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Developing Operational Strategies for the Fort Benning Shallow Solar Pond Domestic Water Heating System:

Performance Testing and Results

Terry R. Sharp

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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DEVELOPING OPERATIONAL STRATEGIES FOR THE FORT BENNING SHALLOW SOLAR POND DOMESTIC WATER HEATING SYSTEM:

PERFORMANCE TESTING AND RESULTS

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ABSTRACT

Performance tests were conducted on six of the eighty individual solar ponds that comprise the Fort Benning Shallow Solar Pond Domestic Water Heating System. The system was originally designed to operate at a 3-inch pond fill and provide 500,000 gallons of heated water daily to a laundry and barracks buildings. Since construction, hot water needs from the system have decreased approximately 50% and the original operating strategy was no longer thought to be optimum for current conditions. New operating strategies were tested that could potentially improve system performance. Specifically, these involved varying pond fill levels from 2 to 4 inches and exposure periods from 1 to 3 days.

Lower pond fills were found to increase final water temperatures for all exposures. At a 1-day exposure, lowering pond fill from 3 to 2 inches increased pond performance (Btu/gal) by 30%. A larger reduction from 4 to 2 inches produced an approximate 62% increase. With hot water demand on the Fort Benning system well below capacity, lowering pond fill is an excellent option for an immediate and significant performance improvement. Although increasing exposure increased final water temperatures in all but one test case, lowering pond fill was more productive.

An individual pond operating at a 3-inch fill and a 1-day exposure collects around 488 MBtu annually which is equivalent to around $4500 in avoided fuel costs. With excess capacity, only the water utilized is saving energy. Therefore, the key operating objective for Fort Benning is to add the most energy possible to the water that is used.

Pond fills at Fort Benning should be reduced to 2 inches and exposures should remain at 1 day (unless more ponds are activated). This should provide an immediate increase in pond performance of approximately 30%. Other measures that can be taken to improve system performance include changing from an evening to a morning fill, reducing the storage tank fill level, minimizing the impact of unheated water on the storage tank water, and identifying additional loads that can be added to the system. Some of these changes can be implemented easily and at low cost. As demand on the system changes, information provided can be used to determine appropriate adjustments to the system operating strategy. By making the recommended changes and adapting to operational changes that occur, system benefits can be improved immediately and in the future, and sustained.

EXECUTIVE SUMMARY

This report describes the results of performance tests conducted on the Fort Benning Shallow Solar Pond Domestic Water Heating System. The system has an installed capacity of 500,000 gallons per day but has lost approximately half of its design load due to shutdown of the post laundry (measurements indicated that only 10% of its capacity was being used in February of 1989). As a result, continuing to operate the system per its original operating strategy was no longer thought to be the best plan for maximizing system benefits. Field testing was undertaken to identify opportunities for improving system performance.

Testing was limited to individual pond performance and was done on six of the 80 ponds in the system. Fill levels and exposure times of the six ponds were varied since these parameters can be controlled and are major influences in determining pond performance. Fill levels of the test ponds were 2, 3, and 4 inches which correspond to pond water volumes of 3740, 5710, and 7480 gallons, respectively. Exposure periods were varied from 1 to 3 days. Weather conditions were recorded over the test period so that their impact on pond performance could be assessed.

Performance testing was originally planned over the nine-month period, January through September of 1989. Solar pond operating problems disabled the system and resulted in the loss of performance data for the final quarter of testing. Mathematical models were created from the data collected and used to determine the effects of different fill levels, exposure periods, weather, and pond fill water temperatures on pond performance. The models were applied to typical weather and pond fill water temperature data for Fort Benning to project annual solar pond performance.

Solar radiation, outdoor air temperature, and pond fill water temperature were determined to be significant factors influencing solar pond performance. Solar radiation was significant for all tests while outdoor air and pond fill water temperatures were most significant for 1-day exposures.

Solar ponds collect the most energy at the highest fill. At lower fills, although less total energy is collected, more energy is collected per unit of water which results in higher water temperatures. This is desirable when operating below capacity as at Fort Benning.

Lowering pond fills increased final water temperatures for all exposures. At a 1-day exposure, lowering pond fill from 3 to 2 inches increased pond performance by 30%. A larger reduction from 4 to 2 inches produced an approximate 62% increase. With hot water demand on the Fort Benning system well below capacity, lowering pond fill is an excellent option for an immediate and significant performance improvement. Lowering pond fills was found to be more important than increasing exposure. Increasing exposure increased final water temperatures in all cases except from a 1 to 2 day exposure at a 2-inch fill. This occurred because pond performance at longer exposures is less predictable due to nighttime energy losses and the higher probability that a poor solar day will occur during a multiple-day exposure. These problems are more significant at the lower 2-inch pond fill.

An individual pond operating at a 3-inch fill and a 1-day exposure collects around 488 MBtu annually which is equivalent to around $4500 in avoided fuel costs. This equates to around $0.80 saved per gallon of pond water used, neglecting distribution losses. Reducing fill to 2 inches will increase this savings to around $1.04 per gallon. With excess capacity, only the water utilized is saving energy. Therefore, the key operating objective for Fort Benning is to add the most energy possible to the water that is utilized. This will maximize energy savings.

Changing from an evening to a morning fill will also improve performance. This will eliminate nighttime energy losses on the first day of exposure and will be most important during winter operations. Two additional changes to improve system performance involve matching the storage tank water level to hot water demand and altering the pond operating strategy so that the amount of unheated supply water entering the hot water storage tank is minimized.

Individual ponds in good repair at the Fort Benning Shallow Solar Pond are performing close to the efficiency for which they were designed. System operations should focus on producing the highest water temperatures while still meeting base hot water demands. Specific actions to accomplish this that can be taken immediately are to:

* reduce pond fills,
* reduce the storage tank water level, and
* change from an evening to a morning fill.

Reducing pond fills alone will increase pond performance 30%. The most important future action that should be pursued is to identify promising end uses that can be added to the system. With less than half of the system capacity utilized, there is potentially more than $200,000 in annual savings that could be achieved if end uses could be added to bring operations near system capacity. Adding end uses will have to be evaluated since the cost effectiveness of this depends on the costs of any additional piping and the refurbishment costs for any needed ponds that are inoperative.

Most of the changes recommended can be implemented easily and at low cost. As demand on the system changes, information provided can be used to determine appropriate adjustments to the system operating strategy. By making the recommended changes and adapting to changes that may occur in the use of the solar pond, the benefits that the system is providing to Fort Benning can be improved immediately and in the future, and sustained.

1. SCOPE

This report describes the results of performance tests conducted on the Fort Benning Shallow Solar Pond Domestic Water Heating System. In addition to the performance results, it contains recommendations that can be implemented to improve both individual pond performance and overall system performance.

2. BACKGROUND

The Shallow Solar Pond Domestic Water Heating System at Fort Benning was designed and constructed to provide 500,000 gallons of hot water daily to barracks buildings and the laundry operation for several thousand troops. Soon after its completion, the hot water needs of the post laundry, the largest single user of preheated water from the system, were dramatically reduced eliminating the need for approximately 200,000 gallons of hot water. Eventually the post laundry was discontinued entirely, and approximately half of the systems capacity was no longer utilized. To partially compensate for this reduction, the makeup water supply for boilers at the central boiler plant was added to the system. The system still, however, operates at less than half of its capacity.

The original operating plan for the system was to operate all ponds at a 3-inch fill and to drain daily. It was estimated that operation would collect approximately $48,000 \times 10^6$ Btu annually.[1] With the current demand below 50% of system capacity, less than $24,000 \times 10^6$ Btu/year are being utilized and, in effect, over half of the ponds are not needed. With this excess available, it was thought that new operating strategies could be identified that would lead to substantial improvements in system performance.

3. PROJECT PURPOSE

The purpose of this project was to determine, through performance testing, the most effective system operating strategy or strategies to maximize the economic benefit from the Fort Benning Shallow Solar Pond Domestic Water Heating System for expected climatic conditions. The strategies considered were limited to varying pond fill levels and exposure times.

4. SYSTEM DESCRIPTION

The shallow solar pond system at Fort Benning is comprised of 80 individual ponds. A schematic of the system is shown in Figure 4.1. Individual ponds consist of two Hypalon rubber bags approximately 7.5 ft wide x 200 ft long. The bags rest on foamed-glass insulation on a sand substrate. They are covered by transparent fiberglass panels attached to concrete side walls. Ponds were constructed to design specifications from the Lawrence Livermore Laboratory.[2] Total capacity of the system is approximately 500,000 gallons.

The shallow solar pond system serves as a pre-heater for a large portion of the hot water used at Fort Benning. After the pond water is heated, it is drained into a sump and then pumped into a large, insulated storage tank (see Figure 4.1). Water is pumped continuously from the tank through a distribution system to several buildings throughout the base. Most of the water heated by the system is distributed to domestic hot water systems located in barracks buildings. Supplemental steam-to-hot water heaters at each building heat the preheated water to the final desired temperature. Steam is provided by a central steam plant fueled by either natural gas or #6 fuel oil.[1]

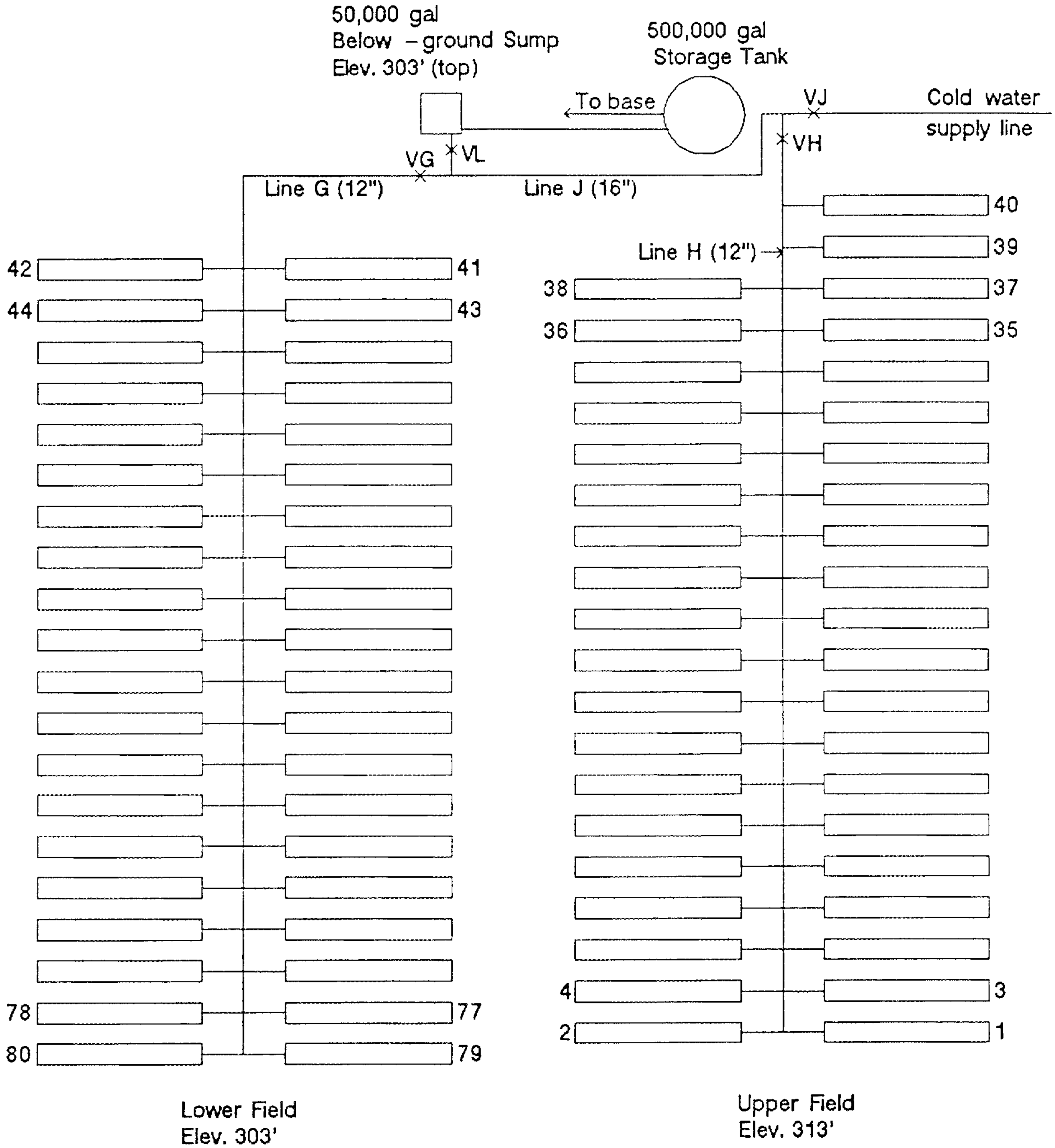

Figure 4.1. Schematic of the Fort Benning Shallow Solar Pond Domestic Water Heating System (not to scale)

5. PERFORMANCE TEST PLAN

5.1 Introduction

The energy collected and the final water temperatures achievable in the Fort Benning solar pond water heating system are largely controlled by:

* available insolation and exposure times,
* pond fill levels and initial fill water temperatures,
* ambient temperatures, and
* glazing transmissivity.

While some of these parameters change significantly from day to day, others experience little or perhaps gradual change over time. By measuring these parameters along with the performance of the system under actual conditions, system performance can be better understood, and operating strategies to maximize energy output can be determined for different combinations of parameters.

Performance testing was limited to the evaluation of individual ponds.[3] Performance of the system was projected from these results. Thus, overall system performance as evaluated here does not account for the system's electricity use or the thermal losses associated with the hot water storage tank and distribution systems.

Performance testing was conducted between January 1, 1989 and September 30, 1989. During testing, periodic problems at the solar pond often resulted in short-term data loss. The most critical data loss, however, was experienced in the final quarter of performance testing between July and September of 1989 when the system was inoperative due to hardware failure in the solar pond control system. The data on which the solar pond performance models in this report are based exclude this missing summer performance data. The models were, however, applied to typical annual weather conditions in or around the Fort Benning area to project year-round performance.

5.2 Test Details

Operational strategies for the system were examined based on the monitored performance of six individual ponds. Test ponds were selected from the lower field (see Figure 4.1) and from operating ponds with clear glazing that had no structural collapse. Three ponds each (1 at each fill) were connected to the Units 1 and 2 data acquisition systems for data collection.

Fill levels of 2, 3, and 4 inches were assigned randomly to each of the six test ponds providing 2 ponds at each level. The exposure time of each pond was varied from one to three days. A typical 30-day test sequence is shown in Figure 5.1.

The solar pond control program was modified to cycle the test ponds between 1, 2, and 3-day exposures and to allow additional drain time for the test ponds to insure that they would be fully drained. No other changes to the normal fill and drain cycles were made. Test ponds were filled in the evening during the normal system fill cycle immediately following the drain sequence. Fill levels (water volumes) of test ponds were calibrated to the level switches that control pond filling by measuring the water level increase in the sump tank when each individual pond was drained. The water volumes corresponding to the 2, 3, and 4-inch fills were 3740, 5610, and 7480 gallons, respectively. Fill level corresponds to the approximate water depth at the geometric center of the bag (100 feet from each end and 3.75 feet from each side). For the design slope of 1 inch per 100 feet, the depth of water at the shallow end will be 1 inch lower than the fill level.

Detailed discussion of this test plan is provided in the Test and Evaluation Plan in the appendix of this report.

Pond	Fill Level (in.)	Day 1	2 3	4 5 6	7	8 9	10 11 12	13	14 15	16 17 18	19	20 21	22 23 24	25	26 27	28 29 30	Points for each exposure, 1	2	3
53	2.0	-	----	--------	-	----	--------	-	----	--------	-	----	--------	-	----	--------	5	5	5
66	2.0	-	----	--------	-	----	--------	-	----	--------	-	----	--------	-	----	--------	5	5	5
54	3.0	-	----	--------	-	----	--------	-	----	--------	-	----	--------	-	----	--------	5	5	5
62	3.0	-	----	--------	-	----	--------	-	----	--------	-	----	--------	-	----	--------	5	5	5
49	4.0	-	----	--------	-	----	--------	-	----	--------	-	----	--------	-	----	--------	5	5	5
75	4.0	-	----	--------	-	----	--------	-	----	--------	-	----	--------	-	----	--------	5	5	5
50	3.0	-	----	--------	-	----	--------	-	----	--------	-	----	--------	-	----	--------	5	5	5

Figure 5.1. Typical 30-day test sequence for a pond. Dashed lines signify 1, 2, and 3 day exposures.

6. RESULTS

6.1 Modeling

For the first quarter of performance testing, simple two-parameter linear models provided excellent representation of pond performance data. Correlation coefficients for the linear model relating final pond water temperature (T_{final}) to the exposure period daily average insolation (I_{avg}),

$$T_{final} = (a \times I_{avg}) + b, \quad (6.1)$$

exceeded 0.95 for all exposures and pond fills. This indicated that solar radiation alone was an excellent predictor for first quarter operation. As testing progressed into the second quarter, average outdoor temperatures and pond supply (fill) water temperatures began to increase and have more impact on final pond water temperatures. The progression of daily average outdoor temperatures and pond fill water temperatures over the test period are shown in Figures 6.1 and 6.2.

These parameters began to influence final water temperatures more and more such that solar radiation alone would no longer provide satisfactory models. Correlation coefficients for the two-parameter linear models based on Equation 6.1 ranged from 0.71 to 0.88.

