SERI/TR-214-1423
UC Category: 63D

Evaluation of Pumps and Motors for Photovoltaic Water Pumping Systems

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June 1982

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A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $ 5.25

PREFACE

This report documents work done on SERI tasks 3825.70 and 1091.50 by members of the Advanced Systems Research Branch of the Solar Electric Conversion Research Division and of the Thermal Systems and Engineering Branch of The Solar Thermal and Materials Research Division. The task extended from October 1980 through September 1981 and was supported by the Division of Photovoltaic Energy Systems, Office of Solar Applications for Buildings of the U.S. Department of Energy.

The authors wish to thank Cécile Leboeuf, Jane Ullman, Rick Noffsinger, and Howard Walker for technical assistance given during the project. Also, appreciation is given to John P. Thornton for his work in the early stages of the project and to Charles Bishop, Chief of the Systems Development Branch in which the majority of the work was accomplished.

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SUMMARY

Two electric, motor-driven water pumps were tested in conjunction with a photovoltaic (PV) array that provided the electrical energy to run the pumps. The purpose of the tests was to evaluate the performance of currently available, low-cost pumping systems powered by PV arrays. The performance and cost of these systems were compared with analogous data from similar, higher priced pumps and motors currently used with many PV water pumping systems.

The two pump systems considered represent production equipment available from U.S. industry and cost less than 50% of equivalent pumps installed with PV pumping systems in the United States and in developing countries. Flow rates, pumping heads, and efficiency were comparable in both test pumps and equivalent pumps. Motor performance, when the motor was directly connected to the PV array and loaded with the pump, was examined. The conclusion drawn from this experiment is that commercially available, low-cost water pump systems will perform satisfactorily when powered by PV arrays.

The test facility constructed for these tests consists of a trailer housing the instrumentation, controls and pump subsystem, and two solar arrays that provided up to 1500 W_p power. Two battery storage subsystems provide instrumentation power when solar energy is not available. This facility can now be used for further tests, for orientation, or to provide hands-on training for persons interested in using PV-powered systems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Concluded)

LIST OF TABLES

SECTION 1.0

BACKGROUND

Water is a prime necessity for human existence, and as the standard of living in developing countries improves, the demand for water increases. Furthermore with the lifestyle change from nomadic hunters to ranchers who raise their food or food for domestic animals, the water requirement has become even greater. Windmills have pumped water in coastal regions and other areas with reliable and consistent winds for centuries. If adequate winds are not available, farmers can often grow only one meager crop per year during the rainy season. Yet with an adequate water supply, this farmer could raise four crops. Photovoltaic (PV) energy conversion provides energy for water pumping and other uses in areas where there is consistent solar insolation but where wind energy is not adequate. Several companies have developed pumps that operate from PV arrays, but they are expensive and have technical limitations.

Guinard of France has developed a pump that uses a dc motor on the surface to drive a pump at the bottom of a well by means of a long shaft connecting the motor to the pump. The shaft requires bearings at 1-m intervals, which adds to the friction already present from the water on the moving shaft. If sand gets in the water, it also gets into the bearings and causes wear.

Tri Solar Corporation of Bedford, Mass., makes a small, submersible water pump that uses a brushless dc motor directly connected to the pump and submerged with it. This pump and motor are necessarily limited to about 1/3 horsepower because the transistors used for commutation of the brushless motor are currently limited in both voltage and current-carrying capability.

In 1980, the cost of both of these pumps was equivalent to the cost of the solar array required to drive them. A major Department of Energy-Solar Energy Research Institute (DOE-SERI) effort was expended to try to decrease the cost of PV arrays. Therefore, this task was initiated to decrease the cost of the pump and motor while increasing simplicity and reliability. The objective of this task was to evaluate pumps and motors together with batteries that could be used with a PV-powered water pumping system. This task was designed to evaluate two pump-motor systems that were less expensive than those systems tested in foreign countries. Another objective of the task was to compare low-cost, electrical vehicle batteries to batteries designed specifically for use with PV systems. The final objective was to provide SERI with a photovoltaic energy source and pump testing capability that could serve as a demonstration for visitors, a systems research facility, and also as a training center for those who wish to learn about water pumping systems.

SERI

SECTION 2.0

APPROACH

Many inputs and requirements are needed to design a PV-water pumping system. The major system design criteria included economy, reliability, maintainability, and safety.

Economy: The system should be of the lowest cost consistent with meeting other requirements.

Reliability: The system should have the minimum number of components, be of the least complexity, and must have been proven through years of usage.

Maintainability: The system should require little or no maintenance and any required must be capable of accomplishment with a minimum of technical knowledge and a minimum of tools.

Safety: The system must offer the minimum hazard to personnel not familiar with operating electrical rotating machinery.

To meet these design criteria, batteries were not considered as a part of the water pumping system. Water can be stored much more reliably and economically than energy needed to pump water. Water storage can be 100% efficient if evaporation is prevented, whereas energy stored in batteries is only 85% to 90% efficient. A nominal, 28-V system was originally chosen because it did not present an electrical shock hazard to inexperienced personnel. However, it appears that developing countries have negligible problems adapting to the higher voltage of the European 220-V standard. To ensure low cost, reliability, and minimal maintenance, standard U.S. pumps and motors with an established record of dependability were needed. Although pumps were available, it was difficult to procure reliable motors. While the brushless, dc motor offered potential reliability and maintainability, it was still in the developmental stage and was not available larger than 1/3 hp. Finally a brush-type, permanent magnet motor was selected, because it started with low current and had lower losses than the more conventional shunt-wound motor. It was available from the Motor Division of Honeywell.

A number of pump types were evaluated for the experiment. It was desirable to use a pump that could be operated over a wide range of well depths. The jet pump, often used for residential water systems in rural areas, was first considered but was rejected due to its inefficiency. This pump moves three to four volumes of water at high velocity around a loop from the top of the well to the bottom and back again for each volume it pumps. The old standby piston pump, operated by hand or wind for many years, was next considered. This pump is the only one to consider for extremely deep wells (of the order of hundreds of metres) but is disadvantageous for use with a solar power system because the load is periodic between the up and the down stroke. This can be balanced by using batteries, which incur an additional expense and maintenance problem. Centrifugal pumps offered the highest efficiency and also offered the optimum operation with a solar-powered system because they could be directly connected to the motor shaft.

A shallow well centrifugal pump was chosen for the experiment because it met the system design standards and could be driven by a surface-mounted motor. The difference in depth between a shallow and a deep well is about 7 m, depending on the altitude above mean sea level. A shallow well can have the pump on the surface and can pump water from any level down to about 7 m below the surface. If the water level is lower than 7 m, the pump must be put into the well and is usually installed below the water level so that it does not have to be primed. (A pump located above the water surface must be primed. That is, the pump and the pipe from the pump to the water in the well must be filled with water before starting the pump.)

The solar array for this experiment was planned to use a single crystal silicon solar cell commercially available in the United States. The array was initially limited to 1 kW_p power because of cost limitations within the task. To achieve the highest system efficiency, the motor with pump load had to be matched to the array so that the motor would operate at full speed and rated torque at the same voltage and current that defined the maximum power point of the array over foreseeable temperature and insolation values. The array also needed sufficient energy to start the motor as early in the day as possible. The array characteristics were plotted and sent to motor manufacturers to determine which motor most closely matched the array when directly connected with no battery or power conditioning. Appendix A explains the motor-array performance requirements. After motor and pump loads were determined and the array was sized, a second solar array was added to provide housekeeping power so that the complete system could operate in an isolated, stand-alone mode.

Pump requirements were met by soliciting information about standard pumps from various pump manufacturers. Most U.S. manufacturers design pumps at speeds that are consistent with induction motors driven from 60-Hz mains. Only a few manufacturers had pump data for speeds other than 1750 and 3500 rpm. The available performance curves were evaluated to determine the pump with maximum efficiency that conformed to the power and rpm outputs expected from the motor and that provided the largest flow rate at the desired head. The step-by-step approach used to determine optimum pump motor combinations is included in Appendix H.

It was the intention of this experiment to build an operational, "stand alone" test facility. When all of the components necessary for the facility were chosen, they included batteries to run the instrumentation during periods of cloud cover and during sunrise and sunset periods. These batteries were also to be evaluated during the battery tests of the project. Where choice of instrumentation was available, instruments powered by 28-V dc motors were selected.

Batteries for the experiment required daily deep discharge at low currents on the order of C/10, where C is the battery capacity in ampere hours. The desire was to evaluate batteries that were designed for daily charge and deep discharge in industrial applications, and to compare these batteries with the C&D battery used by NASA-Lewis and others in several PV applications. Batteries were selected by contacting numerous battery manufacturers and comparing battery specifications and test data to find an appropriate battery for a PV array-powered system requiring daily deep discharge and recharge. Factors that were considered other than electrical performance included maintenance, requirement for distilled water, and the possibilities of replacement or substitution if used in a developing country. Consideration was given only to lead-acid batteries; although nickel-cadmium batteries have excellent cycle lives and are cost effective, they have long procurement lead time, replacement difficulties, and the potential hazards associated with cadmium.

SERI

SECTION 3.0

EXPERIMENTAL SETUP

3.1 FACILITY

It was intended that this experiment be installed on the SERI permanent test facility. Unfortunately negotiations for the site continued for over a year, and when permission could not be obtained by 1 June of 1981, it was decided to install the experiment on the interim test site. A trailer had been obtained and was already stored on the interim test site as was the small prefabricated building intended for use as a well-house to hold the pump. An area had been reserved in proximity to the trailer to mount solar arrays in the event the use of the interim test site became necessary. The trailer had been designed originally as a mobile home, and adaptation to the experiment resulted in the kitchen and living room becoming a workshop. The bathroom became a battery room, one bedroom became the pump room, and the second bedroom became the control center. Figure 3-1 is a photograph of the facility.

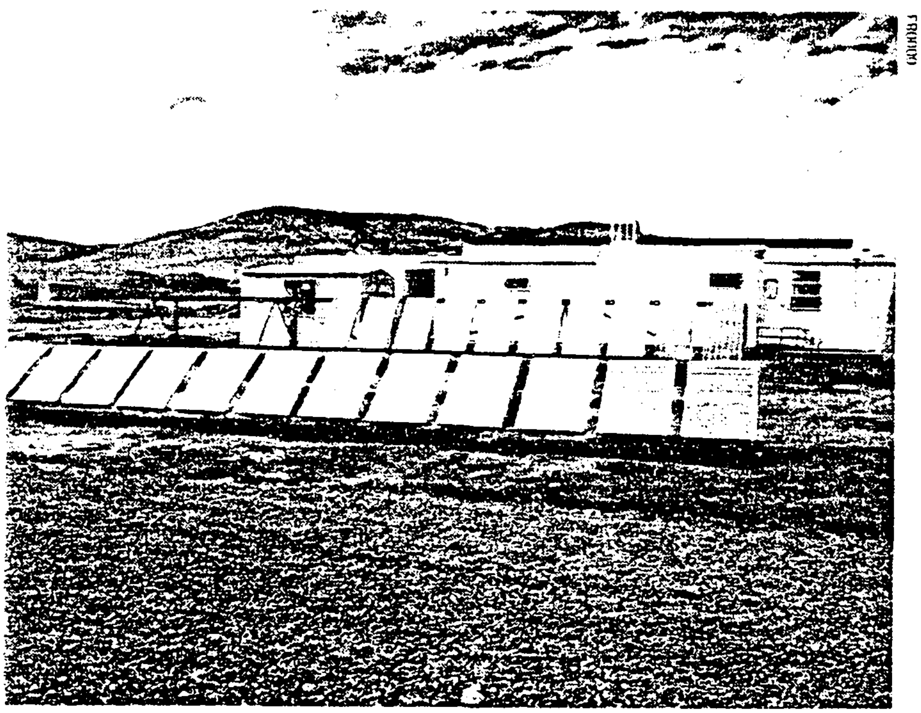

Figure 3-1. Test Facility

3.2 POWER SUBSYSTEM

The power subsystem consisted of the solar arrays, the batteries, and the associated wiring and interconnections. The solar array needed to operate the pump was obtained from Solenergy. The other array, that provided power for the instrumentation system and powered the data system was procured from Solarex. Table 3-1 lists the characteristics of the two arrays.

The Solenergy array was mounted on a support formed by two horizontal wooden poles attached to vertical posts set into the ground. This construction was not only economical but was a representative support that could be built in a developing country with local labor and native materials. Figures 3-2 and 3-3 show the array and its mounting. The spacing between panels decreases wind loading.

The Solarex array was mounted on an adjustable Unistrut framework capable of being adjusted in elevation to achieve optimum acceptance of solar radiation at different times of the year. This framework was also supported on wooden posts set into the ground. Figures 3-4 and 3-5 show the Solarex array and its support structure.

A dc battery was procured that consisted of 12 cells in two separate battery cases from C&D Corporation. This reference battery is representative of those generally used for PV operations. A second battery, the "George" battery, was obtained from Gould; it was designed to operate electric fork lifts. Table 3-2 lists characteristics of the two batteries.

Table 3-1. Characteristics of Solar Arrays

	Solenergy	Solarex
Cell size and type	10-cm diam. single crystal	9.5 cm^2 poly crystal
Panel size	78.1 cm x 121.3 cm	63.5 cm x 120 cm
Panel area	0.947 m^2	0.762 m^2
Cell area/panel	0.613 m^2	0.650 m^2
Number of panels	12	10
Number of cells/pane[a]	78	72
Total area of array	11.3 m^2	7.62 m^2
Voltage at maximum power[a]	31.5 V	31 V
Average peak power[a]/panel	70 W	62 W
Average peak efficiency	11.4%	9.5%
Total power[a]	840 W	620 W
1980 cost	$9318	$10,044
1980 $/W	$11.09/W	$16.20/W

[a]Based on solar irradiance of 1000 W/m^2 and panel temperature of 28°C.

