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# THERMAL PERFORMANCE OF A PHOTOGRAPHIC LABORATORY PROCESS SOLAR HOT WATER SYSTEM

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Space Administration

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# PHOTOGRAPHIC LABORATORY PROCESS

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## INTRODUCTION

NASA's LaRC is using solar hot water heating for a process load in a photographic laboratory. This report evaluates the performance of the hot water system. The system is a 328 $m^2$ vacuum tube collector system; it is to provide 22,000 L per day of 65 degree Celsius hot water to a photographic processing facility, see Figure 1A and 1B. LaRC is located in a coastal area at 37 degrees North latitude and 76 degrees West longitude. The area is subject to 3400 winter degree days per year, a -8°C winter design temperature, and an available city water source temperature of 4°C to 27°C.

The object of the project is to:

(1) Provide hot water to a process system that uses high cost electrical energy as a source.
(2) Determine the thermal performance of the solar system.
(3) Gain operating experience with this type of solar system.

The Government described the system needs in a "Design, Furnish, and Install" type contract. The Contractor selected the type and size of equipment to meet the specified needs. Construction took place from March 1978 to June 1979. Material delivery proolems hindered satisfactory operation until November 1979. During the period of January 1 to December 31, 1980 data was accumulated for the system evaluation.

The operating experience during most of the reporting period was relatively free of equipment and operating problems. Instrumentation was provided for the determination of the system performance.

## SYSTEM DESCRIPTION

The solar heated process water system was designed to provide approximately 22,000 L (5,500 gallons) per day of 66 degree Celsius (150 degree Fahrenheit) process water. The design emphasis was on a system with ease of maintainability. The Government specified the use of evacuated tube type solar collectors since the evacuated tube collector has better year long efficiencies than flat plate collectors at the temperatures required. The solar collectors and system size was selected by the Contractor based on a given energy requirement; a design load requirement of 21,400 KWH (73 million BTU) for the month of July was specified. A solar array of 328 $m^2$ (3,528 $ft.^2$) was selected: the field size is measured from the reflector area of the collector. The collector selected



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was the General Electric TC-100 vacuum tube, provided in prefabricated modules. Because the water flow is contained in a copper tube, the collectors allowed operating pressures that suppressed boiling of the fluid. The collectors can also sustain glass fracture with no coolant loss, see Figure 2A and 2B. The collectors are mounted with a tilt angle of 45 degrees from horizontal and an azimuth, 20 degrees east of south. The collector azimuth was chosen to achieve early morning warm-up giving a closer correlation between the available solar energy and the process load energy use profile. The collectors are mounted five rows deep and 48 collectors per row.

The collector array is fenced in to provide for the systems security. The solar collectors are located on a site approximately 100 meters from the Photo Lab. The piping system is copper and is insulated with fiberglass covered with an aluminum jacket. An energy storage tank of 24,000 L is used. It is housed in the equipment building which also has electric pumps, data recording devices, heat exchangers, water meters, flowmeter and filters.

## SYSTEM CONTROL

A two loop flow concept was selected for the system, see Figure 3A. The process water loop heats raw city water to be used by the system; a closed loop is used in the collectors. The collector loop uses a 50% by volume mixture of ethylene glycol in water for freeze protection. Minimum operation pressure in the collector loop is maintained at 172 kPa (25 psi) to prevent steam formation during high temperature operation. The make-up process water enters the heat exchanger (No. 1) and flows to the larger second heat exchanger (No. 2). Pump 3 circulates the process water through the storage tank and heat exchanger during solar operations. The collector loop water flows counter to the process water entering the second exchanger (No. 2) before passing through the primary heat exchanger (No. 1).

The control method is:

1. Flow to solar collectors is initiated by a solid state solar cell control, which is set at a solar radiation of .010 KW/M2 (34 Btu/sq. ft./hr.). The controller starts the collector flow pump P1. The collector pump operation is inhibited if the collector fluid, as sensed by a temperature probe in a collector tube, exceeds a temperature that would cause thermal shock if cool water were to be suddenly pumped into the collectors.

2. If the collector water temperature is within 3 degrees of the storage tank temperature, the circulating pump P3 is activated.

3. When the process water temperature from the heat exchanger No. 2 is below 65 degrees Celsius (150 degrees Fahrenheit), V2 allows water to flow from the heat exchanger into the storage tank. If temperatures exceed 65 degrees Celsius, V2 allows water flow from the heat exchanger to by-pass the storage tank, and to flow directly to the process load. Pump P3 still maintains a flow of water through the tank and heat exchanger No. 2.

4. If the process water output from the solar system is below 65 degrees Celsius the downstream electric heaters are thermostatically activated.

5. If the solar heated process water is greater than 65 degrees Celsius, the process water is blended with cold water. This is accomplished by using valve V1.

6. Two modes of over temperature protection are provided. The first is a water-to-air heat exchanger located in the collector field; this heat exchanger is equipped with a 3-way valve, V4, that forces water into the heat exchanger only if field temperature exceeds 115 degrees Celsius (240 degrees Fahrenheit) (See Figure 3B). The second over temperature control, uses a thermostatic control set at 126 degrees Celsius (260 degrees Fahrenheit) which by-passes the collector water flow around heat exchanger (No. 2) using valve (V5) and opens a path through valve (V3) so city make-up water flows through heat exchanger (No. 1) and dumps to the ground.

## DATA MONITORING SYSTEM

The instrumentation consists of a data logger which records 16 temperature locations and 2 flow rates every hour. In addition, two watthour meters monitor the energy supplied to the electrical water heaters and the system pumping power; these meters are read monthly.

Figure 4 shows the recorded data from the data logger. It consists of:

- o The day of the year.
- o The time of day

Item 1 thru 9: Temperatures, row discharge values
Item 10: Temperature, solar heated water to load.
Item 11: Temperature, city water.
Item 12: Temperature, circulating water (tank heat exchanger).
Item 13: Temperature, from the collector field discharger.
Item 14: Temperature, top of storage tank.
Item 15: Temperature, bottom of storage tank.
Item 16: Temperature, return collector field temperature.
Item 17: Flow rate, in collector loop.
Item 18: Flow rate, to the load.

## STAND

The collector support is shown in Figure 5. In addition to the collectors the stand is capable of resisting 1.43 kPa (30 psf) horizontal wind load as well as a 1.43 kPa (30 psf) dead load. The height in front precludes snow coverage from the ground while the rear height is low enough that it can be serviced from the top of a truck. Deflection of the main members are designed to be less than .6 cm (0.25 inch).

All support materials were cut to length off-site and assembled with stock angle clips. The design uses complementary cuts of 3.3m and 6.6m of standard 9.9m (30 foot) elements with no waste. The total cost of materials and labor for the 5 row frames and rails, including holes and concrete was $18,000 or a unit cost of about $50 per $m^2$ ($5 per square foot).

The overall system cost of this project was \$225,000 or \$685/$m^2$ (\$64/$ft.^2$). The project cost for the Photo Lab Solar System is broken down by percent of each functional element and listed in Figure 6.