The linear model

$$T_{final} = (a \times I_{avg}) + (b \times T_{avg}) + (c \times T_{fill}) + d, \quad (6.2)$$

where T_{avg} equalled the exposure average outdoor temperature and T_{fill} the pond fill water temperature, was examined as an improvement to the performance model. Correlation coefficients for the four-parameter linear models based on Equation 6.2 ranged from 0.81 to 0.98 indicating much better predictive models than for the two-parameter case. Although each factor was found important, solar radiation remained the

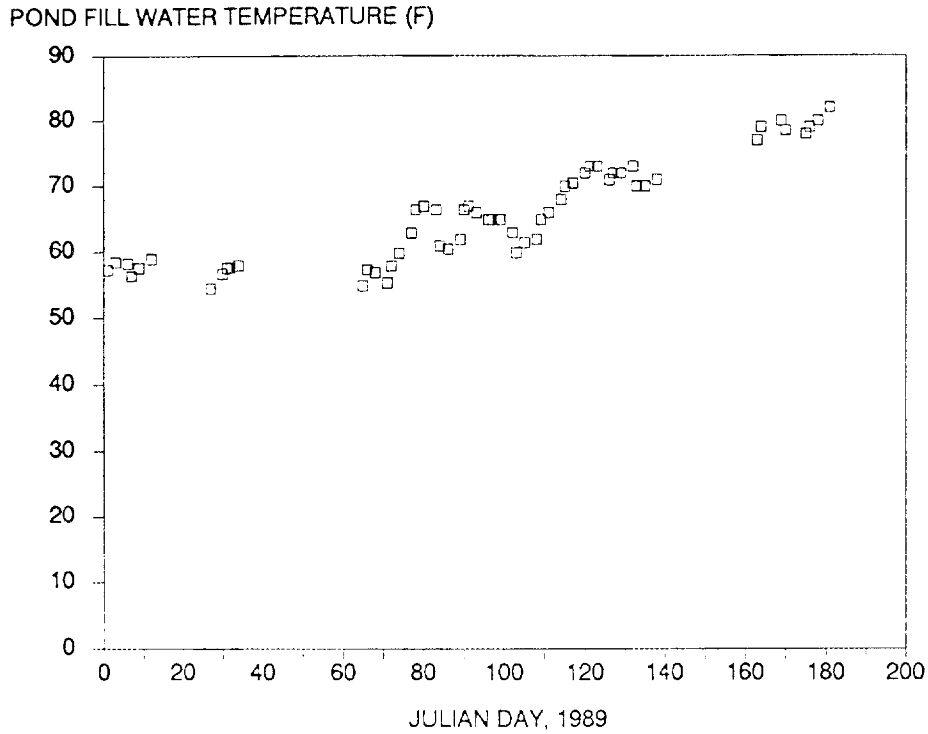

Figure 6.1. 1989 pond fill water temperatures.

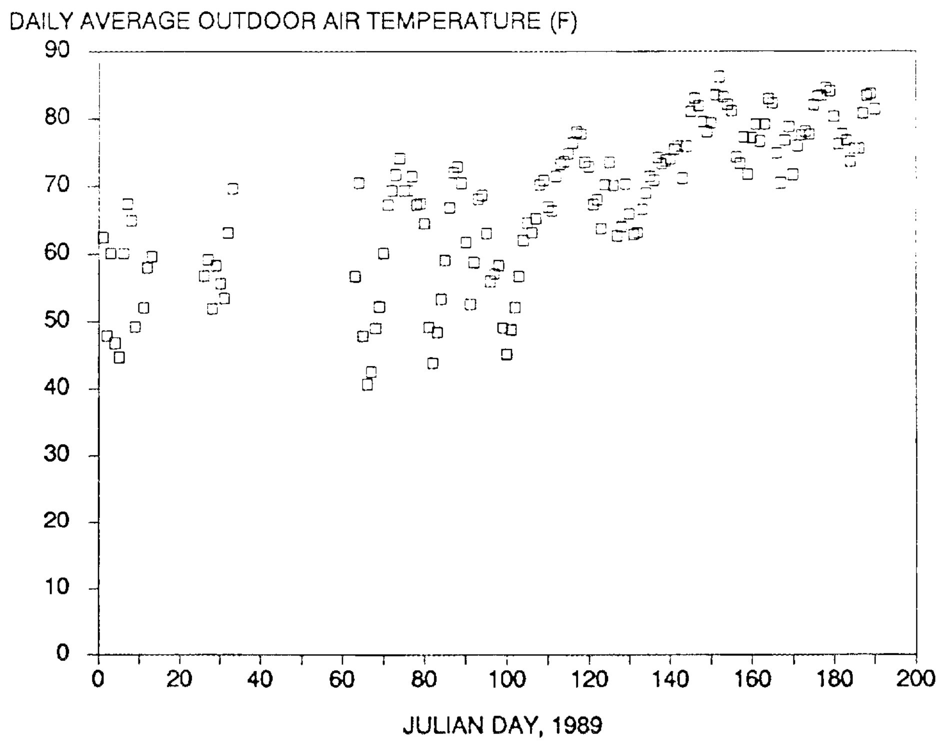

Figure 6.2. 1989 outdoor air temperatures.

best single indicator of final pond water temperature in all cases. The influence that each factor had on final pond water temperature was dependent upon the exposure period and the pond fill. Solar radiation was found to be highly significant (probability, p, greater than 99%) in all cases. Outdoor temperature was found to be highly significant for a 1-day exposure at all fills. Fill water temperature was found significant (p greater than 95%) for a 3-day exposure at all fills. These and other probabilities are presented in Table 6.1. Equation 6.2 was used to model pond performance data for the entire monitoring period.

Table 6.1. Probabilities that I_{avg}, T_{avg}, and T_{fill} are significant parameters in determining final pond water temperatures (%).

Exposure	Fill=2			Fill=3			Fill=4		
	I_{avg}	T_{avg}	T_{fill}	I_{avg}	T_{avg}	T_{fill}	I_{avg}	T_{avg}	T_{fill}
1	99	99	83	99	99	*	99	99	99
2	99	*	*	99	*	*	99	99	*
3	99	*	97	99	*	98	99	*	96

*Probability < 83%.

6.2 Pond Performance

In addition to the performance variation of an individual pond, pond-to-pond variations were found for similar fills and exposures. Resulting final water temperatures for ponds of equal fills and exposures from the Units 1 and 2 data acquisition systems are shown as a function of solar radiation in Figures 6.3 through 6.11. At a 2-inch fill, the Unit 2 pond produced temperatures averaging around 12°F higher than the Unit 1 pond at all exposures. Based on limited data due to control problems on one pond, the Unit 2 pond outperformed the Unit 1 pond by an average of 5°F at a 3-inch fill. Ponds performed approximately the same at a 4-inch fill (within 2°F). Pond-to-pond

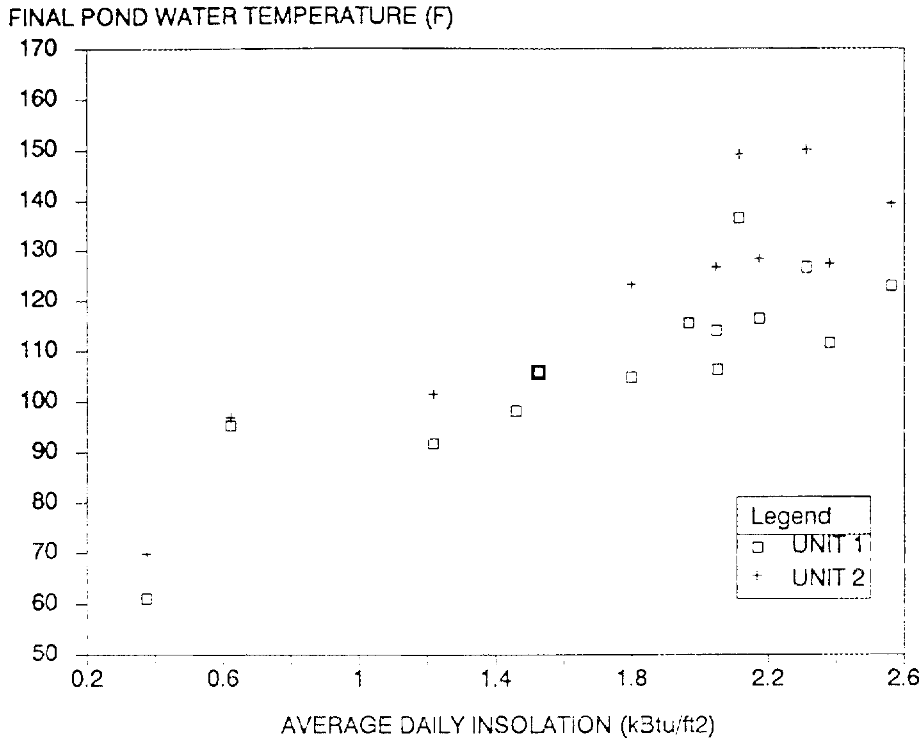

Figure 6.3. Pond-to-pond performance variation: exposure=1, fill=2.

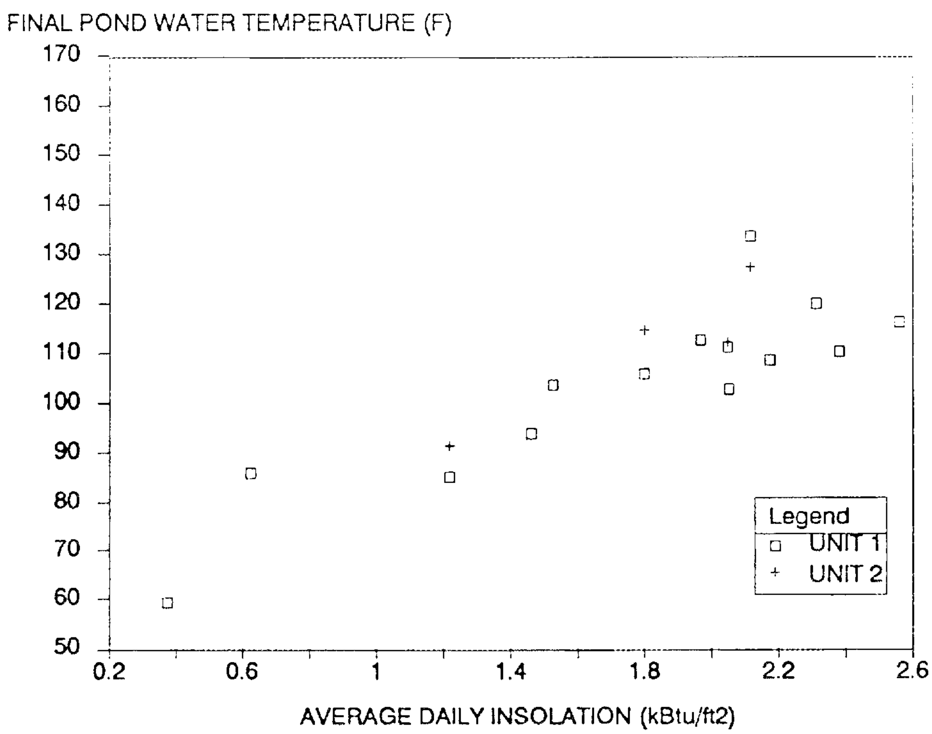

Figure 6.4. Pond-to-pond performance variation: exposure=1, fill=3.

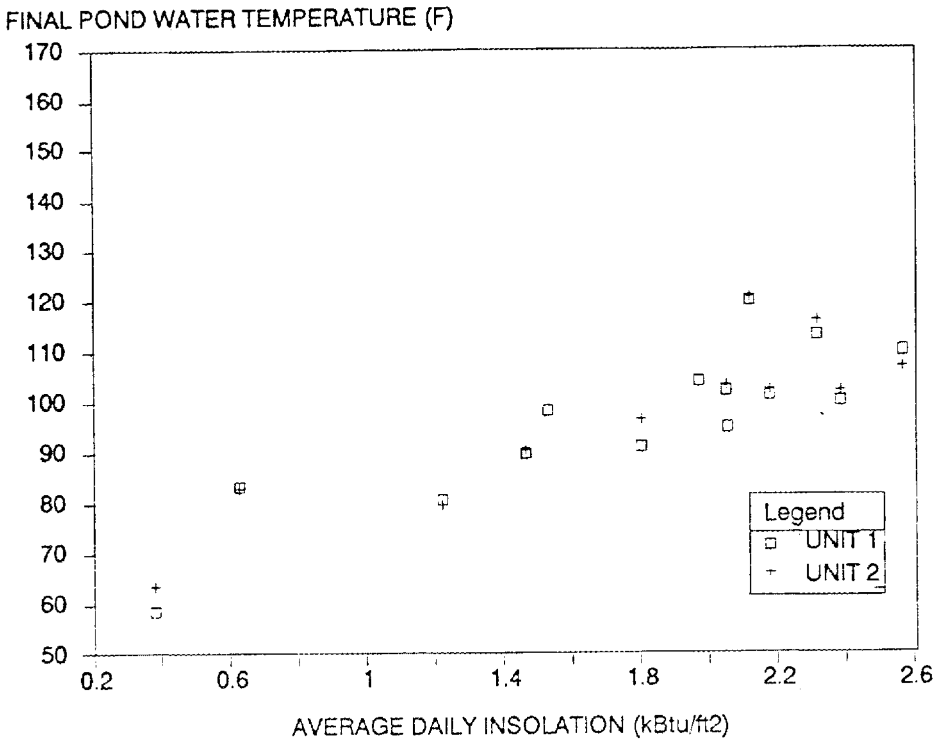

Figure 6.5. Pond-to-pond performance variation: exposure=1, fill=4.

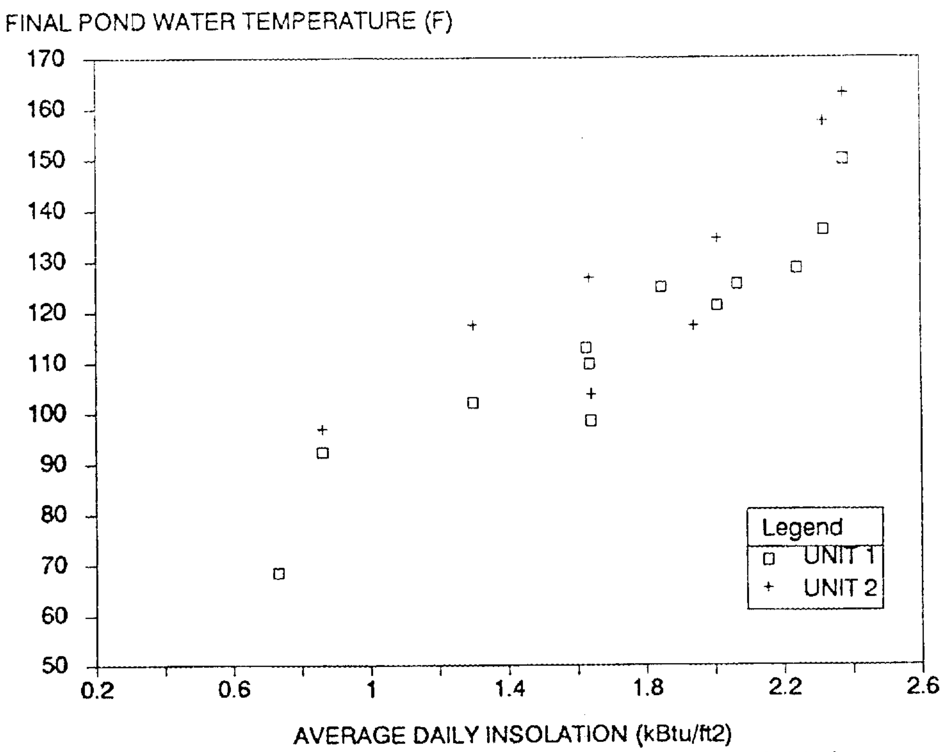

Figure 6.6. Pond-to-pond performance variation: exposure=2, fill=2.

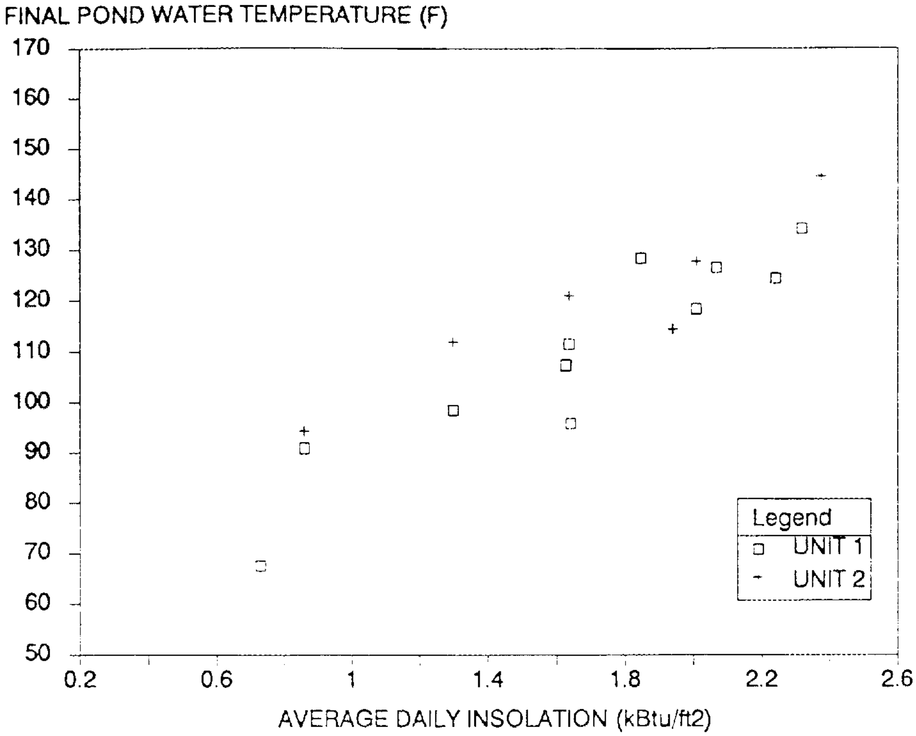

Figure 6.7. Pond-to-pond performance variation: exposure=2, fill=3.

