THE MIAMISBURG SALT-GRADIENT SOLAR POND: MID-1980 STATUS REPORT

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ABSTRACT

The largest salt-gradient solar pond in the U.S. was constructed by the City of Miamisburg, Ohio to provide heat for an outdoor swimming pool in the summer and an adjacent recreational building from October-December. The pond which occupies an area of 2020 m^2 was installed for \$35/m^2 and is conservatively estimated to provide 1012 GJ/year (960 million BTU) at a cost of \$6.80/GJ (\$7.20/MBTU) During July-September 1979, 143.5 GJ (136 million BTU) of heat was utilized. Several unpredicted operational concerns have been noted related to corrosion of the metallic heat exchanger and the failure of selected seams in the plastic liner. Based upon two years of experience, suggestions are made to prevent or minimize these difficulties.

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INTRODUCTION

The City of Miamisburg, Ohio initiated construction of the largest, salt-gradient solar pond in the U.S. during 1977 as part of its Community Park Development Project. The Miamisburg solar pond was not an experimental pond but was designed to supply thermal energy to an outdoor swimming pool in the summer and to a recreational building during the winter. Construction on the Miamisburg pond was completed(1,2,3) in August, 1978, and the first useful heat was removed(4) during July-September, 1979. The thermal performance of the pond will be reviewed briefly together with some unpredicted operational experiences.

DESIGN AND CONSTRUCTION

The Miamisburg solar pond is 54.5 m x 36.4 m (180 ft. x 120 ft) at the top with sides tapered at an angle of 45^{o} (a 1:1 slope) to a depth of approximately 3.0 m (10 ft). The site selected for the solar pond was a settling pond area adjacent to an abandoned power house. This area was drained, and mixed fill had to be added in many places. Then, the excavation work for the solar pond was initiated and completed by October 1977. A 10-15 cm (4-6 in.) layer of sand was spread on top of this rough base. Further site work was interrupted by the severe winter of 1978. After the winter snow melted, the excavation drained rapidly, confirming that the ground water level was well below the pond.

The heavy-duty plastic liner was installed during May 1978. The liner, 0.7 mm thick, made of a chemically resistant polymer-coated polyester fabric has been tested by the manufacturer in outdoor exposure tests to 117°C, the highest temperature of any pond liner available. It should out-perform the 8-10 yr lifetime of vinyl-coated fabrics. The fabric was supplied by the manufacturer in 1.42-m widths and of sufficient lengths to extend across the width of the solar pond. A fabricator assembled these stripes into four large sections by making heat-weld seals along the edges of the stripes with 3.75 cm overlaps. These four sections were installed in the pond excavation and three heat weld seams were made on-site by an installation contractor. A 3% excess of liner material was laid in the excavation in the form of large wrinkles in the liner especially at the corners. This excess material was designed to allow for possible shifting of the supporting ground.

The pond was partially filled with water, ∿ 1.5 m deep, and truck loads of salt, approximately 25 tonnes each, were dumped directly into the pond. Analyses of random samples of the salt showed it to contain 98.6 $\pm$ 0.4% NaCl.

When all of the salt was in the pond (nearly 1100 tonnes), sufficient water was added to bring the depth to 2.1 m. The average salt concentration of the pond water was ∿ 14%, but large piles of undissolved salt were evident. A large portable water pump, with a capacity of 9×10^{-2} m^3/s, was used to circulate the pond water and dissolve the remaining salt. After nearly four weeks, the salt concentration approached 18.5% at all locations and depths in the pond.

During the dissolution of the salt the pH increased from 7.2 to 7.6. Because copper sulfate was to be used for algae control, the pond water was acidified to a pH of $\sim$ 6.1 by the addition of 440 liters of concentrated hydrochloric acid. Sufficient copper sulfate was added to achieve a copper ion concentration of 2 ppm.

The mixing of the acid, copper sulfate, and water brought the depth of the pond to 2.3 m. A new technique for the formation of the salt gradient in a large pond was employed. In this procedure, a circular water distributor (1.2 m diameter) was placed 460 mm below the surface of the salt water. High pressure water was pumped through a 3.2 mm slit at the edge of the distributor at the rate of 7.4×10^{-3} m^3/s. The velocity of this water, 0.6 m/s (2 ft/sec), was sufficient to inject a horizontal layer of fresh water across the width of the pond at the same depth as the distributor. Successive layers of fresh water were added in this fashion to give the necessary salt-gradient, approximately 1 m thick. The top 150 mm of the pond was covered with fresh water.