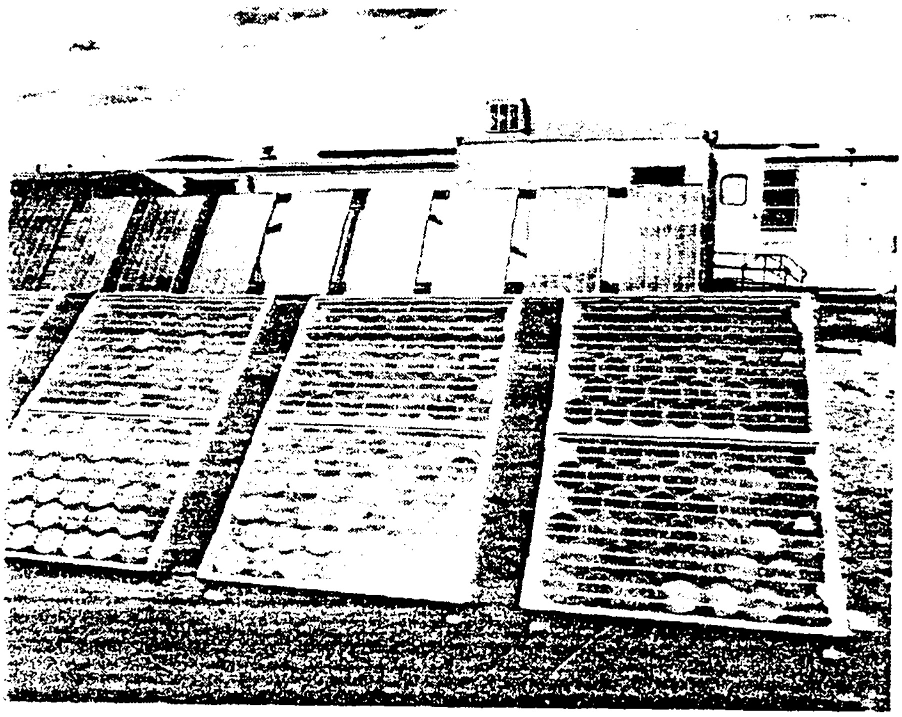

Figure 3-2. Solenergy Array

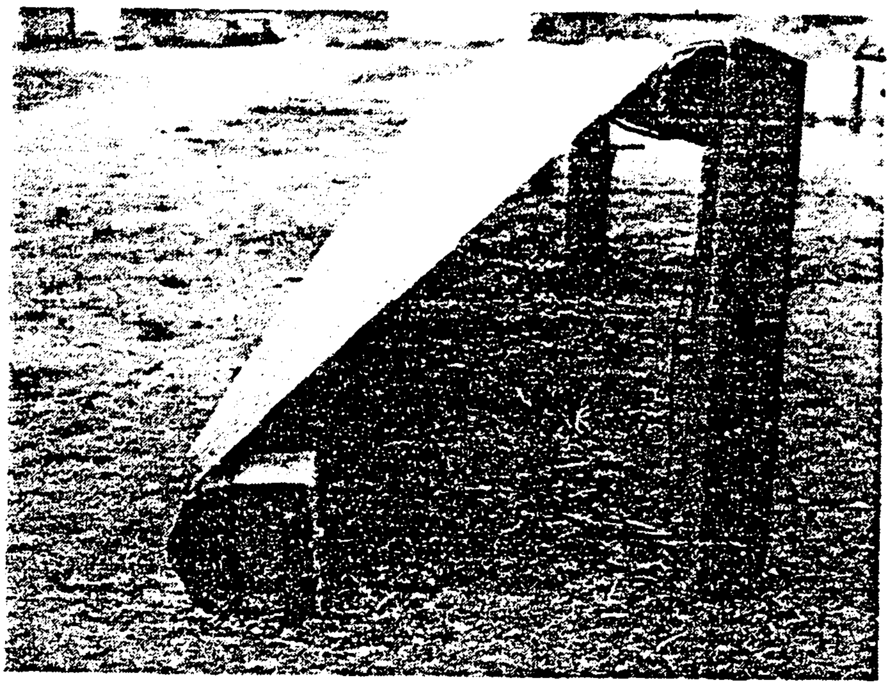

Figure 3-3. Low-Cost Array Support

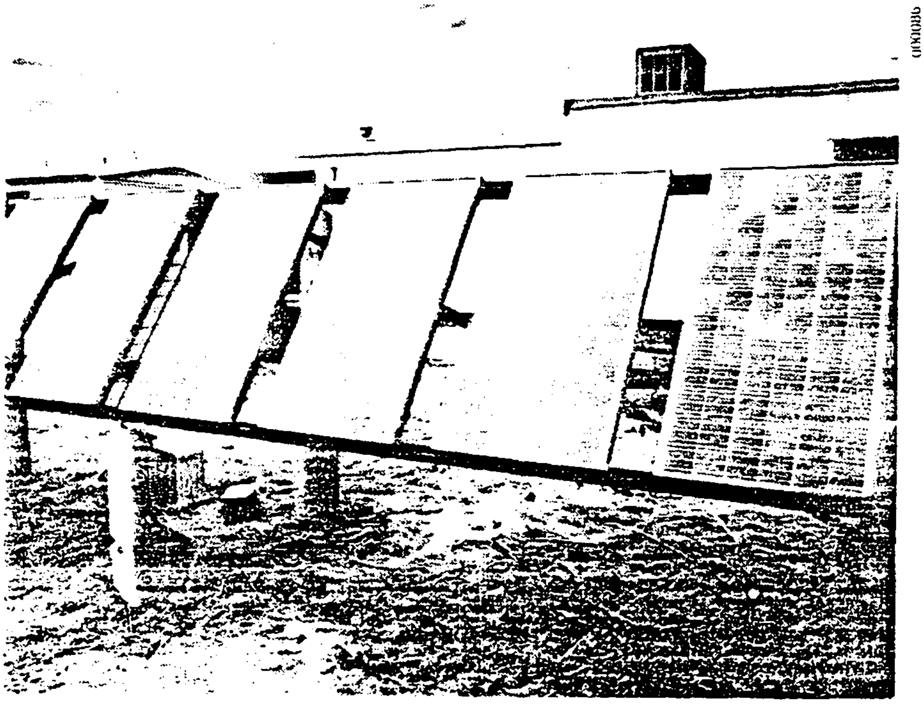

Figure 3-4. Solarex Array

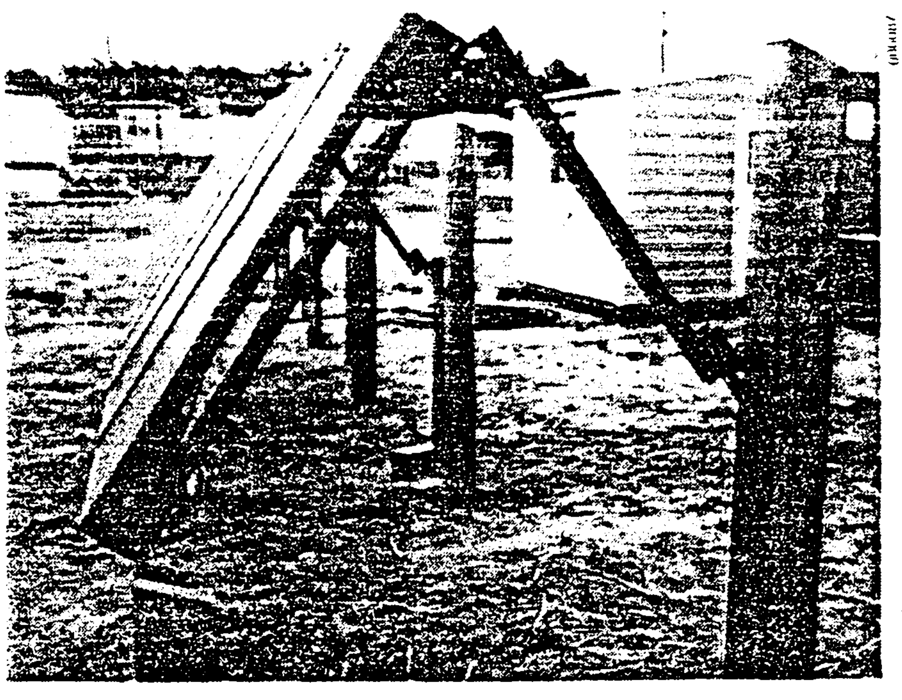

Figure 3-5. Adjustable Array Support

Table 3-2. Battery Characteristics

	C&D GQP75-5	Gould "George"
Cycle life[a]	1500–1800	1000
Ampere-hour	166	180
Plates/cell	5	13
Number of cells/case	6	3
Case dimension LWH	42.5, 16.8, 57.5 cm	26, 18, 20.5 cm
Case weight	100 kg	34 kg
Number of cases	2	4
Total weight	200 kg	136.4 kg
Cost	$1403	$560

[a]Cycle life is defined as the number of discharge (to 80% of capacity) and recharge cycles that can be accomplished before the battery will no longer accept and hold a charge equivalent to 80% of the original.

Figure 3-6 illustrates the schematic of the power system interconnection. The solar arrays were paralleled with diode isolation in a junction box on the back of the array support. Additionally the Solarex array was connected to a dc bus with five separate relay contacts so that segments of the array could be remotely connected or disconnected in five groups for battery charge control. Power leads were connected to a patch panel on the control rack where negative leads were connected through shunts to a ground bus for measuring current, and positive leads were connected to patch terminals. The batteries, the pump motor, and the instrument power inverter were also connected to this patch panel so that multiple connections and changes could be made easily. Provisions were made so that the Solenergy array could be reconnected easily for 60, 90, or 120 V.

The inverter chosen to power the instrumentation requiring ac power was made by Advanced Conversion Devices Company. The unit is rated at 1 kVA, 120 V, 60 Hz, and is designed to operate between 18 and 32 V dc. The output is a nominal sine wave with not more than 5% distortion.

3.3 PUMP SUBSYSTEM

The system used two pump-motor combinations. The first motor was chosen to work with the nominal, 28-V system for safety precautions; the second motor operated at 90 V since this was a U.S. standard for variable speed motors. Table 3-3 specifies the characteristics of these subsystems. Figures 3-7 and 3-8 present the performance characteristics of the two pumps.

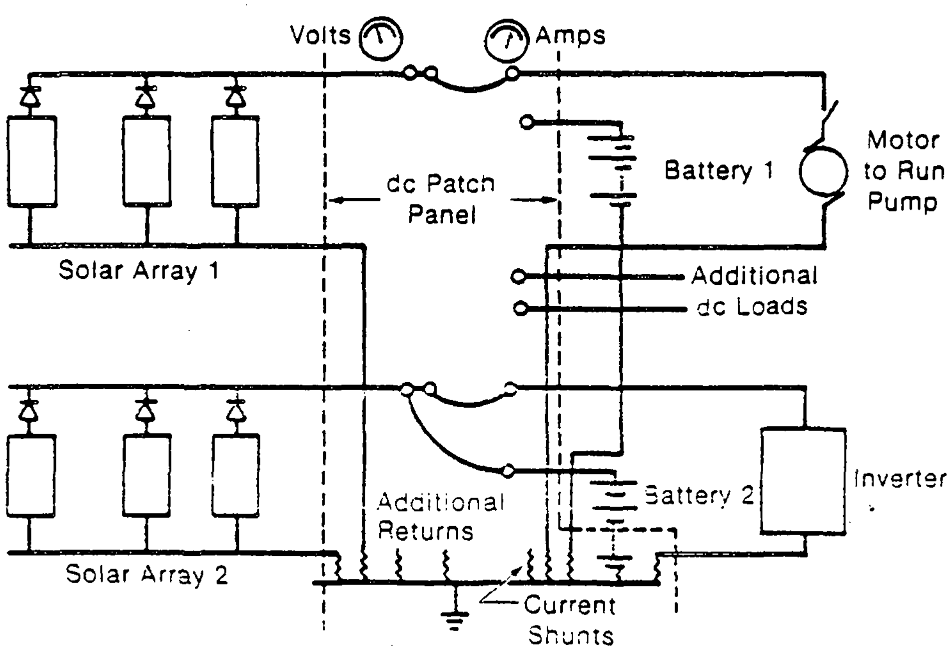

Figure 3-6. Schematic of Power Subsystem

Table 3-3. Characteristics of Motor-Pump Subsystems

	Subsystem 1	Subsystem 2
Motor		
Manufacturer	Honeywell	Honeywell
Type	BA3637-3254-48B	SR53 TEFC-56BC
Voltage	30 V	90 V
Current	24 A	9.5 A
hp	0.8	1
rpm	2600	1750
Pump		
Manufacturer	Pacific Pump Co. (PACO)	Crane-Demming
Type	L-1505.5	3914-131-0U-002
Stage	Single	Single
Inlet pipe size	1 1/2" NPT	2" NPT
Outlet pipe size	1 1/4" NPT	1 1/2" NPT
Bearings	Sealed ball	Sealed ball
Performance	See Fig. 3-7	See Fig. 3-8

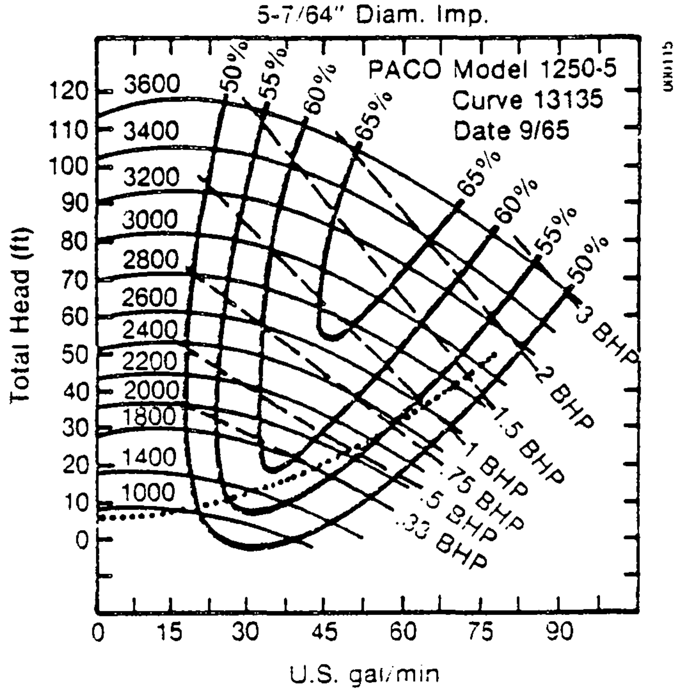

Figure 3-7. PACO Pump, Manufacturer's Data

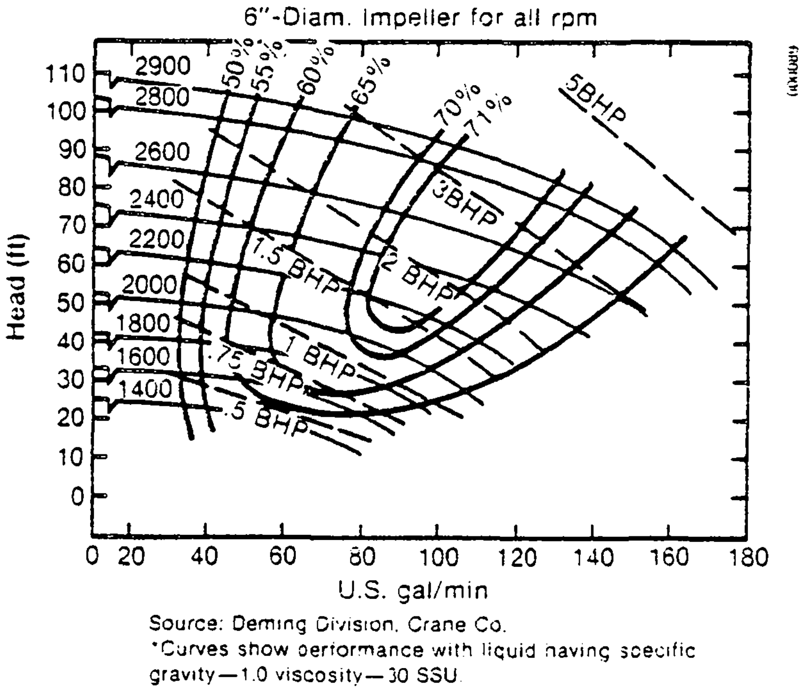

Figure 3-8. Crane-Demming Pump, Manufacturer's Data

The pumps were individually set up as shown in Figs. 3-9 and 3-10. Figure 3-10 also shows the torque sensor mounted between the pump and the motor. In this photograph, water is pumped from a tank directly under the pump and returned to that same tank. The white tank on the right was used as a measured volume to calibrate the flowmeter.

3.4 MEASUREMENT SUBSYSTEM

Figure 3-11 shows the control rack and the readout portion of the measurement subsystem. Insolation is measured with an Eppley Pyranometer mounted at the same azimuth and elevation angle as the fixed Solenergy array and is supported above the trailer on a pole that also holds the wind sensors. A digital volt meter in the top panel produces the readout which is also recorded by the data system.

The second panel produces wind speed and wind direction data. The wind sensor is mounted on a pole beside the trailer at 6 m above the ground. Wind data are also recorded by the data system so that the effects of wind cooling of the arrays can be determined.

The third panel provides visual readout of system voltages and currents. Voltages are measured at either source or load and are brought to the control rack in twisted pair shielded cables. This setup eliminates voltage drop from power lead resistance in the measurements. Currents are all measured with 50-mV shunts and a 15-uV meter calibrated to read the 50 mV full scale which negates the effect of contact resistance in the selector switch.

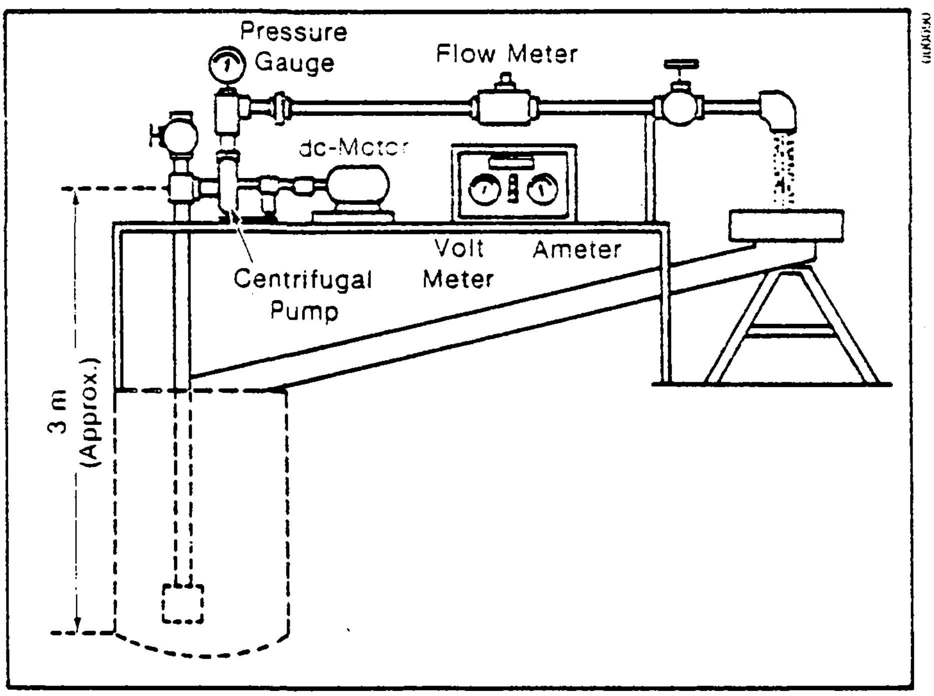

Figure 3-9. Sketch of Pump Subsystem

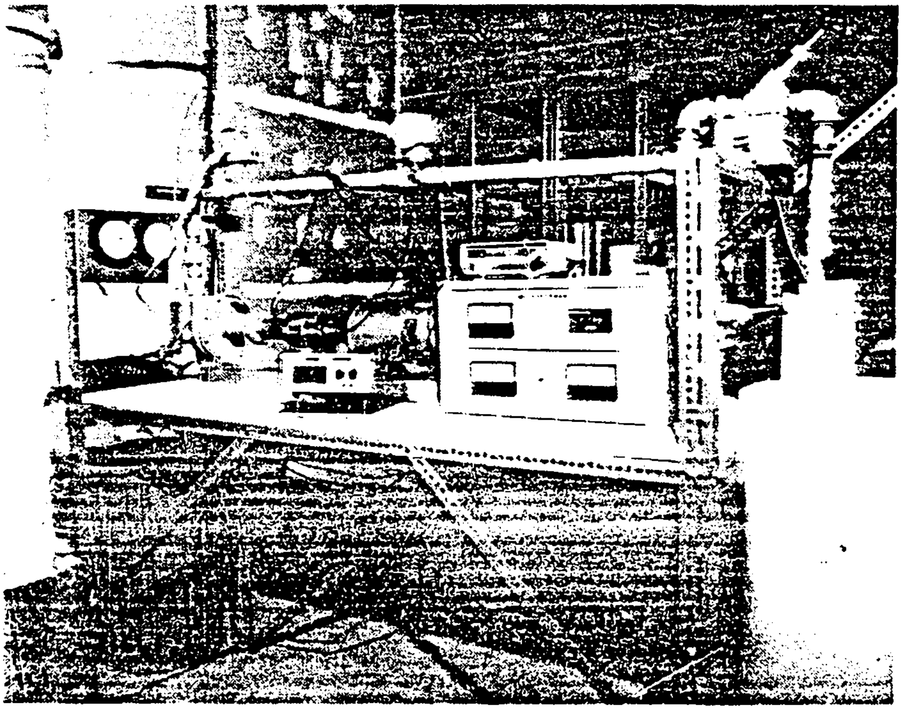

Figure 3-10. Pump Subsystem

The fourth panel contains the Auto Data 10 system. This instrument scans 100 channels at preset rates in a fraction of a second. The basic unit measures voltages but has internal, programmable computation that mathematically manipulates data to provide meaningful readouts (e.g., a thermocouple can be read out in either degrees Fahrenheit or Celsius). The instrument can record flow rate in either gal/min or L/s. It can also multiply voltage and current to give watts that can then be integrated to watt-hours or averaged over a period of time. The data system operates by remote control from a terminal, and a data cassette records data for subsequent analysis.

