DOCUMENT RESUME

ED 166 054 SE 026 576

AUTHOR	Beard, J. Taylor; And Others
TITLE	Annual Collection and Storage of Solar Energy for the Heating of Buildings, Report No. 3. Semi-Annual Progress Report, August 1977 - January 1978.
INSTITUTION	Virginia Univ., Charlottesville. Dept. of Mechanical and Aerospace Engineering.
SPONS AGENCY	Department of Energy, Washington, D.C.
REPORT NO	ORO-5136-78/1
PUB DATE	Jan 78
CONTRACT	E-40-1-5136; EY-76-S-05-5136
NOTE	35p.; Not available in hard copy due to marginal legibility of original document
AVAILABLE FROM	National Technical Information Service (NTIS), U.S. Department of Commerce, Springfield, Virginia 22161 (microfiche $3.00, paper copy $4.50)
EDRS PRICE	MF-$0.83 Plus Postage. HC Not Available from EDRS.
DESCRIPTORS	Analog Computers; *Building Systems; Digital Computers; *Energy; Environmental Research; *Heating; Models; *Solar Radiation; Technological Advancement
IDENTIFIERS	*Research Reports

ABSTRACT

This report is part of a series from the Department of Energy on the use of solar energy in heating buildings. Described here is a new system for year around collection and storage of solar energy. This system has been operated at the University of Virginia for over a year. Composed of an underground hot water storage system and solar collection, the system was tested. Thermal performance results are presented. Analog and digital computer models were used to study the effect of various design modifications on collection and storage performance. (Author/MR)

SE

ORO-5136-78/1

ANNUAL COLLECTION AND STORAGE OF SOLAR ENERGY FOR THE HEATING OF BUILDINGS

Report No. 3

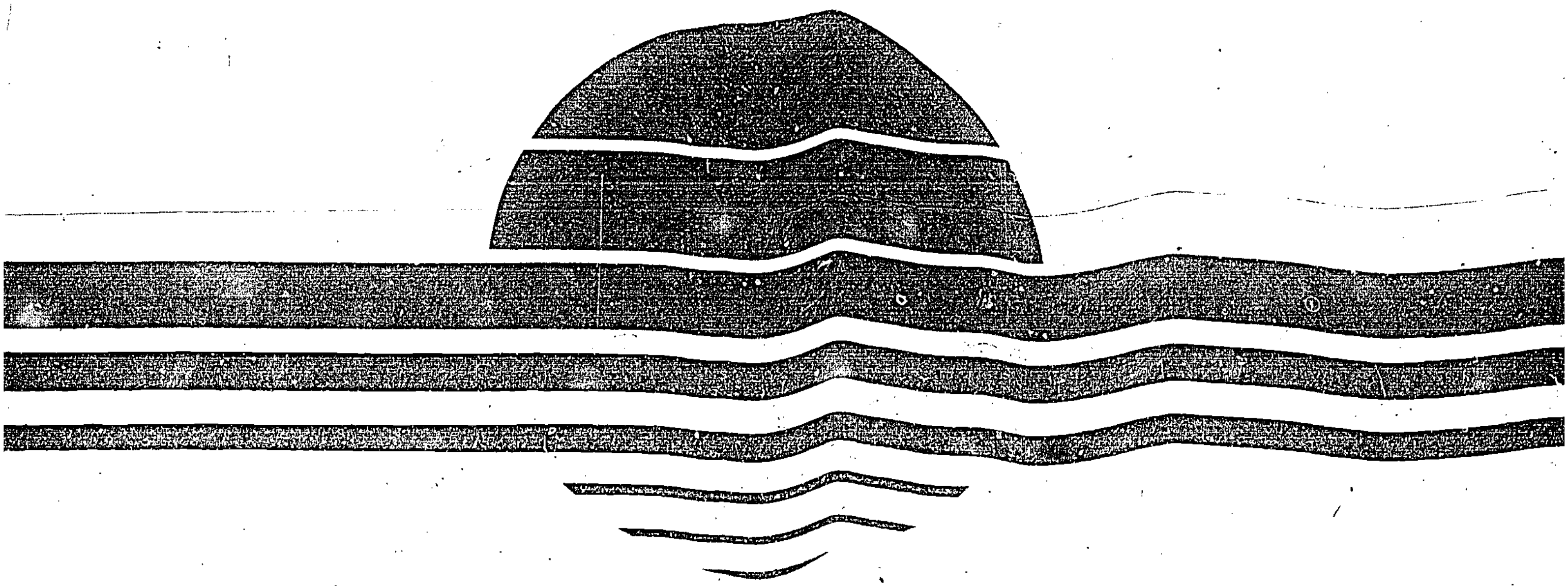
Semiannual Progress Report, August 1977—January 1978

By
J. Taylor Beard
F. A. Iachetta
L. U. Lilleleht
J. W. Dickey

January 1978

Work Performed Under Contract No. EY-76-S-05-5136

University of Virginia
Charlottesville, Virginia



U.S. Department of Energy

Solar Energy

NOTICE

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $4.50
Microfiche $3.00

ORO-5136-78/1
Distribution Category UC-59c

ANNUAL COLLECTION AND STORAGE OF SOLAR ENERGY FOR THE HEATING OF BUILDINGS

Report No. 3

Semi-Annual Progress Report

August 1977 - January 1978

January 1978

J. Taylor Beard

F. A. Iachetta

L. U. Lilleleht

J. W. Dickey

Mechanical and Aerospace Engineering Department
University of Virginia
Charlottesville, Virginia 22901

RLES Report No. UVA/527191/MAE78/101

PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
DIVISION OF SOLAR RESEARCH

UNDER CONTRACT NO. E-(40-1)-5136

TABLE OF CONTENTS

Page

I. Abstract 1

II. Nomenclature 3

III. Narrative 4

A. Research Objectives 4

B. Summary of the Progress 4

Figure 1 - Annual Collector /Storage System, February 1977 6

Figure 2 - Annual Collector /Storage System, March 1977 6

C. Report of the Progress: System Description 7

Figure 3 - Solar System Design 8

Figure 4 - System for Monitoring and Delivering Water 8

Figure 5 - Collector Details 8

Figure 6 - Collector Support Detail 8

D. Report of the Progress: Collection Mode 9

Figure 7 - Collector Thermal Performance 11

Figure 8 - Seasonal Temperatures of Storage System ... 11

E. Report of the Progress: Energy Loss Analysis 12

E-1 Analog Model Description 12

E-2 Digital Simulation Model 14

E-3 Model Verification and Experimental Results 14

Figure 9 - Analog Model Elements 15

Figure 10 - Digital Model Elements 15

Table 1 - Summary of Model Verification 15

Figure 11 - Steady State Losses from Simulation...... 17

Figure 12 - Steady State Losses from Simulation...... 17

Page

Figure 13 - Simulated Seasonal Temperatures with Variable Start-Up 19

Figure 14 - Pool Stratification 19

Figure 15 - Diurnal Temperatures of Ambient Air and Soil at Selected Positions 19

F. Report of the Progress: Influence of Design Changes 19

Table 2 - Effect of Insulation on Pool Heat Losses 20

Figure 16 - Heat Loss as Function of Soil/Air Interface Insulation 21

Figure 17 - Predicted Seasonal Storage Temperatures for System with Solar Collectors Having Three Loss Coefficients 23

Figure 18 - Collected and Lost Energy for System With Collector Having F_RU_L = 2.2 w/m^2°C 23

Figure 19 - Collected and Lost Energy for System With Collector Having F_RU_L = 4.4 w/m^2°C 23

Figure 20 - Collected and Lost Energy for System With Collector Having F_RU_L = 6.6 w/m^2°C 23

G. Report of the Progress: Heating Mode Operation 24

Figure 21 - Monthly Energy for Heating with Solar Assisted Heat Pump 25

H. Activities to Disseminate Project Results 26

IV. TIC Distribution List 29

I. ABSTRACT

A new system for year-round collection and storage of solar heated water for heating of buildings has been operated over the past year at the University of Virginia. The system is composed of an energy storage sub-system, which stores hot water in an underground pool, and of a solar collector sub-system which acts not only to collect solar energy throughout the year but also to limit the evaporative and convective heat losses from the storage system.

Results are presented to illustrate the transient heat transfer from the pool which occurs during the energy collection mode of operation. Thermal performance results are presented illustrating the efficiency of the solar collector under summer conditions (without a reflector) and winter conditions (with assistance from a vertical reflector). Results also show the transient behavior of energy storage in the water and in the earth which surrounds the storage pool.

An analog computer model and a digital computer model have been used to analyze the transient energy phenomena which occur within the earth surrounding the pool. Results of the models are confirmed by an exact mathematical solution and by experimental results.

Analog and digital models were used to determine the influence of various design modifications for improved collection and storage system performance.

The experimental system has been modified to provide for energy extraction through a heat exchanger, to simulate the heat input required

7

for a solar-assisted heat pump for a residential heating application.

Future research will include additional system operation in the collection and heat load mode, performance evaluation, and additional analytical modeling, particularly to identify the influence of additional design modifications on the system operation.

II. NOMENCLATURE

η = collector thermal efficiency

ρ = density

c_p = specific heat

$F_R U_L$ = slope of collector performance curve (heat removal x loss coefficient)

k = thermal conductivity

$\dot{Q}$ = heat loss

$\dot{Q}_o$ = heat loss with earth berm perfectly insulated

R_e = radius to outer isothermal boundary

T_a = ambient temp.

T_e = earth temp. at R_e

T_{in} = collector inlet water temp.

T_{c1} = centerline earth temp. at pool/earth interface

T_{c2} = centerline earth temp. at 1 ft. below pool

T_{c3} = centerline earth temp. at 2 ft. below pool

T_{c4} = centerline earth temp. at 3 ft. below pool

T_p = average pool temp.

T_{p1} = centerline pool temp. at top surface

T_{p6} = centerline pool temp. at 5 ft. depth

T_{p11} = centerline pool temp. at 10 ft. depth.