A row spacing of 6.6m (20 feet) was selected to provide a width necessary for maintenance. In addition, this spacing allowed use of standard structural elements and pipe that are available in 6.6m lengths. The spacing resulted in less than 5% shading at 12 noon during the lowest sun angle in December. Although broader row spacing would reduce shading, larger spacing would increase the cost of piping, insulation, site development, and fencing.

The design used standard high speed (3600 rpm) centrifugal pumps at a price of under \$400 each. Redundant pumps were incorporated on the collector loop to further insure collector coolant flow in case of a pump failure. A simple pressure switch inhibits the back-up pump from operating if the discharge pressure is above 276 kPa (40 psi). Each pump is provided with a check valve to eliminate backflow.

## PERFORMANCE EVALUATION TECHNIQUE

Thermal performance of Photo Lab's Solar Energy System has been accomplished by calculating a set of factors designed to provide evaluation of the thermal effectiveness of the system and its components. These computations are based on a set of performance factors shown in Figure 7. They include:

- Solar Energy Collected
- Solar Energy to Load
- Total Energy to Load
- Auxiliary Energy
- Solar Radiation Available
- % Collector Efficiency
- % Solar Fraction
- % Conversion Efficiency
- % System Losses

## DISCUSSION

In Figures 8 and 9, a typical day's profile is shown for August 8, 1980. This was a clear day with 1854 KWH of solar energy intercepted by the collectors array. The collectors produced at an efficiency of 34 percent or 643 KWH for the day. Between 8:00 a.m. and 4:00 p.m. the temperature <u>into</u> the collectors operated between 57 degrees Celsius and 73 degrees Celsius. The <u>discharge</u> collector temperature peaked at about 2/3 hours before the true solar noon or when the sun's radiation was in line with the collector's azimuth. The solar vertical incident angle was 23 degrees to the collectors.

The process water temperature out of the heat exhanger ran between 54 degrees Celsius and 62 degrees Celsius. Due to the system load the processes required the use of auxiliary energy throughout the day. Since the auxiliary energy was recorded only on a monthly basis, the auxiliary electrical energy for the day and the daily thermal loss cannot be determined.

The process energy load peaked between 6:30 a.m. and 9:00 a.m., see Figure 9. The flow rate was 2000 L/hr (12 gpm). The total process water flow for the selected day was 10,500 L (3500 gal) or about 63% of the orginal designed load.

Figure 9 also shows why the collectors are positioned facing 20 degrees east of South. The graph shows that the azimuth of 20 degrees may be too conservative since the process loads come on much earlier in the day than the availability of collected solar energy.

Pump P1 energized about 7:00 a.m. The pump is controlled to start at 0.010 KWH/M/HR (34 BTU/FT$^2$/HR) of solar radiation: this low value is necessary to prevent overheating of the collectors on cloudy days. On this day, the controller had not given the collectors an opportunity to warm up. The temperature indicators showed that cold water from the collector field was pumped back to the system with a net loss of energy. A better combination of temperature and solar control might limit the energy losses by running the system only when positive energy would be collected.

The system used storage tank energy from 6:30 a.m. to 9:30 a.m. in the morning. At 9:30 a.m. the solar system was producing energy at the same rate that the processes system demanded. Thereafter, energy was stored except for a short period of time at 2:30 p.m. Since the energy consumption rate and the collected solar energy seldom coincide, the usefulness of the storage system is apparent.

Figure 10 shows the monthly energy tabulation for 1980. The system collected a total of 160,254 KWH of thermal energy during the year. Low efficiency was experienced in January and February since the collector pumps were run during the night hours. With this control problem fixed, better efficiencies were experienced. December 1980 also shows a low efficiency since the system was out of operation for 12 days of the month due to equipment failure.

The annual solar energy available to the solar collector array was 467,279 KWH or an average of 4.2 KWH/M$^2$/day which is about 60% of theoretical possible sunshine. This value is compared to 62% sunshine derived in the U.S. Weather Bureau Publication for Local Climatological Data.

The annual process water needs for the system was $3.73 \times 10^6$ L (988,374 gallons). For the 254 days of operation, an average of 14,628 L/d (3870 gal/day) was used or about 70% of the anticipated load. It is expected that as the processed water flow approaches the design load, the field efficiency would increase.

Figure 11 shows the efficiency of the system. The collector array operated for the year at a 34% efficiency and the conversion efficiency was 24%.

The most important comment that can be made on the systems performance is shown in Figure 10, in the difference between the solar energy collected (160,254 KWH) and the solar energy used by the load (115,079 KWH). This indicates a thermal loss of 45,195 KWH or 28 percent of the collected energy. To reduce this loss, the system needs modifications to the controls and better thermal insulation.

At an annual electrical cost of 4 cents per KWH, the thermal processes energy cost used was equivalent to 198,680 KWH x $.04 = $7,947. The solar systems estimated electrical pumping costs was 5 KW x 11 Hr./Day x 364 x $.04 = $800. The solar system saved 115,079 KWH x $.04 = $4603 of thermal process energy or a net savings of $3803 per year. Using simple life cycle costs analysis, the investment of $255,000 divided by $3800 = 67 year payback.

## CONCLUSION

Since June 1979, the 328 $m^2$ vacuum tube type collector solar field has furnished solar heated water for a photographic processing system. The system was designed to supply 22,000 L of water per day at 65 degrees Celsius; the system was expected to handle 75 percent of the annual load. In January 1980, NASA's data evaluation began. The major results and conclusion for this report are as follows:

(1) The total annual thermal load required by the process was 198,680 KWH. Solar energy supplied was 115,079 KWH. The annual solar fraction was 58 percent.

(2) The annual solar array efficiency was 34 percent.

(3) Twenty-four (24) percent of the array intercepted solar energy was supplied to the load.

(4) The difference between the collected solar energy and the solar energy supplied to the load shows a 28 percent energy loss for the year. This is felt to be excessively high and due to insufficient insulation.

(5) The photographic processing system used 3.7 million liters of water as opposed to the 5.5 million liters expected for the year. The lower energy consumption resulted in lower system efficiencies.

(6) During this report year the system operated with system inefficiencies such as, (a) 18 broken vacuum tubes that hampered the collection and caused heat loss for 5 months, (b) the over-temperature, three-way control valve was leaking, causing heat to be diverted to the atmosphere, (c) flow started thru the collector before the solution in the collectors reached temperatures that would produce positive energy, and (d) areas on the storage tank and the end plates on the heat exchangers were uninsulated.