Instruments in the fifth panel (directly above the power patch panel) are used for pump control and monitoring. One meter presents pump pressure as a differential pressure between the outlet of the pump and the pressure in the feed pipe at water level in the storage tank. This pressure is converted to an analog voltage for meter indication on both this panel and a panel by the pump and also for recording. Flow is measured with a turbine-type flowmeter that modulates an RF carrier to provide a rotation rate that can be detected, counted, and presented digitally as shown in the local pump panel, Fig. 3-10, as well as provide an analog voltage for recording and remote readout on the control rack.

Table 3-4 lists measurements taken from the system. Appendix B lists the instrumentation of the system.

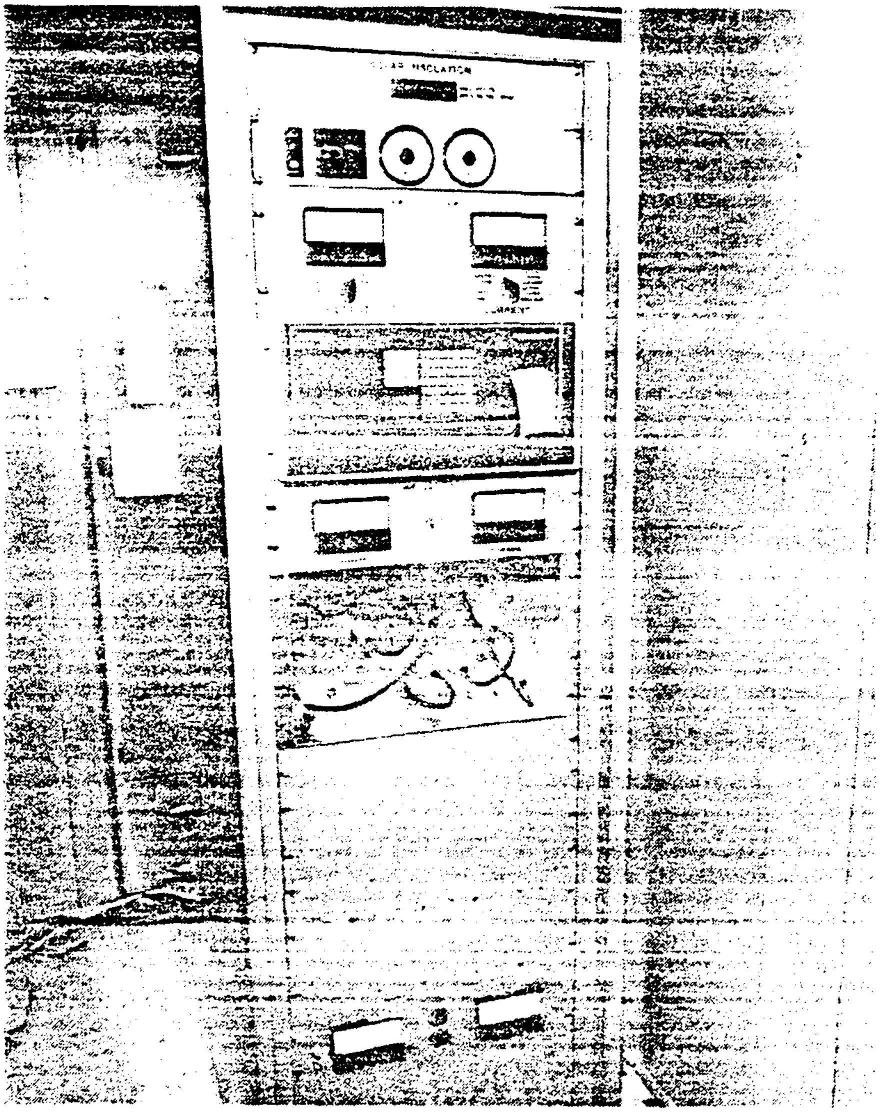

Figure 3-11. Control Rack

Table 3-4. System Measurements

Measurement	Data System Channel	Visual Presentation at Control
Pyranometer (W/m^2)	100	MV
Pyranometer, 15-min average (W/m^2)	180	--
Pyranometer (Wh/m^2)	162	--
Solar Array 1 Voltage	131	V
Solar Array 1 15-min average voltage	185	--
Solar Array 1 Current	101	A
Solar Array 1 Watt-hours	160	--
Solar Array 1 Temperature	111-112	--
Solar Array 2 Voltage	132	V
Solar Array 2 15-min average voltage	186	--
Solar Array 2 Current	102	A
Solar Array 2 Watt-hours	162	--
Solar Array 2 Temperature	113-114	--
Battery 1 Voltage	133	V
Battery 1 Current	105	A
Battery 1 Ampere-hours	163	--
Battery 1 Temperature	118	--
Battery 2 Voltage	134	V
Battery 2 Current	106	A
Battery 2 Ampere-hours	164	--
Battery 2 Temperature	119	--
Pump Voltage	135	V[a]
Pump 15-min average voltage	187	--
Pump Current	103	A[a]
Pump Pressure	107	psig[a]
Pump 15-min average pressure	183	--
Pump Flow rate	108	gpm
Pump 15-min average flow rate	184	--
Pump Total volume (gal)	167	--
Pump Watts output	168	
Pump Motor watt-hours	165	--
Pump rpm	--	a
Pump Motor torque	--	a
Pump Motor temperature	115	--
Pump Bearing temperature	116	--
Ambient Temperature at arrays	110	--
Ambient Temperature at batteries	117	--

[a]Also visually presented at pump location.

Table 3-4. Measurements (Concluded)

Measurement	Data System Channel	Visual Presentation at Control
Inverter dc voltage	136	V
Inverter dc current	104	A
Inverter ac voltage	141	V
Inverter ac current	142	A
Wind velocity (m/s)	109	mph
Wind direction (rad)	137	deg
Special instrumentation		
Counter to provide divisor for averaging	120	--
Reset to reset counter to zero	125	--
Stabilized bus voltage 20-s time constant to prevent hunting of array switching relays	139	--
Array switching relay 29.4 V	150	--
Array switching relay 29.6 V	151	--
Array switching relay 29.8 V	152	--
Array switching relay 30.0 V	153	--
Array switching relay 30.2 V	154	--

[a]Also visually presented at pump location.

SECTION 4.0

PERFORMANCE

Tests were performed on both pump subsystems in the laboratory and in the field using the solar arrays for power.

4.1 LABORATORY TESTS

The pumps were individually set up as shown in the photograph (Fig. 3-10) and run from a dc power supply so that the input power could be controlled. This also provided an opportunity to calibrate the pressure and flow rate sensors. Pressure was calibrated by parallel connection of a reference gauge and comparison of the reading. Flow rate was calibrated by diverting the flow into a calibrated vessel and measuring the time required to flow a given volume.

Data from the 30-V pump subsystem that indicated potential PV performance from manually adjusted voltages were:

- the motor would start turning at 4 V and 6 A;
- after starting, the motor would continue to run down to 2 V; and
- when the power was increased, the pump would start pumping at 850 rpm, which corresponded to 10 V and 6 A.

For the main test, the pump was run by the motor connected to the power supply. The power supply was adjusted to 30 V, and the system turned on so that water flowed. The throttling valve was then adjusted to vary the effective head on the pump and data were recorded. The test was repeated at 24 V.

Motor data were: Voltage
Current
rpm
Torque

Pump data were: Pressure
Flow rate

Computations were then made as follows:

a. Motor input watts = volts · amperes
b. Motor output watts = T · S/K

			Metric	English
where	T	= torque	N-m	in-lb
	S	= speed	rpm	rpm
	K*	=	9.549 N-m/W-rad	84.48 in-lb/W-rad

*Coefficients are derived in Appendix C.

c. Pump output watts = P • F • C

		Metric	English
where	P = pressure	kPa	lb/in^2
	F = flow	L/s	gpm
	C* =	$\frac{1\ W/s}{kPa}$	$\frac{0.439\ W/min/in^2}{lb \cdot gal}$

d. Motor efficiency = motor output × 100/motor input
e. Pump effiency = pump output × 100/motor output.

From these data (which are included in Appendix D), the average motor efficiency was 76.8% when operated at 30 V, and 79.2% when operated at 24 V. Figure 4-1 shows the pump performance during this test. The best pump efficiency was 45.5% which, when multiplied by a motor efficiency of 75.4%, gives a subsystem efficiency of 34%.

Similar tests were performed on the Crane-Demming pump operated by the 90-V motor. The pump operated at different voltages and the pressure was adjusted through a number of steps at each voltage. Appendix E gives the data obtained from these tests. This pump will start turning at 14.5 V and 1.5 A, and will start pumping at 36 V and 2.2 A, which corresponds to 650 rpm. Figure 4-2 illustrates the effect that changes in input voltage with no flow restriction have on various parameters, while Fig. 4-3 presents the change in efficiency and pressure as the flow rate varies.

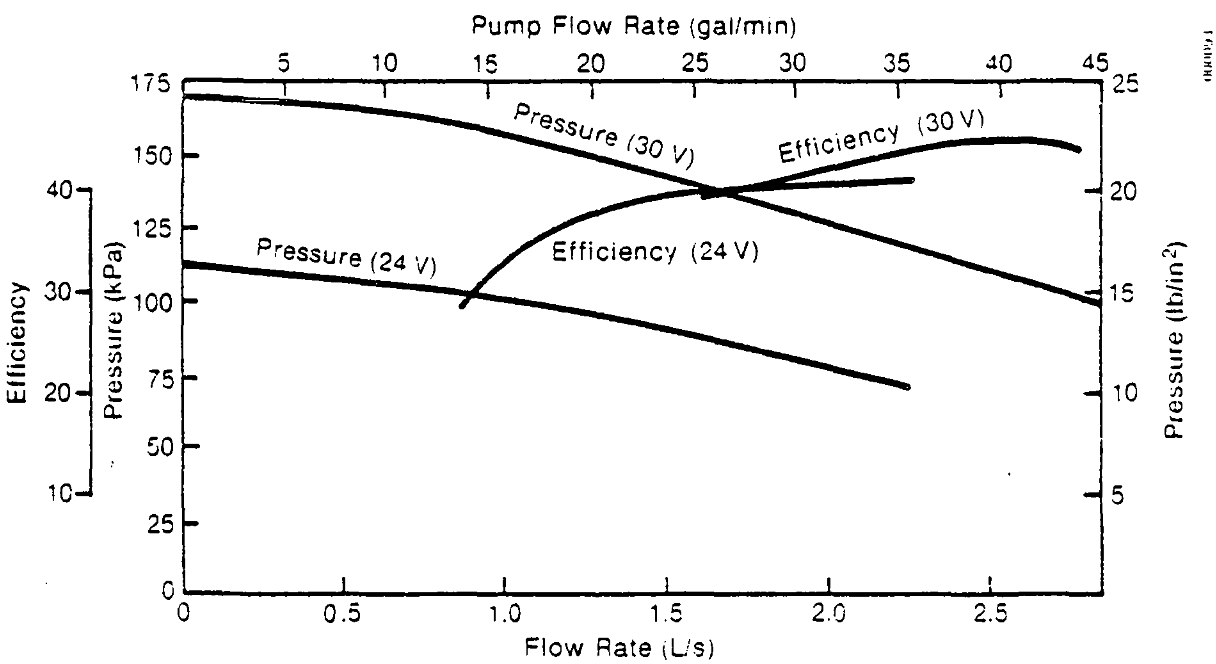

Figure 4-1. Performance and Efficiency, PACO Pump with 30-V Motor

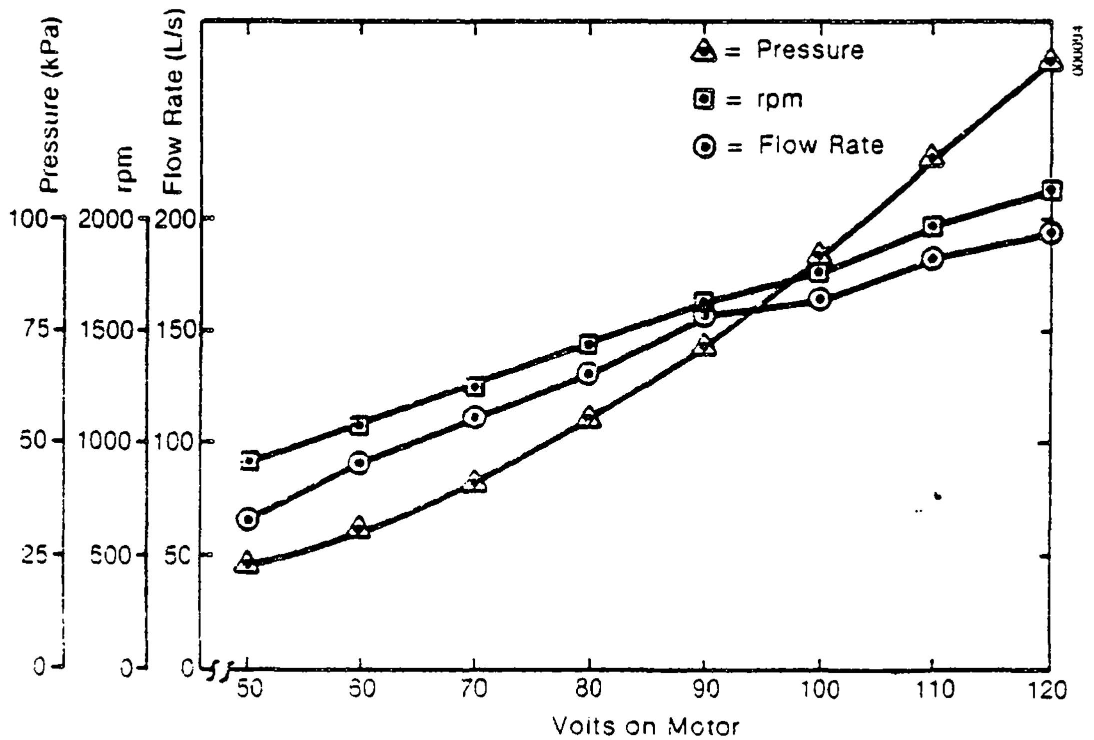

Figure 4-2. Pump Characteristics, Crane-Demming Pump with 90-V Motor

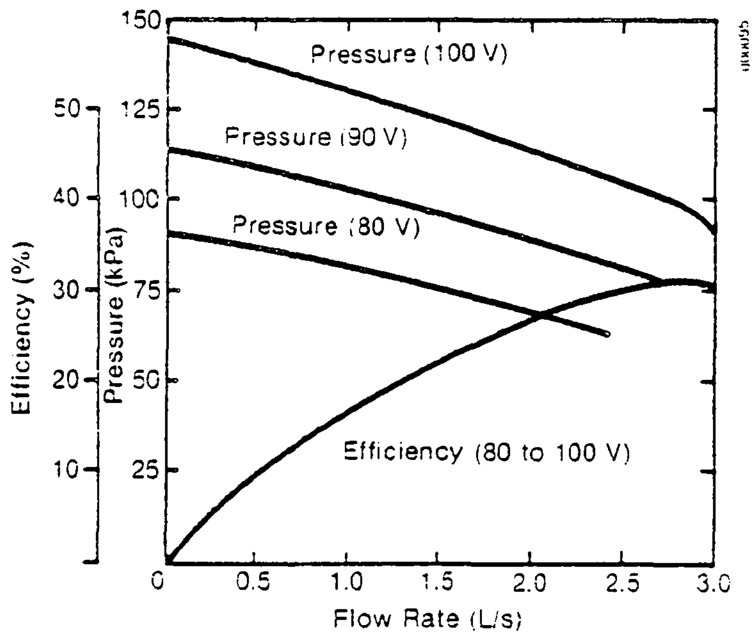

Figure 4-3. Performance and Efficiency, Crane-Demming Pump with 90-V Motor

4.2 SOLAR ARRAY TESTS

The two pump motor subsystems were each set up to operate from the Solenergy array. The pump was connected to the array and started as soon as the available insolation provided sufficient energy. A relay connected to the second array turned on the inverter to power the data system as soon as the Solarex array reached 24 V. The data system then ran on the combined battery-solar power until darkness caused the relay to drop out.

4.2.1 Solar Array Tests on PACO Pump with 30-V Motor

Figure 4-4 plots the performance of the subsystem in a group of current-voltage (I-V) curves of the solar array. These results may be compared with the typical specification for the motor performance shown in Fig. A-1.

Current and voltage increase with insolation along line R representing the effective resistance of the armature and brushes. At point T there is sufficient torque to start the motor turning. Generation of back EMF rapidly increases the voltage on the solar array and the motor with little increase in the current. At point P the pump starts pumping and increases directly with insolation. From the curve it is apparent that the motor would have matched the array more efficiently if it had operated at its 30-V rating instead of at 25 V.

Figures 4-5, 4-6, and 4-7 show the data that resulted after operating the pump for a complete day. These figures show the variation of the insolation, the power generated by the array, and the flow rate of the pump with respect to the time of day. Figure 4-8 shows the change in solar array voltage with respect to insolation. This voltage was about 1 V above the motor because of resistance losses and one diode drop. The double curve resulted because the temperature of the array was warmer in the afternoon so that the voltage was lower for the same value of insolation. This effect is discussed in detail in Sec. 4.3.2 in conjunction with tests on the Crane-Demming pump when temperatures were recorded.

