MASTER

FINAL REPORT

**Experimental and Theoretical Study of Thermal Performance of a
Hybrid Solar System at Living History Farms**

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Experimental and Theoretical Study of Thermal Performance of a
Hybrid Solar System at Living History Farms

by

John R. Hull

September 10, 1980

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RECIPIENTS

External

Ron Lutha (4)
USDOE - CORO

James R. Bieschke (2)
USDOE - CORO

USDOE (ALO) (1)
Special Programs Division

Iowa Energy Policy Council (1)
Des Moines, Iowa

Internal

William Murray (1)
Living History Farms

Ray Crites (1)
Ames Design Collaborative

John Hull (1)
Argonne National Laboratory

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ABSTRACT

This report chronicles the development and study of the salt gradient solar pond and hybrid solar house at the "Farm of Today and Tomorrow" at Living History Farms. The background of the project is given and includes conceptualization to present status. The construction history is summarized. The instrumentation and experimental results from the solar pond are discussed, as well as conclusions in regard to solar pond operation and gradient zone stability.

To date the solar pond has operated for over a year and has supplied interesting experimental observations about stability of the salt gradient. The solar house is still under construction.

I. INTRODUCTION

A. Project Background

This project was conducted by a collaboration between Living History Farms, a historical museum, and an architectural design team under the direction of Ray D. Crites. The project consisted of designing, constructing and monitoring the thermal performance of a solar residence and salt gradient solar pond combined system. A brief report of the initial phase of this project was presented at the 2nd National Passive Conference (1).

Living History Farms was founded in 1967 as a nonprofit, educational, historical foundation to buy land and develop and operate three farms which tell the story of Midwestern agricultural development. The three farms are located on a 500 acre site on Interstate 80 and 35, northwest of Des Moines, Iowa at Exit 32. The three farms include a Pioneer Farm of 1840 and a Horse Farm of 1900, which are both operating, and a Farm of Today and Tomorrow, which is currently being developed. The Farms are open daily for visitors and serve over 100,000 people yearly, of which 40,000 are school children. Crafts, grain harvest, and corn picking festivals are held each year. Living History Farms operates from contributions and fees and is a nonprofit organization.

The Farm of Today and Tomorrow will include a solar residence with solar pond, underground crop museum, and several small-scale prototype farming operations. The farm will utilize current advanced farming

techniques and intends to develop an integrated program utilizing energy conservation and solar energy whenever possible.

The solar project was initially funded by a \$17,000 grant from the Iowa Energy Policy Council (IEPC) to Living History Farms (LHF) in 1975. This grant was used to fund the conceptual design of the residence, build the model from which the picture for Fig. 1 below was taken, and purchase some instrumentation for the pond. In addition, the IEPC grant sponsored a solar pond conference in Ames in December, 1975, featuring invited speakers Carl Nielsen, David Styris, and Ari Rabl.

Starting at the same time as the IEPC grant, the Energy and Mineral Resources Research Institute at Iowa State University provided computer time and the services of John Hull in developing a computer model of the solar pond and in designing the solar pond at LHF. This support resulted in several theoretical solar pond papers (2-4).

In 1977 IEPC provided an additional \$12,000 to help monitor the thermal performance of the house and the solar pond. \$771.40 of this amount was used to purchase additional thermalcouples which were to be placed in the ground around the solar pond. The remainder of the IEPC grant reverted back to the IEPC when the Department of Energy (DOE) announced funding of this project.

In September, 1977 the U.S. DOE awarded a research grant of \$54,500 to Ray D. Crites and the Ames Design Collaborative for this project. These funds were to be used to provide architectural

drawings of the solar pond and solar pond heat exchange system, help construct the solar pond, instrument the pond and house, collect and analyze data from the instruments, provide a computer model of the house-pond system, and report on the thermal performance of the system and the results of the system model.