T_{w1} = earth temp. on 45° pool/earth interface

T_{w3} = earth temp. 3 ft. from 45° pool/earth interface

T_{41} = earth temp., 4 ft. from pool edge, 1 ft. down

T_{42} = earth temp., 4 ft. from pool edge, 2 ft. down

T_{44} = earth temp., 4 ft. from pool edge, 4 ft. down

T_{46} = earth temp., 4 ft. from pool edge, 6 ft. down

III. NARRATIVE

A. Research Objectives

The research objectives include the design, construction, testing and evaluation of a new system for year-round collection and storage of solar energy for the heating of buildings.

The design of the system includes a 103 m^3 (27,400 gal) water storage pool which resembles a swimming pool. The collector sub-system is that of a 53.5 m^2 (576 $ft.^2$) near horizontal open water-channel solar collector having two glazings. The solar collector acts not only to collect solar energy but also to reduce losses from the energy storage pool. Design modifications for improved structural and thermal performance are an important part of the research objectives.

The testing and evaluation program has included the use of standard instrumentation and measuring techniques as well as analytical simulation to determine performance under varying ambient and design conditions. The evaluation also will include structural, operational and economic considerations.

B. Summary of the Progress

A new system for year-round collection and storage of solar heated water for the heating of buildings has been constructed and is being evaluated at the University of Virginia.

In the first year the research included developing improved structural and system design with construction, system operation in the collection mode, testing and evaluation.

Construction of a revised pool design with 103 m^3 (27,400 gallons) of water capacity was completed in November 1976. The solar collector, shown in figure 1, became operational in February 1977.

Various modifications have been made such as the installation of a vertical reflector along the north edge of the pool shown in figure 2, improved glazing attachment, and improved instrumentation for monitoring energy collection and energy loss through the earth berm.

During the fall of 1977 it became obvious that energy losses were becoming significantly greater than energy collection. A study of possible ways to improve the insulation quality of the storage resulted in the conclusion that a full system shut down would be required in order to provide the proper improvement to the insulation. This was judged to be appropriate for follow-on work after the system had been operated throughout the 1977-78 heating season. A decision was made to continue system operation in the heat collection mode with a modified plan for energy extraction. A heat exchanger was provided to simulate the heat input requirements for a solar assisted heat pump for a residential heating application. The system began operation in the heat load mode (with solar collection, when available, as before) in December 1977.

Results are presented of analog and digital computer simulations which illustrate the influence of design modifications on system performance in the collection mode of operation.

Future research will include simulations of other design modifications (such as larger size systems with independent collector arrays) and experimental analysis of system operation in the heat load mode.

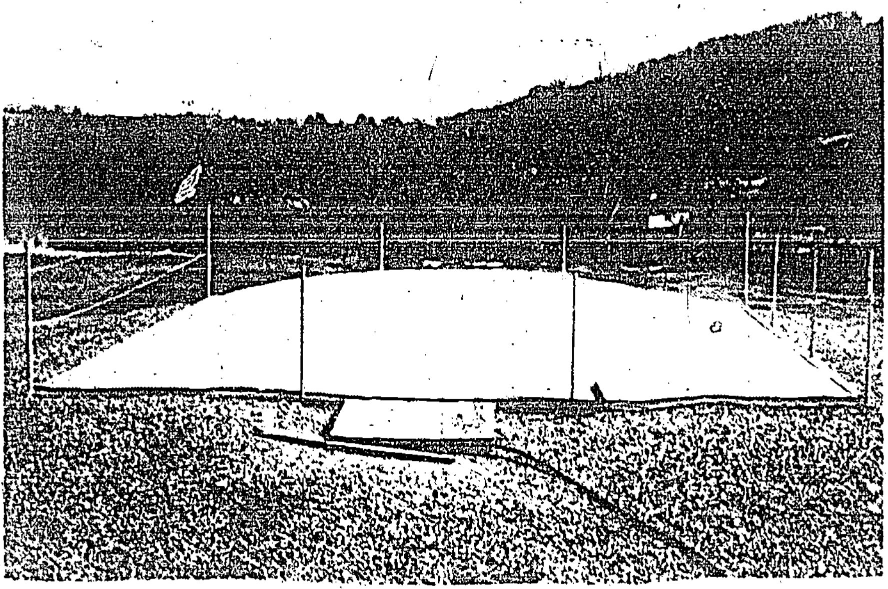


Figure 1, Annual Collector/Storage System, February 1977

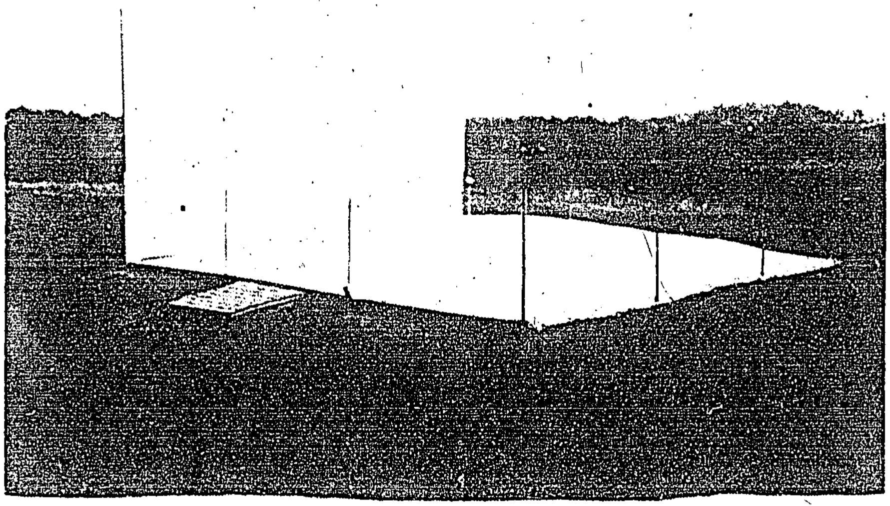


Figure 2, Annual Collection/Storage System, March 1977

11A

C. Report of the Progress: System Description

In May of 1976, the University of Virginia began its research program to evaluate a new system for the year-round collection and storage of solar-heated water which could be used for the heating of a building. The system includes a 53.5 m^2 (576 $ft.^2$) solar collector on the top of a 103 m^3 (27,400 gal) energy storage pool which resembles a swimming pool. Included in the collector are the near-horizontal absorber surfaces, the inner glazing and the outer glazing shown in Figure 3 and the inlet manifolds shown as a top view in Figure 4. The location of the solar collector on the top of the storage pool restricts the convective and evaporative heat transfer relative to that of traditional solar pond systems [1].

As illustrated in Figure 3, the energy storage pool is designed with the sloping earth surfaces at 45°. This design was selected because of the stability of such surfaces without a requirement for structural reinforcement. A traditional swimming pool having vertical walls with reinforced concrete structural support could be used in this system; however, the cost of the reinforced wall structure would be considerable and was judged to be unnecessary.

The pool design includes a factory manufactured 20-mil polyvinylchloride swimming pool liner. All the seams were heat sealed at the factory to assure their integrity. In addition, special care was taken to ensure that this liner would not be punctured. The earth surfaces were smoothed as much as possible and a duPont Company "Typar" (spun-bonded polypropylene) subliner was installed on the earth surfaces to

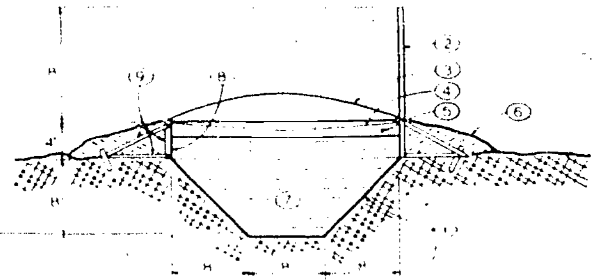


Figure 3. Solar System Design

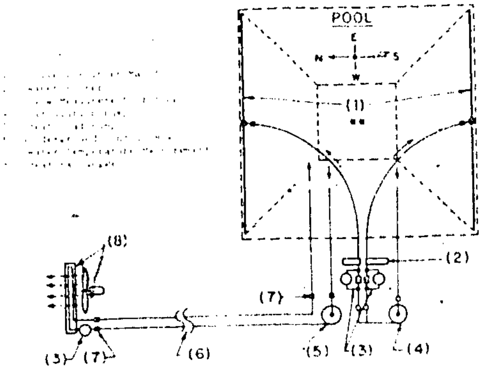


Figure 4. System for Monitoring and Delivering Water

1. Outer Glazing
2. Inner Glazing
3. Collector Inlet Manifold
4. Corrugated Aluminum Collector Plates
5. Collector Mounting Bracket
6. Collector Support Cable/Rod
7. PVC Pool Liner
8. Plywood
9. Rim Strip
10. Batten Strip
11. Spline
12. Pool Liner Anchor Strip
13. Batten Support Strip

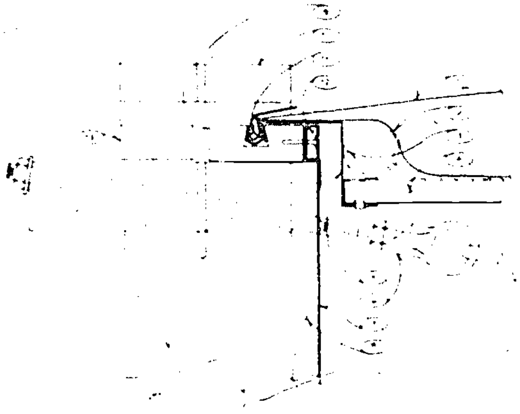


Figure 5. Collector Details

1. Outer Glazing
2. Inner Glazing
3. Corrugated Aluminum Collector Plates
4. Support Cable
5. Support Bracket
6. [illegible] Beads Floating on Water Surface
7. [illegible] Water Outlet

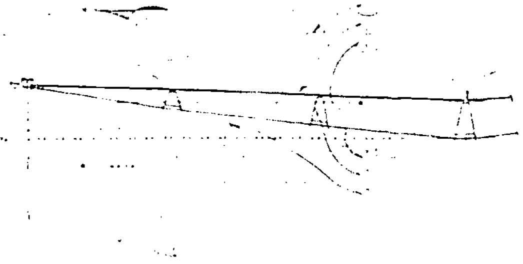


Figure 6. Collector Support Detail

prevent migration of sharp stones, etc., from penetrating the liner.