The sharp rise in the voltage curve at 350 W/m^2-insolation was caused by the back EMF of the motor. Below this insolation the motor does not rotate and the voltage drop was caused by resistance of the armature and brushes. After the motor started, the back EMF allowed the voltage across the array to increase (Figure 4-4 also showed this relationship). Figure 4-9 presents 15-min average flow rate change with voltage on the solar array; the pump started pumping at 7 to 8 V. This flow rate is also plotted against insolation in Fig. 4-10 and again shows the point that pumping started.

The pressure at the pump outlet was referenced to the pressure in the pipe at the water level in the simulated well tank. When the pump is stopped or running below pumping speed, the head of water between the pump and the water level in the tank represents a positive pressure on the reference side of the sensor against atmospheric pressure on the normal pressure side. This is the negative pressure shown in Fig. 4-11. The pressure goes through zero after the pump starts pumping at about 10 V, and creates enough flow to attain atmospheric pressure in the pipe at water level. As flow increases, the pressure increases.

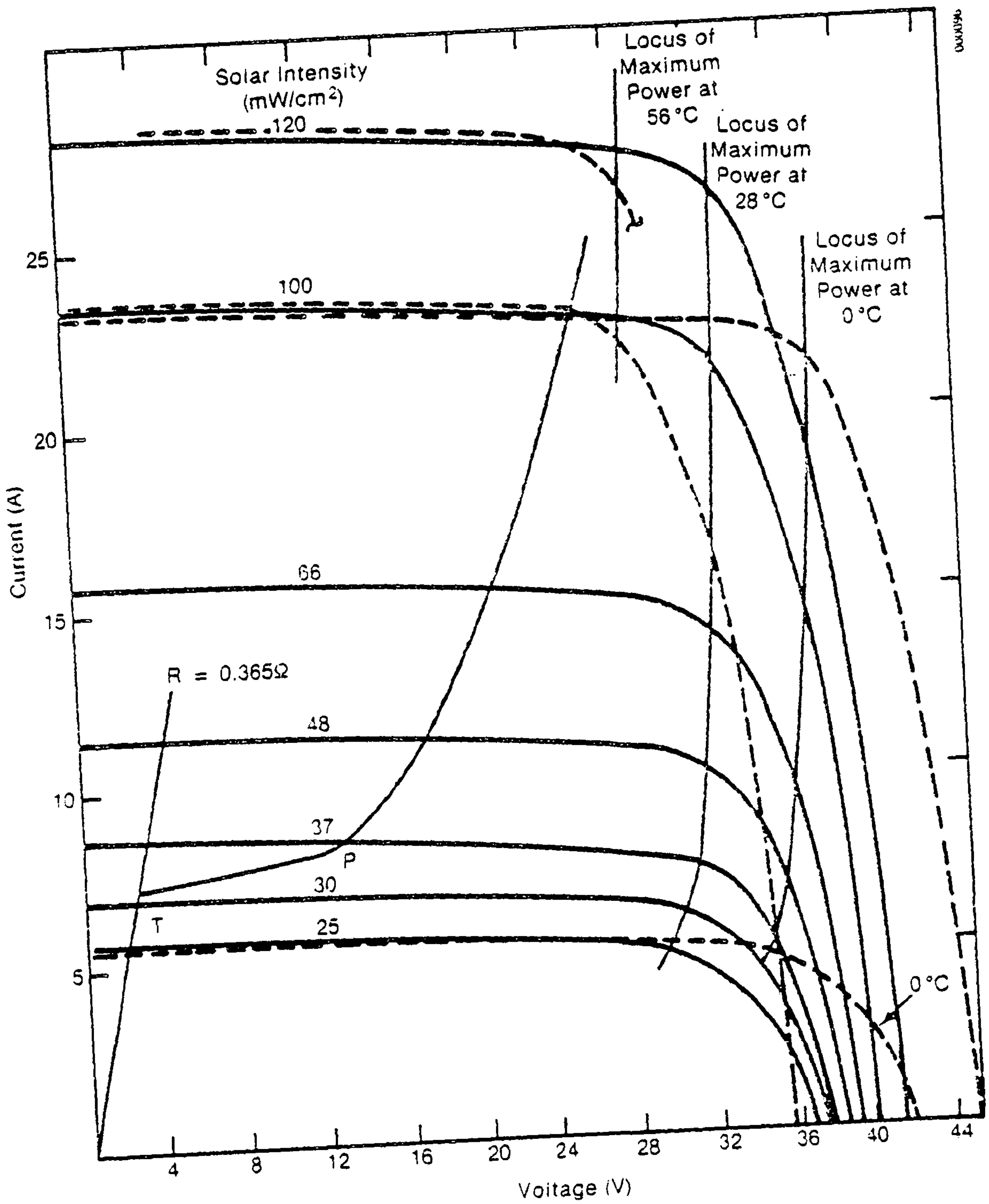

Figure 4-4. Operating Characteristics of 30-V Motor with Solar Array

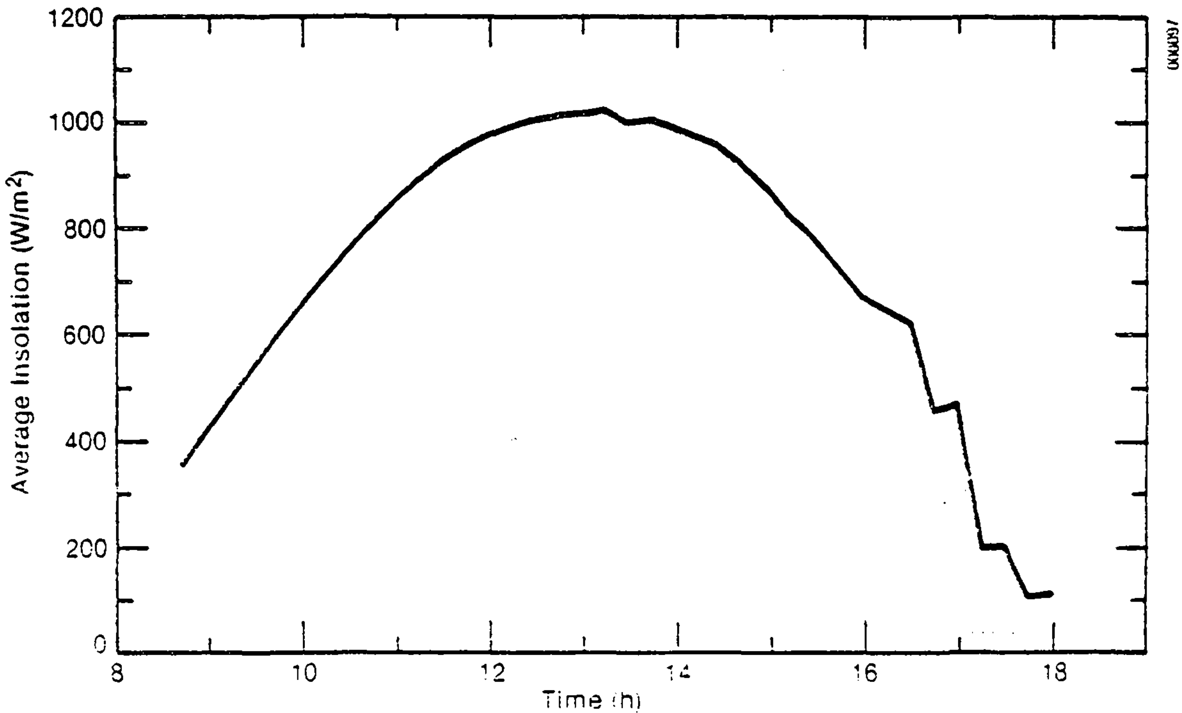

Figure 4-5. Insolation vs. Time, PACO Pump Test

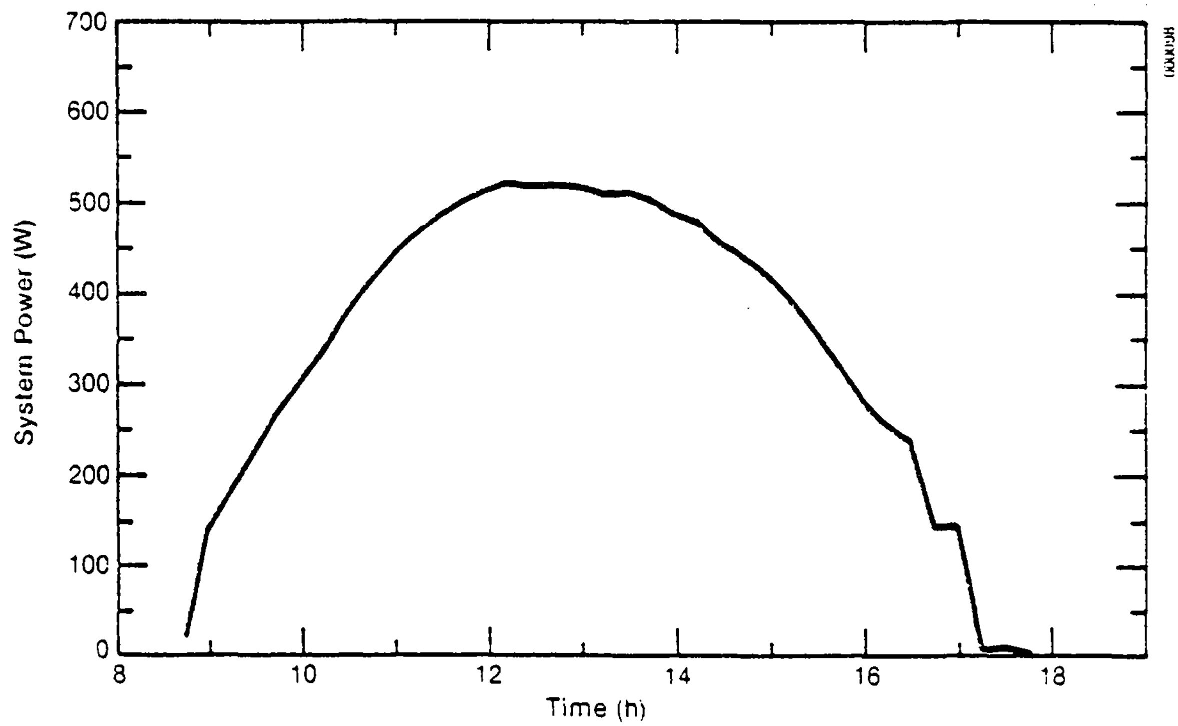

Figure 4-6. Solar Array Power vs. Time, PACO Pump Test

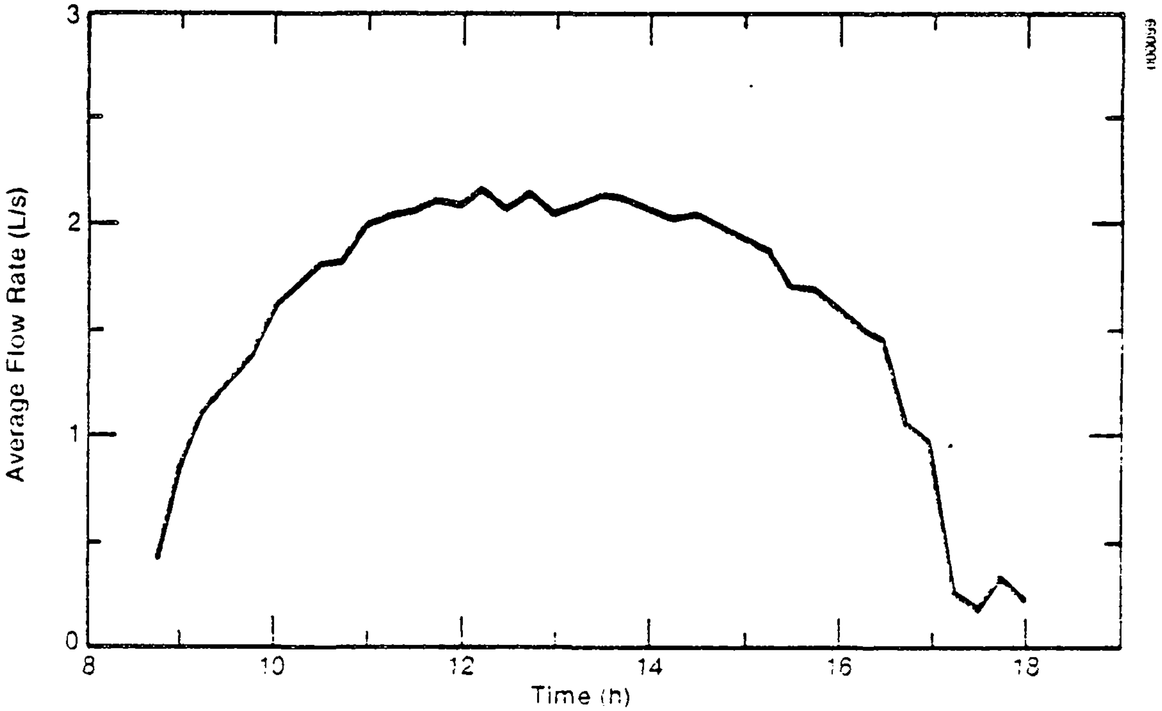

Figure 4-7. Water Flow vs. Time, PACO Pump Test

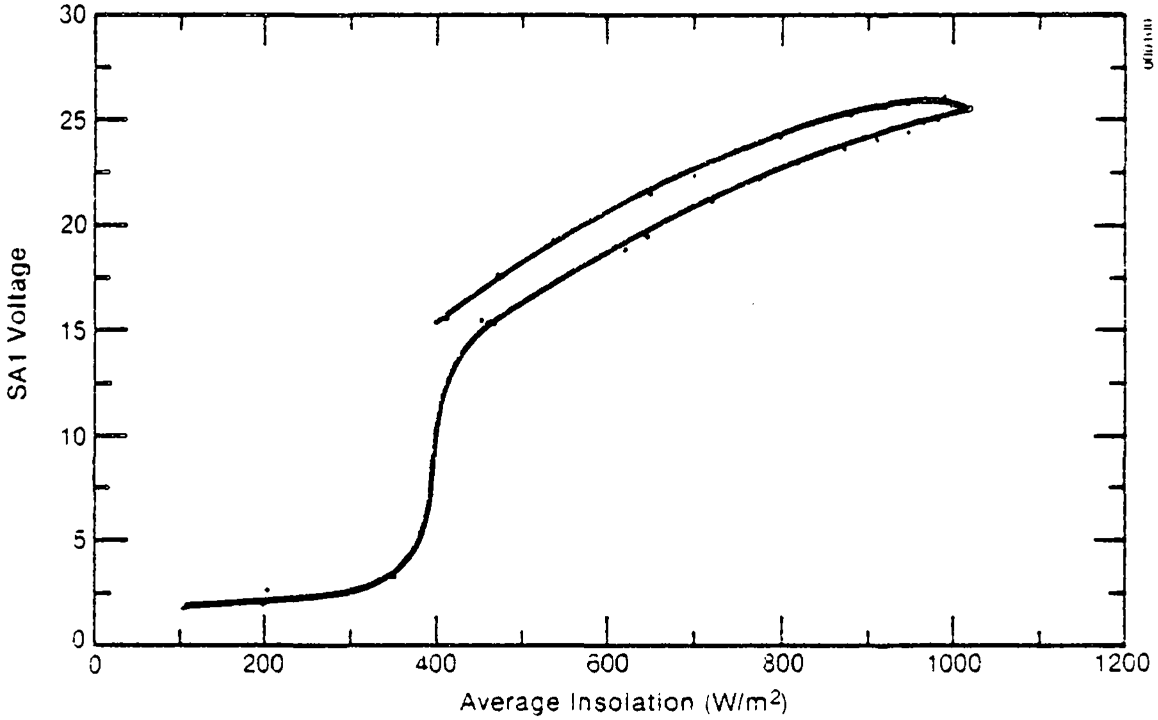

Figure 4-8. Solar Array Voltage Change vs. Insolation, PACO Pump Test

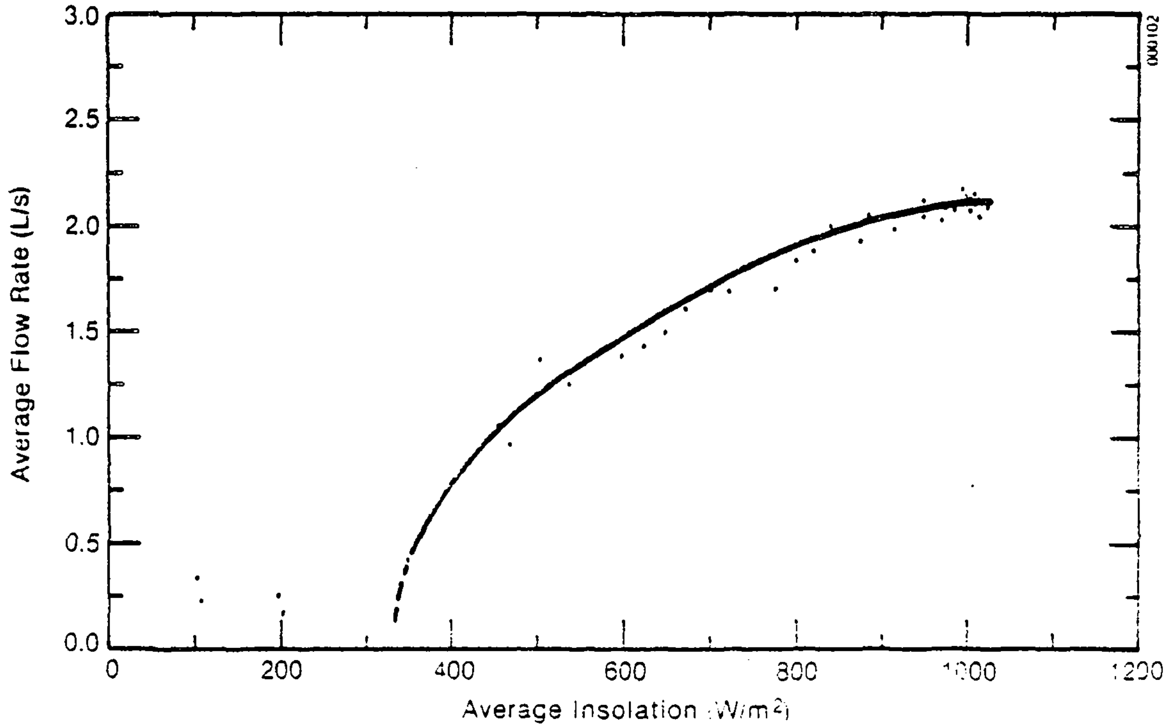

Figure 4-9. Average Flow Rate vs. Voltage, PACO Pump Test

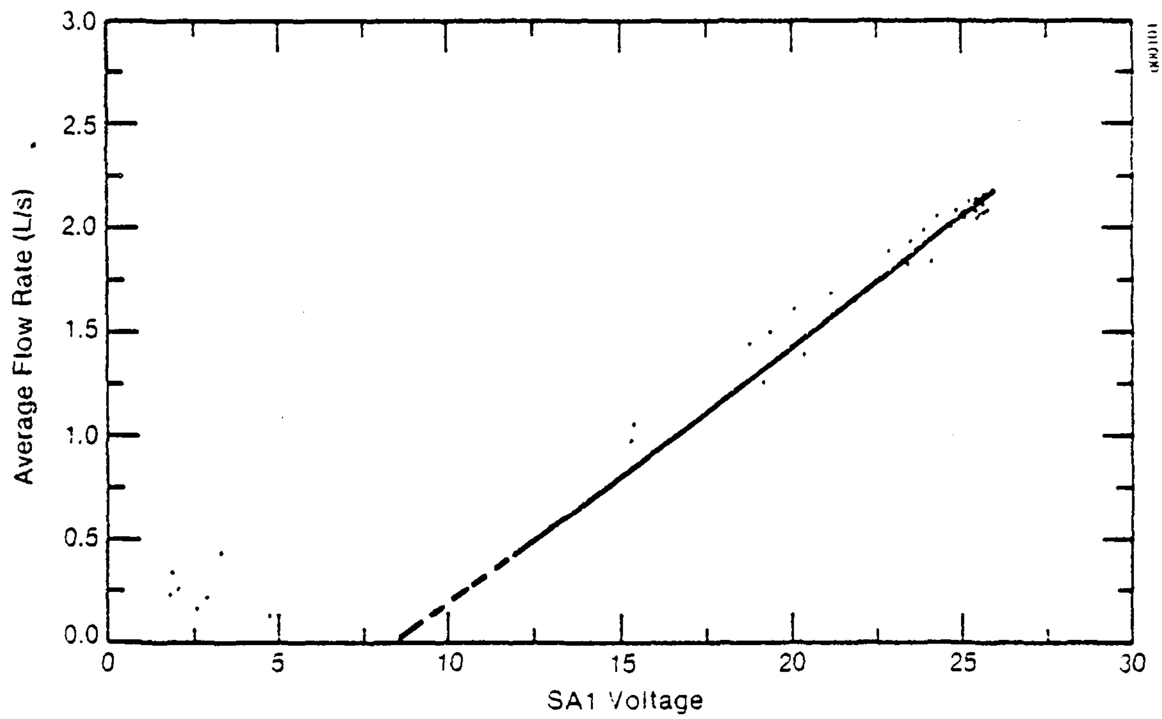

Figure 4-10. Average Flow Rate vs. Insolation, PACO Pump Test

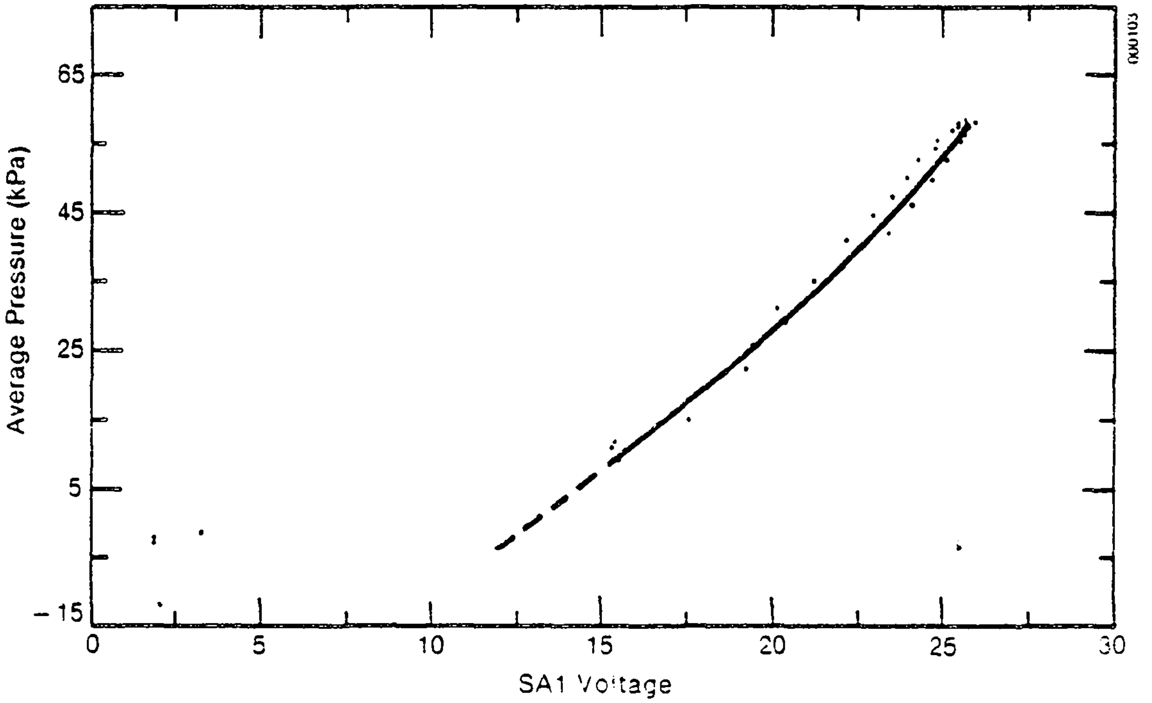

Figure 4-11. Average Pressure vs. Voltage, PACO Pump Test

4.2.2. Solar Array Tests on Crane-Demming Pump with 90-V Motor