The heat exchanger was placed in the north end of the pond for heat removal. It consisted of two tiers of pipe mounted at the 1.5 and 1.8 m levels above the bottom of the solar pond. Each tier was approximately 12.12 x 6.06 m and has eight circuits connecting to a central supply and return header. A typical circuit consists of 16 lengths of 25.4 mm diameter (type M copper) x 6.06 m long tubes connected with U-bends. The total heat exchanger area is approximately 138 m^2 with internal water flow rates up to 6.7 liters/s. The supports for the heat exchanger, fabricated from 51 mm diameter copper tubing, rest on the bottom of the pond.

The construction costs for the pond, Table 1, indicate that the liner and the salt represent the largest capital investment, although no expense has been included for land use.

INSTRUMENTATION

During the construction of the pond, appropriate instrumentation was installed to monitor the performance of the pond. For this purpose, temperature sensors were placed at various depths and locations to measure the heat stored in the pond and the ground beneath the pond. Instrumentation was also provided to measure meterological information, the incident solar radiation and solar energy transmitted as a function of depth in the pond. An automated data collection system records the data on a pre-arranged schedule and stores the information for later digital computerized retrieval.

ROUTINE MAINTENANCE

In order to obtain the maximum solar radiation absorbed in the storage layer, the clarity of the water is of vital importance.[5] Algae growth in the surface convective layer and scattered debris floating on the surface absorb the solar radiation and must be removed. Dissolved copper sulfate has been useful to prevent algae growth; however, the water must be kept in the pH range of 5-6 in order for the copper to remain in solution. Several times during the year, the acidity of the water has to be readjusted by the addition of concentrated hydrochloric acid, requiring approximately 360 liters (90 gal) per year. This procedure, together with frequent skimming of debris from the surface, has maintained good water clarity.

The loss of salt is another consideration in pond maintenance. Small amounts of salt, approximately 2% per year, diffuse continually upward. This salt is removed through the overflow pipe whenever it rains or the surface is washed with fresh water. Disposal of this dilute salty water must be considered based upon the local environment.

NON-ROUTINE OPERATIONAL RESULTS

Large salt losses can occur, of course, if any leak occurs in the pond containment system. Periodic measurements of the salt inventory of the pond has proven advantageous to determine possible salt losses. For this purpose, a density profile of the pond is experimentally determined, and the salt content of each 15 cm layer of the pond is calculated. After one such inventory in August, 1978, an abnormally large loss of salt was discovered. A leak in the liner was suspected and although several techniques were tried to locate it none were successful. The water was too hot for a diver to perform a visual inspection without a water-cooled suit, which was not available. While waiting for the pond to cool, a large amount of concentrated salt solution leaked from the pond. When the pond cooled sufficiently, a scuba diver inspected the liner and determined that a 25 cm long section of a seam had separated. This seam was along one side-wall and in tension at right-angle to the seam. This seam was repaired by the scuba diver under 2.4 m (8 ft) of water, without draining the pond. Subsequently, the liner has been inspected by two scuba divers who located and repaired another seam leakage and determined that the first repair was leak-tight.

Additionally, due to the corrosive nature of the hot, concentrated brine solutions, the integrity of the heat exchanger system must be determined periodically. Our experience indicates that the copper tubing exhibits little attack by the brine solution; however, the original solder joints, composed of 95% tin-5% antimony were severely corroded after only ten months. The entire structure was reconstructed, with the use of a 56% silver brazing alloy, which appears to be satisfactory. Except for the heat exchanger, only plastic parts, such as PVC pipe, etc., are in contact with the salt solution.

THERMAL PERFORMANCE

Numerous observations of the pond's performance have been made from the installed instruments. A plot of one set of data, Fig. 1, indicates the seasonal variation of the storage layer temperature.

The pond reached operational temperatures in June 1979. The first heat extraction from the solar pond occurred during the summer months of 1979, as shown in Table 2. With one-half of the heater exchanger in use, the average heat extraction rate from the pond was 23.06 kW, or 340 W/m^2 of heat exchanger surface. On a particular day of high demand in July, the extraction rate approached 3600 W/m^2 by the heat exchanger for a temperature difference of 12^oC between the intake and return water.