The solar collector selected for the annual collection/storage system is that of a near-horizontal open water-channel solar collector having two glazings as indicated in Figures 5 and 6. The glazing materials are separated by air pressure from a small fan (47 watts) with the inner glazing lying on top of the corrugated metal collector plate. Water flows from the north and the south perimeters of the collector system down the valleys of the corrugations to the center of the pool where it exits and flows through a layer of styrofoam beads floating on top of the water surface.

The glazing material which has been selected is that of a 6-mil thick greenhouse film sold as Monsanto 602. This is a flexible polyethylene "copolymer" greenhouse covering which has a transmittance of 88%. It has been widely used throughout the United States and is available in an adequate size to cover the pool in a continuous sheet. Although it is very inexpensive for a glazing material ($0.28 per square meter) the outer glazing was found to sustain a 8% reduction in transmittance over a five (5) month period of use. The outer glazing was replaced with new Monsanto 602 in July 1977.

D. Report of the Progress: Collection Mode of Operation

The collection and storage system began operation in late February 1977. When adequate solar energy is available, the collection system is turned on by a controller. The hot water from the solar collector flows through the floating beads at the centerline of the pool and into the top of the hot water storage.

One should note that the collectors are near-horizontal which is not the desired orientation, particularly for winter solar energy collection. A vertical reflector has been constructed along the north edge of the collector to increase the energy capture, particularly during the winter months.

Figure 7 displays the thermal performance of the collector as a plot of $(T_{in} - T_a)/I$. One should note that the reflector was not up when the summer performance data were obtained. Also, the winter performance calculations did not provide for the energy intercepted by the reflector to be included in the denominator of the efficiency (output ÷ input) calculation. Consequently the winter performance curve gives a false impression of a reduced value of $F_R U_L$ (slope). It is important to note that the reflector is very important to winter solar energy collection for typical values of $(T_{in} - T_a)/I$ around 0.08 [°Cm²/w].

Figure 8 presents the temperatures observed for the seasonal solar energy storage pool. One notes that the pool and earth temperatures rose steadily until the months of August and September, but then dropped off rapidly. The obvious reason for this change is that the variation in incident solar energy and ambient temperature with season and the fact that the storage pool does not have adequate size or insulation to reduce the relative losses. This experimental observation is consistant with the experience the similar sized pool installation at Ohio Agricultural Research and Development Center [2].

One should note that no programmed energy extraction from storage has occurred for the time period of the data presented. An energy

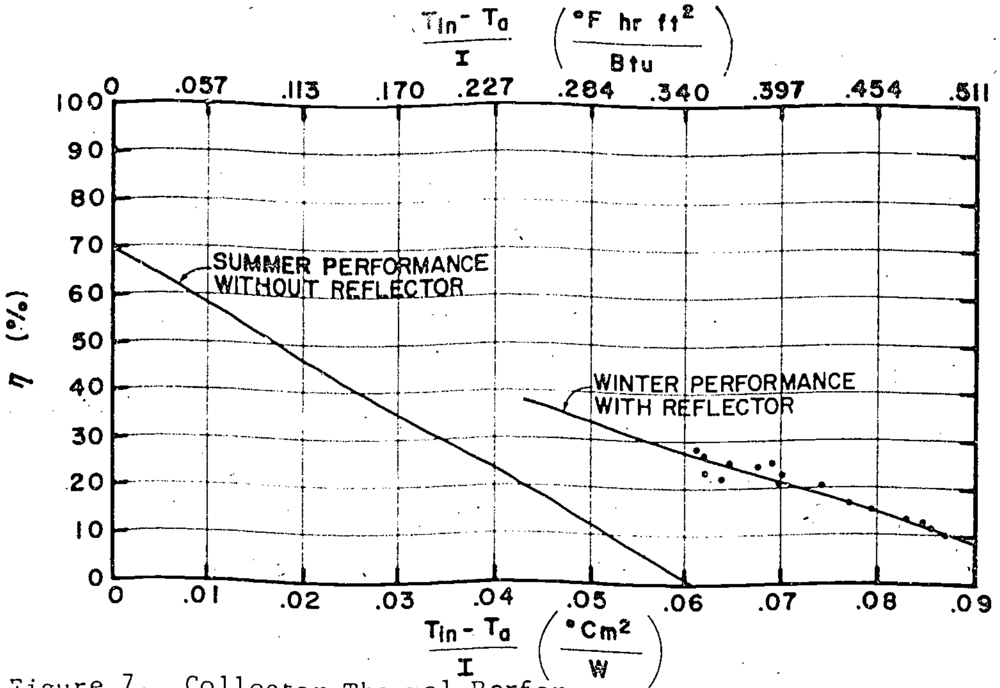


Figure 7. Collector Thermal Performance

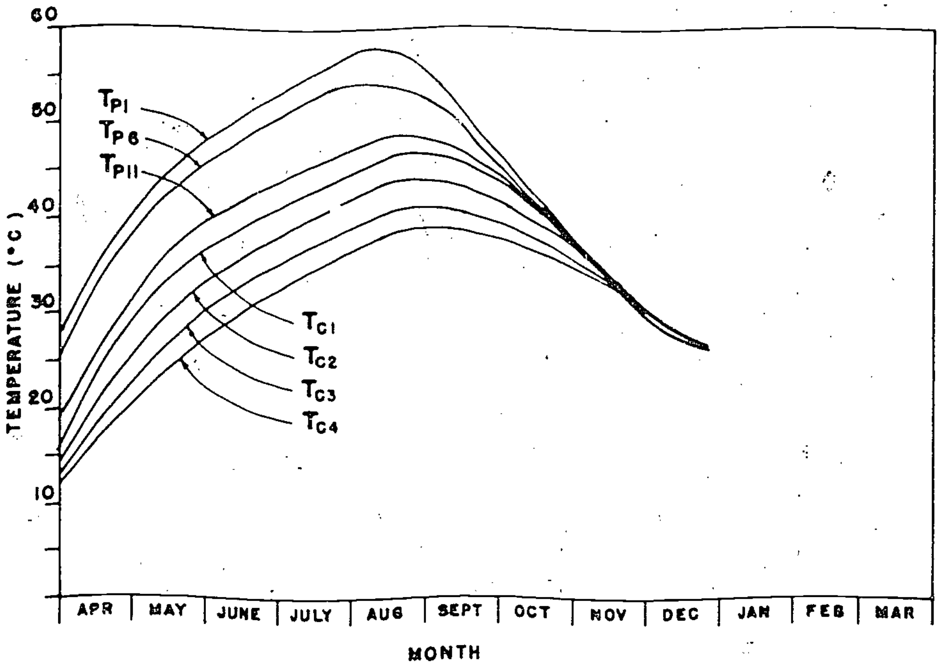


Figure 8. Seasonal Temperatures of Storage System

15

extraction program began operation in December 1977 with energy (hot water) being delivered to a heat exchanger in a proper amount to simulate the requirements of a heat pump for a residential application. The heat load mode of operation is described in a later section.

E. Report of the Progress: Energy Loss Analysis

Energy losses from such solar pools occur by various heat transfer mechanisms and can be attributed to the heating up of the surrounding soil, conduction losses from the top surface directly to the atmosphere, and losses through the soil to the atmosphere. These losses depend on the size and the geometry of the pool, the energy input to the pool from the solar collector, the meteorological conditions and the physical properties of the system.

E-1. Analog Model Description

An electrical resistance-capacitance network has been set up to simulate the heat transfer processes from a hemispherical pool of water to the surrounding soil and through the soil to the ambient air. This network used a modified version of the Heat Exchange Transient Analog Computer developed by R. M. Hubbard [3]. In this analog the temperature is represented by a voltage, the rate of heat flow by current, and thermal resistances and capacities by electrical resistors and capacitors. By using appropriate scaling laws [4], a network can be set up to represent the thermal capacitance and heat transfer resistances for a particular pool geometry. The network can accept properly scaled time-dependent solar energy input and variable ambient and energy demand conditions. Selected parameters can be adjusted easily so as to simulate different design conditions.

For the initial simulation of the storage pool heat loss problem, we chose to consider heat transfer by conduction through soil of uniform and constant physical properties. A hemispherical pool of water was chosen. The soil surrounding the pool was divided into 24 elements as illustrated in figure 9, with nodal points (at the center of each element) interconnected by resistors representing thermal resistances between adjacent points. A vector volume approach [4] was used to determine the effective resistance as the area normal to heat flow changes with both radial and angular positions. The capacitance of each element is directly proportional to its volume. Since the hemispherical heat source has symmetry, only a slice of the surrounding earth need to be considered.

The boundary conditions were applied by connecting the adjacent nodes to appropriate resistors and to voltage sources representing the desired boundary temperatures.

The properties of soil used in the simulation were fixed with:

$\rho = 1,500\ kg/m^3$

$c_p = 880\ J/kgK$

$k = 1.28\ w/mK$

Scaling factors were determined largely by the size and number of resistance and capacitance elements available. The following relations were set between the important variables:

1 volt = 1°C

1 analog second = 1 week real time

1 microampere = 3.84 kw hr/day heat rate

To obtain the above scaling factors, resistors ranging from .26 to 18.6 megohms and capacitors from 0.226 to 440 microfarads were needed.

E-2 Digital Simulation Model

A digital computer simulation model has been developed with the following four components: (a) a one-dimensional finite difference model of the thermally stratified pool of water; (b) a three-dimensional finite difference model of the surrounding soil; (c) a solar collector model based on experimental thermal performance data; and (d) a simple model of the load.

