysis of the effluent samples of the ASU unit were used to calculate emission material balances for a commercial-scale plant and to prepare conceptual designs for the required effluent control systems. This design was used to estimate that the cost of the environmental control systems would add about $2.50 per 10^6 Btu of gas or liquid hydrocarbon product.

In FY 1980 the sampling program will be extended to other gasifier systems to cover as wide a variety of near-term technologies as possible. Further evaluations of effluent control system requirements for the most promising biomass gasifier systems will be used to identify research needs for developing environmental control technologies.

IV. Fermentation Stillage Control

During the past year the demand for gasohol has grown so rapidly that, at times, the demand for fuel ethanol has exceeded its supply. The largest producer of fuel ethanol, an Illinois corn processor, is currently doubling its ethanol capacity to over 100 million gallons per year and at least three corn processors have publicly acknowledged that they are actively considering their own entry into the fuel ethanol business.

All of these current and near-term plants will ferment grains or starch derived from grain. The direct fermentation of grains may create a problem in disposing of the stillage solids. At the present, these solids are a readily marketed, high protein animal feed and are important sources of income to the alcohol producers. This material, called DDG for distillers dried
grains, is now produced at a rate of about 400,000 tons per year. At this rate, the DDG is a small fraction of the 10 million tons per year which is estimated to be the maximum cattle feed market for DDG. However, at some level before that production capacity is reached, the DDG price will probably be depressed by competition with other protein feeds such as soyameal and stillage will become a disposal problem. This would adversely affect gasohol economics if alternate markets for this by-product or satisfactory waste treating technologies are not developed.

In FY 1980, disposal and waste treating of stillage produced from other fermentation feeds -- such as starch from grain; sugar from cane, beets, or sweet sorghum; food process wastes such as potatoes or cheese whey, and cellulose -- will be assessed for potential by-product values. If the apparent by-product value is low or non-existent, the waste treatability of these stillages will be determined.

A second area of study for FY 1980 is to project the environmental impacts of the several gasohol scenarios proposed by DOE for the near- to mid-term. Each of these scenarios assumes only current fermentation technology and sugar or starch feedstocks. In this extension of the stillage work, other process emissions will be considered and the costs of building and operating the environmental control systems will be projected.

V. Alcohol Fuels Assessment

In July 1978 an Alcohol Fuels Policy Review committee was established within DOE. Argonne provided technical support to the review and coordinated several assessments of the potential resource base for a national alcohol program. The individual studies and their major conclusions are summarized below.

"Cropland Reserve for Fuel Productions"

Fuel from field crops is a short-term prospect of limited significance for the country's energy problem but could have major impacts for farm support policy. Current set-aside acreage might produce enough corn to make 2 billion gallons of ethanol but would probably be too expensive a source of fuel ethanol in the long term.

"Availability and Cost of Grain for Use as Alcohol Fuels Feedstocks"

At maximum production rates there will be sufficient grain available, above food, feed and export requirements, to produce about 3.8 billion gallons of ethanol. This study assumed only land from the normal cropland base would be utilized. (Thus the 2 billion gallons per year of the first study is included in the 3.8 billion gallons per year projected here.) One problem noted is that, for a massive ethanol from grain program, additional storage might be necessary to even out the seasonal fluctuations in crop production with respect to ethanol production.
"Availability of 'Agricultural Processing Wastes' for Utilization as a Feedstock for the Production of Alcohol Fuels"

In 1973 over 9,300,000 dry tons of food product wastes were produced in the United States. Almost one-third of this was citrus wastes with corn and potatoes in second and third place, respectively, with each at about 15% of the total. Of this volume of waste, approximately 75% to 80% is currently being utilized as by-products, mostly as animal feeds. While it is technically feasible to produce alcohol from many of these wastes, they may be too widely dispersed to be economically collected and converted into transportation fuels. In particular, some of these wastes appear to be better candidates for other conversion technologies than fermentation, pyrolysis for example. The maximum ethanol production rate from these wastes is about 1.3 billion gallons per year.

"Availability of Sugar Crops for Production of Alcohol Fuels"

This study concluded that sugar cane and sweet sorghum could be used to produce between 5 and 10 billion gallons per year of ethanol in the year 2000. The respective production costs for this range in production capacity were $1.58 and $0.97 for the fermentable sugars in each gallon of ethanol (1978 dollars).

"Availability and Cost of Agricultural and Municipal Residue for Use as Alcohol Fuel Feedstocks"

These residues currently total about 350 million dry tons per year and contain slightly more than 5 quads. By the year 2000 this might rise to 7.5 quads per year. About 80% of these residues are agricultural residues and, therefore, are highly seasonal. Furthermore, they are currently used as soil conditioners and as animal feeds. These factors plus the dispersed nature of this resource are a potential barrier to their use as ethanol feedstocks. However, conversion economics will probably be the determining factor in whether or not these materials are diverted from their current on-farm uses.

Municipal solid wastes (MSW) are produced continuously and currently must be disposed of. Their principal feedstock cost is in processing the MSW to obtain a satisfactory feedstock for methanol fuel production. Other conversion technologies, such as combustion and anaerobic digestion, will compete strongly with methanol for the MSW resource.

"Potential Availability of Wood as a Feedstock for Methanol Production"

Enough wood is potentially available to support a national program which requires the equivalent of either a 10% methanol in gasoline blend or a 10% ethanol blend. The long-term projected cost of feedstock is estimated to be 21-27¢/gallon of methanol and about twice that for ethanol. In the long-term, silviculture energy farms will have a favorable impact on the cost and availability of feedstock.

In FY 1980 this effort will be continuing with Argonne providing review and consulting assistance to DOE and participating on the National Gasohol Commission established by Congress.
VI. Biomass Environmental Technical Support

In FY 1979, assessments of the biomass resource base and biomass environmental research needs were prepared. These studies led to the development and implementation of the biomass environmental research program plan on behalf of DOE. This effort will continue during FY 1980 with increased responsibilities for research coordination and for policy and resource assessment.

VII. Reference


For More Information, Contact: J.B.L. Harkness
Energy and Environmental Systems Division, Bldg. 362
(312) 972-7636

Sponsor: DOE Assistant Secretary for Conservation and Solar Energy
Office of Solar Applications for Industry
Project Officer: R. Costello

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