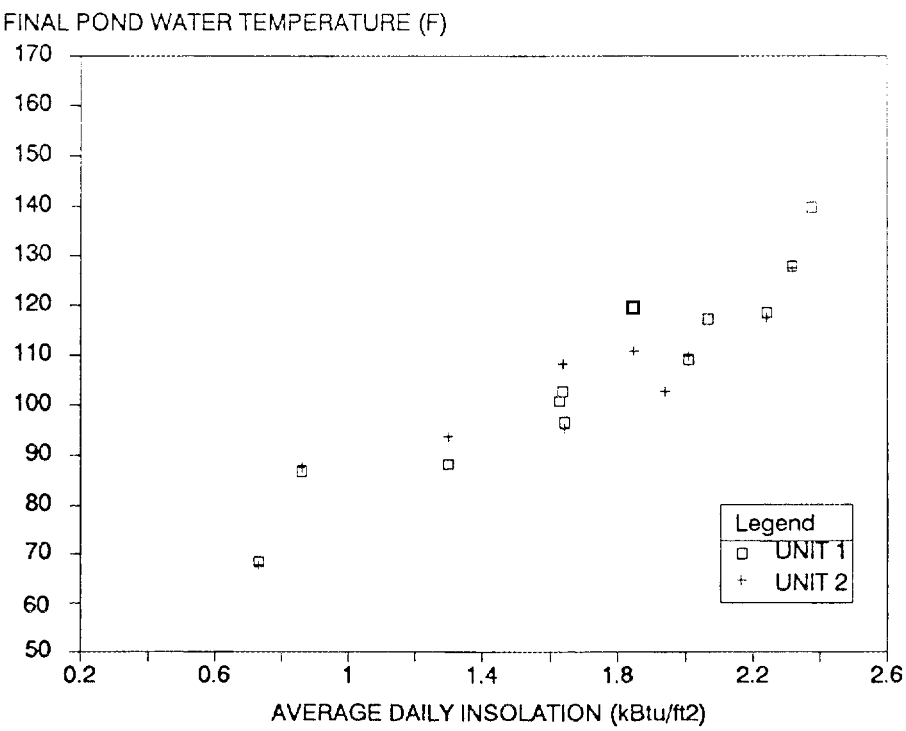

Figure 6.8. Pond-to-pond performance variation: exposure=2, fill=4.

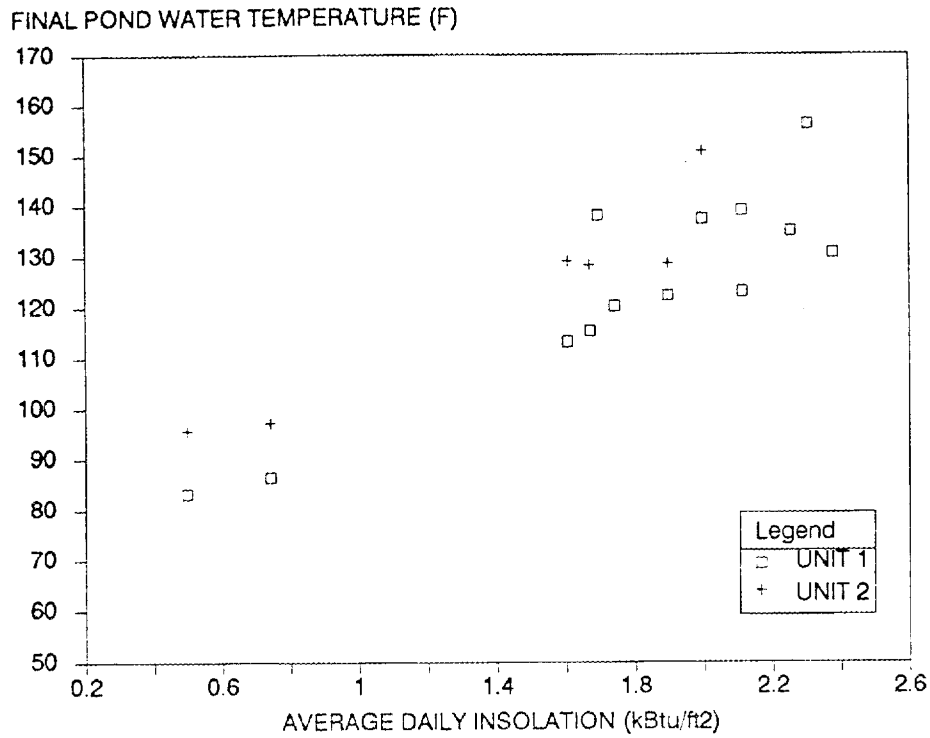

Figure 6.9. Pond-to-pond performance variation: exposure=3, fill=2.

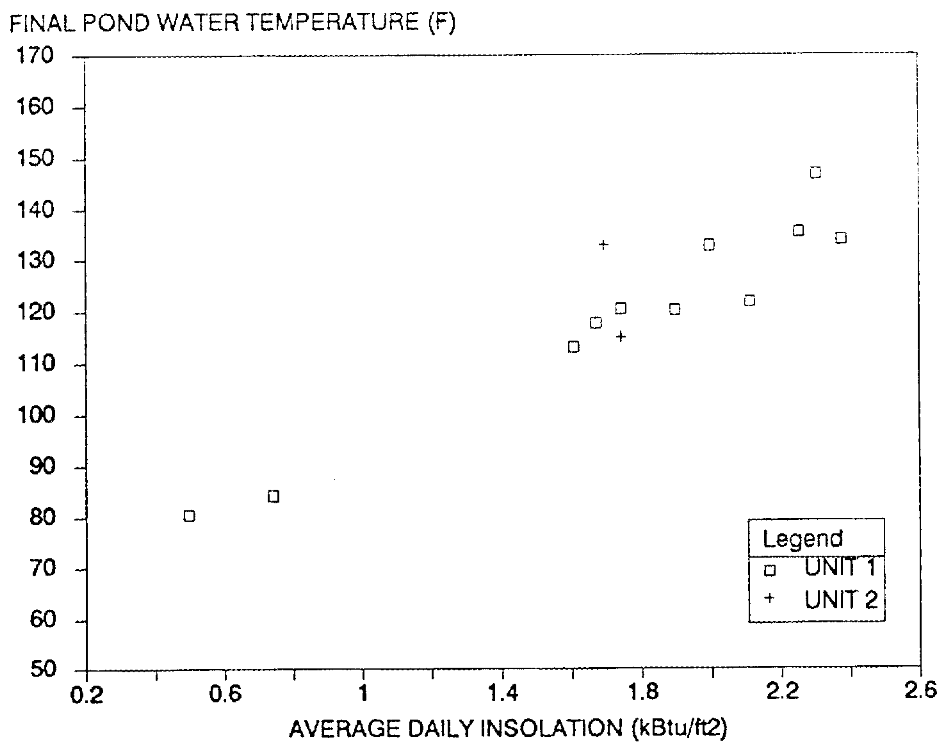

Figure 6.10. Pond-to-pond performance variation: exposure=3, fill=3.

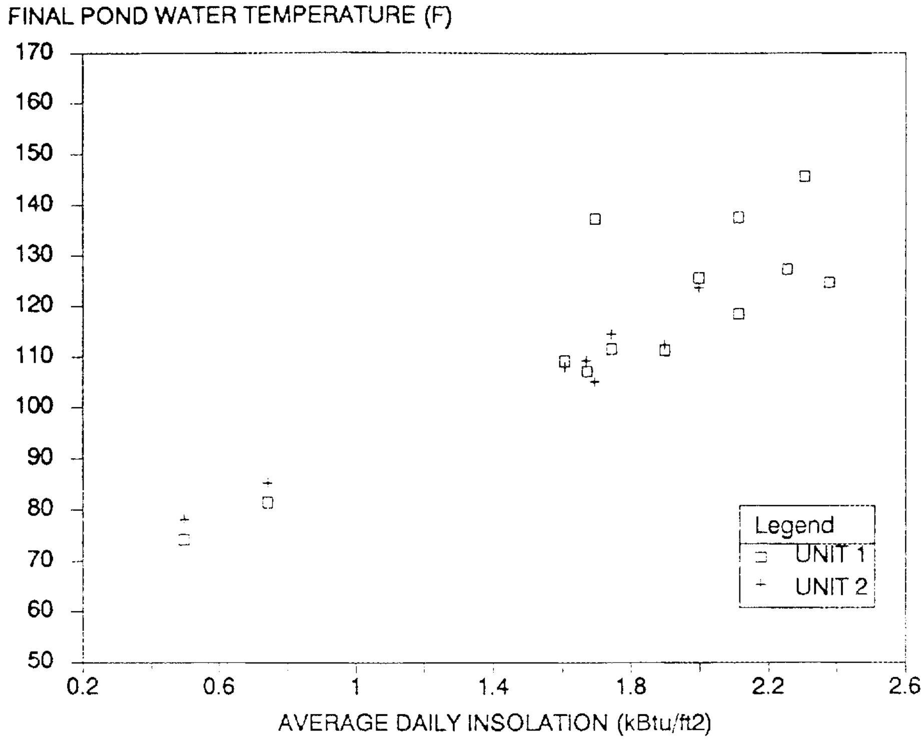

Figure 6.11. Pond-to-pond performance variation: exposure=3, fill=4.

variations were likely due to differences in glazing performance and perhaps small variations in fill. In Figures 6.3 through 6.11, the variation evident in the performance of an individual pond indicates that solar radiation alone does not account for all of the variation associated with pond performance.

Performance models based on the combined measured data from both Units 1 and 2 ponds were used to make performance comparisons between different fills and exposures. Pond performance was modeled for pond fills of 2, 3, and 4 inches and exposures of 1, 2, and 3 days. These models, presented in Table 6.2, relate final pond water temperature to the average daily insolation, the average daily outdoor temperature, and the pond fill water temperature for the three exposure periods. Since the squared model correlation coefficients (R^2) in Table 6.2 range from around 0.8 and up, these simple linear regression models provide good fits to the performance data. The highest R^2 values occur for the shortest exposure, indicating that the models are somewhat better for the 1-day exposure.

The measured performance data are only indicative of what occurred in the first half of 1989 since weather data can differ dramatically from year to year. However, by evaluating the performance models based on typical weather data, estimates of expected solar pond performance can be made. Pond performance was examined by using these models along with typical monthly average outdoor temperature data for Fort Benning[4], the average solar radiation data for Birmingham, Alabama[5], and the measured pond fill water temperatures for 1989 as shown in Table 6.3. Estimates of fill water temperatures were made for the last six months of 1989. The use of measured 1989 pond fill water temperatures in these models as opposed to long-term averages is permissible since the influence of fill temperature on final pond water temperature is limited and large variations from the 1989 data are unlikely.

Table 6.2. Coefficients for linear models relating final pond water temperatures to insolation, outdoor temperature, and pond fill water temperature.

Model: $T_{final} = (a \times I_{avg}) + (b \times T_{avg}) + (c \times T_{fill}) + d$

	Fill	R^2	a	b	c	d
1 day exposure	2	.877	.0211	.637	.547	-.222
	3	.963	.0184	.795	.065	17.5
	4	.978	.0154	.495	.512	4.41
2 day exposure	2	.807	.0354	.551	-.431	50.2
	3	.838	.0311	.466	-.543	66.3
	4	.925	.0269	.572	-.110	29.1
3 day exposure	2	.862	.0232	.191	.810	17.0
	3	.942	.0292	-.049	.747	21.8
	4	.884	.0254	.185	.609	16.0

Table 6.3. Typical weather conditions and pond fill water temperatures at Fort Benning.

Month	Mean Daily Horiz. Solar Radiation, I_{avg}* (Btu/ft2)	Average Outdoor Temperature, T_{out}** (F)	Average Pond Fill Water Temperature, T_{fill}*** (F)
J	712	44.9	57
F	968	48.3	59
M	1284	54.5	61
A	1664	64.7	66
M	1866	71.2	72
J	1904	77.0	79
J	1796	78.8	80
A	1736	78.3	80
S	1443	74.1	76
O	1213	64.2	68
N	856	54.0	61
D	663	47.5	58

* For Birmingham, Alabama. Source: (ASHRAE, 1986)

** For Fort Benning, Georgia. Source: (Facility Design and Planning Engineering Weather Data, Department of the Army, TM 5-785, 1978.)

*** 1989 values. January through June values were measured. July through December values were estimated.

The weather data and pond fill temperatures in Table 6.3 were used with the performance models in Table 6.2 to predict the long-term average performance of the Fort Benning solar ponds relative to fill and exposure. It is important to recognize that the values in Table 6.3 are average monthly values and therefore give an indication of average monthly performance. The actual performance on a given day would be difficult to predict far in advance since solar radiation, the primary influence on final pond water temperatures, can have large day-to-day variations at Fort Benning as shown in Figure 6.12.

Predicted monthly average performances for each fill and exposure are shown in Figures 6.13 through 6.18. Several observations can be made from these results. First, Figures 6.13 through 6.15 indicate that, on average, a 3-day exposure cycle produces the highest final water temperatures. Secondly, the 2-day cycle will typically outperform a 1-day cycle except during summer periods when a lower fill is used. This is likely the result of day-to-day solar radiation variations. Another important observation is that during the winter, on the average, final pond water temperatures can be expected to exceed fill water temperatures indicating that wintertime operation is providing some benefit. Figures 6.16 through 6.18 indicate that the 2-inch fill continuously provides the highest possible water temperatures. This better performance is most pronounced for the shortest exposure. As exposures are lengthened, the pond fill becomes less significant.

Predicted final pond water temperatures (monthly averages) were used to estimate the average annual heat gains that can be expected for individual ponds. Average annual heat gains and corresponding final pond water temperatures are summarized in Table 6.4. These data illustrate several points about solar pond operations. For a 1, 2, or 3-day exposure, a solar pond will collect the most energy annually at the highest fill. For the same exposure, although less energy is collected (Btu) at lower fills, more energy is added to a unit of water (Btu/gal) which results in higher final water temperatures. Reducing

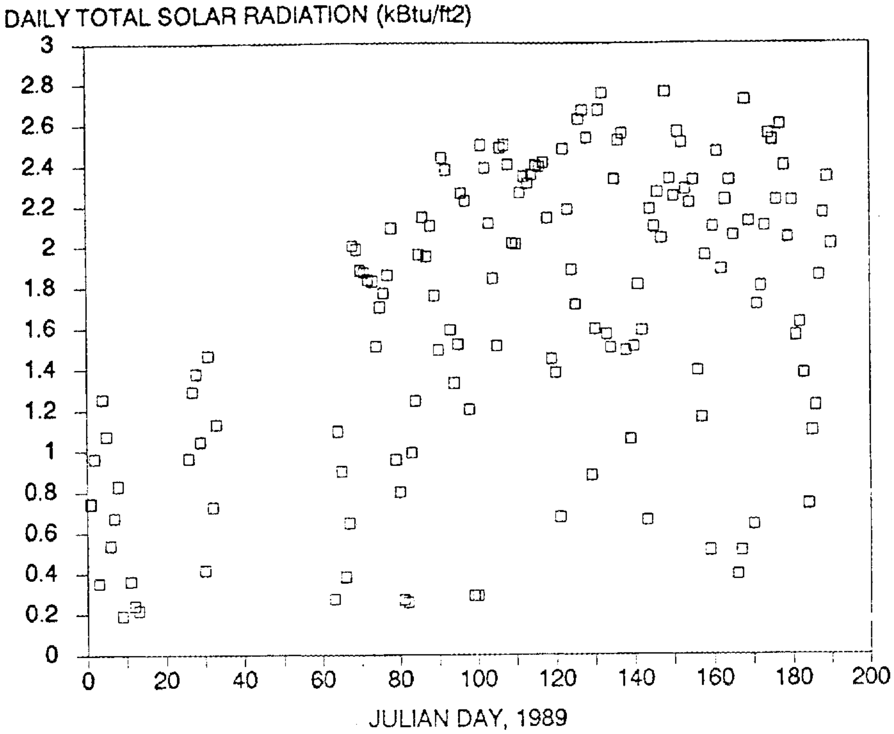

Figure 6.12. Daily solar radiation variations at Fort Benning.

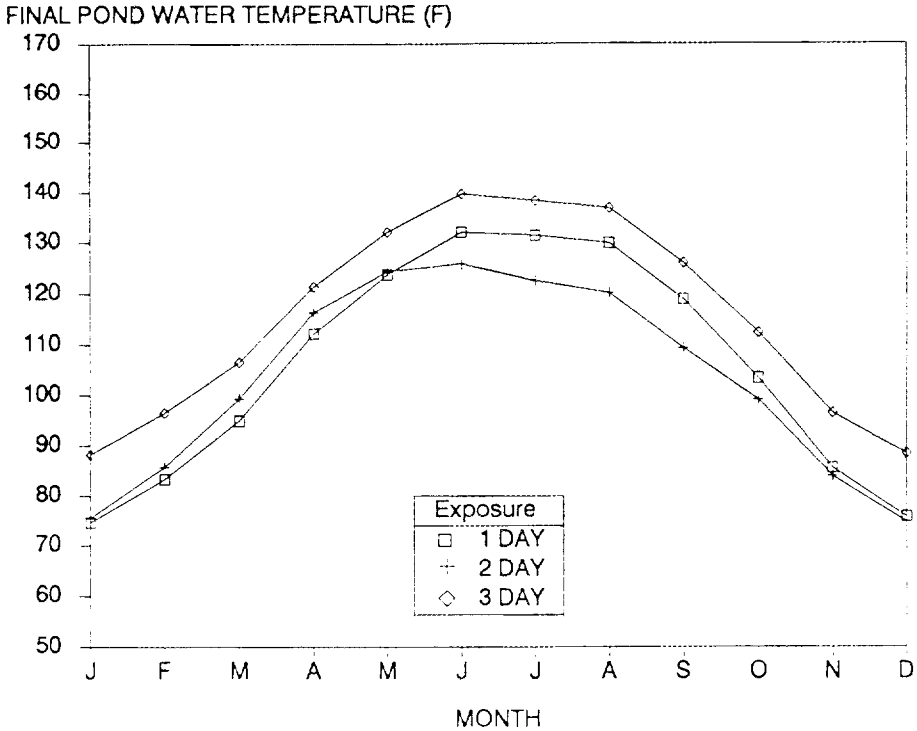

Figure 6.13. Fort Benning model estimates, fill=2.