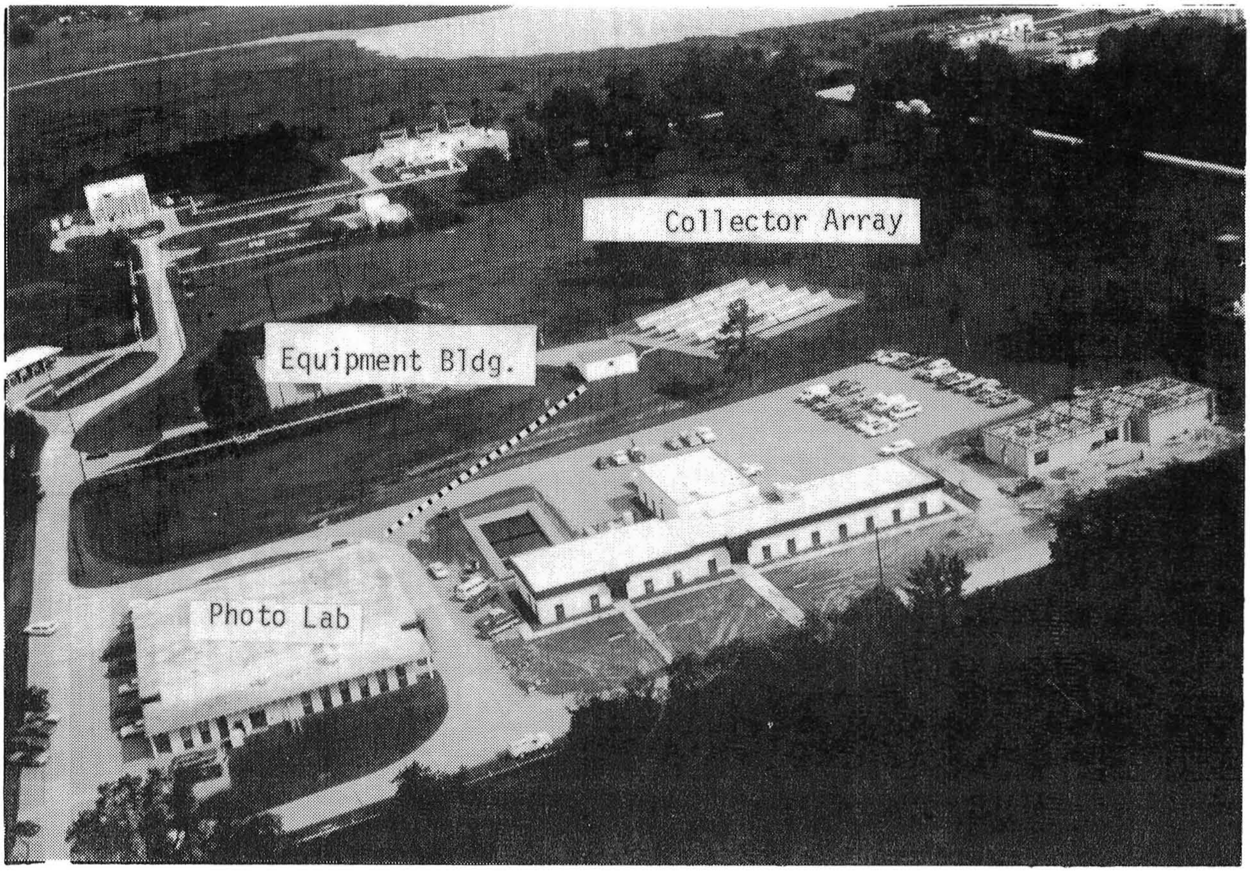
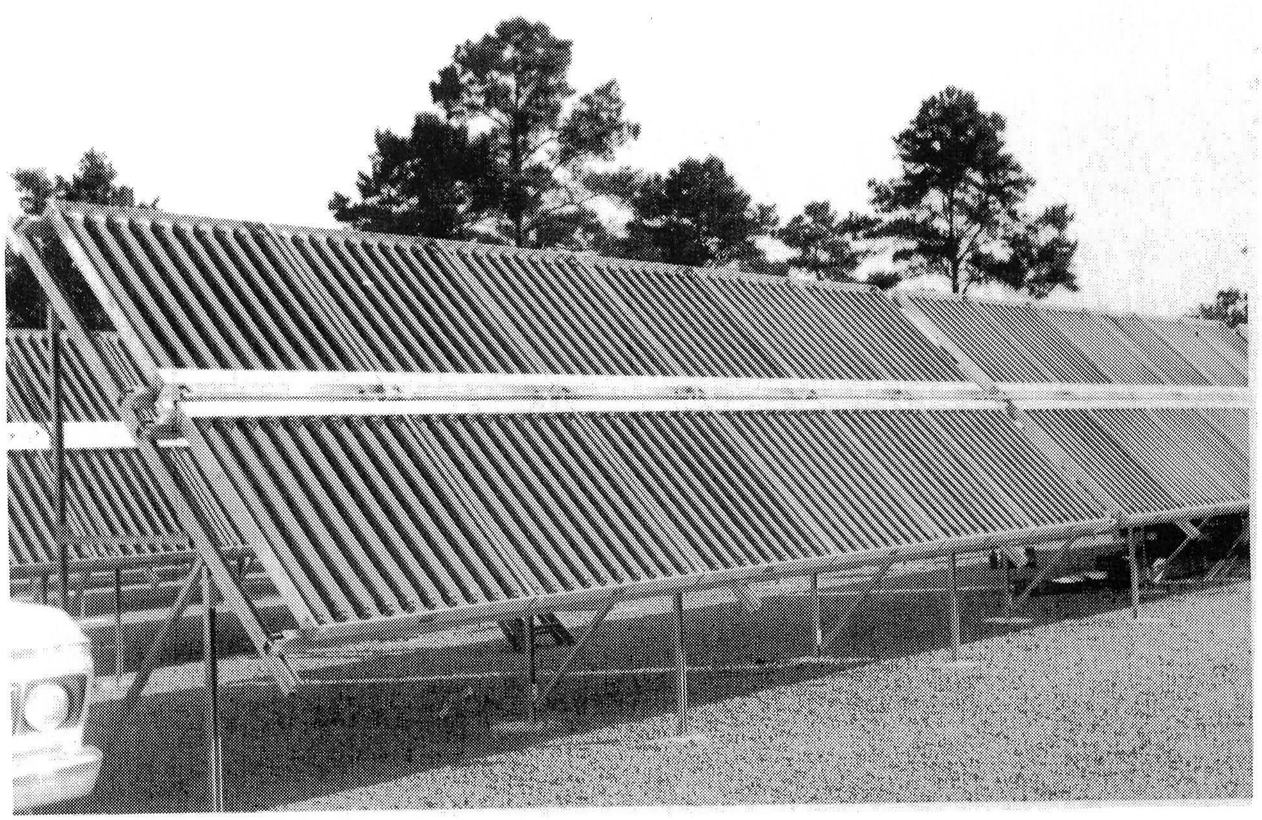



