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Executed by
The World Bank

SMALL-SCALE SOLAR-POWERED IRRIGATION PUMPING SYSTEMS PHASE I PROJECT REPORT

Sir William Halcrow and Partners
in association with the
Intermediate Technology Development Group Ltd.

July 1981

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SIR WILLIAM HALCROW & PARTNERS

CONSULTING ENGINEERS

THE QUEEN'S AWARD FOR EXPORT ACHIEVEMENT 1977

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4th June 1981

Dr.E.M.Mitwally.
Energy Department,
World Bank,
1818 H Street, NW,
Washington DC, 20433,
USA.

Dear Dr.Mitwally,

UNDP/GLO/78/004
SMALL SCALE SOLAR POWERED PUMPING SYSTEM

I have pleasure in enclosing ten copies of our Final Report on Phase I of the Project under the title "Small Scale Solar Powered Irrigation Pumping Systems : Phase I Project Report".

As you know this has been specially prepared from earlier draft reports on the field trials, laboratory tests and system design studies. I believe that within a reasonable compass it appropriately describes the main areas of our investigation for you and the conclusions we have reached on this most important topic. The preparation of the final text has been greatly assisted by the constructive discussions which Mr.Peter Fraenkel and Dr.David Wright had with yourself, Mr.Dosik and your other colleagues in the World Bank and I trust that the result satisfactorily fulfils your requirements.

We look forward to the work to be done over the next year preparing for Phase II for which I believe the Project Report will provide a firm foundation.

Yours sincerely,

A.M.Muir Wood.

NOTICE

PHASE I PROJECT REPORT

This Volume summarises the work done from July 1979 to May 1981 in Phase I of the UNDP Project GLO/78/004 to test and demonstrate suitable solar-powered pumping systems. It is based on extensive Project Records available for reference from the World Bank or Sir William Halcrow & Partners.

A companion Volume 'Small-Scale Solar-Powered Irrigation Pumping Systems: Technical and Economic Review' has also been prepared and is available from the World Bank.

The tables and figures referred to in the Report have been collected together at the end of the text. Five tables have been specially adapted for the Executive Summary and these are placed at the end of the Summary.

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Small-Scale Solar-Powered Irrigation Pumping Systems:
Phase I Project Report

EXECUTIVE SUMMARY

1. INTRODUCTION

1.1 Purpose and Background

The Project was funded by the UNDP and executed by the World Bank. The Consultants appointed to implement the technical work were Sir William Halcrow & Partners working in association with the Intermediate Technology Development Group (both of London, UK). Phase I of the Project commenced in July 1979 and lasted until May 1981.

The main purpose of Phase I of the Project has been to demonstrate and evaluate the use of solar energy for powering small-scale pumping systems to be used for irrigation on typical small land holdings in developing countries, with a view to recommending how the technology should develop.

In this connection, "small" land holdings refers to the millions of intensely cultivated land holdings farmed by poorer farmers in many developing countries, the majority of which have areas of around one hectare or less requiring, typically, about $50m^3$ of water per day per hectare in the irrigation season. The hydraulic power output required to pump such daily volumes from depths of typically 5m, will be of the order of 100-300W.

In order to evaluate pumps for this duty, considerable practical work was required, including field trials of systems and laboratory testing of subsystems and components, followed by an analytical system design study.

As a result of this work, the likely performance to be expected from small-scale solar pumps as the technology matures has been determined with some precision. The advantages and disadvantages of different technical options have been studied and indications obtained about the desirable features to be developed for small-scale irrigation pumping systems.

Some forecasts of the likely price trends and of the factors that affect the economics of such systems have also been made.

During the course of the Project, much useful experience was gained about the procedures necessary for testing the equipment in the field and laboratory and for data collection and reporting. Valuable lessons were also learnt about the collaborative relationships which need to be established with the co-operating agencies in the host countries and these will be useful to future phases of this Project.

1.2 Reports

This Volume contains a description of the project and the substantive conclusions which were reached as a result of the work done in Phase I. An accompanying Volume reviewing the technical state-of-the-art, possible future developments and the general economics of small-scale solar pumps, is entitled "Small-Scale Solar-Powered Irrigation Pumping Systems: Technical and Economic Review".

Phase I of the project conveniently breaks down into three principal components - field trials, laboratory tests and system design studies-and this is the general format of the Project Report and of the summary which follows.

2. FIELD TRIALS

2.1 Objectives

The main objectives of the field trials were:

1. To obtain first hand, reliable and objective performance data for existing systems under field conditions as a prerequisite for assessing how the technology should be improved.

2. To gain experience with the management of field testing, data collection and analysis and reporting.

3. To demonstrate the technology in countries typical of those in which solar pumping may have widespread future application as a preliminary to technology transfer, and to highlight the aspects which most urgently require attention.

4. To provide data for the validation of the mathematical model built as part of the system design studies.

The UNDP selected Mali, Philippines and Sudan to participate in the field trials. The Consultants collaborated with the Solar Energy Laboratory in Mali, the Center for Non-Conventional Energy Development in Philippines, and the Institute of Energy Research in Sudan.

2.2 Selection of Equipment

The Consultants reviewed the availability of small-scale solar pumps suitable for the purposes of the Project. 250 questionaires were sent to potential suppliers throughout the world. However, although many countries have significant R & D programmes, few suppliers were in a position to offer adequately developed systems to satisfy the selection criteria and within the delivery schedule demanded by the Project.

The selection criteria required equipment with the correct delivery for the head specified, typically in the range 1 to 3 litre/sec through a static head of 5 to 10m under peak sunlight conditions. Also, systems were required to be robust and practical, have low maintenance requirements, be efficient and preferably have some promise of capability of manufacture in developing countries. The required delivery time was 13 weeks from time of order.

Only 13 suppliers were able to offer equipment that appeared suitable and a short list was prepared for approval by the World Bank. Finally, 10 different systems were purchased, nine photovoltaic (PV) and one thermal. One PV system was duplicated and so 11 systems in all were purchased for the field trials. In addition, permission was given to monitor an existing system already installed and working in Mali, but not purchased by the Project.

The 12 systems monitored, their respective costs (including air freight to host country), locations and the volume of data collected for them are indicated in Table I.

2.3 Field Programme and Progress

The field programmes in each country were supported by Resident Engineers (RE's), one in each country, posted by the Consultants to assist the national institution install the equipment and to advise the local engineers and technicians in its use and in the monitoring procedures. The RE's had previously visited the manufacturers of the systems they were to install to inspect the equipment prior to despatch and to receive instruction and advice.

The principal parameters measured in the field were concerned with performance assessment, both instantaneously through continuous monitoring of key variables (such as irradiance in the plane of the array, photovoltaic array electrical power output and pumped water flow rate) using chart recorders and cumulatively, by daily readings of inputs and outputs (such as solar energy input during the whole day, electrical energy generated and total quantity of water pumped) registered on totalizers.

In the event, the recording of field data presented some difficulties: technically with the pumping systems and to a lesser extent, with the instruments; and logistically with late deliveries by the manufacturers, damaged key items, and difficulty in arranging transport to the sites. The short time scale of Phase I also created other problems: equipment could only be ordered in January 1980, testing commenced mainly between June and September 1980, and the RE's left their countries by September 1980 (returning briefly later in December 1980 and/or January 1981). Despite these matters, the field trials programme was substantially completed by the end of Phase I.

Of the 12 systems monitored, 10 yielded sufficient continuous data to determine their performance, while two systems could not be tested at all; in one case (a PV system) this was because of delays in arrival of parts and damage in transit, while in the other (the thermal system) technical problems prevented the pump from running for periods long enough for its performance to be determined (though these defects were of a kind which, given time, should be solvable) Of the 10 PV systems from which data were obtained, one borehole pumping system performed almost faultlessly for the whole of the trial period. A number of problems afflicted other PV systems including, for example, two systems with poor suction performance (even under high levels of irradiance), two systems with unreliable footvalves (leading to pumps being difficult to prime or running dry), two systems with wrong wiring or poor connnections (leading to low power output from the arrays), one system with an impeller binding on the pump casing and two systems with unreliable electronics (leading to complete failure). Some faults were repaired in situ, while others required replacement parts. The problems involving poor suction and impeller binding were not resolved within the time scale of Phase I of the Project.

2.4 Conclusions from Field Trials

Table II indicates the principal results obtained from testing all the systems. The maximum instantaneous system efficiency (based on array area) recorded was just over 3%. However, most of the adequately reliable systems were typically 2% efficient and the poorer systems only returned optimum efficiencies of around 1%. Referenced to gross cell area, the maximum system efficiency was just over 4%. Clearly, there is considerable variability in efficiency between different systems, and since the efficiency dictates the size of array necessary for a given output, and array costs dominate, overall efficiency has a major effect on equivalent annual costs.

From an operational viewpoint, the main conclusion was that pumps have to be self-priming, that is, they must be able to start pumping without any need for operator intervention. Non-self priming pumps, if emptied of water due to, say, a leaking footvalve, cannot refill themselves and therefore will simply run dry, overheat and may suffer serious damage.

Wherever possible, centrifugal pumps should be of the immersed type and so dispense with troublesome and energy consuming footvalves. If surface-mounted self-priming centrifugal suction pumps have to be used, care should also be taken to see that the suction head remains moderate.

Numerous relatively minor problems were experienced with many of the systems; for example:

- incorrect wiring supplied
- terminals that did not readily give good electrical connection
- failure of electronic circuitry (due either to overheating or to overload)
- possibility of safety hazard due to dangerous dc voltages
- broken module cover glasses (both in transit and on site)
- suction pipework trapping air in cavities
- footvalves jamming or leaking
- inadequate packing for shipping

It was felt, however, that these problems were not fundamental to the technology and can be overcome during the normal course of development as the technology matures. Certainly, the systems have the potential for reliable operation with minimum maintenance. Regular maintenance jobs should be minimized and made easy to carry out.

3. LABORATORY TESTS

3.1 Objectives

The main objectives of the laboratory testing programme were:

(1) To determine independently the true performance characteristics of selected solar pumping subsystems and components under controlled conditions at full and part-load.

(2) To provide data for the system design studies to enable improved solar pumping systems to be developed.

(3) To help identify the causes of good or bad field-tested system performance.

(4) To provide limited indications of the basic reliability and durability of certain components.

Generally, the component testing programme was designed to investigate performance (i.e., output and efficiency characteristics) rather than reliability or quality. Hence, single items were tested in the case of PV sub systems (motors and pumps) and of thermal systems, but for the reasons given below, five examples of each selected PV module were tested.

The testing programme breaks down into three principal areas of investigation: PV modules, PV subsystems (motor and pump) and thermal systems.

3.2 PV Modules

The choice of PV modules was limited to those which had not been independently tested and publicly reported and which displayed interesting features - technical (e.g. high packing density for cells), commercial (e.g. low cost) or others, such as a product made in India which was indicative of what might readily be manufactured in a developing country. All cells were of the mono-crystalline silicon type. Since these are particularly expensive components which are required to be durable, robust and long-lasting, five examples of each module were purchased for a more detailed investigation of quality and performance. Details of products tested are given in Table III.

The modules were performance tested independently by the Royal Aircraft Establishement (RAE) in the U.K. and by the Jet Propulsion Laboratory (JPL) in the U.S.A. RAE carried out performance tests and ultra-violet accelerated ageing tests and JPL carried out their standard performance and durability testing (a routine generally applied by JPL for the US Department of Energy to most American PV modules). Both testing organizations carried out visual inspections and reported on the condition of the modules before and after testing. The results obtained by each of the organizations for the maximum power output of the same module were very close (average value differed by 0.5%).

3.3 PV Subsystems

The University of Reading in the UK tested pump and motor units from all the PV systems purchased for testing in the field. In addition a selection of four further pumps and two motors were tested. The extra pumps were chosen as representing generic types of pump not otherwise included in the programme but of possible interest for the future design of pumping systems. These included a free-diaphragm pump, a rotary screw (or progressive cavity) pump, a piston pump and a self-priming centrifugal pump. The extra motors included a high efficiency industrial permanent magnet dc motor, similar to those used on most of the subsystems, and a reciprocating linear actuator. Details are given in Table III.

The main requirement of this testing programme was to obtain performance data vital for the system design study over a wide range of full and part-load conditions and typical of those existing in solar pumping applications. Components were also visually inspected after testing to determine their general quality and suitability for inclusion in small-scale irrigation pumping systems.

3.4 Thermal Systems

Virtually all thermal systems were of prototype status - only one such system could be purchased for field trials and even this was not a mature product. The only system which could readily be transported for laboratory testing at the University of Reading was a Stirling cycle solar pump, under development in the USA. Hence the only generally practicable way to gain an insight into thermal system performance and potential was to witness testing at the manufacturers' own test facilities; hence arrangements were made for the Consultants' engineers to monitor tests of three systems under development in Israel, Germany and the U.S.A. Although other systems were known to be under development, it was only possible to make arrangements for those listed in Table III.

3.5 Conclusions of Laboratory Testing

The objectives of the laboratory testing programme were generally achieved, with reports of completed tests on all of the equipment.

Modules

The performances of the PV modules were consistently below their manufacturers' specifications, by from 2½% to 16½%. This has serious implications in view of their high cost ($10 to $20 per peak Watt) and because accurate performance knowledge is necessary for good system design. Cell efficiency varied by over 20% between the best and worst products tested.

Although only one PV module actually failed under the durability testing programme, all products displayed minor flaws or design faults and one or two had potentially serious shortcomings.

Although it is considered that the levels of efficiency (10%+), high quality and long life often claimed for PV arrays in the technical press and in manufacturers' literature are obtainable, such a standard of performance of most currently available products cannot be taken for granted at present.

Motors

The dc motors tested were all permanent magnet machines* of generally high efficiency. Nevertheless a spread of about 15% in optimum efficiency (75 to 87%) was found between the best and the worst performers. This difference can be worth more than the total cost of a motor in terms of extra array costs (at present day prices). Clearly, PV solar pumping systems should use motors of better than 85% optimum efficiency, so long as the cost of PV arrays is dominant.

Pumps

Considerable variability in pump performance was revealed. The best centrifugal pumps were over 50% efficient under optimum operating conditions, while many were only 30 to 40% efficient. A few were less than 20% efficient. It is clear that the choice of pump can be perhaps the single most influential factor in good small-scale solar PV pumping system design. From the system design studies it was found that overall system efficiencies for systems using centrifugal pumps were sensitive to head variation, and it is clearly important to seek pumps whose drop in efficiency when operating away from their optimum head is as small as possible. This objective will help to maintain acceptable performance for situations where the actual head does not coincide with the optimum for the pump or where the head varies either seasonally or due to well draw-down.

Nevertheless, centrifugal pumps appear to be the most promising type of pump for the low head applications (< 10m head) demanded for irrigation, although self-priming capability is essential for practical field use. Positive displacement piston pumps offer good performance (better than 50%) at higher heads (> 10m). They are also relatively insensitive to variations in head or to operating off their optimum head.

Thermal Systems

The performance of the Stirling engine pumping system was disappointing and it failed mechanically partway through the test series. The other systems, all Rankine cycle using Freon type working fluids, performed in line with our expectations and gave overall efficiencies of between 1% and 2%. Examples seem some distance from commercial viability (with the possible exception of the system purchased for field testing), but our system studies showed that this technology could be competitive with PV systems, given suitable development and high volume production.

The system design studies showed that thermal systems would be likely to improve in both efficiency and in cost-effectiveness if tracking concentrating collectors were used instead of the fixed flat plate collectors of the Rankine cycle systems so far tested. Consideration would need to be given to the maintenance requirements which this would impose.

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* One was of the brushless electronically commutated type

4. SYSTEM DESIGN STUDIES

4.1 Objectives

The purpose of the system design studies was to investigate whether, and in what ways, small-scale solar pumping systems might be improved for irrigation purposes and to see whether the specification of an improved system could be developed. This was achieved by examining the cost-effectiveness of a number of technically feasible system options under a variety of operating conditions. For all systems, computer-based mathematical modelling techniques were used to simulate the performance and cost of the main components of both PV and thermal systems.

4.2 Models

The PV systems model was developed using data from the laboratory testing programme, validated by comparison with the field performance data obtained for complete systems. Factors that were investigated are listed in Table IV. A special parameter, the Specific Capital Cost (the capital cost per unit energy output per day in US $ per kJ) was used to assess the cost-effectiveness of the alternative system options examined. For this purpose "normalized" costs were used to give a measure of the capital cost of a different systems, excluding arbitrary factors which may influence the price of individual items.

A simple thermal system model was also produced to investigate the general merits of different thermal system concepts (i.e., the use of different types of solar collector, thermal cycle, working fluid and expander). The Specific Capital Cost was also used to express and compare the cost-effectiveness of thermal systems.

Finally, a simple economic model for PV systems was constructed to investigate the sensitivity of typical PV solar systems to variations in selected economic and technical parameters (discount rate, life, differential movement in real prices) and to compare solar pumping system costs with those of small engine-powered pumping systems. The model calculated the present value of the various cash flow streams. This work is reported in detail in the separate "Technical and Economic Review" volume.

4.3 Conclusions

PV Systems

Significant performance and cost-reducing improvements appear to be readily obtainable with PV systems at the existing level of technology developed from those tested under the programme so far. In particular overall efficiency can be improved by:

- o the use of pumps whose efficiency change with head over the likely working head range is as small as possible.

- o optimisation of the proportion of PV cells that were connected in parallel and series within the module. (One system supplied was almost perfectly optimised, but with another an improvement of 13% in overall system efficiency could be achieved).

- varying the array power to find the optimum value: in one case the Specific Capital Cost dropped by 19% when the array power was increased by 60%, due to a substantial increase in output and efficiency.

- the use of a Maximum Power Point Tracker (MPPT)*. This was investigated and may have little or no benefit on well-matched systems but would be expected to improve less well-matched systems under varying climatic and head conditions. Pumped daily water output was increased typically by 15% on a clear day and by 25% on a hazy day through the use of a MPPT.

- using movable or tracking PV arrays. The increase in output obtained by a perfectly tracked array (over a fixed array) was compared with the increases obtained by arrays reoriented to preset positions once, twice or three times in a day and reset in the evening. It was found that reorentation twice daily allows the use of 95% of the energy received by a continuously tracked array. It is doubtful therefore whether the extra cost and complication of a continuously tracking system can be justified for applications such as irrigation.

- care in specifying pipework for systems. The pipework necessary to connect the pump with the source and to deliver water to the point of application is a simple, but vitally important, part of the solar pumping system. The Specific Capital Cost was minimized for the particular conditions of the tests: it is unlikely that a pipe diameter less than 50 mm should ever be used. The use of inadequate pipe diameters can dramatically reduce the system efficiency and increase the Specific Capital Cost.

The combined result of a number of these improvements for one system is shown in Table V.

In general, the Consultants consider it is feasible to produce small-scale solar pumping systems having overall instantaneous system efficiencies above 4% (some of the systems tested were only around 2% efficient). Specific Capital Costs of around $2.5/kJ** per day should be possible (at present day prices with current technology) compared to a range of $3.1 to $9.8 obtained from model tests on the systems purchased. If PV array prices fall to about 50% of their current lowest level (i.e. reach $4/W peak) then the Specific Capital Cost of $2.5/kJ per day will reduce to about $1.0 yielding water at about one third the cost of the most cost-efficient systems currently available.

Thermal Systems

Data on thermal systems were restricted in scope and quality compared with the PV data, but nevertheless clear conclusions emerged from the studies which analysed over 30 different system options. The principal one is that high temperature

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* A Maximum Power Point Tracker (MPPT) is an electronic control device which continuously adjusts the array voltages to an optimum value to maximise the power output from the array. Its main benefit is increased system efficiency and output, but it also consumes a proportion of the power produced by the array and it can be an expensive component adding significantly to system first costs.

** The unit kilojoule has been used because it is a basic SI unit of energy and because it gives convenient dollar numbers. There are 3600 kJ in one kWh.

thermal systems using concentrating collectors appear to be significantly more cost-effective than low temperature flat plate collector systems, mainly on account of the much smaller collector areas required to yield a given output.

The least cost-effective approach appears to be precisely the one favoured by most current manufacturers (fixed flat plate collectors); the indications are that a system using a linear-focussing equatorially-tracking collector would be about 30 to 40% less expensive, while even higher concentration through the use of a power tower or point focus two-axis tracking collector could result in some slight further improvement in cost effectiveness. Some uncertainties lie in the assumptions concerning the likely costs of tracking mechanisms, but the results are nevertheless significant enough to justify serious study of the use of concentrating and tracking thermal concentrators; and the more complex maintenance requirements this would impose.

Specific Capital Cost analysis on small thermal systems gave $ 2.8/kJ per day for a typical flat plate collector system (similar to the one tested) and $ 1.5 for a Freon vapour Rankine cycle engine with a one-axis tracking parabolic trough (line focus) collector: these costs appear to be competitive with PV systems. Thus it would be premature to dismiss thermal systems at this stage.

5. RECOMMENDATIONS

5.1 General

- Solar pumping for irrigation is most suitable on small farms where low lift pumping is needed, where high value crops are grown and where the demand for irrigation is regular over much of the year.

- Solar pumping should be considered in future phases of these studies for water supply applications as well as for irrigation.

5.2 Technical Development

- Present field trial programmes should be continued wherever feasible

- The conclusions of this Report should be implemented with a view to producing improved PV systems. This may be done by specifying various improved systems with the desirable technical features so far identified, and ordering examples from suppliers capable of demonstrating a competence to respond to a call for tenders.

- The systems produced in this way should then be laboratory tested, prior to any further field testing, to confirm that they achieve specification and to identify any further shortcomings.

- Following satisfactory laboratory tests, such systems may subsequently be field tested.

- o Further design studies, supported by continued field testing of the more successful systems so far installed in the field should be carried out to investigate further possible areas of improvement and to improve the data base.

- o The development of small-scale thermal systems with concentrating and tracking collectors appears to be fruitful and should be encouraged.

- o A review should be made of any worthwhile improvements which may be worth considering to individual components of PV systems. Specification for manufacture should be prepared and tenders invited.

- o Desk studies of the detailed requirements for local manufacture or assembly should be initiated to be followed up, if possible, by case studies.

5.3 Institutional Arrangements

Countries to be involved in field testing programmes should be able to satisfy a number of criteria, the most important being:

- o The existence of important pumping needs for irrigation and water supply in rural areas that could be met by solar powered pumping systems and which would require a range of pump output power suitable for solar systems.

- o The presence of a suitable solar energy resource and the absence of any more readily exploitable alternatives.

- o Government interest in solar pumping and a willingness and ability of host country institutions to provide the necessary technical and logistical support for the reliable field monitoring of the systems.

Country	Location	Water Source	Water Use	Total Head (m)	Equipment Supplier	Equipment Type	Cost c.i.f. ($)	Approximate Rating: Peak flow (l/s)	Approximate Rating: Peak Hydraulic Power(W)	Approximate Rating: Peak Array Power(W)	Date (1) first operated	No. of days on which data recorded: continuous tests	No. of days on which data recorded: cumulative tests	Remarks
Mali	Babougou	Open well	Supply to students hostel	10.0	Briau	PV	14,065	0.3 (at 10m head)	27	315	19 Jul 80	3	83	Under care of FAO. Some data missed because of battery discharge
	Korofina	Open well	Market Garden	3.0-7.0	Photowatt	PV	14,219	1.5 (at 6m head)	90	275	25 Sep 80	1	0	Under care of laboratory. Difficulty in getting system to work limited data collected.
	Yangasso	Borehole	Village water supply	20.0	Pompes Guinard	PV	n/a	2.7	540	1300	Already in operation	3	149	Under care of Mali Aqua Viva Availability for monitoring maximum possible.
	Banankoro and Solar Lab.	Open Well	None	2.0-4.0	SEI	PV Portable	8,625	2.3	115	250	15 Jul 80	3	0	Initial electronic failures limited data collected. Had to be moved to laboratory.
Philippines	Talaksan San Raphael	Small Canal	Rice Irrigation	5.0	Briau	PV	22,094	2.0	100	600	11 Jul 80	30	139	Good quality of data collected despite foot valve problems.
	Talampas Sapang Palay	Stilling Pool	Rice Irrigation	5.0	Omera-Segid	PV	16,417	1.0	50	200	13 Jun 80	23	159	Quality of data affected by poor weather and shading of array.
	Talampas Sapang Palay	River	Rice Irrigation	12.0	Pompes Guinard	PV	17,450	1.0	120	600	13 Jun 80	4	30	Problems with pump priming limited data collected.
	Center for Non-Conventional Engery Development	Tank	-	2.0-5.0	SEI	PV Portable	8,625	2.3 (at 5m head)	115	250	20 Sep 80	6	0	Initial electronic failures limited data collected. Had to be moved to laboratory.
Sudan	Butri	Open well	Orchard & Field crops	9.5-18.0	Arco Solar	PV	5,063	1.0 (at 15m head)	150	530	24 Jun 80	32	177	Availability for monitoring maximum possible.
	Butri	Open well	-	4.9-11.0	Intertechnology Solar Corp	PV	22,462	1.0 (at 8.0m head)	80	530	26 Jul 80	6	0	Mechanical problems with pump operation. Limited data collected.
	Soba	Borehole	-	20.0	Solar Pump Corp.	Thermal	7,500	0.8 (at 15m head)	120	Collector Area 5.1m^2	13 Jan 81	0	0	Delay in installation and difficulty in operating system. Limited data collected.
	Butri	Open Well	-	9.5-11.0	Soterem	PV Tracking	30,475	1.0 (at 8m head)	80	480	not yet run	0	0	Delays in installation prevented completion of system.

(1) Monitoring did not commence on these dates

TABLE I FIELD TRIALS – SITES, SYSTEMS, COSTS AND DATA COLLECTED

Country	System (Type of Pump)	Array Rated Power	Average Peak Power measured @ 1000 W/m² Solar Irrad.	Optimum Head (See Note 1)	Actual Operating Head	Average Peak Hydraulic Power Measured @ 1000 W/m² Solar Irrad	Approx Start Up Solar Irrad	Average Measured Max. Efficiency: System (Note 6) Array	Average Measured Max. Efficiency: System (Note 5) Cell	Average Measured Max. Efficiency: Sub-System	Average Measured Max. Efficiency: Cells	Average Measured Max. Efficiency: Array	Average Daily Efficiency (Note3): (Note 6)	Average Daily Efficiency (Note3): (Note 5)	Average Daily Water Output (See Note 3)	Max Temp Increment of Array Measured	Remarks
	Name	W	W	m	m	W	W/m²	% @ W/m²	% @ W/m²	%	%	%	%	%	m³	°C @W/m²	
Mali	BRIAU (DUVA) (Piston Pump)	316	196	20+	3.6 to 10.9	28	600	0.8 to 800	1.3 @ 800	14	9.0	5.6	0.4	0.7	7.3 @ 5.6m	13.5 @ 800	No major problems with system. Start up achieved significantly earlier by alteration on site of series/parallel configuration.
	PHOTOWATT (Surface centrifugal)	275	146	6	3.2 to 3.7	31	800	1.0 @ 900	1.5 @ 900	21	7.3	4.8	Insufficient Data		Insufficient Data	Insufficient Data	Severe problems with priming System would only work at high irradiance and then not consistently.
	POMPES GUINARD (Borehole centrifugal)	1260	807	–	14 to 20	307	220	2.2 @ 720	3.4 @ 720	39	9.2	5.9	1.3	2.1	31 @ 16.0m head	21 @ 890	System ran without fault.
	SEI (Submersible Unit)	250	202	5	2.6 to 5.3	90	200 to 300	3.1 @ 1000	4.0 @ 1000	45	8.9 Note 2	6.9 Note 2	Insufficient Data		Insufficient Data	22 @ 925	Electronic failures marred otherwise promising performance.
Philippines	BRIAU (Suction centrifugal)	600	410	6	3.7 to 5.0	102	350 to 400	1.4 @ 830	2.4 @ 830	26	9.5	5.6	0.9	1.6	35 @ 4.5m head	23 @ 970	Foot value problems caused dry running and gland failures otherwise generally satisfactory.
	OMERA SEGID (Suction centrifugal)	200	151	5	4.1 to 4.8	47	390	1.8 @ 840	2.9 @ 840	32	10.2	6.4	0.6	0.9 Note 4	5.5 @ 4.3m head Note 4	17 @ 978	Performance improved after module wiring corrected. Low value for daily efficiencies because array partly shaded.
	POMPES GUINARD (Suction centrifugal)	600	422	10	10.2 to 11.0	114	800	1.9 @ 1000	2.3 @ 1000	27	8.9	7.5	Insufficient Data		Insufficient Data	17 @ 960	Suction head near to practical limit made priming and operation very difficult.
	SEI (Submersible unit)	250	240	5	4.5	81	200 to 300	2.8 @ 915	3.6 @ 915	34	10.5 Note 2	8.2 Note 2	Insufficient Data		Insufficient Data	15 @ 785	Tests under optimum head conditions at laboratory confirmed good performance after electronics corrected.
Sudan	ARCO SOLAR (Suction centrifugal)	530	505	9+	9.3 to 16.8	161	350	2.7 @ 1000	3.5 @ 1000	32	11.0	8.5	1.8	2.3	20 @ 11.6m	25 @ 870	Ran almost without fault. Ran dry on one occasion and caused temporary overheating.
	INTER TECHNOLOGY CORP (Regenerative pump)	530	470	7	Up to 11.9	113	400	1.9 @ 1000	2.5 @ 1000	24	10.6	8.2	Insufficient Data		Insufficient Data	16 @ 780	Impeller binding gave trouble throughout period of trial and prevented consistent running.
	SOLAR PUMP CORP (Thermal system)	5.1m²	–	Variable	18	30 (prelimn)	–	–	–	–	–	–	–	–	–	–	Continuous operation not achieved because commissioning problems not overcome.
	SOTEREM (Piston pump)	480	–	10	–	–	–	–	–	–	–	–	–	–	–	–	Components lost or broken and complete installation impossible. Tracking mechanism worked well under test.

NOTES
1. from laboratory tests
2. including max power point tracker losses
3. at 6 kWh/m² (21.6MJ/m²) array solar irradiation
4. at 4.3 kWh/m² (15.3MJ/m²) array solar irradiation (insufficient data for 6kWh/m²)
5. referenced to gross cell area
6. referenced to overall array area.

TABLE II SUMMARY OF SYSTEM FIELD PERFORMANCES

Supplier	Manufacturer	Country of Origin (Supplier)	Model or Type and Specification	Cost(FOB) £	$	Site of Complete System
1. PV MODULES						
Arco Solar	Arco Solar	USA	Model 16-2300, 37 Watts nominal maximum power (one module)	144	330	-
CEL	CEL	India	PM621 7.6 Watts nominal maximum power (one module)	147	247	-
RTC	RTC	France	Model BPX47C, 33 Watts nominal maximum power (one module)	565	1300	-
Solarex	Solarex	USA	Model HE51 JG, 34 Watts nominal maximum power (one module)	380	874	-
2. PV SUB-SYSTEM						
Arco Solar	Mavilor motor Sta-rite pump	USA	Pmdc, model no M0300, 400 Watts rated power, 54 Volts nominal voltage Centrifugal, model J	481	1112	Sudan
Briau	Brot motor Briau pump	France	Pmdc, 450 Watts rated power, 48 Volts nominal voltage Piston, model DUVA 20	987	2270	Mali
Briau	Brot motor Briau pump	France	Pmdc, 240 Watts rated power, 48 Volts nominal voltage Centrifugal, model MGV.40.1	999	2298	Philippines
ITC/ Solar Corp.	Applied Motors motor Roth pump	USA	Pmdc, 480 Watts rated power, 24 Volts nominal voltage Regenerative, model V-140	391	883	Sudan
Omera Segid	Brot motor Essa-Mico pump	France	Pmdc, 190 Watts rated power, 52 Volts minimum voltage Centrifugal	1795	4129	Philippines
Photowatt	Brot motor Brequet pump	France	Pmdc, 190 Watts rated power, 52 Volts minimum voltage Centrifugal, model KSB	1975	4543	Mali
Pompes Guinard	Leroy-Somer motor Pompes Guinard pump	France	Pmdc, 370 Watts rated power, 31 Volts minimum voltage Centrifugal, model Alta X 600/12	1018	2341	Philippines
Soterem	CEM motor Salmson pump	France	Pmdc, 345 Watts rated power, 61 Volts minimum voltage Piston, model PE-99083	473	1088	Sudan
SEI	AEG motor KSB pump	USA	Pmdc, Brushless, 200 Watts rated power Centrifugal, model M	600	1380	Mali and Philippines
3. INDIVIDUAL MOTORS						
SEM	SEM	UK	Permanent magnet dc, 370 Watts rated power	155	357	-
Selwood	Selwood	UK	Permanent magnet dc	240	552	-
Hitachi Metals	Hitachi Metals	Japan	Reciprocating actuator	63	140	-
4. INDIVIDUAL PUMPS						
Godwin	Godwin	UK	Self-priming, centrifugal Cobra pump	Free	Loan	-
Godwin	Godwin	UK	Piston pump with hand wheel	Free	Loan	-
Mono	Mono	UK	Monolift progressive cavity pump model C32 B620	913	2100	-
Selwood	Selwood	UK	2 inch diaphragm, model Mk 4 simplite	683	1571	-
5. THERMAL SYSTEMS						
-	Dornier	W. Germany	Complete pumping system with Freon engine being developed in association with BHEL (India)	-	-	Tested at Works
-	Ormat	Israel	5kw energy converter with Freon turbine Generator	-	-	Tested at Works
-	Solar Pump Corp.	USA	Complete pumping system with Freon engine, as supplied for field trials in Sudan	-	-	Tested at Works
-	Sunpower Inc.	USA	Stirling engine (free piston) and diaphragm pump			Tested at University of Reading

Pm = Permanent Magnet

TABLE III LABORATORY TESTED SYSTEMS AND COMPONENTS

	Factor Investigated	Outline Description
1.	Static head variation	Investigate effect of changing static head from 2.5m to 10.0m (all 9 reference systems).
2.	Solar day variation	Insolation data for a typical hazy day substituted for clear reference day data (all 9 systems).
3.	PV array optimization	Array nominal voltage varied keeping power constant to find optimum voltage. Voltage then held constant at optimum value and power varied to find optimum power (all 9 systems).
4.	Impedance matching	The use of a perfect array maximum power point tracker, first with zero losses and then with 10% of output power losses. Also crude impedance matching by series parallel switching at certain times of the day (three systems only).
5.	Sun tracking	The effect of continuous sun tracking by the array was compared to manual tracking with one, two or three array movements per day (at "correct" and at "incorrect" times of day), (three systems only).
6.	Pipework variation	The effect of changing system losses by increasing or decreasing delivery pipe length and diameter (two systems only).
7.	Cost sensitivity	The effect of changing the array cost relative to the balance of system .

N B. The effect of the changes investigated was assessed in terms of the daily pumped output and Specific Capital Cost. The mathematical model built as part of the system design studies was used for this work.

TABLE IV- SENSITIVITY ANALYSIS OF PV PUMPING SYSTEMS

MODIFICATION	Effective[1] Overall efficiency (%)	Specific Capital Cost ($ / kJ per day)	Daily output at 5m head (standard clear day (m^3)	Effect compared with basic system Volume pumped	Spec Cap Cost
None - System as supplied	2.2	3.4	44.9	1.00	1.00
Voltage and power optimized by changing array cells series/parallel arrangement	2.6	3.0	46.6	(2)	0.88
MPPT (10% losses) (Maximum Power Point tracker)	2.5	3.1	51.2	1.14	0.91
Manual tracking of sun (2-adjustments of array position per day)	2.9	2.6	57.7	1.30	0.94
Voltage and power optimized plus manual tracking	3.3	2.3	60.3	(2)	0.68
MPPT plus manual sun tracking	3.1	2.5	62.3	1.39	0.74

Notes : (1) based on irradiation on fixed array.

(2) power is reduced and so pumped volume is not comparable with basic system

TABLE V - RESULTS OF MAKING 'IMPROVEMENTS' TO A PV PUMPING SYSTEM BY USING THE MATHEMATICAL SIMULATION MODEL

GLOSSARY OF TERMS

GLOSSARY OF TERMS

Solar pumping covers a number of technologies, each with its own set of terms. For the convenience of readers and to assist those who may be unfamiliar with solar terminology a glossary of the terms used in the Report have been prepared.

Wherever possible, standard definitions have been used and these are referenced as appropriate. S.I. units normally used have been added where appropriate.

Absorber

The absorber is that part of a solar collector which converts the incident solar radiation into heat and from which the heat is removed by the transfer fluid. If an absorbing liquid is used then this may constitute both the absorber and the heat transfer fluid. (Ref 1)

Absorptance

Absorptance is the fraction of the radiation incident on a body that is absorbed by the body.

Air Mass

The length of path through the Earth's atmosphere traversed by the direct solar beam, expressed as a multiple of the path traversed to a point at sea level with the sun at zenith. (Ref 2)

Angle of Incidence of Direct Solar Radiation

The angle of incidence of direct solar radiation is the angle between the direct solar radiation beam and the outward drawn normal from the plane of the solar collector or array. (Ref 1)

Aperture Area

The aperture area of a solar collector is the opening or projected area of a collector through which the unconcentrated solar energy is admitted. (Ref. 1)

Anti-reflective Coating

An anti-reflective coating is a coating (or treatment) applied to a surface to increase the amount of solar penetration. This may be applied to surfaces of solar cells or to the cover glass of a solar collector or photovoltaic module.

Array Efficiency, Overall

The electrical power output of an array at an instant divided by the total solar power incident upon the entire frontal area of the array.

Array, Solar

(See solar array)

Average Cell efficiency (of a photovoltaic array)

The electrical power output of an array at an instant divided by the total solar power incident upon the entire frontal area of solar cells in the array.

Average Pumped Head

The average pumped head generated by a pumping system over a defined period of time is the total hydraulic energy delivered by the system in that time divided by the total weight of water pumped in that time. (The total hydraulic energy is the integration over time of the pumped power at an instant).

Collector

(See solar collector)

Concentration Ratio

The concentration ratio of a concentrating collector is the aperture area divided by the absorber area.

Concentrator

A concentrator is a system to increase intensity of solar radiation on a given area.

Concentrating Collector

A concentrating collector is a solar collector which uses reflectors, lenses or other optical elements to concentrate the solar energy incident on the aperture onto an absorber, the subtended surface area of which is smaller than the aperture area. (Ref. 1)

Continuous System Performance Data

Data obtained from a system under test when continuously monitored over a given time period and from which performance at any instance can be assessed.

Cumulative System Performance Data

Performance data integrated over a given time period (usually a day) obtained by taking integrated or cumulative readings of the system performance at the end of each time period.

Daily Cell Efficiency (of a photovoltaic array)

The electrical energy output of a photovoltaic array divided by the solar energy incident upon the entire solar cell area of the array during a period of one day.

Daily Overall System Efficiency (of a solar pumping System)

The hydraulic energy delivered by the pump divided by the solar energy incident upon the entire frontal area (photovoltaic systems) or aperture area (thermal systems) of the solar array during a period of one day.

Diffuse Solar Irradiance

The radiant power from the sky (excluding by shading the power within the solid angle subtended by the sun's disk) incident upon unit surface area (See also Ref. 3)
Units: W/m^2

Direct Solar Irradiance

The radiant power from the sun within the solid angle subtended by the sun's disk incident upon unit surface area. (See also Ref. 3)
Units: W/m^2

Emittance

Emittance is the radiation emitted by a body divided by that which would be emitted by an ideal black body at the same temperature and under similar conditions.

Evacuated Tube Solar Collector

An evacuated tube solar collector is a solar collector in which the absorber is positioned in one or more glass tubes and the heat loss from the absorber is suppressed by means of an evacuated layer between the absorber and the outer cover of the tube.

Flat-plate Solar Collector

A flat-plate collector is a solar collector whose aperture area is essentially identical to the area of the absorber surface, employs no concentration and in which the absorbing surface is essentially planar. (Ref. 1)

Fresnel Lens

A lens having the same optical profile as a conventional lens but in which the thickness is reduced by steps at intervals over the surface of the lens.

Global (Solar) Irradiance

The total solar radiant power incident upon unit area of a horizontal surface. Global Irradiance = Direct Irradiance (horizontal) + Diffuse Irradiance (horizontal) (Ref. 2)
Units: W/m^2

Heliostat

An electromechanical device that automatically orientates a mirror so that direct radiation is reflected on a fixed position regardless of the position of the sun.

Hydraulic Power

(See Pumped Power)

Incidence Angle

(See Angle of Incidence)

Insolation

(See Solar Irradiation)

Instantaneous Overall System Efficiency (of a solar pumping system)

The hydraulic power output of the pump at any instant divided by the solar power incident on the entire frontal area of the array (flat-plate photovoltaic systems) or aperture area (concentrator and thermal systems) at the same instant when operating under quasi steady state conditions. (In this Report efficiency is generally used without the adjective instantaneous).

Instantaneous Cell Efficiency (of a photovoltaic array)

The electrical power output of a flat-plate solar array at any instance divided by the solar power incident on the total gross area of the array cells at the same instant when operating under quasi steady state conditions.

Instantaneous Subsystem Efficiency (of a solar pumping system)

The hydraulic power output of the pump at any instant divided by the electrical power delivered to the motor at the same instant and when operating under quasi steady state conditions.

Irradiance

The radiant power incident upon unit area of a surface (See also global irradiance, solar irradiance and total irradiance. In this report irradiance is solar irradiance).
Units: W/m^2

Irradiation

The radiant energy received by unit area of a surface during a given time period. (The time integral of irradiance).

Local Apparent Time (LAT)

LAT is the system of astronomical time in which the sun always crosses the true N–S meridian at 12 noon. This system of time differs from local time according to longitude and time zone. The precise displacement also varies with the time of the year.

Maximum Power Point (of a photovoltaic module)

The power at the point on the current-voltage characteristic where the product of current and voltage is a maximum (Ref. 2)

Maximum Power Point Tracker (MPPT)

An electronic control device which continuously adjusts the voltage output of a photovoltaic array to an optimum value to maximize the array power output.

Module, Photovoltaic

(See Photovoltaic Module)

Module Area

The entire frontal area of the module including borders, frame and any protruding mounting lugs. (Ref. 2)

Packing Factor (of a photovoltaic module)

The entire frontal area of the solar cells in the module divided by the entire frontal area of the module.

Peak Power (of a photovoltaic module)

The power output of a photovoltaic module at a reference temperature under specified working conditions under a solar irradiance of 1000 watts per square metre with an air mass 1.5 spectrum.

Photovoltaic Cell

(See solar cell)

Photovoltaic Module

The smallest complete environmentally protected assembly of interconnected solar cells. (Ref. 2)

Photovoltaic Array

A mechanically integrated assembly of modules (or panels) together with support structure (but exclusive of foundation, tracking, thermal control and other components), as required to form a dc power producing unit. (Ref. 2)

Power Tower or Solar Tower

A tower placed so that the reflected direct radiation from heliostat mirrors can be focussed on a boiler or absorber mounted on top of it.

Pumped Head

The total energy added to the water by a pump per unit weight of water measured between the inlet and the outlet. It is equal to the difference between the sum of the velocity and pressure heads at outlet and inlet.

Pumped Power

The pumped power of a pump is the product of mass flow rate, specific weight and pumped head at an instant. To obtain the input power to the pump it is necessary to divide by the efficiency of the pump.

Pyranometer

A radiometer normally used to measure global irradiance (or, with a shade ring or disc, diffuse irradiance) on a horizontal plane. It can also be used at an angle to measure the total irridiance on an inclined plane, which in this case includes an element due to radiation from the foreground. (Ref. 2)

Quasi-Steady State Condition

The condition of a system when all the variables affecting its performance are at or close to a steady state, such that small variations in these variables will not significally affect its measured performance.

Rankine (Cycle) Engine

A heat engine working on the Rankine thermodynamic cycle.

Reflectance

The radiation reflected from a surface divided by the radiation incident on that surface.

Selective Surface (of an absorber)

An absorber is considered to be selective if it substantially absorbs all incident solar radiation whilst simultaneously exhibiting a low hemispherical emittance at longer wavelengths. (Ref. 1)

Solar Elevation

The angle between the direct solar beam and the horizontal. (Air mass is the cosecant of Solar Elevation.) (Ref. 2)

Solar Array

A number of individual solar collection devices (thermal or photovoltaic) arranged in a suitable manner to collect solar energy.

Solar Azimuth

The angle between the local meridian and the direction of the sun measured in a horizontal plane.

Solar Cell

Also known as a photovoltaic cell. A semiconductor device which can convert radiation directly into an electrical current. The basic photovoltaic device which generates electricity when exposed to sunlight.

Solar Collector (Thermal)

A solar-thermal collector is a device which absorbs solar radiation, converts it into heat and passes this heat on to a circulating heat transfer fluid. (Ref. 1)

Solar Concentrator

(See Concentrator)

Solar Radiation

Radiation emitted by the sun in the form of electromagnetic waves or particles.

Solar Irradiance

The radiant solar power incident upon unit area of a surface at an instant . (See total irradiance and global irradiance)
Units: W/m^2

Solar Irradiation (Insolation)

The time integral of solar irradiance.
Units: MJ/m^2

Solar Pond

An artificially enclosed body of water containing a stratified solution which absorbs and stores solar radiation as heat.

Solar Sensor (measuring instrument)

A photovoltaic device adapted for the measurement of solar irradiance.

Solar-Thermal Process

A process in which solar energy is converted and utilized as heat.

Specific Capital Cost (of a solar pumping system)

The capital cost of a system (operating under reference conditions) per useful energy output over a standard solar day.
Units: $/kJ per day

Single axis sun tracking system

A mechanism for maintaining the plane of a solar array or other object in the general direction of the sun perpendicular to the direct solar beam by means of adjusting the array about one axis only.

Static Head (of a solar pumping system)

The difference in elevation of a source of water and the discharge point or control surface of a pump installation

Stirling Engine

A heat engine working on the Stirling thermodynamic cycle.

Two-axis sun tracking System

A mechanism for maintaining the plane of a solar array or other object perpendicular to the direct solar beam by means of adjustment in two axes so that it tracks the apparent motion of the sun.

Total (Solar) Irradiance

The total solar radiant power incident upon unit area of an inclined surface. (Ref. 2)
Units: W/m^2

REFERENCES

1. Commission of the European Communities
Recommendations for European Solar Collector Test Methods. (Liquid heating collectors). – January 1980

2. Commission of the European Communities
Standard Procedures for Terrestrial Photovoltaic Performance Measurement. CEC Specification No. 101 (EUR 6423 EN)

3. World Meteorological Organisation
Guide to Meteorological Instrument and Observing Practices.
1971 (Fourth Edition)

CONVERSION FACTORS

Area	1 ha	=	2.471 acres
Energy	1 J	=	9.485×10^{-4} BTU
	1 kWh	=	3.600 MJ
		=	8.60×10^{2} kcal
		=	3.4×10^{3} BTU
Flowrate	1 l/s	=	15.85 US GPM
Irradiance	1 W/m^2	=	0.317 BTU/ft^2–h
Irradiation	1 MJ/m^2	=	88.1 BTU/ft^2
	1 kWh/m^2	=	3.600 MJ/m^2
		=	317 BTU/ft^2
		=	86.0 Langleys
Power	1 watt	=	3.41 BTU/h
		=	1.36×10^{-3} hp

PROJECT REPORT

PART I – SUMMARY REVIEW

1. SCOPE AND PURPOSE OF PROJECT

1.1 Scope for Solar-Powered Pumping in Irrigation Practice

The use of solar energy for pumping irrigation water on small farms in the developing world is one of great promise and has excited the imagination of solar technologists, irrigation engineers and development planners in recent years. This application of solar energy has a number of attractions: for example it is available just when the need for pumped water is greatest; it can be tapped at the point at which it is to be applied; and it is under the control of the farmer who wants to use the water.

Although the feasibility of solar-powered pumping has been demonstrated, the technology is expensive but immature. Nearly all the solar pumping equipment available at present is either prototype status or is in its first production run, and so further development is required to produce systems and components which are efficient, robust, reliable, genuinely economic, and which can be made (or assembled) and maintained in the developing world.

To give the reader a feel for the range of flows and powers involved in small-scale irrigation pumping, some typical values are presented and discussed in the paragraphs following.

The areas of very many of the farms in the developing world are in the range of 0.5 to 2 hectares. The quantity of water needed to irrigate a given area depends on the crop, cropping calendar, soil, land topography, climate and method of water distribution but typical figures vary from 4000 m^3/ha with good distribution and management to 13,000m^3/ha per crop. If a crop matures in 120 days (say) the average daily requirement for water can range from about 35 m^3/ha to over 100 m^3/ha. Assuming an average of 6 hours pumping per day, with a peak flow 30% greater than the average, the peak pumping capacity required for one hectare will be in the range from 2 to 6 l/s.

The power of a pumping system is proportional to the product of flow rate and head. For a head of 5 metres, the required peak pumped power thus ranges from about 100 to 300 watts per hectare, while for a 10 metre lift the power requirements are double these figures. There are many areas in the world where the water table is within 10 metres ohe ground surface and low head irrigation using traditional methods, is already practised. Thus small-scale solar-powered pumping systems, with an installed pump power output in the range 100-300 watt/ha for a 5m head, or 200-600 watt/ha for a 10 m head, are of primary interest for irrigating areas of up to 1 ha; the number of small-holdings of this area runs into millions and solar pumps have the potential to meet this requirement. Although considerably larger power outputs are technically possible, the small-scale approach helps to encourage the development of a pump of a cost and size suitable for use by one farmer: thus the technical and managerial problems of multiple use are avoided. Fortunately it is likely that there will be relatively little economy of scale in the size of individual solar pumps, which means that there will be little or no economic advantage for agriculture in concentrating pumping capacity in a few places and having extensive and costly distribution systems. It is important to appreciate that the balance to be struck when using solar pumps will be different from the balance when using engine pumps, with considerable economies of scale.

A factor which bears on the use of these pumps is that the relatively low flows which they provide for field application (compared with some conventional methods) must be used with maximum efficiency. This may mean the adoption of different irrigation techniques, e.g. if flood methods are used, dividing the total area into very small units for sequential application over a two week period (say), or using locally made impermeable field distribution channels, or drip feed techniques to minimise conveyance and evaporation losses. All such possibilities will of course, have to be designed in conjunction with the requisite storage.

To be attractive economically, the cost of water delivered by the pump must be less than the value of the benefits obtained by use of the irrigation water, either through improved yields or by enabling a second (or different) crop to be grown. A cost ceiling of around US $0.05 per cubic metre (1979 prices) for irrigation water has been accepted within the World Bank as a realistic norm. although clearly this will depend on the crops and field application efficiency. Thus, if solar pumping systems are to be genuinely economic on their own account (and not simply shown to be comparable with possibly uneconomic diesel engines), they will need to deliver water at a cost not exceeding the equivalent of the 1979 figure.

The analysis reported in the accompanying Technical and Economic Review suggests that at the present time photovoltaic (PV) systems are being offered on the market at prices which are up to four times greater than those at which it would be economic to use them for irrigation. Since the cost of the PV module is presently the predominant element in the system cost (up to 75% of the total) and reductions in the unit price of PV modules are expected, there is reason to think that, with responsible development and improvements to system efficiencies, PV powered pumping systems have a reasonable prospect of becoming economic in the next 10 years.

Although solar thermal systems have a longer history than photovoltaic systems, extending back over 100 years, their early potential was not realised because of the widespread availability of cheap conventional steam-powered engines, complemented later by the adoption of oil-fuelled engines. Small PV-powered systems received an enormous boost from advances made by the space programme and thermal systems have lacked a similar injection of development ideas and finance in recent years. Thus at the present time there are no thermal systems available on the market which have been fully demonstrated in rural situations.

Despite this an objective review should not rule out thermal systems. They have attractive features - the technology is simpler and there may be some economy of scale and interest in this method of energy conversion has increased in recent years.

1.2 UNDP/World Bank Project

Against the background outlined above, the United Nations Development Programme and the World Bank considered that the time was right to investigate the development of small-scale pumping systems for use in developing countries.

Accordingly a project document was signed by the UNDP and World Bank in June 1978 which provided for the development of small-scale pumping systems for water supply and irrigation applications in developing countries which:

(a) are based on renewable energy sources;
(b) are decentralized;
(c) have costs low enough for small farmers;
(d) have minimal and simple operation and maintenance requirements; and
(e) have good prospects for local manufacture and/or assembly.

The UNDP and World Bank decided that the work should first concentrate on the use of solar energy and investigate its application to irrigation pumping. The first phase of the project was mounted with the overall objective of advising the UNDP and World Bank on whether solar pumping technology was in such a position that it would be worth promoting its development to make it appropriate for pumping water under the conditions that prevail on small farms in the developing world and if so, what steps should be taken. The enquiry was thus open, although it was expected that the potential of the technology would be recognised and that further development would be recommended. [The terms of reference provided for systems to be considered which could provide a flow of not less than 1 l/s and stipulated that attention should be concentrated on pumps with an output in the 100 to 500 watt range, although pumps with powers of up to 2000 watts would not be excluded if suitable examples were found in the course of the work.]

The main activities in Phase I were to include field trials of possible systems, laboratory tests on principal components and system design studies. In undertaking this work the importance of manufacture (or at least assembly) of the systems in developing countries themselves was recognised.

At a very early stage in project preparation (before the Consultants were involved) discussions were held under UNDP auspices to decide on the locations of the field trials. Agreement was reached in principle for the participation of India, Mali, Philippines and Sudan but in the event India did not participate in the field trials which were, therefore, hosted by and carried out in Mali, Philippines and Sudan.

1.3 Activities in Phase I

The programme of work undertaken in Phase I included the following principal activities:-

1. Reviewing recent developments in the technology of the utilisation of solar energy for small-scale irrigation pumping;

2. Collecting and evaluating technical data and costs on thermal and photovoltaic pumpings systems and components which can be ordered to a delivery schedule and price, and recommending the equipment which should be purchased for field trials and laboratory tests, with subsequent detailed evaluation;

3. Organising field trials of selected and approved systems in collaboration with research and development agencies in the host countries, and collecting and analysing performance data;

4. Identifying suitable organisations for testing components for solar pumping systems under laboratory conditions and preparing a test programme;

5. Supplementing existing laboratory and field test data by conducting laboratory testing of selected components at approved testing organisations and collecting and analysing performance data;

6. Based on the results of 3 and 5 above, undertaking a brief system design study with a view to recommending how systems and components could be developed to make them more suitable for use by farmers in developing countries and preparing outline specifications for such improvements;

7. Studying the feasibility of mass production of solar-powered pumping systems and components in developing countries and estimating the manufacturing costs and prices for which they could be sold;

8. Preparing interim and final reports on Phase I, including recommendations and budget for work to be undertaken in Phase II.

It had been intended that a preliminary market survey should be conducted, but it was finally agreed that this should be dropped from the programme for Phase I. This was because the potential market for appropriate solar pumps was already evident and, before a more detailed evaluation could usefully be made, a clearer idea was needed of the capabilities and prices of the most suitable pumping systems which were likely to be produced. This information would not be available until after Phase I of the Project was concluded.

During this phase of the Project, no formal study was made of the social acceptability of solar pumping technologies in rural communities in developing countries, or of the ways in which these technologies should be introduced, financed and distributed. The importance of these non-technical aspects for the final successful application of solar pumping is fully recognised, but it was felt that these questions could only be addressed credibly when truly reliable, efficient and economic systems were within sight of development.

The on-farm trials in Phase I have, of course, yielded some useful information about farmer reaction, but it is important to remember that the primary purpose of the field trials in Phase I was to monitor the performance of the present generation of systems under field conditions in order to obtain the data needed for the improvement of the equipment.

1.4 Administration and Management

1.4.1 Contract

The World Bank, acting as the Executing Agency for the United Nations Development Programme (UNDP), appointed Consultants for Phase I of the Project on 1 July 1979. This phase was originally scheduled to last 18 months, but towards the end of 1980 the Bank agreed an extension of the Contract to 30th April 1981 and a corresponding increase in the budget allocation. This extension allowed for extra time for work in the host countries and for more extensive system design studies.

Throughout the Contract period, the consultants worked closely with the UNDP Project Manager at the World Bank, Dr. E.M. Mitwally.

1.4.2 Consultants' Organisation and Management

Sir William Halcrow and Partners carried out the Project working in association with the Intermediate Technology Development Group Limited (ITDG) of London. Halcrow/ITDG established a small executive Project Management Group responsible for all day to day matters, allocation of responsibilities, review of progress and approval of reports. Arrangements were made for specialist advice to be given by a number of the leading UK experts in solar pumping technology and a Management Advisory Group was set up to provide a forum for a general review of progress and for an exchange of views and information. The names of the members of the Project Management and Management Advisory Groups and our Specialist Advisors are given in Appendix A.

Sir William Halcrow and Partners placed contracts for the provision of equipment directly with suppliers and with the Royal Aircraft Establishment and the University of Reading for parts of the laboratory test programme. Agreement was reached with the Jet Propulsion Laboratory, USA for it to undertake some work on PV modules at no cost to the Project.

1.4.3 Participating Research and Development Agencies

The energy research agencies nominated by the Governments of the host countries to be responsible for the conduct of the field trails were as follows:-

- Mali: Laboratoire de l'Energie Solaire (Solar Energy Laboratory-SEL) of the Direction de l'Hydraulique et de l' Energie (Director : Mr. Cheikna Traoré)
- Philippines: Center for Non Conventional Energy Development (CNED) of the Ministry of Energy (Administrator: Dr. E N Terrado)
- Sudan: Institute for Energy Research (IER) the National Council of Research (Director Dr Yehia Hamid)

The Consultants Resident Engineers were attached to the respective agency which made staff and support facilities available to assist the Project.

1.5 Future Phases of the Project

It is intended that further work to achieve the long term objectives of the Project should be carried out in future phases. It is anticipated that the following activities would feature in additional work:

- o further design development extending the work initiated in Phase I under the system design studies;
- o procurement of improved photovoltaic and/or thermal systems based on the results of the system design studies;
- o field testing in the host countries of the improved systems; and
- o detailed market surveys and studies regarding the feasibility of local manufacture.

Proposals for Phase II Preparation stage (leading to Phase II) are under consideration by the UNDP and the World Bank.

1.6 Reports

1.6.1 Structure and Objectives of Phase I Project Report.

This volume contains a summary of the work undertaken in Phase I of the Project, describes our conclusions and makes recommendations for the future development of solar pumps. It is based on an extensive Project Record. Particular points of interest in the Report include the following:

o Selection of equipment

Considerable effort attended the appraisal of solar pumping systems, subsystems and components available for purchase to a budget and time schedule, and 245 organisations were contacted. It is some measure of the general immaturity of this technology that in the final analysis only 10 different systems proved to be available for purchase within a realistic delivery period and budget. Other systems were under development but not available for purchase.

o Field Trials

A vital part of the Project was the field trials to be conducted in close collaboration with the participating agencies in the host countries. These trials (along with laboratory tests) have their origins in the principle that independent tests on performance, operation and reliability of systems are essential before decisions can be made responsibly about the future direction of this technology. It is believed that these trials represented the first comparative tests on a number of commercially available systems under the control of an independent consultant. The data obtained made an important contribution to the system design studies. A key factor in the field trials was the appointment of Resident Engineers to each country.