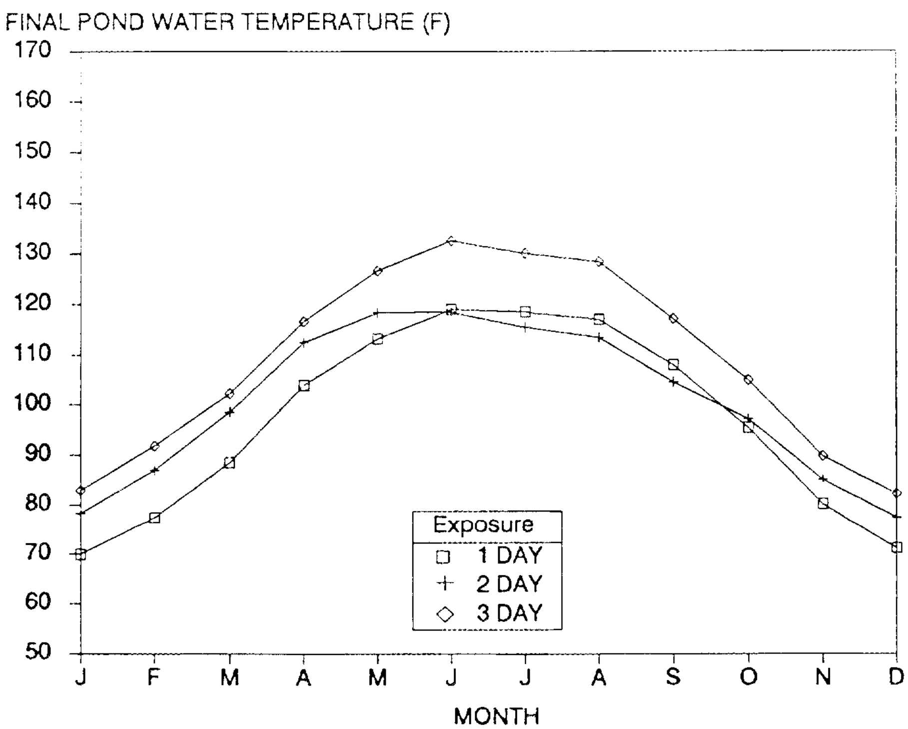

Figure 6.14. Fort Benning model estimates, fill=3.

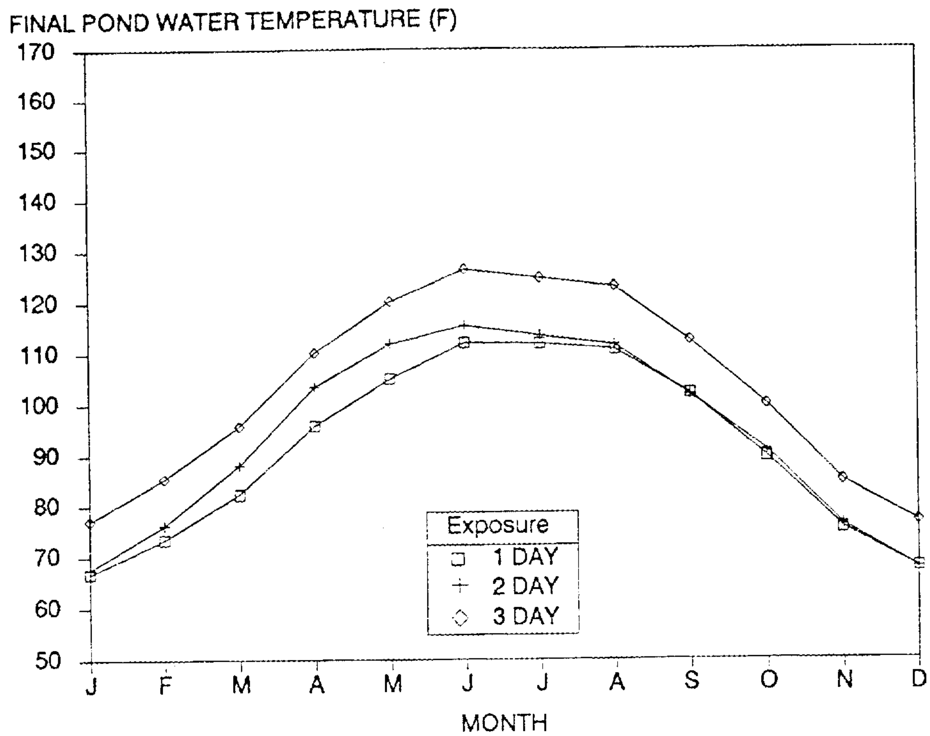

Figure 6.15. Fort Benning model estimates, fill=4.

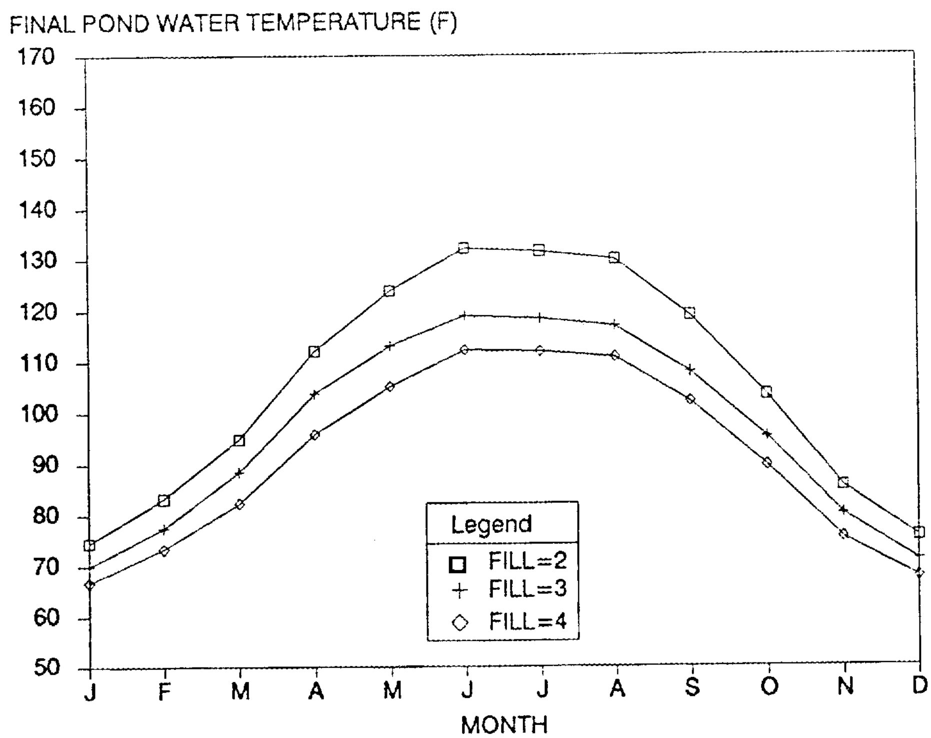

Figure 6.16. Fort Benning model estimates, exposure=1.

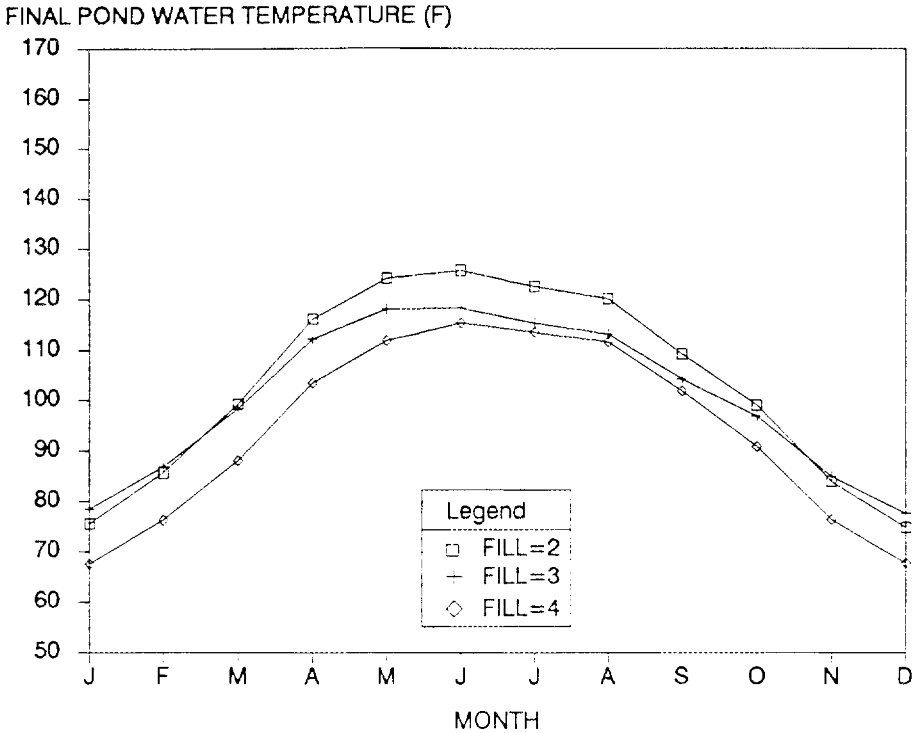

Figure 6.17. Fort Benning model estimates, exposure=2.

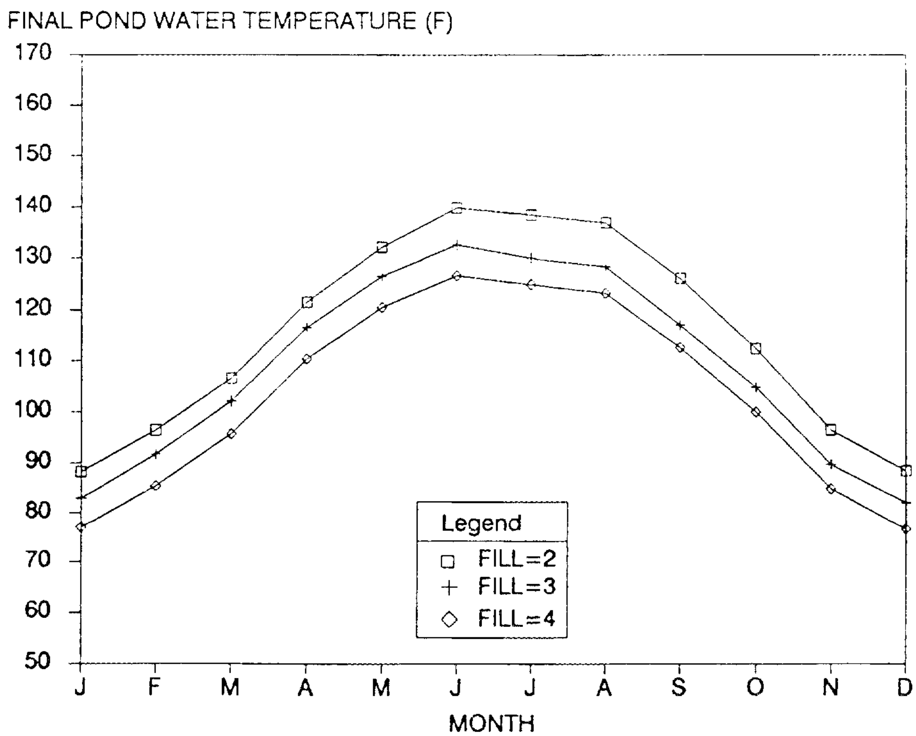

Figure 6.18. Fort Benning model estimates, exposure=3.

the pond fill from 4 to 2 inches provides higher water temperatures than doubling the exposure, although both operating plans would support the same demand.

Annual heat gains in Table 6.4 illustrate the substantial energy gains that changing fills and exposures can achieve. For a 1-day exposure, a pond with a 2-inch fill will provide 62% more energy to a gallon of water than a 4-inch fill (787 vs. 485 Btu/yr/gal). If the exposure were increased to 3 days, the 2-inch fill will provide more that twice the energy to a gallon of water than a 1-day exposure at a 4-inch fill (991 vs. 485 Btu/yr/gal).

Table 6.4. Estimated annual average pond energy gains and final water temperatures.

	Fill=2 (3750 gal/pond)			Fill=3 (5600 gal/pond)			Fill=4 (7500 gal/pond)		
Expo-sure	$\bar{Q}$	$\bar{Q}/V$	$\bar{T}_{final}$	$\bar{Q}$	$\bar{Q}/V$	$\bar{T}_{final}$	$\bar{Q}$	$\bar{Q}/V$	$\bar{T}_{final}$
days	MBtu/yr	Btu/yr/gal	°F	MBtu/yr	Btu/yr/gal	°F	MBtu/yr	Btu/yr/gal	°F
1	424	787	106	488	604	97	523	485	91
2	396	735	103	549	679	101	582	540	94
3	534	991	115	689	853	109	795	738	103

* The "–" above column headings indicates an annual average. V is pond volume. MBtu = 1,000,000 Btu.

6.3 Comparisons to Previous Work

There is available limited work that has been done on the performance of similar solar pond systems. The Fort Benning system was constructed based on the Design Guide for Shallow Solar Ponds prepared by the Lawrence Livermore Laboratory (LLL).[2] This guide provides design details which includes sizing the system based on predicted pond performance. The ponds referred to in the design guide contain a single 16-foot wide bag with a clear top whereas the Fort Benning ponds contain two 7.5-foot wide bags with black tops. Their performance should, however, be expected to be similar based on results from previous side-by-side tests.[6] The performance models of individual Fort Benning solar ponds are compared to 1-day performance predictions from the design guide for the Fort Benning climate in Figure 6.19. The predicted 1-day pond performance from the design guide is considerably greater than that measured at Fort Benning. During the winter, the performance difference ranges from about 4 to 7^{o}F depending on the fill. During the summer peak, this difference ranges from about 7^{o}F for the 4-inch fill to near 30^{o}F at the extreme for a 2-inch fill.

Comparison was also made to the work done by Silver and Burrows for the Tennessee Valley Authority (TVA).[6] In this work, both clear-top and black-top bags were tested. The ponds were similar to those at Fort Benning except that the bags were 1/4 as long (50 feet). Their results should be comparable since tests were conducted in Chattanooga, Tennessee, approximately 150 miles due North of Fort Benning. The TVA data represent averaged daily results for test periods ranging from 3 to 14 days. The TVA and Fort Benning results are shown in Figures 6.20 and 6.21. Comparisons were made by using the TVA weather data and pond fill temperatures in the Fort Benning models. These comparisons are in much better agreement than those made using the LLL design guide predictions. Temperature variations were within 14^{o}F at the 2-inch fill and within 7^{o}F at the 4-inch fill. In addition, neither data set consistently outperformed the other throughout the year.

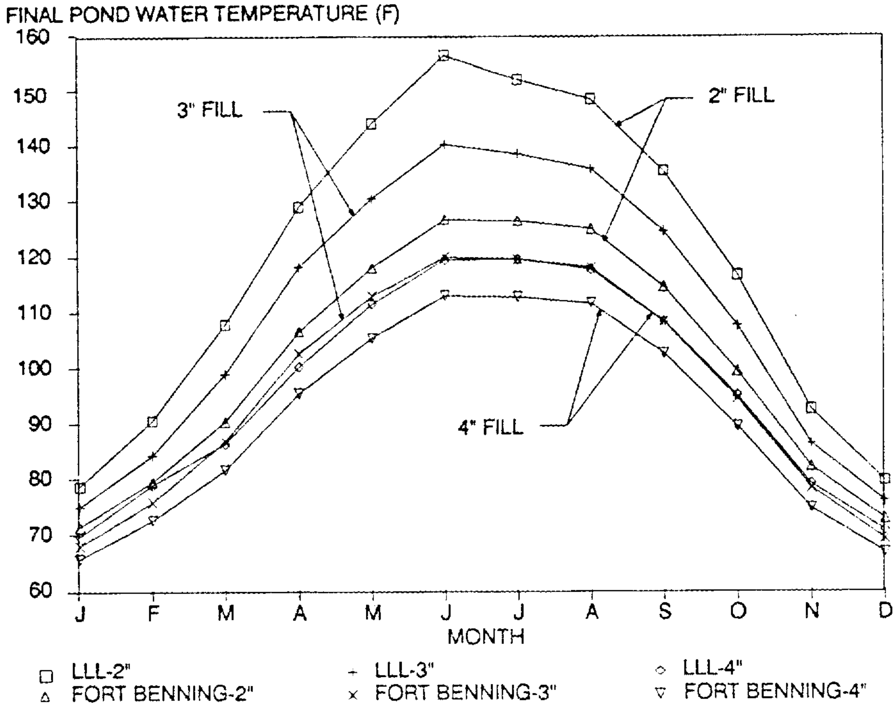

Figure 6.19. LLL data versus Fort Benning models, exposure = 1.

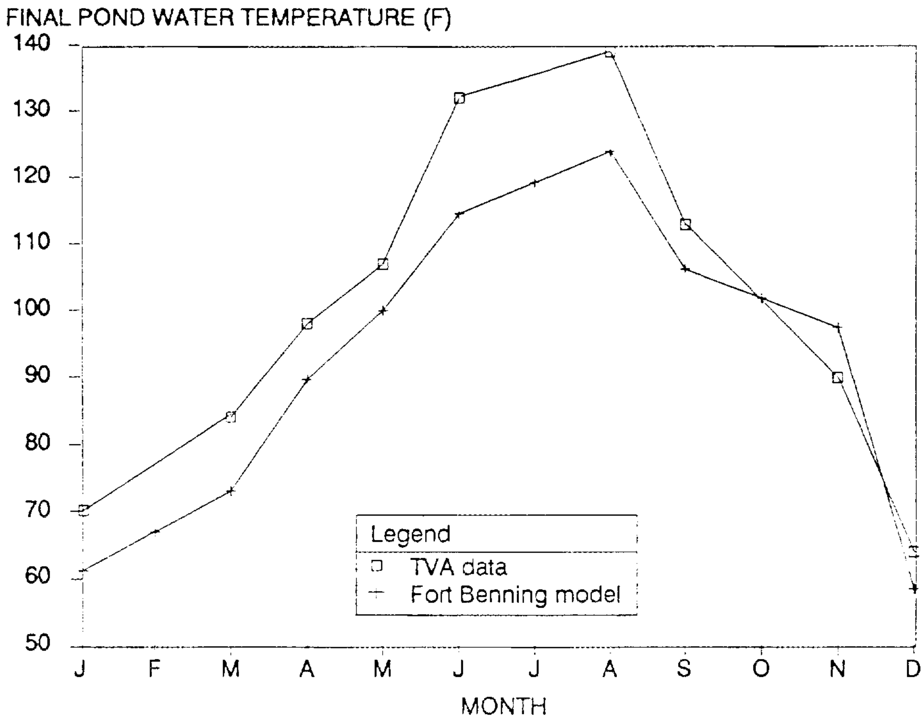

Figure 6.20. TVA data versus Fort Benning model, exposure=1, fill=2.