B. Hybrid Solar Residence

The solar heated residence for the Farm of Today and Tomorrow, design by Ray D. Crites and the Ames Design Collaborative and currently under construction, will incorporate many energy conserving and passive solar principles. A greenhouse is incorporated into the residence, and the house is covered by large amounts of earth insulation. Although most of the heat in the residence will move by natural means, the house is called a hybrid solar residence, since small fans will occasionally be used to move heat. This will improve both the efficiency of the solar system and the comfort level of the house. A small adjacent salt gradient solar pond will supply supplemental space heat to the 262 m^2 of heated area in the structure and will preheat domestic hot water.

A model of the solar residence and solar pond is shown in Fig. 1 below. A floor plan of this residence is shown in Figs. 2 and 3. Extensive use is made of south facing windows which, during the day, admit solar energy which will be absorbed by the massive concrete structure of the house and stored for use at night. Insulating drapery will reduce heat loss through these windows at night. A roof overhang

Fig. 1. Model of house and solar pond.

MAIN LEVEL PLAN

Fig. 2. Main level plan of house.

Fig. 3. Lower level plan of house.

over the south windows is designed to provide appropriate shading of direct sunlight during the summer while allowing extensive penetration of direct sunlight during the winter. Solar gain through the south windows will be enhanced in the winter due to sunlight reflecting off the farm pond immediately to the south of the house.

Greenhouse space, incorporated into the residence on both sides of the living space, also collects solar energy, provides some food, absorbs CO_2 and generates O_2 , and additionally provides beneficial visual and emotional effects derived from living with plants.

The top, east, and west sides of the house will be completely covered by 1 to 3 meters of earth, which helps reduce heat losses, provides some additional thermal mass, and makes the passive solar system feasible. Earth underneath the lower concrete slab cannot be used as heat storage due to the high water table in the area. Soil samples of the building site indicate several slow moving sand-water streams. Heat losses will be controlled by insulation under the lower slab and by careful drainage of the building site.

Much of the collected heat will tend to migrate via natural convection toward the ceiling of the upper level. When the air temperature near the ceiling of the upper level is sufficiently great, a small fan will transport the stratified warm air near the underside of the roof to the lower level, where it will be introduced into the bedrooms and be allowed to return to the greenhouse to be recycled.

A connected hydronic network of water pipes, embedded in the concrete slab of both the upper and lower floors, will provide an uniform floor temperature throughout the house. During the heating season, the upper floor will receive most of the incoming solar radiation, and the top part of the upper-level floor slab will be covered with ceramic tile, which will quickly heat up. When the temperature difference between the upper-level floor slab and the lower-level floor slab becomes sufficiently great, a pump will operate, and water will circulate in the hydronic network, carrying heat from the upper slab to the lower slab. During the night this heat will radiate and naturally convect into the living space.

When sufficient sunlight is not available, and when heat from the thermal mass of the house has been depleted, heat will be withdrawn from the solar pond through a liquid to liquid heat exchanger and circulated through the hydronic network of the floor slabs. It is estimated that except for small amounts of electrical energy to operate fans and water pumps, the passive solar system and the solar pond will provide 100% of the space heating needs of the house.

During the cooling season, the house will operate partially in the passive mode. The roof overhang will intercept incoming direct insolation, and most of the diffuse radiation can be reflected by the insulating drapes. The surrounding earth, at a lower temperature than the house, will absorb some of the heat. Water from the bottom of the farm pond will be circulated in the hydronic network in the floor slabs to compensate for sensible heat gain. A heat pump will provide auxiliary cooling and dehumidification.

C. Solar Pond

The solar pond is a solar collector and seasonal heat storage device. Before describing a solar pond, let us briefly review what happens in an ordinary pond, such as a farm pond. Part of the sunlight incident on the pond is absorbed in the water, and part is absorbed on the bottom of the pond. Being warmer, and hence less dense than the cooler water above it, the heated water begins to rise, setting up convection currents that eventually lead to dissipation of the absorbed heat at the surface of the pond. A solar pond is designed to suppress this convection and retain the heat at the bottom of the pond.