Starting tests similar to those made on the PACO system were performed on the Crane-Demming pump-motor system. Figure 4-12 illustrates the characteristic curves of the Solenergy array reconnected to generate 90 V, overlaid with the operating line of the motor driving the pump. As insolation increases to 12.5 mW/cm^2, the current increases toward point R, which represents the resistance of the armature and brushes. When the current reached 1.2 A, the 0.28-N-m starting torque is achieved, and the motor starts. Rotation generates a back EMF which quickly increases the array voltage. Pump speed, voltage, and current all rise with increased insolation to point P where the pump starts moving water. As insolation increases, the operating curve passes through the maximum power point of the array that promotes maximum efficiency of the array-motor combination.

Data on the Crane-Demming pump were taken on numerous days, all with some cloud cover. Figure 4-13 shows the time variance of insolation on 9 September 1981; Fig. 4-14 shows the system power delivered by the solar array to the motor with respect to time. The flow rate created by the pump with this insolation and power is illustrated in Fig. 4-15. The average voltage of the solar array is about 1 volt above the pump voltage because of the isolating diode and loss in the leads. The variance of 15 min averages of

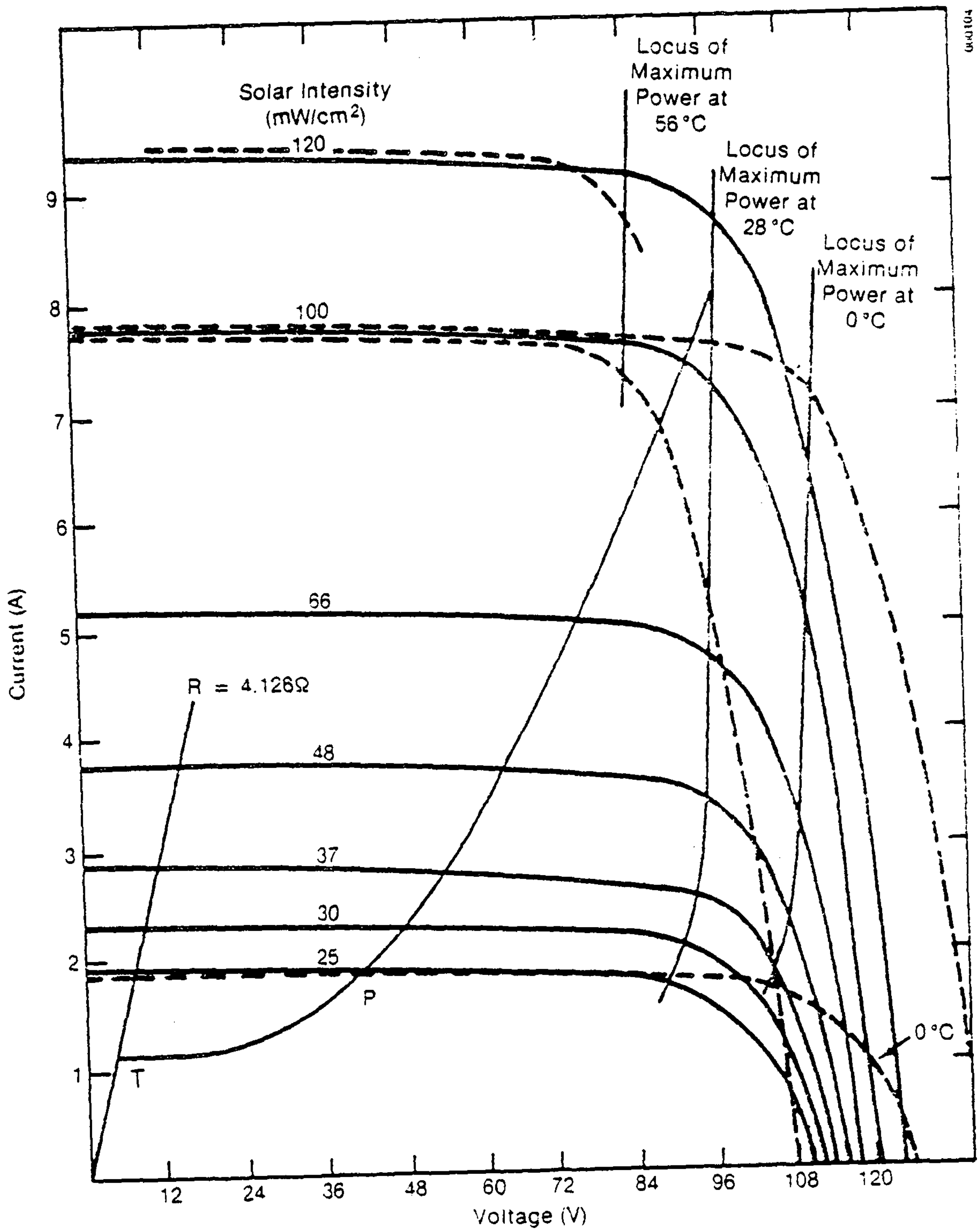

Figure 4-12. Operating Characteristics of 90-V Motor with Solar Array

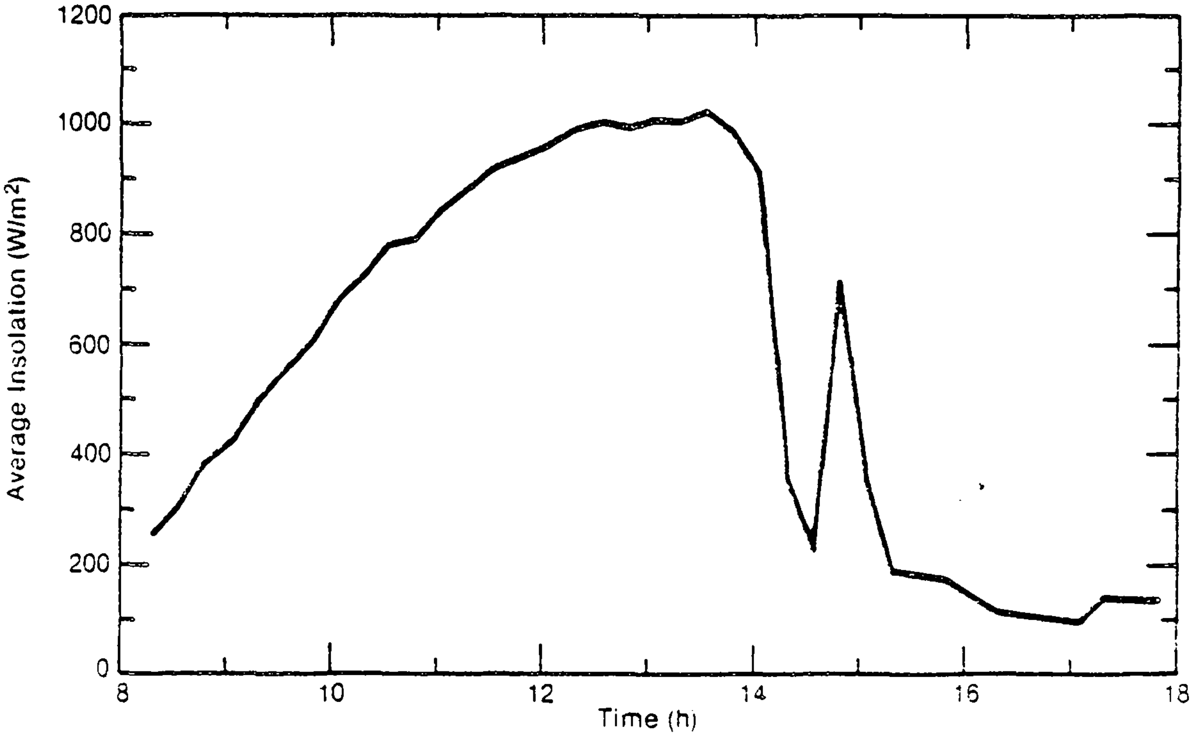

Figure 4-13. Average Insolation vs. Time, Crane-Demming Pump Test

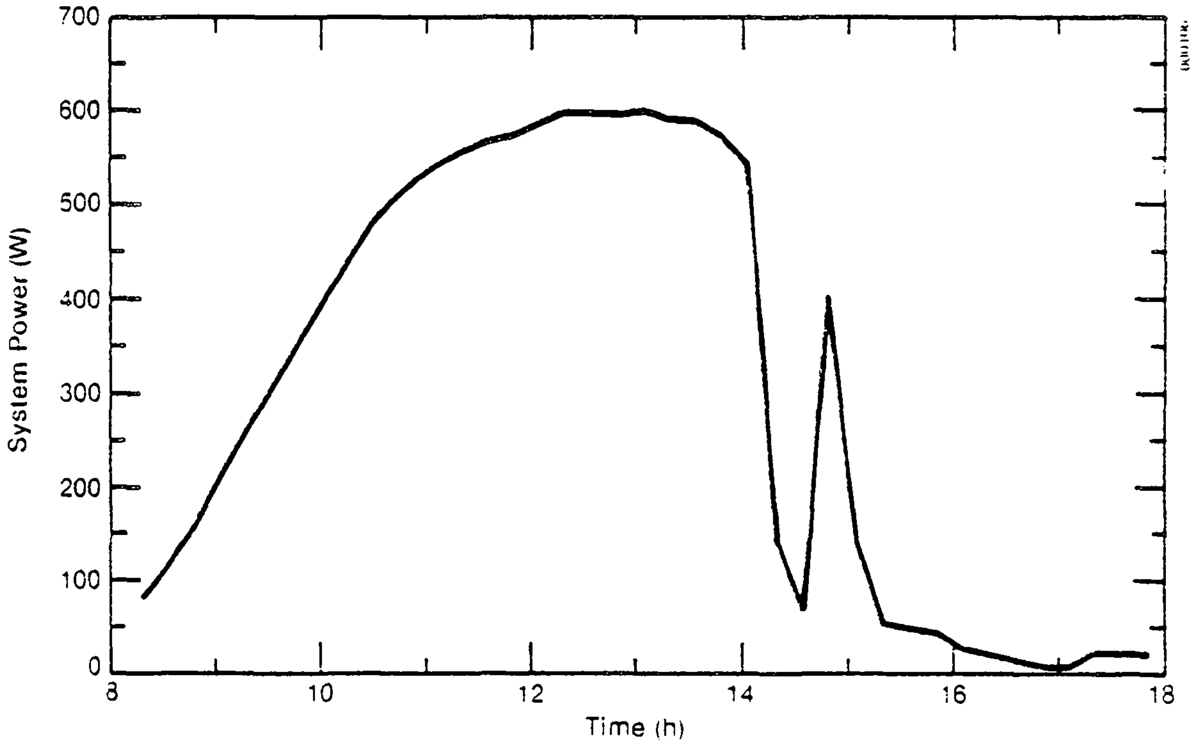

Figure 4-14. System Power vs. Time, Crane-Demming Pump Test

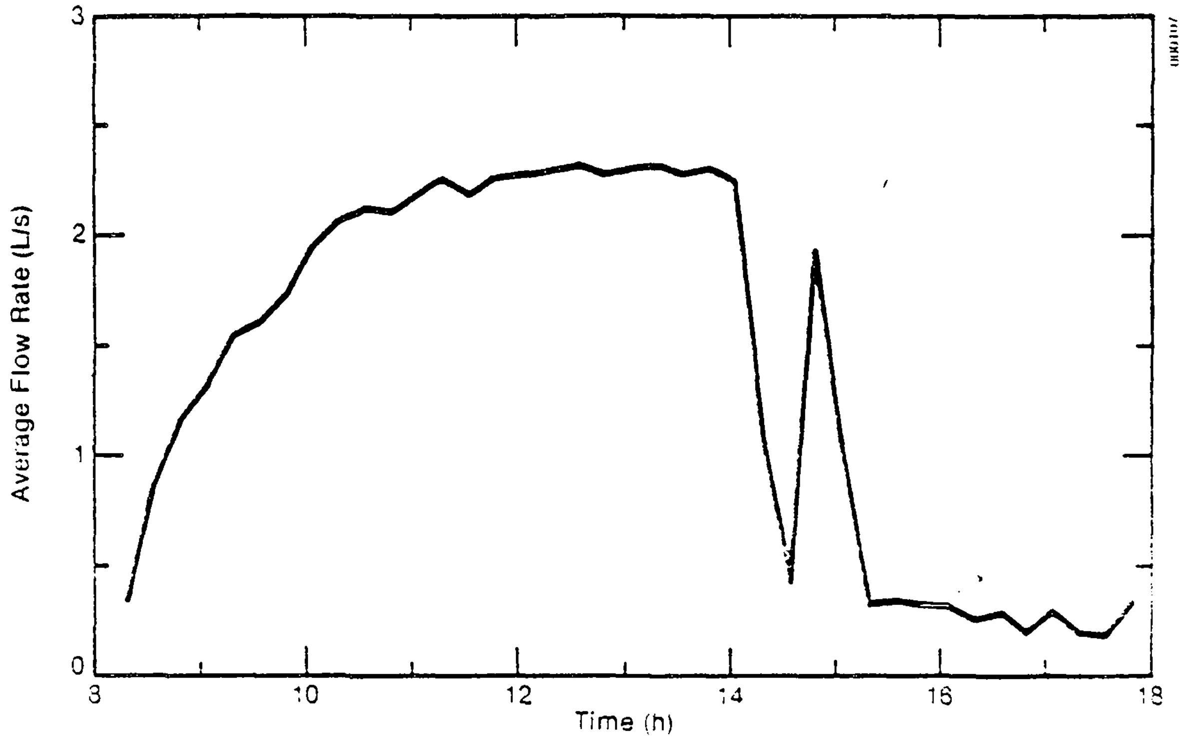

Figure 4-15. Average Flow Rate vs. Time, Crane-Demming Pump Test

this voltage with insolation is shown in Fig. 4-16. A fast increase in voltage occurred at 100 W/m^2 solar irradiance because of an increase in back EMF caused by speed up of the motor (Fig. 4-12). The flow of water started at about 40 V and increased linearly with voltage (Fig. 4-17). The indicated flow rate, below the voltage required to create pumping speed, is caused by system noise in the radio frequency flow rate sensor. This is demonstrated more clearly in Fig. 4-18 where flow rate is plotted against insolation. The variance of pressure with respect to solar array voltage is identified in Fig. 4-19, which shows an apparent negative pressure at the start as was explained for the PACO pump.