- o Collaboration with the Research Agencies in the Host Countries

  At all stages, close co-operation with the participating institutes in host countries was maintained, to ensure that their advice and experience was taken into account in formulating the programme for the field trials and in executing the work. This collaborative arrangement assisted the transfer of technology between manufacturers and developing countries and also between developing countries.

- o Laboratory Tests

  Laboratory tests were planned to take account of other reliable laboratory results and to complement the field trials. All subsystems which were tested in the field were also tested in the laboratory, together with a number of individual motors and pumps bought separately. Although results can be regarded as indicative only of the generic characteristics of the type of equipment selected (because only one sample of each was tested) data on the performance of motors and pumps over the full performance range of interest to designers of solar pumping systems were obtained. These laboratory data provided another vital input to the system design studies and enabled the performance of each major component to be characterised in the mathematical model constructed as part of the system design study.

- o System Design Studies

  The system design studies represented to the Consultants the principal opportunity to take the technical initiative and to apply the knowledge gained from the field trials and laboratory tests to the improvement of photovoltaic solar pumps. An essential part of this work was the construction of a mathematical model which has enabled a study to be made of some of the interacting factors which influence the performance of these systems. A first study was also made of a thermal pumping system but since it is more difficult to describe the individual performance of thermal components than of photovoltaic systems, the conclusions from this part of the work are more tentative; nevertheless some useful points emerged.

1.6.2 Technical and Economic Review

- o A State-of-Art Report was submitted to the World Bank in January 1980. This has been revised and updated and, under the title "Technical and Economic Review", was submitted to the Bank as a companion Volume to this Report. It is freely available from the Bank, but for the convenience of readers a very brief outline of its contents is given in the following paragraph.

The Review discusses the general technical and power requirements for small-scale irrigation and reports on a study of system economics, reviewing the effects of variation in the major influences on solar pumping and the differential movement in prices. The principal photovoltaic and thermal prime-mover power options available for small-scale irrigation pumping and the engineering requirements for this type of system are described. A technical assessment is made of the main types of solar pumping system available and information is given on possible future trends. The Review concludes with a comparison of the relative efficiencies and costs of the main system options which are currently available and with an estimate of the costs for which it may be possible to produce these systems in the future.

FIELD TRIALS

1 Introduction

2.1.1 Purpose of field trials

The Project was structured in the belief that independent tests on the performance, operation and reliability of systems and components are essential before responsible decisions can be made about the future development of the technology.

The basic purpose of the field trials was to permit the performance and reliability of selected small-scale solar pumping systems to be evaluated objectively under the sort of conditions found on farms in the developing world. The systems were instrumented and monitored so that their efficiency and performance could be calculated.

Considering the difficulty and expense of gathering reliable field data, it is perhaps not surprising that so little of it is available. It is our firm conviction, however, that progress can only be made on the basis of such data, and so considerable emphasis was placed on this aspect of the work.

2.1.2 Benefits

The benefits of the field trials can be summarised as follows:

- They provided a practical demonstration of small-scale solar pumping technology and identified the good and bad aspects of each system.
- A range of solar and hydraulic conditions were covered so that the measurements give a reasonable indication of performance of the most promising of the present generation of systems.
- They enabled the mathematical model built as part of the system design studies to be validated. Without this, the model could not have been used with confidence and the system design studies would have suffered correspondingly.
- An exchange of information took place between the staff of the participating research agencies and the Halcrow/ITDG team.
- They forced attention upon those qualities of the available equipment which made them more (or less) suitable for use by farmers in the developing countries. Decisions on the future can now be made on the basis of practical field experience, whereas evaluation made solely as the result of theoretical or laboratory studies might not have revealed the true strengths and weaknesses of present technology.

2.1.3 Countries, sites and systems

The UNDP and World Bank arranged for Mali, Philippines and Sudan to host the field trials. As noted in Chapter 1 a national energy research agency was designated by each Government to be responsible for working with Halcrow/ITDG: in Mali this was the Solar Energy laboratory (SEL): in the Philippines it was the Center for Non-Conventional Energy Development (CNED): and in the Sudan it was the Institute of Energy Research (IER).

A number of combinations of systems and sites were considered and, taking account of the limited budget and time scale of Phase 1 of the Project, it was decided to test four systems in each country. Ten different systems were purchased, one being duplicated in Mali and the Philippines. One system was already installed and operating in Mali and permission was obtained to monitor it as part of the Project. A summary of systems and sites is given in Table 1.

2.1.4 Visits

Preparatory visits were made by the UNDP Project Manager from the World Bank and members of the Halcrow/ITDG Project team to each of the host countries in September and October 1979 to explain the purpose of the Project and the place of the field trials in it, to agree on criteria and procedures for site selection and on the programme to be followed and to make detailed arrangements for the conduct of the trials. From time to time return visits were made to each country by members of the management team.

2.1.5 Duration

The duration of the field trials within the Project was necessarily limited. The arrival of the Resident Engineers in the three host countries in March 1980 saw the start of significant activity and this continued at a high level to the end of that year. The Resident Engineers for Mali and the Philippines left at the beginning of October 1980 but made short return visits in December 1980. In the case of Sudan (where progress was hindered by serious logistical problems) the Resident Engineer returned to the United Kingdom for four weeks in November and December 1980, and finally left the Sudan in mid February 1981.

2.2 Selection of Systems

A world-wide list of 245 organisations who were either potential suppliers or else were developing relevant equipment was drawn up and a covering letter, questionaire and prospectus describing the Project was sent to each organisation in August 1979. 107 organisations responded. This information formed the basis for the Consultants recommendation on the systems and components which were to be purchased for the field trials and laboratory tests.

The aim of the process of evaluation was to arrive at a short list of manufacturers of systems and components which would form the basis on which the programme of field trials (and laboratory tests) in Phase I would be drawn up.

The assessment of the initial information was guided by criteria, the more important of which were as follows:

- o Equipment must satisfy the Project specification. (In terms of output flow and head).
- o Delivery should be within 13 weeks of order.
- o Systems should have technical merit and good performance.
- o Systems should be robust and practical for the duty envisaged and if possible, offer some evidence of reasonable life.
- o Equipment was preferred which had some promise of becoming suitable for manufacture in the developing countries.
- o The suppliers were preferred who had previous experience of operating their systems in developing countries.
- o Systems should have low maintenance requirements.
- o Systems should be offered at a reasonable cost in relation to their output and size.
- o The manufacturer or supplier should offer an adequate range of back-up servies (e.g. assistance and/or advice with installation, maintenance, testing etc.)
- o The supplier should have overall credibility in terms of technical expertise, back-up capability and delivery.

A 'suitablity rating' was awarded to each system, to rank them into three categories on the basis of the level of compliance with the criteria listed above, the equipment specification and the technical and commercial credibility of the supplier.

The information supplied by the manufacturers and suppliers with suitability ratings of 1 or 2 (the highest ratings) were checked in detail and where necessary follow up enquiries were made to clarify or confirm doubtful points. The number of suppliers whose quipment was awarded suitably ratings of 1 or 1-2 was eventually reduced to 19.

A provisional short-list was then prepared of systems which appeared technically acceptable for the small-scale solar pumping purpose of the Project and which were available to a cost and delivery time consistent with the overall programme.

Elimination of the least cost-effective equipment then yielded a number of suppliers who claimed to be able to offer complete pumping systems suitable for the purpose of this Project within the equipment budget available. Suppliers who on subsequent follow-up still offered a credible system for delivery within about 13 weeks were placed on the final short list of complete systems, from which the systems to be deployed in the field were then selected. The short list is given in Table 2.

Great care was taken in making these selections and it is not thought that any system available commercially at reasonable cost was precluded from the field trials.

2.3 Monitoring of System Performance in the Field

The principal interest was in the following performance parameters:

- o solar irradiance at any instant (global and in plane of array)
- o cumulative solar irradiation
- o power, voltage and/or current output from array
- o static head at any instant and average over day
- o pumped head at any instant
- o flow rate at any instant
- o cumulative volume pumped over a day

Because of restraints it was not possible to measure every parameter at every site but a cost-effective programme was devised which produced sufficient data for an assessment of system performance. Some data on ambient conditions (temperature, humidity and wind) was also collected. The various parameters which were measured and instruments used are set out in Table 3.

The primary data collected on performance was of two main types:

a) Continuous data on solar irradiance (global and in the plane of the array), array power output, water flow rate and pumped head. Chart recorders were used to make assessments of instantaneous values of irradiance, array power and voltage output, and flow, while other parameters were monitored at ¼ and ½ hour intervals. From this information system efficiency and performance could be determined throughout the day and as a function of solar irradiance.

The collection of this information required relatively sophisticated instruments operated by staff from the participating agencies with assistance from the Resident Engineers.

b) Daily cumulative data which gave a picture of the total solar energy input to the array (solar irradiation) and the pumped output over a complete day. This information was obtained from integrating counters. It was thought that this information was probably simple enough for it to be obtained by farmers, but during the trials the staff of the participating agencies were usually involved.

The normal field procedure envisaged visits each day to each system to record daily cumulative measurements of system performance and one visit per week to each system to make continuous measurements on system performance throughout the day. A record was also to be kept of any fault, breakdown or other incident which affected the operation of the system. It was, however, expected that local variations would need to be made according to the circumstances encountered and this programme, desirable though it was, made logistical and management demands which outstripped the resources available to the participating research institutions.

Great stress was laid on the need to check and calibrate the monitoring instruments used. Experience has shown that, under field conditions, the calibration of some of the measuring instruments will drift. Care was taken therefore to check their calibrations regularly as well as to protect the instruments from rain and direct solar radiation. Any data recorded from instruments whose calibrations were in doubt have been excluded.

It was important to have enough data to check that each system was behaving consistently over a period of time and to obtain information about its performance over the whole range of irradiance values. Clearly once the performance was reliably established over the whole range of irradiance usually experienced there was little point in collecting further identical data simply for its own sake, other than to check on consistency and accuracy. Although instantaneous response to a given level of irradiance should always be more or less the same, the daily output and response to daily irradiation will vary according to the pattern of the individual daily solar regimes.

A document outlining the field procedures to be used was drawn up by the Consultants for the Resident Engineers. This included a standardised scheme for testing and provided data collection proforma sheets to be used. Thus the data obtained from the three host countries was comparable and presented in a similar format for analyses.

2.4 Field Trials in Mali

2.4.1 Participating Institution

The agency for solar energy research work in Mali is the Laboratoire de l'Energie Solaire (Solar Energy Laboratory SEL) which is a division of the Direction de l'Hydraulique et de l'Energie.

The present Director is Mr. Cheikna Traore. Senior Staff of the Laboratory, Mr. Modibo Dicko and Mr Nto Diarra supported the Project and appointed Mr M. Diarra Principal Counterpart and Mr. F. Dembele Assistant Counterpart to work with the Consultants Resident Engineer, Mr. A. R. O'Hea.

2.4.2 Sites

Table 1 summarises the main features of the works and systems adopted in the host countries. Table 4 gives details and costs of each system chosen for Mali.

For convenience brief details of the sites are summarised below:

- Yangasso is 380 km east of Bamako on the road to San. At this site in December 1979 Mali Aqua Viva installed a 1300 W vertical -axis Pompes Guinard pump on a borehole. The water rest level was about 14m below ground level and the drawdown was about 5m. Permission was obtained to monitor it as a part of the Project. The water has not yet used for horticultural or agricultural purposes.

- Babougou is 310 km north-east of Bamako on the bank of the Niger, and is the site of an FAO seed farm producing rice seed for an adjacent rice-growing scheme. The Briau Duva surface-mounted positive displacement piston pump was used here. It was intended the water should be used for irrigating a vegetable garden.

- Banankoro is 21 km south of Bamako on the road to Bougouni. The site is a low-lying field irrigated by watering can from a number of shallow open wells to produce vegetables. The water level was 2 to 3m below ground level. The SEI portable unit incorporating a maximum power point tracker was used here for a time to water vegetables. Unfortunately the farmer fell ill so the pump was transfered to the Solar Energy Laboratory in Bamako.

- Solar Energy Laboratory in Bamako. A test rig was designed so as to be able to monitor the SEI pump at the Laboratory itself. Because of administrative delays at the Laboratory the rig was not ready by the end of the Resident Engineer's stay. However by December 1980 considerable progress had been made in the construction of the rig.

- Korofina is a district of Bamako where plots are intensively cultivated as market gardens. Irrigation is by watering can from a large number of open wells with the water level typically 3 to 6m below ground level. The Photowatt surface mounted horizontal axis centrifugal pump was used here.

2.4.3 Progress

The main dates related to progress are summarised in Table 5. The first four months were mostly spent settling the selection of the sites and clearing the equipment from the Malian Customs. Progress thereafter was steady but was limited by logistical difficulties.

Table 10 summarises the total data resources obtained from the continuous and cumulative measurements and the uses made of it. Most data was obtained from the Pompes Guinard and Briau Duva systems, which operated through most of the trial period; the data from the Photowatt system was limited by the time spent trying to overcome the problems experienced in getting the pump to operate properly and to overcome its priming problems: while the SEI data was limited by the time spent overcoming its initial electronic failures and establishing a test rig for it at the Laboratory.

2.4.4 Continuation of Field Work

a) Pumps outside Bamako

The two pumps at Yangasso and Babougou are too far from Bamako to be visited by the Solar Energy Laboratory without special outside funding for the purpose. Arrangements were therefore proposed for the data from the daily monitoring to be sent directly to the Consultants by local staff.

For the pump at Yangasso, Mr Guy Olivier of COMES, based at San with Mali Aqua Viva, kindly agreed to do this until his return to France in February 1981. The readings are then due to be taken daily by the Secretary of the Yangasso District, Mr Noumouri Traore.

Ms. Christel Hansen of the FAO farm at Babougou kindly agreed to see that data was collected and the pump cared for until her return to Germany in June 1981, and to ask the local staff to continue with these tasks until the end of 1981.

b) Pumps in or near Bamako

The Laboratory have stated their intention of monitoring the Photowatt pump at Korofina as soon as a replacement arrives and of setting up the SEI pump at the Laboratory and monitoring it, and of sending the results to the Consultant at regular intervals.

Any additional data will be analysed when received by the Consultants.

2.5 Field Trials in the Philippines

2.5.1 Participating Institutions

The Center for Non Conventional Energy Development (CNED) was established by the Government of the Philippines in 1978 to lead in and manage the conduct of research, development and demonstration programs designed to harness nonconventional energy sources. The Center is headed by Dr. E N Terrado who holds the post of Administrator. Since August 1980 the Project has been the responsibility of Dr Rufino H Ibarra, Head of the Solar Energy Division in the CNED.

Throughout the field trials, day to day operations have been the responsibility of Mr. E. Quibilan, an electrical engineer, aided by Mr. D. Domondon a chemical engineer assisted by several young graduate engineers, and by the Centers's technical support staff.

The Consultants Resident Engineer was Mr. R J Hacker who worked closely with Center personnel.

The Farm Systems Development Corporation (FSDC) is a corporate arm of the Ministry of Public Works which was established for the purpose of promoting rural development, princir "y by increasing the productivity of farmers who own a farm area of only a few hectares.

The FSDC was thus a natural choice of the CNED for a partner in these field trials, because of its experience of extension work among farmers through field officers.

The FSDC is headed by the Administrator, Mr. T C Rey Jr. One of the major programs of the FSDC is the Barangay Irrigators' Service Association (Barangay ISA) Program. This program involves the formation of a group of farmers, each with access to a limited area of land, into an association whose initial objective is to install and operate an irrigation system for their farms.

2.5.2 Sites

Two sites were proposed by the FSDC and accepted by CNED Both are existing Irrigator's Service Assocation (ISA) sites and both had already established a reputation for being progressive, co-operative and using their water efficiently. They are:

- o ISA at Talampas, Gulod, Sapang Palay, Bulacan
- o ISA at Talaksan in San Raphael, Bulacan

The ISA at Talampas has sixty member families who irrigate an area of seventy two hectares for rice. They use a mains electric pump of seventy five horse power which draws water from the irrigated Santa Maria river and lifts it about 37m.

The ISA at Talaksan has twenty seven member families and irrigates an area of approximately forty hectares using a diesel pump which lifts water approximately 18m to a small canal from the regulated Angat River. The crop is almost exclusively rice.

The sites are in the province of Bulacan between 40 and 70 km to the North of Manila and within 1½ hours drive of the CNED office.

Shortly after the arrival of the Resident Engineer in the Philippines an inspection of the sites was made jointly with the staff of the Center and the FSDC. As a result the Omera Segid system was situated at the top of the slope at Talampas leading up from the river. The farmer intended to use the water to irrigate land over the brow of the hill and promised to keep small trees, which threatened to shadow the array, trimmed back.

The Pompes Guinard system was confirmed for installation near the existing pumphouse on the high river bank with a view to assisting with the irrigation of paddy near the river.

At Talaksan, a site was found for the Briau pump by the small canal, quite close to the access track and with a potentially large area for irrigation to the north, previously out of command of the canal. It was decided to locate the SEI pump near the Briau pump.

Table 1 summarises the sites and systems adopted, while
Table 6 gives details of each system chosen for the Philippines.

2.5.3 Progress

The progress made in installing, commissioning and testing the pumps in Philipines is set out in Table 7. A regular pattern of monitoring with reliable observations was not established until mid-August 1980.

Table 10 summarises the total data resource obtained from the continuous and cumulative measurements and the uses made of it for analysis. Despite a problem over a footvalve and leaking glands a large quantity of data was obtained from the Briau system. The Omera Segid system looked reliable although for the first few months it was clear that the power from the array was not up to specification. After the modules had been dismantled and wiring reconnected, the power output improved and some useful data was obtained. Unfortunately the vegetation was not cleared as promised and the array suffered from some partial shading which adversely affected the performance of the system. The Pompes Guinard surface suction pump was installed on the river bank well clear of possible river flood levels but just within the suction lift specified by the manufacturer. It became clear, however, that the lift was too great, for the pump suffered from continual priming problems and data was difficult to collect. The SEI system suffered from electronic failures initially and after these were overcome it was agreed that the CNED should test the system at its laboratory in Manila pending agreement on a final fixed location for the pump. Some data was collected towards the end of 1980.

2.5.4 Continuation of Field Work

- General Programme

  It is highly desirable to continue a programme of monitoring for at least twelve months in order to cover a full cycle of climatic variation and irrigation water demand. For the field trials in the Philippines, the monitoring must thus continue to at least July 1981.

  The Center has agreed to continue the monitoring programme into 1981, so long as essential support is provided by the UNDP/World Bank. This support is primarily in the form of the provision of a vehicle for project transport until such time as they can provide their own. Continuation of the monitoring programme entails the collection of daily performance results, but with less emphasis on continuous system performance monitoring. Once a body of data has been built up on the continuous system performance the use of further sets of data is confined to recording performance under different climatic conditions and checking for deterioration in performance. Therefore the frequency of such testing may eventually be reduced.

  Naturally the continuous operation of the systems means that the Center will have to undertake any necessary work for maintenance and be responsible for the security of the systems and instruments.

o Work on the Briau System

This system works well in its present location. Therefore the need is to continue the monitoring programme and execute any necessary maintenance.

o Work on the Omera Segid System

The normal performance characteristics of the pump have been established but (as noted above) in the last months of 1980 its daily performance was increasingly restricted by shadows from nearby trees. (A shadow over one cell only is sufficient to negate the output of the whole module containing that cell). The only lasting solution to this problem was to relocate the pump. Therefore during the visit of the Resident Engineer in December 1980 a new site was found for the Omera system. This site is also on land owned by a member of the ISA and the pump could be used to draw water from a small stream (said to be reliable) and lift it about four to five metres. Choice of this site necessitates placing the motor and pump on a small frame/foundation separate from the solar array frame since the banks of the stream are wooded and there would otherwise be a new risk of tree shadows on the array. The Center arranged to include this work in its programme for 1981.

o Work on the Pompes Guinard System

Towards the end of 1980, an engineer from Pompes Guinard visited the site and confirmed that the net positive suction head was too great and that the pump should be relocated lower down the river bank and nearer normal river level. The CNED accepted these proposals and agreed to make arrangements to complete the work required.

o Work on the SEI System

At the end of 1980 this system was operational but had been subject to very little testing. There was therefore a need to gather data on its performance under different climatic conditions, at different pumping heads, and at different alignments for the solar arrays. The Center was equipped to continue this testing in the test rig at the Center: after data has been obtained it is hoped that it will be transferred to the field.

o Use of Pumps for Irrigation

Out of the four pumps tested, only the Briau could have been used for irrigation during 1980, but the ISA did not organise the use of the water. There remains a strong desire actually to use the pumps to assess the maximum area which can be sucessfully irrigated. These aims may be achieved in 1981 when the Guinard and Omera systems are expected to be operational, and the SEI system becomes available for field development.

o Related Studies

A part of the overall Project is the collection of data on farmer's views on use of the pumps for irrigation. In September 1980 the World Bank approved the commissioning by the Center of a sociologist to make a small study of these matters. The study was scheduled to commence in January 1981.

Any additional data will be analysed when received by the Consultants.

2.6 Field Trials in Sudan

2.6.1 Participating Institution

The participating research institution which hosted the field trials in the Sudan was the Institute of Energy Research which is a part of the National Council for Research: The Director of the Institute is Dr. Yehia Hassan Hamid.

The Institute staff who contributed to the Project work with the Consultants' Resident Engineer, Mr. A P Napier, were: Mr. Mohammed El Tayeb Mansour, a mechanical engineer, Mr. Mohammed Osman Sid Ahmed a physicist on working leave from research at University of Reading, Mr Shuommo, a mechanical engineer, and Mr Hashim, an electrical engineer.

2.6.2 Sites

It was intended originally that all four systems should be located at Soba, the Research Station of the Institution of Energy Research about 18 km south of Khartoum. This depended on the completion of a well, the construction of which fell behind schedule.

It was then decided that the Solar Pump Corporation system should occupy the only borehole at Soba and that a new site should be found for the remaining three systems. The water level at Soba varied from 12m to over 20m below ground level, but this was not expected to be a problem to the piston pump on the SPC system.

During Dr. Mitwally's visit in April 1980, a site on a privately owned estate near Butri, 9 km from Soba, was found. This had two open wells sunk about two years ago and which were used for the irrigation of an orchard and other crops.

The static lift at Butri was between 9.5m and 11m. Two of the three PV systems had no difficulty with that head. The third system was not really suited to it but for lack of a better alternative it was decided to go ahead. The solar pumps were used for irrigation and to fill an overhead storage tank. Water was distributed through a 100m long hose.

A summary of the systems and sites is given in Table 1. Table 8 gives details of each system chosen for the Sudan.

2.6.3 Progress

The progress made in installing, commissioning and testing the pumps in Sudan is set out in Table 9.

Table 10 summarises the total data resource obtained from the continuous and cumulative measurements and the uses made of it for analysis.

Considerable time was spent in the early months sorting out logistics in clearing equipment through customs and in arranging for the replacement of damaged items.

Although the SPC thermal system was the first to arrive, a replacement well-jack suitable for the water depth at Soba was delayed, and so attention was directed first to installing and commissioning the Arco Solar & ITC/Solar Corporation systems.

No major problems were experienced with the Arco system and a considerable quantity of data was collected. The unfortunate loss of some of the data was made good in early 1981. Mechanical problems were experienced with the pump impeller of the ITC system and these limited the number of occasions when it could be monitored.

Although installation of the SPC system went smoothly, problems occurred in commissioning which could not be resolved while the Resident Engineer was in Sudan. The system could not be made to work consistently for long enough periods to monitor performances and thus no data was obtained.

Various items for the Soterem system were lost or damaged and the installation of the system could not be completed before the Resident Engineer left. However useful tests were carried out on the tracking system.

2.6.4 Continuation of Field Work

The desirability of continuing with some of the field measurements was agreed with the Institute of Energy Research. The main items of work to be undertaken were:

- o Arco Solar System

  Daily cumulative data should continue to be collected to check on consistency of performance while continuous monitoring should be undertaken once a month. Brush wear should be checked.

- o ITC/Solar Corporation System

  In an attempt to overcome the impeller binding problem a short shaft motor-pump connection with the impeller mounted independently of the shaft has been fitted. If possible the assembly was to be mounted on a float and continuous and cumulative data obtained.

- Solar Pump Corporation (thermal) system

  An SPC engineer visited the installation in March 1981. A number of adjustments were made to the system (for example length of stroke, pipework) and the system then pumped for periods of up to 45 mins. Further consideration needs to be given to the choice of the appropriate working fluid for engines working in areas where the ground-water temperature is high (@ about 30^{o}C).

- Soterem tracking system

  The installation should be completed and the full range of monitoring tests instituted.

  In line with the Institute's, national role for testing solar pumps, it is planned to develop the Soba site and its hoped to transfer the pumps presently located at Butri to Soba. This will require the completion of another well.

Any additional data will be analysed when received by the Consultants.

2.7 Field Trial Results

2.7.1 Continuous System Performance

The main objectives of continuous system performance monitoring were to assess and evaluate the overall and sub-system performance of each system over typical solar days and at various levels of solar irradiance, and to make inter-system comparisons. As the layout of each system and its operating conditions at each site were different, a common basis for comparison had to be found. The main parameter which has been used to assess the performance, independently of the layout, is the system efficiency. Data was obtained from 10 out of the 12 systems installed.

The main environmental factor affecting the output of the system is the intensity of the solar irradiance in the plane of the array. For these reasons it was decided to calculate the array efficiency (ηc), subsystem efficiency (η sub) and overall efficiency (η) using data obtained under a range of array solar irradiation. Thus given a solar regime for another site, performance over a day may be estimated from the results after assumptions have been made for the array orientation.

The actual flow rate produced by a system for a given value of solar irradiance at a given static head is of course very important when assessing system performance. To compare subsystem performance it was necessary to record instantaneous values of array power output and hydraulic power output. (The hydraulic power putput is the product of the flow rate, specific weight of water and pumped head). The losses in the pipework (footvalve, bends, friction and outlet) were calculated theoretically and checked against field measurements in order to assess the pumped heads as accurately as possible.

Considerable thought was given to the clearest way to tabulate and present the mass of data collected during the field trials.

It was decided that continuous system performance should be presented in two series of graphs:

- o Series 1: to show how solar inputs, hydraulic outputs and efficiencies varied over the day.
- o Series 2: to show how the electrical output, hydraulic power, and efficiencies varied with solar irradiance.

A list of these plots is given in Table 11.

2.7.2 Cumulative System Performance

The main objective of the monitoring of the cumulative performance data was the assessment of the overall system output in terms of cubic metres of water pumped over an extended period.

In addition the daily average array, subsystem and overall efficiencies, were also calculated in order to indicate the system's ability to make use of all the solar energy available to it during the day.

To complete the overall assessment of daily system performance, the following extra parameters were measured on a daily basis at certain sites:

- o Number of hours for which system actually worked.
- o Maximum ambient temperature
- o Wind run and hence average wind speed

The days on which rainfall occurred were also noted.

In order readily to assess the average daily performance, the results obtained from the cumulative data have been presented graphically. Details of the graphs whch have been prepared are listed in Table 12.

2.7.3 Results

A summary of system performance in the field is given in Table 13. The sults given in Table 13 have been obtained from best fit curves to the data.

Full details of all results are given in the Project Record. As examples of typical data, ..ference should be made to Figure 1 for a chart record, to Figures 2, 3, 4, 5, 6 and 7 for continuous system performance results from each host country and to Figures 8, 9 and 10 for sets of cumulative results from each host country.

2.7.4 Accuracy of results

An assessment of the accuracy of measurement of performance parameters normally requires repeatable measurements of the variable under nominally identical conditions, and a calculation of variance. In the nature of the case, such repeated measurements under identical conditions were not possible in the field and it is possible only to make estimates of accuracies from a knowledge of the behaviour of the instruments and the ways in which they were used. Measurement errors can be assessed from the calibration checks.

The solar sensors were referenced to the pyranometers throughout the field trials. A comparison of the two pyranometers in the Philippines after 6 months in the field showed agreement between the two instruments to within ± 2%. Recent EEC and IEA comparative calibrations of pyranometers has also shown that accuracies of approximately ± 4% are associated with these instruments. At any time therefore the readings of solar sensors when referenced to a pyranometer are likely to be within ± 6% of the true value allowing for temperature and spectral response effects.

The calibrations of the energy meters were tested under the Consultants' supervision at the supplier's works prior to despatch. Under laboratory conditions an error of less than ± 1.5% was observed. Under field conditions inaccuracies of ± 3% are assumed.

The flowmeters were calibrated on site before or during testing on most test days. As a result of tests performed in the field an error on the measurement of instantaneous flowrate of less than ± 5% is assumed (except at very low flow rates). The manufacturers' claim accuracy of ± 1% of full scale, but generally the instruments were operating well below maximum flow. If water levels were steady, measurements of static lift to within ± 1% should be expected. However as pumped head is used in the calculation of system efficiencies an error of ± 2% is more likely on this parameter.

The following measurement errors are suggested for the system efficiencies, based on the root mean square (rms) of the individual errors associated with each related parameter

o	array efficiency	± 6.9% (of value)
o	subsystem efficiency	± 6.2% (of value)
o	overall efficiency	± 8.2% (of value)

The array and overall efficiency error both assume an error in the measure -ment of array or cell area of ± 1.5%. In addition some data scatter will also result from the impossibility of achieving the steady-state conditions during the testing. The results of tests on systems in the Philippines were more likely to be influenced by non-steady conditions due to frequent passing clouds.

Varying water levels may also affect the accuracy of calculated hydraulic power output and system efficiencies and may affect the results of some systems. When possible a correlation between water level and pumped flowrate has been obtained in order to check on well water levels when not recorded frequently during a cumulative testing period.

Taking all the above into consideration an error band of ± 10% is suggested for the results of system efficiencies. Support for them and the accuracy is obtained from the generally consistent way in which the results from different days plot onto one curve of efficiency versus solar irradiance (see for example the plot for the Arco Solar system in Sudan Figure 6A).

2.7.5 Comparison of measured performance with rated value

A comparison was made of the rated and measured performance of the systems based upon measured average peak hydraulic power output (or where appropriate the daily pumped output) and the rated value derived from the system suppliers' data.

The approximate rated value for each system is given in Table 1 and the measured performance in the field is given in Table 13.

Three systems performed better that their rated value and two systems were within 10% of rated performance.

One system experience periodic impeller binding which prevented consistent running at rated performance and four systems performed significantly below rated performance.

Insufficient data were obtained on the Solar Pump Corporation Thermal System because of commissioning problems and, on the Soterem PV system because of lost or damaged components that delayed installation.

3. LABORATORY TESTS

3.1 Scope and Purpose of Laboratory Test Programme

The programme for the laboratory testing of selected components and subsystems that form part of a solar-powered pumping system was prepared taking into account the considerable amount of test data already available from independent testing organisations in several countries. During the Project photovoltaic modules, motors, pumps, engines and complete PV subsystems of solar-powered pumping systems were subjected to tests on performance. Products were inspected for the quality of manufacture. Data on solar thermal collectors were obtained from other laboratories.

The testing programme had a number of interrelated purposes, the most important of which were as follows:

- to determine independently the performance characteristics and efficiencies of selected components and subsystems under controlled test conditions at full and part load.
- to determine and rank the suitability of different generic types of component and subsystems for solar-powered pumping applications,
- to provide data for the characterisation of the performance of the main components inside pumping systems for use within the mathematical model constructed as part of the system design studies.
- to provide information complementary to the field trials programme in particular to help identify the causes of poor system performance.
- to assist with the identification of component, subsystem or complete system failure modes, and
- to provide indications of the basic reliability and durability of certain components.

It should be emphasised that the results of the laboratory tests were only intended to indicate the performance of the components and subsystems tested. It was not within the scope of the laboratory test programme to become a qualification programme as normally undertaken by national standards organisations and only one sample of motors and pumps was bought for test. Five examples of each module selected for test were purchased for a more detailed investigation of the quality and performance of these expensive components. Nevertheless much useful information was gained to supplement existing data and, in particular, to compare with and to some extent calibrate the results obtained from the field trials.

3.2 Selection of Equipment for Testing

The selection of equipment for laboratory testing was closely integrated with the selection of complete pumping systems for field trials. It was decided that, as far as possible, all key components of the individual systems selected for field trials should be purchased for laboratory test. In addition, certain photovoltaic modules, motors, pumps, heat engines and prototype complete thermal systems were also listed where these had technical features of particular interest.

The equipment purchased for laboratory tests, including some thermal systems tested at manufacturers works is listed in Table 14.

a) Photovoltaic Modules:

It was not necessary to purchase examples of all the different photovoltaic modules used in the complete systems being field tested, since in many cases independent and reliable test data was already available from the programme carried out by JPL on behalf of the US Department of Energy.

After reviewing all relevant technical and commercial factors, five examples of each of the four photovoltaic modules listed in Table 14 were purchased for testing. They were chosen because none of the four modules have previously been tested by JPL. They also have the following special features of particular interest to this Project:

- Arco Solar offered the lowest cost module currently available. Their arrays were used for their own and several other of the complete systems being field tested.
- CEL produce a range of relatively inexpensive modules manufactured in a developing country from imported crystalline silicon.
- RTC is one of the principal manufacturers of photovoltaic modules in Europe. An RTC array was used for the Omera system field tested in the Philippines. Not being an American product, RTC modules would not normally be tested by JPL.
- Solarex is the world's leading manufacturer of photovoltaics and the module chosen for testing was a high density type with square cells which had not previously been independently tested.

b) Pumps and Motors

Nine different photovoltaic pumping systems were subject to field trials and an identical pump and motor from each system was purchased for laboratory testing. In addition, four individual pumps representing extra generic types of pump not used in the field programme but of potential value for solar pumping systems, and one dc motor were either purchased or obtained on free loan for inclusion in the testing programme. A reciprocating linear actuator was also purchased for testing in a special rig to gauge its suitability for driving a diaphragm pump. The motors and pumps belonging to subsystems and those bought individually are all listed in Table 14.

The features of interest in these individual components were as follows:

- Godwin hand pump had been designed for hard use in developing countries and was typical of the thousands of piston units used in rural areas.

- o Godwin 'Cobra' centrifugal pump was typical of a number of robust self-priming centrifugal pumps.

- o Mono pump operates on the rotary screw (progressive cavity) principle, the only one of its type in the test programme.

- o Selwood 'Simplite' free diaphragm pump was of interest because of its reciprocating motion and because it was self priming.

- o SEM dc permanent magnet motor was reported to be very efficient, and typical of industrial dc permanent magnet motors available on the world market.

- o Hitachi reciprocating actuator was of interest because of the possibility of using it directly coupled to a diaphragm pump, so avoiding rotary components.

c) Heat Engines

We had originally proposed to test two heat engines, the Metal Box India Ltd 'Fluidyne' and the Sunpower Inc. 100W 'Beale' engine, both of which operate on the Stirling cycle. In the event, the Fluidyne was not commercially available in time for testing as part of Phase I and so only the Sunpower Inc 100W 'Beale' engine and integral pump was purchased.

d) Thermal systems for laboratory testing at manufacturers works

Testing was carried out at the manufacturers' works on the three thermal systems listed in Table 14. The main reasons for making the tests at manufacturers works were that (apart from SPC) they were insufficiently developed to make field trials worthwhile and too large and expensive to transport to a central test facility.

e) Solar thermal collectors

Apart from collectors associated with complete systems, it was decided not to purchase any solar thermal collectors for testing under the Project, for two main reasons:

a) the cost of purchase, transportation and testing would be high, and

b) extensive testing by independent authorities has already been conducted on many products of potential interest of sufficient accuracy to characterise performance for the systems design studies.

We have been able to gather, through correspondence and visits, much useful performance data on a wide range of solar thermal collector types. This has been particularly useful in carrying out the design studies on thermal systems.

In future phases it will, of course, be necessary to carry out field and laboratory tests on selected designs.

3.3 Testing Organisations

3.3.1 Royal Aircraft Establishment (RAE), at Farnborough, UK.

The RAE was included in the photovoltaic testing programme because of their extensive experience in testing PV cells and in order to include accelerated ultra-violet exposure tests, for which RAE already had a suitable test rig. The agreed test sequence at RAE was as follows:

- o visual inspection
- o electrical performance
- o insulation resistance
- o ultra-violet irradiation
- o insulation resistance
- o electrical performance
- o visual inspection
- o relative spectural response } (on sample cells)
- o measurement of temperature coefficients } (on sample cells)

3.3.2 The Jet Propulsion Laboratory (JPL) at Pasadena, USA.

JPL is the principal photovoltaic testing authority for the US Department of Energy and has generally set accepted standards for PV testing. JPL confirmed that they were willing to carry out at no charge to the Project their current range of tests in accordance with their publication 'Block IV Solar Cell Module Design and Test Specification for Intermediate Load Center Applications.'

A synopsis of this test specification is given in Table 15.

3.3.3 University of Reading (UR) Reading UK.

Arrangements were made with the Department of Engineering at the University of Reading for performance testing and visual examination of all the pumps and motors and also of the 100W Beale-engine/pump unit.

3.3.4 Manufacturers' Works

The Consultant's staff monitored testing on complete thermal systems at the works of Dornier (West Germany), Ormat (Israel) and Solar Pump Corporation (U.S.A.).

3.4 Laboratory Test Results

3.4.1 Photovoltaic (PV) Modules

The principal objectives of the tests on the four PV modules have been set out in Table 15. The results of tests on the electrical performance on delivery of each module are given in Table 16 and a typical electrical performance characteristic is shown in Figure 11. The measured temperature characteristics of the modules tested are given in Table 16A.

The main results of tests on each module and recommendations for improvement are given below.

a) Arco Solar modules - type ASI-16-2300

The results of environmental tests on the Arco modules are given in Table 17. All modules tested had a maximum power output under reference conditions within the manufacturers ± 10% tolerance on the nominal rated value of 37 watts. However, all modules were marginally below the nominal value. The results suggested that the modules would be more fairly rated at 36 watts maximum power output.

One of the modules had a cell efficiency of 12.9% the maximum cell efficiency of any module tested. The overall module efficiency (based upon gross module area) was also high averaging 9.7%.

The modules withstood, without damage or degradation, the twist, mechanical cycling and hail impact test, but one module suffered encapsulant delamination and back surface blistering after humidity cycling. Frame sealant extruded during temperature cycling on all modules: in two cases the extrusion went through the encapsulant into the cell area.

Minor manufacturing imperfections were found on four of the five modules on delivery including cracked, spalled and chipped cells.

Recommendations for improvement include:

- Increase the electrical isolation between the cells and busbar and between the cell string and the module frame.
- Redesign module frame end members and refine edge sealant injection process to eliminate bowing of frame end members.
- Improve adhesion of acrylic back covering.

b) CEL modules type PM621.

The result of environmental tests on the CEL modules is given in Table 18. All modules tested had a maximum power output under reference conditions less than the manufacturers nominal rated value of 7.6 watts. The test results suggest the module would be more fairly rated at 7.0 watts maximum power.

The modules exhibited average cell and module efficiencies of 9.9% and 5.8% respectively.

The electrical isolation of the modules was found to be unsatisfactory on all modules tested and all modules were found to have minor manufacturing imperfections. Electrical isolation was further degraded by environmental testing.

One module suffered a permanent open circuit of the cell string as a result of thermal cycling. An analysis of the failure showed that this was caused by a broken cell interconnect as a result of no stress loops in the interconnects.

Two modules irradiated with ultra-violet showed a colouring of the encapsulant, one experienced delamination and another further colouring when subjected to humidity cycling.

One module cell string shorted to frame when subjected to the twist test.

The modules withstood the hail test without sustaining damage.

Recommendations for improvements include:

- Addition of a cell interconnect expansion loop to relieve stress concentrations.
- Use of two or more cell interconnects per cell.
- Prevention of solder from coating and stiffening the expansion loop of the interconnects.
- Elimination of the air gap between the glass cover and encapsulated cell string.
- Increase the encapsulant thickness between the cells and substrates to reduce relative movements.
- Protection of the output terminals
- Use of different edge sealant.
- Frame surfaces to be grounded.
- Improvement of the electrical isolation of the cell string

c) RTC modules type BPX 47C

The results of environmental tests on the RTC modules are given in Table 19. All modules tested had a maximum power output under reference conditions within the manufacturers' ± 13% tolerance on the nominal rated value of 32.7 watts, but all were below this nominal value. The test results suggest the module would be more fairly rated at 30 watts.

The modules exhibited average cell and module efficiencies of 10.6% and 6.6% respectively.

The electrical isolation of the module cell string was found to be unsatisfactory on all four of the modules tested on delivery but all were satisfactory after completion of environmental tests.

The modules were the only type to suffer no permanent degradation as a result of environmental testing.

The modules were found to have very few manufacturing imperfections.

Recommendations for improvement include:

- o Reduction of module size, without degrading the present good durability characteristics.

d) Solarex modules type HE51JG

The results of environmental tests on Solarex modules are given in Table 20. All modules tested had a maximum power output significantly below the nominal manufacturer's rated value of 34 watts ± 10%. The test results suggest the module would be more fairly rated at 28 watts.

The modules exhibited high average cell efficiencies of 11.6% and average module efficiencies based upon gross module area of 10.0%. The 10.0% module efficiency was the highest average module efficiency of the four types of modules tested due in part to the use of squared off cells to achieve a high packing factor.

The modules in general experienced little physical degradation from environmental testing with the exeption of one module which suffered a cracked cell as a result of humidity cycling and one module which suffered a temporary increase in cell string series resistance during the twist test.

Recommendations for improvement include:

- o Improve encapsulation process to eliminate air bubbles
- o Use alternative module backing materials to prevent possible moisture penetration.

e) Results of tests on individual cells

The results of tests to determine the relative spectral response of individual cells representatives of each of the four types of modules tested showed that the Arco and Solarex cells were responsive to a marginally wider waveband than the RTC and CEL cells. The Arco and Solarex cells were found to be the most efficient during the module testing.

Module cell string temperature coefficients determined from tests on the individual cell were in general in agreement with those determined from measured module temperature coefficients.

3.4.2 Motors

a) Rotary dc machines

The main objectives of this part of the testing programme were to establish the general performance characteristics of the nine motors used in the field tested systems and three others of possible interest for PV system design. Two of the additional motors were permanent magnet dc machines (manufactured by SEM and Selwood) and the third was a permanent magnet linear actuator manufactured by Hitachi (reported in section (b) below). One of the dc permanent magnet motors was electronically commutated and this required no brushes.

All the motors were performance tested and then individually appraised in terms of maintenance requirements, weight, type of construction, and any other features of relevance for their use in a solar pumping system.

Performance testing involved the derivation of the relationship between speed-torque and voltage-current over the operating range of the motor. These were carried out at constant voltage reducing in steps of 20% for each test run. Since the same motor was also used to drive the pump in its tests, care was taken to cover as much of the range required by the pump as possible. Further tests were run at elevated temperature by enclosing the motor in an insulated box, to determine the effect of increased temperature on motor performance. A schedule of these tests is given in Table 21.

A standard reaction dynamometer test bed was used and it was possible to record results with a high level of precision due to the accurately measurable nature of the variables associated with electric motors. The one unit that presented some difficulty was the testing of the Hitachi linear actuator.

A summary of motor test results is given in Table 22. The performance of each motor was plotted in a field of voltage and current for various values of speed and torque and approximate lines for constant speed and torque were indicated. An example is shown in Figure 12A.

Relationships based on small motor machine theory between voltage (V) current (I) speed (N) and torque (T) were first derived, with the advice of Dr L.L. Freris, the Project Adviser for electrical machines. It was found that these were similar to relatively simple relations of the form:

$$N = aV + bI + c$$
$$T = dV + eI + f$$

where a, b, c, d, e and f are constants. For the present stage of the Project it was considered reasonable to adopt these simple relations and to calculate values of the constant from the field data obtained for each machine using standard statistical techniques. Table 23 gives the equations determined for each motor and lines for constant speed, torque and efficiency were then readily obtained. An example is shown in Figure 12B without the individual test data points.

All the motors tested returned efficiencies at full rated power in the range expected of well-designed dc permanent magnet motors. The measured values ranged from 72% to 86%. The lowest efficiency at half rated power dropped to 68%. There is a premium on subsystem components where efficiency remains at high levels over a wide operating range. No motor reached its point of best efficiency within the limits of rated current and voltage used in the test.

However two motors failed during the test programme: the Leroy-Somer (Pompes Guinard) motor failed for reasons that were not visibly obvious and was replaced by the manufacturer. The brushless motor in the SEI system (made by AEG) suffered a number of failures (both in the laboratory and in the field) all due to failure of components in the electronic commutation circuitry, possible due to overheating. These were replaced by the manufacturer. It must be noted that at least one failure of the AEG motor was due to the method of testing first used which produced excessive transient currents which would not have occurred with a PV powered system. The possibility of this was not foreseen by either the manufacturer, Consultant or University of Reading.

b) Reciprocating linear actuator

A test programme was devised to obtain an indication of the performance of the Hitachi linear actuator if it were used to power a suitable water pump. The manufacturer's rating for the motor is 50W output when supplied at 100 volts, 50 Hz. It was intended to test the motor over a range of supply voltages and frequencies, but it was soon found however, that even when running off load from a 50 Hz supply, the actuator did not oscillate freely with any appreciable amplitude. Furthermore, when the voltage was increased above about 60 volts , the motor would lock at the extreme end of its stroke.

The full results are given in Table 24 and plotted in Figure 13 which show reasonable agreement with the manufacturer's claims. The efficiency of the actuator was found to be very low, at about 5%, giving a peak power output of about 1.3W. No doubt some improvement of the efficiency could be achieved with a different switching arrangement to ensure that the polarity changed when the actuator reached the end of its stroke (ie, variable frequency switching, matched to load).

3.4.3 Pumps

Nine out of the thirteen pumps tested were from the small-scale solar pumping systems purchased for field trial. All of these units could only be tested using the motor supplied with their respective systems, hence in some cases it was not possible to test the pumps at speeds or power ratings beyond the capability of the motors supplied. As a result, the useful operating range of all pumps was not covered completely.

Four individual pumps, representative of other types of pump, were also tested. They were of the following types:

- o self-priming surface-mounted centrifugal pump;
- o traditional robust hand pump;
- o rotary screw (progressive cavity) pump;
- o a free diaphagm pump.

Motors had to be obtained specially for testing three pumps and their own electrical performances were determined as part of the motor test programme.

The head/flow characteristics of the pumps were determined for different speeds and torques, over an outlet head range of 0 to 8m and an inlet head range for suction pumps of up to 8m. The delivery head was varied in steps of about 1.5m and the inlet head in steps of about 2.0m. Since the Project was related to irrigation pumps applicable to low head, no attempt was made to test any pumps at static heads in excess of about 12m.

A schedule of governing head conditions is given in Table 25. Each test was first carried out at the rated voltage for the motor (varying the current over the appropriate range); and then at progressively lower values of voltage. The minimum voltage and current values required to start each pump and at which it stalled were also recorded.

Although no attempt was made to carry out 'consumer' type tests, a visual appraisal was made of the pumps to note relevant design features.

The performance of each pump was first plotted graphically in the form shown typically in Figure 14, which shows the total pumped head, flow, rotational speed and pump efficiency for each test run. Contours of speed, efficiency and shaft input power were then plotted, by numerical interpolation. For ease of reading, tracings were then made showing just the contours without the individual test run points and these are shown in Figures 15 to 27. Where available, manufacturer's performance curves have been added for comparison purposes.

The head, flow and efficiency data for the centrifugal pumps was also recalculated in non-dimensional terms as unit head and unit flow, using the definitions given in ISO standard 2548

$$h = \frac{g.H}{\omega^2 D^2}$$

$$q = \frac{g.H}{\omega d^3}$$

where H is pumped head (m) Q is flow (m^3/sec), D is impeller diameter (m) and ω is rotational speed (radius/sec) all expressed in consistent units.

This approach yields one curve out of the field of data, reveals the scatter in the results, enables one pump to be compared with another on a unified basis, produces one efficiency curve with a definite peak at a specific speed and enables the results to be extrapolated to other heads and speeds within the overall limits of the motor and pump.

The unit head and flow curves for each centrifugal pump are plotted in Figure 28 with the corresponding efficiency curves shown in Figure 29.

Table 26 summarises the principal features of pump performance in the laboratory.

The recorded efficiencies of the pumps tested varied with head and flow in the manner expected of centrifugal and positive displacement pumps. Each centrifugal pump attained its best efficiency point and the values returned were in the range from 39% to 53%. The efficiencies of two pumps were lower than this: one (Omera Segid) is believed to have been tested with a damaged impeller and hence was consistently under-performing; the other (Godwin Cobra) was designed to rotate very quickly (up to 9000 rpm) and it is possible that excessive energy loss occurred in the transmission between motor and pump. It is interesting to note that some pumps had a 'peakier' efficiency curve than others: systems with pumps with flatter efficiency curves will be able more satisfactorily to handle situations in which the actual head differs from the design head and situations in which the head regime varies during the period of operation. Every predictable percentage point improvement to pump performance means a significant saving in the cost of the array.

The other performance feature worthy of note is that some head-flow curves at the low flow end sloped more steeply than others. Pumps with flatter head-flow curves will be more sensitive to reductions in speed (or increases in head) and may cease pumping altogether if the speed drops. Pumps with sloping performance curves will continue to pump albeit at a low rate. This characteristic of the pumps is recorded in Table 26 by the parameter 'speed sensitivity' which gives the percentage reduction in speed from the speed at the best efficiency point to the speed at which pumping stops. The two pumps with lowest values of 'speed sensitivity' were those which had priming problems in the field. Good suction performance is vital for all surface-mounted centrifugal suction pumps. The results show that the suction lift should never exceed 3m and should preferably be less than this. Self priming is essential. Immersed pumps do have a clear advantage here and enable troublesome footvalves to be dispensed with.

The weights of the pumps varied considerably. The weight per unit hydraulic power output at the point of best efficiency varied by a factor of about 5. This will have cost implications.

The efficiency of the positive displacement pumps continued to increase with increase in head as is expected. Since they were designed for higher heads than those covered in the laboratory tests, their points of best efficiency were not reached. The higher values recorded were in excess of 50%.

The free-diaphragm pump did not have a good efficiency, and caused heavy pulsation in power demand which could cause problems with a PV array. The diaphragm backing plate fractured under tests because the casting was faulty.

The rotary screw (progressive cavity) pump had a useful performance characteristic part way between the centrifugal pump and the positive displacement pumps. Although its efficiency at 5m head was in the 23% range, it rose to 32% at the highest test head in the laboratory (13m). Since it can handle solids in the water, it could be a suitable candidate for high head pumping.

The handpump was chosen to be representative of long standing hand powered designs which have seen long and reliable service in developing countries. It returned a performance characteristic typical of positive displacement pumps but it was not surprising that its efficiency was low. The test of this pump helped to confirm that there is unlikely to be a future for solar powered versions.

3.4.4 Thermal systems

Tests were made on thermal systems at the University of Reading and at manufacturer's works.

a) Sunpower Inc. 100W 'Beale' Engine.

The basic design of the engine/pump is illustrated in Figure 30. The working fluid is helium charged to 5 Bar. The water pump is of a diaphragm type. The engine is suitable for being heated by concentrated solar radiation but was heated by means of electrically powered heaters in the laboratory tests. Maximum power input is limited to 2000 watts applied at a temperature of 650 ^{o}C. Nominal engine frequency is 16.5 Hz. The system was rated by the manufacturer as 100 watts hydraulic output and the operational envelope limits the maximum pumped head to 7 metres.

The test programme adopted at the University of Reading was the determination of the hydraulic power output of the system and overall instantaneous efficiency over a range of static water lifts at various input powers under steady state conditions.

Tests were conducted at static heads of 1, 4 and 5 metres. A full range of tests conducted at various input powers was not possible, however, because of the failure of a threaded coupling in the engine during tests. This resulted in the engine leaving the housing and suffering damage. Prior to this failure, four sets of measurements were recorded as set out in Table 27 and are presented in Figure 31.

The fact that the thread failure occured indicates the present state of development of this engine.

The performance obtained at UR was found to be below that claimed by the manufacturer. The unit was found to require a power input of more than 1kW before it would pump through heads of 4 metres or more. The unit is not designed for lifting water through heads greater than 7 metres and this severely limits the scope of its application. An engine pump efficiency of less than 2% was determined and a peak hydraulic power output of only 23.5 watts was measured.

It should however be noted that the results of the mathematical model studies on thermal systems have shown that, if an efficient Stirling engine can be made, the compact construction of the engine and its possible low production cost could make such systems competitive with other solar-powered water pumps.

The unit exhibits the following good design features:

- an hermetically sealed engine requiring minimal maintenance.
- no lubrication is required other than from the working fluid,
- an engine suitable for operation with air, helium or hydrogen as the working fluid,
- an engine made to a high standard of finish

The following poor design features were also noted:

- the thread on the pump to engine connecting bolt was badly cut and undersize.
- maintenance of the engine when required was difficult
- the regenerator was inaccessible
- due to the position of the regenerator, the walls of the cylinder were thin and easily damaged.

b) Dornier Systems solar pump

Testing of this pump was witnessed by engineers at the manufacturers works at Friedrichshafen, West Germany.

A schematic diagram of the Dornier solar pump is shown in Figure 32.

Persistent bad weather prevented the pump from being powered by solar energy at Friedrichshafen so electrical tape heaters were used to input heat at rates between 4 and 9kW in order that the motor and pump could be monitored.

Following an initial assessment of the results it was deduced that the instrumentation supplied by Dornier to measure the flowrate of the working fluid (Freon) in the heat engine had developed a fault. The analysis of the results was therefore undertaken with the Freon flowrate being determined by calculation.

Measurements taken and overall engine/pump efficiencies are presented in Table 28.

Engine/pump efficiency was calculated as being 3.5% maximum indicating an overall system efficiency (from solar power to hydraulic power) of approximately 2%, assuming 60% collector (instantaneous) efficiency.

The tests on the Dornier solar pump in general confirmed the manufacturer's performance figures.

In the Consultant's opinion, the Dornier solar pump is a well engineered but rather complex system for a developing country. Dornier themselves recognise this and explain that the system is a prototype which would be simplified in the event of a decision to produce in significant numbers.

In March 1981 Dornier supplied a second prototype solar pump to BHEL in Hyderabad, India. BHEL participated in the design of this second prototype designed to deliver 4 litres per second through 15 metres. The detailed design of the piston rings, metallic bellows surrounding the crankshaft and Freon feed pump were improved. Various options on the solar collector are being considered as well as a protective housing for the engine.

Dornier estimate a mass-produced 1000 Watt hydraulic power unit would cost DM 41,600 (US $23000), almost 70% of which would be for solar collector manufacture. The cost of $23/peak hydraulic watt installed is comparable with other solar water pump mass-production estimates.

For example our cost estimates for a small flat plate collector organic Rankine cycle engine system indicates approximately $ 17/peak hydraulic watt is achievable.

c) Ormat Energy Converter

Testing of the Ormat 5 kW (electrical) turbine energy converter was witnessed by Dr. G. Rice our Heat Engine Adviser, at the Ormat works at Yavne, Israel.

The duration of the tests were restricted to one day due to an electrical fault in the turbine control unit but nevertheless useful data were obtained.

The Ormat Energy Converter (OEC) tested was a unit rated at 5 kW electrical output designed for low temperature (c.100°C) operation. It comprised a vapour generator, a turbine, an electrical generator, a feed pump and a condenser. The Freon working fluid is vapourized in the vapour generator by the energy source which can be from solar collectors but was (for the purposes of the tests,) a gas-fired boiler. The vapour is expanded through the turbine so driving the electrical generator. The vapour is liquified in the condenser and returned to the vapour generator by the feed pump. A schematic of the system is shown in Figure 33.

The Freon flowrate was determined from an energy balance in the vapour generator.

A set of four runs were undertaken to simulate solar heating conditions at different temperatures and heat inputs. Results are given in Table 29.

Runs 1 and 4 give the more representative performance values for this plant, with overall efficiency varying from 5.4% to 6% for a temperature variation of the working fluid of 65°C to 72°C respectively and constant condenser temperature of about 23°C. The percentage of the Carnot efficiency is 42.6% and 42.8% for Runs 1 and 4 respectively. These values seem consistent when analysed in conjunction with the Rankine efficiency of 10.8% for Run 1. The efficiency of the turbo-generator was calculated for Run 1 as 57%. Depending on the efficiency of the generator, the turbine efficiency is possibly as high as 70%.

Ormat believe the optimum blade/speed ratio for the turbine corresponds to a frequency of 700 Hz. It is noted that for each of the test runs the blade speed ratio was off-optimum since the frequency of power generation was approximately 760 Hz for Runs 3 and 4 and approximately 850 Hz for Runs 1 and 2.

The plant is considered to have good performance in relation to the tested temperature ratios chosen to simulate flat plate solar heating. If the system were powered by solar collectors with an instantaneous operating efficiency of 60% then solar power to electrical power conversion could be almost 3.6%.

The system is well designed and constructed to what appeared to be a high standard with good inspection and final test procedures. The reliability claimed is high, but the cost is also high with present ex works cost approximately US $30,000. i.e. $6 per peak watt of engine power delivered, the same as cost estimates for the engines of the Dornier and Solar Pump Corporation Systems. The plant is also large in terms of specific power output. Most of the plant size is related to the evaporator and condenser units.

The plant could not be readily manufactured in a developing country or maintained in a rural community but on the other hand its hermetic sealing, good reliability and maintenance free characteristics are attractive features.

d) Solar Pump Corporation solar pump

The Solar Pump Corporation system was the only complete thermal system with 50-100 watt hydraulic power output available for testing at the time of selection. The system therefore attracted considerable interest and it was decided to test one at the manufacturers works and purchase another for the field trials programme in Sudan.

The SPC solar pump incorporates a single-valved reciprocating Freon engine mounted in a fixed flat plate solar collector of approximately 5 sq. m. The reciprocating motion of the engine is coupled to a positive displacement water pump and the pumped water is passed through the engine condenser mounted in the collector support structure. The Freon feed pump is also driven by the engine reciprocating motion. The SPC solar pump is shown schematically in Figure 34.

At the time of the tests the solar beam was almost normal to the collector plane.

It can be seen from the results presented in Table 30 that the system was effectively running at a steady pumping speed of 21 strokes per minute from 1220 to 1311 hours on the 26 March 1980, lifting water at approximately 0.6 l/s from 7.5 metres below ground (hydraulic power output, 44W) with an average overall system efficiency of 0.89%.