FIGURE 1 - DOTTED LINE INDICATES APPROX. POSITION OF THE UNDERGROUND WATER LINE



ROW 1 OF COLLECTOR ARRAY

FIGURE 1B

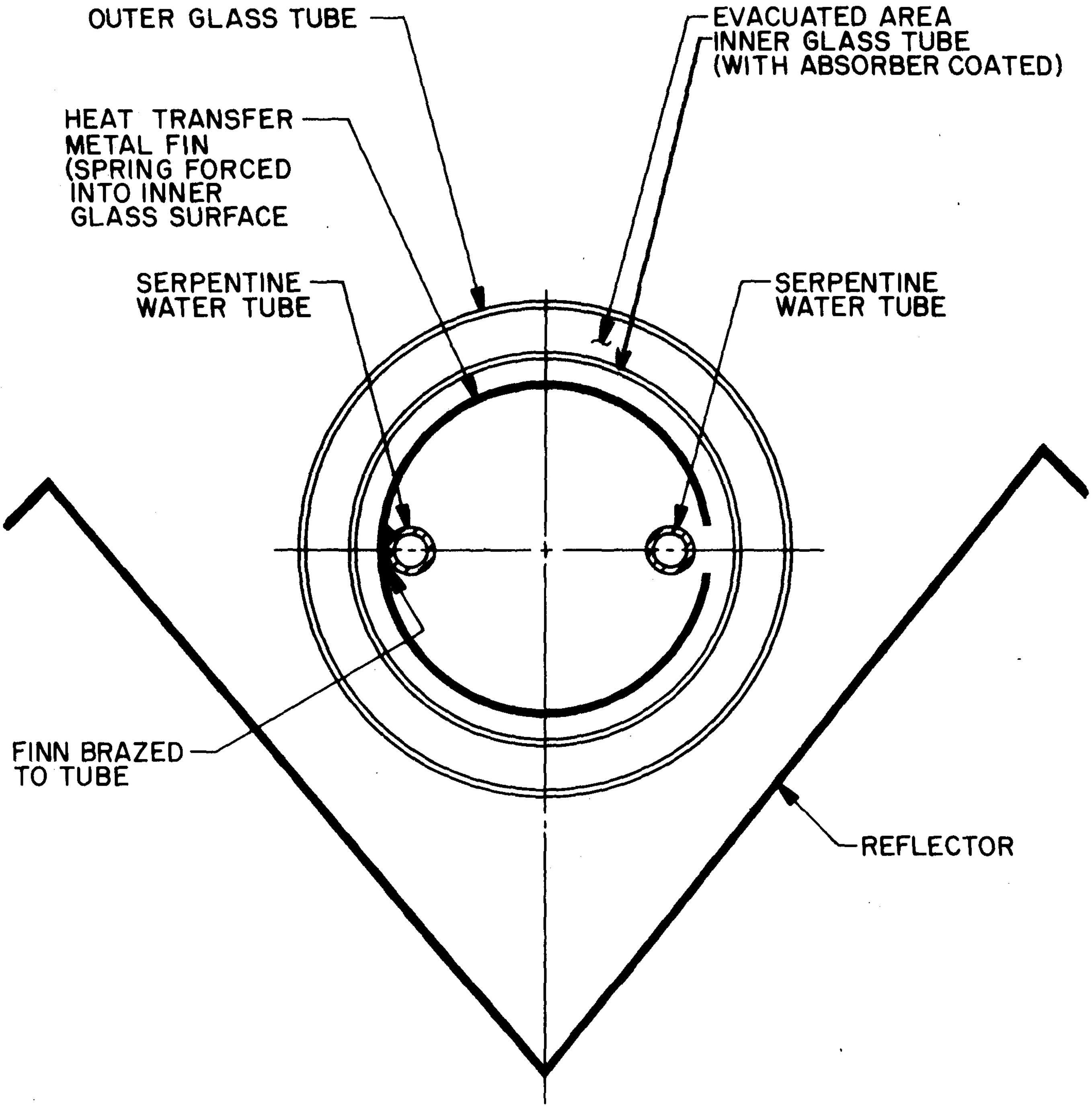
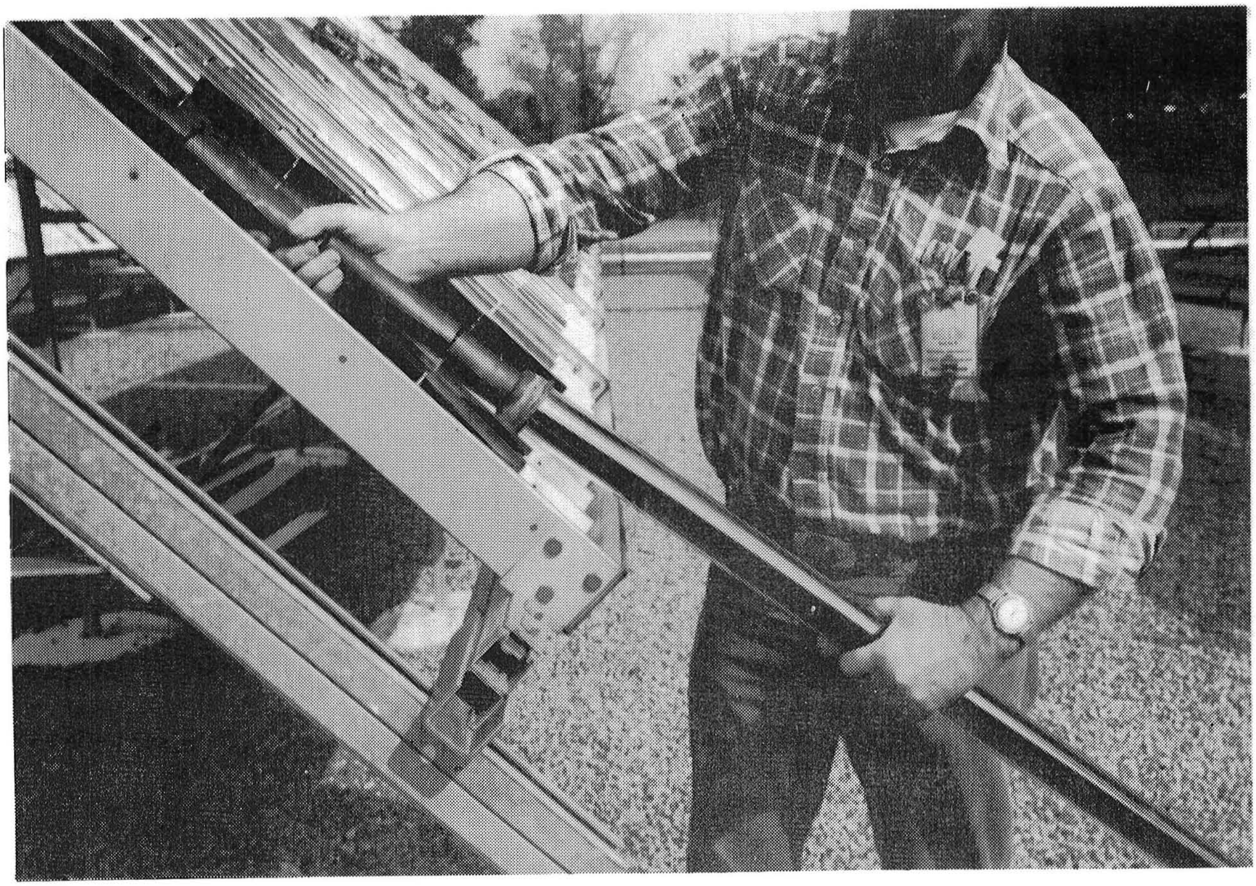