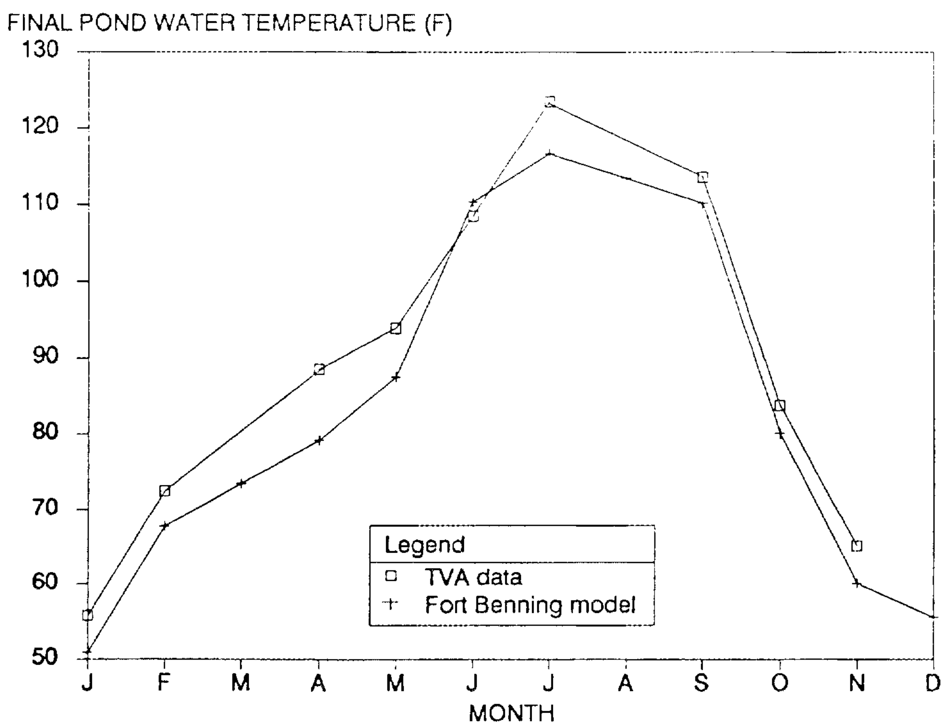

Figure 6.21. TVA data versus Fort Benning model, exposure=1, fill=4.

6.4 System Performance and Cost Savings

The net heat gained, Q, by an individual pond can be calculated from the expression

$$Q_{pond}\ (\text{Btu}) = 15{,}500 \times \text{Fill (inches)} \times (T_{final} - T_{fill}) \qquad (6.3)$$

where temperatures are in ^{o}F. The efficiency of the pond is simply the net heat gained divided by the total incident horizontal solar radiation. Using typical solar radiation data and T_{fills}, at a 3-inch fill the calculated monthly pond efficiencies at Fort Benning range from 28 to 35% and average 33%. At the same fill, ORNL (McCold) estimated the Fort Benning solar pond system efficiency average to be 35%[1] (ORNL's estimated system efficiency represents the amount of radiation captured in the out-flow of hot water from the storage tank whereas the measured value 33% is the capture represented in the exiting pond water. The efficiency based on the storage tank exit water temperature should be less than the efficiency at the pond exit due to thermal losses through the storage tank walls). Similarly, the average annual pond heat gain was measured to be 488 x 10^6 Btu at the 3-inch fill. McCold estimated the average annual system heat gain from a single pond at a 3-inch fill to be 540 x 10^6 Btu, a difference of approximately 10%.

McCold indicated that 70% is a typical efficiency for steam boiler fuel-to-DHW (domestic hot water) conversion. Neglecting distribution line losses which would occur from both the solar pond to the end use and from the central steam plant to the end use, at this efficiency, a Btu gained in the solar pond would be equivalent to 1.43 Btu of fuel at the central plant. This relation is

$$\underset{\text{(solar pond)}}{\text{Savings per MBtu}} = 1.43 \times \underset{\text{(heating plant)}}{\text{Cost per MBtu of fuel}} \qquad (6.4)$$

where MBtu = 10^6 Btu. Based on this relation, if fossil fuel at the heating plant costs \$6.5/MBtu then savings at the solar pond are equivalent to \$9.3/MBtu collected. An individual pond operating at a 3-inch fill and an average annual pond efficiency of 33% would produce annual savings of \$4500 based on 488 MBtu collected if used daily throughout the year.

An important point should be considered when estimating system performance at Fort Benning. In February 1989, the average daily demand for hot water from the solar pond was measured to be around 35,000 gallons over a consecutive 7-day test period. The underground water lines that supply ponds contain approximately 10,000 gallons of unheated water that drains into the sump along with pond water during each drain cycle. This amount of water is insignificant if the entire 500,000 gallon capacity of the solar pond were used daily, as in the original design computations for the system. However, at the measured February demand, this underground water represents 29% (10/35) of the daily demand. This may not be that significant during the winter, but during the summer this detriment could be substantial. For example, if 25,000 gallons from the ponds at 135°F goes into the storage tank along with 10,000 gallons of pipeline water at 75°F, the average water temperature into the tank is 17°F below the pond water temperature. The average water temperature going into the tank, $T_{tank(in)}$, can be calculated by the relation

$$T_{\substack{tank \\ (in)}} = [(V_{ponds} \times T_{ponds}) + (V_{lines} \times T_{lines})] / \underbrace{[V_{ponds} + V_{lines}]}_{\substack{\text{(total volume going)} \\ \text{(into the tank)}}} \quad (6.5)$$

where V represents the water volume and T represents the average water temperature for their corresponding subscripts. The impact of this unheated water could be significantly reduced if the volume in the underground lines could be reduced or the exposure cycle increased. For example, a 2-day exposure would effectively double the pond volume drained while keeping the line volume drained the same.

To estimate the solar pond system heat gain, T_{final} in Equation 6.3 should be replaced by $T_{tank(in)}$ calculated from Equation 6.5. The system heat gain is then

$$\underset{(Btu)}{Q_{system}} = 15{,}500 \times \underset{(inches)}{Fill} \times [T_{tank(in)} - T_{fill}] \times \underset{\substack{(to\ support)\\(daily\ demand)}}{(\#\ of\ ponds)}. \quad (6.6)$$

As daily demand from the system increases, $T_{tank(in)}$ approaches T_{final} for a pond. Equation 6.6 can be used along with the results of Equation 6.4 to estimate the expenditure that would be cost justified to perhaps implement new operating strategies or add additional end uses to the solar pond system.

7. STRATEGIES FOR IMPROVING PERFORMANCE

Individual ponds in good repair at the Fort Benning Shallow Solar Pond are providing much of their achievable performance. There are, however, simple changes that can be made that will improve both pond and system performance.

The system is providing only a small part of its potential since utilization is much below its design capacity. System utilization (the percent of the system's ponds required to meet daily hot water demands) at the beginning of this testing was around 10%. Thus, the system was providing around 10% of its potential $400,000/yr in energy savings at full utilization.[1] Under-utilization is by far the most important factor that prevents the system from delivering its potential energy savings. Regardless of utilization, there are operational changes that can be made to improve system performance and provide immediate additional benefits to Fort Benning.

Specific findings concerning solar pond operations and changes that can be made to improve both immediate and long-term benefits from the system are provided in the following discussions targeted at the specific areas where improvements can be made.

7.1 Pond Fill Levels

With the water demand below the system capacity and a desired safety reserve in the storage tank, adjusting pond fills to achieve the highest water temperatures is most important. Pond fills should be adjusted to a minimum level since minimum fills produce the highest water temperatures. Figure 7.1 or the relation

$$\underset{\text{(inches)}}{\text{Fill}} = [\ \underset{\text{(gallons)}}{\text{daily demand}} \ / \ (1870 \ \times \ \#\text{ of operating ponds})\ ]$$

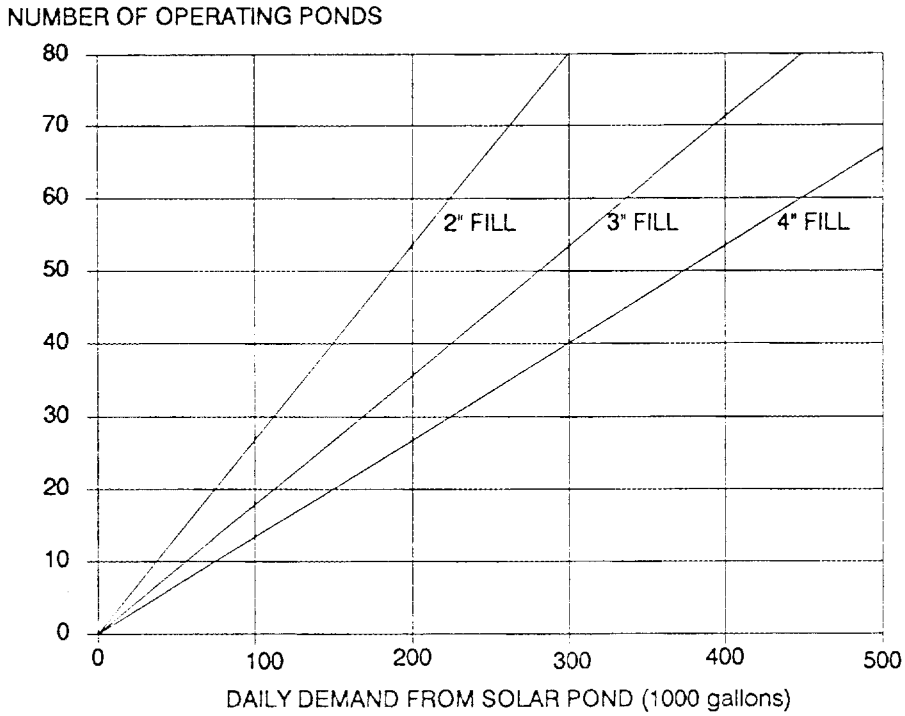

Figure 7.1. Number of ponds required to meet daily hot water demands.

can be used to determine the minimum operating level that will satisfy daily demand based on the number of operating ponds.

Maintaining the water level in a pond to insure that there is separation between the top and bottom of the bag is desirable since long-term contact when combined with exposure can eventually cause the two surfaces to adhere. For top and bottom separation, the minimum operating fill for a pond is 1 inch since the substrate for a bag is sloped 2 inches over the 200-foot bag length. It may be desirable to operate above a 1-inch fill to insure separation since the substrate may have shifted somewhat since construction and because of the difficulty in adjusting the pond fill switch to a specified fill.

Although final pond water temperatures increased for all exposures when the pond fill was reduced, this does not verify that further reduction of the fill (below 2 inches) will produce higher water temperatures. For a 1-day exposure, pond operation below a 2-inch fill may result in higher pond water temperatures. However, the benefits of multiple-day exposures at fills below 2 inches are more uncertain. As the pond fill is decreased, the water bag surface area to water volume ratio increases. This impacts the heat loss to heat gain ratio of a pond. This problem could possibly be detrimental for multiple-day exposures.

7.2 Exposure Periods

Increasing the exposure period between pond drains should be considered. Increasing exposure increases final pond water temperatures and daily fills as now done are not necessary. At low demand, only a few ponds require draining to refill the storage tank to its control level. As a result, some ponds will sit full over several days before being drained. This same scenario will occur when the exposure is increased, but now the filling of underground lines with supply water will no longer occur daily.

7.3 Storage Tank Fill Level

The operating level of the storage tank was reduced during this testing to 25 feet. This corresponds to approximately 350,000 gallons of water (approximately 14,000 gallons per foot). Readjusting this operating level should be considered whenever a significant change occurs in the water demand from the system. The volume in the storage tank should be set as low as possible while maintaining sufficient backup within the tank to provide continuous service through the typical downtimes that are sometimes needed to make repairs. Figure 7.2 can be used to determine the tank water level that should be maintained to provide daily demand and backup. If a 5-day backup was desired and the current demand on the system was 50,000 gallons per day, then 300,000 gallons or 22 feet would be the desired tank water level (based on a 1-day exposure cycle). The tank level is set in Drum 136 of the solar pond operating program.

If the tank is operated near full when the demand is low, the high temperature water that is drained into the tank daily will have little impact on the tank water temperature since the daily volume added will be small compared to the total water volume in the tank. The impact that a drain cycle would have on the storage tank average water temperature can be calculated by an equation similar to Equation 6.5 (by adding similar volume and temperature terms for the storage tank water).

The approximate demand on the system can be determined by shutting down the solar pond for a period and measuring the change in the tank water level. It is best to use a longer period for averaging if possible since day-to-day use could vary significantly. The best way to do this is to increase the storage tank level to near full temporarily so that the system can be shut down over a series of days.

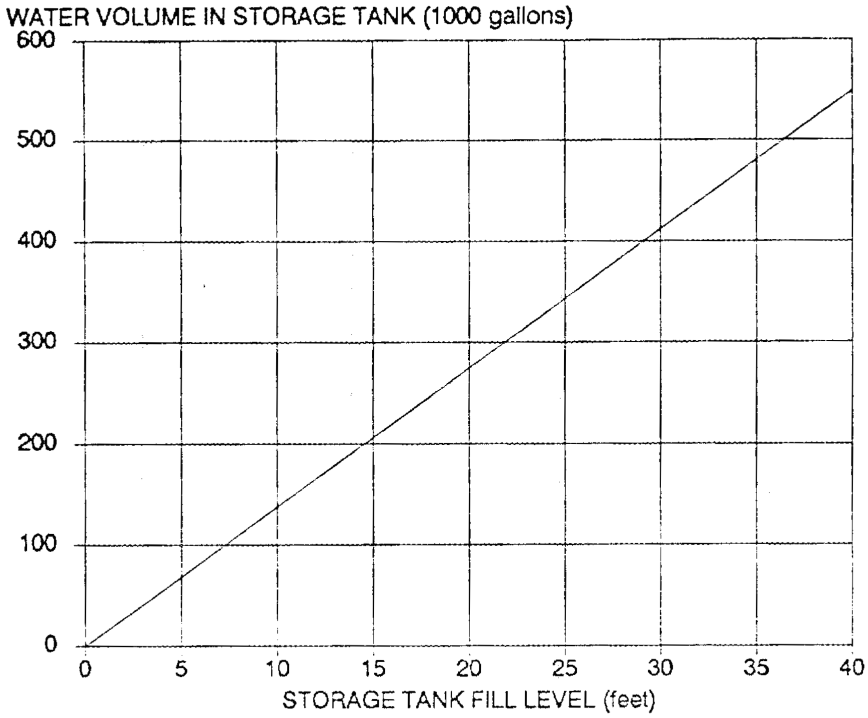

Figure 7.2. Storage tank volume versus tank fill.

7.4 Fill/Drain Strategy

The current operating strategy at the solar pond begins to fill ponds immediately after completion of the evening drain cycle. This normally results in the ponds sitting full overnight waiting on the solar heating cycle to begin. At some point, nighttime temperatures drop below pond fill water temperatures during much of the year as shown if Figure 7.3. During the winter, substantial unnecessary nighttime energy losses from the pond water occur. Winter nighttime exposures can range up to around 11 hours. Nighttime energy losses are reflected in the measured localized pond water temperatures shown in Figure 7.4.

The pond fill strategy should be changed to a morning fill cycle that would allow all ponds to be filled just prior to sunrise. The system operating program fills a new pond every two minutes. Therefore, for the entire system of 80 ponds, the fill cycle would have to begin 160 minutes (2 and 1/2 hours) before sunrise. Nighttime exposure might be suitable during the summer, but it should be avoided in other quarters.

7.5 System Utilization

The Fort Benning solar pond system was originally constructed to satisfy a daily demand of 500,000 gallons. Over time, the reduced need for hot water at the base reduced the daily demand from the system to less than half of its capacity. Even with the large number of ponds that are currently off-line, there is still excess capacity operating. This essentially results in hot water sitting in the ponds and not being used while non-renewable fuel is being consumed for water heating at other base sites. If potential end uses can be identified that may be added to the system cost effectively, they should be investigated since the system is now operating with excess capacity and since hot water from the system can offset substantial fuel costs. Not only would added end uses reduce base fuel costs, they would provide an

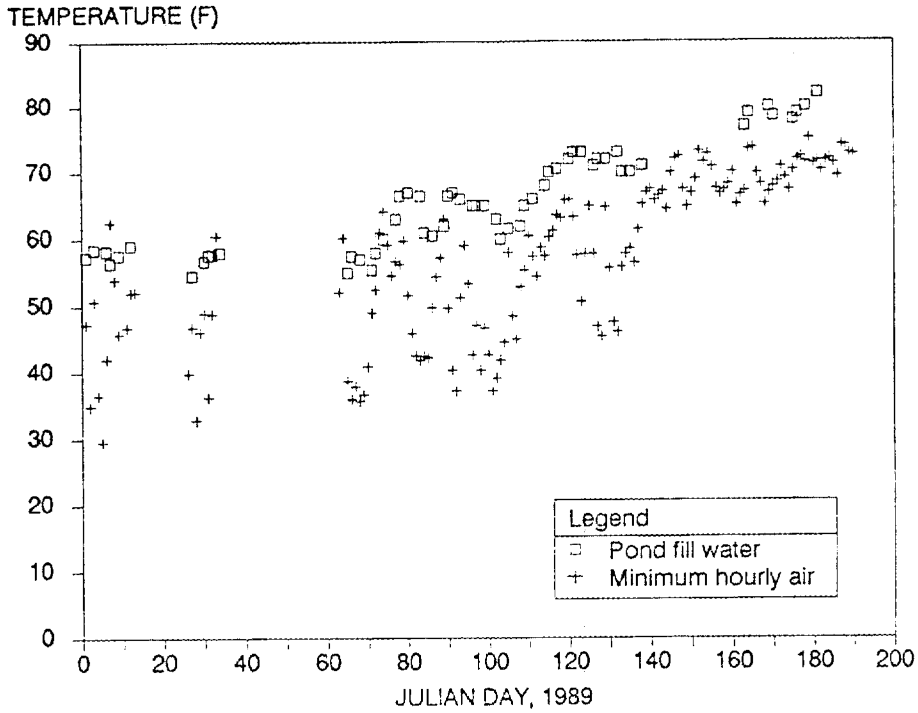

Figure 7.3. Pond fill water temperatures versus minimum outdoor air temperatures.