Tests performed on the 27 March at the same head of 7.5 metres indicate a reduced efficiency, probably because the solar collector was again heating up. With some assistance the pump did start operating when the incident solar irradiation was approximately $580W/m^2$.

Tests were successfully performed at 12 metres lift on the 26 March and the results from the steadiest of the test periods (at 1350 hours) indicated that an efficiency of 0.86% was achieveable. The flow was 0.33 litres/sec at a pumping speed of 13 strokes per minute with a hydraulic power output of 39 W. (leakage at the well head was apparent so the actual flowrate was probably slightly underestimated).

The system continued to pump satisfactorily until the irradiance fell below $500W/m^2$, when the head was changed to approximately 7 metres. The system then continued to pump until the irradiance fell to below $400\ W/m^2$.

Determination of the collector efficiency was not possible because the Freon mass flowrate could not be measured accurately.

The environmental conditions present during the tests greatly affect the pump performance. During all test periods the ambient air temperature was in the range of 14^oC to 16^oC which is relatively low for a sunny climate. The heat losses from the collector are proportional to the temperature difference between the collector and the ambient air so the collector was operating at a lower efficiency than could be achieved on a warmer day.

A condition advantageous to the operation of the pump during the test was the high levels of solar irradiance. In addition the low temperature of the water passing through the condenser would be beneficial to the Freon engine efficiency.

The Solar Pump Corporation agreed that these results were representative of the performance under the test conditions. SPC claim the system will operate at up to 30 strokes per minute delivering approximately 0.85 litres/sec when pumping through 12 metres under optimum conditions (a peak hydraulic power of approximately 100 watts). Independent tests by University of Arizona suggest a hydraulic power output of 70W is possible at an efficiency of 1.4%.

The SPC solar pump is an innovative design with good features which has the potential to be a workable small-scale solar thermal system that is of a size applicable to many millions of farmers. Present technical problems mean that, although the system is operational, considerable attention to design and maintenance requirements is required before the system could be considered reliable enough for use in remote areas.

3.4.5 Visits to other organisations

Many organisations throughout the world have been testing, developing and/or demonstrating solar equipment, some of which may form part of a solar-powered pumping system. As a result of the limited duration of the laboratory test programme undertaken under Phase I, it was apparent that information could be obtained from such organisations which would be useful for the design study activities. The organisations listed below were therefore visited in order to obtain a wide range of information.

- Commissariat a l'Energie Solaire (COMES), France
- DSET Laboratories, USA
- Jet Propulsion Laboratory, USA
- Joint Research Centre of the European Communities, Italy
- Kinetics Corporation/Sun Power System, USA
- Mabosun SAS, Italy
- Martin Marietta, USA
- Metal Box (India) Ltd. India
- NASA/Lewis Research Centre, USA
- Northrup Inc. USA
- Sandia National Laboratories, USA
- Sofretes, France
- Solar Energy Research Institute, USA
- Solar Kinetics, USA
- Wyle Laboratories, USA
- US Department of Energy

4. PHOTOVOLTAIC SYSTEM DESIGN STUDIES

4.1 Introduction

4.1.1 Purpose

The overall purpose of these studies was to develop and specify a system (or systems) which can deliver a given quantity of water through a specified head and distance at the lowest unit life cycle cost. It was convenient to express this in terms of cost per unit energy output per day ($ /kJ).

Since capital costs will predominate, at this stage of the Project it was thought reasonable to present cost data on the basis of the capital cost per unit useful energy output per day (termed the 'Specific Capital Cost'). Recurrent costs can, of course, be readily included through the normal discounting techniques.

In these system design studies the cost effectiveness of a number of technically feasible system options for solar pumps under a variety of operational conditions were examined. In this process the sensitivity of system performance and cost to changes in the controlling parameters and state variables were examined as a means of assisting the identification of those parts of the system which are critical for the future development of this technology.

4.1.2 Limitations

The main general limits that were placed on the work were as follows:–

a) The power range: the data on which the model was based was obtained from systems providing a hydraulic pumped power output in the range from 150 to 600 W, but the system model is designed so that it can be used for studies which can be extrapolated as necessary up to 2000W.

b) Static/dynamic modelling: An accurate simulation for a solar pumping system requires the inclusion of all the system time constants involved in order to achieve the correct dynamic response to a change in input. Such simulation would obviously be extremely complex and is not important in the analysis of PV systems over periods of time in excess of a few seconds. Modelling of dynamic response is very important to thermal systems. It was therefore decided that a steady-state model should be produced as a first step. Such a model can still be used however, in simulating the performance and output of a pumping system over a specified typical day.

c) Application of pumped water: The modelling work was limited to the solar pumping system work itself as this was the focus for this Phase of the study. The vital importance of the way in which the flows provided by solar pumps are applied in irrigation practice is of course clearly recognised, but within the time scale of Phase 1 it would have been impossible to have done justice to the problems presented in modelling the many factors involved in irrigation practice.

Due to the time scale of the Project it was only possible to carry out preliminary studies using a mathematical model: much essential data only became available within a few weeks of preparing this Report. Nevertheless some very worthwhile and previously unknown conclusions were deduced. Some of the systems used in the field trials were analysed, re-optimised and assessed in terms of their cost effectiveness.

4.1.3 Benefits

A computer based mathematical model which simulates the performance of a complex system can provide a most valuable means of rapidly assessing the performance and benefit to be gained from various system configurations and the sensitivity of system performance and cost to carefully chosen changes in design parameters or input costs.

Any equation is a mathematical model in the strict sense of the word but the phrase nowadays is used to mean the mathematical representation of a complex system comprising of a set of physical and economic interactions. In the model each significant relationship must be quantified and the nature of their inter-relationship unambiguously expressed. The resulting set of equations can be so large that the only practicable way for them to be solved is through the use of a computer.

It is always useful to adopt a modular approach when modelling systems. Each module is based upon a recognised component of the real system and contains the 'performance relationship' (in terms of the design variable, 'process stream' parameters and state parameters) and makes provision for the input of cost data in an agreed form. Care has to be taken of course that the individual modules can be linked to form a credible system.

The benefits of the model once constructed include:

a) It makes the best use of what system data is available.

b) It enables the effect of changing design parameters and state variables on the whole system to be evaluated quickly. This process can be formalised in what is known as 'sensitivity analysis' when one of the parameters is changed systematically, and its effect on the remainder of the system observed.

c) It may be used to assess the output of the systems under a range of input conditions and over a considerable period of time.

d) It can be used to assess the effectiveness of an assumed improvement in the performance of a component, thus enabling a judgement to be made on the increase in cost it would be worthwhile to pay for such an improvement.

e) It permits the ready comparison of different systems.

The use of such models in no way eliminates the need for the engineering designer. Rather it sharpens his appreciation of the critical points in the system and provides him with a tool by which truly professional decisions may be made.

4.2 Photovoltaic System Model

4.2.1 Construction

At its simplest, a photovoltaic pumping system consists of three main components: a plane fixed array, a dc electric motor and a pump with associated suction and delivery pipework. Various degrees of sophistication and complication may be incorporated into the system. The block diagram in Figure 35 indicates the main 'modules' which were built into the model. The range of variation of the input power to each module was specified, as were the ranges of other independent and state variables which affect the performance of that module. In this way, it was possible to define a generalised stream parameter or operator function which simulated the behaviour of the component being modelled. This was either in the form of an algorithm or simply a set of published performance characteristics expressed in suitably digitised form. Each module was thus modelled as an independent exercise initially until apparently satisfactory responses were obtained. Having achieved these, the modules were then linked to form the model of a complete system, including the necessary interactions and feedback. The model computes the efficiency of the chosen system(s), either instantaneously, under specified input and output conditions, or in terms of the integrated daily energy input and output. The Specific Capital Cost is calculated as a measure of cost effectiveness.

4.2.1 Assumptions

Although the model was primarily developed to investigate pumping systems in the size range covered by the Project (ie, 100 to 2000 W pumped power), there is fundamentally no limit to the size of system that can be modelled.

The limits and assumptions made at this stage may be summarised as follows:

a) The model is a steady-state one and simulates the performance throughout a period of varying solar input by taking a series of 'snapshots' and integrating the results.

b) The array operating temperature is not calculated but is defined for each run (it was considered impracticable to attempt to model array temperatures as a function of ambient conditions).

c) The model starts at the footvalve (or pump intake if the unit is submersible) and terminates at the point of discharge of the pump delivery pipework.

d) Resistive losses in the electrical connections are neglected.

e) Since the system modelled includes the suction and delivery pipework, account must be taken of the head losses in the pipework when assessing the performance of the pump itself. There is, of course, an optimum diameter to suit a given set of input conditions, array, motor, pump combination and output requirements.

f) Systems are compared on the basis of Specific Capital Cost, and not on the basis of cost of unit volume of water.

4.2.3 Characteristics of principal components

The structure of the computer program was developed from the basic block diagram illustrated in Figure 35. Before discussing the flow diagram as finally evolved, it may be helpful to consider the general characteristics of each main component. These are sketched in Figure 36.

o Solar Input:

The model distinguishes between direct and diffuse solar irradiation and also computes the direction of irradiation as a function of time through the day. The solar input may be available in various forms. eg continuous or hourly, total or diffuse.

o PV Array:

Any photovoltaic array will have a unique current voltage characteristic (IV curve) for a given irradiance reaching the cells at a given temperature. Performance data is published by manufacturers based on standard performance tests and is typically given in the form illustrated in Figure 36 (a). The effect on the IV curve of changing the temperature at a constant irradiance is shown in Figure 36 (b).

o Electric Motor:

The most convenient form of describing the performance of an electric motor is to relate the input voltage V and current I (and power factor in the case of ac motors) to the output torque T and speed N. As the voltage and current available from the PV array widely vary with incident irradiance, it is necessary to define the motor's characteristics throughout its practical range of torque and speed. This was done on the basis of the laboratory data. Performance may be represented as in Fig. 36 (c).

o Pump:

There are many types of pump but in general the performance of any pump can be represented graphically by plotting total head across the pump H against flow Q for different operating speeds N. Torque contours can also be plotted, as shown typically in Figure 36 (d).

o Hydraulic System:

The pipework and pump combination for a given system will have a unique head/flow characteristic determined purely by the static head and the pipework properties (length, diameter, friction factor, bends, specials). The hydraulic system characteristic is illustrated in Fig. 36 (e).

o Costs:

It was decided to make a number of simplifying assumptions for modelling costs. To derive a valid result for the true average unit cost of water, it would have been necessary to know or assume the pattern of its solar inputs and hydraulic outputs over a typical year. Although for a specific system and site it would have been possible to make reasonable estimates of these parameters (and hence derive the unit cost of water) it was decided that for direct comparison of different system configurations, at this stage of the work a simpler parameter would be adequate. Thus the capital cost per unit energy output in a standard day, or Specific Capital Cost was adopted. It is equal to:

$$S = \frac{C}{\rho g V H_s}$$

where

C = total capital cost of system ($)
ρ = density of water (Kg/m^3)
g = acceleration due to gravity (m/s^2)
V = total volume pumped per standard $6kWh/m^2$ day (m^3)
Hs = static head (m)

The Specific Capital Cost is expressed in this Report as $/kJ per day. The total volume of water pumped in the day is readily obtained by integration of the volume pumped in each time step. It is valid to compare systems on the basis of Specific Capital Cost if it may be assumed that the lifetime, interest rate, load factor, pipework configuration and operating and maintenance costs are similar. The cost of a unit volume of water pumped through a given head is then some fixed multiple of the Specific Capital Cost.

The total capital cost is built up from the following elements:

- array cost (including any tracking system)
- motor cost
- pump cost
- pipework cost
- other costs (such as maximum power point tracker)
- installation costs.

Cost functions may be defined for each element (in terms such as cost per unit weight or cost per unit rated power output) and the total cost then readily computed for a given system

In the studies reported in this Volume, the cost data used were prepared on the basis of the cost of components in a typical developing country, for large volume orders (500 +) and allowing for transport and for assembly in the country concerned. These costs were related of course, to the prices quoted when the equipment was purchased for the Project, but an attempt was made to eliminate the many arbitrary factors which affected those prices so as to produce homogeneous data for use in the mathematical model studies. This was done on the assumption that a realistic price would be linked to the weight of the principal components; adjustments were made to quoted prices on the basis of the recorded weight. Account was taken of the advice of the Project specialist advisers, in particular Mr W Armstrong, the Industrial Adviser. The cost figures are therefore 'typical' without necessarily being those which would be paid in any specific country. The normalised cost data is given in Table 31.

4.2.4 Impedance matching

Although common in electrical engineering practice, the phase 'impedance matching' is not familiar to irrigation and water engineers and so a brief explanation is given below with particular reference to photovoltaic pumping systems.

The word 'impedance' implies resistance and formally is the ratio of voltage to current. In the present connection however, it is more useful to think of impedance in terms of a locus of voltage and current which characterises the source of energy (the PV array) and the consumer of energy (the motor and pump).

For a given irradiance the output of a PV array is a whole range of voltages and currents defined by the I-V characteristic (see Figure 36 (a)). There is one combination of voltage and current for which the power output is a maximum and a locus can be drawn through the maximum power points produced at various levels of solar irradiance.

However the actual voltage and current output depends on the requirements of the water pump and hydraulic system. To meet a given hydraulic duty (pumped head and flow), the pump has to be rotated at a certain speed and torque: in turn this requires a certain voltage and current input to the motor. A specified hydraulic duty is thus translated into specific voltage and current requirements.

In order to achieve maximum overall system efficiency at all levels of solar irradiance the voltage-current characteristic of the water/pump/ hydraulic system should match the locus of maximum power points of the array. The system designer will seek to obtain this goal by careful selection of array, motor and pump, and this process is termed 'impedance matching'. The impedance can be matched artificially by an electronically controlled dc to dc transformer used as a maximum power point tracker (MPPT) but this uses a certain amount of power itself and can be quite expensive.

4.2.5 Validation

The principal sources of performance data for use in the model were the field trial results and the laboratory test results. This information was supplemented by PV module, pump and motor data obtained from other sources, plus advice received from the Project Advisers.

As far as was practicable, each subroutine in the program was separately checked for internal consistency as it was written. Then, to validate the program as a whole, results from the field trials on the Arco Solar system in Sudan, the SEI system in Mali and the Briau system in the Philippines were used to validate the model. After some initial problems in setting up hydraulic system characteristics in the model which corresponded correctly to the field conditions, the model reproduced flow rates to within 10% maximum and 3% average of the field data for the same solar irradiance. Figures 37, 38 and 39 show these comparisons.

4.3 Basic Investigations

The basic objective of the design studies using the model was to obtain information to enable the most cost effective system to be identified for a given application.

To provide a base from which systematic variations could be made, and on which results could be compared, reference conditions for a typical application were established. The general reference conditions were as set out in Table 32. The reference conditions chosen for the systems themselves are set out in Table 33.

Two types of solar day were used in the initial series of test runs. Most of the runs were carried out with solar day type 1 conditions, which correspond to a typical clear day in a dry country such as Sudan, see Figure 40 (a). Some runs were carried out with solar day type 2 conditions, which correspond to a typical hazy day in the Philippines, see Figure 40(b). The solar irradiation value for the clear day is 6kWh/m2 (21.6 MJ/m2) and for the hazy day is 4.65 kWh/m2 (16.7 MJ/m2).

An initial basic study was carried out to investigate the effect of varying components and operating conditions in a systematic manner. These studies were carried out for the nine different systems for which full and reliable performance data were available from the laboratory testing, with additional runs made for systems incorporating different pumps and motors.

The basic studies using the model involved six series, each designed to investigate the effect of varying one feature from the reference conditions. Brief details of each series are given below.

o Series 1–Static head variation

Static head varied from 2.5m to 10.0m (in steps of 2.5m) and was applied to all nine systems. The runs include the reference conditions. Short term variations in static head arising in the course of a day (ie, well drawdown) were not specifically investigated, although the results of the long term static head variation runs do give an indication of likely performance for a given range of short term variations.

o Series 2–Solar day variation

The investigation started with a check of flow rate as a function of irradrance and daily pumped outputs as a function of global irradiation (one system) Insolation data for the typical hazy day (solar day type 2) instead of the typical clear day (solar day type 1) reference condition were then applied to all nine systems. Solar irradiance data for each month in the Philippines were also used to examine the performance of the Arco system in more detail and to indicate annual performance.

o Series 3–PV array variation

First the nominal voltage of the array was varied keeping the total power constant, in order to find the optimium operating voltage for the standard condition. Then the total power was varied keeping voltage at the optimium previously determined, to find optimium power. This was then applied to nine systems.

o Series–4 Impedance matching

The effect of using a MPPT with first zero and then 10% internal losses was investigated. The effect of crude impedence matching by changing series/parallel switching at certain times of the day was also investigated. Applied to the Arco, Briau (Duva) and SEI systems only, to obtain representative results.

o Series–5 Sun tracking

The effect of continuous tracking of the sun and also the effect of manual tracking were investigated. Applied to the Arco, Briau (Duva) and Soterem systems only, to obtain representative results.

o Series–6 Pipework variation

The effect of changing system losses by increasing or decreasing the delivery pipe length and diameter was investigated. Applied to the Arco and Briau (Duva) systems only, to obtain representative results.

4.4 Results of Basic investigations

A selection of the results obtained from the runs of computer model defined above are presented below. Full details are in the Project Record.

4.4.1 Head

The way in which the volume of water pumped over a day varies with static head was analysed for each system. Results are summarised in Table 34.

The results for the Arco system for the standard clear and hazy days, are plotted in Figure 41 which shows that output decreases almost linearly with increasing head. It should be noted that this does not correspond to a constant efficiency except in the 7.5m to 10m range. The head-output relation for a constant efficiency curve is also shown. Results obtained from the Pompes Guinard system were similar.

Because the systems (including the pipework) are all of different sizes it is also necessary to compare them on the basis of daily overall system efficiency, which is plotted in Figure 42 as a function of head for the systems employing centrifugal pumps and for which the data could be obtained. This shows that with these systems the best efficiency is achieved with a head of about 7.5m to 8.0m. The peak is very pronounced in the case of the Pompes Guinard system, efficiency doubling between 2.5m and 7.5m.

The performance of the Briau (Duva) pump was also simulated over a range of heads: as suggested by the laboratory results on this positive displacement pump the overall system efficiency increased with increase in head.

4.4.2 Variation of solar regime

The performance of each of the systems under the reference conditions was calculated with the standard hazy day (solar day type 2) used as input. The total volume pumped through a 5m static head and the daily overall efficiency is compared with the clear day efficiency for the same reference conditions in Table 35. It is interesting to note that three systems achieved the same overall efficiency on the hazy day as on the clear day, while the other systems efficiences are lower (in one case only one third of the clear day efficiency). These differences are probably due to the degree to which the output characteristics of the array remain matched to the water pump load under varying irradiance.

Flow rate is a function of solar irradiance, as demonstrated by Figure 39 A similar curve was produced when the reference conditions were the basis of the simulation.

It is also of interest to assess the effect of variation in the profile of solar irradiance on the daily pumped output. For this exercise data from the Philippines was used. For each calender month the average daily solar irradiance profile was calculated, inputed into the Arco simulation model and the daily pumped output was determined for the reference conditions. The average daily solar irriadiation was also calculated for each month, and the corresponding values of pumped output are plotted in Figure 43, along with a point for the standard clear day profile. The scatter, which falls within a band of ± 10% of the mean is due to the difference in shape of the irradiance profle from month to month. The width of the band will reflect the consistency of the solar profile through the year. The system pumped 12000 m^3 through a head of 5m under the reference conditions and Philippines solar input data.

4.4.3 Array Optimisation

The mathematical model can be used as a tool to examine different array cell connection configurations to determine the sensitivity of system performance to such changes, and so to arrive at an array design which will deliver the most water for the least cost (other conditions remaining constant).

The first part of this exercise was to calculate pumped water output as a function of array voltage, keeping total power constant. This is the same as varying the series-parallel connections of the photovoltaic modules within a given array. The optimum voltage corresponds to the maximum power point on the I–V characteristic, and this varies with irradiance.

Each system was tested by increasing and decreasing the number of series cells in the array in units of 10% of the number as supplied, keeping total number (and hence power constant) to see if output increased and if there was a maximum. Table 36 summarises the results.

An improvement of 13% can be achieved with the Arco system by reducing the number of cells in series (and hence the voltage) by 20%. In theory these increased performances should be achieved without extra expenditure, because the array power (and life) stays constant. These changes made no difference to the Pompes Guinard and Omera Segid systems.

This optimisation was also performed for the standard hazy day conditions for the Arco and Pompes Guinard systems. The results for Arco system plotted as daily overall system efficiency as a function of array voltage, are presented in Figure 44. Those for Pompes Guinard were of similar form and clear optima were found in all cases.

The overall efficiency for a hazy day is greater than for a clear day and the voltage at which this peak occurs is lower for the hazy day. This latter observation is to be expected because the maximum power point occurs at a lower voltage with decreasing irradiance (as illustrated in Figure 36) On the hazy day the array will operate on a lower I–V characteristic for more of the time. The Arco system gave it best performance on a clear day with an array voltage 20% less than supplied while for the Pompes Guinard system the clear day optimum voltage is almost exactly as supplied.

Because of the sensitivity of overall system efficiency to voltage it is important that the array performs to specification. The influence of static head on optimum voltage was also checked and it was found that in the range from 2.5m to 7.5m there is no change in optimum voltage.

In the second part of the exercise the array current (or rated power) was optimised since increasing or decreasing the power of the array causes the pumped water output to increase or decrease and this means different costs. This optimisation must be done on a cost basis.

For each system the array was increased and decreased in multiples of 10% and the Specific Capital Cost compared to see if there is a minimum. In each case the optimum voltage was used. The results of this analysis are summarised in Table 37.

In can be seen that the Pompes Guinard system does not benefit from changing array power; indeed this is the only system for which the array appears to have been optimised accurately by the supplier. The benefits of increasing array power can be seen to be very significant in the cases of the Briau and Photowatt systems: increasing array power by 20% and hence cost by slightly less than this amount increases output so much that the Specific Capital Cost and therefore cost of water is reduced by a quarter. (The apparent undersizing of the Omera array may be due to the fact that the model used the laboratory data for pump efficiency which is known to be low).

The effect on the Arco system's overall system efficiency-head relation of using an array optimised for both voltage and power is demonstrated in Figure 45. At a head of 7.5m the daily system efficiency increased from 2.55% to 2.98%.

4.4.4 Impedance matching

As explained in section 4.2.4 on impedance matching an electronic maximum power point tracker (MPPT) can be used artificially to alter the voltage - current characteristic produced by a photovoltaic array so that it always supplies the maximum power to load. This compensates automatically for changes in irradiance or static head and other influencing factors such as temperature as well as changes in the load itself. Two of the systems purchased for field trial, the Soterem and SEI, incorporated an MPPT.

No MPPT was tested as part of the laboratory work and so for the design studies we have considered an MPPT which operates ideally (this should be nearly achievable in practice) and has parasitic energy consumption of either zero or 10% of the array output during the day.

The addition of an MPPT to the Arco system under reference conditions was investigated in terms of improved daily output and overall system efficiency. The daily output was increased typically by around 15% when an MPPT with 10% losses was used and by 25% to when the MPPT was assumed to have few losses. The effect of the MPPT on overall system efficiency on the standard clear day is shown in Figure 46.For ease of comparison the curves for the system supplied, and with voltage and power optimsised (as discussed in section 4.3.4) are also shown. The voltage power optimised curve is very close to the curve for an MPPT with 10% losses and this suggest it would be worth looking into ways of manually adjusting the series/parallel connections in array. While this would require a more complex wiring system there would not be the same parasitic power consumption as with an MPPT.

4.4.5 Sun tracking

It is well understood that the daily output of a photovoltaic array will be maximised if it is maintained at all times pointing normal to the sun.

The increase in energy intercepted by a perfectly tracked array over a fixed array pointing due South at an inclination of 15^{o} is 24% on a standard clear day.

At at static head of 5m the Arco system started to operate one hour earlier and continued one hour later. Overall 36% more water was pumped: this is more than the energy increase because the pump is operating more efficiently under the higher value of solar irradiance.

The effect on pumped water output of three feasible alternative ways in which the farmer could manually track an array have been analysed and compared with the results obtained from fixed and perfectly tracked array.

The effect of the farmer making two adjustments, so that the array has three predetermined orientations, is shown in Figure 47. Up to 95% of the incident energy received by a perfectly tracked array was received if these two adjustments are made. A most worthwhile increase achieved at no extra system cost.

4.4.6 Pipework Variation

It is essential that the suction and delivery pipework should be included when determining the performance of the pumping system. For each of the systems considered in the design studies, standardised pipework has been included, as indicated earlier in Table 33.

During the design studies an initial appraisal of the effect of increasing and decreasing delivery pipe length and diameter for representative systems was made. Results for diameters of 25, 50, 75 and 100mm are plotted in Figure 48 against Specific Capital Cost. This shows that the optimum diameter for this particular duty is about 75mm, although the value is not critical; it is important however for it to be more than 50mm.

The appropriate diameter will increase with the distance through which the water is to be delivered, but an analysis needs to be made of each situation to determine the minimum diameters of pipe.

4.5 Comparison of Systems on Basis of the Mathematical Model

The mathematical model allows all the systems which have been tested to be compared on a common basis. Without the model this would be difficult because

a) all systems have different sizes and nominal ratings
b) they have been tested under differing field conditions.
c) being generally prototypes the prices paid for the systems are not necessarily indicative of what production prices would be.

As previously explained, the model enables the Specific Capital Cost for each system to be formulated from the basic costs of each of its components, and the performance of all systems can be determined under identical solar conditions through the use of the standard solar days. A comparison on the basis of Specific Capital Costs is useful when considering improved systems. This avoids the danger of seeking high efficiency for its' own sake without regard for its possibly disproportionately high costs.

The calculated costs for each system, based principally on the array power and weight of the motor and pump, are presented in Table 38. Actual prices are also listed for information. It can be seen that in each case (except one) the price paid was greater than the calculated cost. This is to be expected because calculated costs do not include the cost associated with marketing, promotion or development. It is felt that an increase on calculated cost of 50% to 100% is reasonable and on this basis the prices paid for the Briau Duva, Pompes Guinard and SEI systems seem reasonable. One contributing factor for the very low price paid for the Arco system is that four extra modules were supplied by the manufacturer at no cost.

The performance of the systems on the standard clear and hazy days have been used to compute the Specific Capital Cost. As explained earlier, this is the cost per unit hydraulic energy output in one day for a fixed input profile of radiant solar energy, (6 kWh/m^2 on a horizontal surface for the standard clear day; 4.65 kWh/m^2 on the hazy day). The photovoltaic array of each system was also optimised, so as to give the cost/performance of a simply improved version of the same system, The results are summarised in Table 39.

The performance, in terms of the clear day output at 5m static head, for each system is illustrated as a function of array power in Figure 49. The labelled points indicate the system as supplied while radial lines indicate the routes to optimised (for array voltage and power) systems. Overall daily system efficiency contour bands are also included: these are based on array efficiencies of 10% and 12%.

It must be stressed that these results should not be used as a basis on which to pass final judgements on the various systems. The results are indicative of the cost effectiveness of the present generation of pumping systems, but the component performances are being improved and costs require confirmation. The methodology, however, should remain valid. Indeed, we should note that the Pompes Guinard and SEI pumps, which have been shown here as achieving the best efficiency and lowest cost, were not operated successfully in the field, for a variety of reasons. Neverthless the model does indicate what should be achievable.

4.6 Improvement to Basic PV Systems Using the Mathematical Model

The various individual ways in which the performance of existing solar pumps could be improved has been described in section 4.4 and some cost implications have been explored in section 4.5. It was decided that it would be of interest to use the mathematical model to explore the consequenses of making the following improvements simultaneously.

- o better optimisation of solar array connections
- o addition of a maximum power point tracker
- o adoption of manual sun tracking

The Arco system model was chosen for these runs because of its consistent and well-documented performance in the field trials and because, taken individually, significant improvements had been made shown to be possible to this system in the sensitivity analysis.

The results of making these basic improvements are summarised in Table 40. A static head of 5m has been used when making the comparisons. It is noted that the system efficiency is at its best at about 7.5m.

It can be seen that the system as supplied achieves a daily overall efficiency of 2.2% at a Specific Capital Cost of $ 3.40/kJ per day . By optimising the photovoltaic array to match the motor/pump better the efficiency can be increased to 2.6% and the Specific Capital Cost reduced to $ 3.00. This corresponds to an overall improvement in efficiency of 18% and of approximately 13% in Specific Capital Cost.

The use of a simple manual tracking system whereby the array orientation is adjusted twice daily gives an even greater improvement. Effective daily efficiency is increased to 2.9%, Specific Capital Cost reduced to $ 2.60/kJ per day and 30% more water is pumped by the same basic system.

Array optimisation can be combined with manual tracking to improve the effective system efficiency by 50%, which leads to a reduction in Specific Capital Cost of 32%.

The use of a maximum power point tracker (MPPT) is also shown to give improvements, but these are less under these conditions than from simply optimising the array. It should be noted that the benefits of the MPPT will be greatest with varying solar conditions which are not allowed for in this analysis. The performance of the MPPT requires further investigation including the modelling of a system over a complete year or irrigation season at a specific location.

4.7 Examination of Other Feasible System Options

The system design studies have examined some of the more immediate questions and have enabled a preliminary specification to be drawn up. It is envisaged that, given data and development, the model can be used in future to examine the linking of components from different systems, alternative or new components not previously tried in PV pumping systems and the cost effectiveness of postulated performance characteristics.

Ideas which have been considered, but not yet tried include:

a) alternative PV modules
b) the use of simple concentrators
c) the use of alternative motors (eg separately excited dc motors, submersible ac motors)
d) alternative pumps particulary for higher head applications
e) battery options.

Based on experience gained to date from use of the model, it is confidently anticipated that its use will reveal the advantages and disadvantages of these ideas.

5. THERMAL SYSTEMS DESIGN STUDIES

5.1 Introduction and Scope

Most of the earliest work on solar pumping was concerned with the use of heat engines; indeed some of the first achievements in the use of solar energy in the early part of this century were with thermodynamic pumps. In spite of this previous experience it became clear during the early part of this Project that small solar thermodynamic water pumps have not been developed to the stage where reliable systems can be obtained commercially.

We were unable therefore to obtain much first hand experience with, or data from, working solar thermodynamic pumping systems. Data were obtained from only one complete system operating from solar power, that of the Solar Pump Corporation system, when tests were performed on the system at the manufacturers premises. Accordingly it was agreed that the Consultants would undertake the necessary design studies in order to:

(i) determine whether it is feasible that solar thermodynamic pumps could compete with photovoltaic systems.

(ii) identify directions in which technical developments can be made and

taking particular account of what could be manufactured within developing countries, rather than what could be achieved with advanced technologies. It was further agreed that a mathematical model should be constructed and used to achieve these objectives.

5.2 The Model

5.2.1 Approach

The basic components of a solar thermodynamic pump are indicated in Figure 50.

The operating characteristics of solar collectors, engines and heat rejection systems are very sensitive to temperature, and will vary depending on the way the components interact. This means that successful operation of a solar thermodynamic pump is critically dependent on close matching of the components.

Comprehensive mathematical modelling of the performance of a solar thermodynamic pumping system was beyond the scope of this study. Indeed this could not be possible because insufficient data are available to validate such a model.

It was thought however, that it would be feasible to use a simple model to compare the likely performance and costs which might be achieved from different combinations of solar collectors and engines.

The limited validity of this approach is clearly recognised; in particular the dynamic behaviour of thermal systems is of great importance but the resources were not available to study this.

Modules for solar collectors, engines and heat rejection systems were developed and these have been used to compare a variety of possible pumping systems under the same steady-state conditions.

5.2.2 Principal Components

a) Solar Collectors

The types of solar collectors considered in the study were:

- o Flatplate
  - unglazed
  - with glazing, selective surface
  - evacuated
- o stationery concentrator
- o linear focus/single axis tracking
  - parabolic trough
  - Fresnel lens
- o point focus/2-axis tracking
  - parabolic dish
  - central receiver

Details of these are given inTable 41.

The thermal performance of solar collectors has been the subject of intense study and operating characteristics are now well understood as there are plenty of data avaliable, so they can be modelled with precision. However, insufficient data were available for a solar pond to be reliably modelled as a component.

b) Engines

A number of different engines can be employed in solar-thermal systems. Only those which apply the Rankine and Stirling cycles are sufficiently well developed and understood to be considered seriously at present for use in small-scale solar water pumps. The engines considered were:

- o Rankine cycle using Freon (refridgerants R11 & R13)
- o steam engine
- o high temperature air Stirling engine

Little detailed performance data on engines of the size appropriate to the Project are available. Efficiency/temperature characteristics were based on the experience of the Project team and its Advisers.

c) Costs

The component costs used are based on the current prices of solar collectors, as indicated in Table 41. Other costs are based on the Consultants judgement of what they would be if manufactured in quantity in a developing country. An example of the costing for a flat plate collector based system similar to the Solar Pump Corporation system is given in Table 42.

The cost of a sun-tracking system has been taken as $360 with an additional $250 for the high concentration point focus. Engine costs are based on the swept volume and condensor cost on the amount of copper pipe required. The cost of the pump well head assembly and piping has been taken as $600.

The model takes the performance characteristics of different collectors and engines and combines them. The optimum operating temperature for a collector/engine combination under a given solar irradiance is then determined. An example of the results is given in Figure 51, in which collector, engine efficiency and overall system efficiency are shown as functions of operating temperature. When the operating temperature is chosen, the model then calculates the size and cost of the system for a predetermined energy input and output. The input is daily global solar irradiation in the form of a standard day profile of $6 kWh/m^2$, the same as the clear day used with the photovoltaic system model.

The system daily output requirement chosen is 2kWh of shaft energy for the engine equivalent to 0.6 kWh of hydraulic energy with a 30% efficient pump. This efficiency is typical of a positive displacement pump linked directly to the engine but operating at low heads and taking into account linkage losses. Positive displacement pumps are considerably more efficient at high heads (> 15m). This is similar in size to the SPC pump which has been field tested.

The capital cost per unit of water pumped is a function of the unit size. The model was also used therefore to evaluate systems with a delivery of 10kWh/day of shaft energy, or 3.5 kWh hydraulic energy, a higher pump efficiency of 35% being used.

For each system considered the model calculates the area of collector and size of engine/condenser and from this computes the capital cost and also Specific Capital Cost. The results are presented in Table 43 for the 2kWh/day systems.

5.3 Results

The results show a fairly large variation across the spectrum of collector engine combinations. Certain factors are evident however on analysing the results:

a) Systems utilizing tracking collectors are considerably less expensive than equivalent systems incorporating stationary collectors.

b) Flat plate solar collectors driving small Freon engines are amongst the most expensive combinations.

c) Systems using Freon 11 engines appear to be cheaper than systems with the same collector coupled to a steam engine. This is due to the higher efficiency of the Freon 11 engines. However for steam engines condensing at 1 bar use could be made of the waste heat. For these applications the steam engine would represent better value for money. The steam engine would be simpler to produce than the Freon 11 engine and this might make the difference between internal manufacture and importation in some countries which could be a major consideration.

Stirling engines would appear potentially very attractive. However Stirling engines are not yet sufficiently developed as was demonstrated by the poor performance of the example tested at the University of Reading.

d) The fixed E-W trough would appear to be relatively expensive.

e) The small central receiver system would appear to have potential. It can be used either with a Freon 11 engine or a steam engine. This type of system is however the least well developed.

f) A simple parabolic trough or linear lens concentrator is considered attractive due to its simplicity.

g) Among the 10kWh units the cost difference between the different units follows the same general pattern but is much more marked than the 2kWh units.

h) The use of evacuated tube solar collectors considerably reduces the area of solar collector required compared to conventional flat plate solar collectors. Only 40% of the area required for the 2kWh system using double glazed flat plate solar collectors is required if evacuated tube collectors are used.

However the durability of this type of collector under field conditions has yet to be demonstrated.

i) The quantity production of a parabolic trough solar collector with Freon engine could result in systems with a Specific Capital Cost of 1.5 $/ kJ per day.

It would seem reasonable to conclude that the Specific Capital Cost of thermal systems is comparable with photovaltaic systems. For example the projected cost for a small fixed plate solar collector Freon engine system produced in quantity in a developing country, similar to that under development by Solar Pump Corporation is 2.8 $/kJ per day. A photovoltaic system is presently typically 3.4 $/kJ per day.

PART 2 – CONCLUSIONS

6. CONCLUSIONS FROM FIELD TRIALS

6.1 Resumé of Types of Systems Tested

Although the field testing programme was necessarily much shorter in time scale than would be desirable for the testing of equipment that is required to have an operational life of ten years of more (if it is to be successful), and although many of the systems tested were immature in many respects, useful technical conclusions were reached as a result of this work.

Sufficient data to characterise the performance of ten of the twelve systems subjected to tests was collected. Unfortunately the two systems where tests were incomplete (due mainly to damage or loss of components in transit and problems in commissioning) were both uniquely unconventional; one was the only procurable thermal system (from Solar Pump Corporation, USA); and the other was the only system with a tracking photovoltaic array (from Soterem, France).

All the systems tested, therefore, were solar photovoltaic, generally with arrays tilted at an optimum inclination for the latitude of each site, and fixed to a permanent framework on concrete foundations. The only exception was the SEI system which was portable and whose array could be adjusted in azimuth by hand.

Although a careful selection procedure was applied, the few suppliers who could offer systems within the time-scale demanded were given scope to use the technical approach they felt was appropriate to satisfy our specification.

Most suppliers adopted a fairly common approach so the prospect of including the Soterem tracking system was welcomed, despite a rather high cost per peak watt compared with the other systems.

In considering the performance of these systems, it should not be forgotten that they were ordered on the basis of specifications supplied to the Consultant towards the end of 1979 - in many cases the equipment has since been modified.

Tables 6,8 and 10 give details of the systems chosed for field trials. Without exception, all the photovoltaic systems tested used permanent magnet dc motors; most of these were apparently 'off-the-shelf' standard industrial units and of conventional design, with a commutator and brushes, both of which could in the long-term be a source of trouble if not adequately 'preventively maintained' before being too seriously worn for repair. One supplier provided an electronically commutated, brushless, dc permanent magnet motor; this was SEI (with an AEG motor). Although the units supplied failed early in the trials, it is considered that this type of machine could in the long-term offer improved reliability and certainly require less attention.

Since the test sites required static lifts in the range from 3-20 m with most under 10 m, the majority of manufacturers supplied systems with single-stage centrifugal pumps. Many of these were surface-mounted suction pumps, presumably because:

(a) these are generally easier to combine with an electric motor on a base-plate for surface mounting beside open water sources of the type at the test sites. In other words, a system of that kind can quite readily be assembled mainly using of-the-shelf industrial components.

(b) there are problems in devising long vertical-shaft drives and risers for submerged pumps with surface mounted motors, unless these are designed specifically for standard borehole installation.

Exceptions to this rule were the two positive displacement (piston) pumps, (from Briau for their Mali pump and from Soterem), and a regenerative pump (supplied by Inter-Technology Corporation for Sudan).

The Pompes Guinard vertical shaft borehole pump at Yangasso in Mali was one of the few systems tested which was representative of a relatively mature product line, rather than being perhaps one of the first systems of its kind to be assembled. This maturity was one of the factors which resulted in it being the most generally reliable system tested; the other pertinent point is that it was located in a sealed borehole pumping clear water and had no suction problems.

A system purpose-designed for low lift micro-irrigation is the one by SEI, with a submersible integral motor and pump. This unit is very small and compact and the Project had some of the first produced with electronically-commutated motors, earlier versions having more conventional brushed motors.

Finally, the Solar Pump Corporation thermal system had a low speed, reciprocating piston pump, of the kind used traditionally in hand pumps and farm wind-pumps. This was mounted on a borehole of substantially greater depth than the heads applied for the other systems.

The significance of the short-comings of some of the system concepts as well as many detailed engineering inadequacies is discussed in more depth in Section 11.

6.2 General Outline of System Performance

An indication of the relative performance of the various systems is summarised in Table 13. Complete data collected during the field trials appears in the Project Record.

6.2.1 The effect of variation in static head and suction lift.

Before comparing the efficiency figures achieved by different systems, it is important to note that pump efficiency, particulary with centrifugal pumps on low heads, is quite sensitive to head. Therefore, allowance must be made for systems not operating at their design head when comparing them with systems that are. Obviously, systems that do not suffer too serious a drop in performance when operating away from their design head are necessary for applications such as micro-irrigation, where the head may vary significantly (within reasonable limits) from place to place and from season to season.

A related problem with head seriously affected two of the surface-mounted centrifugal pumps; namely inability to retain pump prime due to apparently excessive suction heads. The two in question (Photowatt in Mali and Pompes Guinard in the Philippines), although operating close to their design total static lift, proved much less efficient in the field than expected due almost certainly to the presence of air in the eye of their impellers. The Pompes Guinard system was situated near the practical limit of suction head (5m). Others suction pumps, although not seriously affected in performance by excessive suction lift also gave occasional priming problems, which resulted in minor damage to both the Briau (Philippines) and the Arco Solar (Sudan) units from running dry.

Thus, it may be concluded that non-self-priming centrifugal pumps are generally unsuitable, in principle, for solar power pumping systems, since:

(a) they readily lose their prime due to footvalve leakage when stopped, or due to running too slowly when clouds pass

(b) they can then, in many cases, suffer serious damage through running dry and prematurely wearing out seals, bearings, etc., which depend on water for lubrication.

6.2.2 Optimum efficiencies of the various sytems

Although cost-effectiveness over-rides efficiency in importance, the most efficient systems appear to be the most cost-effective, largely because higher efficiency allows a smaller array for a given output, and array costs tend to dominate. Therefore the efficiency of the different systems is of considerable interest.

It is easiest to assess efficiency under operating conditions. Table 13 indicates the average peak efficiencies recorded for the various systems. (In a few cases there is an apparent inconsistency between the best total system efficiency listed and the product of the array and subsystem efficiency figures given; this was because the best values recorded for the array did not always coincide with the operating conditions which returned the best subsystem efficiency, and the Table indicates 'best' figures not necessarily recorded simultaneously).

The main conclusion from this is that well designed systems should be able to function consistently with efficiencies (based on array area) of over 2% and that over 3% is achievable under favourable conditions from a good design.

The most important factor in achieving high system performance is the efficiency of the motor and pump, particularly the latter.

It is interesting that only three systems returned consistent efficiency figures better than 2% and two of these systems, namely those from SEI and the Pompes Guinard borehole pump, were products developed with a view to manufacture in some quantity. The third system, the Arco Solar unit, which is known to have been put together largely as a 'special' for this Project proved to have been successful attempt at matching off-the-shelf components and returned a consistently above-average performance; it also happened to be one of the most cost-effective systems in terms of capital cost per peak watt of output.

The Briau and Omera Segid systems were runners-up in efficiency terms. The similar Pompes Guinard surface suction centrifugal pumping system would have been comparable had it retained its prime; in fact the laboratory testing programme showed this pump to have a very good efficiency if operated at high speeds on low suction heads.

The Briau Duva positive displacement suction pump returned poor efficiency figures due to being operated well off its optimum pumping head (which ought to be about 20 m rather than between 4 and 10m, the head at which it was tested). Almost certainly this is unsuitable for irrigation applications, but may make a usefull water supply pumping system where consistent delivery in many different locations with widely varying heads could be more important than achieving a high efficiency. However it demonstrated an ability to self-prime, and also ability to pump some flow when functioning well off its optimum head. Positive displacement pumps could well benefit from the inclusion of an impedance matching device.

The remaining two pumping systems did not prove satisfactory in the field trials, returning poor efficiencies and poor reliability. The Photowatt centrifugal pump system proved extremely difficult to prime and only functioned at high irradiance levels; it seems that the motor speed was generally inadequate for the pump, and consequently efficiencies of less than 1.0% were returned. The ITC/Solar Corporation unit used a regenerative (or side-chamber) pump which had very small clearances (a necessity with this type of pump). Serious difficultuies were experienced in keeping it running for any length of time due to rubbing caused by loss of clearance between the impeller and its housing. Eventually the ITC system returned a best efficiency of 1.9%.

It is noticeable that the best solar pumps utilised subsystems (ie motor-pump units) with efficiencies of up to 40%, while the runners up used roughly 30% efficient subsystems and the worst systems had subsystems of only around 20% efficiency. The very best subsystem performance was recorded from the SEI and Pompes Guinard borehole systems, both being submerged impeller pumps (ie no suction) and both incidentally being part of purpose-designed solar pumping systems.

The array performance appears quite variable from Table 13, with a variability in maximum cell efficiency from 7% up to nearly 11%. Overall array efficiency varied from 4.8% to 8.5%. In practice the actual differences between arrays are not likely to be so marked as this might suggest, since array efficiency is dictated by the impedance match between the array and its electrical load. A well matched array and load cause the array to operate near its maximum power point and to thereby appear efficient. Hence the array efficiency figures are in part an indication of the closeness to the maximum power point that is achieved.

However it needs to be recognised that there are smaller order differences in PV array performance which are better investigated through laboratory tests. These can isolate effects due to the array from those due to its load. Some arrays appeared to run rather hotter than others which, as indicated by the test results, meant a marginal loss of power and efficiency. The temperature of an array in the field is dependent on many factors other than its design, including wind speed and direction, and the nature of the immediate surroundings of the array.

6.2.3 Start-up solar irradiance level

The start-up irradiance level has a major bearing on the daily output to be expected from a solar pumping system. The higher the level, the later in the day before the system can start and the earlier it will stop and hence the shorter the time per day it will pump. This factor has a major influence on overall daily efficiency.

However, although it is obviously desirable to have a system which will start at a low irradiance level, it is often difficult to achieve this without compromising the system performance at high irradiance levels. Here the SEI maximum power point tracker obviously gives an advantage in that the SEI system started at quite low irradiance levels (of 200 to 300 W/m^2) and returned a consistent high efficiency right up to levels of over 1000 W/m^2. Pompes Guinard have shown that it is possible to obtain good maximum power tracking simply by good motor-pump unit matching rather than resorting to an electronic logic system.

6.2.4 Daily overall system efficiency

The daily overall system efficiency is the ultimate judge of the performance of a system as it indicates the proportion of solar energy received per day that is converted into useful pumped output. It is in effect dependent on obtaining both a low start-up irradiance level and a good system efficiency at all levels of irradiance, (ie to obtain as long a daily period of operation at as high an efficiency as possible).

At 6kWh/m^2 array solar irradiation, the maximum daily overall system efficiency recorded (based on array area) varied from 0.4% for the Brian Duva system to 1.8% for the Arco system. It should be noted however that there was insufficient data recorded to make an evaluation of the daily overall system efficiency for 5 of the 10 systems tested.

Since the more efficient systems also had the lowest start up solar irradiance requirements, not surprisingly they are significantly more productive for a given daily solar energy input.

6.2.5 Operating experience

The main purpose of these field trials was performance testing, since the tests were not long enough, nor made with enough system samples to obtain a proper indication of true system reliability. A large number of practical lessons useful for future design were learnt in the course of installing, commissioning, running and monitoring the systems. In some cases, suppliers had apparently not appreciated the working condition in which their products would be required to operate; the experience gained from the Project shows how essential it is that all systems under development should undergo a period of field trial before being marketed. It is convenient to describe the lessons learnt in Part 3 of this Report in the context of the recommendations and so to save repetition only a brief resume of the main points will be given below.

The only system which operated virtually faultlessly during the period of testing was the Pompes Guinard bore-hole pump at Yangasso in Mali. Since this was also the only system that had been previously installed before the Project started, it may be that we simply avoided experiencing some of the teething troubles which to a greater or lesser extent affected every other system.

The SEI systems, although good performers for low lift (circa 5m) micro-irrigation, relatively low in cost and carefully thought out in concept, were marred for this Project by a series of electronic failures, both of motor electronic commutators and of the MPPTs, which in the end limited the amount of testing that was possible. If the reliability of this system's electronics can be improved, it will clearly be a very promising system in performance terms. The avoidance of the need for foundations and permanent structures was also an attractive feature.

The Arco Solar and the Briau centrifugal suction pumps performed generally acceptably, with minor faults developing caused by faulty footvalves and, loss of prime followed by dry running. The Omera Segid suction pump worked well after the faulty wiring of the array had been corrected.

As dry running of the Briau positive displacement pump would cause damage to the pump, a float switch had been supplied to cut off the power supply to the pump in the event of the water level falling below the safe operating level. However, the float switch was found to be faulty and was never fully installed but fortunately the water level did not drop to the critical level during the period of the field trials. In addition one of the screws securing the glass front to one of the array modules had been over tightened causing the glass to shatter.

Events proved the Pompes Guinard centrifugal suction pump was operating close to (but still within) the maximum value of net positive suction head (NPSH) specified by the manufacturer. In consequence the priming problems at less than maximum solar irradiance levels meant that only a little performance data was obtained and no real assessment of reliability could be made.

Both the Photowatt and the ITC/Solar Corp. units proved difficult to test as for different reasons they were rarely able to run and then only under conditions of high irradiance. The Photowatt pump was unable normally either to retain its prime or to achieve the static head, and the ITC/Solar pump suffered from mechanical binding and friction between the pump impeller and its casing, despite numerous attempts in the field to repair the trouble.

7 CONCLUSIONS FROM LABORATORY TESTS

7.1 Purpose of Tests

The laboratory tests were intended to provide a more detailed understanding of the performance characteristics of sub-assemblies and components of the field-tested systems, and data for the system design studies.

There was insufficient time and an inadequate number of samples of any single product to draw any quantifiable conclusions on expected life and reliability. However, all components tested were inspected before and after testing to identify any faults or flaws in manufacture of possible significance to long term reliability and performance.

In addition to the tests on photovoltaic system components, a number of prototype thermal systems were studied; one in the laboratory, three at their manufacturers works. At this early stage in their development it was of interest to determine their performance and the efficiency of their various sub-components in support of the thermal engine part of the design studies.

7.2 PV Modules

7.2.1 Performance Testing

Five examples of each of four selected manufacturers modules were tested. In general, close agreement was obtained by RAE and JPL, the average performance discrepancy being 0.5%. This was to be expected since both organisations have considerable experience of testing PV models and will have adopted effective testing procedures. Accurate repeatability was demonstrated by RAE to within 0.8% and by JPL within 1.4%.

The main conclusions from the performance testing were:

- o all the modules tested performed below their manufacturers' claimed nominal rated output and one type was even out of the manufacturers' claimed limits of variability, (See Table 16).

- o there was considerable variability in efficiency in terms of rated output per unit area of cell, (cell efficiency), between products, ranging from under 10% to over 12% – a difference of over 20%. (Again Table 16 refers.)

- o the power drop due to temperature increase was marginally greater with the more efficient types of cell, but the more efficient types still retained a 10% greater output per unit of cell area at 60°C. (Table 16A refers)

- o the spectral response tests indicated that the more efficient cells were responsive to a wider band-width, which was presumably the reason for their greater efficiency.

The Arco Solar and the Solarex modules had the highest performance (although the latter was well below specification), while the RTC and CEL modules performed around 20% worse in terms of cell efficiency.

The implications of these results are that significant differences in performance can occur between different PV products. High efficiency per unit area of cell is important to obtain the best return in energy from the most expensive part of any PV solar pumping system, as the refined silicon costs are likely to be of the same order for high and less high efficiency cells.

Misjudgement of array output resulting from over optimistic manufacturer's claims can upset system designers' calculations and result in less than optimum specification of arrays. In addition, incorrect ratings can mislead procurement agencies when competing types of modules are being considered for a particular project.

7.2.2 Evaluation of durability and reliability

Many of the modules, on inspection, had minor manufacturing imperfections, including in some cases chipped cells.

With the exception of one module, all units survived the testing programme without complete failure. Two of the others suffered some degradation of performance or other symptoms that could affect their performance in the long run. The module which failed was a sample received earlier than the rest, and may not have been of the same quality.

Typical problems included degradation and extrusion of sealant, degradation under ultra-violet and/or humidity testing of the encapsulant (colouring and/or delamination) and poor electrical isolation of the cell strings (offering the risk of an eventual short circuit).

Only one breakage of glass resulted under the hail tests but it is not clear how well this test correlates with field conditions. The experience with the field testing programme was that the glass covers are quite vulnerable with present designs, a broken cover invariably results in a written off module - and the present cost of replacing, say, a typical 36W module is of the order of US $ 360, or more.

There is therfore good reason to favour the use of small modules, such as CEL produce, since a single breakage is less serious cost-wise and its loss may not stop the system operating altogether. It also gives greater flexibility to the system designer in varying the array to motor match by giving a greater number of permutations of voltage and current as well as array power. There may also be a case for using laminated glass covers for small-scale solar pumping applications, where arrays are likely to be more vulnerable to damage from children or animals than in other applications in remote places.

7.2.3 Conclusion

Despite the large sums invested over the last few years in the production and development of PV arrays, which dominate the cost of small PV pumping systems, neither their performance, nor their quality can be taken for granted. Most manufacturers are now prepared to offer a 5-year guarantee, although there is a need for a working life of at least a decade, if good economics are to be achieved. Since the cost of modules is often compared on the basis of cost per peak rated Watt, the fact that one manufacturer's product was from 14 to 19% below specification means they are that much more expensive than would otherwise be anticipated. Such discrepancies are difficult to detect in the field where a large variety of factors could cause variations in apparent array output.

In view of the results obtained from the performance testing of the PV modules, the Consultants believe that there is now a real need for an internationally accepted standard for performance measurement.

7.3 Motors

7.3.1 Performance testing

Tests were conducted on nine types of motor representative of those fitted to the systems tested in the field, and two individual motors.

The main conclusions of interest are the motor efficiencies at various speeds, and the corresponding voltage requirements. These are summarised in Table 22 together with basic motor ratings and weights.

In general, the performance recorded was as expected from dc permanent magnet motors, with efficiency percent figures ranging from optima in the mid 70's to the mid 80's.

By comparison, typical ac induction motors of similar power rating would have efficiencies in the 25 to 65% range while field wound dc motors would be in the 65 to 70% range. Also, ac field wound motors will have a poor part load performance compared with permanet magnet machines. This clearly indicates why permanent magnet motors are preferable to other motors, whilst ac induction motors would require an expensive inverter to produce dc current.

The values of efficiency achieved are set in context then it is appreciated that, with a nominal 500W array costing, for example, typically around US $4000, a 10% advantage in motor efficiency at any speed can save US $400 of array costs.

The motors tested are in two main speed ranges, under 2000 and 2500 to 3500 rpm. There is no significant efficiency advantage apparent for motors of different speeds - the two best motors were in fact rated at 1900 and 3000 rpm respectively. Higher speed motors tend to be smaller and therefore possibly cheaper, but all other things being equal the lives of bearings and brushes are likely to be inversely proportional to speed. However endurance testing to investigate whether the higher speed units actually would have inferior longevity was not attempted: to do so would require sufficient samples of motors to generate statistically significant results, since machine life studies are essentially statistical in nature.

The higher speed units are of attraction to system designers in that centrifugal direct-coupled pumps are both more efficient and less likely to lose their prime at the higher speed levels. Indeed it is worth noting that the Photowatt system, whilst having a very efficient motor (up to 83%) failed to prime in the field, perhaps because of its particularly low speed motor (1250 rpm). In contrast, the more successful suction centrifugal pump systems all used 2000 or 3000 rpm motors (ie Arco (Mavilor 3500 rpm), Briau (Brot 1900 rpm) and Omera-Segid (2000 rpm).

The one motor not from any field tested system (by SEM) was interesting in achieving 76% efficiency at only 600 rpm, and 83% maximum efficiency at 1500 rpm which would make it of interest for driving positive displacement pumps where the low speed of the motor would minimise the speed reduction losses (and costs).

The elevated temperature tests displayed an expected marginal fall off in the performance of some units, no doubt due to increased resistive losses in the armature windings.

The thermal connection between motor and casing has to be good. The connection in the SEI system seemed inadequate; since it is designed to be water-cooled should it run dry there is the obvious risk of overheating and consequent damage to the electronic circuit.

The Honeywell motor although a little less efficient than some of the others, performed satisfactorily even under elevated temperature conditions.

7.3.2 Conclusion

In summary five motors, proved particularly efficient, the best reaching 87% optimum, which is as good as can be expected from motors rated at under 1kW. They also returned very good part-load efficiencies, exceeding 75% at 100W (normally under 25% load). However, the other motors also generally returned very acceptable part-load performance.

If the high performance has not been gained at the expense of longevity or other disproportionate expense, (and it does not appear from the studies so far completed that it has), then the extra 10% efficiency and somewhat better part-load efficiency of the best motors makes a very useful saving in array costs.

7.3.3 Hitachi linear actuator

The reason this device was tested was that it was promoted by its manufacturer as an efficient prime-mover (being a permanent magnet device this is likely anyway). There was also attraction in the simplicity of a simple direct-coupled reciprocating pump designed without any rotating moving parts which might be low in cost, reliable and long-lasting. The main applications claimed by Hitachi were to power small aircompressors or vibratory devices, but it was also claimed this actuator was suitable for powering a water pump.

In the event, the test were inconclusive since no purpose-designed pump was available to load the unit. An attempt was made to construct a pump for it, but due to the limited time available a single friction load was applied instead. The testing programme did indicate the likely problems to be expected in matching a pump to actuators of this kind, in that the efficiency will be poor unless the dynamic load is such that the correct amplitude and frequency are achieved. As the dynamic load will vary with pipe length and static head (unless the main water pipe is isolated with air chambers or similar), it may prove impossible to produce an efficient actuator powered reciprocating pump able to be readily applied in a range of different heads and pipework configurations.

It is also anticipated that there could be problems in producting a suitable low-frequency alternating current supply with the necessary waveform to achieve good conversion efficiency from the dc output of a PV array. A high frequency ac supply, on the other hand, is no more difficult than electronic commutation for rotating motors, but it is likely to be very difficult to devise an efficient high frequency reciprocating pump for use with a high frequency actuator.

Our calculations indicate that using the inertial flow principle, a system could be developed with a resonant frequency of 15Hz, a driving frequency of 10Hz, an effective oscillating mass of 1.0 kg and an actuator displacement of 6mm. Assuming a mean effective force of 60N could then be achieved, the pumped power output from a double acting pump would be 7.2W, giving an overall efficiency of 24% for 30W input power. It is hard to see how this efficiency could be much improved.

As this efficiency is no better than for rotary water-pump systems and bearing in mind the added complication of producing a low fequency supply from a dc photovoltaic array, the use of a reciprocating motor for small-scale solar powered pumping applications would not appear to be worth pursuing.

7.4 Pumps

Tests were conducted on nine pumps representative of those fitted to the systems tested in the field, and four individual pumps.

The key parameters of interest are the pump efficiences at various speeds, in particular at the required operating head. Also of interest is the fall off in efficiency away from the optimum operating point. The main conclusions are presented in Table 26.