As illustrated in figure 10, only one-eighth of the pool and surrounding soil are modeled because of symmetry (no heat flux across planes of symmetry: D, G, and H, shown in figure 10). The boundary condition at the top of the simulated pool is set by the condition of the solar collector. Boundary conditions at planes A and C originally allowed for convective heat transfer [5]; however, the temperatures of the surface nodes with the convective boundary conditions were found to be essentially equal to the ambient temperature. The distance from the pool to boundaries E and F were determined by trial running of the program. A distance of 6.1 m (20 feet) was found to be adequate. Moving these boundaries by approximately 1.2 m or 4 ft. had less than 1.5% effect on the heat loss from the pool.

E-3 Model Verification and Experimental Results

To validate the analog network, the steady state conduction was simulated through a spherical shell with a cavity at a higher temperature than the outer surface. These results are summarized in Table 1. It is interesting to note from Test 1 and 2 that having the constant ground temperature at a finite radial distance of 38.9m from the center of the pool rather than at infinity increases the pool heat loss rate by approximately 10%. The losses to the earth further out may be overestimated slightly but this effect would

TABLE 1

MODEL VALIDATION: STEADY STATE

Pool Temperature T_p = 82°C

Earth Temperature T_e = 10°C

Test	Model	Air/Ground Surface	Const. Temp. Earth at R_e, m	Pool Heat Losses kW-hr/day
1	Theory	Insulated	∞	64.8
2	Theory	Insulated	38.9	71.4
3	Analog	Insulated	38.9	72.6
4	Digital*	Insulated		73.2
5	Analog	T_a = 21°C	38.9	124.6

NOTE: Digital model for truncated pyramid shape. Constant temperature earth at 6.1m from pool sides and bottom.

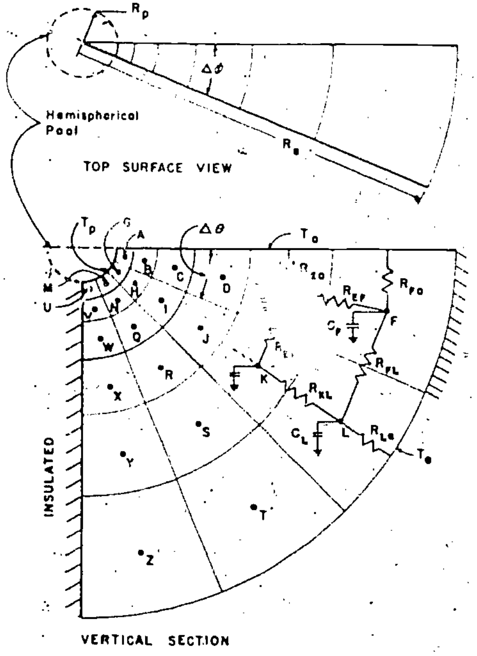


Figure 9. Analog Model Elements

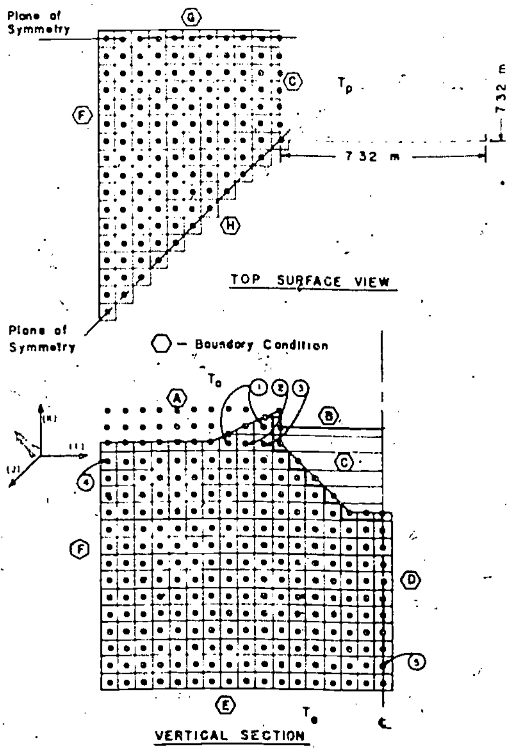


Figure 10. Digital Model Elements

be conservative in considering the performance of the storage pool. The agreement between Test 2 and 3 was excellent.

The digital model was also evaluated under the conditions listed in Table 1. Note that good agreement was obtained between the digital model and the analog model under the conditions where the analog model had a pool perimeter equal to that of the actual pool and the simulated model. This was based on Shelton's conclusion that the heat losses from a hemispherical pool are proportional to the perimeter (radius) rather than the heat transfer surface area (radius^2)[6].

Steady state heat losses from the pool have been simulated over a range of pool, ground, and ambient temperatures. Shelton has analyzed heat losses from a similar hemispherical heat storage device [6]. However, Shelton's results were all based on no heat losses from the soil to the air through the soil-air interface. By considering this heat loss mechanism, the energy losses are considerably increased (approximately 70%) as shown by Test 6 in Table 1.

The limiting (steady state) heat loss results are summarized in figure 11. Note here that the simulated pool losses (which include losses to the ambient as well as to the constant temperature earth) appear to be approximately linear with the difference between the pool temperature and the air temperature. From figure 12 one can discern that the influence of pool temperature minus earth temperature is much less significant than pool temperature minus ambient temperature.

Results of experimental data for the annual collection and storage

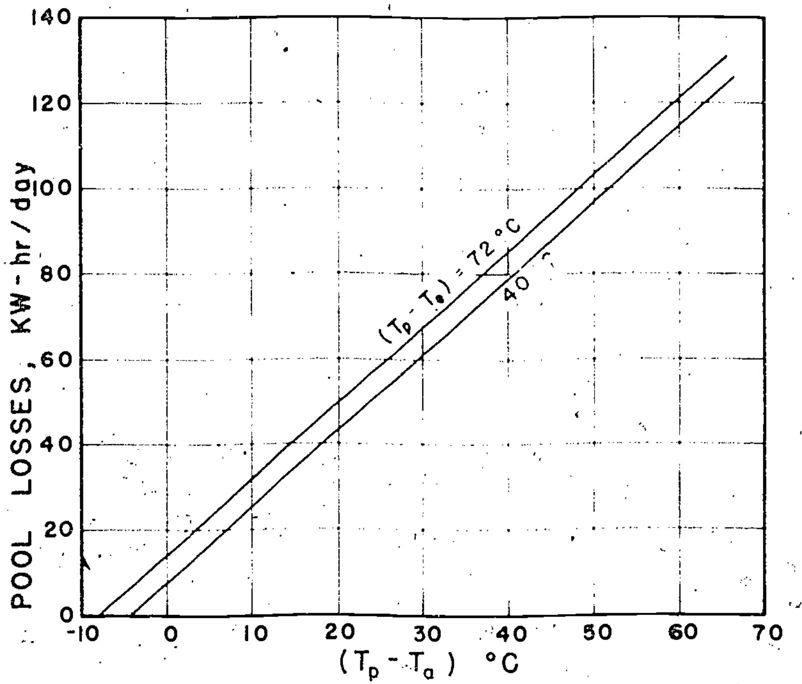


Figure 11. Steady State Energy Loss As Function of $(T_p - T_a)$

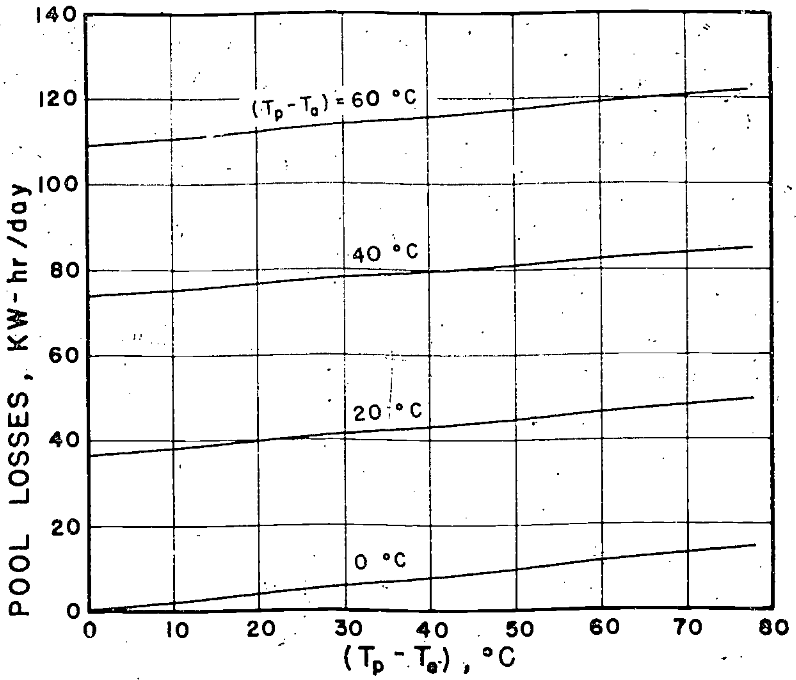


Figure 12. Steady State Energy Loss as Function of $(T_p - T_e)$

system operating in a collection mode were presented in figure 8. One notes that the water storage temperatures were shown to reach a maximum in August which would be an indication of excessive heat losses over energy collected from that time forward.

The digital computer simulation model was run using ambient conditions derived from a 1955 weather tape for Washington, D.C. Although it is clear that the particular weather conditions at the experimental site during 1977 are different from those used in the simulation, the following conclusions can be made.

Simulation shows, as illustrated in figure 13, that a cyclic pool temperature should be expected. The simulation indicates a peak temperature reached on approximately August 1 when the pool had been operating in the collection mode at least since early March. If the pool began operation in the collection mode on July 1, the expected peak temperature would occur approximately September 1 and if the pool began operation on October 1, the peak temperature would occur at approximately November 1. Note also that if the pool had been operating in the collection mode for at least six months, the influence of start up time would be negligible compared to the anticipated temperatures from continuous operation in the heat collection mode.

Pool stratification determined experimentally are in good agreement with the simulation model, as illustrated in figure 14.