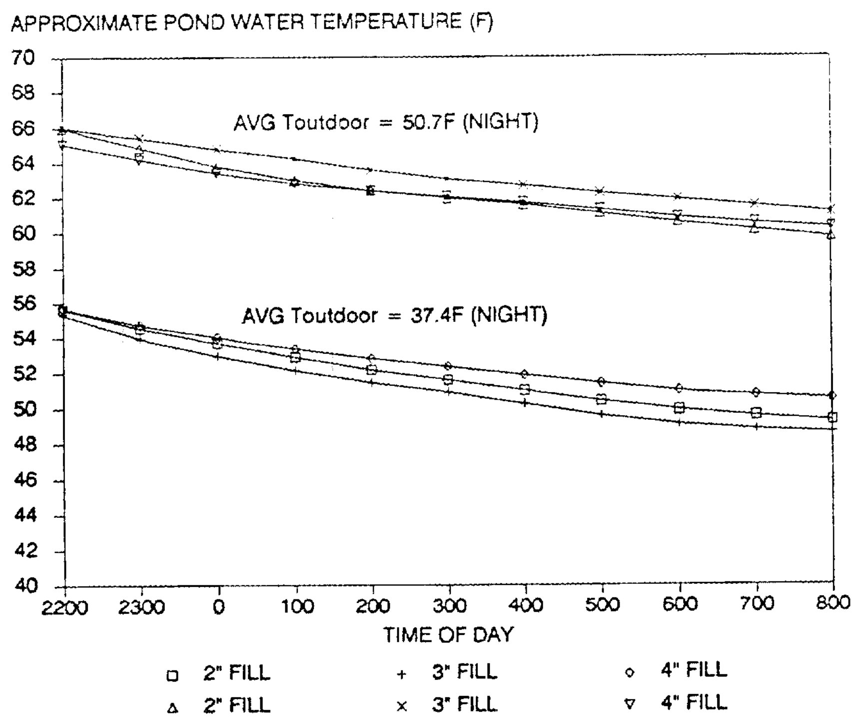

Figure 7.4. Nighttime temperature losses.

overall improvement in the efficiency of the system since on a percentage basis less underground water would go into the storage tank. Also, increased utilization of the system would help lower maintenance costs on a benefit-to-cost basis.

7.6 Unconditioned Supply Water

The current solar pond piping arrangement uses the same underground lines for both pond filling and draining (see Figure 4.1). This design requires that the approximate 10,000 gallons in the underground lines be drained into the sump before the pond water. If the demand on the system is 50,000 gallons per day, then 1/5 of the water entering the storage tank daily is at say 70°F. At this demand, eliminating this problem could easily raise average water temperatures entering the storage tank by 7 to 20°F during most of the year (this represents an approximate 15 to 30% increase in the average daily temperature increase that is achieved in a pond). This one-pipe arrangement, when combined with the pond's current operating strategy and low system utilization, is a major detriment to system performance.

The impact of unheated fill line water on the average temperature of water entering the storage tank can be reduced in several ways. First, a demand increase on the system could minimize its impact. If 200,000 gallons were used per day, the unheated water would make up only 5% (10,000/200,000) of the water going into the storage tank. At this demand it would be of little significance to system performance, as the original design intended. A second way to reduce its impact would be to use a 2- or 3-day exposure cycle. Thus, two or three times as much pond water would enter the storage tank for each fill as compared to a 1-day cycle. Another way, since demand is low, is to only utilize ponds in the lower field (by closing the valve to the upper field, valve VH in Figure 4.1). Since the upper drain lines (lines H and J) contain about 2/3 of the total fill line water, using only the lower ponds would reduce the amount of unheated water drained water drained by 62%. The upper and lower fields could also be alternated daily to reduce the impact by 50%.

A higher cost but more effective way to prevent fill line water from entering the storage tank would be to install a new fill line independent of the drain line. This will require some engineering since the water distribution system is currently sealed and a separate fill line may require some means of allowing air entry to insure that the drain line is emptied during the drain cycle.

8. CONCLUSIONS AND RECOMMENDATIONS

The Fort Benning Shallow Solar Pond System is providing only a fraction of the energy it was originally designed to supply. This is primarily due to the loss of the base laundry which was the largest single user of preheated water from the system. Although pond performance is somewhat lower than design expectations, individual ponds are providing most of the energy they are capable of capturing.

Pond fills and exposure times are key factors influencing solar pond performance. Unlike weather parameters, they can be adjusted to optimize system performance. Higher pond fills collect the most energy (Btu) but lower pond fills produce the highest water temperatures. This occurs because lower pond fills collect more energy per unit of water (Btu/gal). Since the entire capacity of the system at Fort Benning is not needed, the operating pond fill should be changed from its original 3-inch level to 2-inches. Based on performance measurements, this should, on average, provide an approximately 30% increase in the energy added to each gallon of water used annually.

For a specific demand, decreasing pond fill is more productive than increasing exposure. Exposures should not be increased at this time since the number of operational ponds (around 30) may not support the current demand from the system at the recommended 2-inch fill. Longer exposures are not always highly productive due to nighttime heat losses and day-to-day solar radiation variations. A significant amount of collected energy can be lost during nighttime exposures. This is more of a concern at low pond fills where a higher pond surface area to pond water volume ratio occurs. Performance for multiple-day exposures is also strongly dependent on daytime conditions on the last day of the exposure.

Solar radiation, outdoor air temperature, and pond fill water temperature are also significant factors influencing solar pond performance. Solar radiation is highly significant at all pond fills and exposures, whereas outdoor air temperature and pond fill water temperature are most significant at 1-day exposures.

On the average, winter operation of the solar pond is justified. Overall, winter performance could be enhanced if poor solar days could be detected so that draining could be initiated before significant energy losses occur. Although not active at this time, the solar pond operating program originally did this by initiating the drain cycle if the average pond water temperature decreased by 10°F within a 30-minute period.

A Btu gained at the solar pond is equivalent to 1.4 Btu consumed at the central heating plant. If fossil fuel costs are $6.5/MBtu, a single pond operating at a 3-inch fill, with daily draining, will produce annual savings of around $4500. This corresponds to approximately $80,000 saved for every 100,000 gallons utilized from the solar pond.

The following changes are recommended for current operations:

* reduce pond fills to 2-inches,
* lower storage tank level to 17 feet (a 4 day backup at 50,000 gal/day demand), and
* change to a morning fill cycle; begin fill at 0530 Nov.-Feb., 0430 March, April, Sept., and Oct., and 0330 May-Aug.

Recommended changes for future operations are:

* identify and add more end uses to the system (for every 100,000 gallons of added end use, approximately $80,000 could be saved annually), and
* examine alternatives for reducing the amount or impact of unheated pipeline water entering the storage tank.

Actions that can be taken to improve current operations can improve individual pond performance by more that 30% with little effort and cost. Even with the substantial increase achieved from changes to the current operating strategy, there is still potential for approximately doubling the value of the system if additional end uses can be added. Achieving this will depend on the ability to add other base hot water needs to the system cost effectively. Under-utilization is by far the most important factor that prevents the system from delivering its potential energy savings.

The recommended changes for current operations can be implemented easily and at low cost. As demand on the system changes, information presented in this report can be used to determine appropriate adjustments to the system operating strategy. By making the recommended changes and adapting to changes in its future use, the benefits that the solar pond system is providing to Fort Benning can be improved immediately and in the future, and sustained.

9. REFERENCES

1. McCold, L. N. and F. D. Boercker, DOD: Energy Conservation Investment Program (ECIP): Phase I - Planning ECIP Project Validation Design Plan, for the Shallow Solar Pond Hot Water Heater, Project No. 348, ORNL/TM-8934/P1, March 1985.

2. Casamajor, A. B. and R. E. Parsons, Design Guide For Shallow Solar Ponds, Lawrence Livermore Laboratory, UCRL-52385 Rev. 1, Livermore, California, January 8, 1979.

3. "Statement of Work for the Performance Evaluation of Shallow Solar Pond Hot Water Heating System," attachment to letter from John J. Krajewski, Director of Facilities Engineering, U.S. Army Engineering and Housing Support Center, to W. D. Adams, Director, Research and Waste Management Division, U.S. Department of Energy, Oak Ridge Operations, May 27, 1988.

4. Department of the Army, Facility Design and Planning Engineering Weather Data, TM 5-785, July 1978.

5. Degelman, L. O., "Bin and Degree Hour Weather Data for Simplified Energy Calculation," ASHRAE RP-385, 1986.

6. Silver, J. D. and D. L. Burrows, "Shallow Solar Pond Performance Comparison Test Results," ASME-Solar Energy Division, ASES-Engineering Division Annual Meeting, Knoxville, Tennessee, March 1985.

APPENDIX

DEVELOPING OPERATIONAL STRATEGIES FOR THE FT. BENNING SHALLOW SOLAR POND WATER HEATING SYSTEM:

PHASE I - TEST & EVALUATION PLAN

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1.0 SCOPE

This report describes the plan for developing operational strategies that can be used to maximize the benefits from the Fort Benning Shallow Solar Pond Water Heating System.[1] It includes details of performance monitoring that will be done to support the project.

2.0 PROJECT DESCRIPTION

The shallow solar pond system at Fort Benning is a system of 80 individual ponds. Each pond consists of two Hypalon rubber bags approximately 7.5 ft wide x 200 ft long. The bags rest on foamed-glass insulation on a sand substrate. They are covered by transparent fiberglass panels attached to concrete side walls. Ponds were constructed to design specifications from the Lawrence Livermore Laboratory.[2] Total capacity of the system is approximately 500,000 gallons.[3]

The shallow solar pond system is used as a pre-heater for a large portion of the hot water used at Fort Benning. After the water is heated, it is drained into a sump and then pumped into a large storage tank. On demand, water is pumped from the tank through a pipe distribution system to the various end-uses. The major end use for this system is to provide hot water to barracks. Secondary heating is provided by steam-heated domestic water heaters at each building served to heat the water to the desired use temperature. Steam to the building water heaters is provided by a central steam plant fueled by either natural gas or #6 fuel oil.[3,4]

3.0 PROJECT PURPOSE

The purpose of this project is to determine the operating strategies or strategy which will maximize system benefits for varying outdoor temperatures and amounts of insolation. Strategies to be studied are limited to varying fill levels and exposure times.

Although the current operating scheme provides much of the potential benefits available from the system, operational changes may be able to provide substantial improvement. Since the current hot water needs from the system are well below system capacity, operating at maximum collector efficiency may no longer be the best operating strategy.

4.0 SITE ASSESSMENT

A site visit was made on July 19, 1988 by Messrs. Terry Sharp and Mike Hileman of the Oak Ridge National Laboratory and Mr. Chris Irby of the U.S. Army Engineering and Housing Support Center. Site assessment provided the following:

1. Communications with the pond control system via computer were out of service due to a recent equipment failure during a severe lightning storm.

2. A history printout of June, 27, 1988, indicated that approximately 30 ponds were in use. This amount can easily meet estimated water demands.

3. 29 of the 80 ponds in the system were cut off at the field-located slave units. Apparent reasons for cut off were pond inoperability and for maintenance.

4. The current operating strategy begins to drain ponds at 16:30 hours each day and starts refilling immediately after completing the drain cycle. Only the number of ponds needed are drained. The drain and fill cycles are normally completed within approximately 5 hours.

5. The corrugated-fiberglass glazing over the ponds has become cloudy over a significant portion of 4 ponds.

6. The glazing-support structure on many of the ponds partially collapsed in a recent ice storm. Only 16 ponds were judged to have excellent structures (no collapse). 37 were judged to have poor structures. The remaining ponds had experienced differing degrees of structural collapse.

7. Volume of a pond with a 4-inch average fill is approximately 7500 gallons. At the time of the survey, operators estimated the hot water needs from the system to be under 100,000 gallons/day. For 100,000 gallons, the required number of ponds at various fill levels is:

Fill Level (inches) :	2	3	4
No. of Ponds Required :	27	18	13

8. The original pond water temperature sensors were installed underneath individual bags. These sensors will not provide representative average water temperatures since temperature stratification in a bag can range as high as 40 to 50°F from top to bottom.[5]

9. Thermistor-type temperature sensors have been inserted into 16 bags of 16 separate ponds. Only 4 ponds with these sensors have structures in excellent condition. Due to measurement at a point, these sensors are also questionable for representing average water temperatures.

10. The existing pyranometer for solar radiation measurement was out of service and likely unrepairable.

11. The watt-hour meter on the transformer supplying power to the system was not operating.

5.0 PROPOSED TEST PLAN

5.1 Introduction

The energy that can be collected and the final temperatures achievable in a solar pond water heating system are dependent upon many factors. Dominant influences are:

* initial water temperatures and fill levels,
* available insolation and exposure times,
* glazing transmissivity, and
* heat losses to surroundings.

The test plan should allow each of these factors to be accounted for when results are analyzed. Some of these factors should be relatively constant throughout the experimentation.

<u>Testing will be limited to evaluating the performance of single ponds. Performance of the solar pond system will be projected from these results. Therefore, the overall performance of the solar pond system resulting from this work will not account for the system's electricity consumption and the thermal losses associated with the hot water storage tank and distribution systems</u> (See Statement of Work, Reference 1, Section 2.0, Part a).

Although hot water demand will not be measured, results can be provided relative to consumption since ultimately pond fill levels, exposure times, and the number of ponds used will set the maximum daily operating volume of the system.

5.2 Test Details/Procedures

Operational strategies for the solar pond system will be developed based on the monitored performance of six individual ponds. Test ponds were selected from the southern-most half of the solar pond system and from operating ponds with clear covers that had no structural collapse. Test ponds are 49, 53, 54, 62, 66, and 75.

One of three fill levels were assigned randomly to each test pond. Fill levels are 2, 3, and 4 inches providing 2 ponds at each level. The exposure times of each pond will be varied from one to three days. If winter tests show that the longer exposures are continuously detrimental, the three- and perhaps two-day winter exposures may be minimized. A typical 30-day test sequence is shown in Figure 5.1. A seventh pond, number 50, will be kept on-line as a backup in case a test pond goes out of service.

Test ponds will be drained in the appropriate evenings and will be filled during the normal fill cycle of all ponds immediately following the drain sequence. Fill levels (water volumes) of test ponds will be calibrated to the level switches which control the fill and therefore should remain relatively constant throughout the testing. Fill level corresponds to the water depth at the geometric center of the bag (100 ft from each end and 3.75 ft from each side). For the design slope of 1 in./100 ft, the depth of water at the shallow end will be 1 in. less than the fill level.

Pond	Fill Level (in.)	Day 1	2 3	4 5 6	7	8 9	10 11 12	13	14 15	16 17 18	19	20 21	22 23 24	25	26 27	28 29 30	Points for each exposure, 1	2	3
53	2.0	-	----	-------	-	----	-------	-	----	-------	-	----	-------	-	----	-------	5	5	5
66	2.0	-	----	-------	-	----	-------	-	----	-------	-	----	-------	-	----	-------	5	5	5
54	3.0	-	----	-------	-	----	-------	-	----	-------	-	----	-------	-	----	-------	5	5	5
62	3.0	-	----	-------	-	----	-------	-	----	-------	-	----	-------	-	----	-------	5	5	5
49	4.0	-	----	-------	-	----	-------	-	----	-------	-	----	-------	-	----	-------	5	5	5
75	4.0	-	----	-------	-	----	-------	-	----	-------	-	----	-------	-	----	-------	5	5	5
50	3.0	-	----	-------	-	----	-------	-	----	-------	-	----	-------	-	----	-------	5	5	5

Figure 5.1. Typical 30 day test sequence for a pond. Dashed lines signify 1, 2, and 3 day exposures.

Data will be recorded by data loggers automatically. During normal testing, operator interruption should not be required except perhaps in the winter where the test sequences may have to be modified due to low outdoor temperatures.

5.3 Data Collection

Two small, portable data acquisition systems (DAS) will be used for this testing (refer to Appendix A for specifications). The primary purpose of using a DAS separate from the solar pond system central control unit (CCU) is to minimize test dependency on the CCU and Fort Benning personnel. Having the DAS in the field will also be beneficial when verifying proper system operations. Thermocouple temperature probes will be used due to their low cost, long-term reliability, and ease of interfacing with the portable DAS.

5.4 Data Requirements

Data requirements are as specified in Table 5.1. Insolation and outdoor air temperatures will be recorded by the DAS as hourly averages. Hourly averages will be combined during data analysis to generate average values for each exposure period. Water volumes will be obtained from level switch calibrations done prior to testing.

Fill and drain average water temperatures will be determined for each test pond. Average pond water temperatures will be averages of 10 or more instantaneous water temperatures recorded at time intervals spread equally over the fill and drain period of a pond. The temperature sensors used to measure instantaneous water temperatures will be installed in each test pond fill/drain line. The wiring configuration

Table 5.1 Data to be collected

Variable	Description - Measured	Units
A	Exposed collector area of a pond	ft^2
I	Solar insolation	Btu/ft^2
T	Instantaneous pond water temperature	^oF
T_o	Outdoor air temperature	^oF
V	Water volume of a pond	gallons
	<u>Description - Calculated</u>	
E	Efficiency of a pond	
I_{avg}	Average solar insolation for an exposure period	Btu/ft^2
m	Mass of water in a pond	lbm
Q	Energy collected by a pond	Btu
T_{drain}	Average drain water temperature	^oF
T_{fill}	Average fill water temperature	^oF

of the DAS will be such that the DAS will sense the opening and closing of each test pond fill/drain valve (refer to Appendix A for installation diagrams). Thus, the DAS will know when to begin and stop the recording of pond water temperature averages during the drain and fill cycles. Averaged time-series temperature data should provide a reliable measurement of pond average water temperature.

