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

Report No. 2. Annual Progress Report, May 1976—July 1977

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July 1977

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Solar Energy

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July 1977

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I. ABSTRACT

A new system for year-round collection and storage of solar heated water for heating of buildings has been designed and constructed 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.

The annual collection and storage system began operation in late February 1977. Data are presented which illustrates the transient heat transfer which occurs during the start-up phase of operation. Thermal performance results are presented illustrating the efficiency of the solar collector and the variation of solar energy input to storage during a typical day's operation in May. Data are also presented which show the transient build-up of energy storage in the earth which surrounds the storage pool.

An analog model has been developed to analyze the transient energy phenomena which occur within the earth surrounding the pool. These include transient heat losses from the pool to the earth and energy storage within the earth. Results of the analog model for idealized conditions are confirmed by exact mathematical solutions and by numerical analysis using a digital computer.

Future research will include additional system operation in the collection mode, performance evaluation, operation in the heat load mode, and additional analytical modeling.

II. 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-flow (water-trickle) solar collector having two glazings. The solar collector acts not only to collect solar energy but also to reduce heat 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 is to include the use of standard instrumentation and measuring techniques as well as analytical simulation to determine performance under varying ambient exposures. The evaluation also will include economic, structural, and operational 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. The two year research project will provide improved design, construction, testing, and evaluation of this system for the heating of buildings.

The initial design of the system called for a 100,000 gallon water storage pool with a solar collector sub-system mounted horizontally on the top of the pool. The solar collector acts not only to collect solar energy but also to reduce heat losses from the energy storage.

Construction of the initial design of the storage pool began in June of 1976. In August of 1976 the pool suffered a significant leak and a failure of the vertical wall structures.

In September of 1976 a revised design was developed and has been implemented. The revised pool design provides for replacing the deep vertical earth surfaces of the initial design with 45° sloping earth surfaces. The sloping surfaces are proven to be stable without structural reinforcement and offer considerable cost advantages. The water volume of the revised pool design is 27,400 gallons.

The construction of the pool sub-system was completed by late November. Operation of the solar collector sub-system

shown in Figure 1, began in February 1977. The vertical reflector along the north edge of the collector as shown in Figure 2 was erected in March 1977.

In the following sections of this report, results of analytical modeling and of experimental thermal performance of the solar collector and the energy storage will be described.

The next phase of the research will be to determine system performance properties and operational characteristics during the collection and heating modes of operation. Analytical modeling of the system performance will be developed to include simulation of performance under various climatic conditions. The results of the verified analytical model will be extended to consider systems of different sizes, particularly considering the variables of water volume and its influence on relative heat losses. Also the model will be used to study the influence of collector and reflector designs on the system performance.

Figure 1. Annual Collector/Storage System, February 1977

Figure 2. Annual Collection/Storage System, March 1977

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 will be used for the heating of a building. The system includes a 53.5 m^3 (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 [10].

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 "Tyvar" (spun-bonded polypropylene) subliner was installed on the earth surfaces to 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 flow (water-trickle) 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. As illustrated in Figure 5, the collector is supported at the outer edge by a collector mounting bracket which attaches to the rim-strip and the structure of the wall. The inner and outer glazing materials are also anchored and sealed by a spline which is held in place by a batten strip.

Figure 6 illustrates that the collector is supported on its length by special support structures which are

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 Plate
4. Support Cable
5. Support Structure
6. Styrofoam Beads Floating on Water Surface
7. Collector Water Outlet

Figure 6. Collector Support Detail

suspended on the support cables which traverse the pool and are anchored to the pool structure.

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 90%. 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) it may deteriorate and require replacement after extended use.

Provisions are made for the extraction of water from the storage system at any desired depth so that the inlet water to the collectors can be controlled with the accompanying impact on the collector efficiency. One feature of the storage system which is different from traditional solar ponds is that salt or membrane techniques are not used to provide an inversion (hottest water on the bottom of the pond). In fact, the system can operate with normal stratification or maximum stratification depending on the objectives of the application. For example, during the summer when solar energy is being collected for storage, it would be most desirable to bring the lowest temperature water to the collector so that the collection efficiency will be the highest. However, towards the end of the

winter season when the solar pond had low level storage and low temperatures, warmer water from near the top of the pool can be delivered to the solar collector resulting in a hotter water being delivered for heat exchange application.

D. Report of the Progress: System 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 shows the collector performance as a function of time of day for May 6, 1977. By reviewing the insolation data presented, one can note that the day was characterized by bright sunshine with clouds developing in the afternoon. On this day, the inlet water to the solar collector was pumped from the bottom of the pool (approximately 40° C). By performing a manual integration of the data for May 6, 1977, one can show that the collector's average efficiency was approximately 50%.

One should note that the reflector was in a horizontal position on May 6, 1977 in order to determine the base-line

performance of the system without the contribution of the reflector.