Although simulation studies have not been done to consider the influence of diurnal variations of temperatures in the earth berm (adjacent to the pool), experimental measurements have been taken. Figure 15 illustrates the diurnal variations of the ambient temperature and soile temperatures at various locations. One should note that these data were taken on a sunny day (October 7, 1977) followed by a cloudy day having a very light rain. Note also that the ambient temperature and the earth berm temperature to a depth of one foot have significant diurnal variation, but that the earth temperatures at locations below this appear to have near negligible diurnal variations.

F. Report of the Progress: Influencc of Design Changes

On the basis of information presented in the previous section, one may conclude that the high heat losses from the present experimental system make it ineffective for operation as a device for annual storage of year-round collected solar energy for direct heating of buildings. Various design modifications, however, may change this conclusion.

The first design consideration would be that of modifying the system in order to provide for additional insulation. Table 2 summarizes the results of analog simulation studies of the influence of varying amounts of insulation placed at convenient locations within the earth berm. Note that one may conclude that a most important location for placing insulation would be along the interface between the pool structure and the earth berm. This is true because the earth berm in this particular design is relatively ineffective as an insulator, when one considers steady heat transfer over long periods of time.

The effect of insulating the soil/air interface along the earth berm is illustrated in figure 16. The heat loss rates are made non-dimensional

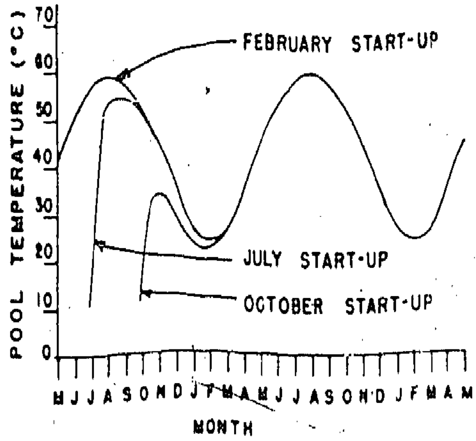


Figure 13. Simulated Seasonal Temperatures with Variable Start-Up

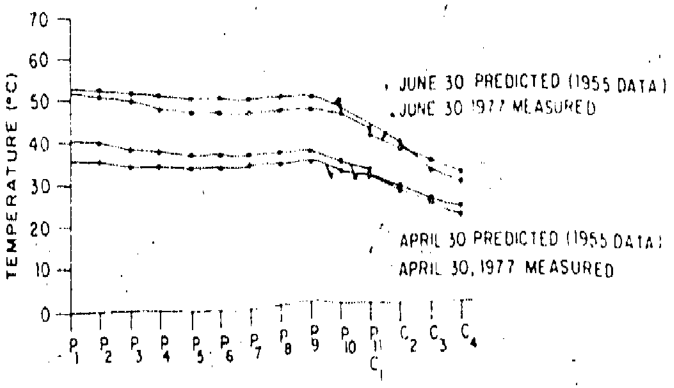


Figure 14. Pool Stratification

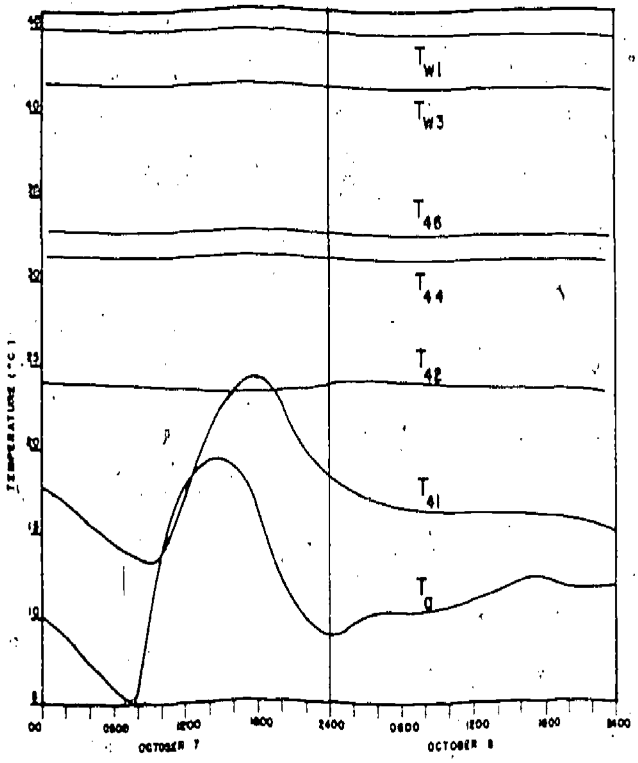


Figure 15. Diurnal Temperatures of Ambient Air and Soil at Selected Locations

TABLE 2

EFFECT OF INSULATION ON POOL HEAT LOSSES

Heat loss results in (kW-hr/day) from analog model with

Pool Temp. $T_p = 51°C$

Ambient $T_a = 22°C$

Earth $T_e = 10°C$

Pool Side Insulation$^{(b)}$, m	Surface Insulation$^{(a)}$, m				
	None	0.025	0.15	0.31	∞
None	62.5	56.6	50.1	47.6	45.0
0.025					41.6
0.15	39.5		35.0$^{(c)}$		36.2
0.31					35.0
∞	36.1				33.5

Notes: (a) 1.75m wide "Styrofoam" insulation on earth/air surface around the pool (horizontal).

(b) 1.40m high (vertical from water surface) "Styrofoam" insulation between pool liner and earth.

(c) 4.34m wide horizontal insulation layer around the pool buried 1.5m below air/earth surface.

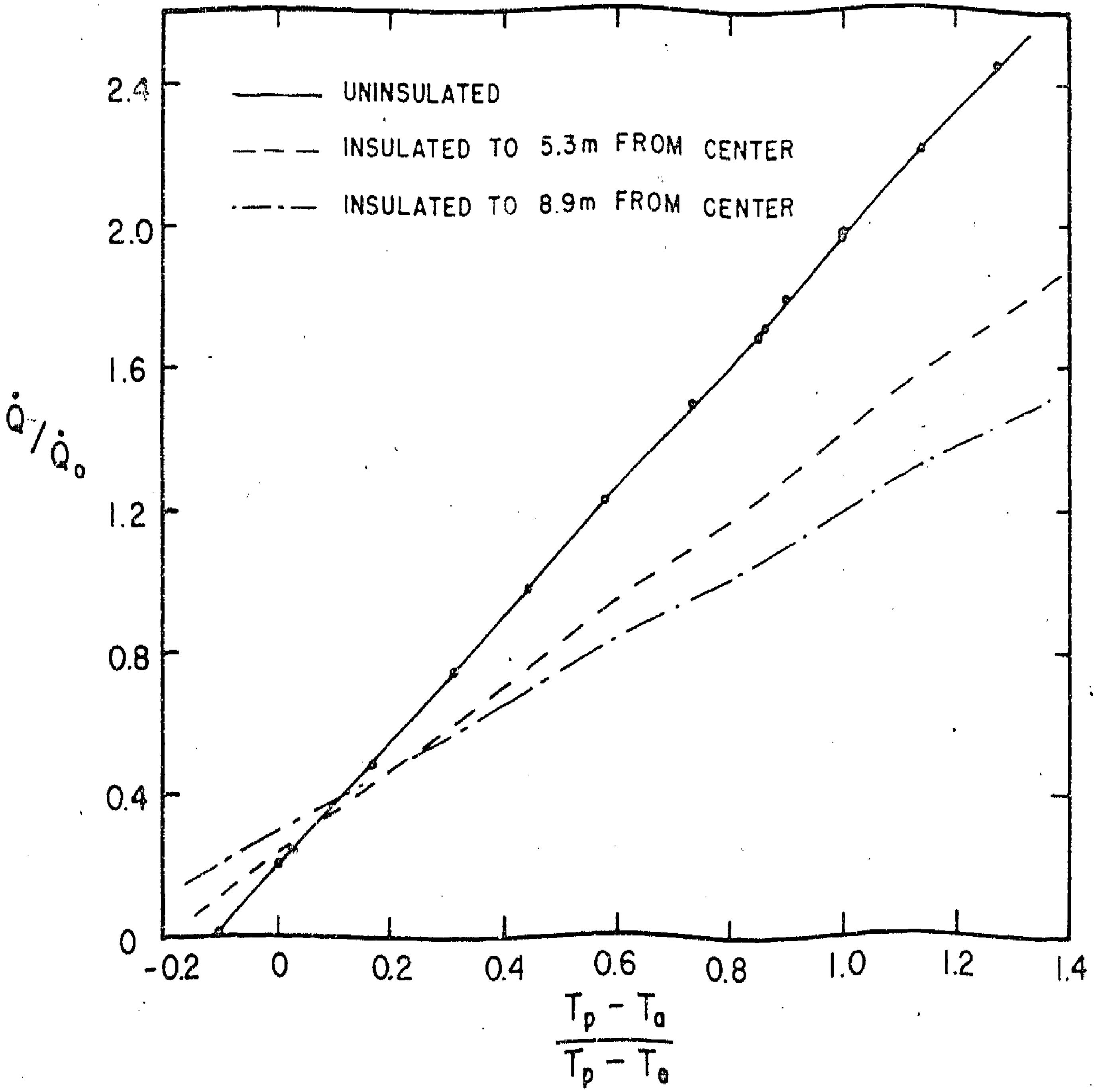


Figure 16. Heat Loss as Function of Soil/Air Insulation

through the use of $\dot{Q}_o$ which is the pool energy loss rate with the soil/air interface perfectly insulated. Note that the solid line in figure 16 would be the anticipated heat transfer from an uninsulated pool through the surrounding earth. This figure also shows the effect of insulating the soil/air interface close to the pool. The area between element "A" of the analog model (figure 9) and the ambient air is a ring with the inside radius of 3.57m (pool radius) and the outside radius of 5.32m. The effect of perfectly insulating this ring of the soil/air interface is shown by the dashed line. If the ring of insulation were extended to include an outer radius of 8.89m (insulating both elements "A" and "B") the heat transfer would be represented by the dot/dash line.