5.5 Calculations

The mass of water in a pond can be calculated based on a water density of 8.29 lbm/gal (at 100°F) and the measured water volume in gallons, V, as:

$$m\ (lbm) = 8.29 \times V$$

The energy collected by each pond, Q, can be calculated using the specific heat of water, C_p = 1 Btu/lbm-°F, and the average fill and drain water temperatures as:

$$Q\ (Btu) = m \times C_p \times (T_{drain} - T_{fill}),\ \text{or}$$

$$Q\ (Btu) = 8.29 \times V \times (T_{drain} - T_{fill}).$$

The different operating strategies being tested will yield different final water temperatures and thus, different energy gains. If the hot water demand is satisfied by the pond system, higher final temperatures will reduce the consumption of non-renewable fuels used to provide secondary heat. Therefore, final water temperatures as related to available solar radiation and hot water demand levels will be an important indicator of the energy saving potential of the pond system.

Pond efficiencies can be calculated by relating the energy collected by a pond, Q, to the average solar insolation, Iavg, as:

$$E = Q / (I_{avg} \times A).$$

5.6 Assumptions and Task Assignments

Assumptions made relative to the success of the project are:

1. The solar pond operator at Fort Benning can modify the control software to operate the test ponds as required by this test plan and the DAS programming.
2. The solar pond control system will operate over most of the test period without major problems affecting the test ponds.
3. Assistance can be provided by Fort Benning solar pond operating and maintenance personnel.
4. The level switches can be calibrated to pond water volumes and will provide repeatable fill levels.

Project success will be dependent on both ORNL and Fort Benning personnel. The list of tasks needed to complete this project and the responsible organizations are summarized in Table 5.2.

Table 5.2 Project Task List

Completion Date	Task	Responsible Organization
Oct. 19 (1988)	Determine test pond operating plan. Assemble test hardware.	ORNL
Oct. 26	Site visit: Verify test pond operation. Verify repeatability of level sensors. Begin hardware installation. Provide test pond operating plan to Ft. Benning.	ORNL/ Fort Benning
Nov. 16	Write CCU program coding to sequence the test ponds per the test plan.	EHSC/ORNL/ Fort Benning
Nov. 22	Change and debug CCU programming for the test ponds.	EHSC/ORNL/
Nov. 22	Write DAS program. Calibrate temperature and radiation sensors.	ORNL
Nov. 29	Drill and tap pipe for temperature sensors.	Fort Benning
Nov. 29	Site visit: Verify test pond operation. Complete hardware installation. Set and calibrate level sensors.	ORNL/ Fort Benning
Dec. 7 - 16	Site visit: Bring system on-line with verified operations.	ORNL
Jan. 1 (1989)	BEGIN TESTING.	

Tasks During The Test Period: JAN. 1 - SEPT. 30, 1989

Fort Benning

Weekly: Visit site. Replace data cassette. Mail original data cassette and daily pond temperature history pages to ORNL.

Jan.- Sept. Alert ORNL whenever problems arise. Visually monitor ponds for freezing. Provide verbal observations regarding pond performance. Per ORNL request, modify operating program to change winter pond test plan if outdoor temperatures mandate a change.

Table 5.2 Project Task List (continued)

Fort Benning (continued)	
Jan.- Sept.	Maintain test ponds in good operational condition. If needed: Supply additional history pages to ORNL periodically. Connect backup test pond to DAS. Repair failed pond if repairable or with ORNL assistance, prepare another backup. Provide minor DAS troubleshooting assistance.
ORNL	
Weekly	Assemble data. Quality check data as received. Track test pond operations using test data and history pages.
Jan. - Sept.	Assist Fort Benning as needed.

6.0 RESULTS

6.1 Theoretical Results

Theoretical pond performance nomograms for the Fort Benning/Atlanta area are shown in Figures 6.1 and 6.2. Several inferences can be made from

these graphs assuming that they will be similar to the actual test results.

Winter Operation: Ambient temperatures and available solar radiation are at their lowest levels during the winter. The pond performance nomograms suggest that operation during severe winter months should be questioned. If the ponds are operated, the lowest fills are the only likely scenario to provide significant benefits. In addition, multiple day exposure is also questionable. If test results suggest a winter shutdown, pond operation may be restarted in late winter. Hot water demands will likely be highest during the winter.

Spring/Fall Operation: Interpolation between the two performance nomograms suggests that various water levels can be used and that multiple day storage may provide benefits. Both of these should be optimized to provide the best benefits for the required water demand.

Summer Operation: Ambient temperatures and available solar radiation are at their highest levels during the summer. Operating strategies can use both different fill levels and different exposure times and obtain substantial benefits from the ponds. These should be matched to

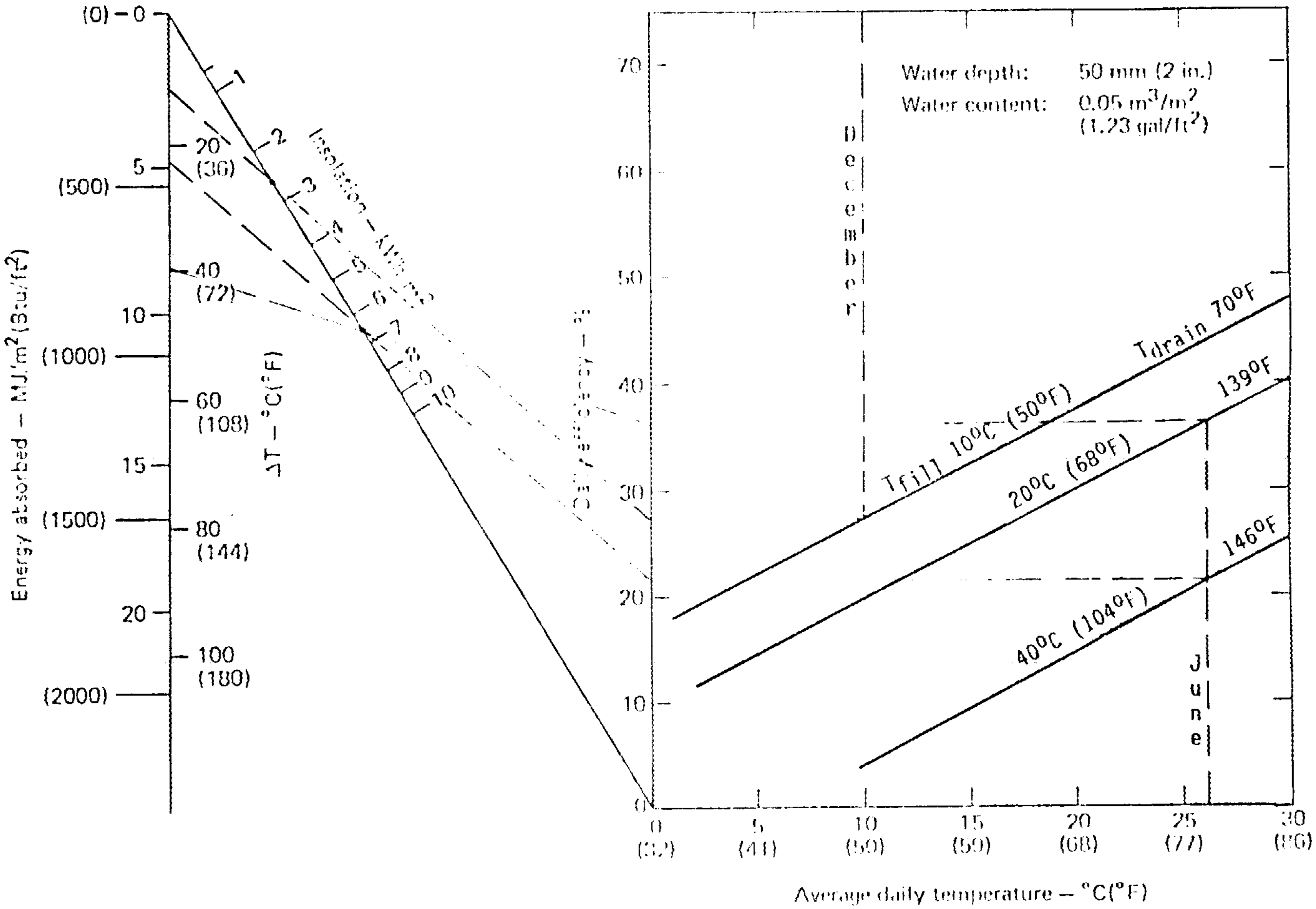


Figure 6.1. Solar Pond Performance Prediction for A 2-Inch Fill

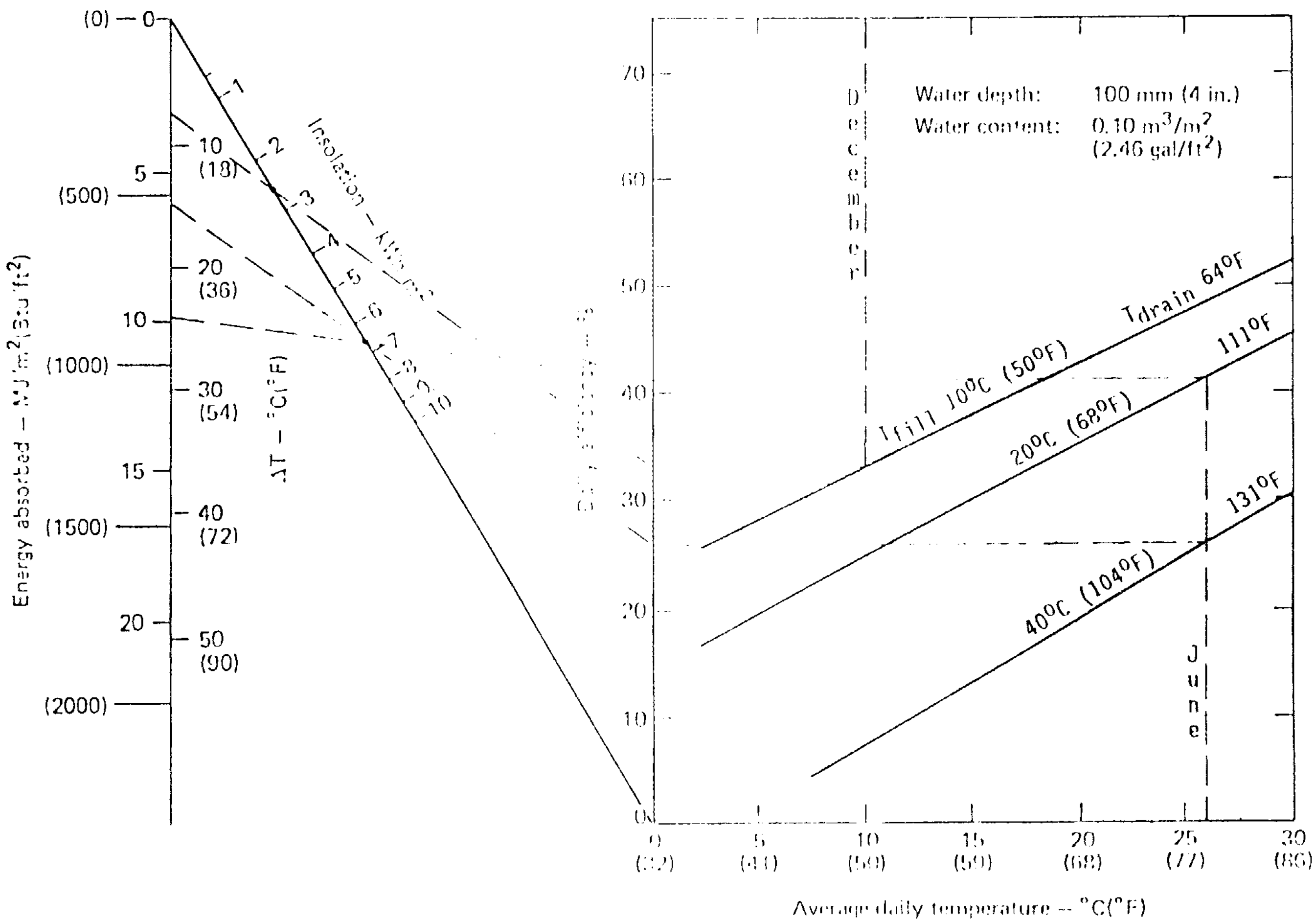


Figure 6.2. Solar Pond Performance Prediction for A 4-Inch Fill

the summer hot water demand. Although the hot water demand will likely be lowest during this period, the performance of the solar pond will be at its peak.

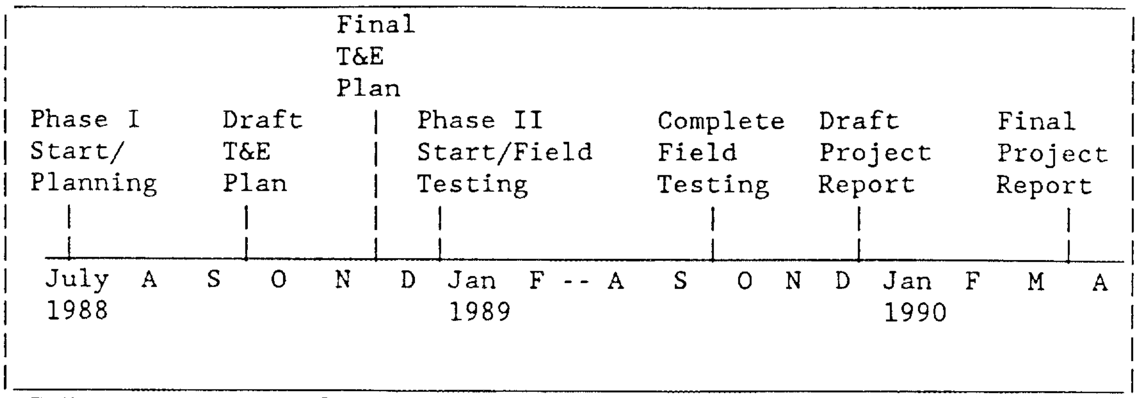
6.2 General Results

This work will relate the energy and temperature gains of the Fort Benning solar ponds to their ambient and operational conditions: outdoor temperatures, incident radiation, exposure times, and fill levels.

The work will produce algorithms that can be used to determine the operating strategy(s) that will optimize the performance of the pond system for differing conditions. Since it is uncertain how many of the ponds will be in service at any given time, results will be related to fill and hot water demand levels to accommodate such variations. The system operator should be able to use the results to adjust operation of the system such that maximum benefits can be achieved at all times.

7.0 PROJECT SCHEDULE

The project schedule is shown in Figure 7.1. Field testing will be done from January through September of 1989. The final report covering the project will be available in April 1990.



T&E - Test and Evaluation

Figure 7.1. Project Schedule

8.0 CONCLUSIONS

Although the shallow solar pond system is currently providing much of its potential benefits, changes in operational strategy may considerably improve performance. Operating strategies that will allow maximum water temperatures to be achieved should be investigated.

Performance testing will be directed at evaluating single ponds. Results will then be extrapolated to estimate the performance of the whole system of ponds. Although many ponds are not in service at this time, enough are on-line to easily satisfy current hot water demands. Existing pond water temperature sensors are located such that measurements will not be representative of average water temperatures. As a result, additional temperature sensors will need to be installed.

The glazing support structure has partially collapsed over many of the ponds. While this may not seriously affect performance in most cases, further collapse may affect performance and perhaps more importantly, result in the rupture of expensive water bags. The structure as built is not of sufficient strength to withstand loads. Although uncommon to the area, any future snow or ice will likely load the structures such that additional collapse will occur.

9.0 REFERENCES

1. "Statement of Work," attachment to letter from John J. Krajewski, Director of Facilities Engineering, U.S. Army Engineering and Housing Support Center, to W. D. Adams, Director, Research and Waste Management Division, U.S. Department of Energy, Oak Ridge Operations, May 27, 1988.

2. A. B. Casamajor and R. E. Parsons, Design Guide For Shallow Solar Ponds, Lawrence Livermore Laboratory, UCRL-52385 Rev. 1, Livermore, California, January 8, 1979.

3. L. N. McCold and F. D. Boercker, DOD: Energy Conservation Investment Program (ECIP): Phase I - Planning ECIP Project Validation Design Plan, for the Shallow Solar Pond Hot Water Heater, Project No. 348, ORNL/TM-8934/P1, March 1985.

4. L. N. McCold and D. R. Miller, DOD: Energy Conservation Investment Program (ECIP): Phase II - ECIP Project Validation Design Plan, for the Shallow Solar Pond Hot Water Heater, Project No. 348, ORNL/TM-8934/P2, July 1985.

5. Discussions with J. D. Silver, Jr., Tennessee Valley Authority, Division of Conservation and Energy Management, Chattanooga, Tennessee.

APPENDIX A

EQUIPMENT REQUIREMENTS

A.1 General Equipment Specifications

Each equipment supplier should provide documentation as applicable for:

1. Complete installation instructions. These should provide sufficient instruction such that all equipment can be installed to satisfy applicable codes, such as the National Electric Code, the National Fire Protection Association, and any additional regulations that may apply to Fort Benning.

2. Calibration procedures and specifications that allow traceability to established standards, for example, the National Bureau of Standards.

A.2 Equipment and Installation

The following equipment will be needed:

9 each	temperature sensors (for test ponds, back-up, outdoor air, & spare)
1 each	solar radiation sensor
2 each	electronic data loggers
2 each	cassette recorders for data storage
1600 feet	thermocouple sensor wiring
1000 feet	110V wiring from valve motors

An instrument cabinet to house the DAS and cassette data recorders will be installed at slave cabinet #7. The central location should reduce wiring complications. A solar radiation sensor will be needed since the one at the site is out of service. The solar radiation sensor will be installed on an unshaded, horizontal plane also located at slave cabinet #7. Wiring will be installed on grade. Small diameter pipe or tubing will be used to enclose the wiring for protection from foot and vehicular traffic.

Three channels on each data logger will be used to measure water temperatures. Three additional channels on each data logger will be used to sense opening and closing of pond valves to trigger pond water temperature measurements. One channel each will be used to measure solar radiation and outdoor air temperature.

Equipment specifications and additional installation details are provided on the device specification pages and illustrations that follow this discussion.