FIGURE 2A- CROSS-SECTION OF ACTIVE COLLECTOR ELEMENTS



VACUUM TUBE BEING PLACED OVER
COPPER FIN AND SERPENTINE
WATER TUBE

FIGURE 2B

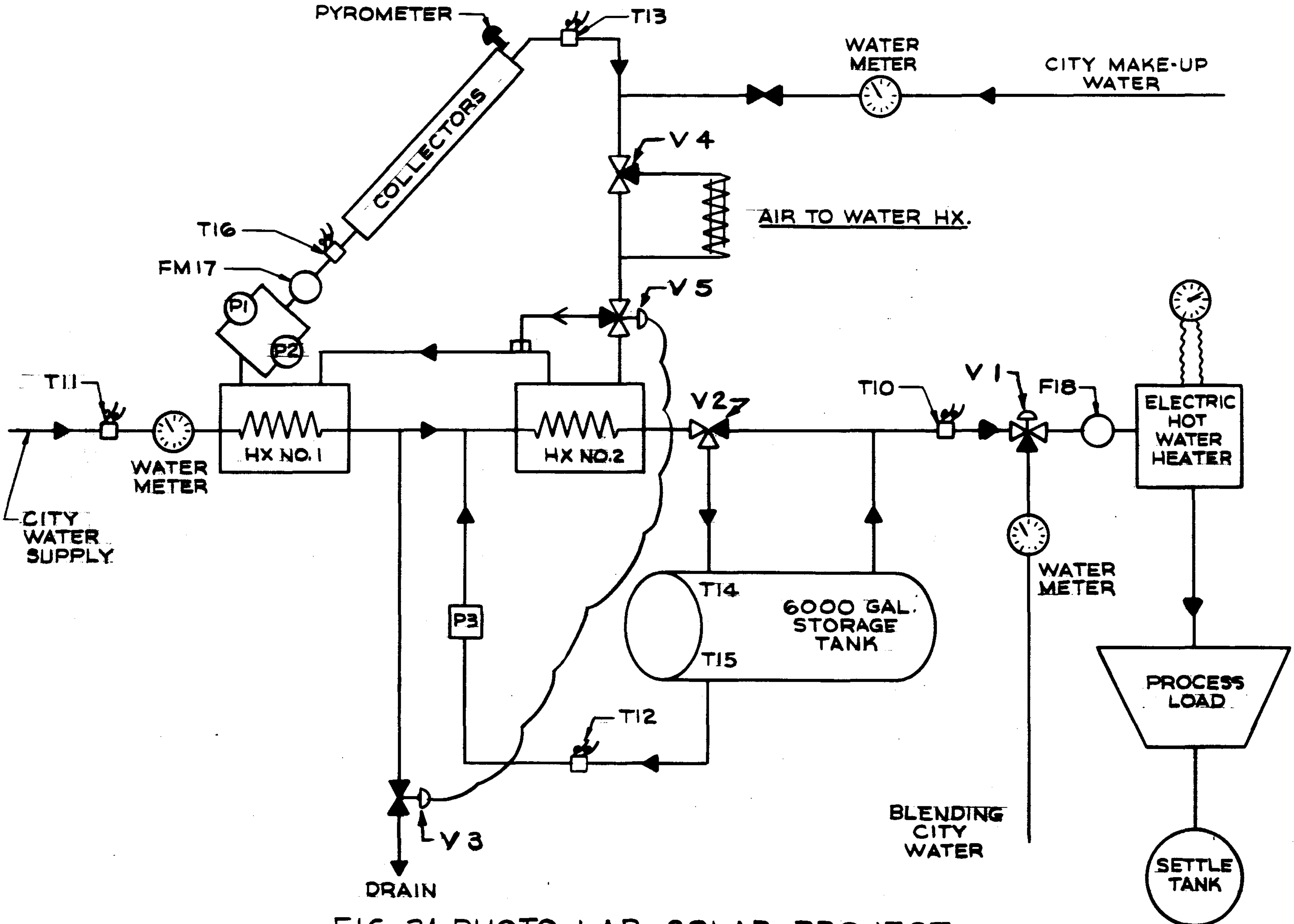
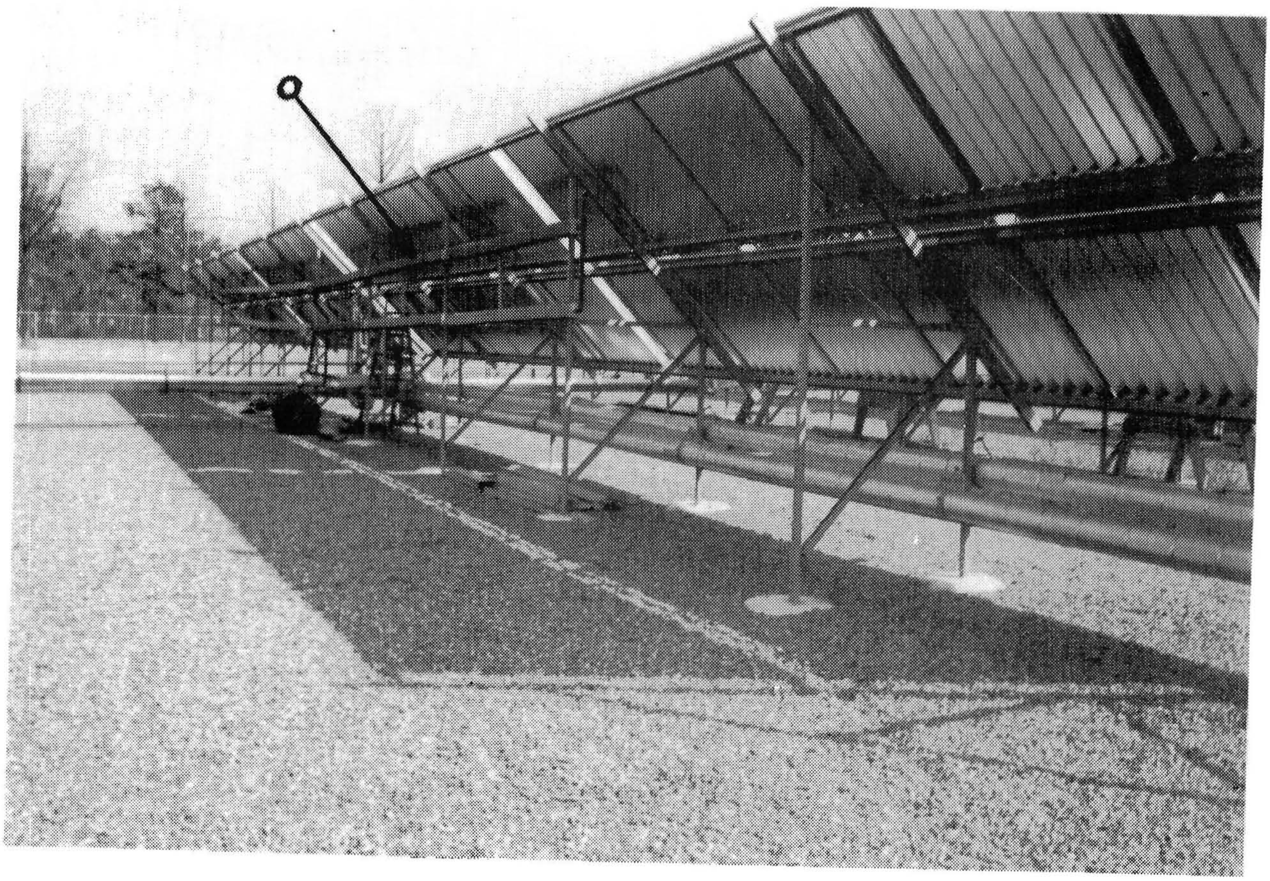