The thermal performance of the pond has been evaluated for a one-dimensional model based on a monthly cycle.[6] The net difference between the monthly energy accumulated in the pond, which occurs by solar radiation being absorbed in the storage water, and the amount of thermal energy removed as useful heat or lost by thermal diffusion to the environment results in a change in enthalpy of the storage layer.

The principal loss mechanism is thermal diffusion upward through the gradient zone caused by the air temperature being lower than the pond temperature. A minor heat-loss path is by thermal diffusion downward into the ground below the pond. Thermal losses do occur at the edges of the pond; however, such losses should be of minor consideration in such a large pond.

In order to experimentally evaluate the solar radiation absorbed in the solar pond ,the optical transmission of the pond water must be determined; however, such measurements proved to be difficult. A water-tight commercial pyranometer was lowered slowly into the pond and constantly compared with a similar instrument which remained above the surface so that variations in the cloud cover were not recorded. In such a pyranometer, the temperature difference is measured, by the use of thermopiles, between an optically absorbing suface exposured to the sunlight and a reflecting surface. Commercial instruments of this type respond satisfactorily to temperature changes by the use of a temperature compensating circuit after the instruments have reached a thermally steady-state condition with respect to the ambient temperature. For a pyranometer which is descending into the solar pond, however, the ambient temperature is constantly changing and a thermally steady-state with the surrounding water may not be attained; consequently, errors may be introduced into the pyranometer readings. For this reason, an experimental pyranometer(7) was developed with low thermal capacity which responded quickly to the changing ambient temperature.

The response of this experimental pyranometer is compared with the commercial instrument, Fig. 2, and the calculated value for "clean" salt water.(8) Both of the experimental measurements indicated lower transmission into the pond than that calculated for water; however, the two measurements differ as to the depth at which this departure occurs. Lower transmission in the pond water is to be expected because of insoluble particles being blown into the open pond and the dissolution of dyes such as the intentionally added copper sulfate and the leaching of pigments from tree leaves, for instance.

The evaluations of the heat loss terms necessitated the determination of the temperature differentials in the water near the top of the storage layer zone, and in the ground immediately below the pond. Examination of the temperature differential in the water revealed that this term over a period of a month approached the value $(T_p - T_a)/\ell$, where T_a and T_p are temperatures of the air and pond, respectively, and ℓ = the thickness of the gradient zone. This assumption overestimates the heat loss[9] during periods of high insolation, but appears to be satisfactory for our location. The term for the heat loss to the ground was evaluated between two temperature measurements made at 0 and 0.5 m below the pond.

These relationships for solar energy heating of the pond together with the assumed relationship for thermal losses were tested by a comparison of the observed temperature with predicted temperatures of the pond at the end of each month for the period January-December 1979, Table 2, based upon measured values of solar radiation, air, ground, and pond temperatures for the period. The low value of 20-23% solar radiation transmission into the storage layer was used in this calculation, based upon the experimental pyranometer data. The calculated values for the resulting temperatures were in reasonable agreement with the observed values ($\pm$ 2.4°C) except for the month of April, when the calculated value was 4.5°C too high. During this month the frozen ground thawed and heavy rains occurred. A large amount of heat was probably conducted from the pond by this water seeping into the ground and flowing along the side-wall of the pond.

Based upon the reasonable agreement shown between calculated and observed values, Table 2, a predicted utilization of the pond was made, Table 3, for an assumed steady-state condition and average values of solar insolation.

The optical transmission of the pond was assumed to follow the value for transmission into clean salt water because neither of the pyranometer data, Fig. 2, have been verified. Also, the heat loss into the ground was calculated based upon the ambient ground temperature; however, the ground under the pond will attain a higher average temperature so that this heat loss term will not be as large as calculated. The heat requirements for each month were used, except that no heat was withdrawn when the pond temperature was below 30°C.

These results predict that heat extraction during the summer months can be 844 GJ (800 million BTU). In addition to heating the swimming pool in the summer months, heat extraction of up to 169 GJ (160 million BTU) from the solar pond can be used to heat the adjacent bathhouse from October through December, without the use of a heatpump. The total heat use predicted for the solar pond indicates that approximately 15% of the annual incident solar radiation is utilized.