Figure 4-20 shows a voltage-insolation curve from data collected on a day when there was little wind and few clouds. The temperature of the array is plotted on the same sheet and explains how two different voltages are obtained for the same value of insolation. When the array is cold, the voltage is higher. This effect was demonstrated on the characteristic curves of the array in Fig. 4-12 and for the PACO pump in Fig. 4-8.

4.3 COMPARISON OF PUMP PERFORMANCE

Because the data were collected in the autumn, rain clouds and sometimes rain were frequently present each afternoon. This condition prevented a realistic comparison of pump systems on a total volume basis. Since total power and total volume pumped varied with daily insolation, data from one day to the next were compared on a volume/kWh basis. These results are given in Fig. 4-21; the first three bars represent the PACO pump and the last four bars represent the Crane-Demming Pump. The variations are primarily due to measurements of insolation below pumping speed, which contributed to input but not to output.

Sir William Harcrow and partners* recently completed a study on water pumping for the World Bank. Table 4-1 is an excerpt from that report with four additional lines showing similar data from the two SERI-tested pump systems. One set of data represents tests and another set represents manufacturers' sales data. From these data it can be seen that the SERI pumps had a slightly larger flow rate than the majority of those tested by Harcrow et al., and were lower in efficiency at low head but higher in efficiency at high head. Typically, the larger the centrifugal pumps, the more efficient they can be made. Clearances represent a smaller percentage of cross sectional area and more care goes into the design because of increased cost. Special purpose pumps generally have higher efficiency than commercial pumps but their cost is also much higher.

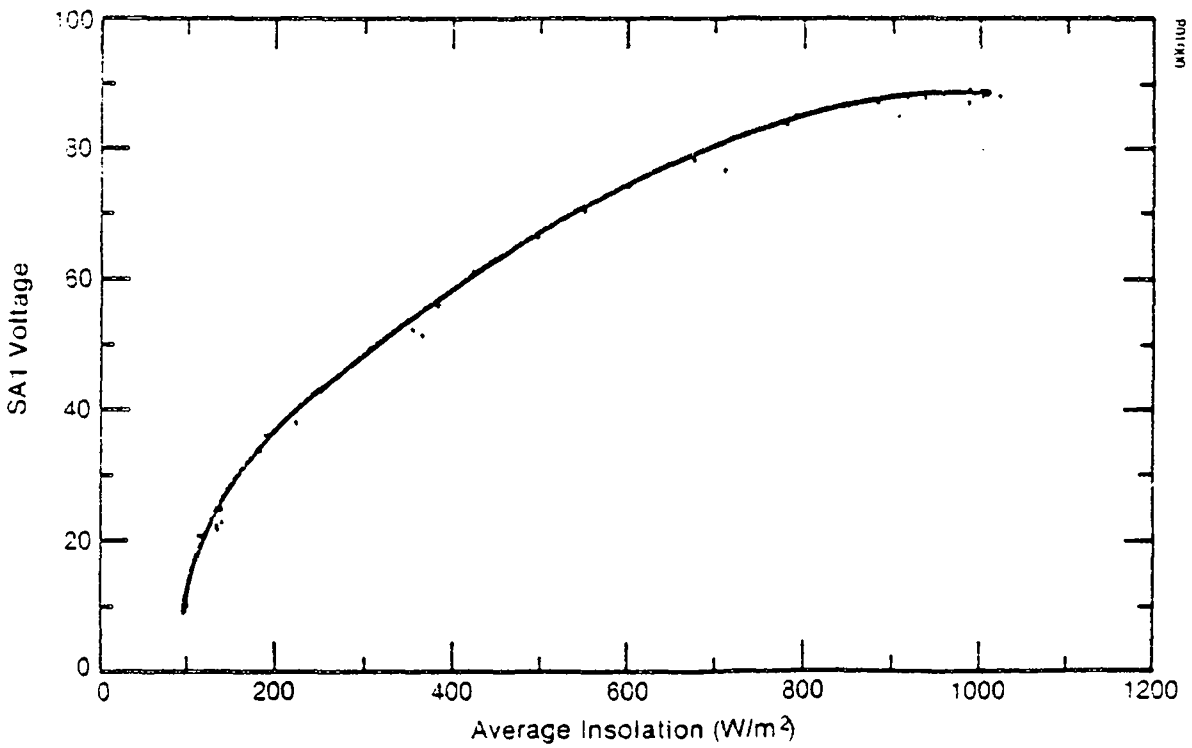

Figure 4-16. Average Array Voltage vs. Insolation, Crane-Demming Pump Test

*Sir William Harcrow and partners, in association with the Intermediate Technology Development Group Ltd. 1981 (July). Small-Scale Solar-Powered Irrigation Pumping Systems": Phase 1. UNDP Project GLO178/004. London.