Two centifugal pumps returned peak efficiencies in excess of 50% while one of the positive displacement pumps was equally efficient but only at heads greater than 14m. Three other centrifugal pumps achieved efficiencies in excess of 40%. In fairness it should be pointed out that the impeller of the Omera Segid pump was found to be damaged and on the basis of it field performance it would be expected that it, too, would have an efficiency in the mid-40s.

Pump efficiency is affected by rotational speed, (generally centrifugal pumps are more efficient at higher speeds). The Pompes Guinard Alta XS 600/12 therefore did well to achieve its best efficiency at only about 1900 rpm. The KSB pump ran at 2600 rpm to achieve its best efficiency. High speed is generally counterproductive in terms of life and high speed centrifugal pumps will, for a given head and flow, have smaller impeller passages and clearances. These are more prone to blockage by suspended solids in the water or to wear and tear and so an efficient low speed centrifugal pump has attractions for these applications.

The slope of the constant speed curves is almost horizontal at low flow rates for four pumps, but inclinded downwards for others (see Figures 15 to 27). With constant speed pumps that are used from mains electric motors, this feature is not critical, but with variable speed pumps (as in solar pumping systems) a near to horizontal slope to the constant speed lines at low flow rates means there is only a small speed reduction needed from the speed for optimum efficiency at optimum head, before flow totally ceases. A parameter the 'speed sensitivity' has been entered in Table 26 to indicate the pumps performance in this respect (See Section 3.4.3 p. 35). Single stage centrifugal pumps are prone to suffer from this problem, and the Pompes Guinard XS 600/12 and Photowatt Breguet KSB pumps do not have favourable characteristics; it may be no coincidence that they had difficulty in maintaining their prime in the field (although Pompes Guinard had an extreme suction head to deal with). The Arco Solar Sta-rite, with much more steeply inclined constant speed curves, can take a 27% speed reduction from optimum speed before flow ceases.

Table 26 also indicates the maximum suction head achieved for stable running during the laboratory tests and confirms that the best suction performance for centrifugal suction pumps was from the Arco Sta-rite.

The efficiency when operating off the optimum head is also of interest, as in many cases it is not possible in practice to obtain accurate specification of the head, or indeed the head may vary with the seasons or due to well draw-down. Since we are interested for this project in heads in the 5 to 10m range, Table 26 indicates the pumps efficiencies for those two heads. Two pumps returned efficiencies at 10m head greater than 45%.

For higher heads, as may occur in water supply applications, the positive displacement pumps could be of real interest. Because of the form of the pump characteristic they are less suited to efficient operation under a range of solar irradiance and it could be worthwhile to include an impedance matching device. Soterem did this but unfortunately within Phase 1 there was no opportunity to test its effectiveness.

The last column of Table 26 shows a most important feature, namely whether or not the pump can self-prine. Surprisingly, the majority of the field tested systems were supplied with surface-mounted suction centrifugal pumps which do not self-prime. Loss of prime can result from a slightly leaky footvalve or from excessive suction heads and the consequence can be the pump running dry and sufferin damaged seals and bearings. In some cases, the heat generated can distort plastic fittings. At the very least it results in loss of output whilst the pump is reprimed.

7.5 Thermal Systems

7.5.1 Engines/pumps

The testing and evaluation of complete solar thermal pumping systems in the laboratory and at manufacturers works have revealed a varied tech nology that exhibits many innovative systems but which in the opinion of the Consultants all require development in order to optimise the designs more effectively and to rationalise and simplify the technology. This is no doubt partly because solar thermal systems do not generally lend themselves to improvisation from off-the-shelf components, as is possible with solar photovoltaic systems.

Tests on the Sunpower Incorporated Stirling engine powered pump at th University of Reading were disappointing with a heat source to pumped water efficiency of under 2%, which is very much lower than expected from a device of this kind and also less than half the manufacturer's claimed performance. In addition, the failure of a component resulted ir damage to the system. These results are not necessarily considered to be representative of the potential performance of Stirling engines in general and this device in particular.

A summary of the reported tests on the performance of complete engine pump systems are presented in Table 44.

The Dornier solar pump (on which tests were observed at the manufactures works with heat not solar energy input) was found to operate satisfactorily with a peak engine-pump efficiency of 3.45% and a peak hydraulic output of 0.22kW. This represents an overall efficiency in the range 1.5 - 2.0%. Simplification of the design is recommended in order to develop it to be suitable for part manufacture in a developing countr Also, the design study results indicate that flat plate collectors, as used by Dornier, are not likely to be a cost-effective approach.

The Solar Pump Corporation (SPC) system (on which tests were observ at the manufacturers' premises) exhibited reliability problems: some dif ficulty was experienced in making a system operational for the tests.

The basic design of this system has potential for remote rural pumping applications and for part manufacture in a developing country. The system was observed to operate with an overall efficiency of 0.9% and produce 45 Watts of hydraulic power but it requires further development to increase efficiency and reliability.

The results of observed tests on the Ormat Rankine cycle energy converter in Israel were encouraging as a heat source to electrical power output efficiency of 6% was recorded when operating with a heat source temperature of 72°C and a condenser temperature of 23°C with a peak electrical output of 4.9kW. The system was well designed and constructed but could not be readily manufactured in a developing country or maintained in a rural community. It should be noted that the Ormat system, if used for pumping, would have an output rating of about 3.5 kW and it is therefore larger than the Project specifications. It is unlikely it would lend itself to being scaled down significantly.

The Project team did not have the opportunity in Phase I to witness tests on other complete solar thermal systems, such as the Mabosun system in Italy and the prototype systems developed by Hindustan Brown Boveri, Jyoti Limited, and the Birla Institute of Technology and Science in India. The Consultants recommend that these systems be evaluated during future phases of the Project.

The commercial prototype of the Fluidyne pump developed by Metal Box (India) Ltd was seen working at the manufacturers works in Calcutta, India. The present pump is designed to be heated by coal, wood or gas and an overall efficiency of 3% is claimed by the manufacturer (with electrical heat input the overall efficiency is about 7%).

7.5.2 Solar Collectors

The results of thermal performance tests on solar collectors were obtained from independent testing organisations. A summary of collector performances for a range of different types is shown in Figure 52.

The long term goal of the US Department of Energy for the performance of linear focus solar collectors is a peak efficiency of 60% at a fluid output temperature of 316°C (600°F) under peak noontime solar irradiance. Of the test results made available to us the parabolic trough solar collectors manufactured by Hexcel and Solar Kinetics in the USA were observed to best approach these design goals with peak efficiencies reported to be 55% and 54% respectively. Sandia Laboratory have reported efficiencies of 58% at 316°C with their engineering prototype trough collector.

The results of tests on parabolic dish solar collectors are limited. Results of tests at Sandia on the General Electric Engineering prototype parabolic dish collector indicated efficiencies below that of the high performance line focus collectors. However the effective heat losses of these types of collectors are lower and hence may be more suitable for high temperature operation.

Test results on evacuated solar collectors manufactured by Owens (USA) and Sanyo (Japan) demonstrated that this type of solar collector exhibits lower heat losses than conventional flat plate solar collectors with collector efficiencies of 50% achievable when operating at temperatures in excess of 60°C above ambient. Fluid ouput temperatures of over 100°C are also possible with this type of collector with stagnation temperatures reported to be in the range of 200°C to 300°C. However their durability under field conditions has yet to be demonstrated.

Many prototype complete solar thermal water pumping systems now incorporate direct evaporating solar collectors in which the engine working fluid is evaporated directly in the solar collector. Athough their operation has been successfully demonstrated with the SPC solar pump no tests on these solar collectors - which are normally of flat plate type- have been independently assessed and the Consultants recommend that these collectors be tested as part of future phases of the Project.

7.5.3 General Comment

From our limited observation we consider that thermal systems have been demonstrated to be a practical solution to solar water pumping but that considerable further development is required in order to rationalise the designs and to improve their reliability and efficiency and to make the designs more appropriate for use and manufacture in developing countries. Also, very little effort has been applied to the development of small-scale systems with concentrating collectors in recent years and no such systems are available for test. Our analysis indicates that this will be a more cost-effective approach. It would be premature at this stage to abandon development work on these systems in exclusive favour of photovoltaic systems.

8. CONCLUSIONS FROM SYSTEM DESIGN STUDIES

8.1 Background to PV System Studies

A main objective of the system design study was to investigate the ways in which small-scale solar pumping systems might be improved.

The main tool of the design study was a computer-based mathematical model for simulating the performance of PV systems. This model was constructed primarily on the basis of physical measurements made on system components during the laboratory testing programme and it was subsequently validated by simulating the performance of some of the systems tested in the field trials, so that its results could be accepted with a measure of confidence. (Separate simpler modelling exercises were also carried out on thermal systems and on the sensitivity of system economics to key variables).

One of the main uses of the PV model was to allow the rapid testing of the sensitivity of small-scale solar pumping systems to changes in key external and internal parameters. The cost-effectiveness of various system options were assessed in terms of a measure called Specific Capital Cost, the ratio of the normalised capital investment cost of a system to its daily hydraulic energy production.

The normalised costs of PV arrays and modules were estimated on the basis of price per peak watt in the usual way, while subsystem components were assessed on the basis of cost per unit weight. Considerable investigation and analysis of component costs were completed by Mr W Armstrong, our specialist Industrial Adviser.

All other things being equal, (such as maintenance and operational lifetimes), the Specific Capital Cost indicates the investment required to achieve a given daily energy output. This gives a useful initial means to rank tne likely cost-effectiveness of different design options. A considerable element of informed professional judgement is then required in order to ensure that the simplified basis for a model (compared with the complexity of real situations) has not lead to erroneous conclusions.

For the purpose of the model, two standard solar days were derived, one for clear sunlight conditions derived from Sudanese data and the other for hazy conditions with passing clouds, derived from Philippines data. In any trial assessment the performance of systems should be examined over a full calendar year. Modern statistical techniques enable daily solar irradiation and water demand to be expressed in the form of a time series, and so exhibit the characteristic fluctuations expected in such natural phenomena over a calendar year. It is recommended that such an analysis be carried out in the next phase of this work.

The computer modelling work could only be started in earnest on completion of the field trials and the laboratory testing programme which were needed to yield the necessary data to run the model. Hence, due to the tight schedule of the first Phase of this Project, all the possible areas of investigation were not pursued.

Some further avenues of investigation are described in Section 8.6.

8.2 Sensitivity to Variations of Head

A pump can be designed for a higher maximum efficiency when the duty head range is very limited. However, if the head should vary from this particular condition the efficiency will fall off sharply. On the other hand, a pump designed for a range of heads may not have the same maximum efficiency but may yet return a better all round performance (in terms of the volume of water pumped) under the varying heads which occur with time and season.

This effect is more critical at low heads, because it is the percentage change of head that is important, ie 1m change from 5m is equivalent to a 2m change at 10 metres.

8.3 PV System Sensitivity Analysis

During the studies, the response of the performance and cost of the reference system to ordered changes in static head, solar day variation, array optimisation, impedance matching, sun tracking and pipework variation were investigated. In every case the model showed the benefits of this approach (as summarised in chapter 4) and the need to take a 'system orientated' view of design.

Significant performance and cost-reducing improvements appear to be readily obtainable with PV systems at the existing level of technology. In particular overall efficiency can be improved by:

- the use of pumps whose efficiency change with head over the likely working head range is as small as possible.

- optimisation of the proportion of PV cells that were connected in parallel and series within the module. (One system supplied was almost perfectly optimised, but with another an improvement of 13% in overall system efficiency could be achieved).

- varying the array power to find the optimum value: in one case there was a significant drop in Specific Capital Cost when the array power was increased.

- the use of a maximum power point tracker (MPPT). This may have little or no benefit on well-matched systems but would be expected to improve less well-matched systems under varying climatic and head conditions. Pumped daily water output was increased typically by 15% on a clear day and by 25% on a hazy day through the use of a MPPT.

- using movable or tracking PV arrays. The increase in output obtained by a perfectly tracked array (over a fixed array) was compared with the increases obtained by arrays reoriented to preset positions once, twice or three times in a day. It was found that reorientation twice daily allows the use of 95% of the energy received by a continuously tracked array. It is doubtful therefore whether the extra cost and complication of a continuously tracking system can be justified for applications such as irrigation.

- care in specifying pipework for systems. The pipework necessary to connect the pump with the source and to deliver water to the point of application is a simple, but vitally important, part of the solar pumping system. The Specific Capital Cost was minimized for the particular conditions of the tests: it is unlikely that a pipe diameter of less than 50mm should ever be used. The use of inadequate pipe diameters can dramatically reduce the system efficiency and increase the Specific Capital Cost.

The combined result of a number of these improvements for one system is shown in Table 40.

8.4 Performance Achievable by PV Systems

On the basis of the laboratory results, supported by field data under good conditions, estimates of target efficiencies for optimum instantaneous system efficiency are as follows:

array cells	11%	at 25°C (10% at NOCT)
connections	95%	
motor	85%	
pump	55%	
pipework	95%	
total for system	4.6%	(based upon array cell area)

This is equivalent to the very best simple systems so far tested. Any ancillaries, such as maximum power point trackers or other power consuming accessories should provide benefits which match their cost and power consumption.

The model studies indicated that the Pompes Guinard surface suction system should achieve the best overall efficiency with lowest capital cost (i.e. maximum Specific Capital Cost) The model showed that the components were well matched and that the best efficiency should occur at a static head of 7.5m. In order to show what efficiency and cost might be achieved through the use of a tracking system with the Pompes Guinard system when operating at its best head, an additional group of runs was carried out. It was found that an effective overall system efficiency (based upon array cell area) of 5.1% ought to be achievable at a Specific Capital Cost, (at present prices) of $1.98/kJ. It was unfortunate that the pump was field tested at the limit of its suction performance and that these encouraging results cannot be corroborated by field data.

8.5 Towards Performance Specification for Improved Photovoltaic Pumping Systems.

Solar pumps should be specified in terms of their daily hydraulic energy output for given daily solar energy inputs. Because of the sensitivity of efficiency to head it is unreasonable for pump performance to be specified at one head and similar efficiency to be expected at another. A format for specifying solar pumps in terms of performance is given in Section 11 of this report.

If the use of solar pumps is to become widespread a relatively small number of standard products must be developed. The cost of separately specifying equipment for every different site would be probibitive. A market survey would be necessary to determine what the best individual pump sizes are for each major application, but it is considered that a range of photovoltaic array power of the pumps from 300 to 900W peak is appropriate, corresponding to hydraulic pumped power in the range 100 to 300W.

In general, the Consultants consider it is feasible to produce small-scale solar pumping systems having overall system efficiencies approaching 4% based upon array area (or 5% based upon cell area). Some of the systems tested were less than 2% efficient. Specific Capital Costs of around $2.5/kJ per day should be possible (at present day prices with correct technology) compared to a range of $3.1 to $ 9.8 obtained from model tests on the systems purchased. If PV array prices fall to about 50% of their current lowest level (i.e. reach $4/W peak) then the $2.5/kJ will reduce to about $1.00/kJ yielding water at about one third the cost of the most cost-efficient systems currently available.

8.6 Conclusions from the Model Studies of Thermal Systems

Data on thermal systems were restricted in scope and quality compared to the PV data but nevertheless certain clear conclusions emerged from the studies which analysed over 30 different options of solar collector and heat engine combinations.

The most cost effective approach appears to be to use concentrating solar collectors. The use of a 2 axis tracking point focus solar collector combined with a Stirling engine would appear potentially attractive. The use of a central receiver (power tower) as the solar collector also appears attractive. However this combination of solar collector and engine is not yet well developed.

A one axis tracking parabolic-trough line-focus solar collector combined with a Freon vapour Rankine cycle engine does however use components which are better developed and this appears to be a cost effective approach.

The analysis of stationary flat plate solar collectors with Freon Rankine cycle engines typical of the type of systems being developed by most current manufacturers indicates that the use of flat plate collectors is one of the least cost effective approaches. The indications are that linear-focussing equatorically-tracking collectors would be 30-40% less expensive and require considerably less land area.

Flat plate solar collectors of the evacuated tube type which exhibit low heat loss have the potential for reducing the array area to 40% of that required with double glazed flat plate solar collectors of the conventional design.

Freon vapour Rankine cycle engine appear to offer a more cost effective approach than steam. Stirling cycle engines do however have the potential for being the least expensive of the heat engines considered. However as demonstrated by the poor laboratory performance of the Stirling cycle engine further development of this type of engine is required.

Specific Capital Cost analysis on small thermal systems gave $2.8/kJ per day for a typical flat plate solar collector system similar to the type tested, and indicated that $1.5/kJ per day may be achievable for a Freon vapour Rankine cycle engine with a one axis tracking parabolic-trough (line-focus) collector. These costs appear to be competitive with photovoltaic systems and potential for further cost reduction is indicated by the use of 2 axis tracking point focus collectors and high temperature air Stirling cycle engines (if these became sufficiently well developed).

System size appears to have a significant effect on the Specific Capital Cost of systems, especially systems utilizing flat plate solar collectors. Typically the Specific Capital Cost of the 10 kWh system may be 40% of that of a 2kWh system. This difference arises from the better engine efficiencies and the reduced effect of fixed cost items. However the smaller units with lower initial capital cost are likely to be more appropriate to the small farmer.

8.7 Value of the Mathematical Modelling Approach

A most worthwhile start has been made in the task of constructing and using a mathematical model to assess solar pumping systems. Although there is a lot more work that can be done, the results obtained to date have once again illustrated the advantages of this type of approach. These include:

a) The benefit of being able to predict performance on solar days with a variety of irradiance profiles.

b) The value of being able to predict output of a solar pumping system over a calendar year or irrigation season.

c) The importance of studying a complete pumping system, particularly the pipework, when considering cost-effectiveness.

d) The ability to optimise systems by varying design parameters, individually or in combination.

e) The ability to rank different systems objectively in terms of technical performance and cost-effectiveness.

f) The simulation of performance of different systems under a variety of conditions.

g) The assessment of performance and cost-effectiveness of systems offered by manufacturers in response to call for tenders to meet particular specifications.

h) The assessment of the cost effectiveness of proposed improvements to individual components.

After a number of improvements have been made to the PV model, the Consultants recommend it should be the basis for the study of such aspects as:

a) Use of maximum power point trackers with more realistic power drain data.

b) Use of ac submersible motors with inverters, for deep borehole pumps.

c) Use of dc motors with separate excitation of field windings.

d) Simulation of positive displacement or multistage centrifugal pumps for higher head application (as required for water supply application).

e) the use of batteries for short and long term electrical storage and matching.

f) further investigation of component costs and sensitivity analyses from varying individual component costs, including new types of component and materials.

g) Use of stochastic techniques to generate time series data on total and diffuse solar irradiance values, for selected tropical areas.

h) Use of stochastic techniques to generate time series data on water demands for agricultural purposes taking account of crop water requirements in relation to rainfall, evapotranspiration and distribution methods, and for domestic requirements in relation to present and future growth and distribution patterns. These would be normalised by region as far as possible.

i) Study of performance and cost effectiveness of different systems operating over a year or irrigation season under the conditions of solar irradiance and water requirement specified in (g) and (h), including the effects of storage on the economics of the system as a whole. The true advantages or disadvantages of tracking and maximum power point trackers would be shown in such studies.

The mathematical model of the thermal system also needs to be enhanced so that these studies can be advanced and definitive conlusions reached about the future of thermal pumping systems.

9. CONCLUSIONS ON MANAGEMENT OF PROJECT

9.1 General

Although the conclusions from the Project are obviously technical in nature, the achievement of technical objectives depends critically on the adoption of appropriate management and administrative procedures. The sections below discuss the more important non-technical factors which influenced the progress of the work, and which need to be taken into account whan planning future field trials.

9.2 Field Trials

9.2.1 Timing of Trials

The timing of the trials was constrained by the overall programme for the Project and by the time systems were installed and ready to operate in some countries, the wet season had started, and conditions were not ideal for the collection of field data. This point must be watched in the future.

9.2.2 Climatic Problems

The conduct of tests in field locations, particularly for continuous monitoring, proved arduous for all staff involved who were required to travel to field sites and then work long hours in exposed situations continously through the day.

For work in the future, the participating institutions need to make proper allowance for these factors and ensure that transport (for example) is available. Strain on staff will then be minimised and errors reduced.

9.2.3 Content of Field Work

The programme of field work originally envisaged making cumulative measurements on each system every day, and continouus performance measurements on each system on one day per week . In addition a log was to be kept of operational problems and breakdowns.

The basic division of the field measurements into cumulative and continuous was sound but the daily and weekly timescales placed too great a strain on the resources available.

It might be argued that in future the continuous measurements should be made at a central laboratory in the host country concerned, but this would remove some of the 'immediacy' of this part of the field trials.

Although the point at which a system should proceed for field trial may be arguable, the Consultants believe that at some stage in development the systems have to be assessed for performance under field conditions. One way to resolve this question would be to start performance assessment at a central location to prove the systems operating characteristics and the monitoring instruments, and then move it to a field location.

On the whole a fair balance seems to have been struck on the parameters which had to be measured to obtain a realistic view of system performance.

During these Phase I field trials the systems were rarely left in the sole charge of the farmers and so it was not possible to obtain their independent views on the potential of the pumps, or the ways in which they would wish to use them.

9.2.4 Observation and reduction of data

The observation and reduction of data has to be conducted by staff with graduate level training. This is because some of the procedures are complex, the instruments need careful handling and the overall performance of the system needs to be checked as the tests progress. The reduction and analysis of the data should be completed soon after the observations, so that checks can be made on uncertain points.

9.2.5 Monitoring instruments

- Supply

  The decision to ship complete sets of instruments to each country proved to be correct. Resident Engineers and local personnel were left with the task of constructing mountings and housings for the instruments.

- Selection

  Generally the instruments selected for the monitoring were adequate for the task, the only real problem being with the multi-tester. This was too sensitive for field work and was replaced with a digital multimeter and a separate digital thermometer, both of which worked well.

- Instrument Failures

  The instruments were air-freighted and, despite being professionally packed, may have been affected by rough-handling. They were then put into service in arduous climatic conditions. Most of the failures were in electronic components, and on occasions data was lost or of doubtful value because of these failures. The chart recorders worked well. The need for robust, well-tried instruments, particulary where they may be unattended by expert staff for days or weeks at a time, was amply demonstrated.

- Instrument Calibration.

  The accuracy of the results obtained from the field trials was critically dependant upon the degree of accuracy of the instrumentation which was assessed from the few calibration checks completed.

Senior staff in the participating institutions should be fully aware of the need to impress on their junior colleagues the importance of frequent instrument calibration.

9.2.6 Testing schedule

Despite various problems with instruments and systems, when everything was functioning as intended it proved possible to carry out the scheme of testing which had been envisaged before the trials commenced. When there were troubles with the instruments there was generally a sufficient degree of redundancy in the instrumentation or adequate spare instruments to ensure that at least the key items of data could be collected.

9.2.7 Management of local support

Because junior staff at the national institutions were naturally not very experienced in undertaking field work of the type necessary for determining the performance of solar pumps, adequate time should be allowed for explaining the procedures, learning to use the instruments and generally to become familiar with the systems. Adequate transport was often lacking although probably more time was spent in arranging for it than on any other administrative support matter. The key is finance and no Government seemed able to provide the funds required.

9.2.8 Administration

It will greatly assist future field work for letters to be exchanged between the Consultant and the participating institution which will include inter alia, the Project objectives, and the respective obligations of both parties to the UNDP, the World Bank and each other.

Co-operation between the staff in the host countries and the Consultant is one of the potentially most fruitful aspects of a project of this kind and consideration of, and attention to the points set out above will help to ensure that this potential is fully realised in the future.

The main points worthy of note are as follows:

a) Preparatory visits to the host countries should be well planned and last long enough to explain the Project to all the national staff who will have a key involvement with it, and to reach agreement on all procedural and technical points of substance.

b) Matters on which it is particularly important to reach agreement are arrangements for the clearance of equipment through customs, responsibility for the insurance of equipment, the provision of transport for expatriate and national personnel, the acceptance of responsibilities for the national inputs by one man at senior level and clear delegation of responsibilities for action in the field. Where two national agencies are involved (for example, one in the energy and one in the agricultural field) there must be clear understanding of their respective roles.

c) Back-up from the local UNDP and World Bank offices for the Project can be very helpful indeed, and provide another channel of communication for the Consultant.

d) The presence of a Resident Engineer representing the Consultant is very important. Since the national participating institution is responsble for all work in its own country, the Resident Engineer's task can be delicate. However, the advice, encouragement, assistance and training given by the Resident Engineer under the direction of the senior staff of the institution is a vital factor in determining and maintaining progress in the field and in recording and returning field data.

e) Senior members of the Consultants project management team need to make visits to the host countries and the sites in the field at not more than 6 monthly intervals to review progress with senior institution staff.

f) The inherent difficulty of a situation in which progress on the project depends on timely action by the national participating institutions for which the Consultant has no direct responsibility has to be recognised. In a formal sense the host countries links are with the UNDP while the Consultants are with the World Bank.

g) Before being accepted for test the complete system with suitable suction and delivery pipework should be tested at the manufacturer's works and the manufacturer should be required to draw up a schedule of tests.

9.3 Administration of Laboratory Tests

The procedure whereby the Consultant places sub-contracts with specialist laboratories or manufacturers for defined tasks of an experimental nature is in principle a most satisfactory arrangement, for through it the necessary range of specialist experimental capabilities can be brought into the project under the management of the Consultant with overall responsibility to the Client.

For this type of arrangment to work successfully a number of points need to be observed.

a) Laboratories should be chosen which have the specialist staff required, experience of contract research and development and possess the necessary experimental facilities,

b) Regard should be paid to the laboratory's existing workload and due allowance made for likely delays in agreeing a work programme.

c) Although there is usually no problem in reaching agreement on the nature of the task, it is wise to obtain written confirmation of the work content and programme to be followed,

d) Financial arrangements need to be spelt out in detail and the consequences of them made clear, especially in relation to any programme overrun,

e) The importance of maintaining an agreed timetable needs to be explained at the beginning, together with the need to keep the Consultant informed about unexpected or unavoidable delays.

f) Frequent personal contact between the Consultant and the laboratory is vital. It is usual to make one person responsible for this liaison from each side and it is obviously helpful if the member of the Consultant's staff has some specialised knowledge of the work to be undertaken by the laboratory. These contacts are of course greatly assisted if the Consultant's office and the laboratory are within easy reach.

9.4 Management of Mathematical Model Construction

Mathematical modelling has increased greatly in popularity in recent years. If the full potential of the model is to be realised without the danger of making over-ambitious claims (and the disillusion which follows when these fail to be realised) it is necessary to have a clear view of the place and purpose of such mathematical models in engineering planning and design, and the objectives of any particular study.

In view of the potential importance to future solar pumping technology of the prototype mathematical model which has been constructed in this Project, and the likelihood it will be progressively developed and become more widely used by others, the cardinal points which have to be borne in mind in this type of work are outlined below.

The process to be modelled must be thoroughly understood and situations in which alternative choices may be made and the factors whose values affect those decisions must be identified. This is often easier said than done: it requires clarity of thought and initially at least may be hindered by preconceived ideas. A particular problem is that the number of design and state variables is usually large, in which case the significant ones have to be identified.

The presentation of models to potential users often leaves much to be desired. Since all the operations in the model have to be presented in mathematical terms there is a temptation to leave the presentation at that level rather than to explain the basic concepts in a simple and visual manner. A Program Users Guide must be written at an early stage. One way of overcoming these problems is to involve the potential user of the model closely in its development and construction. This approach makes large demands on project management staff.

PART 3 – RECOMMENDATIONS

10. THE SIGNIFICANCE OF THE CONCLUSIONS FOR DESIGN

10.1 Photovoltaic Systems

Since most of the systems tested were photovoltaic (PV) type systems and since the Consultants were able, as a result, to model such systems in a more sophisticated manner than thermal systems, a larger quantity of information on these systems resulted. The following notes integrate the findings from the field, laboratory and design study work which have design significance for small-scale PV pumping systems.

a) PV arrays

The performance of these supposedly well-documented and reliable components proved less predictable than expected. Virtually all the array modules independently tested were below their nominal ratings and some were even so far below as to be outside the manufacturer's claimed permissible limits. Due to the high cost of the array, such shortcomings could cause a significant shortfall in both system performance and in system cost-effectiveness. This data came independently from RAE and JPL.

Despite the relatively large sums spent on PV module development, and their general reputation for high reliability, most of the modules tested suffered either from manufacturing or in some cases from design faults. Most of these faults were minor (only one module actually failed under test), but attention to detail still seems to be required. Certainly, interconnect redundancy (which was absent on the one module that failed) is an essential requirement for field applications.

We found the modules vulnerable to breakage, both in transit and in the field, usually through breakage of the cover glass, which in some cases was a simple sheet of thin toughened glass. Generally the consequence of this is the complete loss of a module, many of which are worth at present-day costs several hundred dollars. Two simple solutions appear to be:

- o the general use of laminated glass (or a glass/plastic lamination), so that even if the cover is cracked it will retain its protective capability.
- o the use of smaller module sizes, so that shipping is easier, and damage in transit will be less likely. Spares would be less expensive to stock, and loss of a module would be less serious financially. A further benefit from adoption to this practice would be more accurate array to subsystem matching as a greater choice of array nominal voltage/current combinations would be available to the system designer. It might still be possible for the system to continue to work with the small module missing. The main negative effect would be a more complicated and extensive wiring harness and a lower packing factor.

Our design study analysis indicates clearly that a manually tracked array results in substantial gains in output; typically a 30% increase in water output per day from a given system or a reduction in Specific Capital Cost in excess of 20%.

The sizing of a small-scale irrigation pump is critically dependant on the peak irrigation water demand and the solar energy availability in that month (most months the system will be grossly oversized for the actual water needs). Manual tracking of the array may be very important to minimise this mismatch, since careful tracking during times of peak water demand will go some way to reducing the required system size while at other times of the year less careful or no tracking may be adequate.

Therefore it is open to question whether the extra costs and complication of mechanical automatic tracking systems will be justified, when the benefits will only be really necessary in the irrigation application for a short period of the year. Further investigation of automatic tracking system costs and the actual capabilities of farmers at manual tracking will be essential to clarify this issue.

Problems with the arrays used during the field trials included a lack of consensus by manufacturers as to the correct inclination for optimum performance from the system. (No doubt the effective shedding of dirt and rainwater is an essential point for consideration when deciding on inclination). There are problems in the tropics at equatorial latitudes due to the shallow almost horizontal positioning that is optimum for solar energy collection, but bad for rainwater run off and selfcleaning. Here an adjustable array has obvious benefits, especially if it could be calibrated with recommended positions for different seasons for the region in question.

In addition, some arrays required complicated foundations and accurately positioned holding down bolts. Some arrays seemed to be too close to the ground making them prone to collect dust and also more likely to be damaged by people or animals.

Wiring also presented numerous problems, with badly (or even in some cases wrongly) prepared wiring harnesses, poor instructions and often difficult or poor terminal blocks and connectors. No detailed analysis has as yet been completed on wire losses, but we believe these may be significant in many cases; blocking diodes were another serious energy drain in some cases (and in two examples the systems were supplied with some or all diodes connected back to front). It follows from this that system arrays should ideally:

- o be adjustable in inclination and azimuth (or be fully portable).
- o have simple foundation requirements allowing for imprecise positioning within fixed installations, the array held well clear of the ground. Better still, would be fully portable and selfcontained arrays not requiring any foundations.
- o have very clear and simple instructions
- o have generous wiring and effective mechanical terminal grips to ensure good electrical contact. If possible diodes should be avoided or be sized for low losses.

The design studies indicated that system performance could in many cases be improved by changing the series parallel arrangements of the array cell strings (this is easier in practice with small modules), or by changing the array power rating. In some cases the system was actually improved through the use of a smaller (and cheaper) array. Only one manufacturer appeared to have achieved ideal optimisation of their array and subsystem combination according to the model analysis.

Fully automatic array optimisation, through the use of a maximum power point tracker (MPPT) was also investigated; while this produces significant benefits, the costs are not known fully yet and need further investigation. (Costs includes both financial costs and the energy drain required to run such a device). However, there seems to be a good case for provision of a cruder form of manual MPPT through the provision of a switch to change the series/parallel arrangement under low and high irradiance conditions. This would cost little in financial terms and nothing in energy terms and may be a more appropriate approach for the same reasons outlined above when discussing the respective merits of manual and automatic sun-tracking.

Very low voltage subsystems are undesirable, as they require a low-voltage high-current array with consequent greater resistive line losses, (or the need for heavier and much more expensive cabling to compensate). However, dc voltages greater than about 80V present a serious electrocution hazard and, are to be avoided for safety reasons. (One system tested used 120V dc, but it is understood the manufacturer is changing this to a lower voltage). Hence it appears that systems optimised at about 80V would achieve the best cost-effectiveness without introducing any serious hazard.

b) Motors:

The consensus from the manufacturers for this Project was in favour of dc permanent magnet motors for the entire range of systems tested. In our view this was correct, since this type of motor, although slightly more expensive than field wound motors, offers such a good efficiency, particularly under part load conditions, that it is virtually the only sensible option for this size of system.

The laboratory testing programme indicated that the better dc permanent magnet motors, in the 250 to 500W range of interest for this application, are capable of optimum efficiencies of around 85% and even at half load their efficiencies should exceed 75%. Some of the poorer electric motors were only 75 to 80% efficient (which by comparison with array and pump efficiencies looks rather good); however it is worth noting that an 85% efficient motor requires 9% less array area than one of say 78% efficiency - with a typical 400W array this translates into a capital cost saving at the array of typically one 36W module, worth over $360 at present day prices.

Most of the motors tested were of the conventional segmented commutator with brushes kind. Such machines generally require new brushes at intervals of the order of 2000-4000 hours, and if this is not done some models can suffer irreparable damage. Certain dc motors are being offered with claimed brush lives of about 10,000 hours, and these would be better for this kind of application if the claims are achieved under field conditions. Clearly fail-safe brush design is essential so that the machine will stop once the brushes are too worn, rather than damage itself. No investigation of actual brush life was possible under the brief testing period available.

An alternative type of permanent magnet motor, one of which was tested, is brushless with the magnets in the rotor and an electronically commutated stator. In principle, such machines seem more attractive than brushed machines for small-scale solar pumping, since their only wearing parts are the bearings and any seals. However, the electronics gave reliability problems and it is somewhat less efficient than the better brushed electric motors.

Therefore it is recommended that, although electronically commutated motors are to be prefered in the longer term, the electronics should be fully protected from damage by overheating or by high current or voltage transients (through the use of appropriate protection circuitry). They will also require attention for achieving effective protection from external damage (e.g. from humidity) while retaining effective cooling and protection from the stator winding heat emission through good heat sink design.

Electronically commutated motors with a small number of coils have inherently higher internal losses compared with traditional motors with a large number of commutation segments. In principle an electronically commutated motor with a large number of coils can be built (at a cost) which should have an efficiency comparable with that obtained with traditional designs.

The Hitachi permanent magnet linear actuator which was also tested showed that considerable thought and care is required if such a device is to be effectively matched with a pump. Lack of a suitable pump rendered this part of the programme rather inconclusive as the potential efficiency appeared no better than for rotary pump systems and there are difficulties in producing a low frequency supply. It is doubtful whether this option is worth pursuing actively although contact should be maintained with manufacturers.

It may be worth reassessing the applicability of field wound dc motors to see of they offer any advantage for power conditioning which would offset their somewhat lower efficiencies.

c) Pumps:

In the Consultants view, an essential requirement for any solar pumping system is the use of a pump that will reliably self-prime, even if the foot valve (where fitted) is imperfect. A number of the low head systems supplied for this project were quite inadequate in this respect.

Furthermore, for the low heads that are appropriate for small-scale irrigation (preferably under 5m and certainly less than 10m), positive displacement pumps seem inappropriate on efficiency and size considerations. From the findings so far, a simple single-stage centrifugal pump appears to have the merit of adequate performance potential combined with compactness and simplicity as well as having low starting torque requirements. Centrifugal pumps also offer the possibility of achieving a close natural match with a PV array (without recourse to a MPPT power conditioner) over a broad range of operating conditions.

Pump efficiency is critical to the cost effectiveness of the system and high efficiencies require good design with such small pumps. The indications from the laboratory tests are that an optimum efficiency for small pumps (200 to 500W shaft power requirement) for use at low heads (in the 5 to 10m) range of around 55% is practically realisable and that consistent efficiency of over 45% at reduced speeds or non-optimum heads should also be achieved.

What is not known as yet with any certainty is the trade-off between an efficient high speed impeller with small clearances and the need for an impeller with the longest possible operating life and a good tolerance of solids in the water. Longer term investigation of pump durability will be necessary to arrive at confident conclusions on the likely performance limits that might reasonably be expected.

Off-the-shelf industrial centrifugal pumps, as commonly used for small-scale solar pumping systems at present, are generally designed for single speed operation from mains electric motors. Therefore many are intolerant of any significant speed reduction below the speed for optimum efficiency. Purpose designed pumps for small-scale solar pumping will no doubt allow significant improvements to be obtained which will be measurable in terms of array size reduction through improved efficiency.

The Consultant's design study confirmed that the careless specification of the pipework associated with the pump can very seriously effect system efficiency, particularly with low static heads. This is very important in situations where a medium or long length of pipe is involved. Using the Arco Solar system as an example, when pumping through 29m of pipe, the most cost effective pipe diameter is 75mm. The use of 50mm pipe would cause a 6% increase in Specific Capital Cost and a 4% and 8% reduction in daily output and average overall system efficiency respectively. 37mm (1.5 inch) pipe would have an even more dramatic effect, by increasing Specific Capital Cost by 18% and by reducing daily output and average efficiency by 15% and by 17% respectively. Even smaller pipes, (which some users may be tempted to purchase thinking it would "save" money), would very seriously upset all expectations on cost and output from the system.

In conclusion, there is little doubt that the pump and pipework require a lot of attention to detail if the best system efficiency and cost effectiveness is to be achieved, especially in such low head applications as are appropriate for small-scale irrigation.

10.2 Thermal Systems

The results of observed tests on the thermal systems of Solar Pump Corporation and Dornier have provided effective demonstration of working solar water pumps incorporating flat plate solar collectors and organic vapour Rankine cycle engine combinations. Both these systems in the Consultant's opinion require further rationalization in order to produce a reliable system that is of appropriate construction for developing countries. A decision to produce in large quantities would be required before these systems could compete economically with photovoltaic systems.

The tests observed on the Ormat Energy Converter incorporating the Freon Turbine/Generator were encouraging in terms of efficiency. It should be noted however that the output of the system observed is outside the specification of this Project (i.e. > 2 kW).

The tests on the Stirling cycle engine at Reading University were significant in not only showing the potential but also the immaturity of the designs and the need for further development. The Fluidyne liquid-piston engine-pump on which tests were observed and which also operates on the Stirling cycle also highlighted the rapid progress being made with this type of system.

The problems yet to be overcome to commission the SPC thermal system in the Sudan have demonstrated the importance of field trials in revealing problems that were not apparent when laboratory tests are performed. In this case the different ambient conditions between the laboratory tests and field trials were contributory factors.

The conclusions of the thermal design studies presented in section 8.6 are significant with respect to the present designs of solar-thermal systems and to future designs and their potential.

Systems typical of the type being currently developed by most manufacturers have less potential for low cost production than systems using concentrating solar collectors. Even so, the potential quantity production costs of these systems are comparable with the present cost of photovoltaic systems of the same size and offer greater promise for part manufacture or assembly in a developing country. However if further reductions in the cost of photovaltaics are achieved then these thermal systems will be uncompetitive in terms of cost. For lifting water through high heads (> 15 metres) thermal systems with their low speed operation are well suited for direct coupling to piston pumps.

The potential quantity production costs of systems using point focus solar concentrators involved with Stirling cycle engines or linear focussing solar concentrators combined with organic vapour Rankine cycle engines appear to be comparable with photovoltaic systems even allowing for some fall in photovoltaic prices in the near future. The use of this combination in large scale systems has been demonstrated for example in the US Department of Energy Solar Irrigation Scheme at Coolidge, USA.

Continued development of solar-thermal water pumping systems is therefore justified.

11 DESIGN RECOMMENDATIONS

11.1 Applications

Small-scale solar pumps for irrigation purposes are more likely to be successful if they are:

- o applied in areas where irrigation has been traditionally practised, so that it is only the use of the novel pump technology and not irrigation per se that has to be taught
- o sized for small land holdings of the order of 0.5 ha., for which they are most competitive with the alternatives
- o first promoted in areas which need to be irrigated over most of the year and where multiple cropping might be practised in order to achieve a good year-round load factor for the solar pump
- o preferably restricted, at least initially, to pumping static heads of no more than around 5m (and 10m at the very highest), implying a system output of the order of 100 to 300W peak of hydraulic power for a land area of 0.5 ha.
- o used generally in areas where the provision of fuel for engines is proving increasingly difficult and costly and where mains electric power is absent.

It should be noted that the first costs of the more cost-effective of the present generation of pumps are still at least double that of systems which would represent an economic investment when used for irrigation. The aspect is discussed fully in the Technical and Economic review.

Small-scale solar pumps should also be considered for application to non-irrigation purposes such as village or livestock water supplies, which offer a better load factor (demand being more or less constant all the year around). Another point of fundamental importance is that the price which water can command for domestic purposes is considerably higher than for irrigation. It was beyond the scope of the project so far to investigate these other end-uses but it is expected that solar pumps would be viable at a much higher head (perhaps up to 20m) for this kind of application.

11.2 Photovoltaic System Specification

11.2.1 General

As a result of the studies completed under this project, it is possible to produce an outline specification for a small-scale PV pumping system for irrigation at low heads, that ought to be competitive with small engine powered pumps in many parts of the world.

It must be stressed that this is not the ultimate type of design that is to be recommended, but the logical next step incorporating the principal lessons learnt so far in using present day equipment. It is to be expected, of course, that innovative developments in the technology will introduce new options in the near future that are not considered here, but which have been discusssed in the Project Record and in the Technical and Economic Review accompanying this Report.

11.2.2 Performance Specification Format

The performance of a system should be specified in terms of the hydraulic energy output for a given solar energy input. Because of the sensitivity of system efficiency to head it is unreasonable for pump performance to be specified at one head and similar efficiency to be expected at another head from the same unit. It is therefore proposed that performance should be specified in the following terms:–

a) the pump shall provide a daily output of 'a' m^3, ± x % through a head of 'b' m for a solar irradiation of 'c' kWh/m^2/day and an average daytime ambient air temperature of t ^{o}C.

b) the daily efficiency of the system shall not vary by more than 'd % as static head varies in the range ± 'e' m.

c) daily output should be a simple (known) function of solar input in the range 'f' kWh/m^2/day to 'g' kWh/m^2/day.

The form of these relationships is illustrated in Figure 53.

The value of all the factors 'a' to 'g' will depend on the water needs and the hydraulic and climatic factors at the site. The solar irradiation 'c' will be the standard measurement on the horizontal plane, thus alternative array configurations can be compared. The system performance limits should be guaranteed by the supplier.

The widespread introduction of solar powered pumps is more likely to result from efficient manufacturing of a number of standard designs. It is considered that the most appropriate range of sizes is from 300 to 900 watts peak array power corresponding to a hydraulic pumped power in the range 100 to 300 watts.

As an example a system with a 500 peak watt array and a 5% overall system efficiency should give the following outputs for a daily total solar irradiation of 6 kWh/m^2 (21.6 MJ/m^2):

	180m^3 at 2.5m static head
or	90m^3 at 5.0m static head
or	60m^3 at 7.5m static head
or	45m^3 at 10.0m static head

Of course any one unit will be optimised to give only one of these outputs and will operate at lower efficiency at other heads.

The Specific Capital Cost of the system as defined in section 4.2.3 should be in the order of \$2.5/kJ per day.

11.2.3 System Efficiency Requirement

Maximum system efficiency targets should be set as follows for the next generation of pumping systems:

array cells	11%	at 25°C (10% at NOCT)
connections	95%	
motor	85%	
pump	55%	
pipework	95%	
total for system	4.6%	(based on array cell area)

This is equivalent to the very best systems so far tested. Any power conditioner or other such accessories that consume power, should provide benefits to more than compensate for their cost and power consumption.

11.2.4 Design Point to be observed

In preparing designs to meet performance specifications of the type outlined in 11.2.2 and the target efficiences set out in 11.2.3, it is recommended that manufacturers pay due regard to the following practical design points. These are not listed with the intention of inhibiting future development in any way, but as a convenient resume of the main lessons learnt during Phase I of the Project.

a) General Requirements

- o the system should either be fully portable and mounted on skids or wheels or it should be fixed. In the latter case the array should be mounted at least 1.5m above ground level and bolted to not more than two concrete foundation blocks; the holding down bolts to be positioned to an accuracy no better than 25mm, to allow for errors in the positioning of the foundations.
- o systems should be designed to survive particular local climatic conditions. In areas prone to typhoons or hurricanes it may be necessary to provide for the rapid dismantling and removal to safety of the array.
- o pumps and motors should be provided with sun-shades whenever possible, but be well ventilated if air-cooled.
- o materials exposed to solar radiation (such as plastics) should have proven durability.
- o modules should be individually packed to avoid damage in transit. No single package for the system should exceed 1m x 2m or a weight of 50kg. Safety of contents should not be dependent on being stored any particular way up or on receiving special handling treatment.

- o detailed instructions should be provided, in the local language, for the correct assembly of the system. Also included should be a components list, maintenance and operating instructions and guidance on how to achieve the best output (eg, not using small bore pipes or restricting fittings, not allowing shadows to fall on the array). All documentation should be written in simple terms.

- o the need for routine maintenance lubrication and re-adjustments (eg, belt-drives and waterseal packing) should be minimised and avoided if possible.

(b) Array and Module Requirements

- o lifetime guarantee of say 5 years against faulty quality with no more than 10% degradation of performance to be accepted.

- o small modules (not more than about 20W nominal rating preferred).

- o laminated glass or an impervious and ultra-violet resistant plastic cover.

- o optimum module cell efficiency exceeding 11%.

- o redundant interconnects between cells.

- o no air gap between cell encapsulant and cover glass.

- o generously sized (brass) terminals with grip screws, (plated steel terminals not acceptable) or appropriate plug and socket connectors.

- o weather-sealed terminal boxes behind array.

- o array frame should be capable of being manually tracked on an equatorial axis at intervals through the day.

- o array inclination should be adjustable and preferably engraved with correct angles for different season for the region.

- o cables should be generous in cross-section, to limit resistive losses at full power to no more than 5%; blocking diodes (if required) should result in no more than 2% loss at full power.

- o array nominal voltage under peak sunlight conditions should be around 80V; higher voltages will not be safe, while lower voltages will mean higher currents and larger resistive losses.

- o electronic power conditioners (or other electronic circuitry) should be fully 'tropicalised' and should use components to tropical ambient temperature specifications. Full protection by automatic cut-out against excessive temperature, voltage or current, (prefer automatic reset).

- o quality assurance and testing to be to a satisfactory standard and specified by the manufacturer.

- o module or array performance to be specified on the basis of tests to a stated international standard. The module/array area to which array efficiency is referred is to be clearly defined.

c) Subsystem (motor-pump unit plus fittings) Requirements

- o dc permanent magnet motor preferred unless alternative shown to be of comparable efficiency.

- o fail-safe brush gear (motor stops when brushes too worn), or electronically commutated motor, (see electronic requirements above). If brushes are used, life of 4000 hours minimum required between changes. Sufficient spare brushes for the expected life of the system should be provided.

- o generously sized brass terminals with grip screws (plated steel terminals not acceptable) or appropriate plug and socket connectors.

- o full load motor efficiency should exceed 85%.

- o half load motor efficiency should exceed 75%.

- o motor bearings and other components should be sized for a life in excess of 10,000 hours.

- o submersible units are preferred to eliminate suction problems.

- o if motor not submersible, coupling between motor and pump should permit significant motor and pump angular and/or parallel misalignment. Motor and pump bearings should be entirely independent, except in the case of integral submersible motor-pump units.

- o thermal cut-out required on motor, unless motor can sustain continuous stalled conditions with the maximum array current.

- o pump optimum efficiency should be in excess of 50%.

- o pump should be capable of self-priming in the event of a leaking footvalve (where fitted).

- impeller material, clearances and passages should be suitable for use with water containing suspended silt and/or corrosive salts. Open impellers are preferred.

- where necessary, a suitable strainer for larger particles should be provided and to be sized so as to have negligible effect on performance while clear.

- pumps should not normally weigh in excess of about 30 kg for low head irrigation application, and should preferably be no heavier than 20 kg (assuming peak flow rates in the range of 2-5 l/s).

- pump should have bearings sized for 10,000 hours of operation and be supplied with spare seals or any other consumables to cover that period of operation; prefer ball bearings with grease seals.

- pump characteristic should permit stable operation at sub-optimum speeds.

- pump should be capable of running dry without serious damage if not submersible; alternatively, fail-safe method of protection from running when dry should be provided, and seals designed to suit.

- pipework and fittings should be correctly optimised for minimum system cost, rather than minimum pipework cost; all pipework should be supplied with system to length specified for head and site.

11.3 Thermal System Development

Following the laboratory tests of thermal systems, the system design studies, and the installation in the field of a complete system, definite recommendations for the development of small-scale solar-thermal water pumping systems can be made.

The continued development of solar-thermal systems should be encouraged in particular to demonstrate small-scale systems utilizing concentrating solar collectors with organic Rankine cycle engines or high temperature air Stirling cycle engines.

Existing working systems have been shown to have the potential for quantity production at costs comparable with the present costs of photovoltaic systems. Further development of these type of systems is justified if significant future reductions in the cost of photovolaics is in doubt in which case development should be encouraged to improve the reliability and performance in order to achieve designs more appropriate to the proposed use.

Further work is required in order to broaden the limited scope of the present thermal design studies and in particular to investigate the designs that have been shown to have promise for low cost manufacture.

Specific Capital Cost analysis on small thermal systems gave $ 1.5/kJ per day for a Freon vapour Rankine cycle engine with a one-axis tracking parabolic trough (line-focus) collector. A high temperature air Stirling cycle engine with a point-focus, tracking parabolic dish collector or central receiver collector also should be further investigated as the Specific Capital Cost was determined as being even lower. Components in this type of system are however less developed than those in line-focus collector Rankine cycle engine systems

Components that may form part of an improved solar-thermal system should be evaluated and tested. For example an inexpensive reliable tracking mechanism for a solar collector needs to be investigated.

Improved systems will need thorough laboratory tests followed by field trials. This will also improve the data base for development of the mathematical model.

The sizing of thermal systems needs further study to improve Specific Capital Costs. This is more size dependant for thermal systems than for photovoltaics.

12 FUTURE WORK

The next phase of the Project, Phase II preparation, provides a period in which to reflect on the results obtained from Phase I, to confirm the objectives of Phase II, and to make the necessary preparations for it.

The Consultants think it important to use this period to review the applications, economics and system sizes of solar pumps. As far as applications are concerned, it will be necessary to review the conditions under which solar pumps will be suitable for irrigation purposes and to evaluate in detail the potentially more attractive water supply application. The economic criteria to be satisfied by the pumps will need to be examined in more detail and the relative economic merits of other lifting devices will need to be assessed, so that solar pumps are only demonstrated where there are good prospects for their technical and economic viability. It will also be necessary to study and define the pumping requirements (head, flow and pattern of consumption) in order to build up a profile of market requirements for each application.

The main areas of technical development should be as follows:–

- Present field trial programmes should be continued wherever feasible.
- The conclusions of this Report should be implemented with a view to producing improved PV systems. This may be done by specifying various improved systems with the desirable technical features so far identified, and ordering examples from suppliers capable of demonstrating a competence to respond to a call for tenders.
- The systems produced in this way should then be laboratory tested, prior to any further field testing, to confirm that they achieve specification and to identify any further shortcomings.
- Following satisfactory laboratory tests, such systems may subsequently be field tested.
- Further design studies, supported by continued field testing of the more successful systems so far installed in the field, should be carried out to investigate further possible areas of improvement and to improve the data base.
- The development of small-scale thermal systems with concentrating and tracking collectors appears to be fruitful and should be encouraged.
- A review should be made of any worthwhile improvements which may be worth considering to individual components of PV systems. Specification for manufacture may then be prepared and tenders invited.
- Desk studies of the detailed requirements for local manufacture or assembly should be initiated to be followed up, if possible, by case studies.

Visits need to be made to potential Phase II host countries to explain the Project and explore the possibilities for their future involvement. The countries to be involved need to satisfy a number of criteria the most important being:

- o The existance of important pumping needs for irrigation and water supply in rural areas that could be met by solar-powered pumping systems and which would require a range of pump output power suitable for solar systems.
- o The presence of a suitable solar energy resource and the absence of any more readily exploitable alternatives.
- o Government interest in solar pumping and a willingness and ability of host country institutions to provide the necessary technical and logistical support for the reliable field monitoring of the systems.

Additional visits will be made to select field trial sites for Phase II and to agree and brief the participating institutions.

The final objective of Phase II is seen as the development of solar pumping systems to the stage there they will be suitable for pilot manufacture or assembly in developing countries.

13 ACKNOWLEDGEMENTS

The Consultants wish to express their appreciation to the staff of the World Bank responsible for this UNDP Project, in particular Dr E M Mitwally, UNDP Project Manager, and Mr R S Dosik, the New Energy Sources Adviser.

Relations between the Bank and Consultants were a model of their kind and the Project benefited enormously from the informal and constructive relations which existed between Bank staff and the Consultants senior management.

The Consultants called on the services of a number of specialist advisers in the U.K. who, through the Management Advisory Group, advised the Project Management team and the special sub-committee set up to guide the construction of the mathematical model. Their names are given in Appendix A.

APPENDIX A

HALCROW/ITDG PROJECT TEAM

Project Management Group
Resident Engineers.
Management Advisory Group
Mathematical Model Sub-Committee and Specialist Advisers

–A1–

PROJECT MANAGEMENT GROUP

Project Director	A.M. Muir Wood	Sir William Halcrow & Partners
Associate Project Director	P.L. Fraenkel	Intermediate Technology Development Group Limited
Project Manager	D.E. Wright (Chairman)	Sir William Halcrow & Partners
Deputy Project Manager	M.R. Starr	Sir William Halcrow & Partners
Solar Engineer	A. Derrick	Intermediate Technology Development Group Limited
Solar Systems Engineer	B. McNelis	Intermediate Technology Development Group Limited
ITDG Executive Project Officer	M.F. Sinclair	Intermediate Technology Development Group Limited
Project Engineer	M.B. Aylward (Secretary)	Sir William Halcrow & Partners

RESIDENT ENGINEERS

Mali	A.R. O'Hea	Sir William Halcrow & Partners
Philippines	R.J. Hacker	Sir William Halcrow & Partners
Sudan	A.P. Napier	Sir William Halcrow & Partners

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MANAGEMENT ADVISORY GROUP

The Management Advisory Group consisted of the Project Management Group and the Specialist Advisers to the Project.

Project Director	A.M. Muir Wood	Sir William Halcrow & Partners
Associate Project Director	P.L. Fraenkel	Intermediate Technology Development Group Limited
Project Manager	D.E. Wright (Chairman)	Sir William Halcrow & Partners
Deputy Project Manager	M.R. Starr	Sir William Halcrow & Partners
Solar Engineer	A. Derrick	Intermediate Technology Development Group Limited
Senior Mechanical Engineer	A.W.L. Muir	Sir William Halcrow & Partners
Senior Electrical Engineer	W.V. Pereira	Sir William Halcrow & Partners
Project Engineer	M.B. Aylward (Secretary)	Sir William Halcrow & Partners
Industrial Engineer	D.L. Wright	Intermediate Technology Industrial Services
Irrigation Specialist	P.A. Browne	Sir William Halcrow & Partners
Market Survey Specialist	C.J. Bevan	ULG Consultants Ltd.
Industrial Specialist	W. Armstrong	Consultant
Solar Energy Adviser	B.J. Brinkworth	University College, Cardiff
Mechanical Engineer Adviser	P.D. Dunn	University of Reading
Solar Engines Adviser	G. Rice	University of Reading
Photovoltaic Adviser	F.C. Treble	Consultant
Solar Systems Engineer	B. McNelis	Intermediate Technology Development Group Limited
ITDG Management Adviser	D.H. Frost	Intermediate Technology Development Group Limited
ITDG Executive Project Officer	M.F. Sinclair	Intermediate Technology Development Group Limited

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MATHEMATICAL MODEL SUB–COMMITTEE

The Sub-Committee consisted of the following members:

Deputy Project Manager	M.R. Starr (Chairman)	Sir William Halcrow & Partners
Assoc. Project Diector	P.L. Fraenkel	Intermediate Technology Development Group Limited
Solar Engineer	A. Derrick	Intermediate Technology Development Group Limited
Systems Modeller	E.P. Evans	Sir William Halcrow & Partners
Assistant Systems Modeller	M.W. Duffy	Sir William Halcrow & Partners
Project Engineer	M.B. Aylward (Secretary)	Sir William Halcrow & Partners

advised by the following specialists:

Industrial Specialist	W. Armstrong	Consultant
Mechanical Engineering Adviser	P.D. Dunn	University of Reading
Solar Engines Adviser	G. Rice	University of Reading
Solar Systems Engineer	B. McNelis	Intermediate Technology Development Group Limited
Pumps Adviser	D.J. Saunders	Consultant
Adviser on Numerical Modelling of Solar Energy Systems	R.H. Marshall	University College, Cardiff
Adviser on System Studies of Solar Engines	J.P.A. Lowry	Queen Mary College University of London
Electric Motors Adviser	L.L. Freris	Imperial College University of London

TABLES

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TABLE

		Source	Use	Static Head m	Supplier	Type	Peak Flow l/s	Peak Hydraulic Power watts	Peak Array Power watts	
Mali	Babougou	Open Well	For student showers in hostel	10	Briau	PV	-	27	315	Under care of FAO. Some data missed because of battery discharge
	Korofina	Open Well	Market Garden	3-7	Photowatt	PV	1.5	90	275	Under care of Laboratory. Difficulty in getting system to work, limited data collected.
	Yangasso	Borehole	Village water supply	20.0	Pompes Guinard	PV	2.7	540	1300	Under care of Mali Aqua Viva Availability for monitoring maximum possible
	Banankoro	Open Well	None	2-4	SEI	PV Portable	2.3	115	250	Initial electronic failures limited data collected. Had to be moved to Laboratory.
Philippines	Talaksan San Raphael	Small Canal	Rice Irrigation	5.0	Briau	PV	2.0	100	600	Good quantity of data collected despite foot valve problems.
	Talampas Sapang Palay	Stilling Pool	Rice Irrigation	5.0	Omera-Segid	PV	1.0	50	200	Quantity of data affected by poor weather and shading of Array.
	Talampas Sapang Palay	River	Rice Irrigation	12.0	Pompes Guinard	PV	1.0	120	600	Problems with pump priming limited data collected.
	Non Con Center	Tank	-	2.0-5.0	SEI	PV portable	2.3 (at 5m head)	115	250	Initial electronic failures limited data collected. Had to be moved to Laboratory.
Sudan	Butri	Open Well	Orchard and Field crops	9.5-18.0	Arco Solar	PV	1.0 (at 15m)	150	530	Availability for monitoring maximum possible.
	Butri	Open Well	-	4.9-11.0	Intertechnology Solar Corp.	PV	1.0 (at 8.0m)	80	530	Mechanical problems with pump operation. Limited data collected.
	Soba	Borehole	-	20.0	Solar Pump Corporation	Thermal	0.8 (at 15m)	120	Collector Area 5.1m^2	Delay in installation and difficulty in operating system limited data collected.
	Butri	Open Well		9.5-11.0	Soterem	PV Tracking	1.0 (at 8m)	80	480	Delays in installation prevented completion of system.