A.3 Temperature Sensor Installation

Temperature sensors will be installed in the CPVC drain/fill line for each test pond between the valve and bag fill/drain header. Sensors will be installed according to supplier/manufacturer specifications.

A.4 Equipment Calibrations

The data logger system should be supplied with calibration at purchase. Temperature probes will be calibrated to traceable standards prior to installation. Periodic checks of temperature sensors will be made to insure long-term repeatability. The solar radiation sensor will be calibrated by the manufacturer and certified to a traceable standard.

Pond fill level switches will be calibrated to water volumes by draining individual ponds to the sump and measuring changes in water depth. The repeatability of fill levels set by these switches will be verified before testing to insure viability of this measurement method. Periodic field checks will be made as testing proceeds to check long-term repeatability of temperature sensors and level switches.

A.5 Procurement Specifications and Installation Details

Device: Data logger for use in acquiring, processing, and storing temperature and solar radiation data. The data logger should meet the following criteria:

Input Signal: Can accept and process voltage inputs from standard thermocouple probes and a pyronometer without added external conditioning.

Programmable Functions:
- Arithmetic operations on inputs
- Instantaneous sampling
- Averaging
- Totalizing
- Separate scan and output intervals
- Date and time

Data Storage Medium: Radio Shack CCR-82 Computer Cassette Recorder (RC35)

Power Source: 12V DC supplied by internal, replacable batteries with a lifetime of four months or more at 10 second and longer execution intervals.

Data Recovery Mode: Equipment should be provided to allow data recovery from cassette tape to an IBM personal computer.

Suggested Vendors: Campbell Scientific, Inc.
Logan, Utah 84321

Radio Shack

Item	Estimated Cost (ea.)	Qty.
21X Micrologger	$1900.00	2
RC35 Data Recorder	105.00	2
PC201 Tape Read System	400.00	1
Cassette Tapes	3.50	10

Device: Solar radiation sensor meeting the following criteria:

Sensitivity: 11 microvolts/watt-meter^{-2}

Impedence: 350 ohms approx.

Temperature Dependence: +/- 1.5% constancy from -20 to +40^{o}C

Linearity: +/- 1% from 0 to 1400 watts-meter^{-2}

Cosine Response: +/- 2% from normalization 0-70^{o} zenith angle
+/- 5% 70-80^{o} zenith angle

Suggested Vendor: The Eppley Laboratory, Inc.
Newport, Rhode Island 02840

Item	Estimated Cost	Qty.
Black and White Pyranometer, Model 8-48	$1300.00*	1

* Includes cost of factory calibration.

Device: NEMA Type 1 panel enclosure meeting the following specifications:

Size: Minimum - 20" high x 20" wide x 8 deep

Construction: 14-guage steel finished with gray primer over phosphatized surface.

Accessories: Cylinder lock with 2 keys.

Suggested Vendor: Hoffman Engineering Company
Anoka, MN

Item	Estimated Cost	Qty.
Panel box, NEMA Type 1	$175.00	1

Device: Thermocouple sensor meeting the following criteria:

Sensitivity: Type T

Temperature Range: -270 to 400°C

Linearity: Seebeck Coefficient of 38 mV/°C at 0°C

Feature: Assembly has 1/2" NPT threads for insertion

Suggested Vendor: Omega

Item	Estimated Cost	Qty.
Thermocouple, Model NB2-CPIN-14G-8	$60.00 ea.	9

Table A.1 Data Acquistion System Wiring Summary

Channel Inputs to the Campbell Scientific (CS) Data Loggers							
Test Pond	Fill Level	Signal Type	Slave #	Slave Output Chan. #	Relay #	CS #	CS Chan. #
1	2	Temperature, T1				1	2
(53)		Trigger Volt, V1	7	5	1	1	5
2	3	Temperature, T2				1	3
(54)		Trigger Volt, V2	7	6	2	1	6
3	4	Temperature, T3				1	4
(49)		Trigger Volt, V3	7	1	4	1	7
4	2	Temperature, T4				2	2
(66)		Trigger Volt, V4	9	2	4	2	5
5	3	Temperature, T5				2	3
(62)		Trigger Volt, V5	8	6	5	2	6
6	4	Temperature, T6				2	4
(75)		Trigger Volt, V6	10	3	6	2	7
7	4	Temperature, T7					
(50) Backup		Trigger Volt, V7	7	2	7		
Parameter:							
Outside Air Temperature, To						1,2	1
Insolation, I						1,2	8

Condensed Layout of Data Loggers

	CS-1								CS-2							
Channel	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Signal	To	T1	T2	T3	V1	V2	V3	I	To	T4	T5	T6	V4	V5	V6	I

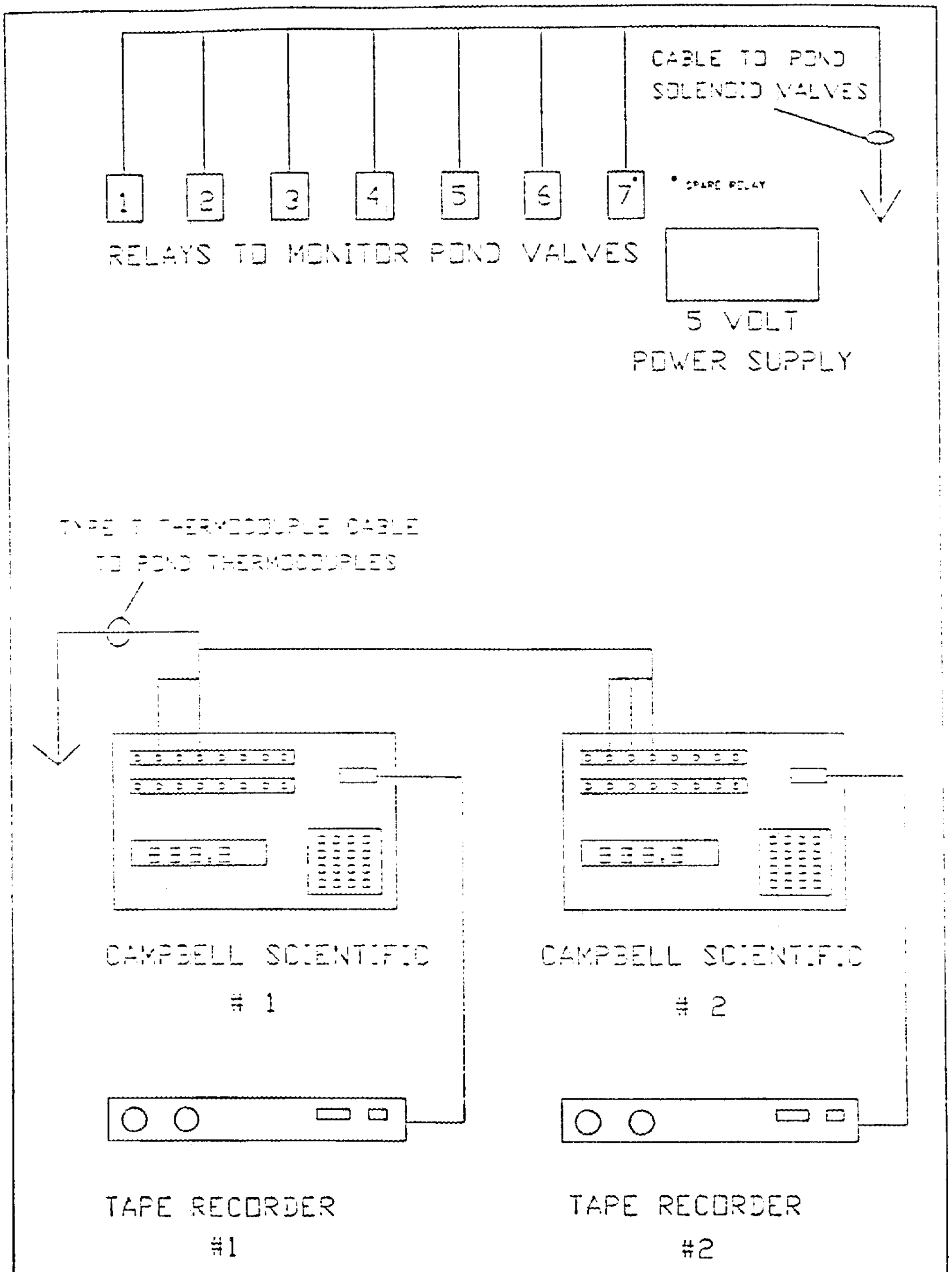


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Fig A1. ORNL DATA LOGGER CABINET LAYOUT	Subject: FORT BENNING SHALLOW SOLAR POND PROJECT	

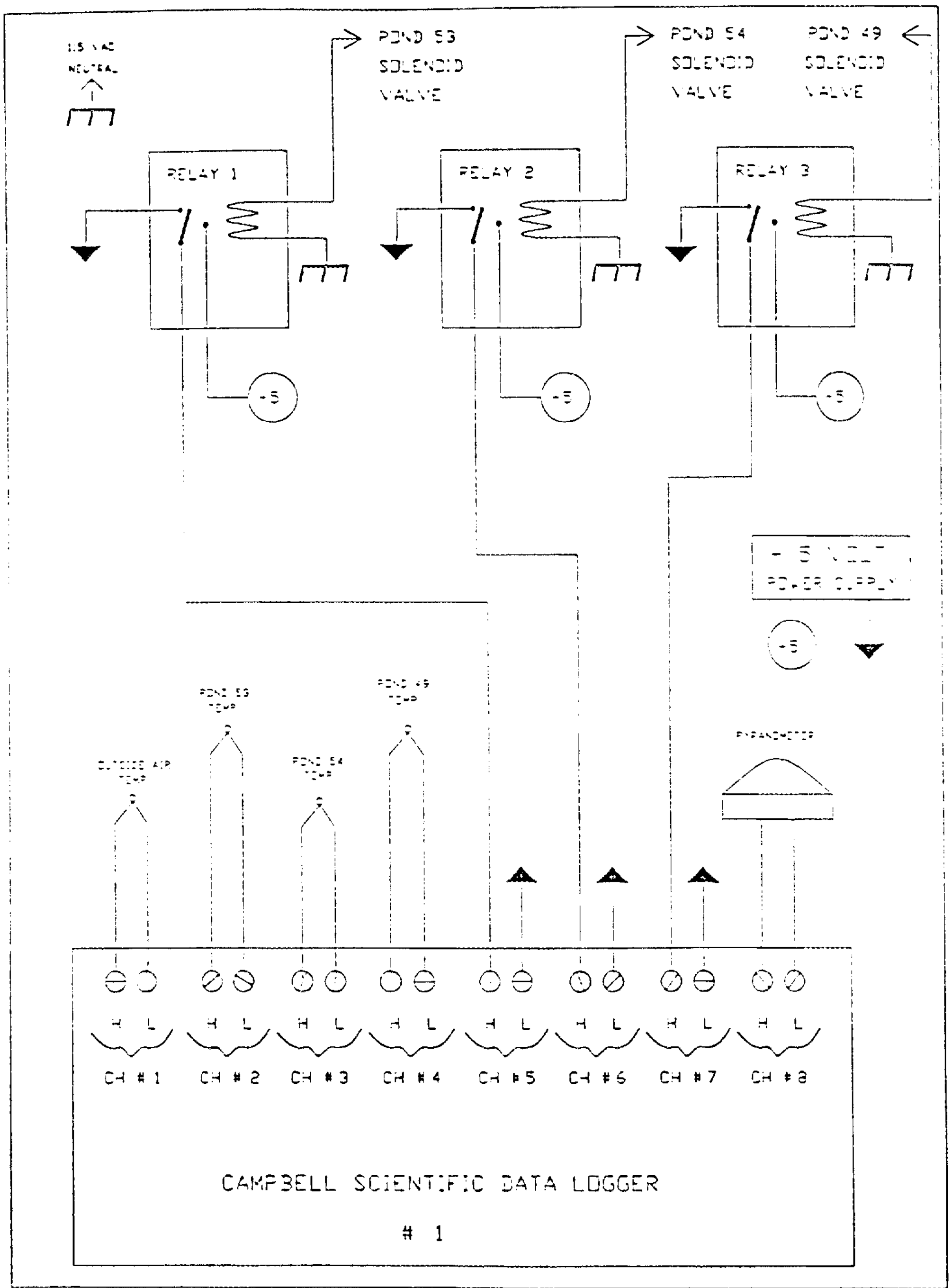

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Fig A2. ORNL DATA LOGGER #1 WIRING DIAGRAM

Subject: FORT BENNING SHALLOW SOLAR POND PROJECT

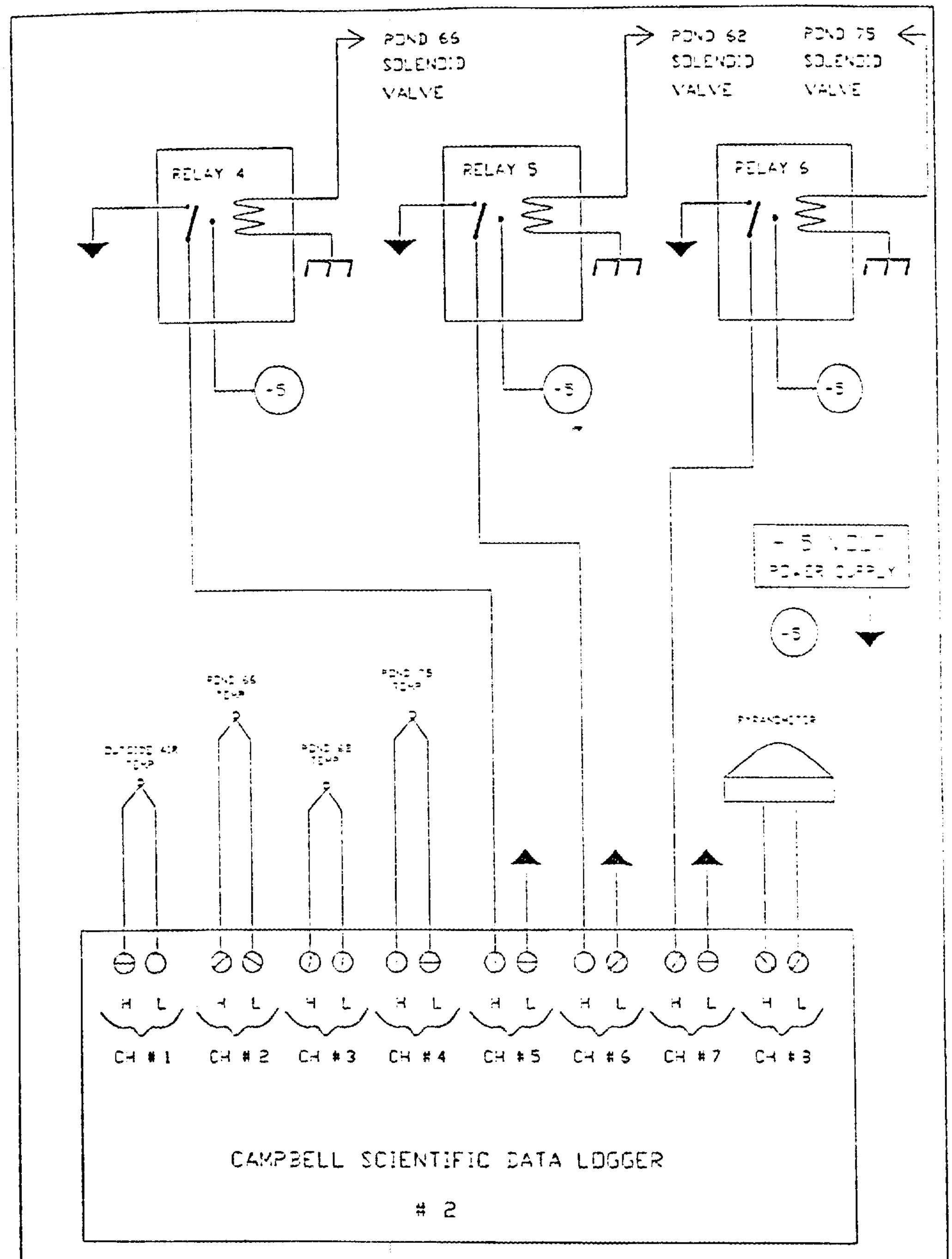

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Fig A3. ORNL DATA LOGGER #2 WIRING DIAGRAM	Subject: FORT BENNING SHALLOW SOLAR POND PROJECT	

INFORMAL DWG.

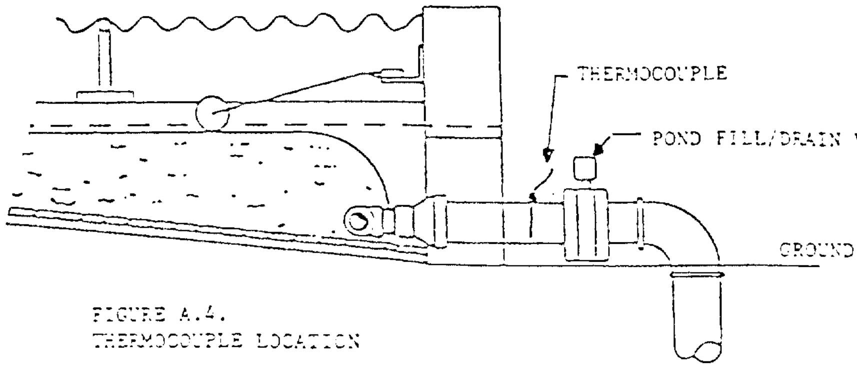

FIGURE A.4.
THERMOCOUPLE LOCATION

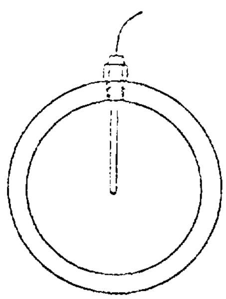

FIGURE A.5
THERMOCOUPLE INSTALLATION SHOWN IN PIPE CROSS SECTION

OAK RIDGE NATIONAL LABORATORY
INSTRUMENTATION AND CONTROLS DIVISION

THERMOCOUPLE LOCATION AND INSTALLATION FOR
FORT BENNING SHALLOW SOLAR POND PROJECT

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DESIGN	DRAWN	DATE	APPROVED	DWG. NO.
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