Based upon the local solar insolation and ambient air and ground temperatures, the efficiency of the pond is predicted[(8)] to be nearly 20%, which would produce 1372 GJ (1300 million BTU) of useful heat. This prediction assumes ideal optical transmission of the water, no ice formation during the winter, the formation of optimum salt and temperature gradients and no edge losses. The pond's performance may not achieve these ideal conditions, but it could be improved, if the load were matched better. For instance, the pond could be used to pre-heat domestic hot water during certain months of the year.

COST EVALUATION

As previously noted, Table I, the entire pond system was installed for approximately $70,000 and has a projected lifetime of greater than 10 years. This lifetime is probably limited by the usefulness of the liner, although it is predicted that a new liner can be installed without draining the pond. For cost evaluation purposes, the installation cost is amoritized at a straight 10% per year. No cost is assigned for routine and non-routine maintenance which is currently being evaluated.(5) The predicted heat extraction from the pond is in the range of 1012-1372 GJ/year. The cost of this heat is, therefore, in the range of $5.10/GJ ($5.20/million BTU) to $6.80/GJ ($7.20/million BTU), which is already competitive with heating by fuel oil. In addition, the pond will conserve, annually, 290 barrels of fuel oil or 1.6 million ft^3 of natural gas.

DISCUSSION

Although several unforseen operational difficulties have arisen with this pond, with proper preventive measures their occurrence can be reduced or their results mitigated, as discussed below. These difficulties are attributable to the fact that the containment of hot water is unfamiliar technology for the fabricators and contractors of industrial ponds.

The preparation of a firm foundation for the pond is essential. The use of rough fill followed by immediate excavation without compacting should be avoided. Also, the slope of the walls should be increased from 1:1 to preferably 3:1. Following both of these suggestions, one should be able to prevent the sagging and shifting of the side-walls and bottom which have occurred in this pond. This ground movement has resulted in high stresses being placed on the liner.

The use of a thick sand layer under the liner may not be advisable. During installation of the liner, the sand was disturbed, especially along the side-walls, and formed depressions under the liner. These depressions have caused additional stresses on the liner. If the sand is not used, then the sharp rocks must be removed to prevent punctures to the liner.

The 3% excess liner material which was initially installed to allow for shifting of the ground is not sufficient. It is recommended, therefore, that perhaps twice as much excess material be installed.

A Quality Assurance Program with in-plant inspections is needed at each step during the fabrication of the plastic liner. This is especially important if a sequence of fabricators prepare the liner. Also, an inspection of all seams must be made after the liner installation is completed.

A method for determining possible leakage from the pond should be developed. A simple system may be to install drainage tile under the pond which can be monitored for salt water content.

Because of the highly corrosive character of the hot, concentrated brine solution, the longer-term integrity of metal heat exchanger is unknown and it may require periodic repair. We recommend, therefore, that the heat exchanger be located outside of the pond, where the repairs can be made more easily. The hot water from the pond would be delivered to the heat exchanger with suitable piping. We have initiated a corrosion testing study in order to determine the most cost effective materials for use in the fabrication of heat exchangers for use with these saline solutions.

The solar pond system at Miamisburg has been up-graded following many of these suggestions. The pond is being returned to its full operational status during the summer of 1980. This requires the addition of salt to replace that which was lost by leakage during 1979, and a reformation of the gradient zone.

Based upon the heat removal results during 1979 and the cost evaluation study, the experience at Miamisburg indicates that a salt-gradient solar pond can be a cost effective source of low temperature heat in most areas of the U.S.

ACKNOWLEDGEMENTS

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Table 1

CONSTRUCTION COSTS
(1977 Dollars)

Solar Pond Cost		
Salt, 1,100 tons @ $17.60/ton	=	$19,400
Liner plus installation	=	22,000
Heat exchanger	=	6,800
Miscellaneous supplies	=	11,800
Labor (excavation, etc.)	=	10,000
Total Installation	=	$70,000

Table 2. Comparison of Predicted and Observed Temperatures of the Solar Pond for 1979