Figure 8 displays base-line thermal performance (without reflector) as a plot of $(T_{in} - T_a)/I$ for data taken between May and July 1977. The collector's performance is nearly identical to that of other open-flow water cooled solar collectors [1].

Figure 9 presents the transient build-up of energy stored in the pool and in the soil surrounding the pool. One should note that no programmed energy extraction from storage has occurred for the time period of the data presented. After energy has been stored in the system during the spring, summer, and early fall, an energy extraction program will be established to show system performance during the heating of a building.

An analysis of the transient behavior of the energy storage in the soil surrounding the pool is developed in the next section.

Figure 7 Incident and Delivered Solar Energy, May 6, 1977

Figure 8 Collector Thermal Efficiency

Figure 9 Transient Build-Up of Stored Energy

E. Report of the Progress: System Models

Digital and analog models are being developed to simulate the operation of the year-round collection and storage of solar-heated water, and to investigate the effect of various design modifications and operating parameters on the performance of a prototype solar pool system. Because of the transient nature of the system with extremely long time constants, computer simulations provide effective means of investigating such changes on a much accelerated time scale. The digital model is capable of yielding results of higher accuracy; however, the analog network is faster, easier to use and less expensive. The analog model is also useful for gaining a "physical feel" for the response of the system to changing conditions and aiding in the development of the digital model.

Development of the two models includes verifying the accuracy of the results by comparing these with available theory and with each other. Comparison with theory is more easily accomplished with the analog network as it is based on spherical geometry for which analytical solutions of conduction heat transfer equations are available. Finally, validation of the simulation models will be attempted by comparing the experimental pool performance with computational results with similar thermal histories. Temperature data are being collected now at key locations

in the pool and in the surrounding earth to facilitate this process.

The properties of the earth used in the simulation models to date were assumed to be spatially uniform and constant over the range of variables investigated. They were fixed at the following best estimates for the soil in our location:

$$\rho = 1500 \text{ kg/m}^3$$

$$C_p = 0.88 \text{ kJ/kg } ^\circ\text{C}, \text{ and}$$

$$k = 1.28 \text{ W/m } ^\circ\text{C}$$

The above properties may need to be adjusted in the final model validation process.

The analog model consists of an electrical resistance-capacitance network designed to simulate the heat transfer processes from the pool to the surrounding earth and air (through the ground). The network uses a modified version of the Heat Exchange Transient Analog Computer (HETAC) developed by R.M. Hubbard [2]. In this analog the temperature is represented by a voltage, heat flow rate by current, and the thermal resistances and capacities by electrical resistors and capacitors.

The storage pool is simulated by a hemispherical constant temperature surface. The volume of the hemisphere corresponds to the volume of water in the prototype pool. The surrounding earth is simulated by 24 elements as shown in Figure 10 with nodal points (at the center of each element)

interconnected by resistors representing thermal resistances between adjacent elements. A vector volume approach [3] was used to determine the effective resistance, as the area normal to heat flow changes with both the radial and θ positions. The capacitance of each element is directly proportional to its volume. Since the hemispherical heat source has ϕ - symmetry, only a slice, $\Delta\phi$, of the surrounding earth needed to be considered. This permitted use of smaller capacitors. Boundary conditions are applied by connecting the adjacent nodes through appropriate resistors to a constant voltage source representing the desired boundary temperature.

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:

$$1 \text{ volt} = 1^{\circ}\text{C}$$

$$1 \text{ second analog} = 1 \text{ week real time}$$

$$1 \mu \text{ ampere} = 3.84 \text{ kW} - \text{hr/day heat rate}$$

To obtain the above scaling factors, resistors ranging from 0.26 to 18.6 megohms, and capacitors from 0.226 to 444 microfarads were needed.

A digital computer simulation is also under development for heat transfer processes associated with the solar pool. It will eventually consist of the following four parts:

- 1) a solar collector model based on experimental performance data;
- 2) a finite difference model of the thermally stratified pool of water;
- 3) a finite difference model of the surrounding earth; and
- 4) a simple model of the load.

Figure 11 illustrates the nodal network adopted for the digital simulation work. Only one eighth of the pool and surrounding earth are modeled because of symmetry about vertical planes bisecting the pool. This determined also the boundary conditions of no heat transferred across planes of symmetry (D, G, and H shown in Figure 11). The boundary condition at the top of the prototype pool is set by the physical conditions, and the others are chosen to facilitate the verification of the model and later to obtain useful information with more realistic temperatures. Boundary conditions at planes A and C originally allowed for convective heat transfer [4], but these have now been changed to isothermal conductive conditions. This is justified as the temperatures of the surface nodes with the convective boundary conditions were found to be essentially equal to the temperature of fluids with which they were in contact. The distance from the pool to boundaries E and F was determined by trial

running of the program. A distance of 10 nodes or 6.1m (20 ft.) was found to be adequate. Moving these boundaries by two nodes (1.22m or 4 ft.) had less than 1.5% effect on heat losses from the pool.