A second design consideration would be to improve the solar collector so as to deliver more energy to storage to offset the losses. One approach would be to improve the orientation of the collector, as near-horizontal collectors are poor collectors except during the summer. This would involve a redesign of the current system, so as to possibly provide for a structural roof over the storage pool, with the collectors mounted on the roof.

Another approach to improved collection would be to use an enclosed-fluid flat plate solar collector instead of the open water-channel collector currently used. Such a change would result in a smaller value of $F_R U_L$ (slope of the performance curve, Figure 7), and consequently higher collection during winter. This approach was investigated with the use of the digital computer model with the collection mode results illustrated in Figures 17, 18, 19 and 20.

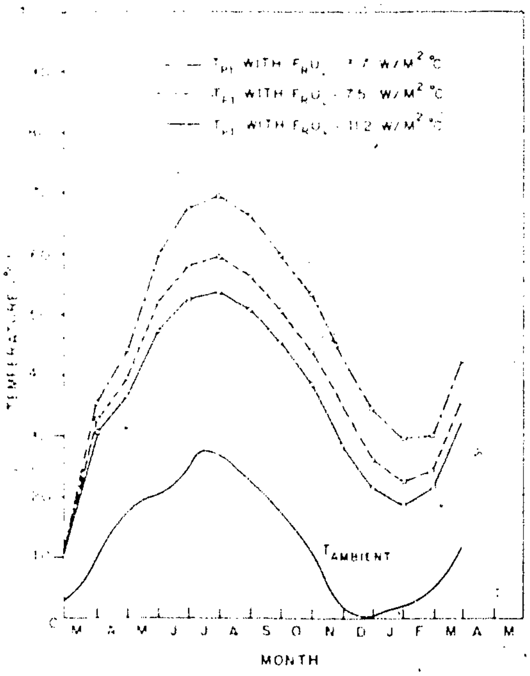


Figure 17. Predicted Storage Temp. for Systems with 3 Collectors

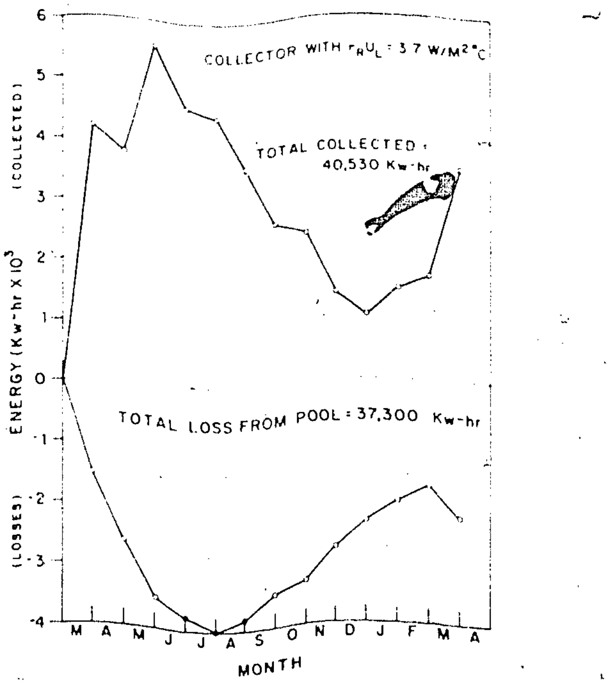


Figure 18. Collected and Lost Energy with F_RU_L = 2.2 w/m²°C

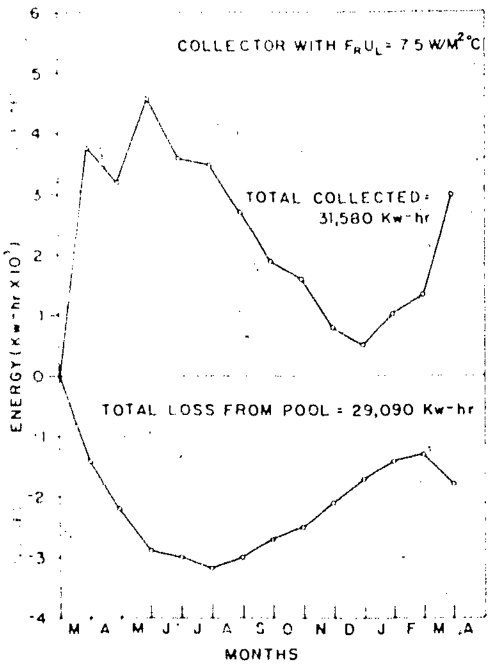


Figure 19. Collected and Lost Energy with F_RU_L = 4.4 w/m²°C

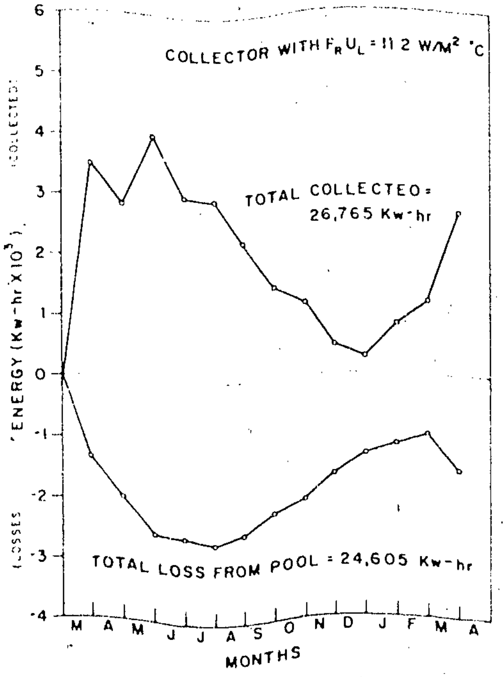


Figure 20. Collected and Lost Energy with F_RU_L = 6.6 w/m²°C

One other design approach would be to significantly increase the size of the collection and storage system. Various investigators have proposed much larger collection areas and storage volumes to gain the effect of relatively lower heat losses [7,8,9,10,11]. Typically heat losses increase with the perimeter of the storage, and collection increases with the area [6].

Various size, geometric, and design considerations will be studied in the next phase of this work. Included will be modeling of various design modifications with system operation in the collection and heating mode, considering both direct heating and solar assisted heat pump operations.

G. Report of the Progress: Heating Mode of Operation

In December 1977, the annual solar energy system was modified to provide for energy extraction through a heat exchanger. Heat extraction was designed to simulate the heat input to a solar assisted (liquid to air) heat pump used for heating a 140 m^2 (1500 ft^2) residence. The residence used in the model was assumed to be insulated to present standards and to have less than 15 percent glass area in the walls [12]. The heating load for such a structure is 12,650 Btu per degree day. The total annual heating load for this home would be 15,600 kw-h (53.2 x 10^6 Btu), based on an 11 year average of Charlottesville, Virginia weather data [13].

The heat pump used in the model was a commercially available water source heat pump [14]. The heat pump model has a COP of approximately 3.3 to 3.7, for water temperatures of 15 to 24°C (60 to 75°F). For inlet water at 15.5°C (60°F) and a flow rate of 1.14 m^3/hr (5 gpm), the unit capacity is 7.6 kw (26,000 Btu/hr) with an energy absorbed from water of approximately

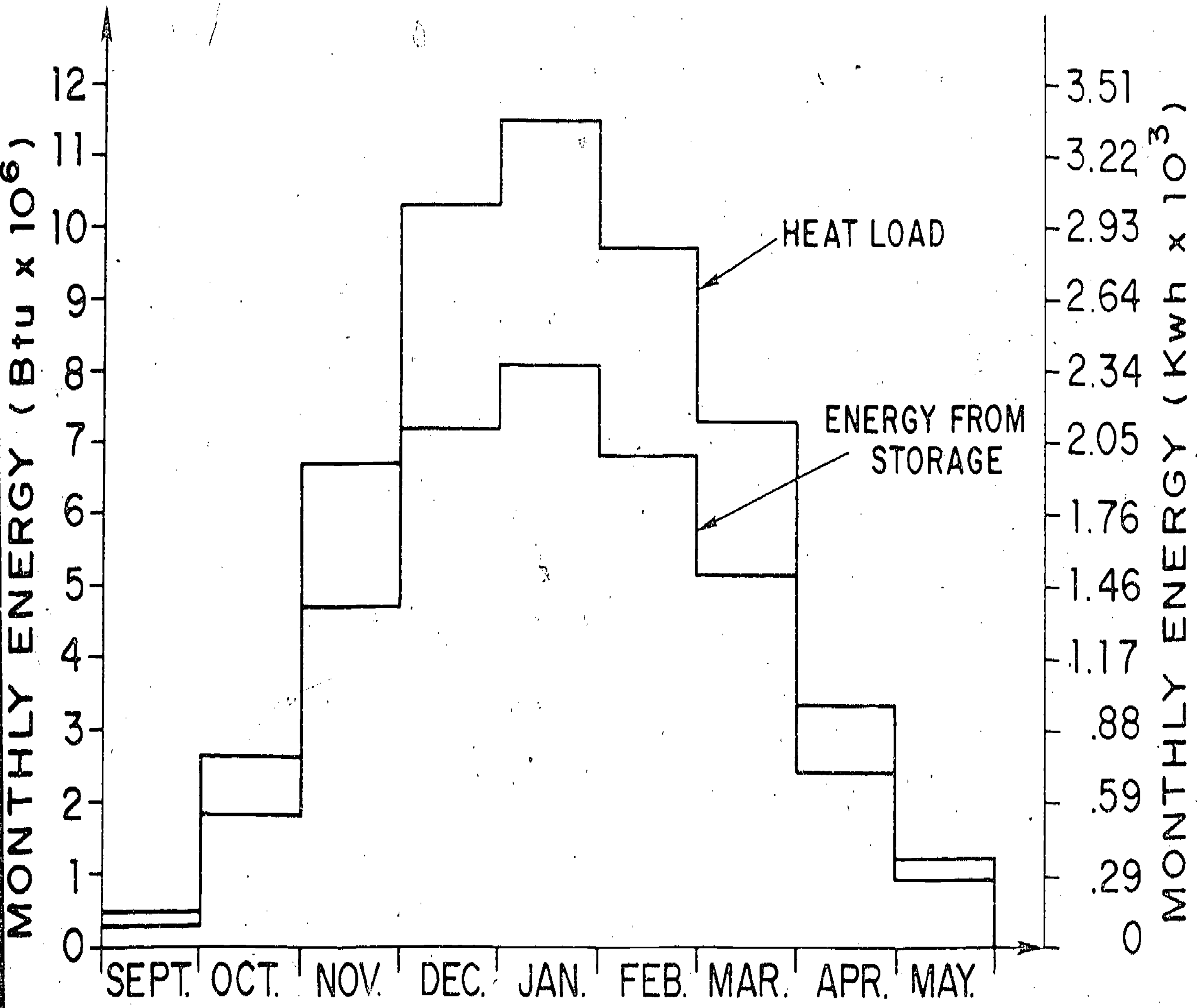


Figure 21. Monthly Energy for Heating with Solar Assisted Heat Pump

5.6 kw (19,000 Btu/hr) and a power input of 2.2 kw. For an inlet water at 23.9°C (75°F) the unit capacity is 8.8 kw with 6.2 kw from water and 2.6 kw from power input.