The salt gradient solar pond is a body of water consisting of a lower convective layer and an insulating layer. The bottom convective layer is a concentrated salt solution. It is covered by the insulating layer, which contains a salt gradient such that water closer to the surface is always less salty than the water below it. If the salt gradient is large enough, there will be no convection in the insulating layer when heat is absorbed on the bottom, since the hotter saltier water at the bottom of the gradient will be denser than the colder less salty water above it. In practice, there is always an upper convective layer above the insulating layer at the surface. This layer is about 20 cm deep in a well maintained pond. Since water is transparent to visible light but opaque to infrared radiation, heat in the form of sunlight reaches the darkened bottom,

is absorbed there, and can escape only via conduction. Since the thermal conductivity of water is moderately low, and since the insulating layer is more than a meter thick, heat escapes upward from the convecting layer very slowly. This makes the solar pond not only a thermal collector but also a seasonal heat storage device. Due to the large heat capacity of water, heat collected in the summer can be stored in the bottom of the pond and used throughout the winter, and the maximum temperature at the bottom of the pond is reached in early fall. A functioning solar pond is about 20-25% efficient in converting solar energy to usable low temperature heat.

The solar pond at LHF will produce low temperature heat (less than 70°C). Typical applications would include space heating, domestic hot water heating, grain drying, and other low temperature industrial process heat applications. It is envisioned that the solar pond is ideally suited for these applications in Midwestern farming regions, where land is available, and potential users are familiar with handling technological innovations. One criteria for such use in relatively small ponds is that the solar pond must function for long periods of time unattended. Thus maintenance must be minimal. To date, solar ponds have achieved more spectacular success in generating electricity with relatively high pond temperatures (90°C) in Israel (5). These ponds are relatively large and require regular maintenance. Many good technical references are available on solar ponds (6-8).

The LHF solar pond was intended to provide all of the auxiliary space heat for the hybrid solar residence. The amount of auxiliary heat required over the course of the year was difficult to calculate, since the performance efficiency of the passive solar system of the house, being of unique design, was uncertain. A conservative design strategy was selected. It was assumed that the house could supply 100% of its heat needs during the time when the sun was above the horizon, but none of its heat needs when the sun was below the horizon. Any excess heat from the pond would be used to heat domestic hot water, so the conservative design would not be wasteful. The heat load of the house was calculated by standard architectural techniques to be 410 W/°C with a load temperature of 18.3°C. Using this heat load, the average weekly temperature data for the area, and the computer program as described in Ref. 2, the surface area, depth of the insulating layer, depth of the convecting layer, and amount of wall insulation was determined. It was also assumed that any heat entering the ground water either from the solar pond or the house would be immediately lost to the system. It is hoped that drainage tiles placed around the pond site will improve the groundwater situation, and that some ground storage will become available. But for the initial design, the worst case situation was assumed.

The solar pond at LHF is a steel reinforced concrete cylinder that is sunk into the ground adjacent to the solar residence. The open top has a radius of 4.8 m. The cylinder is 4.5 m deep. The

concrete vertical walls and circular bottom are 21 cm thick.

Approximately 30 cm of polyurethane insulation is sprayed on the interior walls to thermally insulate the pond from the environment and protect the concrete walls from vertical thermal stress. The urethane insulation is covered with a water impermeable membrane to protect the integrity of the insulation and prevent salt leakage. This liner is the XR-5 by Shelter-Rite, the same liner that was used at the Wooster and Miamisburg solar ponds. The bottom convecting layer is approximately 2.6 m deep and consists of a 20% salt solution. The insulating layer, which contains the salt gradient, is approximately 1.6 m deep.

A copper or stainless steel heat exchange coil will be placed at the top of the convecting layer. Fresh water will be circulated through the heat exchanger, picking up heat in the solar pond and losing heat to the house load, either in the hydronic floor network or in a domestic hot water heat exchanger.

Although an air inflated plastic cover is shown in the model in Fig. 1, it is currently not used on the solar pond.

II. CONSTRUCTION HISTORY

The construction history for this project has been reported in detail in Technical Progress Reports #1-#6. This history is summarized in Table 1 below. Progress since TPR #6, of September 15, 1979, follows Table 1.

Table 1. Chronological Summary of Construction History.