To validate the analog network, the steady state conduction was simulated through a spherical shell with the cavity at a higher temperature than the outer surface. These results are summarized in Table 1. The agreement between Tests 2 and 3 was excellent. It is also of interest to note from Tests 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% only. Thus the losses to the earth further out may be overestimated slightly, but this effect would be on the conservative side of the pool performance.

Transient response of the analog model was somewhat more difficult to verify. This was attempted by first charging the RC-network and then letting it discharge through the points at $R_e = 38.9\text{m}$. This corresponds to the cooling of a sphere (initially at a uniform temperature) suddenly exposed to a constant but lower surface temperature. The results of these tests are shown in Figure 12 and appear reasonably good also.

Initial results from the digital model are listed as Test 4 in Table 1. Agreement between the digital and the corresponding analog results (Test 3) are excellent when compared on an "equal pool perimeter" basis. This was based on Shelton's [5] conclusion that heat losses from a hemispherical pool are proportional to the perimeter rather than the heat transfer surface area.

Steady state heat losses from the pool have been simulated over a range of pool, ground and ambient temperatures. Shelton [5] has analyzed heat losses from a similar hemispherical heat storage device. However, Shelton's results were all based on no losses from the soil to air through the ground-air surface. By considering this heat loss mechanism, the pool losses are essentially doubled as shown by Test 5 in Table 1. The limiting (steady state) heat loss results are summarized in Figure 13. Simulated pool losses, which include here losses to the ambient as well as those to the constant temperature earth, appear to be approximately linear with the temperature difference between the pool, T_p , and the air, T_a . This indicates that losses to the ground beyond the 38.9m radius are small in comparison. This last point is illustrated more dramatically in Figure 14 where the temperature difference between the pool and the earth appears to have a much smaller effect on pool losses than the pool-air temperature difference.

Similar results from the digital model are not yet available.

Results of early data and computer simulations have demonstrated the build-up of collected energy during the initial charge-up phase of the pool operation. Although the boundary conditions used in the simulations to date may not have been the most realistic ones, the results with the models so far indicate that heat losses from the prototype pool are low enough to permit significant storage of collected solar energy in the pool on an annual basis.

Future work will include modifications to the models to incorporate variable energy input from the solar collector to the storage pool as well as the energy demand by the load. This will be necessary before model validation with performance data from the prototype pool can be attempted.

Future work will also include studies to determine the influence of size on the performance of this annual collection/storage system. Of interest will be the influence of increased collection areas and water volumes on the relative heat losses and performance of the energy storage. The model will first be verified for the existing geometry and then be scaled up for other size considerations.

Table I
SUMMARY OF MODEL VERIFICATION

Pool Temperature $T_p = 82^\circ\text{C}$
Ambient Air $T_a = 21^\circ\text{C}$
Earth Temperature $T_e = 10^\circ\text{C}$

Test	Pool Shape	Model	Air/Earth Surface	Pool Heat Losses, kW-hr/day	
				Volume Basis (u)	Perimeter Basis (f)
1	HS (a)	Theory (c)	Insulated	49.7	64.8
2	HS	Theory (d)	Insulated	54.7	71.4
3	HS	Analog (d)	Insulated	55.7	72.6
4	TP (b)	Digital	Insulated		73.2
5	HS	Analog (d)	21 °C	95.6	124.7

Notes: (a) HS refers to hemispherical pool
(b) TP refers to truncated pyramid.
(c) Heat conduction from HS pool of 3.57 m radius to constant temperature earth at $R_e = \infty$
(d) Constant temperature earth at $R_e = 38.9$ m.
(e) Hemispherical pool volume equal to water volume in prototype pool.
(f) Perimeter of hemispherical pool equal to the perimeter of prototype pool (29.3 m or 96 ft.)

Figure 10. Analog Model Elements

Figure 11. Digital Model Elements

Figure 12. Transient Response of Analog Network

Figure 13. Steady State Pool Losses as Function of $(T_p - T_a)$ From Analog Simulation

Figure 14. Steady State Pool Losses as Function of $(T_p - T_c)$ from Analog Simulation

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G. Activities to Disseminate Project Results

The results of this research project are limited at this time. Therefore, the activities to disseminate the research results are limited to statements of project description and the early results reported here.

Two papers have been presented; one to the conference on Solar Energy in Cold Climates (University of Detroit, June 7-8, 1976), and one to the conference "Solar Three: Capturing the Sun" (Northwestern University in Evanston, Illinois on November 20, 1976). The manuscripts developed for these conferences have been distributed at the conference and to various persons who have requested it by mail.

Research results are reported in papers which have been accepted for the International Solar Energy Society Congress in India in November of 1977 and at the Winter Annual Meeting of the American Society of Mechanical Engineers in Atlanta, Georgia in late 1977.

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