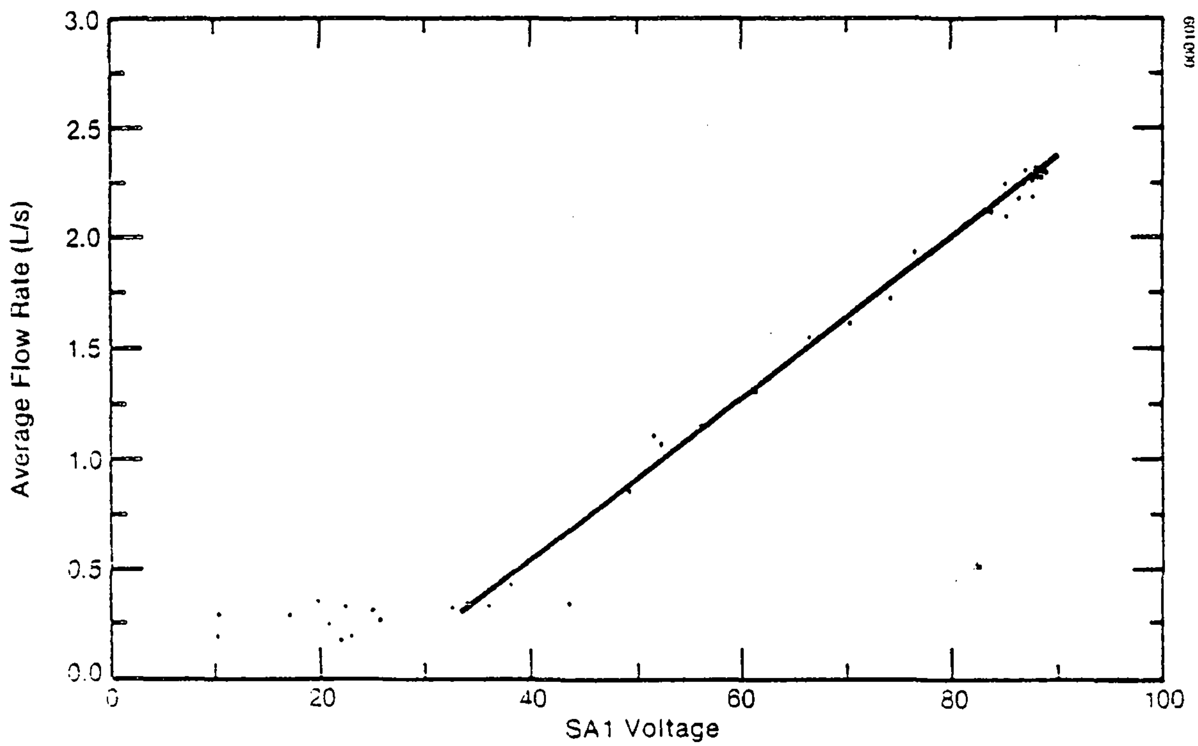

Figure 4-17. Average Flow Rate vs. Solar Array Voltage, Crane-Demming Pump Test

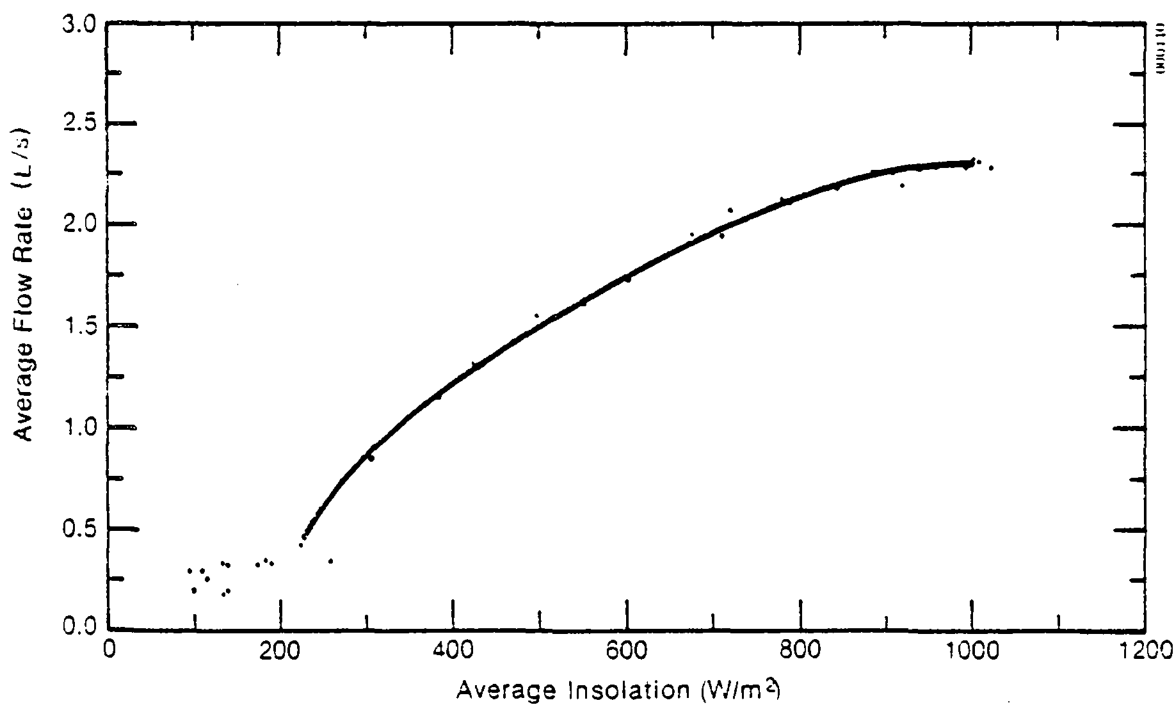

Figure 4-18. Average Flow Rate vs. Insolation, Crane-Demming Pump Test

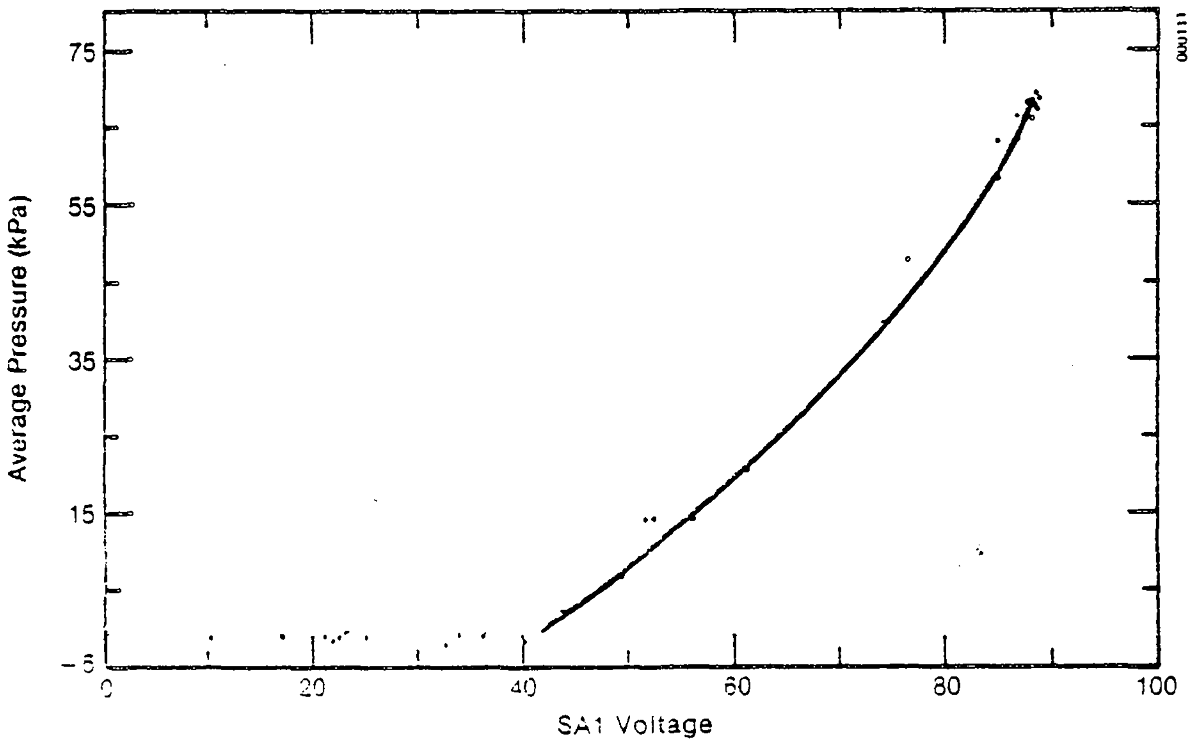

Figure 4-19. Average Pressure vs. Solar Array Voltage, Crane-Demming Pump Test

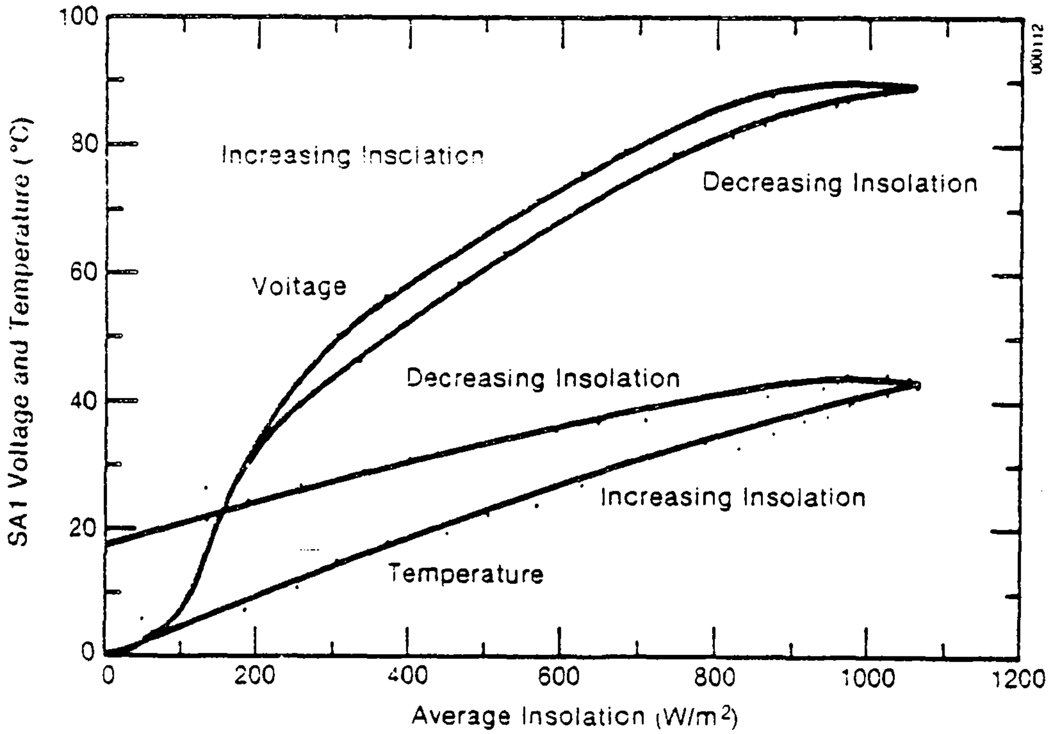

Figure 4-20. Average Voltage and Temperature vs. Insolation

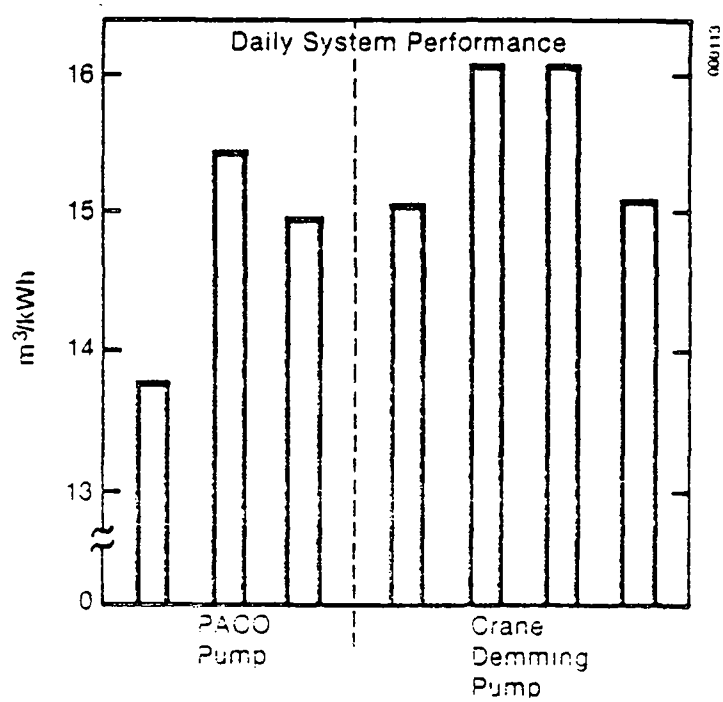

Figure 4-21. Pump Performance Comparison

Table 4-1. Comparison of Pump Characteristics

Supplier	Pump	Type	Speed Range (rpm)	Starting Torque (N-m)	Best Efficiency (%)	Speed For BEP[a] (rpm)	Head For BEP[a] (m)	Flow For BEP[a] (L/s)	Self-Prime
ARCO Solar	Sta-Rite J 1/3 hp	Centrifugal	3250 to 2000	0.09	46	2750	9	1.3	No
Briau	Briau MCV-40-1	Centrifugal	2250 to 1500	1.25	>38[b]	2250	5	1.65	No
ITC Solar Corporation	Roth 107	Regenerative	1750 to 700	0.39	>35	1250	7	0.65	Yes
Omega Segid	Essa Mico	Centrifugal	2270 to 1850	no data	23[d]	2270	3.3	0.55	Yes
Photowatt	Breguest KSB	Centrifugal	1400 to 1000	0.24	[illegible][d]	[illegible]	5.3	1.45	No
Pompes Guinard	Alta KS 600/12	Centrifugal	1900 to 1400	0.23	52	1900	10.5	2.15	No
Solar Electric International	KSB M	Centrifugal	2600 to 2200	no data	[illegible]	[illegible]	[illegible]	[illegible]	Yes
Godwin	Godwin Cobra	Centrifugal	2000 to 3000	0.30	[illegible]	[illegible]	9	[illegible]	Yes
SERI Test[c]	PACO 1250-5	Centrifugal	2670 to 950	0.45	26.3	2470	10.7	2.0	No
SERI Test	Crane-Demming	Centrifugal	2130 to 850	0.28	31.5	1810	9.5	2.0	No
PACO[d]	PACO 1250-5	Centrifugal	3600 to 1300	no data	65[d]	3600[d]	20[d]	[illegible][d]	No
Crane[d]	Crane-Demming	Centrifugal	2900 to 1400	no data	[illegible][d]	2900[d]	26[d]	7.2[d]	No

[a]BEP = best efficiency point

[b]Optimum head exceeds range covered by tests so significantly higher efficiencies may be possible.

[c]Evidence of pump damage which may account for low efficiency

[d]Manufacturer data pump only

SECTION 5.0

CONCLUSIONS AND RECOMMENDATIONS

The experiment showed that commercial pumps and motors that are available off-the-shelf as standard equipment from reputable manufacturers can pump water with reasonable efficiency. The standard units can be matched to a solar array to effectively use photovoltaic energy. The pump systems are self-starting with adequate insolation and do not need to be supplemented with maximum power trackers or batteries. As the cost of solar arrays decreases because of SERI/DOE research and development and because of mass production, the portion of the system cost represented by the pump and motor will effectively increase. Use of low cost units such as those tested will then materially decrease the overall system cost, and the simplicity and reliability of the systems will increase life expectancy.

The most important consideration in system design is the match between the pump motor and the solar array; that is, the operating point of the motor under load must correspond with the loci of maximum power points on the array over the majority of the pumping speed range. The second most important factor is selection of the pump to match the conditions of variable speed, needed head, and maximum flow. Pumps with high efficiency over a wide speed range are desirable as well as pumps with speed curves that parallel the head axis on the head-versus-flow curves. Pumps with speed curves that parallel the flow axis will easily lose suction when speed decreases. Self-priming pumps are slightly less efficient than those that are primed. If a pump operates in a location where it can be checked each morning to ensure that it starts pumping when the sun comes up, the higher efficiency pump is recommended. If the pump cannot be checked frequently, or if the available technology does not have the capability of priming the pump, a self-priming pump is recommended. There is always the possibility of a grain of sand or a piece of vegetation getting caught in a foot valve and allowing the prime to be lost overnight or during cloud cover. If a self-priming pump is used, the foot valve and the resulting friction head loss through it can be deleted, possibly compensating for the lower efficiency of the pump.

This effort was conducted solely on low-head pumps. A similar effort should be undertaken to find and evaluate deep well pumps necessitating the use of submersible motors. As high-power electronics develop, the use of brushless dc motors in the 1-hp range should be investigated. Methods of adapting variable speed controls used for ac motors should be investigated for starting an ac pump motor with low insolation and maintaining it at maximum speed consistent with available insolation throughout the day. Deep well pumps need to be evaluated for different depths when run at variable speeds. Axial flow pumps may be more efficient at intermediate depths of 5 to 30 m than the multistage turbine pumps required for depths over 30 m.

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APPENDIX A

MOTOR-SOLAR ARRAY PERFORMANCE REQUIREMENTS

Figure A-1 represents the response curves of a solar array that provides power for a dc motor and pump load. The family of solid curves indicates the performance at 28°C and varying insolation intensities. The lower intensities represent periods close to sunrise or sunset. The value 100 mW/cm^2 represents nominal noon intensity and 120 mW/cm^2 represents intensities at noon on an exceptionally clear day, such as the day following a snowstorm. Dashed line curves show performance at 0° and 56°C at 100 mW/cm^2, 56°C at 120 mW/cm^2, and 0° at 25 mW/cm^2.

The point on any temperature-intensity curve at which the array operates is a function of the connected load. The optimum place to operate on the 120 mW/cm^2-56°C curve is point A, the maximum power point. Points B and C represent the most likely maximum power points for normal operation of the array. Point C is the design power at 768 W. The loci of the maximum power points for 0°, 25°, and 56°C are shown crossing the intensity curves.

If a motor that was mechanically coupled to a centrifugal pump were connected directly across the arrays, the desired motor performance, with respect to the array, is shown by the circle dotted line curves.* The sloping line from the origin to R represents the dc resistance of the armature with no rotation. This is arbitrarily shown as 0.33 ohms (4 V and 12 A). As the intensity increases after sunrise, the current through the armature increases to point T where sufficient torque is built up to start rotation. When rotation starts, the back EMF generated in the armature raises the voltage as the speed increases to point P. At this point, sufficient load is imposed on the motor by the pump to stabilize speed, current, and voltage which will not increase until the solar intensity rises and provides more power. As more power is available, both current and voltage increase until the maximum power available is achieved. For maximum operating efficiency, the motor driving the pump should operate at the maximum power point of the array as much as possible. The motor performance curve should ideally become parallel to and lie between the loci of maximum power points at 56° and 28°C for all intensities above 48 mW/cm^2.

*For a more detailed discussion on the performance of motors directly connected to solar arrays, see: J. A. Roger. 1979. "Theory of Direct Coupling Between DC Motors and Photovoltaic Solar Arrays." Solar Energy. Vol. 23; pp. 192-198.

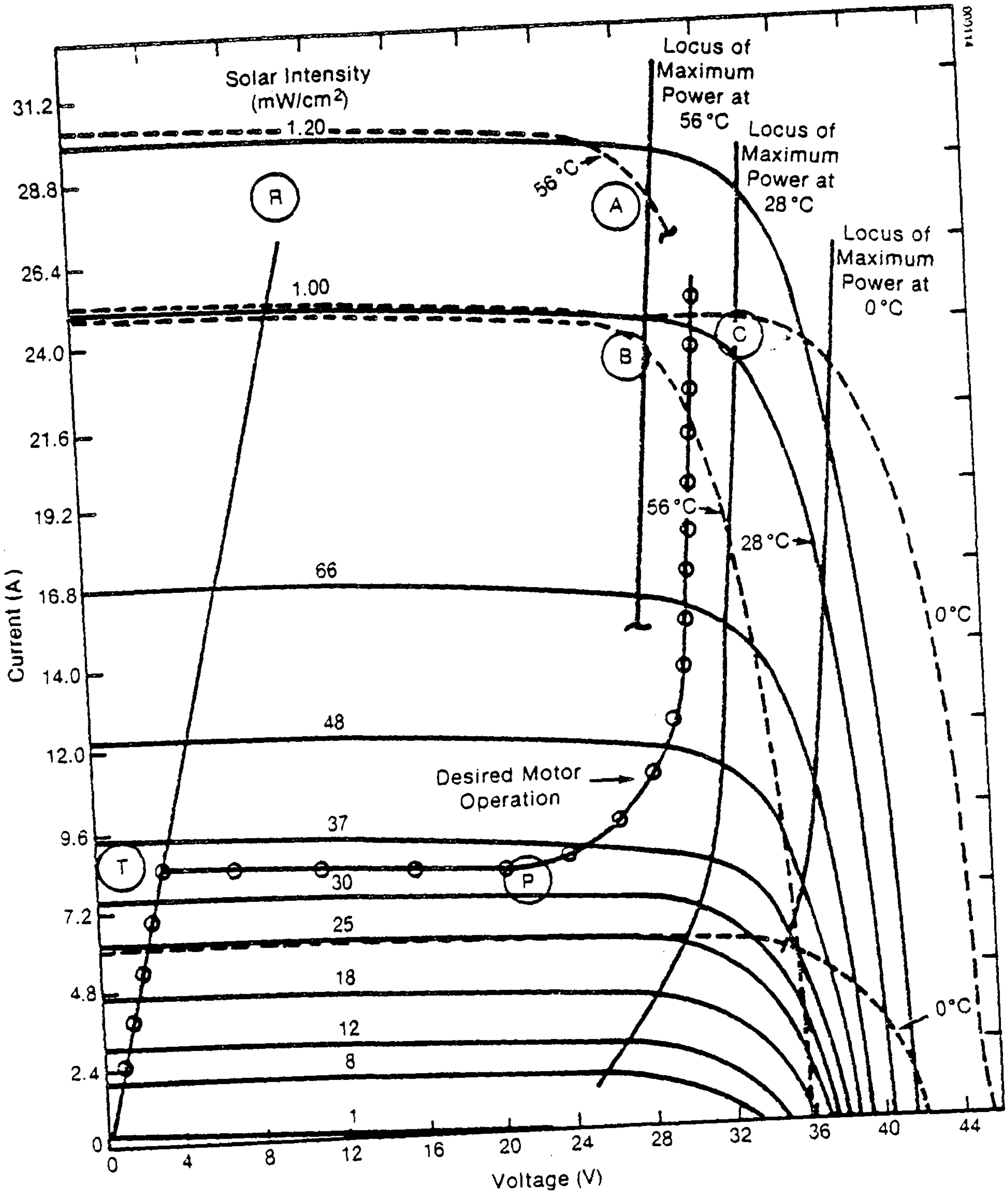

Figure A-1. Response Curves of a Solar Array

APPENDIX B

EQUIPMENT LIST

Equipment	Company	Model	Serial Number
Pyranometer	Epply	PSP	19381F3
Wind	R. M. Young	Propvane 35403C	None
Pressure	Robinson Halpern	152B-P130D-F-V-41	4340
Flow	Flow Technology	FT-20NK-90LJGO LFA-303-KLX	2B800 50115
rpm/Torque	LeBowe	1104-500	1404
Voltage	Simpson Type 524	15114	NA
Current	Simpson Type 524 15μA Simpson Shunt 50A 50MV	15092 6709	NA NA
Data System	Accurex	Auto data 10	3-365
Data Recorder	Techtran	817TI	4986/4987
Thermocouple	Gordon	T-24-1-CU504	NA
Battery	Gould	George Power 24	NA
Battery	C&D	6QP75-5	NA
Motor (30 V)	Honeywell	BA3637-3254-48B	None
Pump	Pacific Pump Co. (PACO)	11-12505-701091	FSB65182
Motor (90 V)	Honeywell	SR532-2212-56BC	None
Pump	Crane-Demming	1 1/2 8 F6	181

APPENDIX C

COMPUTATIONS AND CONVERSIONS

a. Watts = volts • Amperes

b. Watts, motor out = Torque • rpm/K

$$= T(\text{in-lb}) \cdot \frac{\text{ft}}{12\ \text{in}} \cdot \frac{\text{rev}}{\text{min}} \cdot 2\pi \frac{\text{rad}}{\text{rev}} \frac{746\ \text{W}}{\text{hp}} \frac{\text{hp-min}}{33{,}000\ \text{ft-lb}}$$

$$= T(\text{in-lb}) \cdot \frac{\text{rev}}{\text{min}} \cdot \frac{1}{84.48}$$

$$\therefore K = 84.48\ \frac{\text{in-lb}}{\text{W-rad}}$$

$$\text{Watts} = T(\text{N-m}) \cdot \frac{\text{rev}}{\text{min}} \cdot \frac{\text{min}}{60\ \text{s}} \cdot 2\pi \frac{\text{rad}}{\text{rev}} = T(\text{N-m}) \cdot \frac{\text{rev}}{\text{min}} \cdot \frac{1}{9.549}$$

$$\therefore K = 9.549\ \text{N-m/W-rad}$$

c. Watts, pump out = Pressure • Flow Rate • C

$$= P \frac{\text{lb}}{\text{in}^2} \cdot \frac{144\ \text{in}^2}{\text{ft}^2} \cdot \frac{\text{ft}^3}{62.35\ \text{lb}} \cdot \frac{\text{gal}}{\text{min}} \cdot \frac{8.33\ \text{lb}}{\text{gal}} \cdot$$

$$\frac{\text{hp min}}{33{,}000\ \text{ft-lb}} \cdot \frac{746\ \text{W}}{\text{hp}}$$

$$= P \frac{\text{lb}}{\text{in}^2} \cdot \frac{\text{gal}}{\text{min}} \cdot 0.4349\ \text{W}$$

$$\therefore C = 0.4349\ \frac{\text{min} \cdot \text{in}^2 \cdot \text{W}}{\text{lb} \cdot \text{gal}}$$

$$\text{Watts} = P(\text{kPa}) \cdot \frac{\text{L}}{\text{s}}\ .$$

d. Torque = in-lb • 0.11298 = N-m
N-m • 8.851 = in-lb

e. Pressure $= \frac{lb}{in^2} \cdot 6.895 = kPa$

$kPa \cdot 0.145 = \frac{lb}{in^2}$ (psi)

f. Volume = gal · 3.7854 = L
L · 0.2642 = gal

APPENDIX D

Table D-1. Data on PACO Pump with 30-V Motor
(Laboratory Tests)

V	A	Motor Input (Watts)	Torque (N-m)	Torque (in-lb)	Speed (rpm)	Motor Output (Watts)	Motor Efficiency (%)
30.0	30.5	915.0	2.7	24	2410	678.8	74.2
30.0	29.0	870.0	2.6	23	2430	656.0	75.4
30.0	28.6	858.0	2.6	23	2440	663.9	77.4
30.0	28.0	840.0	2.5	22	2450	634.0	75.4
30.0	27.5	825.0	2.5	22	2470	641.6	77.8
30.0	27.0	810.0	2.4	21	2480	616.2	76.1
30.0	26.2	786.0	2.4	21	2500	619.0	78.7
30.3	23.0	696.9	2.0	18	2570	544.5	78.0
31.0	19.0	589.0	1.7	15	2680	458.0	77.8
						Avg.	76.8
24.0	22.3	535.2	2.0	18	1980	432.7	80.8
24.0	21.3	511.2	1.9	17	2000	402.0	78.6
24.0	20.0	480.0	1.7	15	2030	360.4	75.0
24.0	18.0	432.0	1.6	14	2090	346.3	80.2
24.5	14.0	343.0	1.2	11	2170	282.5	82.4
						Avg.	79.2