Month	Monthly Insolation Absorbed (GJ)	Monthly Losses (GJ)		Heat Used (GJ)	Temperature of Storage Water (°C) End of Month[a]	
		top	bottom		Calculated	Observed
Jan.	26.6	86.9	7.2	----	30.8	31.1
Feb.	47.3	59.3	3.7	----	29.1	28.3
Mar.	127.6	38.6	23.8	----	34.5	32.8
Apr.	157.1	44.3	19.3	----	42.8	38.3
May	240.9	52.4	43.8	----	54.2	53.3
June	229.6	63.6	63.3	25.3	65.2	64.4
July	242.1	95.3	62.2	69.6	65.6	67.8
Aug.	206.1	140.2	70.0	45.8	56.3	57.8
Sept.	173.4	111.9	56.4	3.2	55.7	53.3
Oct.	107.2	142.3	20.2	----	42.2	41.7
Nov.	50.2	89.6	18.8	----	36.2	37.8
Dec.	50.6	72.4	7.8	----	34.4	35.6

[a] The temperature at the start of each month was taken to be the ending temperature observed from the previous month.

Table 3 - Predicted Heat Extraction from the Solar Pond Based Upon Average Solar Insolation

Month	Monthly Insolation Absorbed (GJ)	Monthly Losses (GJ)		Heat Used (GJ)	Temperature of Storage Water (^oC) Calculated
		top	bottom		
Jan.	27.7	80.2	7.2	----	24.7
Feb.	38.5	51.7	3.7	----	23.4
Mar.	174.6	38.1	22.9	----	30.8
Apr.	193.1	52.3	21.9	----	38.6
May	353.2	63.5	26.5	316.5	31.7
June	386.8	30.1	16.2	316.5	30.5
July	385.6	20.9	14.0	----	54.7
Aug.	351.4	100.8	30.4	116.1	60.2
Sept.	256.3	117.4	30.8	95.0	59.3
Oct.	153.3	153.6	48.4	10.6	54.0
Nov.	69.3	135.3	23.6	89.7	39.6
Dec.	65.8	99.0	23.4	68.6	29.3

TITLES FOR FIGURES

1. Annual variation of the temperature of the Pond Storage Water

2. Solar radiation transmission into the pond as measured by two pyranometers and compared to the calculated transmission for water (smooth curve).