Note: The approximate ratings are based on data given by the suppliers.
Costs are given in tables 4, 6 and 8.

<u>TABLE 1</u> <u>Systems and sites used for field trials</u>

MANUFACTURER OR SUPPLIER	SYSTEM TYPE	PEAK PUMPED POWER [1]	FOB PRICE [2]		PRICE PER PEAK PUMPED watt	
			£	$	£	$
Lucas World Service, UK	PV	75 W [3]	13,998	30,795	186	410 (Note 6)
Solar Electric International, USA	PV	85 W	3,750	8,250	44	97
Briau SA, France	PV	100 W	6,470	14,235	65	142
Inter Technology Corp, USA	PV	130 W	9,090	19,995	70	154
CIPEL/Photowatt, France	PV	150 W	5,665	12,463	38	83
Pompes Guinard, France	PV	250 W	8,375	18,425	33	74
Omera Segid, France	PV	67 W [4]	5,095	11,210	76	167
Soterem, France	PV	82 W [5]	13,455	29,600	164	361 (Note 6)
Arco Solar, USA	PV	135 W	2,400	5,278	18	39
Solarex, USA/Solarpak, UK	PV	200 W	6,030	13,260	30	66
NV Philips /Nolte, Holland	PV	195 W	19,450	42,790	100	219 (Note 6)
Solar Pump Corp, USA	Thermal	120 W	3,410	7,500	28	63

Notes:

1 Peak pump power for 1000 W/m^2 irradiance

2 Prices valid during November 1979, in UK £ and US $ equivalent £1 = $2.20.

3 75 W average over 5 hours per day (system includes battery storage)

4 50 W at 750 W/m^2 insolation quoted.

5 Tracking system.

6 Systems with storage and/or tracking have a lower peak pumped watt value in relation to their total daily output, making the price per peak pumped watt appear higher for fair comparison, by between 50% and 100% or more in some cases. This is because the electrical power supply to the pump is much less variable between sunrise and sunset.

Table 2 Systems short-listed for field trials

PARAMETER (UNITS)	COMMENT	ESSENTIAL MEASUREMENT	SECONDARY MEASUREMENT	ESSENTIAL MEASUREMENT	SECONDARY MEASUREMENT	INSTRUMENT	SUPPLIER (COUNTRY)
Global Solar Irradiance (watts/sq m) and global integrated solar irradiation (MJ/sq m/day) measured on horizontal plane.	This is a standard meteorological measurement directly comparable to records from many countries. Global irradiation (direct plus diffuse) was normally measured but spot readings of the diffuse component could be obtained		o		o	Pyranometer + integrating counter	Eppley (USA) Delta T (UK)
Solar irradiance (watts/sq m) and integrated solar irradiation (MJ/sq m/day) in the plane of array.	In order to measure directly the irradiance and irradiation in the plane of the array, sensors were attached to one side of each array. Spot readings of the diffuse component also could be obtained.	o		o		Chart recorder Solar Cell Sensor SS100 + integrating counter	TOA (Japan) KBE (Germany) Delta T (UK)
Solar irrad. (watts/sqm)	For general checks.					Band meter	Dodge (USA)
Angle of Solar incidence (degrees arc)	Measurement of the angle of incidence between the direct solar beam and the normal to the array plane.		o			Sundial type	Constructed on site
Power (kW) and Energy (MJ or kW hrs) output from the photovoltaic array.	The power and energy transferred from the Array to the motor was measured. Provision was also made to measure the voltage (volts) and current (amps) separately so as to establish the operating conditions for the arrays and motors.	o			o	Chart recorder Energy meter	TOA (Japan) Ormand and Stollery (UK)
Flow rate (litre/second) and cumulative volume pumped (cu m/day)	It was essential to measure the flow rate and cumulative volume pumped.	o		o		Paddle wheel transducer, cumulative counter and analog signal conditioner	Cole Parmer (USA)
Static head (metres) (suction lift + discharge lift)	The elevation of the source water level, pump centreline and discharge point (pipe centre line or water level control in tank) was measured.		o		o	Scale or well dipper	
Pumped head (metres) and estimated mean daily pumped head (metres)	It was essential to measure the total head across the pump. If direct measurements were not possible these values were calculated from a knowledge of the flow rate, total static lift, and the characteristics of the delivery pipework. The mean daily head was estimated from the continuous measurements of the pumped head.	o			o	Pressure gauge or manometer	
Ambient temperature (degrees centigrade)	The maximum ambient temperature was measured at each site and at certain sites a continuous recording of temperature was obtained as temperature is known to affect the efficiency of many system components.		o		o	Max. thermometer thermocouple probe. Thermohygrograph	Casella (UK) Levell (UK) Casella (UK)
Wind Run (metres)	The wind has a cooling effect on the system and therefore the wind run was measured at certain sites.		o		o	Recordong anemometer	Casella (UK)
Component Temperatures (degrees centigrade)	Since the efficiency of some components varies with temperature, provision was made to record component temperatures.		o		o	Thermocouple probe	Levell (UK)
Humidity (percentage)	Humidity was recorded continuously at certain sites in case a measurable relationship with performance could be established.		o		o	Whirling hygrometer Thermohygrograph	Casella (UK) Casella (UK)
Pumping hours	The number of hours a system operated in a day was measured on some systems				o	Switched timer assembled from components	Various

Table 1 Performance parameters measured and instruments selected for field trials

SITE	YANGASSO	BABOUGOU	KOROFINA	BANANKORO
Source	Borehole	Well	Well	Well
Approximate head	20m	5 to 10m	3m	2 to 4m
SYSTEM SUPPLIER	POMPES GUINARD	BRIAU	PHOTOWATT	SOLAR ELECTRIC INTERNATIONAL
PUMP MAKE	POMPES GUINARD	BRIAU	BREGUET-KSB	KSB
Type	F 6.5.8 ET	Duva 20	Etanorm 32-125	-
Action	Centrifugal multistage	Volumetric piston	Centrifugal	Centrifugal
Position	Submerged	Surface	Surface	Submerged
Axis	Vertical	-	Horizontal	Vertical
Discharge	-	-	2.4 l/s	2.4 l/s
Head	-	-	5.2 m water	4.5m
Speed	-	-	1450 rpm	-
MOTOR MAKE	LEROY-SOMER	G BROT	G BROT	KSB
Type	APF 100 S4	5.06.90/806P	90/60 GB	-
Position	Surface	Surface	Surface	Submerged
Axis	Vertical	Horizontal	Horizontal	Vertical
Coupling	Shaft	Belt	In-line flexible	Close
Commutation	Brushes	Brushes	Brushes	Electronic
Current	15A DC	11A DC	4.6A DC	-
Voltage	62V	52V	52V	60V
Power	795W	450W	190W	-
Speed	1800 rpm	1500 rpm	1400 rpm	3000 rpm
Torque	4.22Nm	2.9Nm	-	-
ARRAY MAKE	SOLAREX	PHOTOWATT	PHOTOWATT	ARCO SOLAR
Type	4200	31 F 36 GC	-	ASI 16-2000
Orientation	By season	Fixed	Fixed	Portable
Cell Area	$10.5m^2$	$2.63m^2$	$2.28m^2$	$2.27m^2$
Array Area	$16.6m^2$	$4.20m^2$	$3.50m^2$	$2.96m^2$
Nominal power	1260W	316W	275W	250W
Connection to motor	Direct	Direct	Direct	Via max.- power controller
COST				
CIF Bamako	-	$ 13500	$ 13500	$ 10200

Note: Data is derived from Supplier's literature and equipment markings.

Table 4 Details and costs of systems selected for Mali

Event	Pump Systems and Locations			
	Briau (Duva -20) Babougou	Solar Electric International Banankoro and Solar Laboratory	Photowatt Korofina	Pompes Guinard Yangasso
Arrival at Airport	17 June 1980	2 June 1980	Panels - 6 May 1980 Pump Set 8 July 1980	N/A
Cleared Customs	12 July 1980	12 July 1980	12 July 1980	N/A
Site preparation started	31 July 1980	N/A	19 August 1980	N/A
System arrived on site	27 July 1980	15 July 1980	19 August 1980	N/A
Erection completed	8 August 1980	15 July 1980	24 August 1980	N/A
System first operated	29 July 1980	15 July 1980	25 Sept. 1980	N/A
Regular monitoring started	12 August 1980	-	-	6 June 1980

TABLE 5 Progress on installation and commissioning of systems in Mali

SITE	LABORATORY (Manila)	TALAKSAN (San Raphael)	TALAMPAS (Gulod)	TALAMPAS (Gulod)
Source	Tank	Small Canal	River	Tank
Approximate Head	2 - 6 m	4m	11m	5m
SYSTEM SUPPLIER	SOLAR ELECTRIC INTERNATIONAL	BRIAU	POMPES GUINARD	OMERA-SEGID
PUMP MAKE	KSB	BRIAU	POMPES GUINARD	ESSA-MICO
Type	-	MGV 40-1	M2-11-40	V2
Action	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Position	Submerged	Surface	Surface	Surface
Axis	Variable	Vertical	Horizontal	Horizontal
Discharge	2.4 l/s	2.0 l/s	1.0 l/s	1.0 l/s
Head	4.5m	5.0m	12.0m	5.0m
MOTOR MAKE	AEG	G BROT	LEROY-SOMER	G BROT
Type	-	35.912	AP71	36.103
Position	Submerged	Surface	Surface	Surface
Axis	Variable	Vertical	Horizontal	Horizontal
Coupling to Pump	Close	Close	Rigid-in-line	Close
Commutation	Electronic	Brushes	Brushes	Brushes
Voltage (approx)	60V	60V	30V	30V
Power	-	240W	370W	132W
Speed	3000 rpm	2300 rpm	1700 rpm	2400 rpm
ARRAY MAKE	ARCO SOLAR	SOLAR POWER CORPORATION	FRANCE PHOTON	RTC
Type	ASI 16-2000	G361	FPC 36V	BPX 47C
Orientation	Portable	Fixed	By Season	Fixed
Cell Area	$2.27m^2$	$4.52m^2$	$4.88m^2$	$1.65m^2$
Array Area	$2.96m^2$	$7.73m^2$	$5.80m^2$	$2.71m^2$
Nominal Power	250W	600W	600W	200W
Connection to Motor	via max. power tracker	direct	direct	direct
COST				
CIF Manila	F.O.C.	$ 21200	$ 16700	$ 15700

Note: Data is derived from suppliers' literature and equipment markings

Table 6 Details and costs of systems selected for Philippines

Event	Pump Systems and Locations			
	Briau Talaksan (San Raphael)	Omera Segid Talampas (Gulod)	Pompes Guinard Talampas (Gulod)	Solar Electric International Laboratory (Manila)
Arrival at Manila Airport	17 April 1980	28 March 1980	13 April 1980	12 July 1980
Cleared from Airport	16 May 1980	17 April 1980	23 April 1980	8 August 1980
Site preparation started	21 May 1980	1 May 1980	5 May 1980	8 Sept. 1980
System delivered to site	4 June 1980	14 May 1980	19 May 1980	N/A
Erection completed	10 July 1980	13 June 1980	10 June 1980	20 Sept. 1980
System first operated	11 July 1980	13 June 1980	13 June 1980	20 Sept. 1980
Monitoring started	11 July 1980	24 June 1980	25 June 1980	11 Dec. 1980

TABLE 7 Progress on installation and commissioning of systems in the Philippines

SITE	BUTRI	BUTRI	SOBA	BUTRI
Source	Well	Well	Borehole	Well
Approx. Head	12m	12m	18m	12m
SYSTEM SUPPLIER	ARCO SOLAR	INTER-TECH SOLAR CORP.	SOLAR PUMP CORP.	SOTEREM
PUMP MAKE	J and JB	ROTH	MIDWELL WELL SUPPLY CO.	POMPES DELOULE
Type	Sta-rite	60-8	2½x8" inside diameter and stroke	PE 9903.8
Action	Centrifugal	Regenerative turbine	Piston lift pump	Piston positive displacement
Position	In well	Submerged	Submerged	In well
Axis	Vertical	Vertical	Vertical	Horizontal
Discharge	-	1.33 l/s	-	-
Head	-	8m	-	-
Speed	3500 r.p.m.	1750 r.p.m.		
MOTOR MAKE	Mavilor	Applied Motors	SPC	CEM
Type	MO 300	BA3628½ H.P.	Expansion	F12M4H
Position	above water	above water	surface	above water
Axis	Vertical	Vertical	40°	Horizontal
Coupling	direct	direct	mechanical linkage	2 stage belt drive
Commutation	Brushes	Brushes	-	Brushes
Current	9A	20A	-	-
Voltage	54V	24V	-	61V
Power	400W	400W	-	345W
Speed	3000 r.p.m.	1800 r.p.m.	-	-
Torque	11.25 lb. in	18 lb. in.	-	-
ARRAY	ARCO SOLAR	ARCO SOLAR	-	MOTOROLA
Type	ASI-16-2000	ASI-16-2000	Thermal solar collector	MSP43A40
Orientation	variable	variable	fixed	automatic tracking
Cell area	4.58m^2	4.58m^2	-	
Array Area	5.92m^2	5.92m^2	5.1m^2	-
Nominal power	530 Watts	530 Watts	-	480 Watts
Connection to motor	Direct	Direct	-	Through max power tracker and current regulator
COST				
CIF Khartoum	$4800	$21500	$12000	$31300

Note: Data is derived from suppliers' literature and equipment markings.

TABLE 8 Details and costs of systems selected for Sudan

Event	Pump Systems and Locations			
	Arco Solar Butri	Inter Technology Solar Corporation Butri	Solar Pump Corporation Soba	Soterem Butri
Arrival at Airport	7 May 1980	30 April 1980	29 April 1980	2 August 1980
Cleared from Airport	24 May 1980	12 May 1980	2 May 1980	27 August 1980
Site preparation started	26 April 1980	26 April 1980	30 April 1980	26 April 1980
System arrived on site	5 June 1980	14 June 1980	21 May 1980	2 October 1980
Erection completed	21 June 1980	21 June 1980	9 Sept. 1980	14 October 1980
System first operated	24 June 1980	26 July 1980	13 Jan. 1980	28 Jan. 1980
Monitoring started	4 August 1980	-	-	-

Table 9 Progress on installation and commissioning of systems in Sudan

		CONTINUOUS DATA				CUMULATIVE DATA			
COUNTRY	SYSTEM	NO. OF DAYS ON WHICH DATA WAS RECORDED	NO. OF DAYS SUITABLE FOR ANALYSIS	NO. OF DAYS ACTUALLY ANALYSED AND RESULTS TABULATED	NO. OF DAYS GRAPHICALLY PRESENTED	NO. OF DAYS ON WHICH DATA WAS RECORDED	NO. OF DAYS ACTUALLY ANALYSED AND RESULTS TABULATED	NO. OF DAYS GRAPHICALLY PRESENTED	REMARKS
Mali	Briau (Duva)	3	3	3	1	83	43	16	Cumulative data interrupted by discharge of instrument power supply. Data obtained at two ranges of pumped head.
Mali	Photowatt	1	1	1	1	0	0	0	Data collection limited because system would not operate below 800W/m^2 array solar irradiance.
Mali	Pompes Guinard	3	3	3	1	149	149	132	System installed before start of field trials. PV energy meter not installed. Representative continuous performance data obtained.
Mali	SEI	3	2	2	1	0	0	0	Initial failure of system electronics delayed installation. Representative continuous performance data obtained.
Philippines	Briau	30	21	5	1	139	102	53	Good quantity of representative continuous data and cumulative data obtained despite foot valve problems.
Philippines	Omera Segid	23	6	6	1	159	97	52	Quantity of representative data collected limited by poor weather conditions and shading of array in afternoons
Philippines	Pompes Guinard	4	1	1	1	30	0	0	Problems with priming of pump limited data collection.
Philippines	SEI	6	2	2	1	0	0	0	Initial failure of system electronics limited data collection.
Sudan	Arco Solar	32	16	5	1	95	81	54	Good quantity of representative data obtained.
Sudan	ITC/Solar Corp.	6	5	5	1	0	0	0	Mechanical problems with pump operation limited data collection.
Sudan	Solar Pump Corp.	0	0	0	0	0	0	0	Commissioning problems prevented continuous operation
Sudan	Soterem	0	0	0	0	0	0	0	Tracking mechanism tested but lost and damaged components prevented complete installation.

TABLE 10 *Summary of continuous and cumulative system performance data resources*

Series 1 Variation of system performance with time

1	Solar irradiance in the plane of the array vs time (Gp vs t)
2	Flow rate vs time (Q vs t)
3	Array power output vs time (Pc vs t)
4	Hydraulic power output of the system vs time (Ph vs t)
5	Static lift vs time (Hg vs t)
6	Pumped head vs time (H vs t)
7	Overall system efficiency vs time (η vs t)
8	Sub- system efficiency vs time (η sub vs t)

Series 2 Variation of system performance with solar irradiance

9	Overall system efficiency vs Solar irradiance in the plane of the array (η vs Gp)
10	Sub-system efficiency vs Solar irradiance in the plane of the array (sub vs Gp)
11	Array system efficiency vs Solar irradiance in the plane of the array (ηc vs Gp)
12	Array power output vs Solar irradiance in the plane of the array (Pc vs Gp)
13	Hydraulic power output of the system vs Solar irradiance in the plane of the array (Ph vs Gp)

Table 11 List of plots for presentation of continuous system performance data

1	Daily volume of pumped water vs Daily solar irradiation in the plane of the array ($\bar{Q}$ vs $\bar{G}p$)
2	Daily overall system efficiency vs Daily solar irradiation in the plane of the array ($\bar{\eta}$ vs $\bar{G}p$)
3	Daily sub-system efficiency vs Daily solar irradiation in the plane of the array ($\bar{\eta}_{sub}$ vs $\bar{G}p$)
4	Daily array efficiency vs Daily solar irradiation in the plane of the array ($\bar{\eta}_c$ vs $\bar{G}p$)

Table 12 List of plots for presentation of cumulative system performance data

Country	System (Type of Pump)	Array Rated Power	Average Peak Power measured @ 1000 W/m² Solar Irrad.	Optimum Head (See Note 1)	Actual Operating Head	Average Peak Hydraulic Power Measured @ 1000 W/m² Solar Irrad.	Approx Start Up Solar Irrad	Average System (Note 6)	Measured System (Note 5)	Max. Efficiency Sub-System	Cells	Array	Average Daily Efficiency (Note 6)	(Note 3) (Note 5)	Average Daily Water Output (See Note 3)	Max Temp Increment of Array Measured	Remarks
	Name	W	W	m	m	W	W/m²	% @ W/m²	% @ W/m²	%	%	%	%	%	m³	°C @ W/m²	
Mali	BRIAU (LUVA) (Piston Pump)	316	196	20+	3.6 to 10.9	28	600	0.8 to 800	1.3 @ 800	14	9.0	5.6	0.4	0.7	7.3 @ 5.6m	13.5 @ 600	System efficiency improves at higher heads. System suitable for high suction heads. Start up achieved significantly earlier by alteration on site of array series/parallel configuration as start up solar irrad. reduced to 300 W/m².
	PHOTOWATT (Surface centrifugal)	275	146	6	3.2 to 3.7	31	800	1.0 @ 900	1.5 @ 900	21	7.3	4.8	Insufficient Data		Insufficient Data	Insufficient Data	Poor performance. Severe problems with priming. System would only work at high solar irrad. and then not consistently.
	POMPES GUINARD (Borehole centrifugal)	1260	807	-	14 to 20	307	220	2.2 @ 720	3.4 @ 720	39	9.2	5.9	1.3	2.1	31 @ 16.0m head	21 @ 890	Good performance in terms of system efficiencies. Components appear to be well matched. System ran without fault.
	SEI (Submersible Unit)	250	202	5	2.6 to 5.3	90	200 to 300	3.1 @ 1000	4.0 @ 1000	45	8.9 Note 2	6.9 Note 2	Insufficient Data		Insufficient Data	22 @ 925	Good performance in terms of system efficiencies. Good daily output efficiency indicated from high maximum efficiencies and early start up as a result of use of max. power point tracker.
Philippines	BRIAU (Suction centrifugal)	600	410	6	3.7 to 5.0	102	350 to 400	1.4 @ 830	2.4 @ 830	26	9.5	5.6	0.9	1.6	35 @ 4.5m head	23 @ 970	Satisfactory performance
	OMERA SEGID (Suction dentrifugal)	200	151	5	4.1 to 4.8	47	390	1.8 @ 840	2.9 @ 840	32	10.2	6.4	0.6	0.9 Note 4	5.5 @ 4.3m head Note 4	17 @ 970	Satisfactory performance. Average daily water output and efficiency low because array partly shaded in afternoons
	POMPES GUINARD (Suction centrifugal)	600	422	10	10.2 to 11.0	114	800	1.9 @ 1000	2.3 @ 1000	27	8.9	7.5	Insufficient Data		Insufficient Data	17 @ 960	Performance poor at low solar irradiance because suction head near to practical limit. Satisfactory performance indicated if at lower suction heads.
	SEI (Submersible unit)	250	240	5	4.5	81	200 to 300	2.8 @ 915	3.6 @ 915	34	10.5 Note 2	8.2 Note 2	Insufficient Data		Insufficient Data	15 @ 785	Good performance in terms of system efficiencies. Good daily output efficiency indicated from high max. efficiencies and early start up as a result of use of max power point tracker.
Sudan	ARCO SOLAR (Suction centrifugal)	550	505	9+	9.3 to 16.8	161	350	2.7 @ 1000	3.5 @ 1000	32	11.0	8.5	1.8	2.3	20 @ 11.6m	25 @ 870	Good performance. System matched for high peak delivery.
	INTER TECHNOLOGY CORP (Regenerative pump)	550	470	7	Up to 11.9	113	400	1.9 @ 1000	2.5 @ 1000	24	10.6	8.2	Insufficient Data		Insufficient Data	16 @ 780	Satisfactory performance in terms of system efficiencies but impeller binding problem prevented continuous running.
	SOLAR PUMP CORP (Thermal system)	5.1m²	-	Variable	18	30 (prelim.)	-	-	-	-	-	-	-	-	-		Continuous operation not achieved because of commissioning problems.
	SOFRETEM (Piston pump)	480	-	10	-	-	-	-	-	-	-	-	-	-	-		Testing incomplete although tracking mechanism demonstrated and worked well.

TABLE 13 Summary of system field performance

Notes:
1. from laboratory tests
2. including max power tracker losses
3. at 6kWhm/m² (21.6MJ/M²) array solar irradiation
4. at 4.3kWhrs/m² (15.5MJ/m²) array solar irradiation insufficient data for 6kwhrs/m²)
5. referenced to gross cell area of array
6. referenced to overall array area

Supplier	Manufacturer	Country of Origin (Supplier)	Model or Type and Specification	Cost (FOB) £	Cost (FOB) $	Site of Complete system
1. PV MODULES						
Arco Solar	Arco Solar	USA	Model 16-2300, 37 watts nominal maximum power	144	330	-
CEL	CEL	India	PM621 7.6 watts nominal maximum power	107	247	-
RTC	RTC	France	Model BPX47C, 33 watts nominal maximum power	565	1300	-
Solarex	Solarex	USA	Model HE51 JG, 34 watts nominal maximum power	380	874	-
2. PV SUBSYSTEMS						
Arco Solar	Mavilor motor Sta-rite pump	USA	Pmdc, model no M0300, 400 watts rated power, 54 Volts nominal voltage Centrifugal, model J	481	1112	Sudan
Briau	Brot motor Briau pump	France	Pmdc, 450 watts rated power, 48 Volts nominal voltage Piston, model DUVA 20	987	2270	Mali
Briau	Brot motor	France	Pmdc, 240 watts rated power, 48 Volts nominal voltage Centrifugal, model MGV. 40.1	999	2298	Philippines
ITC/ Solar Corp.	Applied Motors motor Roth pump	USA	Pmdc, 180 Watts rated power, 24 Volts nominal voltage Regenerative, model 7-140	391	883	Sudan
Omera Segid	Brot motor Essa-Mico pump	France	Pmdc, 132 watts rated power, 30 Volts minimum voltage Centrifugal	1795	4129	Philippines
Photowatt	Brot motor Brequet pump	France	Pmdc, 190 watts rated power, 52 Volts minimum voltage Centrifugal, model KSB	1975	4543	Mali
Pompes Guinard	Leroy-Somer motor Pompes Guinard pump	France	Pmdc, 370 watts rated power, 31 Volts minimum voltage Centrifugal, model Alta X 600/12	1028	2341	Philippines
Soterem	CEM motor Salmson pump	France	Pmdc, 345 watts rated power, 61 Volts minimum voltage Piston, model PE-99083	473	1088	Sudan
SEI	AEG motor KSB pump	USA	Brushless, 200 watts rated power Centrifugal, model M	600	1380	Mali and Philippines
3. INDIVIDUAL MOTORS						
SEM	SEM	UK	Permanent magnet dc, 370 atts rated power	155	357	-
Selwood	Selwood	UK	Permanent magnet dc	240	552	-
Hitachi Metals	Hitachi Metals	Japan	Reciprocating acuator	63	140	-
4. INDIVIDUAL PUMPS						
Godwin	Godwin	UK	Self-priming, centrifugal Cobra pump	Free	Loan	-
Godwin	Godwin	UK	Piston pump with hand wheel	Free	Loan	-
Mono	Mono	UK	Monolift rotary screw pump model C32 3620	913	2100	-
Selwood	Selwood	UK	2 inch diaphragm, model Mk4 Simplite	683	1571	-
5. THERMAL SYSTEMS						
-	Dornier	W. Germany	Complete pumping system with Freon engine being developed in association with BHEL (India)	-	-	Tested at Works
-	Ormat	Israel	5kW energy converter with Freon Turbine/Generator	-	-	Tested at Works
-	Solar Pump Corp	USA	Complete pumping system with Freon engine, as supplied for field trials in Sudan	-	-	Tested at Works
-	Sunpower Inc.	USA	Stirling engine (free piston) and diaphragm pump			Tested at Universit of Reading

TABLE 14 Laboratory tested systems and components

Test	Description
1. PHOTOVOLTAIC MODULES	
1.1 Visual inspection	Each module was examined for defects arising from faulty soldering or assembly, delamination, corrosion or cracked cells and glass covers;
1.2 Electrical Performance (CEC Specification No. 101 and JPL 5101-16A)	The voltage current characteristic of each module was determined using a Large Area Pulsed Simulator (LAPSS) at both the RAE and JPL facilities. The maximum power output, the open circuit voltage and the short circuit current as determined by this test are of particular interest. Differing test procedures adopted within Europe and the USA has resulted in RAE referring their results to 25°C and 1000 W/m² Solar irradiance whereas JPL refer their results to 28°C and 1000 W/m² solar irradiance. These results of tests are however easily compared by applying module temperature coefficients as determined by RAE and JPL. Both RAE and JPL reference the results to the agreed Air Mass 1.5 solar spectrum.
1.3 Nominal Operating Cell Temperature - NOCT (JPL 5101-16A)	In order to acquire sufficient data to allow an accurate determination of the nominal operating temperatures of the solar cells of the modules under a standard environment one of each type of module was instrumented to measure cell temperature under outdoor conditions in a test stand as described in section 4.4. The NOCT is defined as the cell temperature when the module is open circuit and orientated normal to solar noon under the Standard Thermal Environment (STE) which is defined as: Solar Irradiance = 800 Wm^{-2} Ambient air temperature = 20°C Surrounding wind speed = 1 ms^{-1} The procedure for adjusting the measured cell temperature for points obtained close to but not exactly at the STE is given in JPL Specification 5101-16A.
1.4 Temperature Coefficient (JPL 5101-16A)	Temperature coefficients relating to the module short circuit current, open circuit voltage and maximum power output were determined for each type of module by performing an electrical performance test at 60°C instead of the normal ambient temperature.
1.5 Insulation Resistance (RAE)	The insulation resistance was measured between the shorted output terminals of the module and its metallic frame using a Megohmeter at a voltage of 1000V dc, applied for one minute. This test conducted by RAE is similar to the Electrical Isolation Test performed by JPL. (See 1.6).
1.6 Electrical Isolation (JPL 1501-16A)	Each module tested was subjected to a maximum of 2000 Volts of direct current voltage for 1 minute. The module was under observation for arcing and flashover during the test period and the leakage current monitored.
2. ENVIRONMENTAL TESTS	
2.1 Ultra Violet Irradiation	Each module tested at RAE was irradiated with the UV equivalent of 30 mean days of Global Solar Radiation as received in a sunny climate. This UV irradiation was derived from the average daily solar irradiation recorded in Malta throughout 1977 which was 523 mW hr cm^{-2}. Of this irradiance 6.9% is in the UV region of less than 0.4 uM. and therefore the UV continuous equivalent of 1.51 mW cm^{-2} for 30 days was applied under accelerated conditions using a UV simulator.

Table 15 Details of tests on PV modules (Sheet 1 of 2)

Test	Description
2.2 Thermal Cycling (JPL 1501-16A)	The modules were subjected to 50 temperature cycles varying between -40°C and +90°C with a rate of change of temperature not exceeding 100°C per hour. The module was monitored during the tests.
2.3 Twist (JPL 5101-16A)	The modules were subjected to a twist test by means of mounting the module to a substrate and deflecting one corner of the substrate by ± 20 mm per metre lengths. The modules were instrumented to monitor if open or short circuit conditions occurred.
2.4 Hail Impact (JPL 5101-16A)	The modules were subjected to normal impact loading with a 20 mm iceball travelling at a terminal velocity of 45 mph (20.1 m/sec) fired at the modules most sensitive spots. The sensitive part of the module cover was determined by destructive testing of one module using a 38 mm iceball fired with increasing velocity at candidate points such as module corners or edges, edges of cells, points of minimum cell spacing, points of superstrate support and points furthest from supports.
2.5 Humidity Cycling (JPL 1501-16A)	The modules were subjected after pre conditioning to 5 temperature cycles each of 24 hours duration when the relative humidity is 90-95% The modules were subjected to an electrical performance test within 1 hour of removing the modules from the humidity chamber.
2.6 Mechanical Cycling (JPL 1501-16A)	When supported only at the design support points a uniform load of 2400 Pa was applied to the surface of the modules tested and cycled 10,000 times in alternating negative and positive directions at a rate not exceeding 20 cycles per minute. The modules were instrumented to monitor if open or short circuit conditions occurred.

3. PHOTOVOLTAIC CELLS

The following investigation tests were performed by RAE on cells supplied by the module manufacturer as being representative of those used in the modules:

3.1 Cell Relative Spectral Response (CEC Specification No. 101)	The relative spectral response of the cells were measured in accordance with the CEC Specification No. 101, using a monochromator.
3.2 Cell Temperature Coefficients	The temperature coefficients of the cells were determined by determining cell voltage current characteristics at 15°C, 25°C, 45°C and 65°C using a variable temperature solar cell mounting block.

Table 15 Details of tests on PV modules (Sheet 2 of 2)

Module	S/No.	Test Lab.	LABORATORY TEST RESULTS (1)					MANUFACTURERS SPECIFICATION			MAXIMUM POWER OUTPUT VARIATION	
			Open Circuit Voltage (V)	Short Circuit Current (A)	Maximum Power (W)	Cell Efficiency (%)	Overall Module Effcy. (%)	Open Circuit Voltage (V)	Short Circuit Current (A)	Maximum Power (W)	From Manufacturers Specification (%)	From Average of Modules Tested (%)
Arco Solar ASI-16-2300	135068	RAE	20.2	2.50	35.25	12.3	9.5	20.3	2.5	37 ± 10%	- 5	-2.2
	135076	JPL	20.75	2.48	36.20	12.7	9.7				- 2	+0.5
	135259	JPL	20.79	2.50	36.89	12.9	9.9				- 0.5	+2.4
	135362	JPL	20.64	2.48	35.16	12.3	9.5				- 5	-2.4
	135493	RAE	20.3	2.55	36.64	12.8	9.8				- 1	+1.6
	Average				36.03	12.6	9.7				- 2.5	
CEL PM 621	127C79-153	RAE	20.3	0.44	6.60	9.3	5.5	21.0	0.46	7.6	-13.5	-5.4
	127C79-271	JPL	21.63	0.443	7.36	10.4	6.1				- 3	+5.7
	127C79-272	JPL	21.43	0.440	6.98	9.8	5.8				- 8	+0.2
	127C79-273	JPL	20.99	0.439	6.86	9.7	5.7				- 9.5	-1.5
	127C79-274	RAE	21.3	0.43	7.02	9.9	5.9				- 7.5	+0.9
	Average				6.96	9.8	5.9				- 8.5	
RTC	361603	JPL	21.11	1.926	29.96	10.6	6.6	21.0	2.1	32.7±13%	- 8.5	+0.2
	361604	JPL	21.11	1.992	30.03	10.6	6.6				- 8	+0.5
	361605	RAE	20.8	2.00	30.63	10.8	6.8				- 6.5	+2.4
	361606	RAE	20.8	2.00	30.44	10.8	6.7				- 7	+1.9
	361612	JPL	20.96	1.890	28.40	10.0	6.3				-13	-5.0
	Average				29.89	10.6	6.6				- 8.5	
Solarex HE51JG	508208	JPL	19.12	2.063	28.15	11.5	9.9	20.5	2.1	34±10%	-17.2	-0.6
	512662	JPL	18.80	2.068	27.81	11.4	9.8				-18.2	-1.8
	512663	RAE	19.2	2.05	28.99	11.9	10.2				-14.7	+2.3
	512664	RAE	19.2	2.05	27.59	11.3	9.7				-18.9	-2.6
	512666	JPL	19.79	2.106	29.12	11.9	10.3				-14.4	+2.8
	Average				28.33	11.6	10.0				-16.5	

Table 16 Electrical performances of modules on delivery

Notes: (1) At 28°C

Module	S/No.	Maximum Power Output (Watts) 28°C *	60°C	Temperature Coefficient: Open Circuit Voltage mV/°C	Short Circuit Current mA/°C	Maximum Power mW/°C	NOCT °C	Power Drop %/°C	Average Cell Efficiency 28°C *	60°C	Nominal Power at NOCT (one test module)
Arco Solar ASI-16-2300	135068	34.41	29.01	-87.5	+1.19	-169		0.49	12.0	10.1	31.57 watts
	135076	35.18	30.18	-84.4	+0.75	-156		0.44	12.3	10.6	
	135259	36.00	31.17	-86.3	+0.78	-151	52.0	0.42	12.6	10.9	(2.15 amps x 14.7 volts)
	135362	34.58	29.70	-87.5	+1.31	-153		0.44	12.1	10.4	
	135493	35.89	30.98	-87.8	+1.41	-153		0.43	12.5	10.8	
	Average	35.21	30.21	-86.7	+1.09	-156		0.44	12.3	10.6	
CEL PM 621	127C79-153	6.93	6.03	-81.3	+0.27	- 28		0.40	9.8	8.5	6.52 watts
	127C79-271	7.36	-	-	-	-	47.0	-	10.4	-	
	127C79-272	6.92	-	-	-	-		-	9.7	-	(0.40 amps x 16.3 volts)
	127C79-273	6.81	6.18	-73.4	+0.20	- 20		0.29	9.6	8.7	
	127C79-274	7.46	6.55	-75.6	+0.11	- 28		0.38	10.5	9.2	
	Average	7.10	6.25	-76.8	+0.19	- 25		0.35	10.0	8.8	
RTC BPX47C	361603	29.03	26.40	-88.4	+0.78	- 82		0.28	10.3	9.3	25.87 watts
	361604	29.58	26.32	-84.4	+0.56	-102		0.34	10.5	9.3	
	361605	28.87	25.61	-83.1	+0.78	-102	53.5	0.35	10.2	9.0	(1.76 amps at 14.7 volts)
	361606	28.67	25.91	-98.4	+1.03	- 86		0.30	10.1	9.2	
	361612	27.79	24.91	-78.1	+0.78	- 90		0.32	9.8	8.8	
	Average	28.79	25.83	-86.5	+10.79	- 92		0.32	10.2	9.1	
SOLAREX HE51JG	508208	29.99	24.30	-95.3	+1.34	-178		0.59	12.3	10.0	24.30 watts
	512662	28.10	23.93	-76.9	+0.94	-130		0.46	11.5	9.8	
	512663	29.29	24.40	-103.1	+1.25	-153	53.5	0.52	12.0	10.0	(1.80 amps at 13.5 volts)
	512664	27.35	-	-	-	-		-	11.2	-	
	512666	29.36	24.60	-76.6	+0.78	-149		0.51	12.0	10.1	
	Average	28.82	24.31	-88.0	+1.08	-153		0.52	11.8	10.0	

* Note: Performance at +28°C are JPL base values not performance on delivery.

Table 16A Temperature characteristics of modules tested

MODULE	TEST APPLIED	REPEAT ELECTRICAL PERFORMANCE Maximum Power Output (watts)	% Change from Base Value	Date	REPEAT VISUAL INSPECTION AND OTHER COMMENTS
135068	RAE on delivery	35.25	Base	27th June 1980	-
	Ultra-violet irradiation	35.39	+0.5	11th August 1980	Dull appearance of front contacts
	JPL on delivery	35.01	-	10th September 1980	-
	JPL Pre-test	34.41	New Base	19th September 1980	-
	Thermal cycling	34.25	-0.5	2nd October 1980	Frame sealant extruded at both ends and into cell area in 2 places
	Humidity cycling	34.30	-0.3	15th October 1980	No degradation observed
	Mechanical cycling	34.21	-0.6	30th October 1980	No degradation observed
	Twist	34.56	+0.4	5th November 1980	No degradation observed
	Hail impact	34.41	0.0	7th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	7th November 1980	Satisfactory
135076	JPL on delivery	36.20	-	20th May 1980	-
	JPL Pre-test	35.18	Base	19th September 1980	-
	Thermal cycling	34.76	-1.2	2nd October 1980	Frame sealant extruded both ends
	Humidity cycling	34.84	-1.0	15th October 1980	No degradation observed
	Mechanical cycling	34.77	-1.2	30th October 1980	No degradation observed
	Twist	35.25	+0.2	5th November 1980	No degradation observed
	Hail impact	35.23	+0.1	7th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	7th November 1980	>50 μA leakage with 2000 volt after 42 seconds
135259	JPL on delivery	36.89	-	20th May 1980	>50 μA leakage.
	JPL Pre-test	36.00	Base	19th September 1980	-
	Thermal cycling	35.75	-0.7	2nd October 1980	Frame sealant extruded both ends and into cell area
	Humidity cycling	35.54	-1.3	15th October 1980	Delamination in 3 places and back surface blistering in 7 places
	Mechanical cycling	35.58	-1.2	3rd November 1980	No degradation observed
	Twist	36.00	0.0	5th November 1980	No degradation observed
	Hail impact	24.09	-5.3	7th November 1980	Sensitivity sample. No damage from 38mm at 45 ms^{-1} but some electrical degradation
	Repeat electrical isolation	-	-	7th November 1980	Further isolation degradation observed. >50 μA leakage at 1750 volts dc
135362	JPL on delivery	35.16	-	20th May 1980	
	JPL Pre-test	34.58	Base	19th September 1980	Variation: -0.3% 2 Oct; -1.1% 15 Oct; -0.4% 3 Nov; -0.1% 5 Nov; -0.5% 7 Nov.
135493	RAE on delivery	36.59	Base	27th June 1980	-
	Ultra-violet irradiation	36.50	-0.2	12th August 1980	Dull appearance of front contacts
	JPL on delivery	36.28	-	10th September 1980	>50 μA leakage
	JPL Pre-test	35.89	New Base	19th September 1980	Frame sealant extruded both ends
	Thermal cycling	35.42	-1.3	2nd October 1980	No degradation observed
	Humidity cycling	35.55	-0.9	15th October 1980	No degradation observed
	Mechanical cycling	35.64	-0.7	3rd November 1980	No degradation observed
	Twist	36.02	+0.4	5th November 1980	No degradation observed
	Hail impact	35.93	+0.1	7th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	7th November 1980	Further isolation degradation >50 μA leakage after 13 seconds

TABLE 17 **Results of environmental testing on Arco solar modules**

MODULE	TEST APPLIED	REPEAT ELECTRICAL PERFORMANCE Maximum Power Output (watts)	% Change from Base Value	Date	REPEAT VISUAL INSPECTION AND OTHER COMMENTS
127C79-153	RAE on delivery	6.60	Base	16th June 1980	Edge sealant diffusing into encapsulant.
	Ultra-violet irradiation	6.62	+0.3	12th August 1980	Excessive colouring of encapsulant, dull appearance of front contacts and joining connectors
	JPL on delivery	6.98	-	10th September 1980	No change
	JPL Pre-test	6.93	New Base	18th September 1980	≥ 50 µA leakage at 40 volts dc.
	Temperature cycling	0.00	-100	2nd October 1980	8 cell interconnects fractured, further diffusion of edge sealant into encapsulant
	Humidity cycling	0.00	-100	15th October 1980	Delamination at both output terminals
	FURTHER TESTING INAPPROPRIATE				
127C79-271	JPL on delivery	7.36	-	24th July 1980	CONTROL MODULE
127C79-272	JPL on delivery	6.98	-	24th July 1980	1 cell cracked 15mm edge to edge.
	JPL Pre-test	6.92	Base	18th September 1980	50 µA leakage at 490 volts dc.
	Temperature cycling	6.85	-1.0	2nd October 1980	No degradation observed
	Humidity cycling	6.88	-0.6	15th October 1980	No degradation observed
	Twist	6.89	-0.4	5th November 1980	Short circuit to frame observed.
	Hail impact	6.85	-1.0	6th November 1980	Glass cover shattered on first hit with 38mm iceball at 4.5 ms^{-1}
	Repeat Electrical isolation	-	-	6th November 1980	≥ 50 µA leakage at 250 volts dc
127C79-273	JPL on delivery	6.86	-	24th July 1980	-
	JPL Pre-test	6.81	Base	18th September 1980	50 µA leakage at 790 volts dc.
	Temperature cycling	6.82	+0.1	2nd October 1980	No degradation observed
	Humidity cycling	6.75	-0.9	15th October 1980	No degradation observed
	Twist	6.79	-0.3	5th November 1980	No degradation or short/open circuit observed
	Hail impact	6.74	-1.0	6th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	6th November 1980	≥ 50 µA leakage at 740 volts dc
127C79-274	RAE on delivery	7.03	Base	1st August 1980	-
	Ultra-violet irradiation	7.05	+0.3	16th August 1980	Colouring of encapsulant, dull appearance of frontcontacts and interconnects
	JPL on delivery	7.53	-	10th September 1980	No change of appearance
	JPL Pre-test	7.46	New Base	18th September 1980	50 µA leakage at 550 volts dc.
	Temperature cycling	7.40	-0.8	2nd October 1980	No degradation observed
	Humidity cycling	7.38	-1.1	15th October 1980	Further colouring of encapsulant under glass cover
	Twist	7.38	-1.1	5th November 1980	No degradation or short/open circuit observed
	Hail impact	7.37	-1.2	6th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	6th November 1980	50 µA leakage at 250 volts dc

TABLE 18 Results of environmental testing on CEL modules

MODULE	TEST APPLIED	[illegible] Maximum Power Output (watts)	% Change from Base Value	Date	REPEAT VISUAL INSPECTION AND OTHER COMMENTS
361603	JPL on delivery	29.96	-	30th April 1980	-
	JPL Pre-test	29.03	Base	18th September 1980	Control Module: Variation: +0.6% 3 Oct; +0.8% 15 Oct; +0.4% 27 Oct; +1.2% 29 Oct; +1.4% 5 Nov.
361604	JPL on delivery	30.03	-	30th April 1980	-
	JPL Pre-test	29.58	Base	19th September 1980	-
	Thermal cycling	29.14	-1.5	3rd October 1980	No degradation observed
	Humidity cycling	29.04	-1.8	15th October 1980	No degradation observed
	Mechanical cycling	29.18	-1.4	27th October 1980	Intermittent open circuit due to loose terminal screw. Satisfactory after retightening
	Twist	28.87	-2.4	29th October 1980	No degradation observed
	Hail impact	29.32	-0.9	5th November 1980	Sensitivity sample. Cover glass damaged on 8th hit by 38mm ball at 28 ms^{-1}
361605	RAE on delivery	30.60	Base	26th June 1980	-
	Ultra-violet irradiation	30.76	+0.5	12th August 1980	Dull appearance to front cell contacts and cell collector grid fingers
	JPL on delivery	29.15	-	10th September 1980	$\geq$50 µA leakage at 660 volts dc.
	JPL Pre-test	28.87	New Base	19th September 1980	-
	Temperature cycling	28.89	+0.1	3rd October 1980	No degradation observed
	Humidity cycling	28.60	-0.9	15th October 1980	No degradation observed
	Mechanical cycling	28.76	-0.4	27th October 1980	No degradation observed
	Twist	28.57	-1.0	29th October 1980	No degradation observed
	Hail impact	28.78	-0.3	5th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	6th November 1980	Satisfactory
361606	RAE on delivery	30.45	Base	27th June 1980	-
	Ultra-violet irradiation	30.66	+0.7	23rd August 1980	Dull appearance to front cell contacts and cell collector grid fingers
	JPL on delivery	29.56	-	10th September 1980	$\geq$50 µA leakage at 510 volts.
	JPL Pre-test	28.67	New Base	19th September 1980	-
	Temperature cycling	28.97	+1.0	3rd October 1980	No degradation observed
	Humidity cycling	28.74	+0.2	15th October 1980	No degradation observed
	Mechanical cycling	28.88	+0.7	27th October 1980	No degradation observed
	Twist	28.79	+0.4	29th October 1980	No degradation observed
	Hail impact	29.00	+1.2	5th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	6th November 1980	Satisfactory
361612	JPL on delivery	28.40	-	30th April 1980	$\geq$50 µA leakage at 710 volts.
	JPL Pre-test	27.79	Base	19th September 1980	-
	Temperature cycling	28.04	+0.9	3rd October 1980	No degradation observed
	Humidity cycling	27.73	-0.2	15th October 1980	No degradation observed
	Mechanical cycling	27.77	-0.1	27th October 1980	No degradation observed
	Twist	27.67	-0.4	29th October 1980	No degradation observed
	Hail impact	27.85	+0.2	5th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	6th November 1980	Satisfactory

TABLE 19 Results of environmental testing on RTC modules

MODULE	TEST APPLIED	Maximum Power Output (watts)	% Change From Base Value	Date	REPEAT ELECTRICAL PERFORMANCE AND OTHER COMMENTS
508208	JPL on delivery	28.15	-	14th April 1980	-
	JPL Pre-test	29.99	Base	28th April 1980	-
	Thermal cycling	29.59	-1.3	12th May 1980	No degradation observed
	Humidity cycling	29.37	-2.1	22nd May 1980	No degradation observed
	Mechanical cycling	29.39	-2.0	2nd June 1980	No degradation observed
	Twist	29.37	-2.1	3rd June 1980	70 Ohm increase in series resistance during test
	Hail impact	29.74	-0.4	17th June 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	17th June 1980	Satisfactory
512662	JPL on delivery	27.81	-	11th April 1980	-
	JPL Pre-test	28.10	Base	28th April 1980	-
	Thermal cycling	27.20	-3.2	12th May 1980	Minor power degradation
	Humidity cycling	26.93	-4.2	22nd May 1980	Minor power degradation
	Mechanical cycling	27.59	-1.8	2nd June 1980	No degradation observed
	Twist	27.39	-2.5	3rd June 1980	No degradation observed
	Hail impact	27.65	-1.6	17th June 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	17th June 1980	Satisfactory
512663	RAE on delivery	28.94	Base	16th June 1980	-
	Ultra-violet irradiation	29.16	+0.8	12th August 1980	Front contacts and cell grid fingers dulled. Substrate slightly yellowed
	JPL on delivery	29.88	-	10th September 1980	$\geqslant$50 µA leakage observed with 1310 volts.
	JPL Pre-test	29.29	Base	19th September 1980	-
	Thermal cycling	29.44	+0.5	3rd October 1980	No degradation observed
	Humidity cycling	29.60	+1.1	16th October 1980	No degradation observed
	Mechanical cycling	29.25	-0.1	29th October 1980	No degradation observed
	Twist	29.51	+0.8	30th October 1980	No degradation observed
	Hail impact	29.75	+1.6	6th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	6th November 1980	Satisfactory
512664	RAE on delivery	27.63	Base	12th August 1980	-
	Ultra-violet irradiation	27.59	-0.1	13th August 1980	Front contacts and cell grid fingers dulled. Substrate slightly yellowed
	JPL on delivery	27.78	-	10th September 1980	$\geqslant$50 µA leakage observed with 1500 volts.
	JPL Pre-test	27.35	New Base	22nd September 1980	
	Thermal cycling	28.30	+3.5	3rd October 1980	No degradation observed
	Humidity cycling	28.00	+2.4	16th October 1980	No degradation observed
	Mechanical cycling	28.14	+2.9	29th October 1980	No degradation observed
	Twist	27.94	+2.2	30th October 1980	No degradation observed
	Hail impact	28.31	+3.5	6th November 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	6th November 1980	Satisfactory
512666	JPL on delivery	29.12	-	11th April 1980	-
	JPL Pre-test	29.36	Base	28th April 1980	-
	Thermal cycling	28.96	-1.4	12th May 1980	No degradation observed
	Humidity cycling	28.69	-2.3	22nd May 1980	1 cell cracked 35mm
	Mechanical cycling	28.83	-1.8	2nd June 1980	No degradation observed
	Twist	29.05	-1.1	3rd June 1980	No degradation observed
	Hail impact	29.01	-1.2	17th June 1980	No damage from 19mm iceball at 20 ms^{-1}
	Repeat electrical isolation	-	-	17th June 1980	Satisfactory

Note: Control Module was supplied from other modules available to JPL

TABLE 20 Results of environmental testing on Solarex modules

Code	Supplier	Motor	No of Test Runs Pump Matching	 Constant voltage	 Temp rise
A	Arco Solar	Mavilor M0300	44 + 51	24	7
B	Briau	Brot 450W	45	46	8
C	Briau	Brot 240W	34	45	8
D	ITC	Applied 480W	23	32	12
E	Omera	Brot 132W	33	33	9
F	Photowatt	Brot 190W	35	49	5
G	Pompes Guinard	Leroy Somer 370W	56	30	5
H	Soterem	CEM	34	26	Note 1
J	SEI	AEG	13	38	Note 2
P	SEM	SEM 370W		28 + 69	31
-	Selwood	Normand Electrical Ltd 746W	Note 3	48	

Note 1 Temperature rise test not carried out as motor urgently required in Sudan to replace motor lost in customs

Note 2 Temperature rise test not carried out on advice of manufacturer, due to risk of causing damage to electronic circuit

Note 3 Tested separately excited so only run at constant voltage to obtain efficiencies for pump testing

Table 21 Schedule of motor tests

CODE	SUPPLIER	MOTOR	WEIGHT (Kg)	RATED INPUT POWER (W)	RATED INPUT VOLTAGE (V)	AMBIENT TEMPERATURE 20-25°C EFFICIENCY AT 100% RATED POWER	AMBIENT TEMPERATURE 20-25°C EFFICIENCY AT 50% RATED POWER (90%V, 55%I)	AMBIENT TEMPERATURE 50°C APPROX EFFICIENCY LOSS AT 100% RATED POWER
A	Arco	Mavilor	5.5	400	54	77%	74%	2%
B	Briau	Brot 450W	15.0	450	48	86	83	3
C	Briau	Brot 240W	11.0	240	48	77	68	3
D	ITC	Honeywell	9.1	370	24	81	79	4
E	Omera	Brot 132W	3.6	132	30	77	72	0
F	Photowatt	Brot 190W	10.0	190	52	82	74	2
G	Pompes Guinard	Leroy Somer	24.1	370	31	81	79	2
H	Soterem	CEM	15.0	345	61	84	86	3
J	SEI	*AEG	2.7	250	60	72	78	Note 1
P	SEM	SEM	-	370	48	82	74	3

* : Brushless machine

Note 1: Not tested at elevated temperature, to avoid risk of damaging electronics

TABLE 22 Summary of motor test results

SYSTEM	a	b	c	d	e	f
A	70.4	- 69.2	- 16.6	-8.45×10^{-4}	0.136	-0.0674
B	36.1	- 12.3	- 25.8	-1.89×10^{-3}	0.265	-0.0867
C	51.3	- 12.5	-145	-3.99×10^{-3}	0.189	0.0308
D	83.3	- 14.7	- 32.7	1.36×10^{-3}	0.115	-0.169
E	84.0	- 54.5	- 85.7	-1.08×10^{-3}	0.116	-0.0340
F	28.2	- 19.9	18.4	-8.80×10^{-4}	0.330	-0.112
G	67.6	- 19.9	6.49	-1.24×10^{-3}	0.139	-0.0973
H	61.7	- 65.4	- 22.3	-1.69×10^{-3}	0.152	0.0607
J	49.8	-206.	203	0	0.188	-0.0494
P	33.1	- 14.0	15.5	-3.22×10^{-3}	0.292	-0.172

Speed $= N = aV + bI + c$

Torque $= T = dV + eI + f$

Table 23 Motor performance equations

MANUFACTURER: HITACHI METALS | TYPE LA 11A50 | VOLTAGE: 100V | RATED INPUT POWER: 50W | FREQUENCY: 50Hz

MEASUREMENT METHOD	VOLTAGE: AVO METER	CURRENT: AVO METER		POWER: DYNOMOMETER WATT METER			FREQUENCY: OSCILLOSCOPE				FORCE: RING DYNOMOMETER STRAIN GAUGE/ OSCILLOSCOPE				DISPLACEMENT: INDUCTIVE DISPLACEMENT TRANSDUCER/ OSCILLOSCOPE				WORK: FORCE-DISPLACEMENT LISSAJOUS FIGURE AND WEIGHING SHAPE				
MEASUREMENTS	UNITS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
VOLTAGE	V	40	40	40	45	45	45	45	45	50	50	50	50	55	55	55	55	60	60	60	65	65	65
CURRENT	mA	485	485	525	480	500	545	610	665	550	570	550	590	610	600	635	685	540	580	630	510	550	630
INPUT POWER (READING)	W	17	17	18.7	19.5	21.0	23.0	26.0	28.5	27	28	27	29	31	30	31.5	34.5	30.0	33.0	35	32	35	41
WATTMETER CORRECTION	W	-1.6	-1.6	-1.6	-2.0	-2.0	-2.0	-2.0	-2.0	-2.5	-2.5	-2.5	-2.5	-3.0	-3.0	-3.0	-3.0	-3.6	-3.6	-3.6	-4.2	-4.2	-4.2
INPUT POWER (CORRECTED)	W	15.4	15.4	17.1	17.5	19.0	21.0	24.0	26.5	24.5	25.5	24.5	26.5	28.0	28.5	28.5	31.5	26.4	29.4	31.4	27.8	30.8	37.8
OSCILLOSCOPE SENSITIVITY (FORCE)	mV/div	10	10	10	10	10	10	10	10	10	20	20	20	20	20	20	20	20	20	20	20	20	20
OSCILLOSCOPE SENSITIVITY (DISPLACEMENT)	mV/div	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
FREQUENCY	Hz	5	4.5	4.0	5.4	5.0	4.8	4.2	3.7	5.9	5.3	4.8	4.5	5.9	5.6	5.3	4.2	6.1	5.9	4.8	6.3	6.0	5.0
WEIGHT OF FORCE- DISPLACEMENT AREA	mg	221	221	238	223	228	245	246	263	250	128	117	125	123	122	118	124	77	92	104	91	105	85
MULTIPLYING FACTOR (WEIGHT TO WORK)	mJ/mg	.898	.898	.898	.898	.898	.898	.898	.898	.898	1.796	1.796	1.796	1.796	1.796	1.796	1.796	1.796	1.796	1.796	1.796	1.796	1.796
WORK OUTPUT	mJ	198	198	214	200	205	220	221	236	225	230	210	225	221	219	212	223	138	165	187	163	189	152
POWER OUTPUT	W	.992	.891	.855	1.081	1.024	1.056	.928	.873	1.33	1.22	1.01	1.01	1.30	1.23	1.12	.937	.842	.941	.898	1.03	1.13	.760
EFFICIENCY	%	6.5	5.8	5.0	6.2	5.4	5.0	3.9	3.6	5.4	4.8	4.1	3.8	4.6	4.6	3.6	3.0	3.2	3.2	2.9	3.7	3.7	2.0
LENGTH OF STROKE	mm	4.4	4.6	4.5	4.2	4.2	4.7	4.7	4.7	5.1	4.4	4.8	4.6	4.3	4.6	4.5	4.2	3.6	3.5	3.7	2.9	3.4	3.0
MEAN EFFECTIVE FORCE PER STROKE	N	22.5	21.7	23.9	23.6	24.2	23.6	23.6	25.3	28.6	24.9	21.8	24.2	25.5	23.7	23.4	26.3	18.9	23.4	25.1	28.1	27.6	25.3
PEAK FORCE	N	36.8	36.8	36.8	40.5	40.5	40.5	39.3	44.2	55.2	49.0	41.7	49.1	49.1	44.2	49.1	49.1	36.8	49.1	46.6	58.9	63.8	54.0

NOTES: This motor could not be made to operate on A.C. into a simple resistive load. The above results were obtained with a d.c. supply, reversing the polarity with mechanical switches to obtain the oscillatory motion.