FIG. 3A PHOTO LAB SOLAR PROJECT



REAR OF COLLECTORS SHOWING AIR HEAT
EXCHANGER USED FOR TEMPERATURE
LIMITATION

FIGURE 3B

## DESCRIPTION OF HOURLY RECORD

| | | |
|---|---|---|
| 18 | 3.6206 | V |
| 17 | 1.5531 | V |
| 16 | 136.9 | °F |
| 15 | 125.1 | °F |
| 14 | 125.0 | °F |
| 13 | 148.6 | °F |
| 12 | 118.6 | °F |
| 11 | 79.7 | °F |
| 10 | 125.6 | °F |
| 9 | 158.2 | °F |
| 8 | 148.7 | °F |
| 7 | 148.0 | °F |
| 6 | 153.4 | °F |
| 5 | 148.4 | °F |
| 4 | 145.5 | °F |
| 3 | 150.4 | °F |
| 2 | 146.2 | °F |
| 1 | 147.0 | °F |
| 0 | 147.3 | °F |

000001
206:15:18:50

FIG. 4

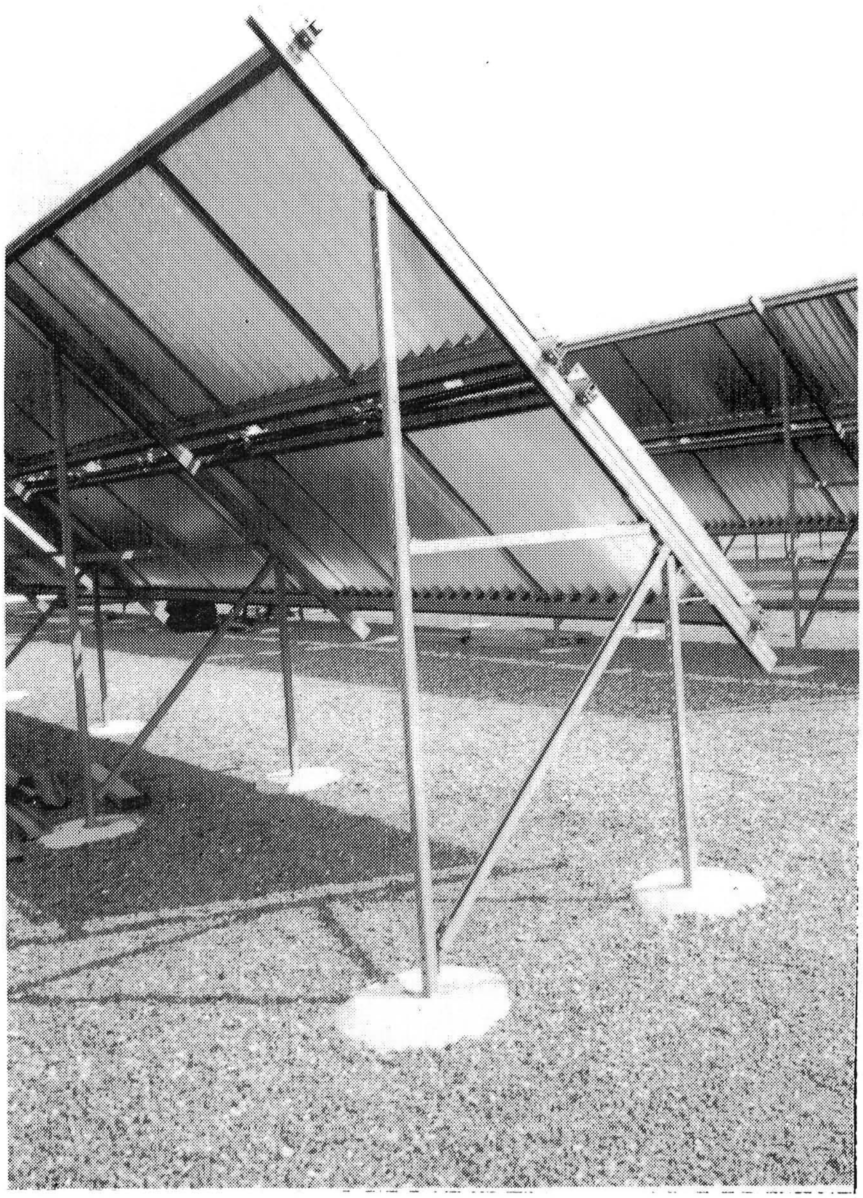


FIGURE 5 - SUPPORT FRAME (COLLECTORS)

## PROJECT COST PERCENT BREAKDOWN

| | PERCENT OF COST |
|---|---|
| ENGINEERING, DESIGN, & CONSTRUCTION MANAGEMENT | 6 |
| SOLAR COLLECTOR AND MANIFOLDS | 40 |
| MOUNTING AND ASSEMBLY OF COLLECTORS | 7 |
| STRUCTURE FRAMES AND FOUNDATION | 5 |
| SITE PREPARATION, GRAVEL BASE AND FENCE | 5 |
| MECH. BUILDING ERECTION W/TANK BASE | 5 |
| STORAGE TANK | 6 |
| UNDERGROUND PIPING (300 FT.) | 2 |
| UNDERGROUND WATER SUPPLY (150 FT.) | 1 |
| INSULATION | 3 |
| PUMPS, HEAT EXCHANGERS, FILTERS | 3 |
| PLUMBING, INSTALLATION & MATERIAL | 7 |
| ELECTRICAL INSTALLATION & EQUIPMENT | 6 |
| CONTROLS | 1 |
| INSTRUMENTATION | 1 |
| CHECKOUT & TESTING | 2 |

FIG. 6

FIG 7 CALCULATIONS

SOLAR ENERGY COLLECTED, KWH $QC = \sum (T_{13} - T_{16}) \times F_{17} \times T_{1} \times .00243$