The average monthly total space heating demand and the requirements for energy input from solar heated water storage are illustrated in Figure 21.

The heat pump will be modeled by dumping an amount of energy from the solar pool equivalent to that required by the heat pump. The water flow to the heat exchanger will be maintained at the same rate as that required for an actual heat pump to allow a realistic study of the heat transfer mechanisms in the solar pool. The amount of energy dumped will be determined by integrating hourly data. The air flow to the heat exchanger will be adjusted semi-weekly to maintain the average monthly energy required for the heat pump.

H. Activities to Disseminate Project Results

Papers have been presented to the Conference on Solar Energy in Cold Climates (University of Detroit, June 7-8, 1976) and to the conference "Solar Three: Capturing the Sun" (Northwestern University in Evanston, Illinois on November 20, 1976).

In addition, a paper, "Heat Transfer Analysis of a System for Annual Collection and Storage of Solar Energy," was presented to the 1977 ASME Winter Annual Meeting in Atlanta, Georgia, and was published in Heat Transfer in Solar Energy Systems, ASME Publication No. H00104.

Papers have been accepted also for presentation and publication in the proceedings of the International Solar Energy Society Congress 1977 in New Delhi, India (January 16-21, 1978) and of the Southeastern Seminar on Thermal Sciences, 14th Annual Meeting, North Carolina State University, Raleigh, April 6-7, 1978.

References

1. Nielsen, C.E., "Experience With a Prototype Solar Pond for Space Heating," Proceedings of 1976 Joint Solar Energy Conference: Sharing the Sun, Solar Technologies for the Seventies, published by American Section, I.S.E.S., Vol. 5, pp. 169-182 (Winnipeg, Canada, August 15-20, 1976).

2. Badger, P.C., Short, T.H., Roller, W.L., and Elwell, D.L., "A Prototype Solar Pond for Heating Greenhouses and Rural Residences," Proceedings of the 1977 Annual Meeting, American Section, I.S.E.S., Vol. 1, Section 33, pp. 19-22, (Orlando, Florida, June 6-10, 1977).

3. Hubbard, R.M., Analog Equipment Available in the Department of Chemical Engineering, University of Virginia, Charlottesville, Virginia, RLES Report, May 1965.

4. Karplus, W.J., Analog Simulation, McGraw-Hill, (1958).

5. Adams, J.A. and Rogers, D.F., "Computer-Aided Heat Transfer Analysis," McGraw-Hill, 1973.

6. Shelton, J., Solar Energy, Vol. 17, No. 2, pp. 137-143, 1975.

7. Givoni, B., "Underground Long Term Storage of Solar Energy," Solar Energy, Vol. 19, No. 6, pp. 617-623, 1977.

8. Cavalleri, G., and Foligno, G., "Proposal for the Production and Seasonal Storage of Hot Water to Heat a City," Solar Energy, Vol. 19, No. 6, pp. 677-683, 1977.

9. Torrenti, R., Bomal, R., and Alexandroff, G., "Optimal Dimensions of a Solar Energy Interseasonal Storage Tank," paper presented at the RencontreInternationale de la Comples en France, Ales, France, September 25-30, 1976.

10. Torrenti, R., Bomal, R., and Alexandroff, G., "Energetical Evaluation of the Advantages of an Interseasonal Storage of Solar Energy in the Case of Building Heating Projects in Northern Countries," paper presented at the Rencontre Internationale de la Comples en France, Ales, France, September 25-30, 1976.

11. Torrenti, R., "Bassins de Stockage de Longue Duree de l'Energie Solaire," paper presented at Journees Solaires de Nice, April 13-16, 1977, Palais des Expositions de Nice, Service d'Etudes Energetiques, CEN-Saclay, B.P. No. 2 - 91190 Gif-sur-Yvette, France.

References (cont'd)

12. "An Economic Analysis of Solar Water and Space Heating," Document No. DSE-2322-1, Division of Solar Energy, Energy Research and Development Administration, Washington, D.C.

13. Degree day data from the University of Virginia Heating Plant, Charlottesville, Virginia.

14. Carrier Water Source Heat Pump 50WQ, Brochure No. 50WQ-2P, Carrier Corporation.

TIC DISTRIBUTION LIST

Patrick F. Akehurst
4138 Joppa Road
Baltimore, MD 21236

Ametek
Power Systems Group
One Spring Avenue
Hatfield, PA 19440
Attn: J.C. Bowen

Arkla Industries, Inc.
400 E. Capitol
Little Rock, ARK. 72203
Attn: T.M. Helms

Bruce L. Bakken
Solar Development Co. Inc
450 Southview Blvd.
South St. Paul, Minn.
55075

E.M. Barber
School of Architecture
Yale University
180 York Street
New Haven, Conn. 06520

Everett Mc. Barber, Jr.
Sunworks
669 Boston Post Road
Guilford, Conn. 06437

Irwin R. Barr
AAI Corp.
P.O. Box 6767
Baltimore, MD 21204

William Beckman
Dept. of Mechanical Engr.
U. of Wisconsin
Madison, Wisconsin 53706

Dr. Harold Bennett
Michaelson Laboratory
Naval Weapons Center
China Lake, CA 93555

Prof. Karl W. Boer
Institute of Energy
Conservation
Univ. of Delaware
Newark, DEL. 19711

Dr. Gustavo Bert Brown
Centro de Investigacion
de Materials
Circuito Exterior, C.U.
Mexico 20 DF/UNAM/MEXICO

George A. Bush
Lawrence Livermore Labs
Livermore, CA 94550

Sheldon S. Butt
Director, Market Research
& Planning
Olin Brass Corp.
East Alton, Ill. 62024

J. Garry Cottingham
Brookhaven National Lab
Bldg 911B
Upton, N.Y. 11923

David C.W. Chan
The Mitre Corp.
P.O. Box 208
Bedford, Mass. 01730

Jack M. Cherne
TRW Inc. - Solar Energy
One Space Park
Redondo Beach, CA 90278

Robert S. Cole
Department of Physics
U. of North Carolina
Asheville, NC 28804

Stanley A. Davis
Argonne National Lab
Bldg. 214
9700 S. Cass Ave.
Argonne, Ill. 60439

Prof. John Duffie
U. of Wisconsin
1500 Johnson Drive
Madison, Wisc. 53706

R. Dunkle, Ch. Scientist
CSIRO-Div. of Mech. Engr.
P.O. Box 26
Highett, Victoria
AUSTRALIA 3190

Prof. D.K. Edwards
School of Engr.&Applied
Science
UCLA
Los Angeles, CA 90024

James Eibling
Battelle Memorial Inst.
Battelle Columbus Lab.
Columbus, Ohio 43201

Guy Ervin, Jr.
Atomics International
8900 DeSoto Avenue
Canoga Park, CA 91304

Richard Evans
Manufactured Homes Div.
Boise Cascade
P.O. Box 8051
Roanoke, VA 24014

R.C. Evans
Evans Precision, Inc.
P.O. Box 366
320 Locust Street
Lancaster, OH 43130

Erich A. Farber
U. of Florida
Solar Energy Lab
Gainesville, FLA
32611

William C. Dickinson
Lawrence Livermore Lab
P.O. Box 808
Livermore, Ca. 94550

Herbert W. Hoffman
Oak Ridge Nat'l. Lab
P.O. Box Y
Oak Ridge, Tn. 37830

General Electric
Solar Technol.Programs
P.O. Box 8661
Philadelphia, PA 19101
Attn: D.L. Kirkpatrick

Ron Goodman
LOF Tech. Center
1701 E. Broadway
Toledo, Ohio 43605

P.F. Goolsby, Solar Pgms.
Prod. Development Div.
Reynolds Metal Co.
5th and Cary
Richmond, VA

Robert E. Grenier
R.L.G Associates, Inc.
177 Blue Stone Drive
Woonsocket, R.I. 02895

Richard P. Hankins
Hankins and Anderson, Inc.
Box 6872
Richmond, VA 23230

Lloyd O. Herwig
Adv. Solar Energy R.&Tech
NSF/RANN
Washington, D.C. 20550

James E. Hill
Center for Building Tech.
U.S. Dept. of Commerce
Nat'l. Bureau of Stds.
Washington, D.C. 20234

Kenneth G.T. Hollands
Dept. of Mech. Engr.
U. of Waterloo
Waterloo N2L-3G1,
CANADA

Michael J. Holtz
A.I.A. Research Corp.
1735 New York Ave., NW
Washington, D.C. 20006