Fall 1977	- solar pond excavation begins
Spring 1978	- tiling site, pouring concrete floor of solar pond
Summer 1978	- forming and pouring concrete walls of solar pond and mechanical room of house
Spring 1979	- insulation sprayed on pond, pond liner installed, pond filled, gradient established
Summer 1979	- excavation for main part of house begins, footings poured
Winter 1979	- roof of house formed and poured
Spring 1980	- dirt under house roof removed

The roof of the solar house was constructed by shaping plywood forms over a mound of earth. The concrete was poured over these forms and covered with sprayed on urethane insulation. The urethane was then covered with a water impermeable sprayed on butyl rubber compound. Since this construction took place in the winter, a temporary building was erected over the earth mound and heated to allow proper curing of the concrete. A thermal break was placed between the main part of the roof and the roof overhang.

A finite element computer program (SAP-IV) was used to analyze the structural requirements of the roof. The program used the thin shell method and employed 126 nodes and 99 elements. Earth was

removed from around the roof shell in the spring of 1980. The resulting structure is shown in Fig. 4.

As evident from Table 1, construction has been characterized by slow progress. The house, initially conceived in 1975, is still under construction 5 years later. This slow progress is due to a number of factors. The major factor is that Living History Farms has had to bear most of the financial burden of construction. From all grant funding, only \$15,000 was allocated for construction. This is less than 5% of the total construction budget. When the unexpected ground water problem became evident, supplemental funds were requested and denied. Another factor is Living History Farms' commitment to other projects, including the unprecedented visit of Pope John Paul II in October 1979.

Fig. 4. House as of April, 1980.

III. INSTRUMENTATION

Temperature instrumentation for the solar pond consists of a fixed array of thermocouples and several thermocouples which can be lowered into the pond at arbitrary depth. The thermocouples are stainless steel sheathed iron-constantan type and are connected to a digital thermometer. The fixed thermocouples are located in the earth around the pond and within the insulation on the interior of the pond as illustrated in Fig. 5. Further details of their emplacement were given in TPR #1.

Scanning temperature measurements consist of a thermocouple taped to a long wooden stick. Meter sticks taped to the wooden stick indicate the depth below the surface of the end of the thermocouple. Temperature measurements at a given depth within the solar pond are made by lowering the thermocouple to the desired depth and waiting for thermal equilibrium. A scan of the entire depth of the pond at 5 cm intervals takes from 30-60 minutes.

Salinity at a given depth in the pond is determined by withdrawing fluid from that depth and weighing a fixed volume of the fluid at a recorded temperature. The salinity and density in the pond can then be determined by Table IX.5 of Ref. 2.

Due to the slow construction of the house and termination of this research grant, no instruments were installed in the house.

A-3,4,5,6,7,8,9,10,11; B-4,7,9; C-1,2,7; D-1,2,7;

E-3 at 1, 3 at 2, in side insulation;

where, measured up from the bottom of the pond floor slab:

1 = 2.8 m; 2 = 1.2 m; 3 = .35 m; 4 = .25 m; 5 = .15 m; 6 = 0 m;

7 = -.5 m; 8 = -1 m; 9 = -1.5 m; 10 = -2 m; 11 = -2.5 m.

Fig. 5. Location of fixed solar pond thermocouple array.

IV. SOLAR POND RESULTS

As described in TPR #5, the solar pond was filled and the salt gradient was established in the pond in the spring of 1979. Coarse, industrial grade salt was used which contained considerable quantities of dirt. After the salt dissolved, the water was not filtered before the gradient was established. It was expected that the dirt would rapidly settle to the bottom.