Where $T_{13}$ = Temp. Out of Collector, $^{o}F$

$T_{16}$ = Temp. Into Collector, $^{o}F$

$F_{17}$ = Flow Rate Thru Collectors, GPM

$T_{1}$ = Measure Period, minutes

$.00243 = \frac{\text{Pounds}}{\text{Gal}} \times \text{specific heat } \frac{\text{Btu}}{^{o}F\ \#} \times \frac{\text{KWH}}{\text{Btu}}$

SOLAR ENERGY TO LOAD, KWH $QS = \sum (T_{10} - T_{11}) \times F_{18} \times T \times .00243$

Where $T_{10}$ - Temp. of Solar Heated Water to Load, $^{o}F$

$T_{11}$ = Temp. of City Water, $^{o}F$

$T_{18}$ = Flow Rate to Load, GPM

$T$ = Measuring period, minutes

TOTAL ENERGY TO LOAD, KWH $QL = \sum (150 - T_{11})\ F_{18} \times T \times .00243$

AUXILIARY ENERGY QA = KWH Meter Reading

SOLAR RADIATION AVAILABLE QI = Reading taken from other systems at LaRC in KWHR corrected for $45^{o}$ tilt and $20^{o}$ E of S azimuth

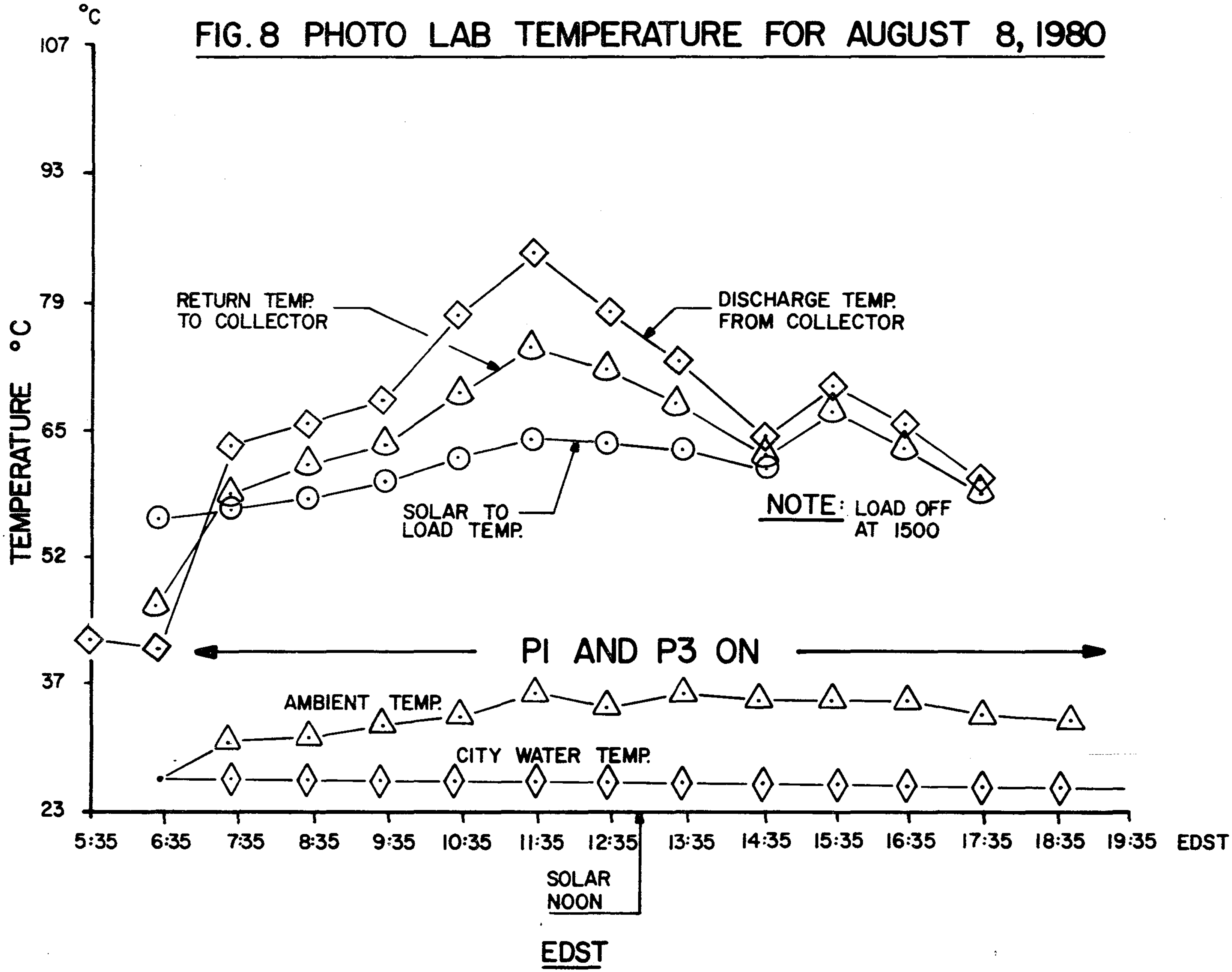
% COLLECTOR EFFICIENCY $CE = \frac{\text{QC, Solar Energy Collected}}{\text{QI, Solar Radiation Available}}$

% SOLAR FRACTION $SF = \frac{\text{QS, Solar Energy to Load}}{\text{QL, Total Energy to the Load}}$

% CONVERSION EFFICIENCY $IE = \frac{\text{QS, Solar Energy to Load}}{\text{QI, Solar Radiation Available}}$

% SYSTEM LOSSES $SL = \frac{\text{QC, Total Energy Collected - QL, Total Energy to Load}}{\text{QC, Total Energy Collected}}$

FIG. 8 PHOTO LAB TEMPERATURE FOR AUGUST 8, 1980



# FIGURE 9

## HOURLY ENERGY PROFILE FOR AUGUST 8, 1980

### Σ DAILY PERFORMANCE

| | |
|---|---|
| AVAILABLE RADIATION | 1854.59 KWH |
| ENERGY COLLECTED | 643.00 KWH |
| COLLECTOR EFFICIENCY | 34.67 % |
| TOTAL LOAD | 858.40 KWH |
| ENERGY SUPPLIED TO LOAD | 688.08 KWH |
| SOLAR FRACTION | 80.16 % |