Honeywell Systems & Res.
Center
2600 Ridgeway Pkwy.
Minneapolis, Minn. 55413

Attn: Henry Mar

Prof. Hoyt C. Hottel
Dept. of Chemical Engr.
MIT
Cambridge, MASS. 02139

Prof. Everett D. Howe
Dept. of Mech. Engr.
U. of California
Berkeley, CA 94720

Prof. Jack R. Howell
Dept. of Mech. Engr.
U. of Houston
Houston, TX 77004

George Immerwahr
Solar City Industries
1204 Jackson St, SE
Albuquerque, NM 87108

Inter-Technology Corp.
100 Main Street
Warrenton, VA 22186

Attn: Dr. Fred Costello

George S. James
NSF - Information Resource
1800 G. Street, NW
Washington, D.C. 20550

Dr. Ali M. Kipper
Sch. of Engr. & Applied
Science
Geo. Washington University
Washington, D.C. 20052

Richard A. Klecker
Western Sun Systems
Route 1, Box 1532
Bend, Oregon 97701

George J. Kominiak
Division 5834
Sandia Laboratories
Box 5800
Albuquerque, NM 87115

Richard J. Leuba
School of Engineering
NC State University
Box 5518
Raleigh, NC 27607

Dr. Noam Lior
U. of Pennsylvania
Dept. of Mech. Engr.
111 Towne Bldg., D3
Philadelphia, PA 19174

Lockheed Missiles&Space
3251 Hanover Street
Palo Alto, CA 94304

Attn: W.E. Shannon

George O.G. Löf
Solar Energy Applications
Laboratory
Colorado State Univ.
Ft. Collins, Colo. 80523

Harold G. Lorsch
Franklin Inst. Res. Lab
Philadelphia, Pa. 19103

James R. Lowery
Code EH-24
NASA/MSFC
Marshall Space Fl. Cen.
Alabama 35812

Martin-Marietta
Box 179
Denver, Col. 80201

Attn: Lanny Schooler

P.H. Mathes
Granger Associates
1400 N. Uhle Street
Arlington, VA 22201

Prof. Marshall F. Merriam
Dept. of Material Sci.
Hearst Mining Bldg.
U. of California
Berkeley, CA 94720

Benjamin D. McCubbins
Carolina Solar Corp.
301 N. Main Street
Salisbury, NC 28114

Charles Bankston
Los Alamos Scientific
Lab
Group Q-DOT, Box 1663
Los Alamos, NM 87544

Robert H. Murray
Skidmore, Owings & Merrill
990 SW 5th Avenue
Portland, ORE. 97204

Glen E. McDonald
Power Appl. Br. NASA/Lewis
21000 Brookpark R.
Cleveland, OH 44135

C. Leon Neal, Appl. Engr.
NC Science & Technol.
Research Center
Res. Triangle Pk., NC
27709

Optical Coatings Lab.
2789 Griffen Avenue
Santa Rosa, CA 95403

Attn: R.M. Winegarner

Owens-Illinois, Inc.
P.O. Box 1035
Toledo, Ohio 43666

Attn: R.E. Ford

PPG Industries, Inc.
One Gateway Center
Pittsburgh, PA 15222

Attn: R.G. Gallagher

Revere Copper & Brass
P.O. Box 151
Rome, NY 13440

Attn: W.J. Heidrich

P. Richard Rittlemann
Burt, Hill & Assoc.
610 Mellon Bank Bldg.
Butler, PA 16001

Robert L. San Martin
Energy Res. & Dev. Inst.
Box 3449
N.Mexico State Univ.
Las Cruces, NM 88003

Mehmet K. Selcuk
JPL - Bldg. 277 Rm.202
4800 Oak Grove
Pasadena, CA 91013

Prof. B.O. Seraphin
Optical Sciences Center
U. of Arizona
Tucson, AZ 85721

Benjamin Shelpuk
RCA Corp.
Bldg. 10-8
Camden, NJ 08102

William A. Shurcliff
19 Appleton Street
Cambridge, MA 02138

Robert W. Porter
1801 Nottingham Road
Newark, Del. 19711

Dr. Norman D. Shutler
Acting Dep. Asst. Adm.
for General Enforcement
Environ. Prot. Agency
Washington, DC 20460

Frederick F. Simon
NASA-Lewis M.S. 500-201
21000 Brookpark Rd.
Cleveland, OH 44135

Prof. P.R. Smith
Mechanical Engr. Dept.
N.Mexico State Univ.
Las Cruces, NM 88003

Dr. Harold Spuhler
Nat. Science Foundation
AERT/RA
1800 G. Street, NW
Washington, DC 20550

Elmer R. Streed
Natl. Bureau of Stds.
BR B-104
Washington, DC 20234

H. Tabor, Sci. Director
The Scientific Research
Dancider Bldg.
Hebrew Univ. Campus #3745
Jerusalem, ISRAEL

Dr. H.E. Thomason
609 Cedar Ave,
Oxon Hill
Ft. Washington, Md. 20022

H.J.L. Thomason, Jr.
609 Cedar Ave.
Oxon Hill
Ft. Washington, Md. 20022

Dr. P.D. Thompson
USDA
Agricultural Res. Center
Bldg. 173, ARC-East
Beltsville, MD 20705

Prof. Raymond Viskanta
Sch. of Mech. Engr.
Purdue University
Lafayette, Ind.

Albert Weinstein
Westinghouse Electric
Mail Stop 999
P.O. Box 1693
Baltimore, MD 21203

J. Richard Williams
Assoc. Dean for Research
Engineering College
GA Inst. of Technology
Atlanta, GA 30332

Mr. Peter Wood
Energy Conservation Sys.
327 W. Vermijo
Colorado Springs, Colo.
80903

Marvin M. Yarosh,
FLA Solar Energy Center
State Univ. Sys. of FLA
P.O. Drawer N
Cape Canaveral, FL 32920

Charles Younger
Solar Energy Br./MS500-201
21000 Brookpark Rd.
Cleveland, OH 44135

Prof. John I. Yellott
Coll. of Architecture
Arizona State University
Tempe, Arizona 85281

Dr. Harry S. Zwibel
Civil Engr. Lab.
Code L80
Port Hueneme, CA 93043

Patrick F. Akehurst
4139 Joppa Road
Baltimore, Maryland 21236

Bruce L. Bakken
Solar Development Co., Inc.
450 Southview Blvd. South
St. Paul, Minnesota 55075

J. Bougard
Servide de Thermodynamique
Faculte Polytechnique de Mons
31, Boulevard Dolez
7000 Mons
Belgium

Professor H. C. Bryant
Professor of Physics
University of New Mexico
Albuquerque, New Mexico 87131

G. Cavalleri,
Centro Informazioni Studi Esperience,
Segrate, Milano,
Italy and Istituto di Fiscia

Patsy S. Chappelear
McDermott Hudson Engr.
P. O. Box 36100
Houston, TX 77036

T. C. Chawla
Building 208
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

David Claridge
Office of Tech. Assessment
U. S. Congress
Washington, D. C. 20510

Joe Dodson
Mischer Solar
2801 N. Loop West
Houston, TX 77008

Dubin Bloome Associates
42 W. 39th. Street
New York, N. Y. 10018

R. C. Evans
Evans Precision, Inc.
P. O. Box 366
320 Locust Street
Lancaster, Ohio 97701

David Faiman
Institute for Desear Research
Ben-Gurion University
Sede Boqer Campus,
Irsrael

Walter E. Fox
703 Greenleaf Drive
Monroeville, Pa., 15146

F. Geoola
Materials & Energy Res. Ctr.
Arya-Mehr University of Tech.
P. O. Box 41-2927
Tehran/Iran

B. Givoni
Desert Research Institue
Ben-Furion University
Beer Sheva, Israel

Ralph Grief
University of California
College of Engireering
Berkeley, CA

Robert E. Grenier
R.L.G. Associates, Inc.
177 Blue Stone Dr.
Woonsocket, RI 02895

Frank von Hippel
Princeton University
School of Engineering &
Applied Science
Center for Environmental Studies
The Engineering Quadrangel
Princeton, New Jersey 08540

Prof. Frank C. Hooper
Mech.Engr. Dept.
University of Toronto
Toronto, Ontario
Canada

George Immerwahr
Solar City Industries
1204 Jackson Street SE
Albuquerque, NM 87109

D. A. Kudise
Ben-Gurion University of
the Negev
Dept. of Chemical Engineering
Beer-Sheva, Israel
P. O. B. 2053

Richard A. Klecker
Western Sun Systems
Rt. 1 Box 1532
Bend, Oregon 97701

Pio Caetano Lobo
Universidade Federal
da Paraiba
Laboratório de
Energia Solar - CT
58.000 Joao Pessoa,
Pb: Brasil

B. D. McCubbins
Caroline Solar Corp.
301 N. Main Street
Salisburg, NC 28144

William Metz
Building 911 B
Brookhaven National
Laboratories
Upton, N. Y. 11973

Prof. Carl E. Nielsen
Dept. of Physics
Columbus,Ohio 43210

W. Richard Powell
Johns Hopkins Univ.
Applied Physics Lab.
Johns Hopkins Road
Laurel, MD 20810

Prof. R. Ramakumar
School of Electrical
Engineering
Oklahoma State Univ.
Stillwater, OK 74074

Keith Sharp
Colorado State Univ.
Dept. of Mech. Engr.
Fort Collins, Colorado

S. V. Sheldon, Manager
Special Products
Scientific-Atlanta. Inc
3845 Pleasantdale Road
Atlanta, GA 30340

T. H. Short
Agricultural Engr. Dept
Ohio Agri. Res. & Dev.
Wooster, Ohio 44691

Roger Torrenti
Comissariat a l'Energie Atomique
Service d'Estudes Energetiques
B. P. No. 2
91190 Gif sur Yvette
France

Prof. Gunnar Wettermakr
Division of Physical Chemistry
The Royal Institute of Technology
S-100 44 Stockholm 70
Sweden

John C. H. Woo, Manager
Trans Systems Corporation (T/SC)
Madison Bldg.
118 Park St, S.E.
Vienna, Virginia 22180

Institute for Energy Analysis
P. O. Box 117
Oak Rdige, TN 37830

*U.S. GOVERNMENT PRINTING OFFICE: 1978-740-306/4434. Region 4.