As described in TPR #5, the salt gradient was established with a method invented by Zangrando (9). Establishing the gradient in the solar pond is based on the fact that when fresh water is introduced at a given level in an uniform salt solution, the introduced fresh water, being less dense than its surroundings, will rise upwards, mixing with the salt solution above the injection level (forming a more dilute homogeneous mixture), while the water below the injection level is more dense than the now slightly diluted mixture above the injection level, the situation is stable. Initially then, one injects fresh water at the level where one desires the gradient to begin. As the solution in the upper portion of the pond becomes dilute, the injection level is raised. The injection level reaches the surface when the pond is full. This is illustrated schematically in Fig. 6. A nearly uniform gradient is established when the insulating layer is initially only half full and the level of injection is moved upward at a rate twice that at which water enters the pond (i.e. when the water level rises 1 cm, the injection level should be raised 2 cm), so that

fresh water
injection
hose

(a)

(b)

(c)

—————→ S

Fig. 6. Schematic diagram of gradient formation technique. (a) At beginning. (b) Halfway. (c) At end. (●●●) represent salinity S.

the distance between the desired final water surface and the instantaneous water surface is always the same as between the instantaneous water surface and the injection level.

After the gradient was established, the water was so dirty that the incident sunlight was totally absorbed in the first 50 cm of water resulting in a thermal inversion throughout the lower part of the pond. This resulted in the suspended dirt falling very slowly to the bottom. Transparency slowly improved with time, but much of the summer insolation was inefficiently collected (8-9 % calculated collection efficiency), with the pond reaching a maximum temperature of 43°C in late September. Clearly it would have been prudent to filter the water first.

The solar pond was plagued with transparency problems throughout its operating history. This is largely due to its location in the middle of a construction site. After 1½ years of operation, it was noted that 2-3" of dirt had accumulated on the bottom of the pond. It should be noted that no maintenance procedures were attempted on the pond during its operating history. Other solar ponds have not experienced as much transparency problems as the Living History Farms solar pond (5).

A more serious problem encountered by the LHF solar pond was wind induced instability in the nonconvecting layer. Strong winds with high frequency components cause the pond to slosh. The amplitude of the sloshing on windy days would approach 30 cm, with a major

period of several seconds. This produced oscillations throughout the entire depth of the pond which persisted long after the wind stopped. This sloshing initiated a very large upper convective layer (occasionally as much as 90 cm) which is evident in all the temperature profiles. Earth berming around the outside of the pond walls reduced the sloshing somewhat. The most likely mode of pond oscillation is shown in Fig. 7a. However, after the roof of the house was completed, a strong west wind blowing over the roof caused 30 cm amplitude Bessel function type of oscillation, shown in Fig. 7b.

The large upper convective layer would break up into smaller layers after a heavy rain. These smaller layers would usually persist for several days to a few weeks before recombining into a single layer. The experimental observations reported above prompted a theoretical calculation of wind induced instability in salt gradient solar ponds (10). These calculations show that horizontal water motion in the pond can definitely lead to instability of the salt gradient. If maximum horizontal velocities occur at the top of the pond, then this mechanism accounts for the growth of the upper convective layer due to wind. The reader is referred to Ref. 10 for details.

Fig. 7. Most common sloshing modes in solar pond.

Wind is a well known cause of salt gradient instability in all solar ponds, however other ponds have not suffered as severe consequences. The reason is unknown. Possibly sloping sides on other ponds act as spending beaches. Possibly the larger size of other ponds is the determining factor. Clearly the behavior at the LHF solar pond is a resonance phenomena. The pond is just the right size to resonate in the existing wind conditions. Perhaps this defines a smallest size for solar ponds based on stability effects.

In the winter of 1980 an ice cover protected the pond. This allowed the gradient to partially recover. However, spring winds almost completely eliminated the gradient. As of the date of this report, the gradient is being reestablished. Several feet of the top of the pond has been drawn off. New salt has been added to the bottom. A transparent cover is being fabricated to fit over the top of the pond. This cover should keep out dirt and debris, as well as protecting the pond from wind effects.

V. SUMMARY

Due to slow construction progress and termination of the research grant, no experimental results were obtained for the hybrid solar residence. The house is still under construction.

The solar pond was constructed and operated for over a year. The dirt initially suspended in the water reduced the average collection efficiency for the year to 8-9%. This value was somewhat higher toward late fall, when much of the dirt had settled out. Wind induced instability in the salt gradient of the solar pond has been a major problem, virtually destroying the gradient in the spring of 1980. A theory has been proposed to account for this phenomena (10). The theory's applicability to other solar ponds is as yet unknown.

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