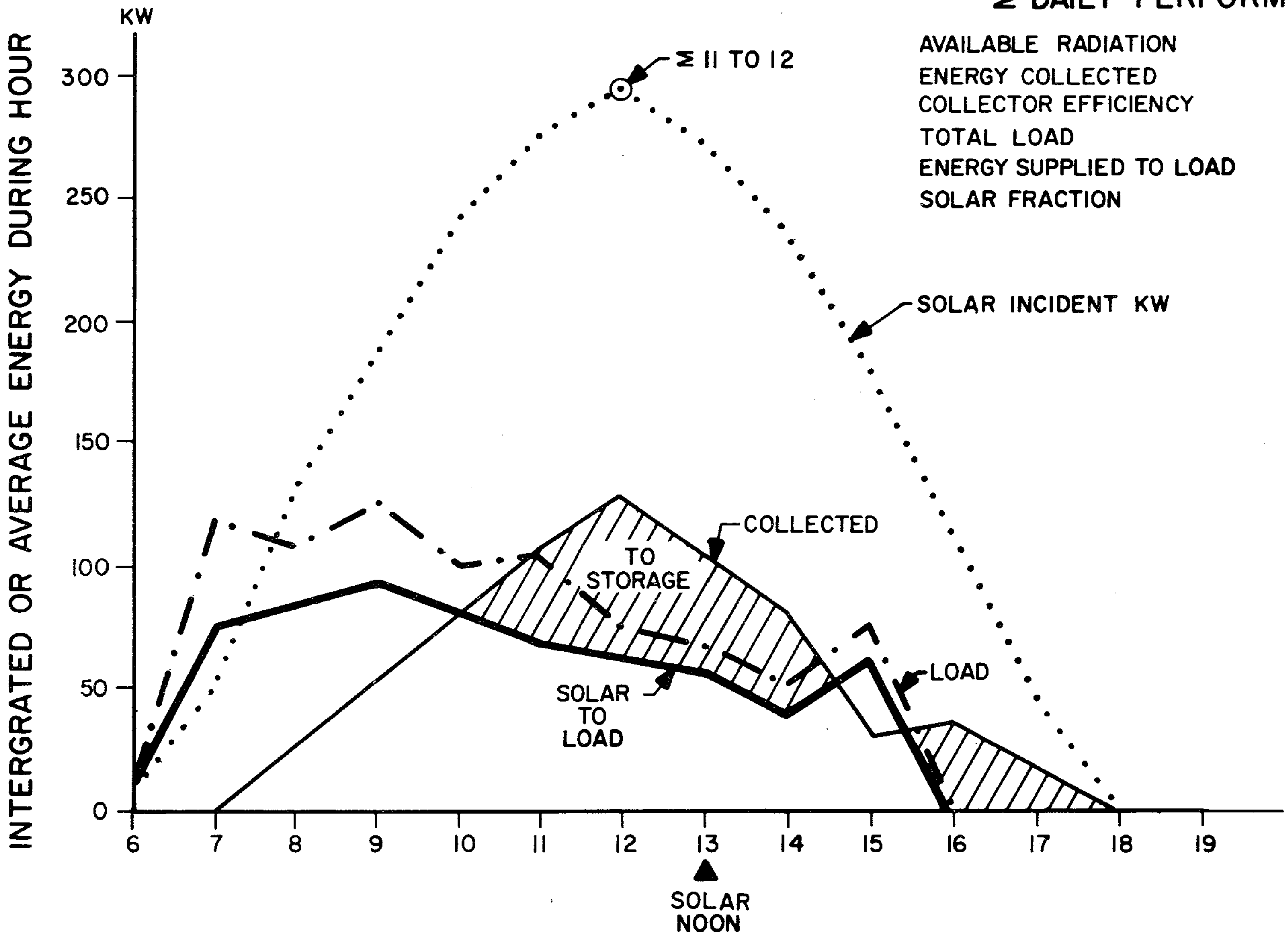


FIGURE 10

1980 ENERGY PERFORMANCE FOR
PHOTO LAB SOLAR PROJECT

| MONTH | SOLAR RADIATION AVAILABLE, QI (KWH) | SOLAR ENERGY COLLECTED, QC (KWH) | MONTHLY WATER METERED WITH (F18) (Gallons) | TOTAL ENERGY TO LOAD QL (KWH) | ENERGY SOLAR TO SOLAR QS (KWH) | ELECTRICAL AUX. ENERGY, QT (KWH) |
|---|---|---|---|---|---|---|
| Jan. | 21,901 | 6,587 | 56,947 (-)* | 13,845 | 5,043 | 8,802 (-)** |
| Feb. | 42,872 | 12,023 | 74,648 (-) | 17,230 | 8,277 | 8,953 (-) |
| Mar. | 37,852 | 13,405 | 89,682 (-) | 20,758 | 9,635 | 11,123 (-) |
| Apr. | 48,052 | 18,293 | 82,286 (79750) | 18,829 | 11,402 | 7,427 (-) |
| May | 43,325 | 14,406 | 84,260 (85100) | 17,449 | 10,624 | 6,825 (7,000) |
| June | 41,696 | 15,048 | 76,093 (-) | 14,952 | 10,937 | 4,015 (3,600) |
| July | 49,304 | 16,619 | 85,624 (-) | 15,692 | 12,811 | 2,881 (3,600) |
| Aug. | 49,305 | 17,124 | 77,170 (75,570) | 14,428 | 11,910 | 2,518 (2,800) |
| Sept. | 38,619 | 14,892 | 89,587 (90,200) | 15,638 | 11,154 | 4,484 (4,600) |
| Oct. | 40,205 | 14,554 | 104,692 (105,182) | 21,098 | 11,451 | 9,647 (9,565) |
| Nov. | 30,650 | 10,580 | 69,077 (-) | 15,042 | 7,389 | 8,253 (8,353) |
| Dec. | 23,901 | 6,715 | 98,306 (-) | 13,119 | 4,446 | (8,353) (-) |
| Total | 467,279 | 160,254 | 988,374 | 198,680 | 115,079 | 83,601 |

* Check data with positive displacement meter. ** Check data with KWH meter, QA.

Figure 11 - MONTHLY EFFICIENCY DATA FOR YEAR

All Data in Percent

| Month | Monthly Collector Efficiency | % Load By Solar (Solar Fraction) | Percent Incident To Load | Percent System Loss |
|---|---|---|---|---|
| Jan. | 30 | 36 | 23 | 23 |
| Feb. | 28 | 48 | 19 | 31 |
| March | 35 | 45 | 23 | 28 |
| April | 38 | 61 | 23 | 37 |
| May | 33 | 61 | 25 | 26 |
| June | 36 | 73 | 26 | 27 |
| July | 34 | 81 | 26 | 23 |
| Aug. | 34 | 82 | 24 | 30 |
| Sept. | 38 | 71 | 28 | 25 |
| Oct, | 36 | 54 | 28 | 20 |
| Nov. | 35 | 47 | 24 | 30 |
| Dec. | 28 | 34 | 19 | 33 |
| Years Total | 34 | 58 | 24 | 28 |

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15. Supplementary Notes

16. Abstract


This paper describes the thermal performance of Langley Research Center's Photo Lab Solar Process Hot Water System located in Hampton, Virginia for the year 1980. The system was designed to supply 22,000 liters (5,500 gallons) per day of 66°C (150°F) process water for photographic processing. The $328 m^2$ (3,528 sq. ft.) solar field has supplied 58% of the thermal energy for the system during the test period. Techniques used for analyzing various thermal values are given. Load and performance factors and the resulting solar contribution are discussed.


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