TABLE 24 Results of tests on linear actuator

Code	Supplier	Pump													
A	Arco Solar	Sta-Rite	Inlet head	m	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-1.0	-2.0	-3.0	-5.0	-6.0
			Outlet head	m	8.5	6.7	4.8	2.8	1.0	0.2	4.25	4.25	4.25	4.25	4.25
			No. of runs		4	5	5	5	5	5	5	5	5	5	5
B	Briau	Duva 20	Inlet head	m	-3.0	-3.0	-3.0	-3.0	-3.0	-1.0	-5.0	-7.0	-8.0		
			Outlet head	m	8.0	6.1	3.9	2.0	0.34	5.9	5.9	5.9	5.9		
			No. of runs		5	5	5	5	5	5	5	5	5		
C	Briau	MGU. 40.1	Inlet head	m	-1.0	-1.0	-1.0	-1.0	-1.0	-2.0	-3.0				
			Outlet head	m	0.0	1.2	2.1	2.9	4.0	2.2	2.2				
			No. of runs		7	6	6	5	3	4	3				
D	ITC	Roth U-140	Inlet head	m	0.1	0.1	0.1	0.1	0.1						
			Outlet head	m	1.4	2.5	4.3	5.9	8.3						
			No. of runs		5	5	5	5	3						
E	Omera Segid	Essa Mico	Inlet head	m	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-2.0	-3.0	-4.0		
			Outlet head	m	4.6	4.0	3.0	2.08	1.1	0.28	0.28	0.28	0.28		
			No. of runs		1	4	5	5	5	5	5	5	1		
F	Photowatt	Breguet	Inlet head	m	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-2.0	-4.0			
			Outlet head	m	4.5	4.1	3.0	1.9	0.84	0.16	1.16	1.16			
			No. of runs		4	1	4	5	7	8	8	1			
G	Pompes Guinard	Alta XS	Inlet head	m	-1.0	-1.0	-1.0	-1.0	-2.0	-3.0	-4.0	-5.0	-6.0		
			Outlet head	m	5.97	3.99	1.94	0.25	4.0	4.0	4.0	4.0	4.0		
			No. of runs		8	8	8	8	8	8	8	6	2		
H	Soterem	Salmson	Inlet head	m	-3.0	-3.0	-3.0	-3.0	-5.0	-0.7					
			Outlet head	m	6.3	4.0	2.1	0.15	5.0	5.0					
			No. of runs		6	6	6	10	5	3					
J	Solar Electric International	KSB	Inlet head	m	0.5	0.5	0.5								
			Outlet head	m	5.8	3.9	2.0								
			No. of runs		3	5	5								
K	Godwin	Cobra	Inlet head	m	-3.0	-3.0	-3.0	-3.0	-3.0	-1.0	-5.0	-7.0			
			Outlet head	m	8.4	6.1	4.1	2.9	0.26	2.9	2.9	2.9			
			No. of runs		4	6	6	7	8	8	7	5			
L	Godwin	Hand pump	Inlet head	m											
			Outlet head	m											
			No. of runs												
M	Mono	C32 - B620	Inlet head	m											
			Outlet head	m											
			No. of runs												
N	Selwood	Mk. 4 Simplite	Inlet head	m											
			Outlet head	m											
			No. of runs												

Table 25 Schedule of governing head conditions for pump tests

CODE	SUPPLIER	PUMP	TYPE	MASS kg	SPEED RANGE (RPM)	STARTING TORQUE Nm	STALLING TORQUE Nm	BEST EFFICIENCY η %	SPEED FOR BEP (b) (RPM)	HEAD FOR BEP (b) (m)	FLOW FOR BEP (b) (l/s)	SPECIFIC SPEED 1 TYPE NUMBER (c) K	SPEED SENSITIVITY %	MAX EFFICIENCY AT 25% INCREASED HEAD %	MAX. EFFIC. AT INCREASED HEADS %		MAX. SUCTION HEAD m	[illegible]
															5m	10m		
A	ARCO SOLAR	STA-RITE J ½ Hp	CENTRIFUGAL	9.5	3250 to 2000	0.09	0.09	46	2750	9	1.3	0.360	27	42	45	>47	6	No
B	BRIAU	BRIAU DUVA 20	PISTON	90	194 to 35	6.30	6.30	> 50 (a)	150 - 200	>16 (a)	0.2-0.4	-	>80	> 50	27	41	> 8	Yes
C	BRIAU	BRIAU MGV-40-1	CENTRIFUGAL	44	2250 to 1500	1.25	0.30	> 30 (a)	2250	5	1.65	0.536	11	~ 40	>40	out of range	2 - 3	No
D	ITC SOLAR CORPORATION	ROTH 107	REGENERATIVE	13	1750 to 700	0.39	0.23	> 35	1250	7	0.65	0.140	44	~ 32	32	>30	N/A	[illegible]
E	OMERA SEGID	ESSA MICO	CENTRIFUGAL	28	2270 to 1850	-	-	23 (e)	2270	5.5	0.55	0.326	12	out of range	25	out of range	3 - [illegible]	[illegible]
F	PHOTOWATT	BREGUET KSB	CENTRIFUGAL	54	1400 to 1000	0.24	0.19	45 (a)	1400	5.5	1.85	0.317	~ 4	out of range	>46	out of range	2 - 3	No
G	POMPES GUINARD	ALTA XB 600/12	CENTRIFUGAL	90	1900 to 1400	0.83	0.43	52	1900	10.5	2.15	0.285	~ 5	~ 50	~46	>55	5	No
H	SOTEREM	DELOULE PE 9908	PISTON	95	3300 to 1900	0.38	0.34	40	170 to 200	10.5	1.05	-	>80	~ 25	<25	40	5 - 6	Yes
J	SOLAR ELECTRIC INTERNATIONAL	KSB M	CENTRIFUGAL	10	2600 to 2200	(d)	(d)	52	2600	4.5	2.10	0.729	~ 8	> 50	>52	out of range	N/A	Yes
K	GODWIN	GODWIN COBRA	CENTRIFUGAL		9000 to 5000	0.80	0.76	12	9000	9	0.6	0.802	20	~ 10	~9	>11	7	Yes
L	GODWIN	GODWIN X HAND-PUMP	PISTON		20 to over 40	-	-	> 21 (a)	20 - 40	>11 (a)	0.5-1.5	-	>80	> 21	10	19	N/A	Yes
M	MONO PUMPS	MONO C32 P631	ROTARY SCREW		1100 to 260	-	-	> 32 (a)	1100	>16 (a)	2.20	-	36	> 32	22	31	N/A	Yes
N	SELWOOD PUMPS	SIMPLITE 2 MK 4	DIAPHRAGM		70 to 30	-	-	> 37	35	11	0.50	-	out of range	> 37	28	>35	> 5	Yes

TABLE 26 Principal features of pump performance in laboratory

Notes:
(a) Optimum head exceeds range covered by tests so significantly higher efficiencies may be possible
(b) BEP = best efficiency point
(c) Dimensionless form of specific speed, "Type Number" K (referred to in Intl Standard ISO 2548) is defined as

$$K = \frac{2\pi n Q^{\frac{1}{2}}}{(gH)^{\frac{3}{4}}}$$

where n = rotational speed
Q = flow rate
H = total head

(d) No data as pump and motor enclosed
(e) Evidence of pump damage which may account for low efficiency

HEATER VOLTAGE (V)	INPUT CURRENT (A)	HEAD TEMPERATURE (°C)	HEAD HEAT LOSSES (W)	ENGINE INPUT POWER (W)	FLOW l/s	HYDRAULIC POWER (W)	ENGINE/PUMP EFFICIENCY (%)
STATIC HEAD 5 METRES							
200	6.0	610	34	1166	0.18	8.8	0.76
210	6.2	635	34	1268	0.31	15.1	1.16
STATIC HEAD 4 METRES							
200	6.0	610	34	1166	0.44	17.3	1.48
210	6.2	635	34	1268	0.66	23.5	1.85
STATIC HEAD 1 METRE							
175	5.4	510	29	916	0.77	7.5	0.82

TABLE 27 Summary of test results from Sunpower Incorporated Stirling cycle engine/pump

Run	Freon Enthalpy gain in collector (kJ/kg)	Freon temperature at engine inlet (^{o}C)	Freon Mass flowrate (kg/s)	Engine input power (kW)	Engine speed cycles/min	Flowrate (l/s)	Head (m)	Hydraulic power output (kW)	Engine/Pump efficiency %	Pump volumetric efficiency %
1	209	68.5	.0304	6.35	68	1.12	19.9	0.219	3.45	78
2	209	70.0	.0308	6.43	68	1.09	19.8	0.212	3.30	76
3	210	73.0	.0272	5.71	53	0.84	23.9	0.197	3.45	75
4	216	85.5	.0371	8.00	57	0.87	26.1	0.223	2.79	72
5	216	85.0	.0361	7.80	56	0.87	27.2	0.232	2.97	73
6	205	58.5	.0252	5.16	71	1.22	12.3	0.147	2.85	82
7	203	61.0	.0207	4.20	56	1.19	10.5	0.123	2.93	99
8	210	80.0	.0355	7.46	62	1.35	15.7	0.208	2.79	96
9	212	84.5	.0379	8.02	60	1.32	15.1	0.196	2.44	97
10	208	67.0	.0273	5.67	65	1.42	14.3	0.199	3.51	97

TABLE 28 Results of tests on Dornier system

Run	1	2	3	4
Generator voltage (Volt):	124.8	125.7	127.6	128.4
Generator current (A):	39.5	38.5	28.5	29.5
Turbine frequency (Hz):	850	840	750	760
Vapour generator pressure (mbar):	2100	2010	1630	1700
Condenser pressure (mbar):	380	379	360	362
Ambient temperature(°C):	18.5	18.5	17.5	17.0
Vapour generator temperature (°C):	72.1	71.1	63.9	64.9
Condenser temperature (°C):	23.4	23.2	22.1	22.2
Vapour generator hot water input temp (°C):	79.0	79.3	71.4	71.3
Vapour generator hot water outlet temp (°C):	74.3	73.0	66.1	67.3
Condenser cold water input temp (°C):	19.3	19.2	18.4	18.9
Condenser cold water outlet temp (°C):	24.5	24.4	23.3	23.5
Water flow rate vapour generator (m^3):	15.0	10.4	10.1	15.4
m^3/hr condenser	12.6	12.6	12.6	12.6

(a) Measurements

Run	1	2	3	4
Heat supplied (kW)	82.19	76.38	62.4	70.07
Heat removed (kW) from the condenser	76.44	71.44	71.46	67.62
Turbo generator output (kW)	4.93	3.58	3.64	3.79
Overall efficiency %	6.0	4.7	5.8	5.4
Carnot efficiency %	14.1	13.9	12.4	12.6
Percentage of carnot efficiency %	42.6	33.8	46.7	42.8

(b) Results

Table 29 Tests on Ormat Energy Converter

Date	Time (Hrs)	Solar Irad. in Collector Plane (W/m^2)	Diffuse Solar Irrad (%)	Water Temp. (°C)	Ambient Temp. (°C)	Collector Pressure (PSI)	Pumping Speed (strokes per min)	Static Head m.	Flowrate (litres/sec)	Hydraulic Power Output (watts)	Overall System Efficiency %
26 Mar 80	1200	1004	8	20.5	16	45	19½	7.5	0.56	41.2	0.80
"	1210	1005	8	20.5	15	45	20½	7.5	0.59	43.4	0.85
"	1220	997	8	20.5	15	45	21	7.5	0.60	44.2	0.87
"	1230	1003	8	20.5	15	45	21	7.5	0.59	43.4	0.85
"	1240	983	8	20.5	15	45	21	7.5	0.63	46.4	0.92
"	1250	967	8	20.5	15	44	21	7.5	0.59	43.4	0.88
"	1300	962	9	20.5	15	44	21	7.5	0.61	44.9	0.91
"	1311	944	10	20.5	15	43	21	7.5	0.60	44.2	0.92
"	1500	422	45	20.5	14	41	7	7	0.12	8.2	0.38
26 Mar 80	1331	863	12	20.5	15	46	12½	12	0.26	30.6	0.69
"	1342	881	12	20.5	15	47	13	12	0.30	35.3	0.78
"	1350	879	12	20.5	15	45	13	12	0.33	38.8	0.86
"	1358	790	32	20.5	15	44	12½	12	0.32	37.7	0.93
"	1410	661	35	20.5	15	43	10	12	0.25	29.4	0.87
"	1420	558	37	20.5	15	42	9½	12	0.22	25.9	0.91
"	1430	498	47	20.5	14	42	9	12	0.16	18.8	0.74
27 Mar 80	0935	665	10	21	16	43.5	15	7.5	0.26	19.1	0.56
"	0945	677	11	21	16	43.5	15½	7.5	0.32	23.6	0.68
"	0955	775	10	21	16	43.5	16	7.5	0.38	28.0	0.71
"	1005	860	10	21	16	44	13	7.5	0.44	32.4	0.74
"	1015	845	10	21	16	44	16½	7.5	0.37	27.2	0.63
"	1027	912	10	21	16	45	17	7.5	0.48	35.3	0.76
"	1035	933	10	21	16	45.5	17	7.5	0.48	35.3	0.74

Table 30 . Results of tests on SPC Solar Pump.

1 Plane PV arrays

Nominal max power Wp	100	500	3000
Total installed cost $	2000	6500	39000

(interpolate linearly between points)

2 Plane PV array with 1-axis tracking system
(inclination seasonally adjusted)

Nominal max power Wp	100	500	3000
Total installed cost $	3500	8000	54000

3 DC motors

Weight kg	1	30
Total cost $	50	690

4 Pumps

Weight kg	5	100
Total cost - centrifugal $	115	2300
- positive displacement $	155	3100

5 Pipework
(a) Fixed costs

Systems with surface pump $	90
Systems with submersible pump $	60

(b) Straight pipe

Pipe dia mm	25	37	50	75
Cost per metre $	6	8	10	12

6 Maximum Power Point Tracker (MPPT)
All sizes : $ 250

TABLE 31 Reference cost data for PV model studies

Solar day:	Type 1
Date:	Equinox
Ambient temperature:	30°C
Water temperature:	20°C
Array temperature:	50°C
Array type:	Fixed plane array
Array inclination	15° to horizontal
Array azimuth:	Due South
Array latitude:	15° North
Static head Hs:	5.0m
Pipe friction f:	0.007 in $h_l = \frac{4flv^2}{2gd}$
Time step:	60 mins

TABLE 32 General reference conditions for PV model studies

System Code	A	B	C	D	E	F	G	H	J
Supplier	ARCO	BRIAU	BRIAU	ITC	OMERA	PHOTOWATT	PG	SOTEREM	SEI
Array-module make	Arco	Photowatt	Solar	Arco	RTC	Photowatt	Fr. Photon	Motorola	Arco
-module type	2000	31F 36GC	G12 361	2000	BPX47C	41F51GC	FPC 36V	MSP43A40	2000
-No of modules	16	16	16	16	6	10	20	12	8
-rows in series	4	4	4	2	2	2	2	4	8
-rows in parallel	4	4	4	8	3	5	10	3	0
-nom power Wp(1)	528	308	600	528	200	268	600	480	264
-nom voltage V_{oc}	64.4	48.0	33	32.2	32.8	32	31	63.2	129
Motor-make	Mavilor	Brot	Brot	Honeywell	Brot	Brot	Leroy-Somer	CEM	AEG
-type	PMDC	PMDC	PMDC	PMDC	PMDC	PMDC	PMDC	PMDC	brushless DC
-rated power W	400	450	240	480	132	190	370	345	200
-rated voltage V	54	48	48	24	30	52	31	61	110
-weight kg	5.5	15.0	11.0	9.1	3.6	10.0	24.1	15.0	2.7
Pump-make, reference	Sta-rite	Duva 20	MGV-40-1	60-8	ESSA-MICA	Breguet KSB	AltaXS 600/12	PE9908	KSB-M
-type	½hp cent	pos. disp	cent	regen.	cent	cent	cent	pos. disp	cent
-weight kg	9.5	90.1	44.1	12.7	27.7	54.5	90.1	95.5	10.0
Transmission-type	direct	belt	direct	direct	direct	direct	direct	belt	direct
-ratio (motor/pump)	1.0	8.5 : 1	1.0	1.0	1.0	1.0	1.0	13 : 1	1.0
- efficiency % (estimated)	100	(3)	100	100	100	100	100	(3)	100
Pipework-suction dia mm	50	50	50	-	50	50	50	50	-
- suction length m	2.0	2.0	2.0	-	2.0	2.0	2.0	2.0	-
-90° bends (suction)	1	1	1	-	1	1	1	1	-
-foot valve	1	1	1	-	1	1	1	1	-
-delivery dia mm	50	50	50	50	50	50	50	50	50
-delivery length m (2)	Hg+4.0	Hg+4.0	Hg+4.0	Hg+6.0	Hg+4.0	Hg+4.0	Hg+4.0	Hg+4.0	Hg+6.0
- 90° bends (delivery)	2	2	2	2	2	2	2	2	2

(1) at 1000 W/m^2 and 28°C

(2) Hg = static head

(3) included in pump performance data

Table 33 PV system reference data

System	TOTAL VOLUME OF WATER PUMPED (M^3) head = 2.5m	5m	7.5m	10m
A. ARCO	52.9	44.9	34.6	25.1
B. Briau Duva	19.2	16.0	15.2	12.6
C. Briau	N/D	45.7	-	-
D. ITC	37.8	30.7	24.3	17.4
E. Omera	18.0	11.2	-	-
F. Photowatt	N/D	21.5	-	-
G. Guinard	75.3	70.1	57.6	33.0
H. Soterem(1)	-	34.9	-	-
J. SEI	N/D	28 (2) 29.9(3)	-	-

Notes: N/D = no data
(1) with MPPT (10% losses) and perfect tracking
(2) with MPPT (10% losses)
(3) operating with array voltage halved, power constant

TABLE 34 Daily water pumped as a function of head

SYSTEM	HAZY DAY PERFORMANCE		CLEAR DAY OVERALL DAILY EFFICIENCY %
	VOLUME PUMPED (m^3), H = 5m	OVERALL DAILY EFFICIENCY %	
A. ARCO	34.0	1.7	1.7
B. Briau Duva	13.0	0.9	0.9
C. Briau	25.3	0.9	1.3
D. ITC	22.2	1.0	1.1
E. Omera	6.2	0.7	0.9
F. Photowatt	5.7	0.5	1.4
G. Pompes Guinard	56.5	2.1	2.1
H. Soterem (1)	23.8	1.1 (2)	1.3 (2)
J. SEI (3)	15.4	1.6	2.2

Notes: (1) with MPPT (10% losses) and perfectly tracking array
(2) based on solar irradiation incident on array
(3) with MPPT (10% losses)

TABLE 35 Comparison of system performance on standard clear and hazy days

SYSTEM	DAILY OUTPUT AS SUPPLIED (H = 5m) (m^3)	OPTIMUM NO OF CELLS IN SERIES ±%	OUTPUT WITH OPTIMISED SERIES STRING (m^3)	INCREASE DUE TO OPTIMISATION %
A ARCO	44.9	-20	50.6	13
B Briau Duva	16.0	+10	17.2	8
C Briau	45.7	-20	50.2	10
D ITC	30.7	-10	32.2	5
E Omera	11.2	0	-	0
F Photowatt	21.5	+10	23.7	10
G Guinard	70.1	0	-	0

TABLE 36 Effect of changing array cell series connections on system performance (for constant total array power)

	SPECIFIC CAPITAL COST AS SUPPLIED $/kJ per day	OPTIMUM POWER CHANGE (AT OPTIMUM VOLTAGE) ± %	SPECIFIC CAPITAL COST OF OPTIMISED SYSTEM $/kJ per day	REDUCTION IN SPECIFIC CAPITAL COST %
A ARCO	3.4	-10	3.0	12
B Briau Duva	9.8	0	9.12	7
C Briau	4.6	+20	3.4	25
D ITC	5.0	0	4.8	5
E Omera	7.4	+70 (1)	5.8	21
F Photowatt	5.3	+20	3.8	27
G Guinard	3.1	0	3.1	0

Note:(1) Results may be affected by low pump performance data from laboratory

TABLE 37 Effect of changing array power (at optimum voltage) on Specific Capital Cost

SYSTEM	PRICE PAID (DELIVERED) $	CALCULATED COST $	PAID/ CALCULATED	CALCULATED SYSTEM COST PER PEAK WATT $/Wp
A. Arco	5,063	7,430	0.7	14.1
B. Briau Duva	14,065	7,670	1.8	24.9
C. Briau	22,094	9,280	2.4	15.5
D. ITC	22,462	7,550	3.0	14.3
E. Omera	16,417	4,070	4.0	20.4
F. Photowatt	14,219	5,590	2.5	20.9
G. Guinard	17,450	10,630	1.6	17.7
H. Soterem	30,475	11,300	2.7	23.5
J. SEI	8,625	4,580	1.9	17.3

TABLE 38   Comparison of calculated costs and prices paid for systems

System	Specific Capital Cost $ /kJ per day (5)			
	Clear Conditions (1)		Hazy Conditions (1)	
	as supplied	V&P optimised	as supplied	V&P optimised
A ARCO	3.4	3.0	3.5	2.6 (2.8)(4)
B Briau Duva	9.8	9.1	9.3	8.8 (4.6)(4)
C Briau	4.1	3.4	5.8	
D ITC	5.0	4.8	5.4	
E Omera	7.4	5.8	10.5	
F Photowatt	5.3	3.8	15.5	
G PG	3.1	3.1	2.8	2.8
H Soterem(2)	6.7	-	7.7	-
J SEI(3)	3.3	-	4.7	-

Notes:

(1) Normalised to 6kWh/m^2 for standard solar day

(2) With MPPT (10% losses) and perfect tracking system

(3) Includes MPPT (10% losses), Fixed array

(4) Using configuration optimised for clear conditions

(5) 5m static head

TABLE 39 Comparison of Specific Capital Cost for all systems tested

MODIFICATION	Effective[1] Overall Daily efficiency %	Specific Capital Cost $ / kJ per day	Daily output at 5m head (standard clear day) (m^3)	Effect compared with basic system	
				Volume pumped	Spec Capital Cost
None - System as supplied	1.7	3.4	44.9	1.00	1.00
Voltage and power optimized by changing array cells series/parallel arrangement	2.0	3.0	46.6	(2)	0.88
MPPT (10% losses) (Maximum Power Point tracker)	1.9	3.1	51.2	1.14	0.91
Manual tracking of sun (2-adjustments of array position per day)	2.2	2.6	57.7	1.30	0.94
Voltage and power optimized plus manual tracking	2.5	2.3	60.3	(2)	0.68
MPPT plus manual sun tracking	2.4	2.5	62.3	1.39	0.74

Notes: (1) based on irradiation on fixed array (referenced to array area).
(2) power is reduced and so pumped volume is not comparable with basic system.

TABLE 40 Results of making 'improvements' to A PV pumping system by using the mathematical simulation model

SOLAR COLLECTOR TYPE	CONSTRUCTION DETAILS	COST ($\not{\!\!}$/m^2)	DATA SOURCES FOR PERFORMANCE DATA
1. flat plate, single glazed	Matt black non selective absorber, single glass aperture covers conventional construction	108	Various published test results and mathematical modelling
2. flat plate, double glazed	Matt black, non-selective absorber, two glass aperture covers, conventional construction	130	Various published test results and mathematical modelling
3. evacuated tube	Selective surface absorber in evacuated tube with reflective backing	230	Results of independant tests on collectors manufactured by Sanyo (Japan) and Owens (USA). Manufacturers' data from Philips (Europe) and Ormat (Israel)
4. compound parabolic	Deep parabolic trough reflectors which reflect direct and also diffuse radiation from the general direction of the sun onto the absorber. Single sheet aperture cover. Sun tracked	120	Calculated performance from mathematical modelling
5. East-West low concentration trough	Low concentration cylindric parabolic trough reflector with absorber tube in glass receiver cover. Does not require continuous tracking if axis aligned East-West but occasional repositioning required	120	Derived from mathematical modelling
6. North-South trough, unglazed absorber	Glass reflector parabolic trough reflector, unglazed non selective absorber tube, aligned N-S single axis sun tracking	110	Derived from mathematical modelling
7. North-South trough, glazed absorber	As collector type 6 but with absorber tube in glass receiver cover.	120	Derived from mathematical modelling
8. North-South trough, Manufacturer A	Commercially available collector. Metallized acrylic reflector, steel absorber tube with black chrome reflective surface and glass receiver cover. Single axis sun tracking	140	Results of tests by Sandia National Laboratories, USA
9. North-South trough, Manufacturer B	Commercially available collector. Aluminized reflector, black chrome selective surface on absorber tube, glass receiver cover. Single axis sun tracking	140	Results of tests by Sandia National Laboratories, USA
10. Linear Fresnel lens concentrator	Commercially available collector, black chrome selective surface on copper absorber tube, in steel trough fibre glass insulated and with acrylic Fresnel lens concentrator/cover. Single axis sun tracking	140	Manufacturer's data
11. Point focus parabolic dish - type A	Existing design. Mirror glass mosaic parabolic dish reflector of concentration ratio 40 non-selective absorber. Two axis sun tracking	190	Determined by mathematical modelling and designers data
12. Point focus parabolic dish - type B	Commercially available parabolic dish mirror reflector of concentration 200 non-selective spherical surface copper absorber. Lower dish reflectance - receiver absorbtance product than collector 11. Two axis sun tracking	190	Based upon manufacturer's data
13. Central receiver - power tower	Array of coupled reflectors focussing onto a stationary central receiver. Concentration ratio of 50. Two axis sun tracking	120	Determined by mathematical modelling and designers data

TABLE 41 Solar collector types used in thermal design studies

System Option	Flat plate solar collector Freon organic Rankine cycle engine Non-tracking 2kWh/day engine output		
Solar Collector	Area required	: $36.3m^2$	
	Cost basis	: $108/$m^2$	
	Component cost	:	$3920
Engine	Equivalent swept volume	: 1.11 litres	
	Cost basis	: $525/litre	
	Component cost	:	$ 580
	Additional fixed costs	:	$ 690
Condenser	Equivalent tube length	: 50.7m	
	Cost basis	: $7/m	
	Component cost	:	$ 355
Pump (10m depth)	Fixed cost	:	$ 400
Well head assembly and piping	Fixed cost	:	$ 200
		Total cost	$6145

TABLE 42 Example of thermal system costing

SYSTEM OPTION	COLLECTOR TYPE (SEE TABLE 41)	TRACKING	ENGINE TYPE	OPTIMUM OPERATING TEMPERATURE (NOTE 1) (°C)	2kWh ENGINE DAILY OUTPUT (NOTE 2) PEAK ENGINE POWER OUTPUT WATTS	COLLECTOR AREA m^2	CAPITAL COST ¢	SPECIFIC CAPITAL COST ¢/kJ (per day)
1	Flat plate single glazed	Yes	Organic Rankine Cycle (R11)	80	278	20.6	4410	2.0
2	Flat plate single glazed	No	Organic Rankine Cycle (R11)	80	491	36.3	6150	2.8
3	Flat plate double glazed	Yes	Organic Rankine Cycle (R11)	90	274	18.8	4540	2.1
4	Flat plate double glazed	No	Organic Rankine Cycle (R11)	90	474	32.5	6300	2.9
5	Evacuated tube	Yes	Organic Rankine Cycle (R11)	150	256	8.1	3680	1.7
6	Evacuated tube	No	Organic Rankine Cycle (R11)	150	409	12.9	4530	2.1
7	Compound parabolic	Yes	Organic Rankine Cycle (R11)	130	261	10.3	3210	1.5
8	E-W low concentration trough	No	Organic Rankine Cycle (R11)	105	777	35.0	6170	2.9
9	N-S trough unglazed absorber	Yes	Organic Rankine Cycle (R11)	100	492	20.9	4360	2.0
10	N-S trough glazed absorber	Yes	Organic Rankine Cycle (R11)	140	441	13.1	3490	1.6
11	N-S parabolic trough - Manufacturer A	Yes	Organic Rankine Cycle (R11)	150	384	10.0	3310	1.5
12	N-S parabolic trough - Manufacturer A	Yes	Steam, condenser @ 0.16 bar	190	401	10.8	3850	1.8
13	N-S parabolic trough - Manufacturer A	Yes	Steam, condenser @ 1 bar	190	401	16.4	4110	1.9
14	N-S parabolic trough - Manufacturer B	Yes	Organic Rankine Cycle (R11)	150	384	9.9	3290	1.5
15	N-S parabolic trough - Manufacturer B	Yes	Steam, condenser @ 0.16 bar	190	400	10.6	3820	1.8
16	N-S parabolic trough - Manufacturer B	Yes	Steam, condenser @ 1 bar	190	400	16.1	4070	1.9
17	Linear Fresnel lens concentrator	Yes	Organic Rankine Cycle (R11)	150	451	13.2	3800	1.8
18	Linear Fresnel lens concentrator	Yes	Steam, condenser @ 0.16 bar	190	530	17.0	4930	2.3
19	Linear Fresnel lens concentrator	Yes	Steam, condenser @ 1 bar	190	530	25.8	5520	2.6
20	Point focus parabolic dish - type A	Yes	Organic Rankine Cycle (R11)	150	370	7.8	3370	1.6
21	Point focus parabolic dish - type A	Yes	Steam, condenser @ 0.16 bar	190	382	8.3	3860	1.8
22	Point focus parabolic dish - type A	Yes	Steam, condenser @ 1 bar	190	382	12.6	4170	1.9
23	Point focus parabolic dish - type A	Yes	Stirling Cycle	500	443	4.4	2420	1.1
24	Point focus parabolic dish - type B	Yes	Organic Rankine Cycle (R11)	150	361	8.6	3770	1.7
25	Point focus parabolic dish - type B	Yes	Steam, condenser @ 0.16 bar	190	366	8.8	4180	1.9
26	Point focus parabolic dish - type B	Yes	Steam, condenser @ 1 bar	190	366	13.3	4550	2.1
27	Point focus parabolic dish - type B	Yes	Stirling Cycle	500	406	4.3	2660	1.2
28	Central receiver - power tower	Yes	Organic Rankine Cycle (R11)	150	366	7.7	2790	1.3
29	Central receiver - power tower	Yes	Steam, condenser @ 0.16 bar	190	377	8.1	3230	1.5
30	Central receiver - power tower	Yes	Steam, condenser @ 1 bar	190	377	12.3	3220	1.5
31	Central receiver - power tower	Yes	Stirling Cycle	500	423	4.0	2060	1.0

Note 1. Ambient temperature 20°C, coolant temperature 30°C
Note 2. 6kWh/m^2 (21.6MJ/m^2) daily Global solar irradiation

TABLE 43 Results of thermal systems mathematical modelling

System Supplier	Description	Peak Power Recorded	Peak Efficiency Recorded	Comments
Solar Pump Corporation (USA)	- Direct evaporating flat plate solar collector - Freon Rankine Cycle Engine - Positive displacement pump	45 watts (hydraulic)	0.9% (overall)	- simple innovative design - difficulty experienced in making system operational - further development recommended to improve reliability and efficiency
Dornier Systems GmbH (West Germany)	- Heat pipe solar collector array - Freon Rankine Cycle Engine - Positive displacement pump	230 watts (hydraulic)	3.5%(engine/pump) 1.9%(estimate of overall)	- complex but well engineered design - simplification of design recommended to make it more appropriate to the application
Ormat Turbines Limited (Israel)	- Freon Rankine Cycle engine incorporating a turbine - Electrical generator	4 930 watts (electrical)	6.0% (engine/generator)	- complex but well engineered design - high efficiency - simplification of design recommended to make it more appropriate to the application
Sunpower Incorporated (USA)	- Stirling Cycle Engine - Diaphragm Pump	23.5 watts (hydraulic)	1.8%(engine/pump)	- component failure during test - low efficiency - simple design but development recommended to improve reliability and efficiency

Table 44 Summary of results of tests on thermal systems

FIGURES

LIST OF FIGURES

FIGURE

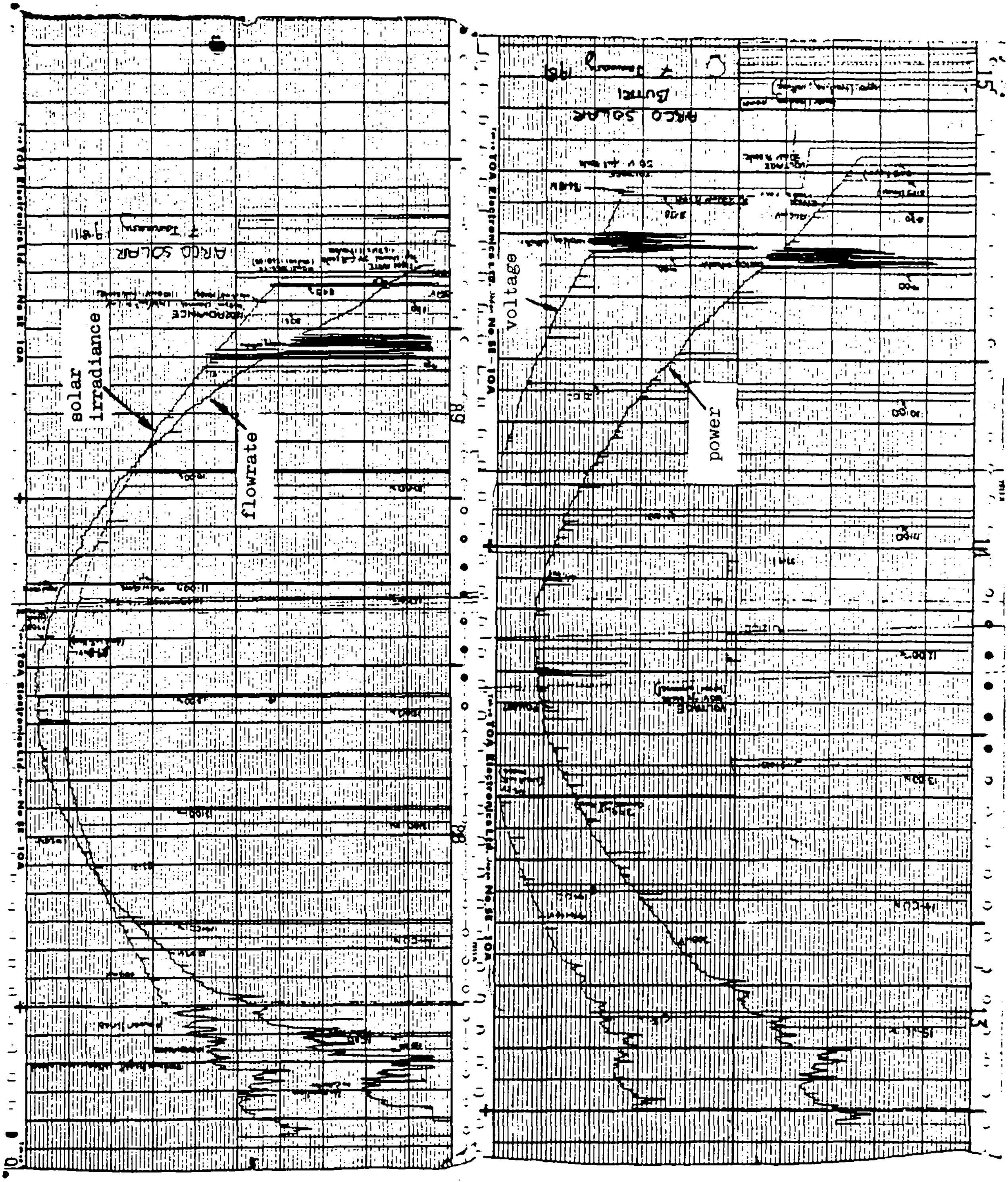


FIGURE 1 Example of chart recorder trace

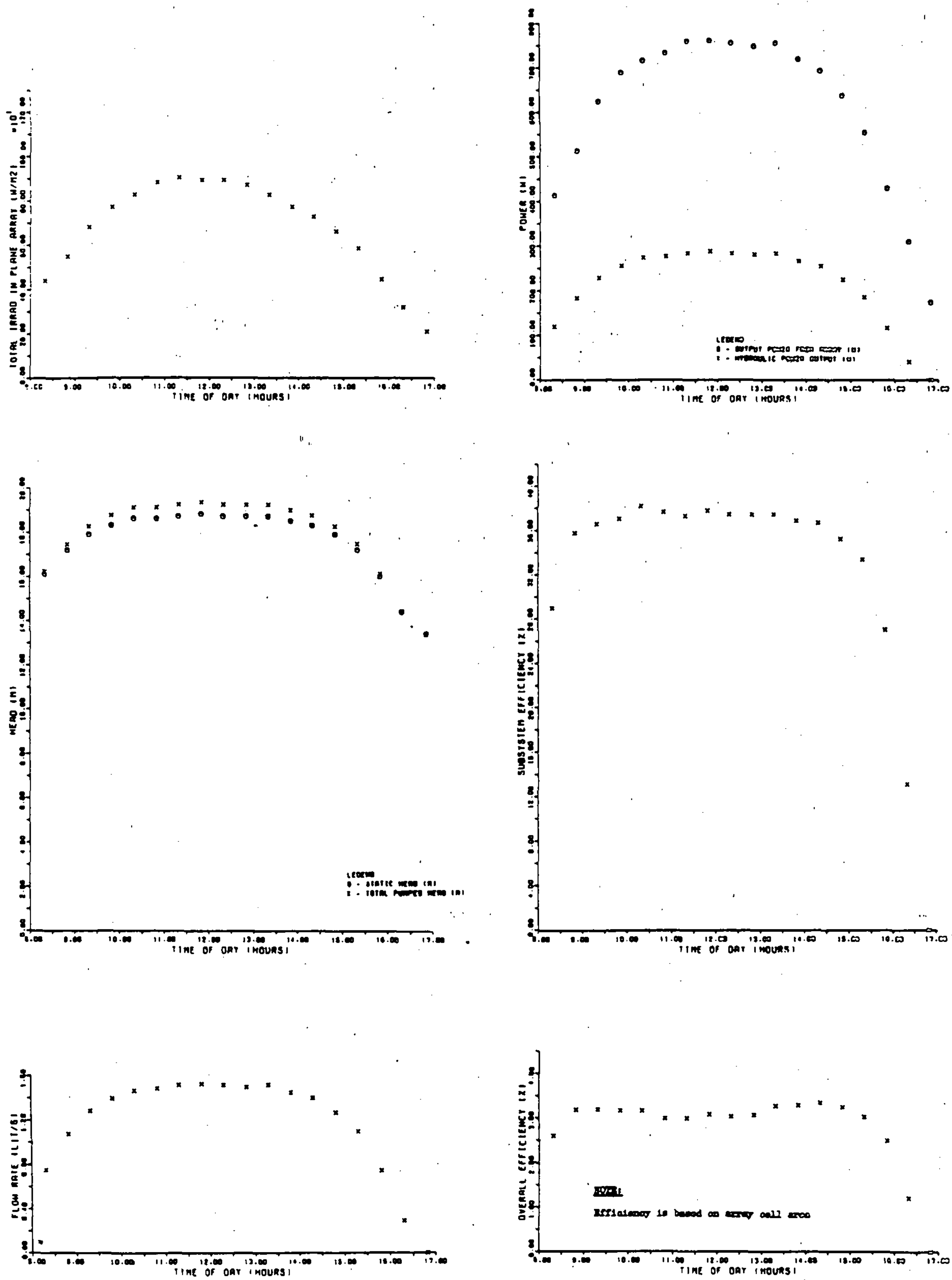


Figure 2 Performance of Pompes Guinard system in Mali v. time (15 September 1980)

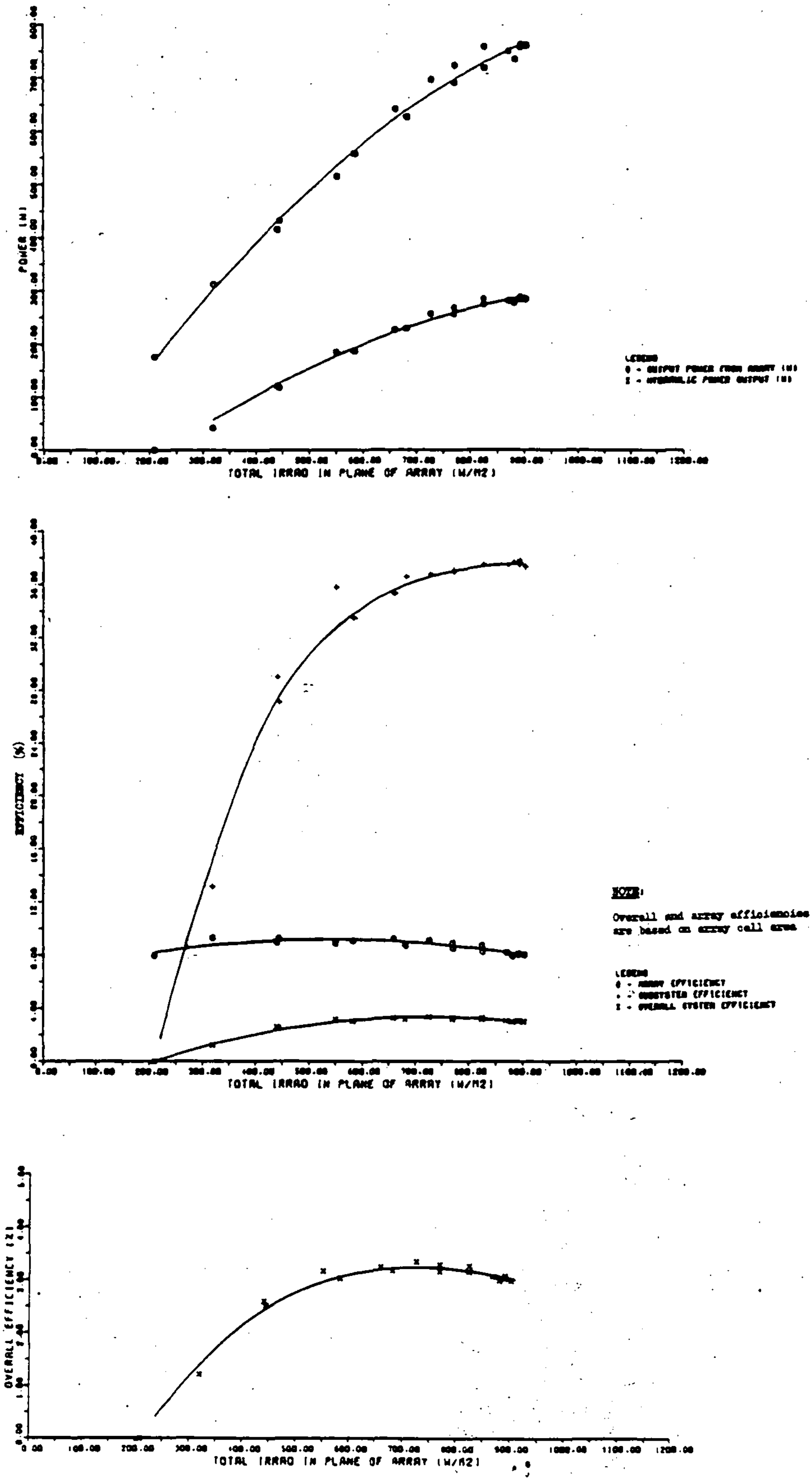


Figure 3 Performance of Pompes Guinard system in Mali v. irradiance (15 September 1980)

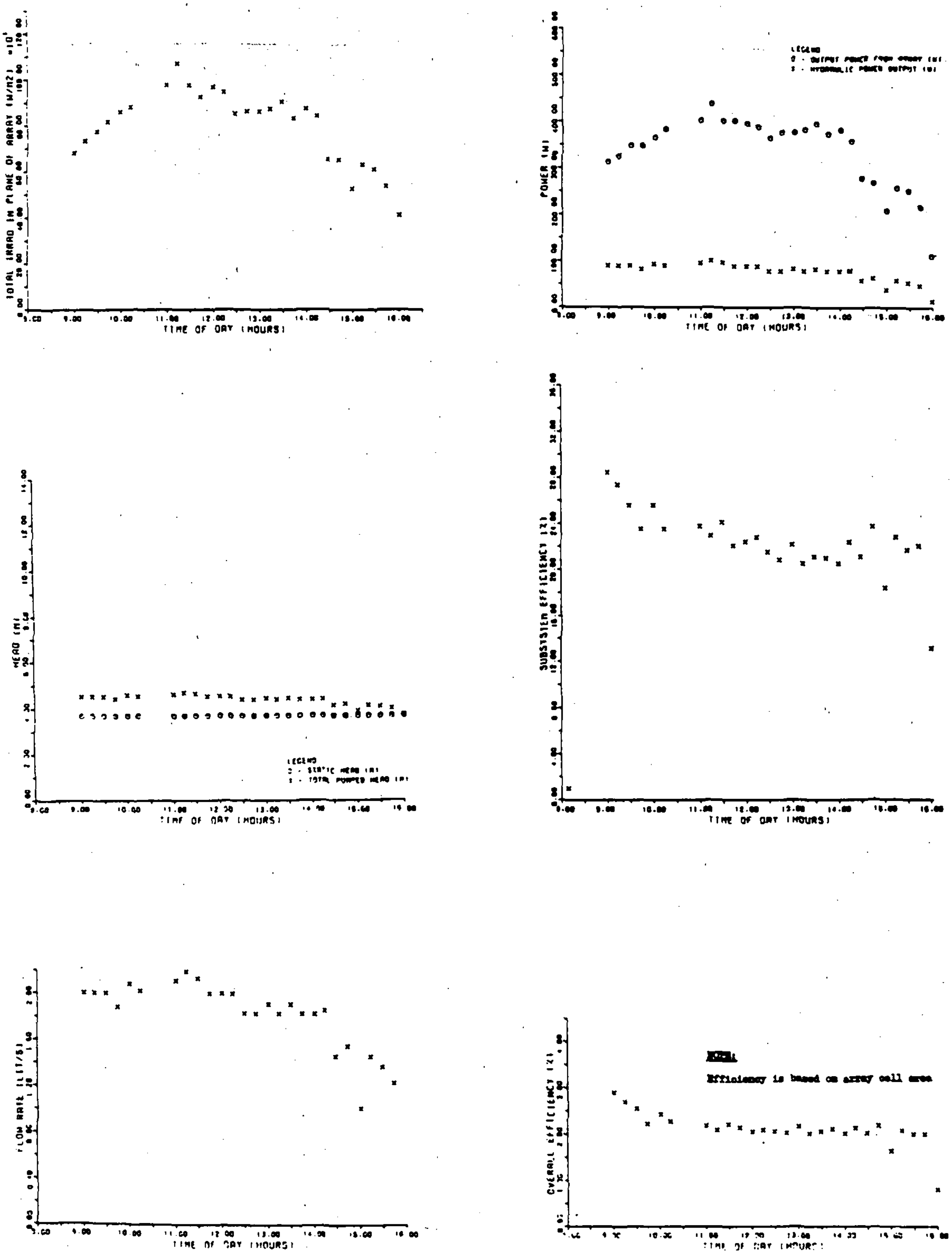


Figure 4 Performance of Briau system in Philippines v. time (17 December 1980)

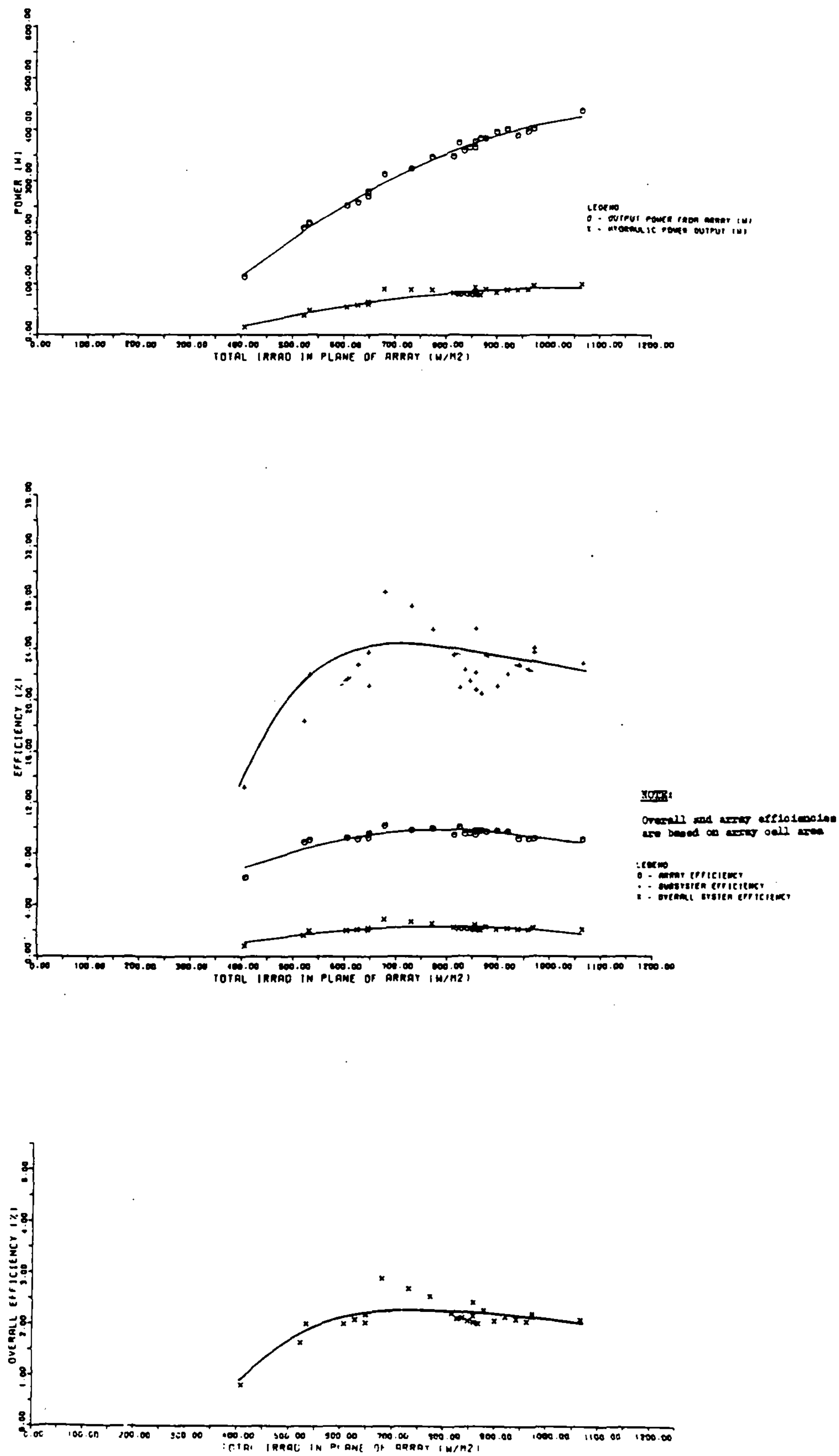


Figure 5 Performance of Briau system in Philippines v. irradiance (17 December 1980

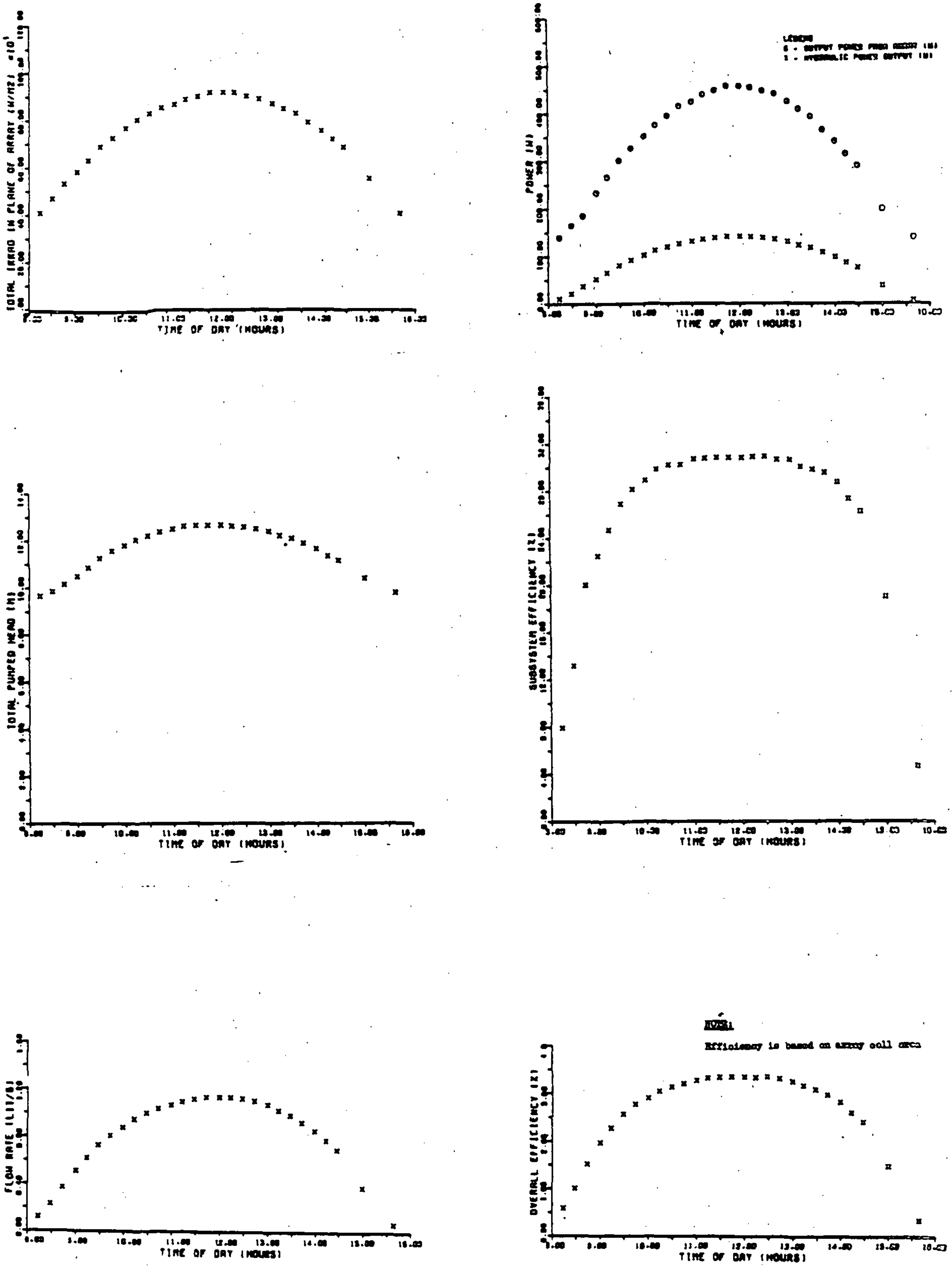


Figure 6 Performance of Arco Solar system in Sudan v. time (7 January 1981)

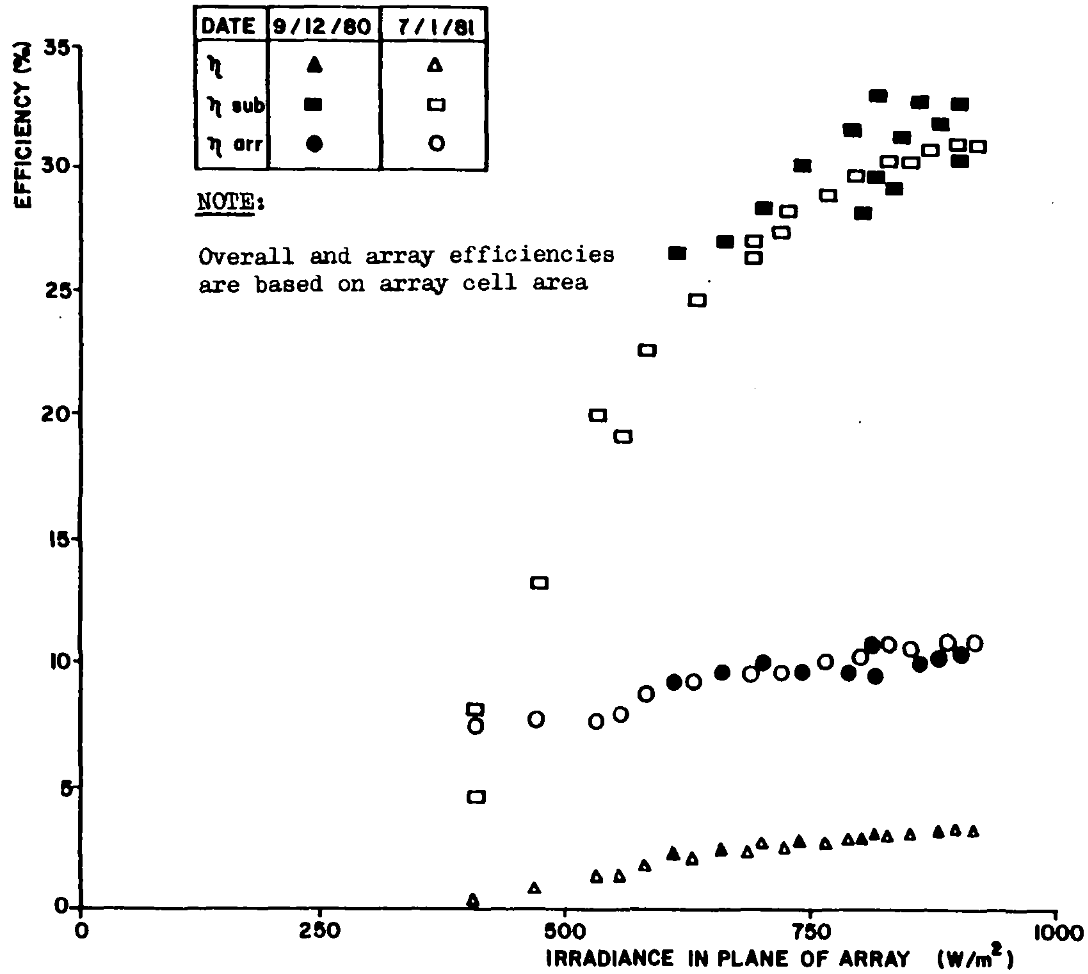


Figure 6A Comparison between performance of Areo Solar System in Sudan v. irradiance on different days