	Motor Output (Watts)	Motor Efficiency (%)	Pressure (kPa)	Pressure (psi)	Flow Rate (L/s)	Flow Rate (gpm)	Pump Output (Watts)	Pump Efficiency (%)	System Efficiency (%)
Test at 30 V	678.8	74.2	101.4	14.7	166.2	43.9	301.5	44.4	32.9
	656.0	75.4	115.8	16.8	142.7	37.7	295.9	45.1	34.0
	603.9	77.4	122.7	17.8	133.6	35.3	293.6	44.2	34.2
	634.0	75.4	124.1	18.0	119.2	31.5	264.9	41.8	31.5
	641.6	77.8	131.0	19.0	115.1	30.4	269.8	42.0	32.7
	616.2	76.1	134.4	19.5	104.5	27.6	251.5	40.8	31.0
	619.0	78.1	141.3	20.5	96.5	25.5	244.3	39.5	31.1
	544.5	78.0	158.6	23.0	55.6	14.7	158.2	29.1	22.7
	458.0	77.8	168.9	24.5	0.0	0.0			
	Avg.	76.8							
Test at 24 V	432.7	80.8	74.5	10.8	135.1	35.7	180.0	41.6	33.7
	402.0	78.6	82.7	12.0	108.6	28.7	160.9	40.0	31.5
	360.4	75.0	93.1	13.5	85.6	22.6	142.6	39.6	29.7
	346.3	80.2	103.4	15.0	53.0	14.0	98.1	28.3	22.7
	282.5	82.4	0.0	16.5	0.0	0.0			
	Avg.	79.2							

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APPENDIX E

Table E-1. Data on Crane-Demming Pump with 90-V Motor
(Laboratory Tests)

Voltage (V)	Current (A)	Power (W)	Speed (rpm)	Torque		Pressure		Flow Rate	
				(N-m)	(in-lb)	(kPa)	(psi)	(L/s)	(gpm)
50	3.3	165	920	1.1	10	20.7	3.0	66.2	17.5
60	4.0	240	1080	1.5	13	31.0	4.5	90.5	23.9
70	5.0	350	1250	1.8	16	41.4	6.0	111.7	29.5
80	6.0	480	1440	2.3	20	55.2	8.0	130.6	34.5
90	7.5	675	1620	2.8	25	72.4	10.5	157.1	41.5
100	8.5	850	1770	3.3	29	91.0	13.2	164.7	43.5
110	10.0	1100	1960	3.7	33	113.1	16.4	181.3	47.9
120	11.0	1320	2120	4.4	39	134.4	19.5	193.0	51.0

Table E-2. Crane-Demming Pump with 90-V Motor (Laboratory Tests)

Voltage (V)	Current (A)	Power (W)	Speed (rpm)	Torque		Motor Output (Watts)	Effi-ciency (%)	Pressure		Flow Rate		Pump Output (Watts)	Pump Efficiency (%)	System Efficiency (%)
				(N-m)	(in-lbs)			(kPa)	(psi)	(L/s)	(gpm)			
80	6.5	520	1510	2.5	22	391.2	75.6	63.4	9.2	2.4	38.5	154.0	39.2	29.6
80	6.5	520	1500	2.5	22	390.6	75.1	65.5	9.5	2.3	36.1	149.1	38.2	28.7
80	6.4	512	1520	2.4	21	377.8	73.8	69.0	10.0	2.0	31.6	137.4	36.4	26.8
80	5.9	472	1560	2.0	18	332.4	70.4	82.7	12.0	0.8	13.0	67.8	20.4	14.4
80	5.2	416	1580	1.9	17	317.9	76.4	92.4	13.4	0.0	0.0			
90	7.9	711	1670	2.9	26	513.9	72.3	78.6	11.4	2.7	43.5	215.7	42.0	30.4
90	8.0	720	1680	2.9	26	517.0	71.8	81.4	11.8	2.6	40.5	207.8	40.2	28.9
90	7.8	702	1680	2.9	26	517.0	73.6	82.7	12.0	2.5	39.3	205.1	39.7	29.2
90	7.0	630	1710	2.6	23	465.5	73.9	96.5	14.0	1.5	23.6	143.7	30.9	22.8
90	6.1	549	1750	2.2	20	414.2	75.5	110.3	16.0	0.3	4.5	31.3	7.6	5.7
90	6.0	540	1760	2.1	19	395.8	73.3	116.5	16.9	0.0	0.0			
100	9.0	900	1810	3.5	31	664.1	73.8	92.4	13.4	3.0	47.5	276.8	41.7	30.8
100	9.1	910	1850	3.5	31	678.8	74.6	100	14.5	2.8	45.3	285.7	42.1	31.4
100	8.8	880	1880	3.3	29	645.3	73.3	110.3	16.0	2.2	34.9	242.8	37.6	27.6
100	8.2	820	1900	3.0	27	607.2	74.0	124.1	18.0	1.5	23.5	184.0	30.3	22.4
100	7.4	740	1940	2.7	24	551.1	74.5	137.9	20.0	0.4	7.2	62.6	11.3	8.5
100	7.2	720	1960	2.6	23	531.6	74.1	146.2	21.2	0.0	0.0			

APPENDIX F

Table F-1. Performance Summary for PACO Pump System (Solar Tests; Data Taken on 1 September 1980)

Time	Insolation (kWh/m^2)	Motor (kWh)	Volume Pumped (L)	Pump (kWh)
8:45	0.003	0.0	12.9	0.0
9:00	0.101	0.03	506.6	0.001
9:15	0.214	0.074	1418.5	0.004
9:30	0.343	0.13	2513.5	0.011
9:45	0.49	0.198	3775.3	0.019
10:00	0.649	0.277	5199.5	0.032
10:15	0.821	0.364	6732.6	0.048
10:30	1.005	0.461	8303.2	0.065
10:45	1.203	0.57	10002.9	0.086
11:00	1.411	0.687	11739.5	0.11
11:15	1.63	0.81	13530.7	0.135
11:30	1.859	0.941	15365.7	0.163
11:45	2.098	1.078	17282.7	0.192
12:00	2.341	1.217	19182.2	0.222
12:15	2.59	1.361	21127.3	0.254
12:30	2.842	1.504	23048.8	0.285
12:45	3.009	1.649	24973.9	0.316
13:00	3.355	1.793	26900.5	0.347
13:15	3.612	1.935	28815.1	0.378
13:30	3.868	2.076	30721.3	0.408
13:45	4.126	2.217	32643.5	0.439
14:00	4.378	2.353	34544.0	0.468
14:15	4.625	2.487	36442.2	0.498
14:30	4.866	2.616	38306.0	0.525
14:45	5.102	2.74	40128.6	0.551
15:00	5.328	2.858	41922.5	0.575
15:15	5.542	2.969	43659.3	0.597
15:30	5.743	3.072	45312.0	0.617
15:45	5.93	3.164	46860.2	0.633
16:00	6.104	3.245	48348.3	0.646
16:15	6.267	3.315	49694.7	0.657
16:30	6.413	3.374	50874.3	0.664
16:45	6.556	3.43	52037.1	0.671
17:00	6.679	3.473	53002.4	0.674
17:15	6.766	3.495	53553.6	0.675
17:30	6.82	3.498	53832.2	0.674
17:45	6.858	3.5	54098.3	0.674
18:00	6.886	3.501	54342.1	0.674

Table F-2. Average Data for PACO Pump System (Data Taken on 1 September 1981)

Time	Insolation (W/m^2)	SA1* Current (A)	SA1 Voltage (V)	Pump (V)	Pressure (kPa)	Flow Rate (L/s)
8:45	351.5	8.402	3.322	2.523	-1.2	0.4
9:00	415.87	9.771	15.598	14.649	9.4	0.8
9:15	475.28	11.225	17.634	16.535	15.2	1.1
9:30	539.65	12.704	19.258	17.996	22.6	1.2
9:45	599.08	14.063	20.457	19.096	29.2	1.4
10:00	653.52	15.276	21.456	19.932	34.5	1.6
10:15	703.05	16.261	22.243	20.657	38.1	1.7
10:30	747.62	17.285	23.505	21.769	42.2	1.8
10:45	802.05	18.334	24.141	22.38	46.1	1.8
11:00	841.64	19.147	24.765	22.941	49.8	2.0
11:15	886.22	19.912	25.177	23.229	52.6	2.0
11:30	925.83	20.621	25.59	23.529	55.5	2.1
11:45	950.56	21.136	25.714	23.703	56.5	2.1
12:00	975.34	21.566	25.814	23.741	57.6	2.1
12:15	995.12	21.87	26.026	23.878	58.3	2.2
12:30	1005.04	21.965	25.739	23.616	57.9	2.1
12:45	1010.01	22.011	25.702	23.592	58.6	2.1
13:00	1014.96	22.141	25.515	23.379	56.5	2.0
13:15	1024.85	21.805	25.49	23.354	57.5	2.1
13:30	1000.11	21.931	25.49	23.342	58.2	2.1
13:45	1005.1	21.672	25.304	23.218	57.1	2.1
14:00	985.24	21.321	24.903	22.842	55.6	2.1
14:15	970.39	21.006	24.803	22.703	54.3	2.0
14:30	950.62	20.378	24.342	22.331	52.7	2.0
14:45	915.96	19.898	23.992	22.081	50.0	2.0
15:00	876.32	19.243	23.566	21.73	47.5	1.9
15:15	821.89	18.439	22.98	21.194	44.7	1.9
15:30	777.33	17.5	22.206	20.457	41.0	1.7
15:45	722.87	16.406	21.207	19.558	35.2	1.7
16:00	673.36	15.017	20.17	18.721	31.1	1.6
16:15	648.61	14.133	19.421	18.022	25.9	1.5
16:30	623.83	13.548	18.833	17.51	22.8	1.4
16:45	455.52	9.967	15.462	14.513	11.9	1.1
17:00	470.36	10.121	15.374	14.388	11.2	0.9
17:15	198.05	4.406	2.086	1.661	-11.8	0.3
17:30	203.01	4.257	2.648	2.236	-4.8	0.2
17:45	103.97	2.278	1.886	1.649	-2.8	0.3
18:00	108.93	2.278	1.898	1.649	-2.1	0.2

*SA1 is Solar Array #1 from Solenergy.

APPENDIX G

Table G-1. Performance Summary for Crane-Demming Pump System (Solar Tests; Data Taken on 9 September 1981)

Time	Insolation (kWh/m^2)	Motor (kWh)	Pump Volume (L)	Pump (kWh)	Time	Insolation (kWh/m^2)	Motor (kWh)	Pump Volume (L)	Pump (kWh)
8:20	0.002	0.001	10.3	0.0	12:05	2.524	1.497	24261.3	0.329
8:35	0.074	0.027	585.0	0.001	12:20	2.773	1.65	26348.3	0.368
8:50	0.16	0.064	1489.8	0.003	12:35	3.024	1.803	28416.0	0.407
9:05	0.26	0.113	2569.2	0.009	12:50	3.277	1.956	30510.4	0.447
9:20	0.379	0.174	3835.0	0.017	13:05	3.53	2.108	32596.3	0.487
9:35	0.512	0.246	5283.5	0.03	13:20	3.789	2.263	34710.0	0.627
9:50	0.659	0.33	6812.0	0.045	13:35	4.047	2.415	36797.6	0.566
10:05	0.821	0.426	8474.4	0.065	13.50	4.301	2.564	38895.7	0.605
10:20	0.998	0.536	10256.9	0.09	14:05	4.548	2.71	40983.8	0.643
10:35	1.187	0.656	12135.7	0.118	14:20	4.728	2.806	42627.4	0.665
10:50	1.387	0.785	14089.4	0.149	14:35	4.807	2.834	43333.1	0.667
11:05	1.597	0.919	16064.9	0.182	14:50	4.929	2.892	44502.3	0.677
11:20	1.819	1.060	18122.8	0.218	15:05	5.082	2.974	45999.4	0.694
11:35	2.048	1.203	20141.2	0.254	15:20	5.151	2.997	46566.1	0.695
11:50	2.263	1.348	22175.3	0.291					

Table G-2. Performance Summary Crane-Demming Pump (Data Taken on 9 September 1981)

Time	Insolation (W/m^2)	SA1* Current (A)	SA1 Voltage (V)	Pump Voltage (V)	Pressure (kPa)	Flow Rate (L/s)	Time	Insolation (W/m^2)	SA1 Current (A)	SA1 Voltage (V)	Pump Voltage (V)	Pressure (kPa)	Flow Rate (L/s)
8:20	257.45	1.993	43.698	43.149	1.9	0.3	13:20	1005.06	6.749	88.147	87.511	67.0	2.3
8:35	306.97	2.458	49.432	49.581	6.9	0.8	13:35	1024.89	6.739	88.024	87.387	68.1	2.3
8:50	386.17	2.977	56.1	55.975	14.2	1.2	13:50	990.23	6.634	87.137	86.501	66.2	2.3
9:05	425.79	3.457	61.348	60.996	20.6	1.3	14:05	911.05	6.396	85.193	84.556	63.1	2.2
9:20	500.06	3.932	66.492	66.092	27.7	1.5	14:20	366.39	2.838	51.682	51.407	14.5	1.1
9:35	554.51	4.346	70.462	69.987	33.3	1.6	14:35	222.82	1.774	38.269	38.007	0.1	0.4
9:50	604.03	4.746	74.247	73.885	39.6	1.7	14:50	713.01	5.246	76.689	76.302	47.7	1.9
10:05	678.29	5.14	78.219	77.694	45.6	1.9	15:05	356.49	2.813	52.356	52.056	14.4	1.1
10:20	722.88	5.533	81.544	81.057	51.8	2.0	15:20	188.15	1.529	36.12	35.895	-0.9	0.3
10:35	782.28	5.85	83.953	83.466	56.5	2.1	15:35	183.2	1.439	33.923	33.748	-0.8	0.3
10:50	792.18	6.05	85.277	84.652	58.3	2.1	15:50	173.3	1.369	32.624	32.399	-2.0	0.3
11:05	846.61	6.234	86.522	85.948	62.5	2.2	16:05	138.64	1.109	24.992	25.079	-1.0	0.3
11:20	886.22	6.364	87.134	86.485	63.4	2.2	16:20	113.88	1.014	21.007	20.833	-0.9	0.3
11:35	920.88	6.464	87.858	87.321	65.7	2.2	16:35	108.93	0.899	17.086	17.023	-1.0	0.3
11:50	940.68	6.559	87.908	87.209	66.0	2.3	16:50	99.03	0.749	10.267	10.254	-1.3	0.2
12:05	960.48	6.659	88.383	87.733	66.0	2.3	17:05	94.07	0.759	10.329	10.079	-1.1	0.3
12:20	990.21	6.759	89.034	88.322	68.5	2.3	17:20	138.64	1.079	22.981	22.856	-0.5	0.2
12:35	1005.06	6.754	88.859	88.297	67.2	2.3	17:35	133.68	1.019	21.944	21.594	-1.4	0.2
12:50	995.18	6.754	88.699	88.112	67.5	2.3	17:50	133.63	1.019	22.506	21.594	-1.1	0.3
13:05	1010.01	6.789	88.834	88.31	69.2	2.3							

*SA1 is Solar Array #1 from Solenergy.

APPENDIX H

PROCEDURE FOR DESIGN OF A WATER PUMPING SYSTEM

The design of a water pumping system is accomplished as follows:

Given: Available funds, head to which water must be pumped, insolation and temperatures for the area, and knowledge that water is available.

Procedure:

1. Allocate 80% of funds to solar array. (As array costs decrease, this allocation can decrease.)
2. Determine array size in peak watts and watt hours/day that can be procured. Installed costs of the array must be determined for the time period and location desired. In 1981 installed costs in the United States were of the order of $16 per peak watt.
3. Using 75% efficiency for a typical motor and 95% efficiency for electrical connections, determine power available for pumping.
4. Enter pump curves with horsepower and head, and find pump that will provide maximum flow rate at maximum efficiency.
5. Determine piping requirements and compute friction head for this flow rate.
6. Go back to pump curve and determine new operating point using basic head plus friction head and available horsepower. Iterate steps 4,5, and 6 until a maximum flow rate can be determined.
7. Find a dc motor that will match the power and speed requirement defined by the pump curve. In general, off-the-shelf motors should be selected using the highest standard voltage up to 220 V for domestic systems; higher voltage can be considered for commercial systems.
8. When the motor most closely meeting the requirements is found, go back to step 3 and see if anything has changed. If necessary, update.
9. Design array so that the pump-loaded motor operating point in amperes and volts (I and V) corresponds to the maximum power point on the I-V curve of the array as defined by the expected insolation and average maximum array temperatures. Solar arrays can be formed by series parallel connection of panels. Care must be taken to match the current of all series-connected panels as closely as possible or the estimate of 95% connecting efficiency used in step 3 will be exceeded.
10. Now add exact costs of array, pump, motor, wiring, pipe, and installation. If the costs are within budget all is well, if not go back to step 1 and iterate again.

Document Control Page	1. SERI Report No. SERI/TR-214-1423	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle
Evaluation of Pumps and Motors for PV Water Pumping Systems

5. Publication Date
June 1982

6.

7. Author(s)
David Waddington and Ann Herlevich

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

10. Project/Task/Work Unit No.
1091.50

11. Contract (C) or Grant (G) No.
(C)
(G)

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Two electric, motor-driven water pumps were tested in conjunction with a photovoltaic (PV) array that provided the electrical energy to run the pumps. The purpose of the tests was to evaluate the performance of currently available, low-cost pumping systems powered by PV arrays. The performance and cost of these systems were compared with analogous data from similar, higher priced pumps and motors currently used with many PV water pumping systems. The two pump systems considered represent production equipment available from U.S. industry and cost less than 50% of equivalent pumps installed with PV pumping systems in the U.S. and in developing countries. Flow rates, pumping heads, and efficiency were comparable in both test pumps and equivalent pumps. Motor performance, when the motor was directly connected to the PV array and loaded with the pump, was examined. The conclusion drawn from this experiment is that commercially available, low-cost water pump systems will perform satisfactorily when powered by PV arrays.

17. Document Analysis

a. Descriptors Electric motors ; Performance testing ; Photovoltaic power supplies ; Performance testing

b. Identifiers/Open-Ended Terms Solar Energy Research Institute Test Facility ; low head pumps

c. UC Categories
63D

18. Availability Statement
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

19. No. of Pages
66

20. Price
$5.25

Form No. 0069 (3-25-82)