TEMPERATURE OF POND STORAGE WATER

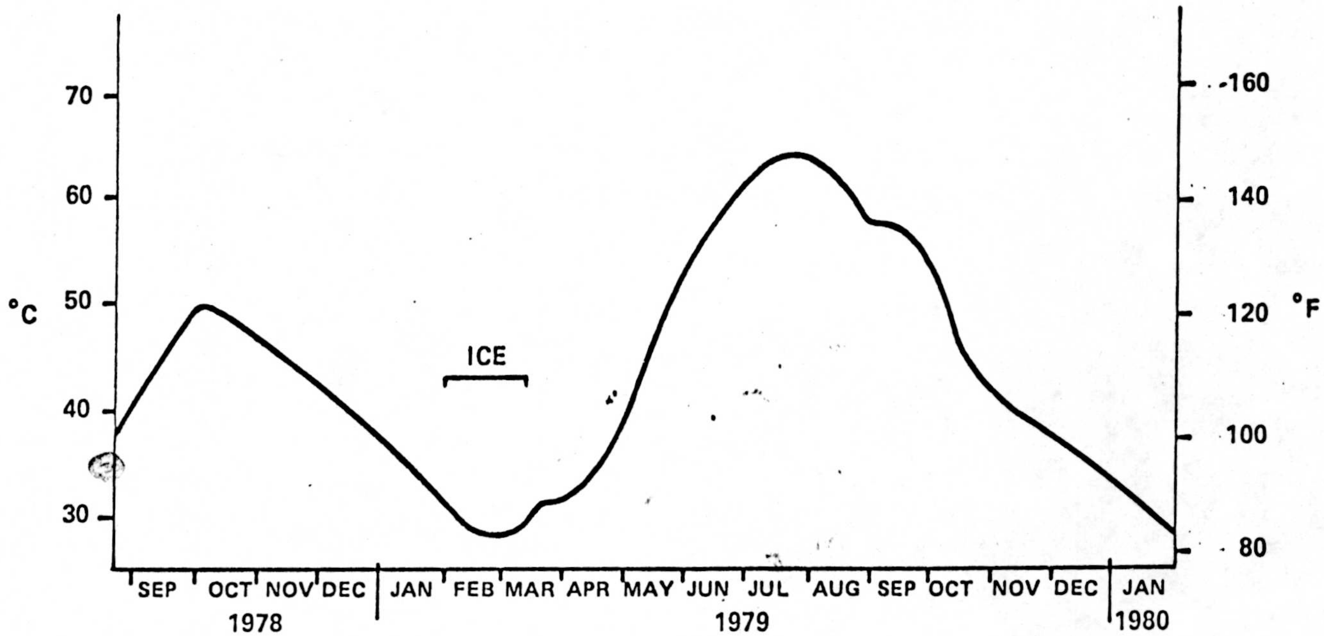
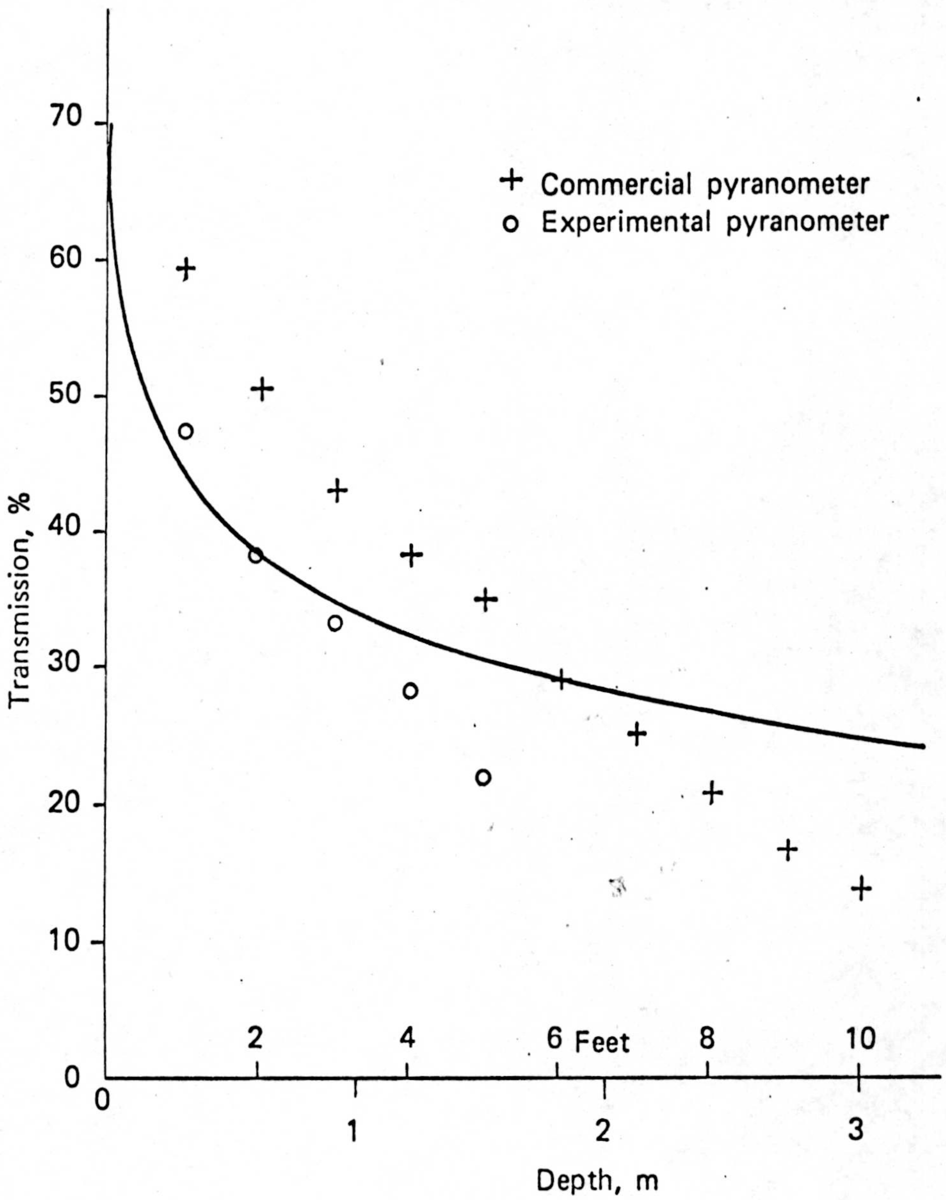


Fig 1



Transmission, %
70
60
50
40
30
20
10
0
Commercial pyranometer
Experimental pyranometer
2
4
6 Feet
8
10
0
1
2
3
Depth, m

Fig 2