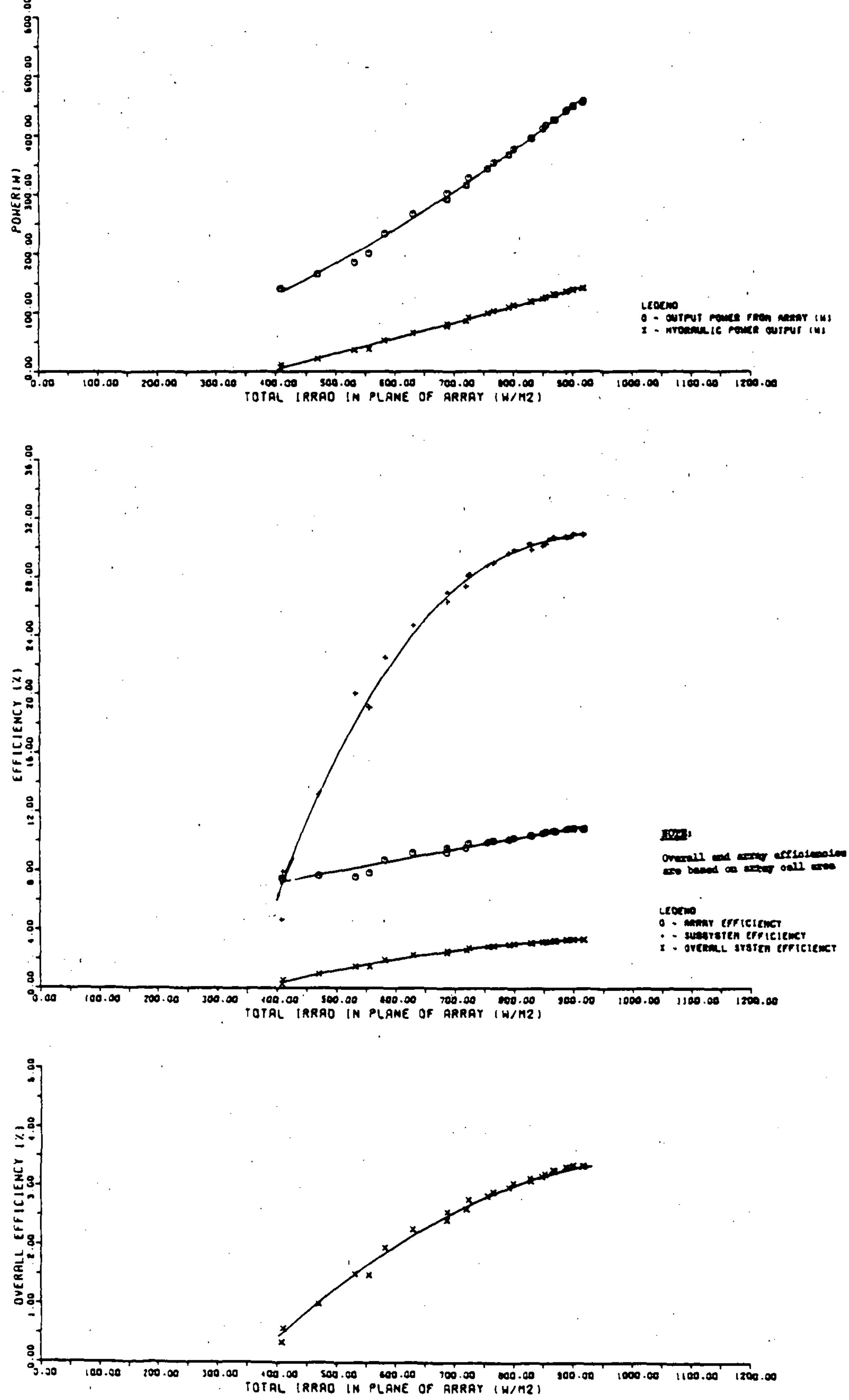
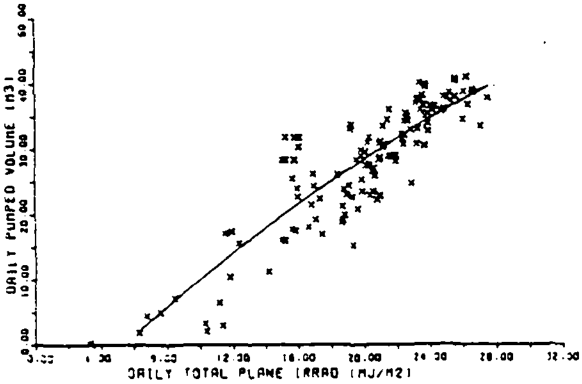
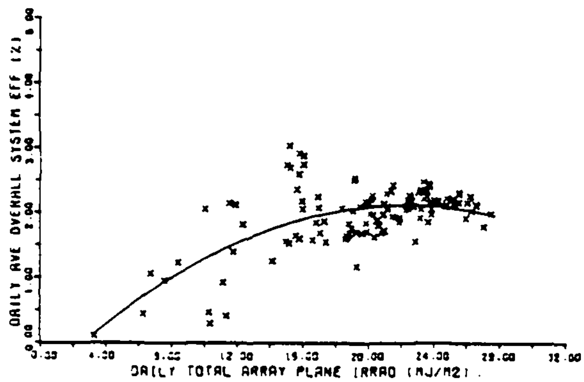


Figure 7 Performance of Arco Solar system in Sudan v. irradiance (7 January 1981)





Note: Array and sub-system efficiencies unknown as array energy output not recorded

Efficiency is based on array cell area

Figure 8 Daily output of Pompes Guinard system in Mali (Data obtained in the period 7 June 1980 to 3 December 1980)

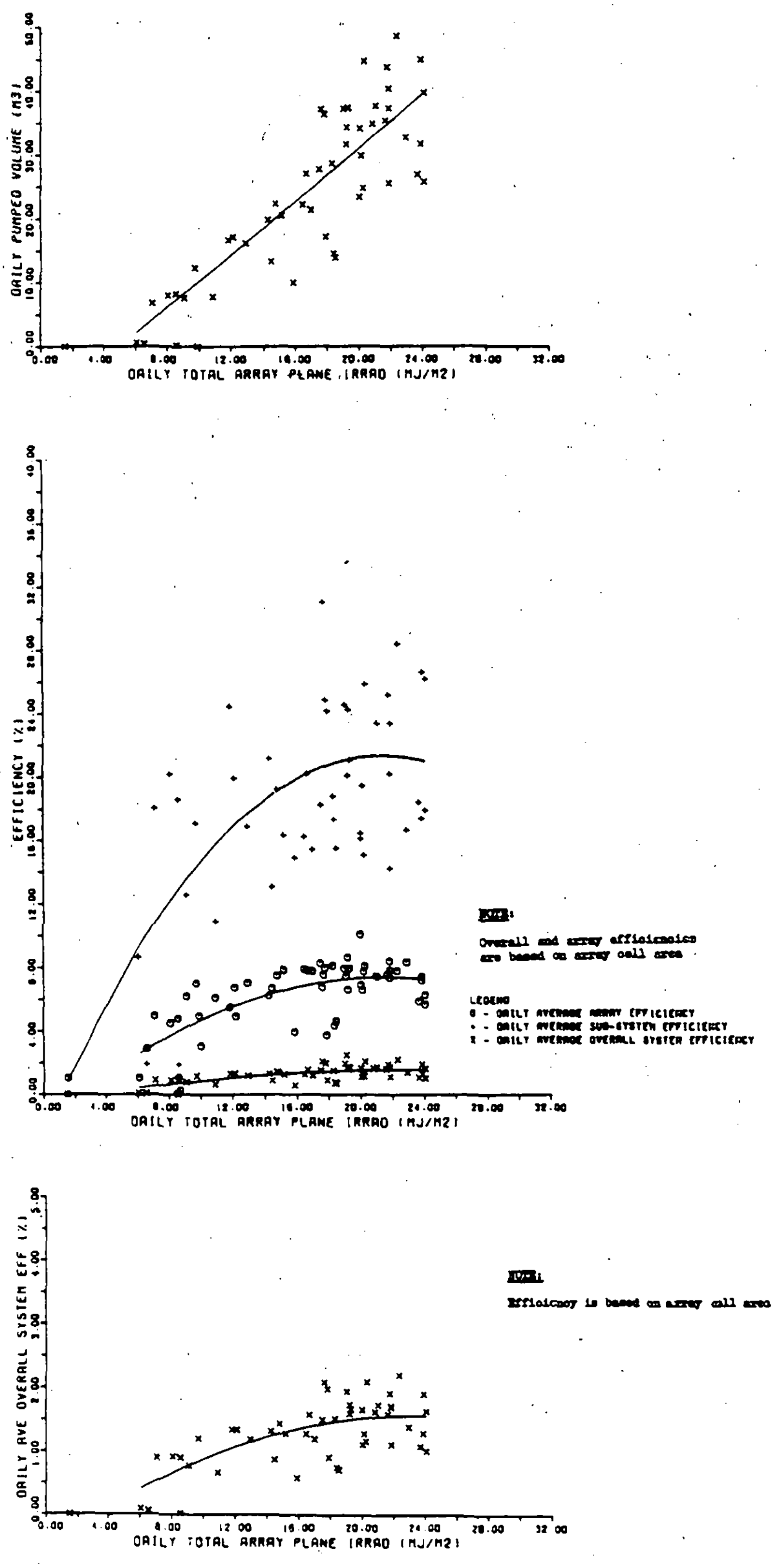


Figure 9 Daily output of Briau system in Philippines (Data obtained in the period 15 August 1980 to 4 December 1980)

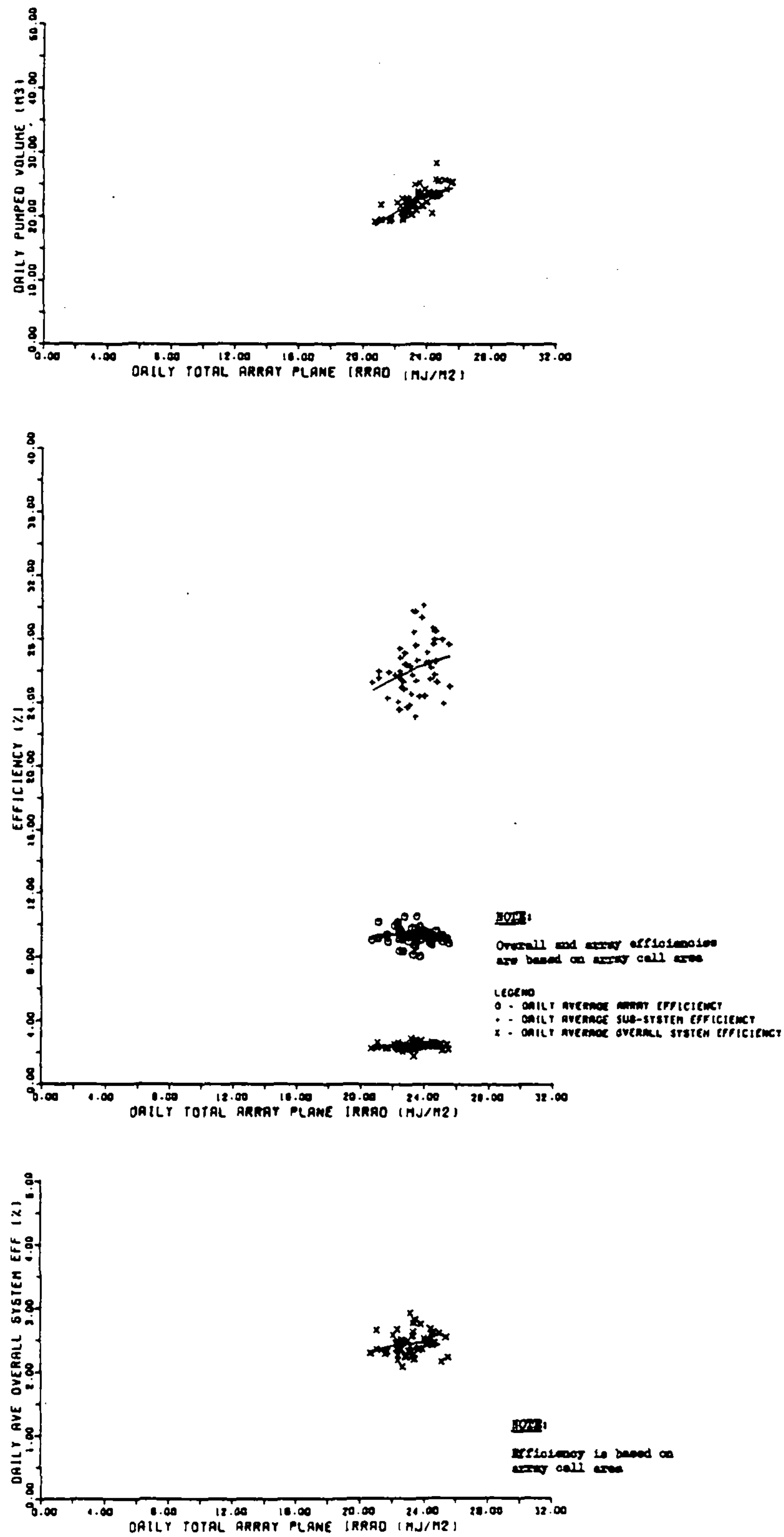


Figure 10 Daily output of Arco Solar system in Sudan (Data obtained in the period 4 October 1980 to 9 February 1981)

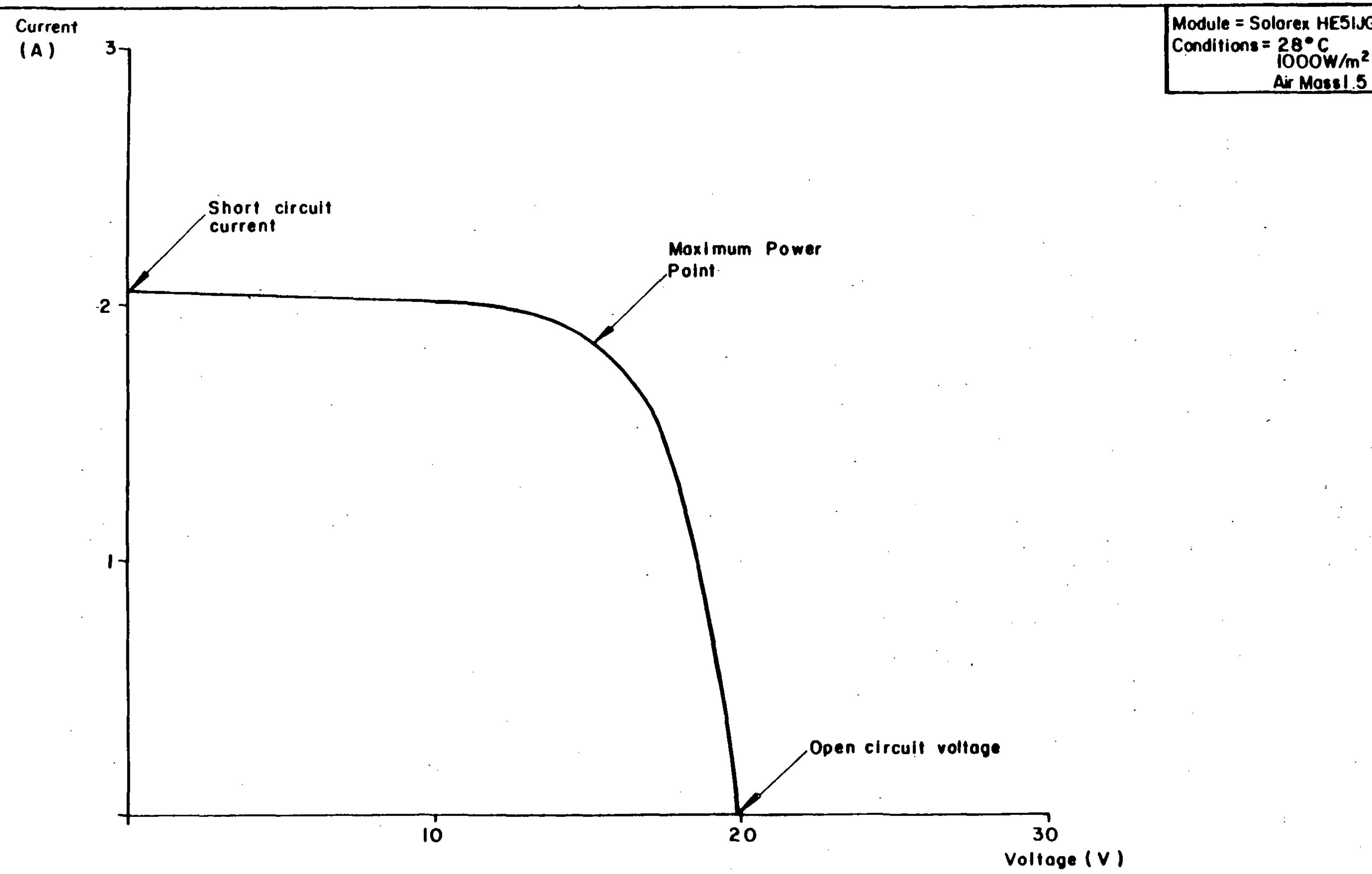


Figure 11 Typical measured electrical performance of a PV module

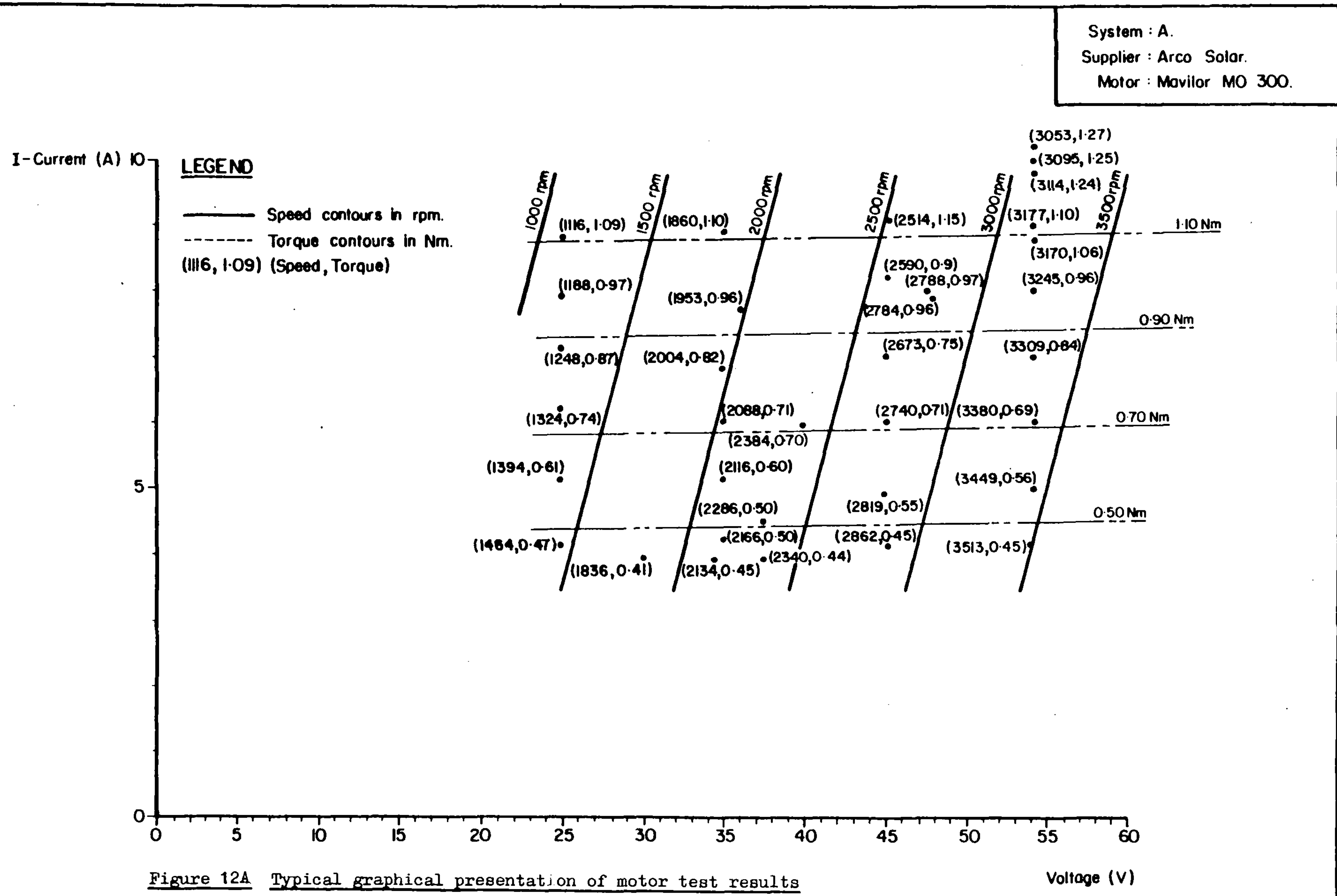


Figure 12A Typical graphical presentation of motor test results

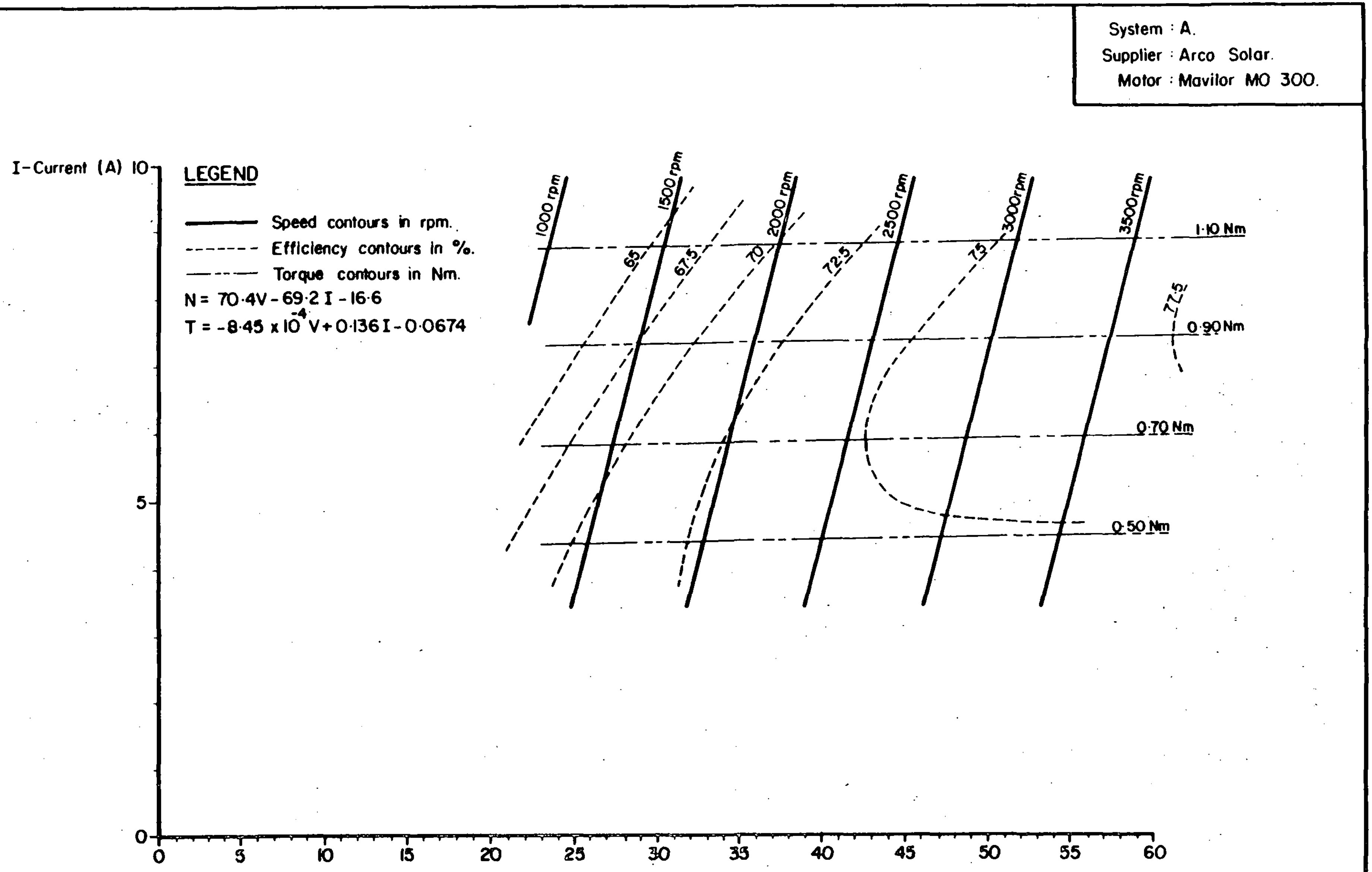


Figure 12B Motor Performance System A

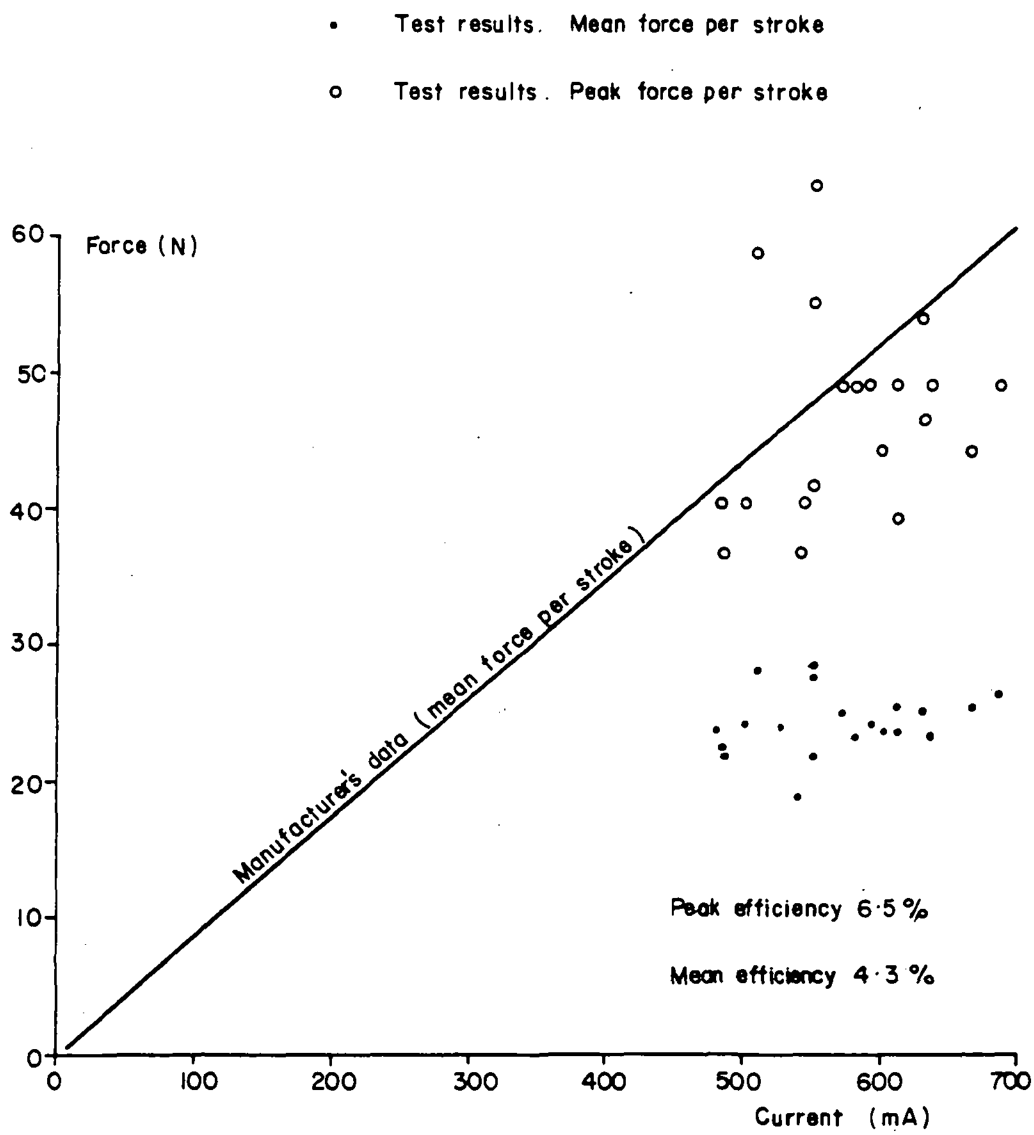


Figure 13 Performance of linear actuator

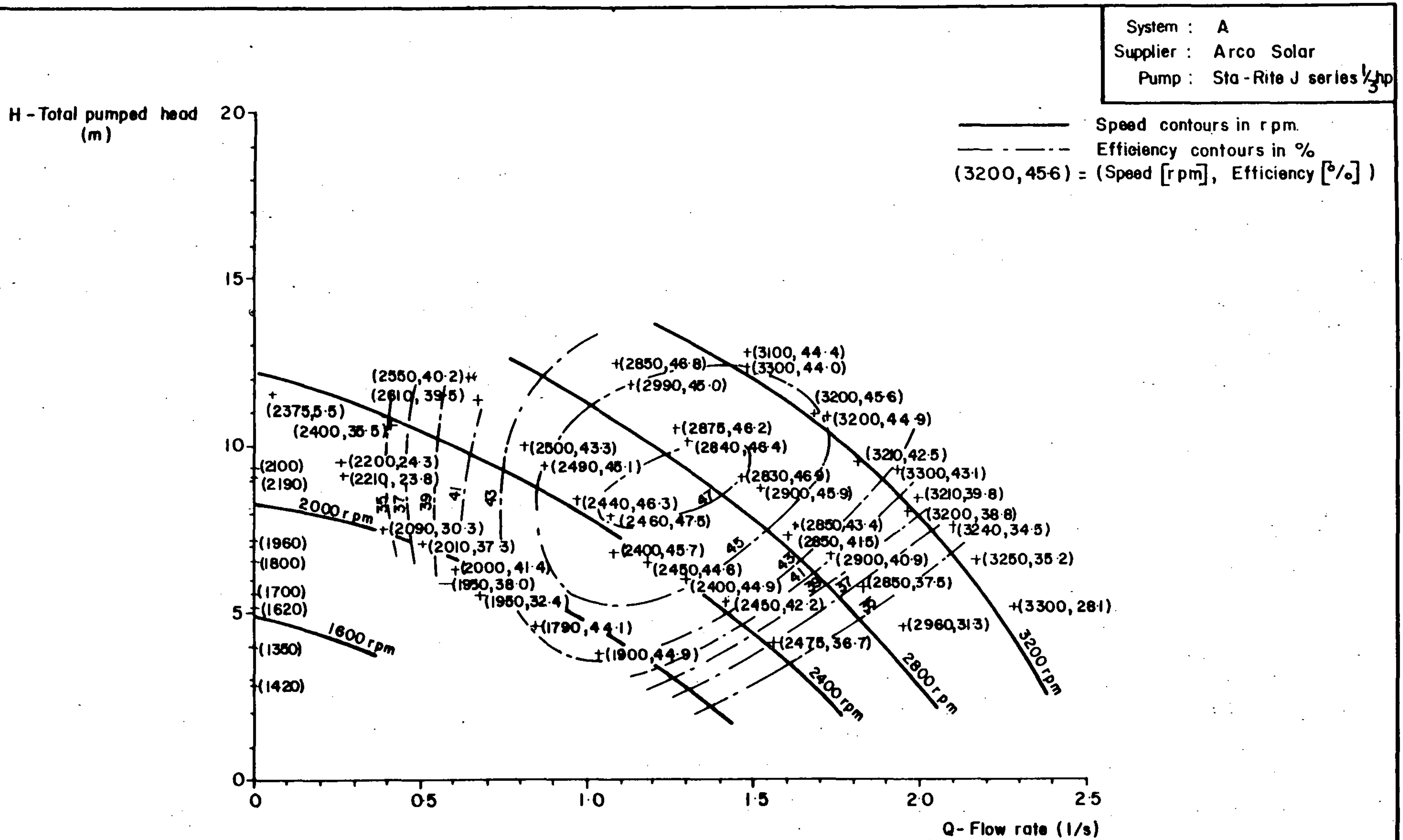


Figure 14 Typical graphical presentation of pump test results

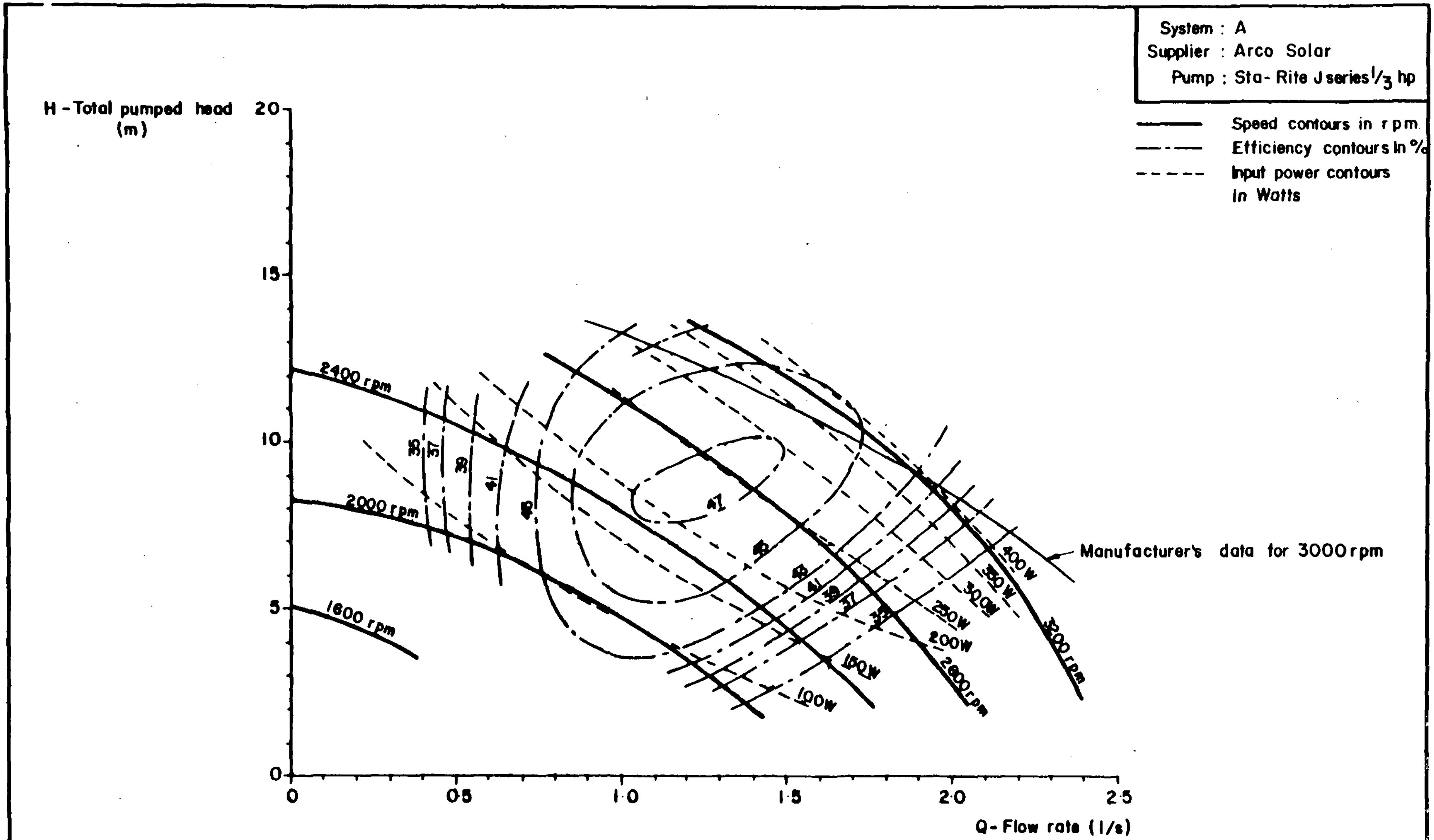
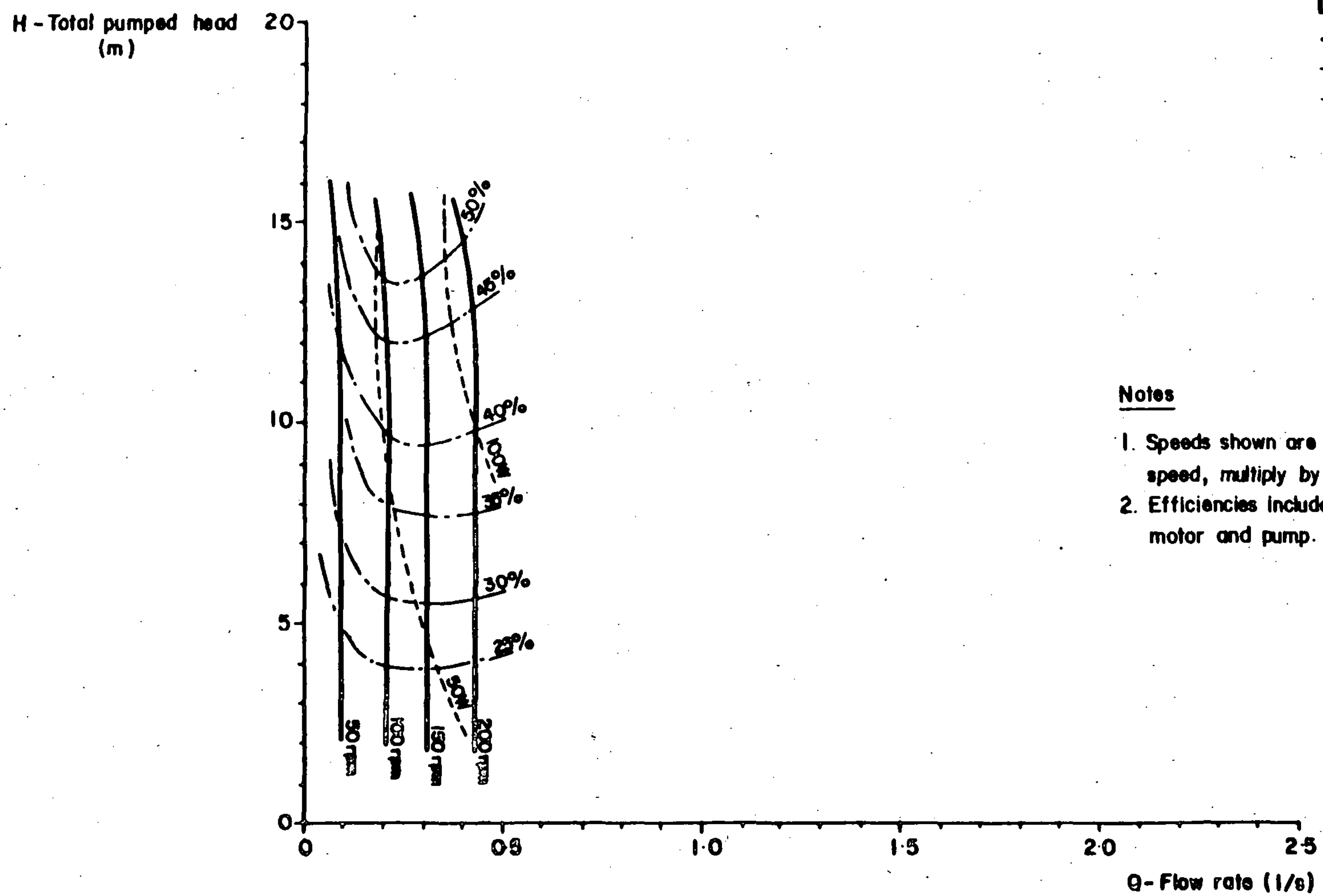


Figure 15 Pump Performance System A

System : B
Supplier : Briau
Pump : Duva 20

- Speed contours in r p m.
- Efficiency contours in %
- Input power contours in Watts



Notes

1. Speeds shown are pump speeds. For motor speed, multiply by 8·5.
2. Efficiencies include belt transmission between motor and pump.

Figure 16 Pump Performance System B

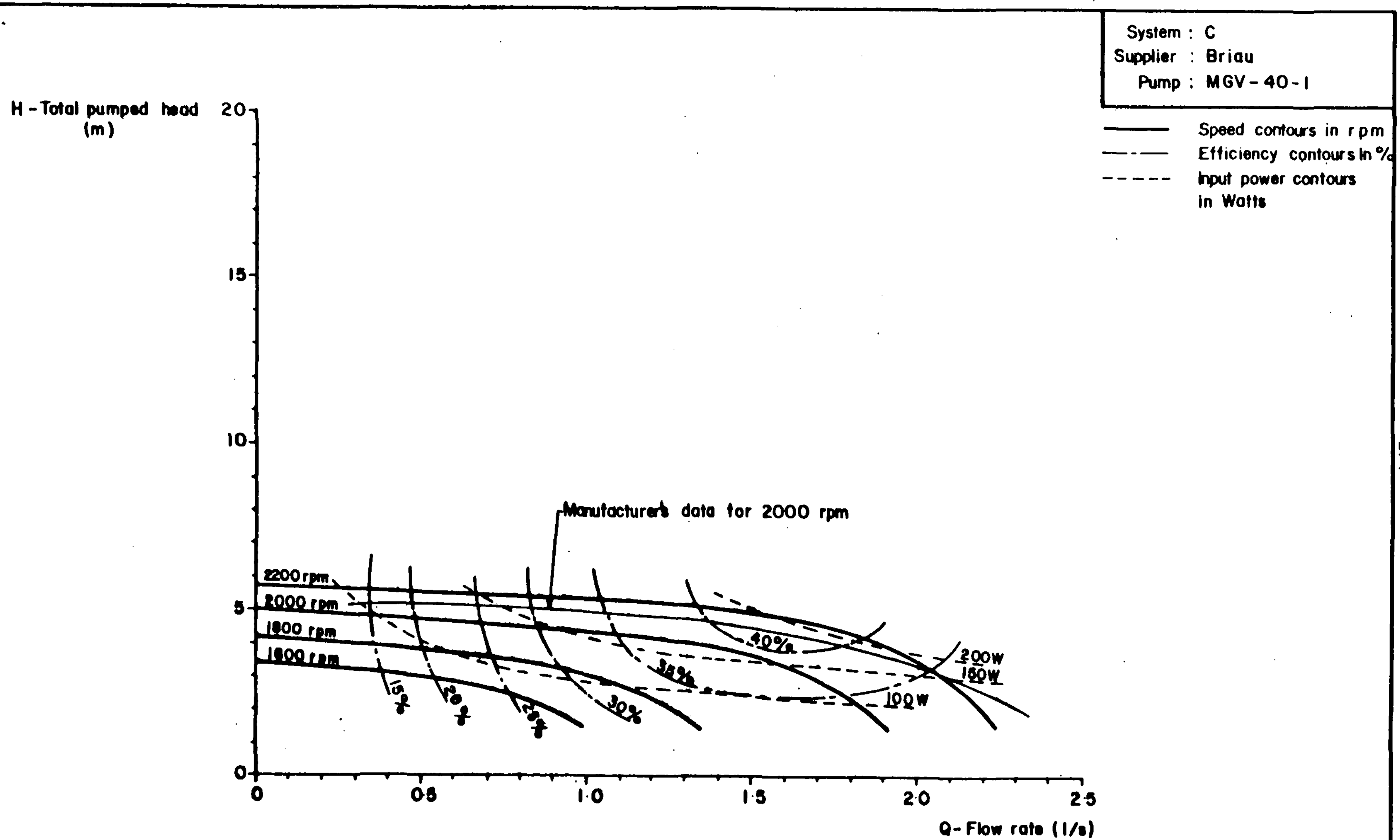


Figure 17 Pump Performance System C

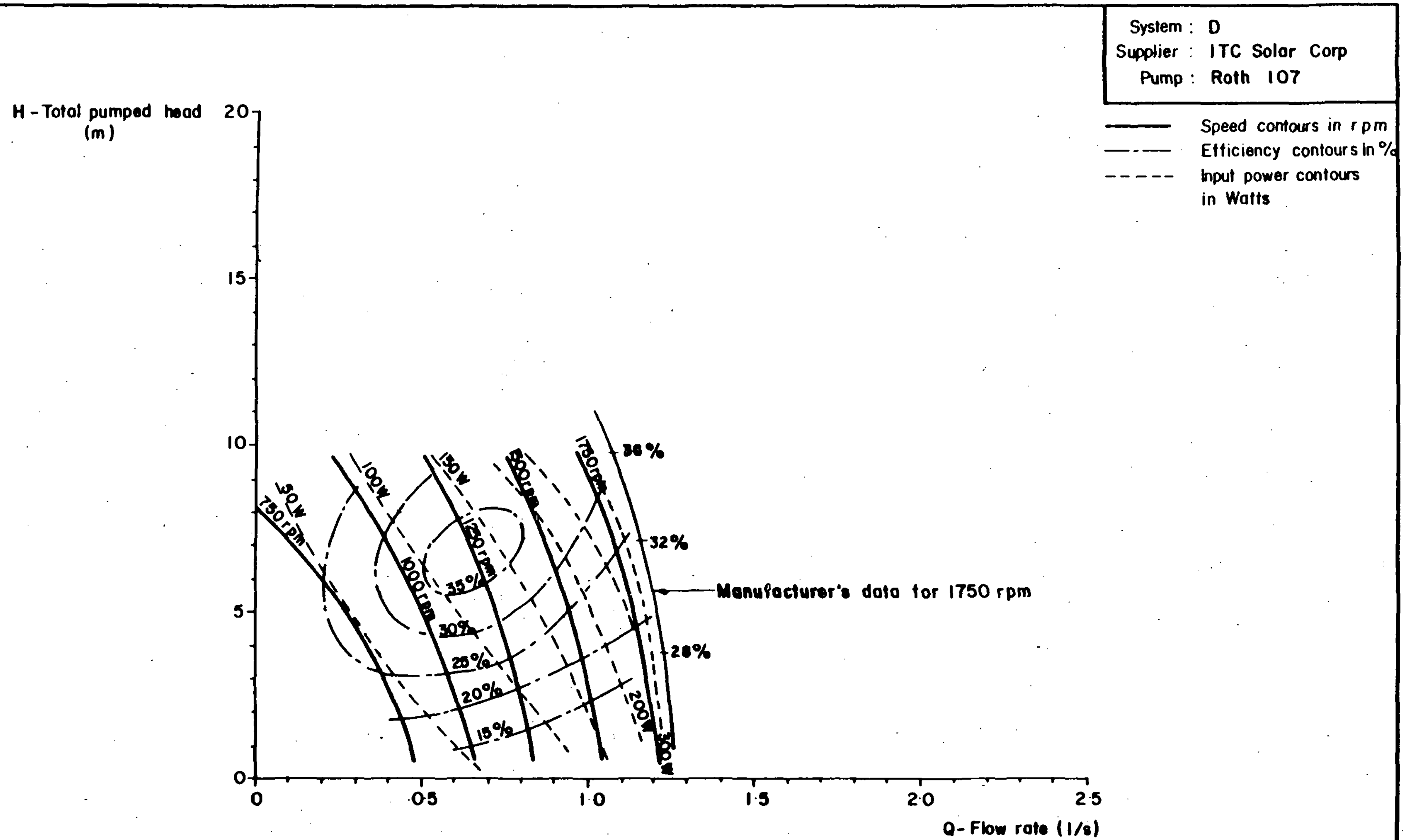


Figure 18 Pump Performance System D

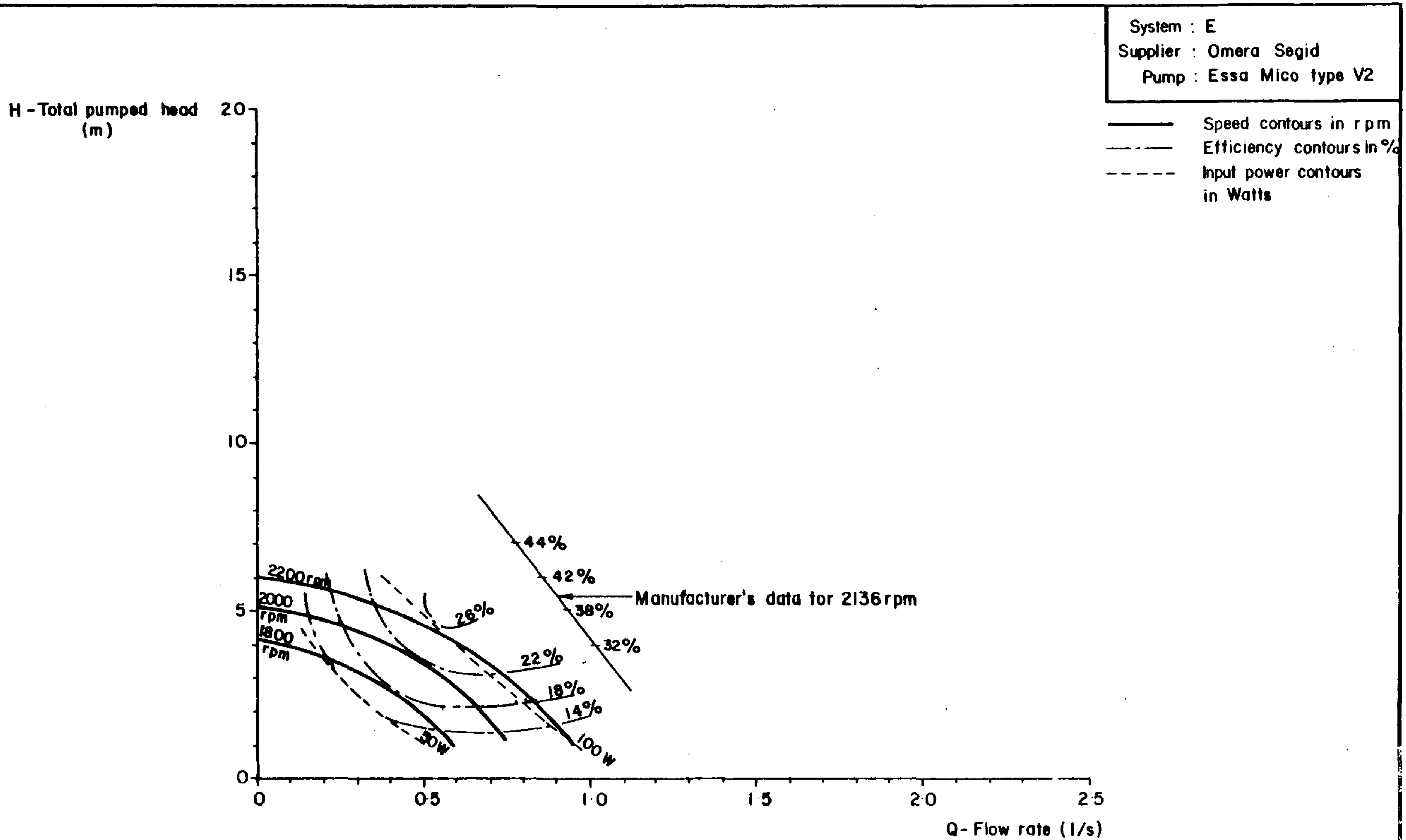


Figure 19 Pump Performance System E

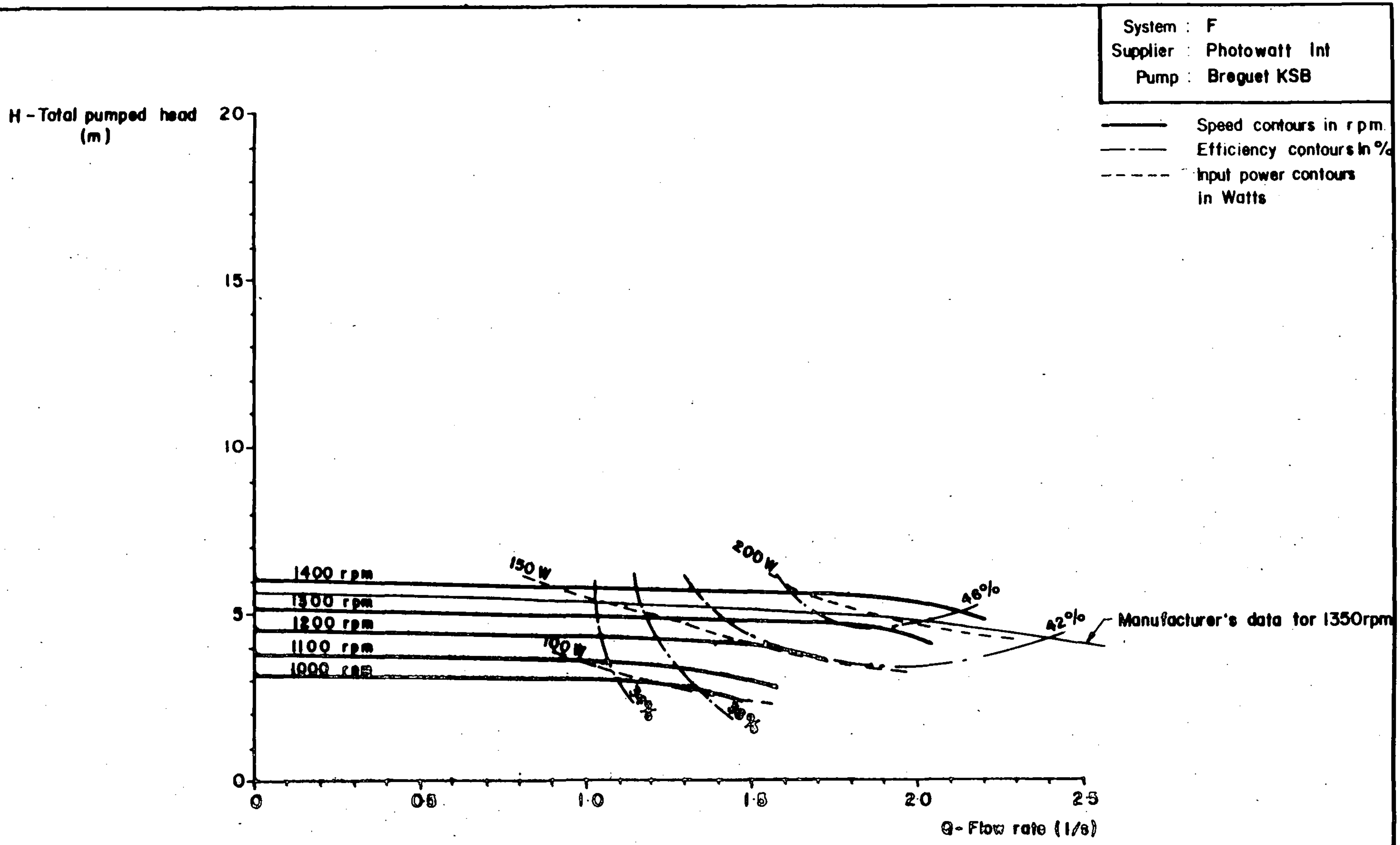


Figure 20 Pump Performance System F

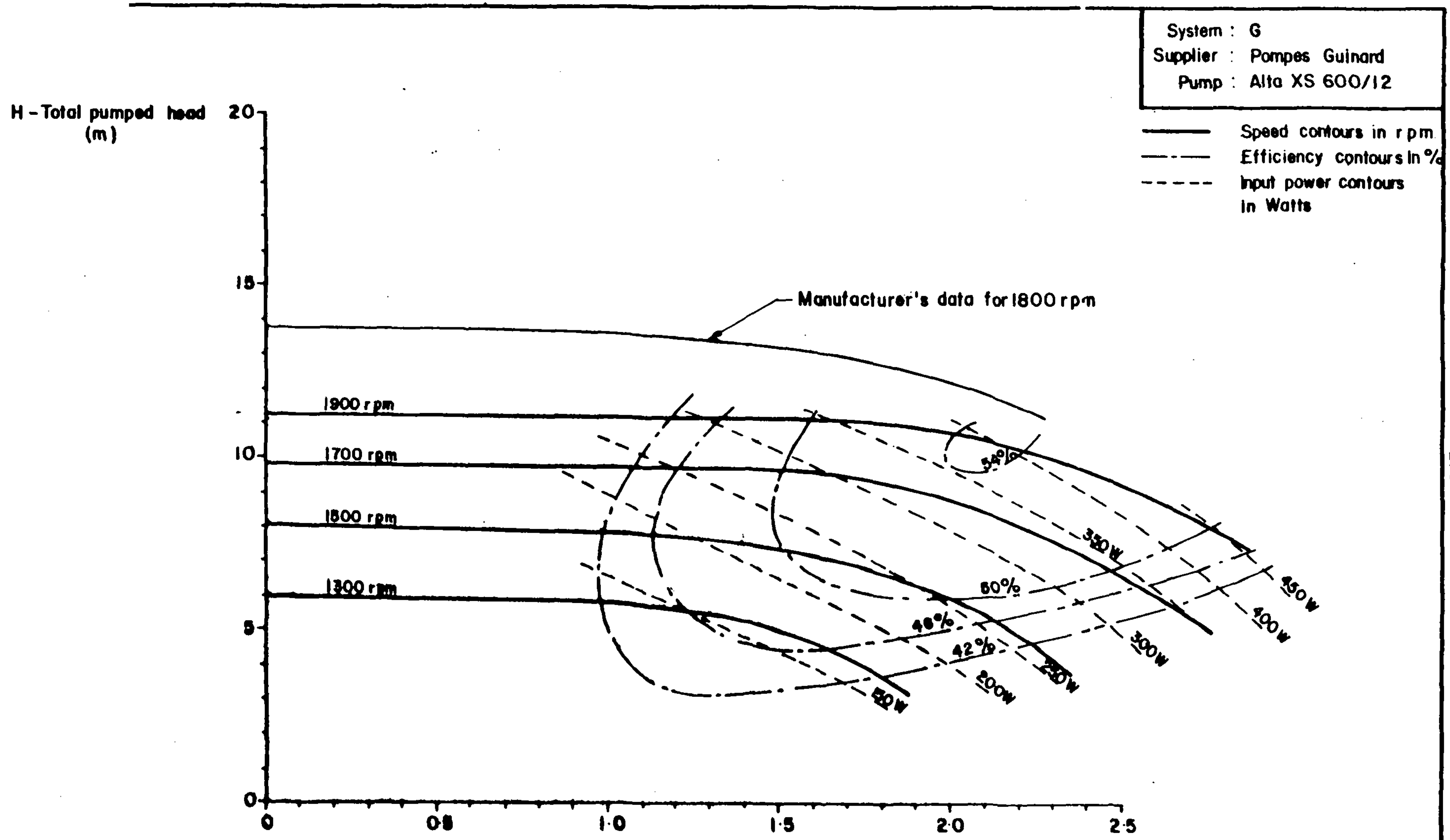


Figure 21 Pump Performance System G

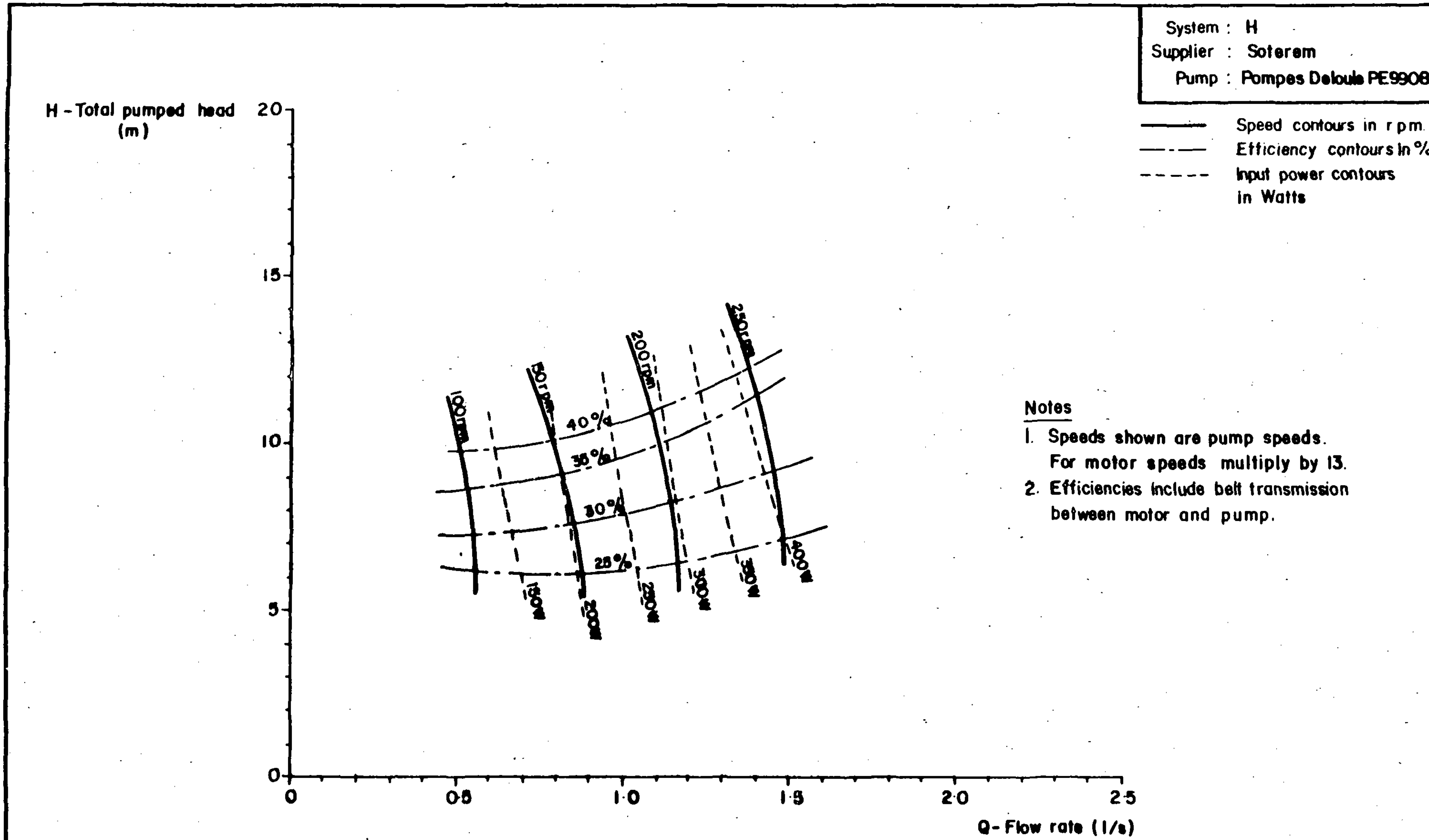


Figure 22 Pump Performance System H

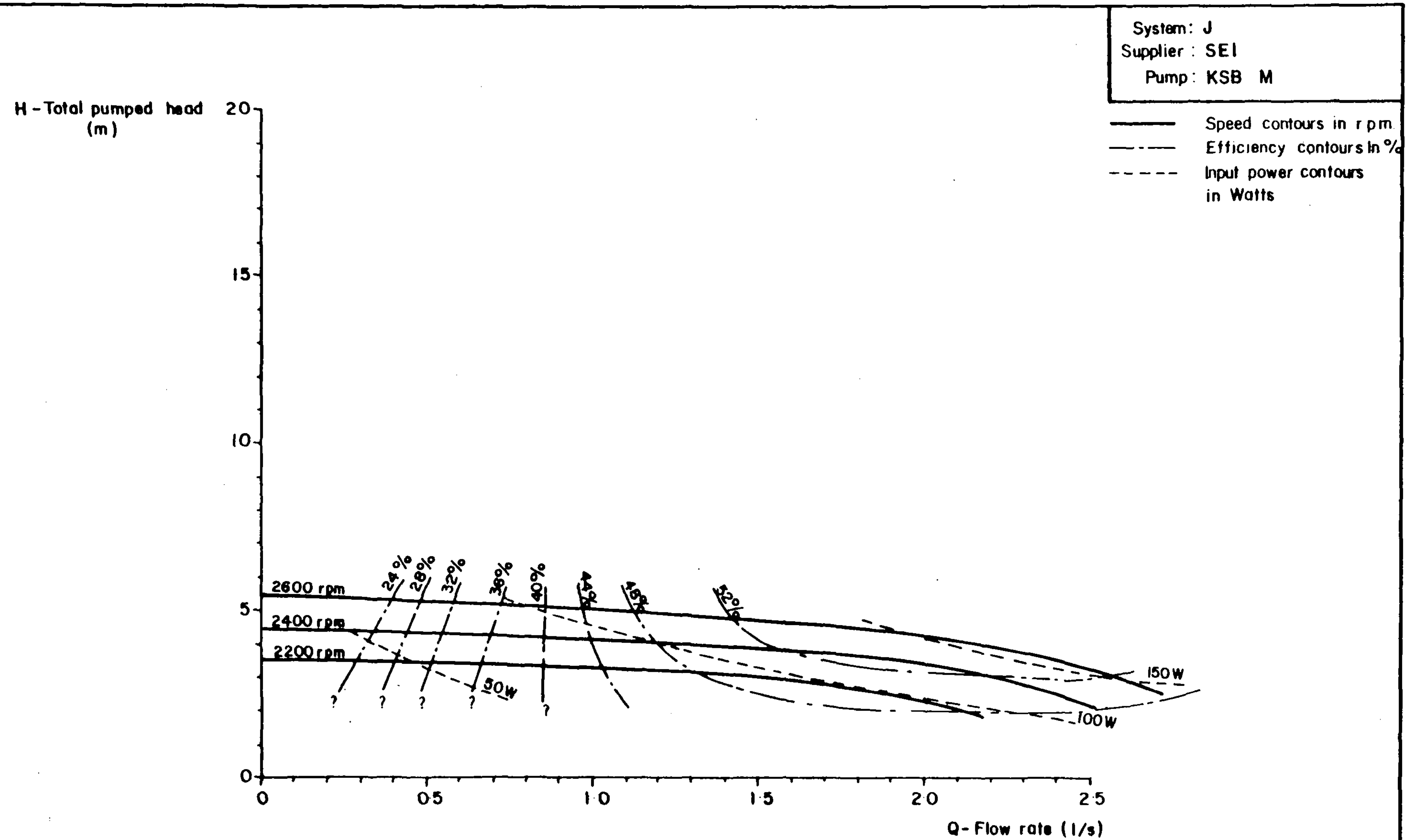
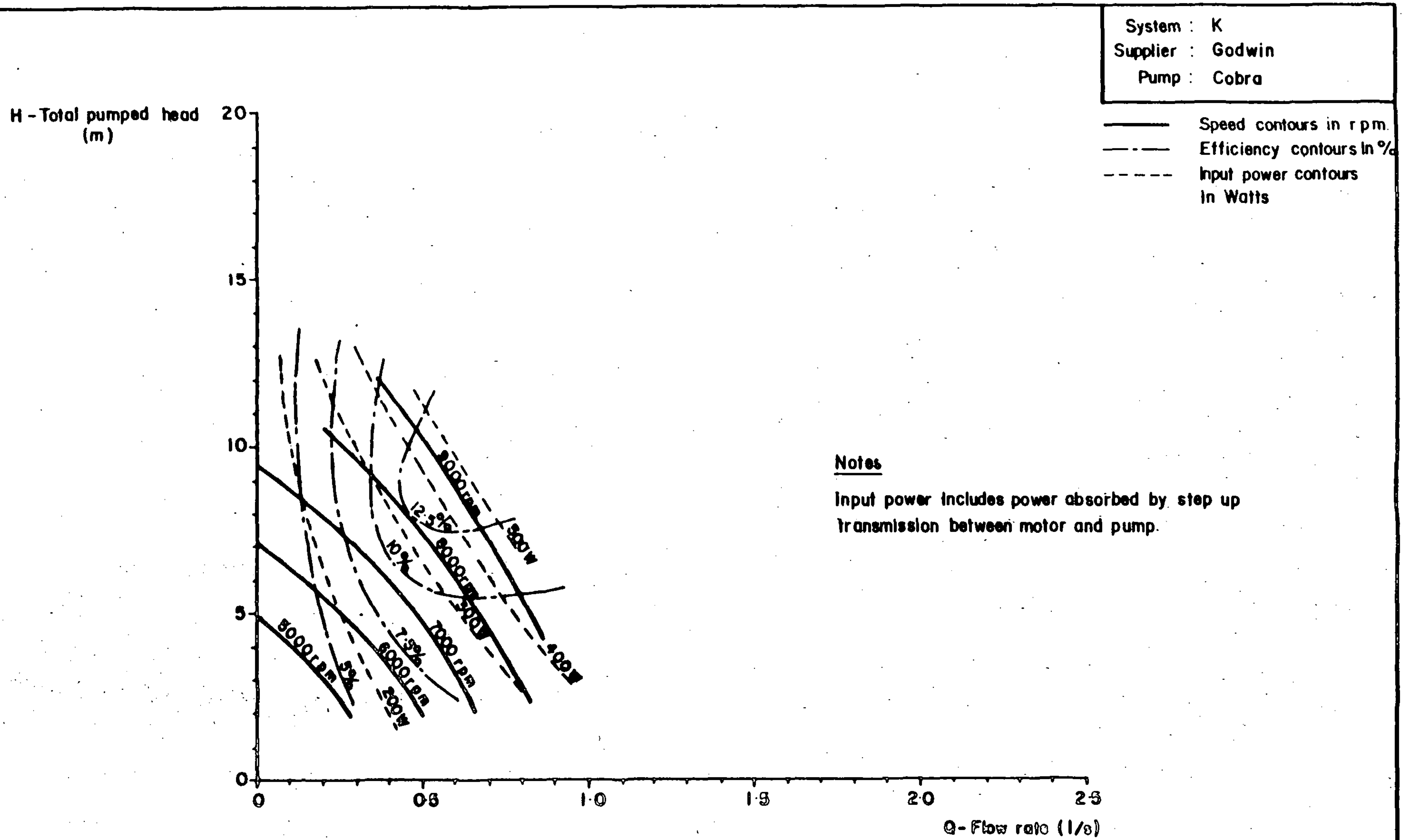


Figure 23 Pump Performance System J



Notes

Input power includes power absorbed by step up transmission between motor and pump.

Figure 24 Pump Performance System K

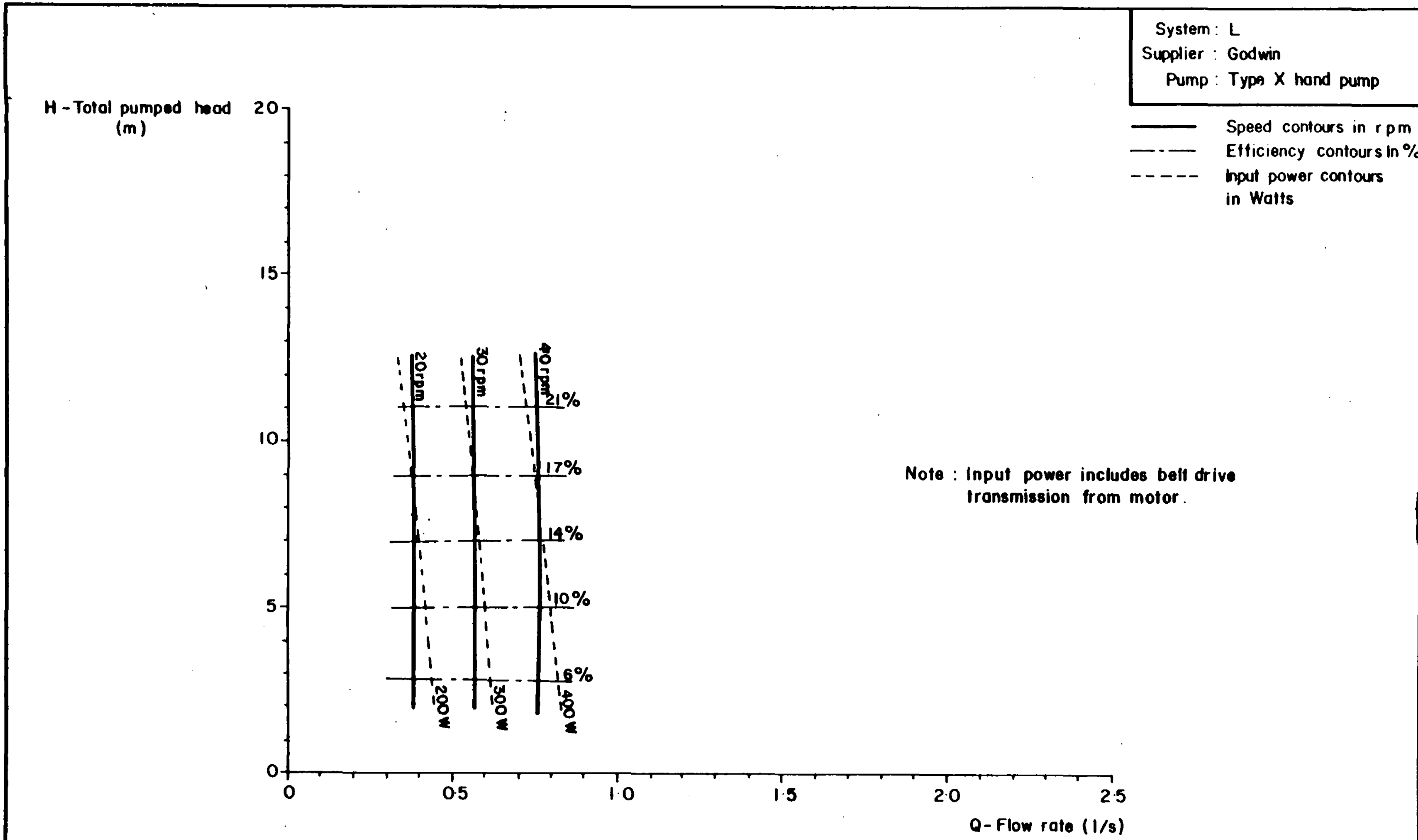


Figure 25 Pump performance System L

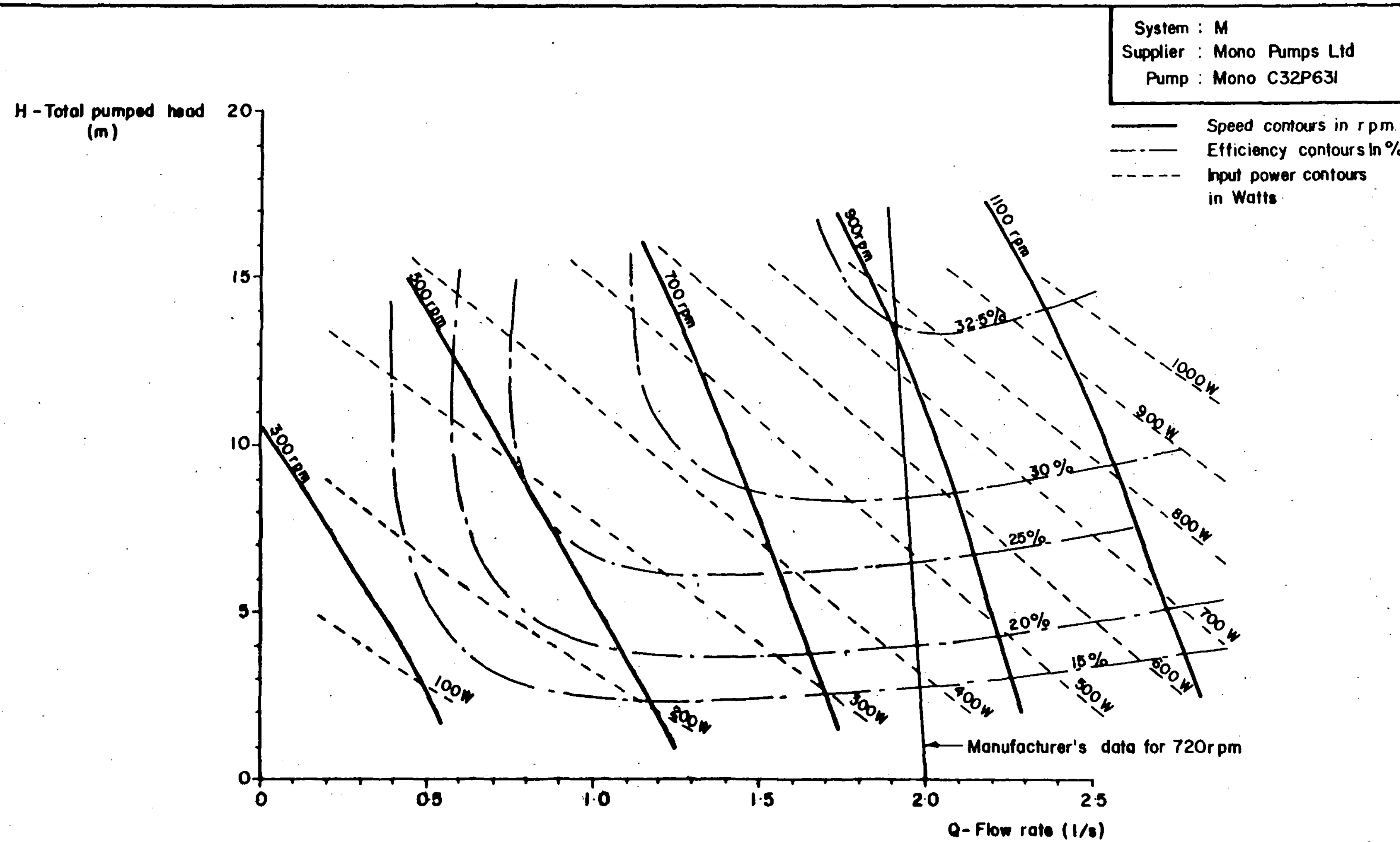


Figure 26 Pump Performance System M

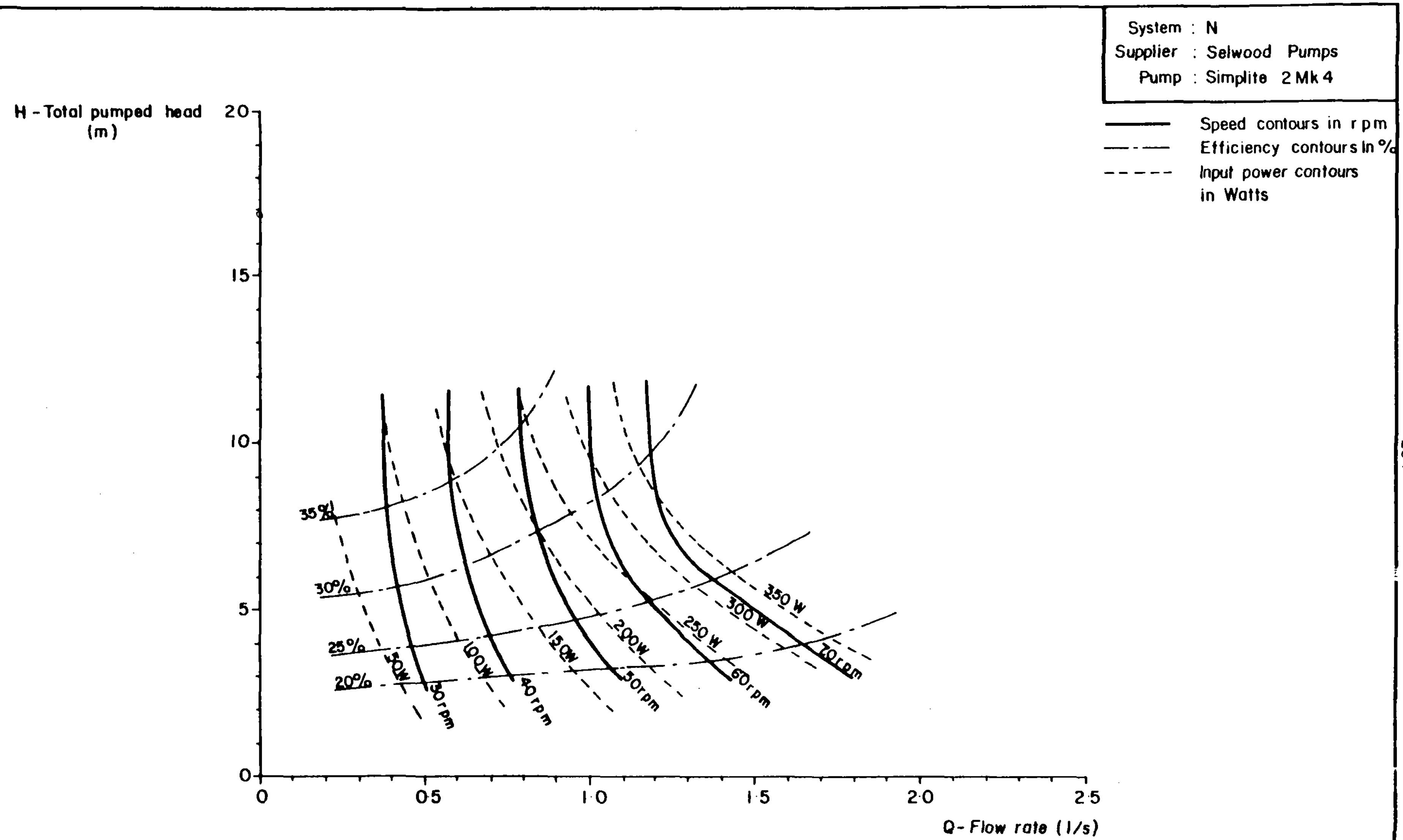


Figure 27 Pump Performance System N

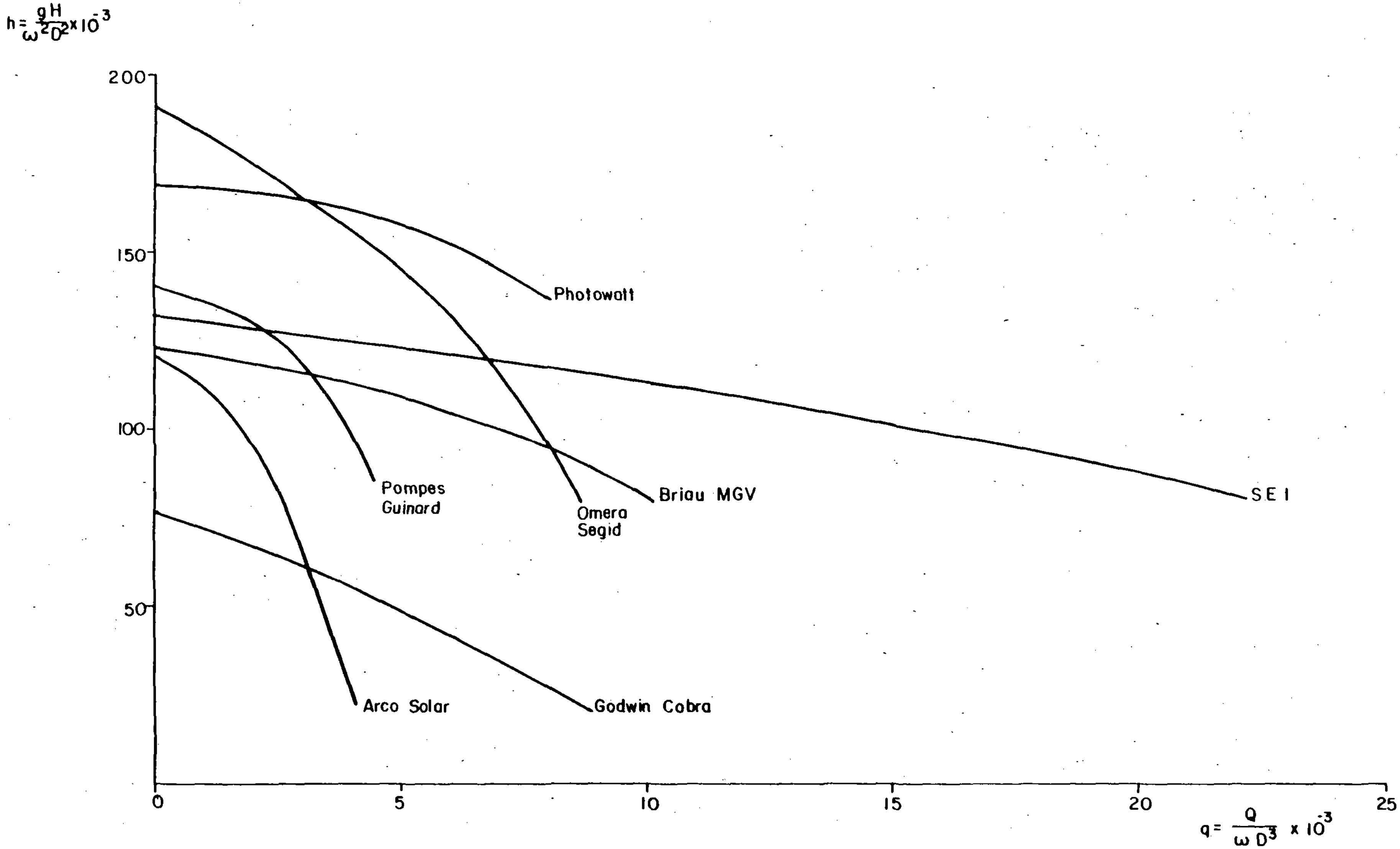


Figure 28 Unit flow head curves for centrifugal pumps

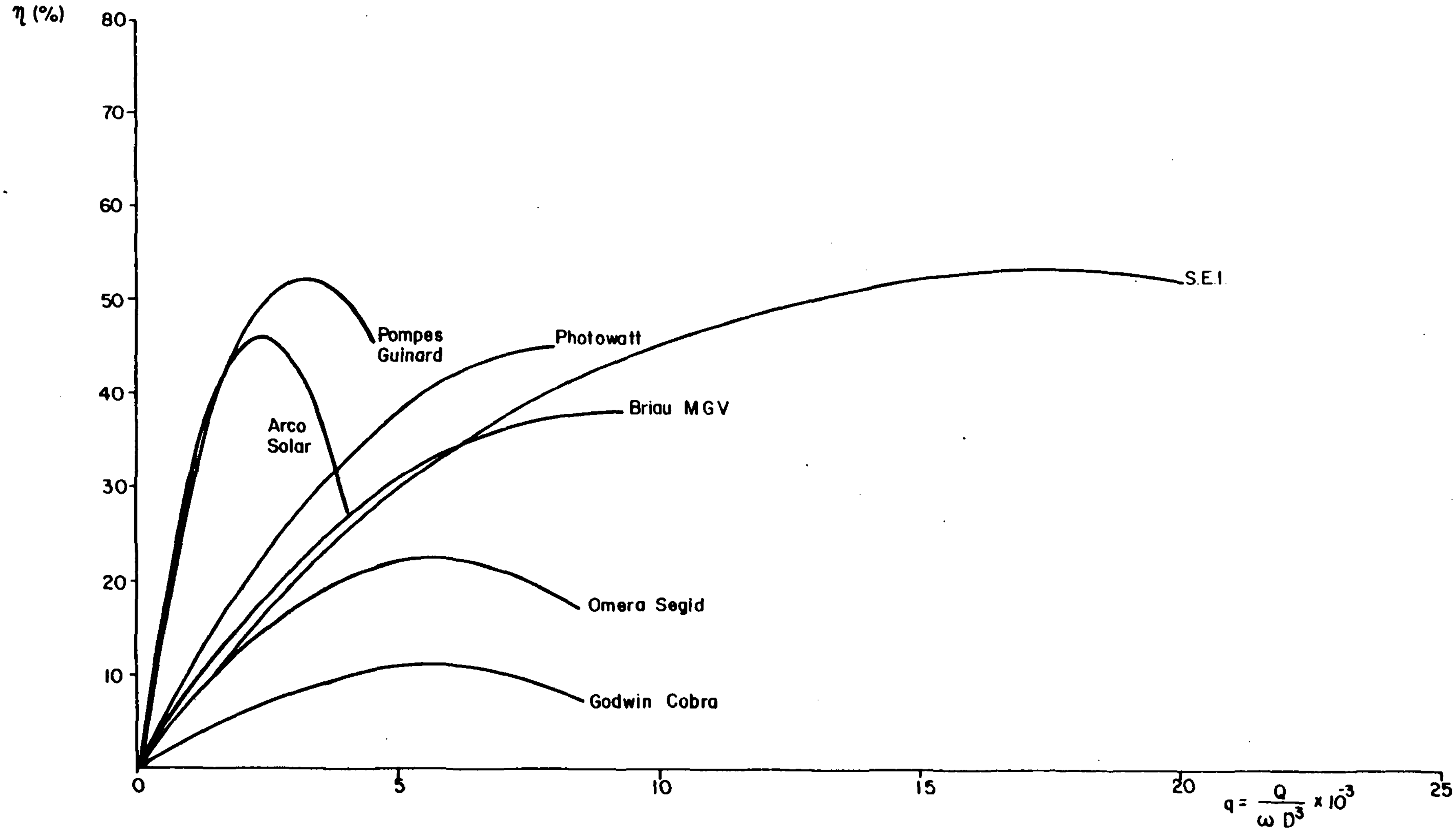


Figure 29 **Efficiency curves for centrifugal pumps**

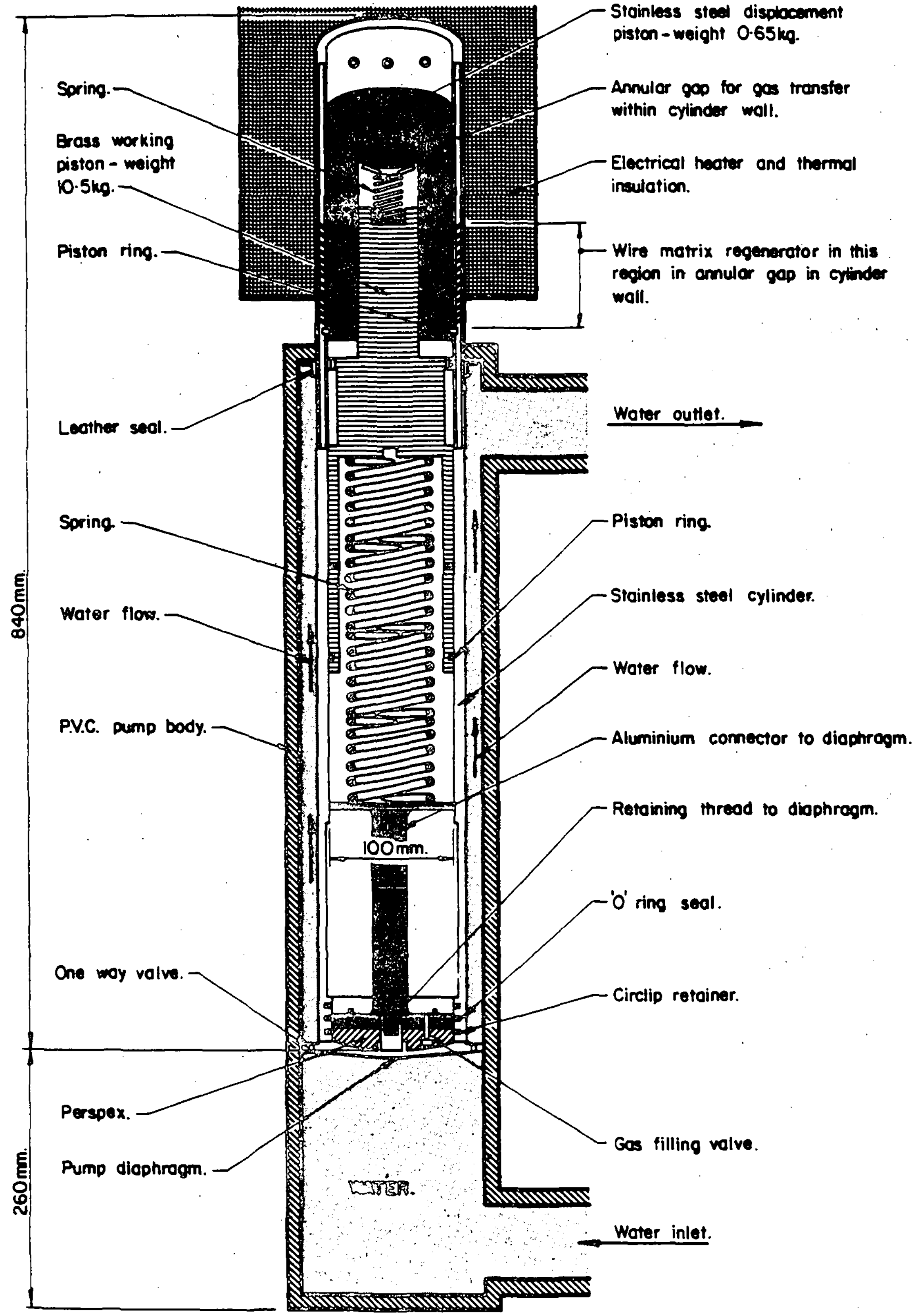


Figure 30 General arrangement of Sunpower Inc. Stirling engine

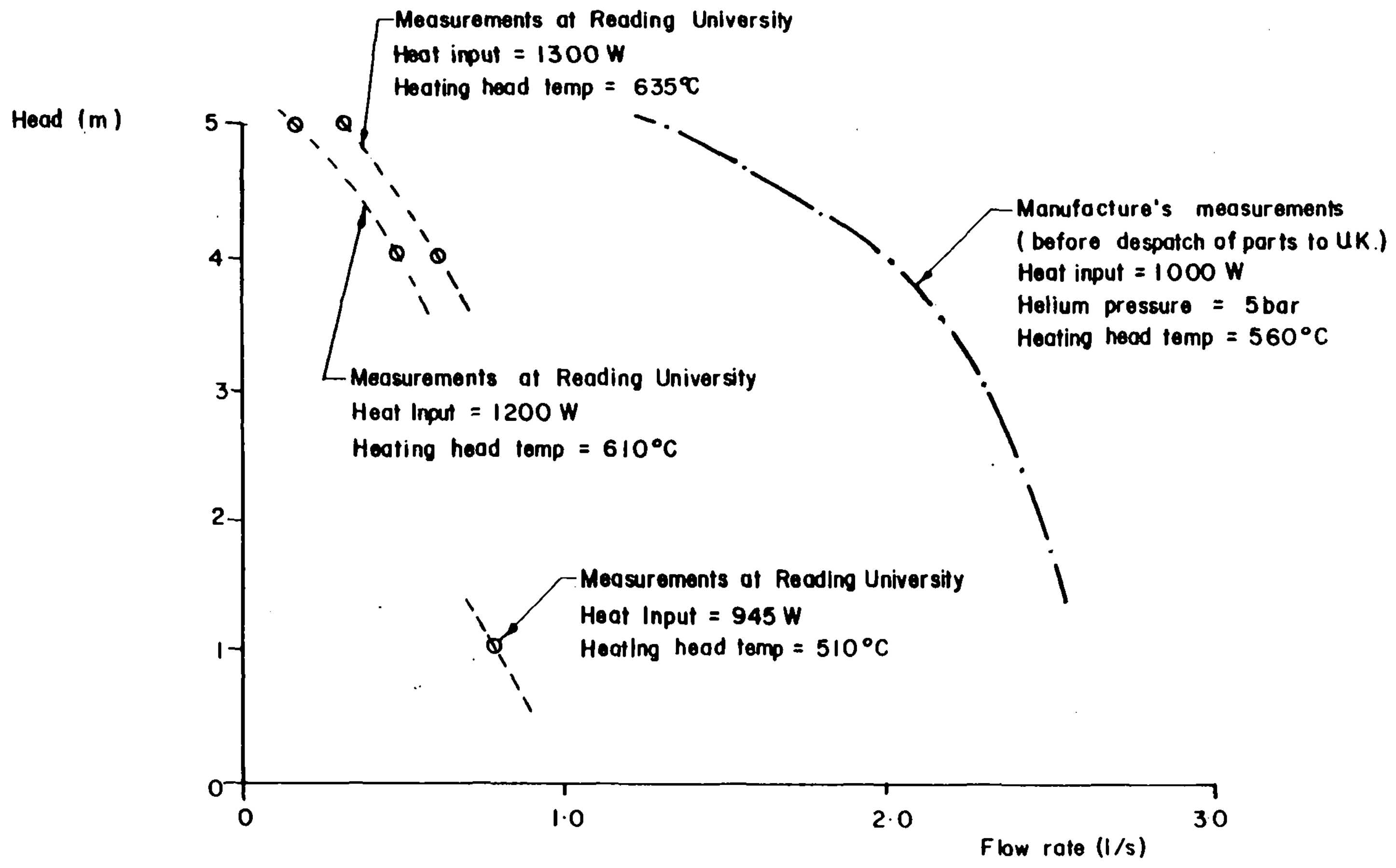


Figure 31 Performance of Sunpower Inc. Stirling engine

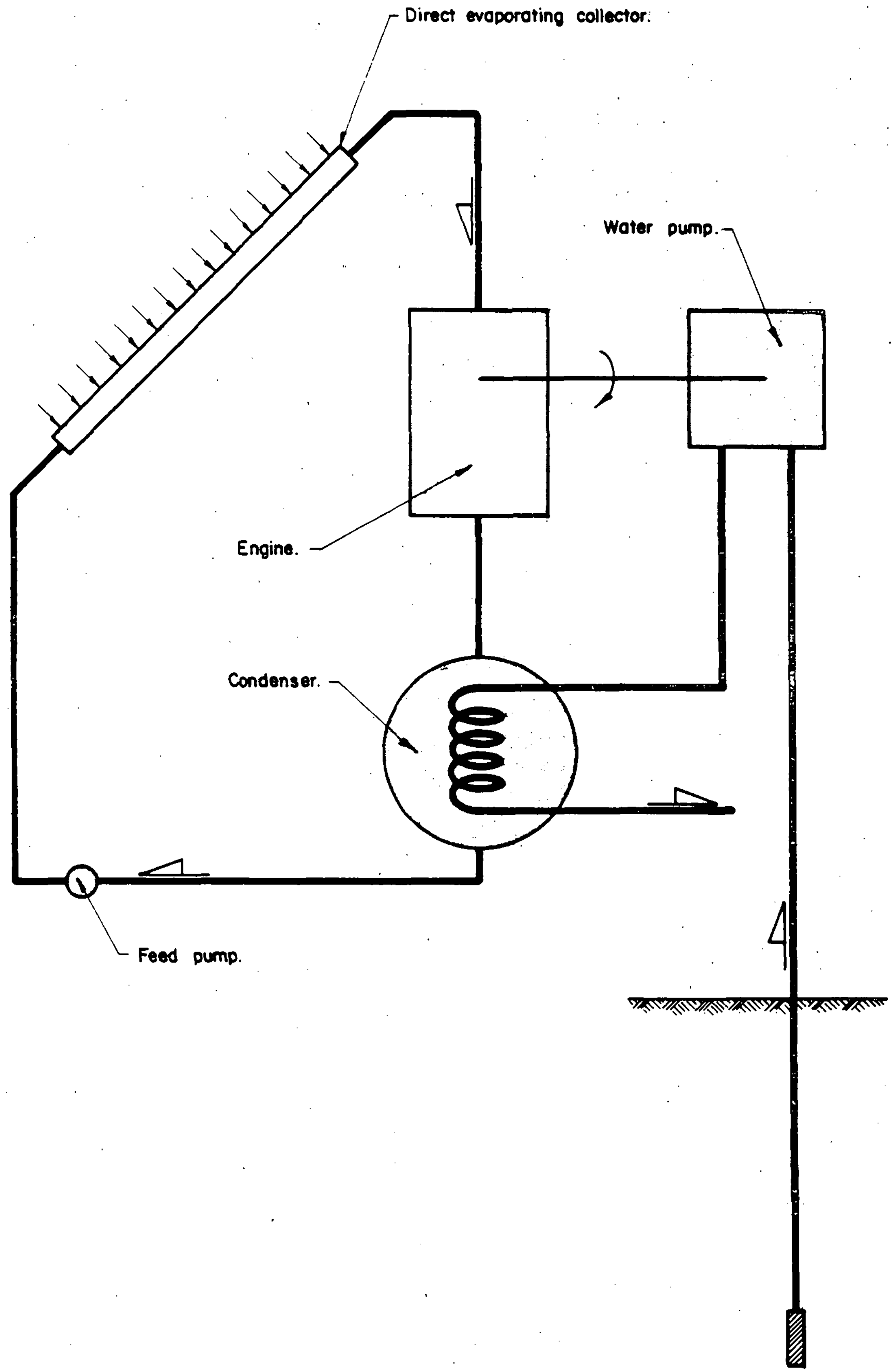


Figure 32 Schematic of Dornier Solar pump

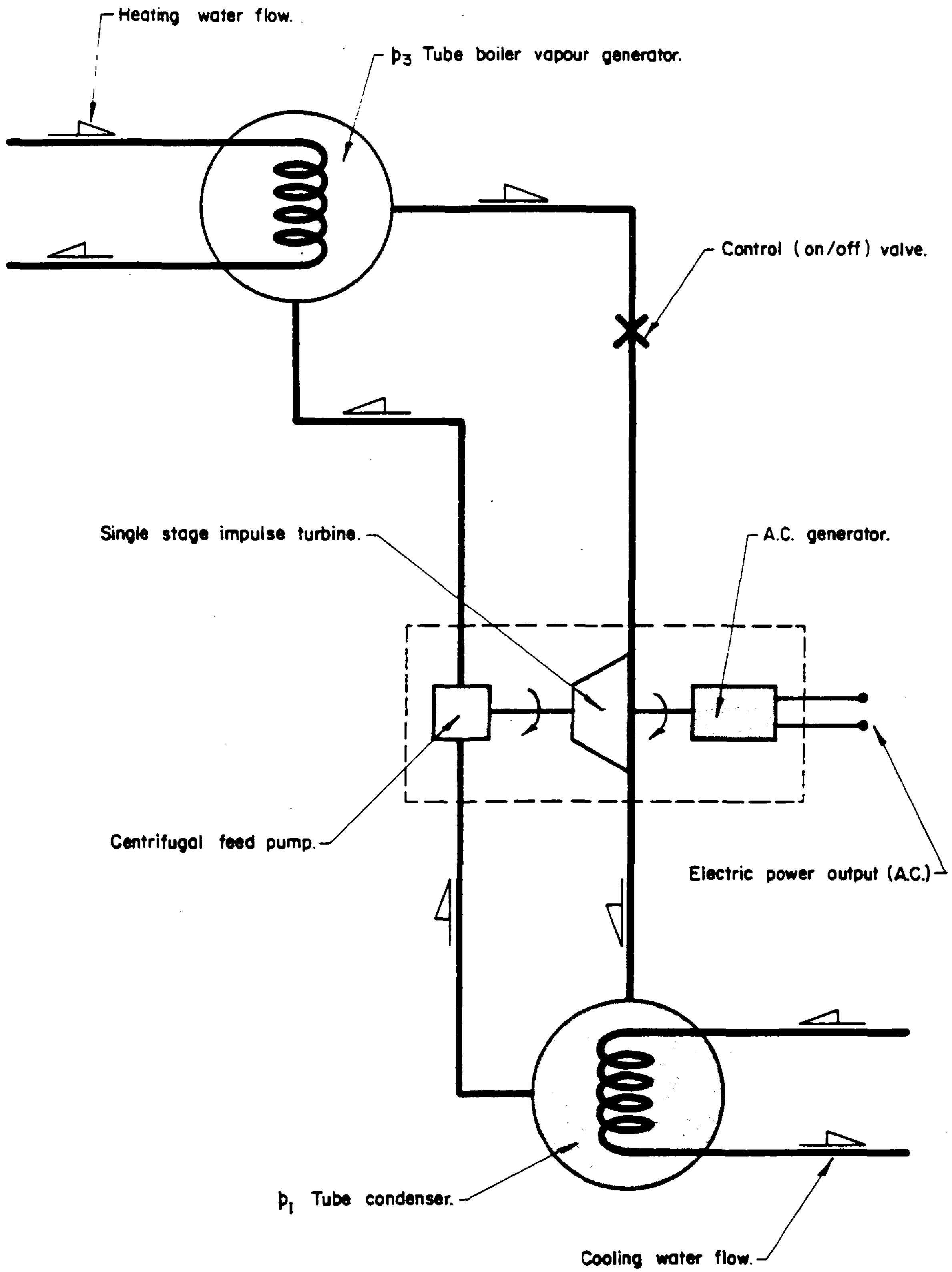
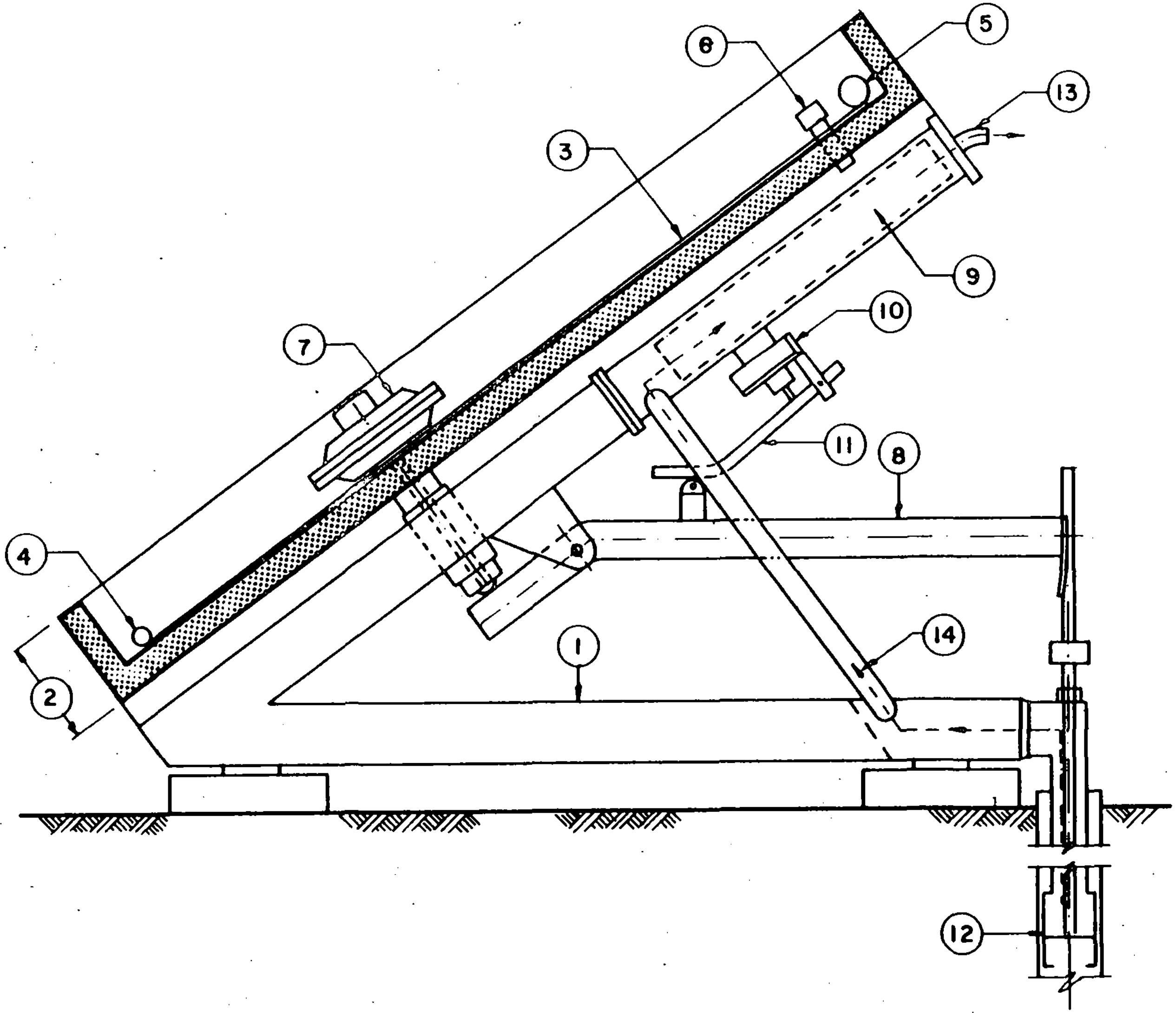


Figure 33 Schematic of Ormat Energy Converter



KEY

1. Support frame
2. Collector frame outside
3. Freon boiler
4. Freon liquid distributor header
5. Freon vapour header
6. Vapour pressure control valve
7. Freon engine and valve
8. Lever arm
9. Condenser
10. Freon liquid pump
11. Pump operating lever arm
12. Well pump cylinder assembly
13. Water discharge
14. Arrows indicating water flow.

Height : 1·8 metres
Width : 2·7 metres
Length : 2·0 metres

Figure 34 Schematic of SPC solar pump

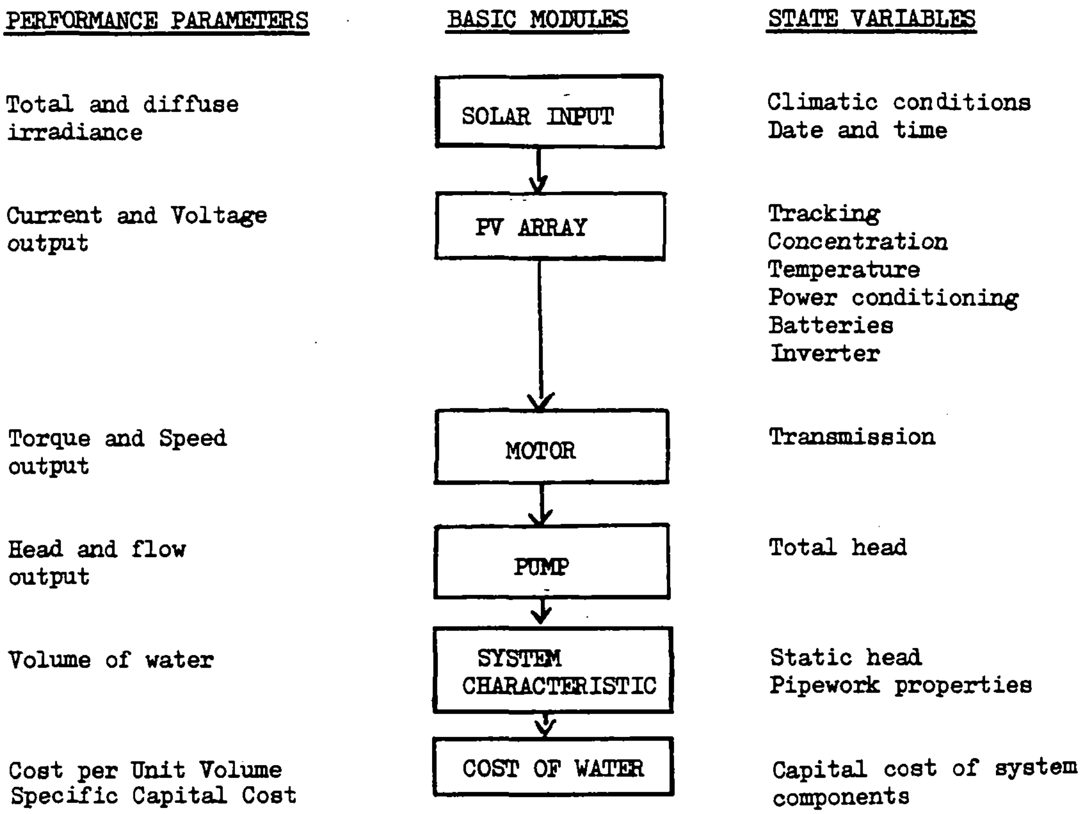


Figure 35 Block diagram for PV system model

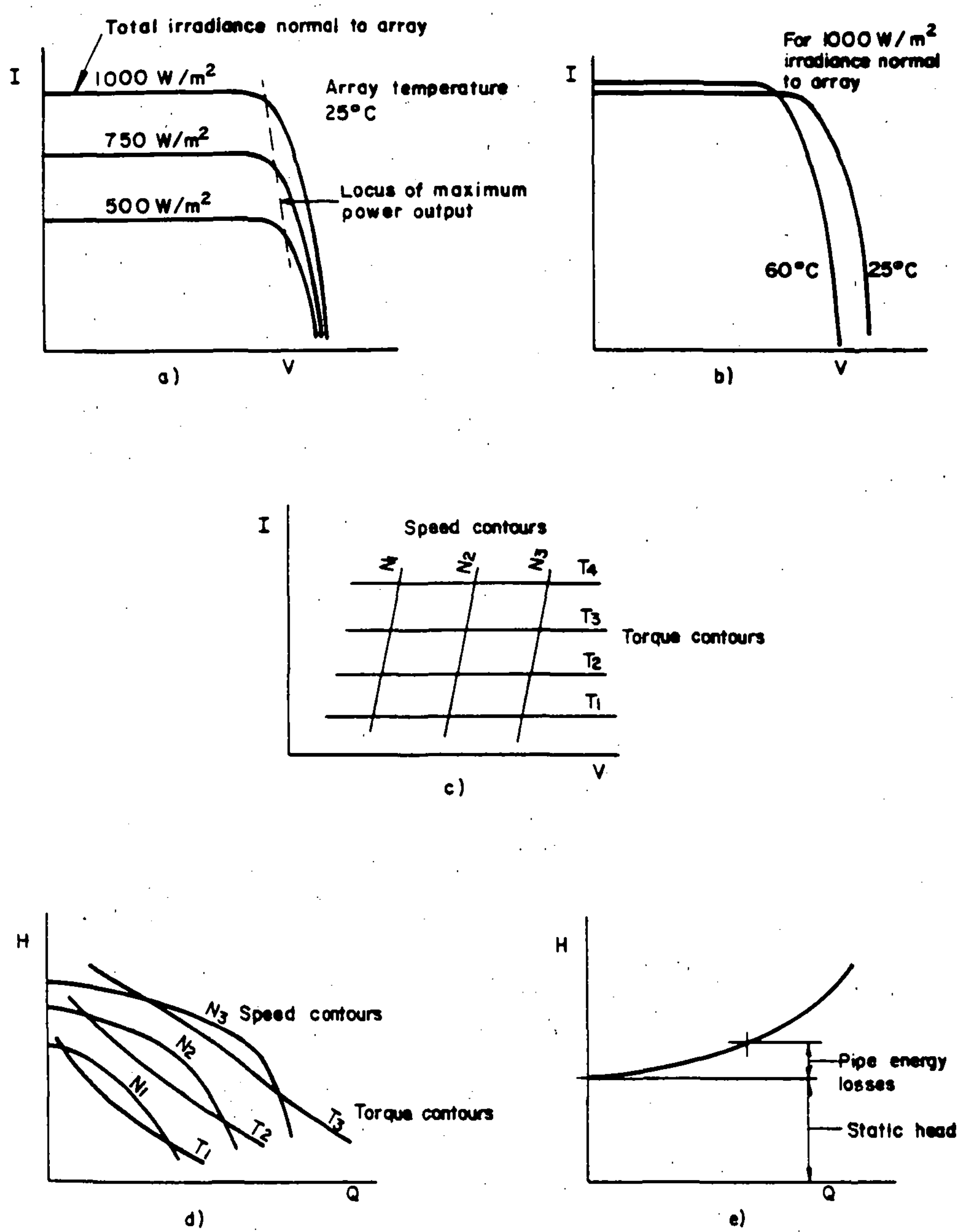


Figure 36 Performance characteristics of each module in PV model

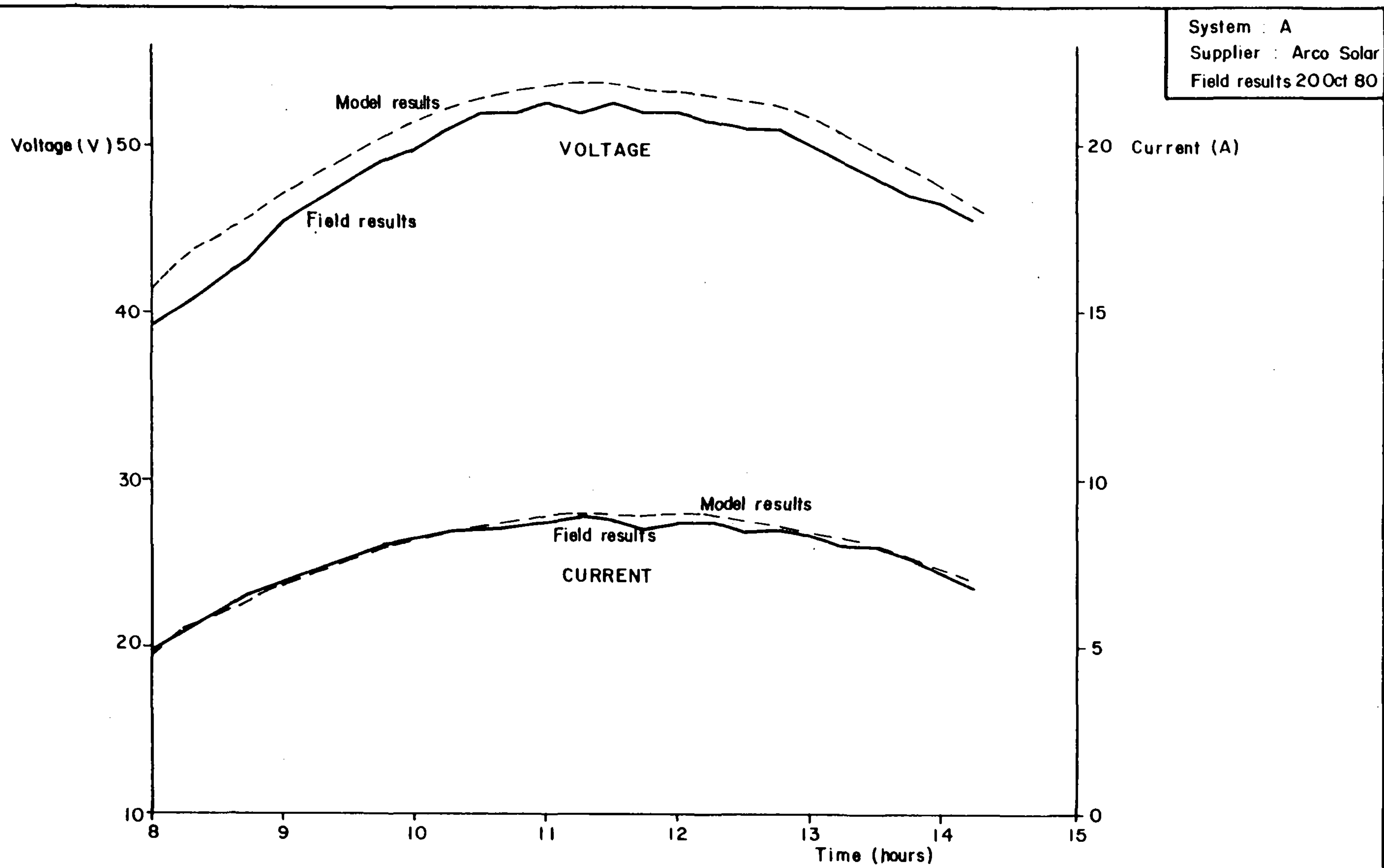


Figure 37 Validation of PV system model (array output)

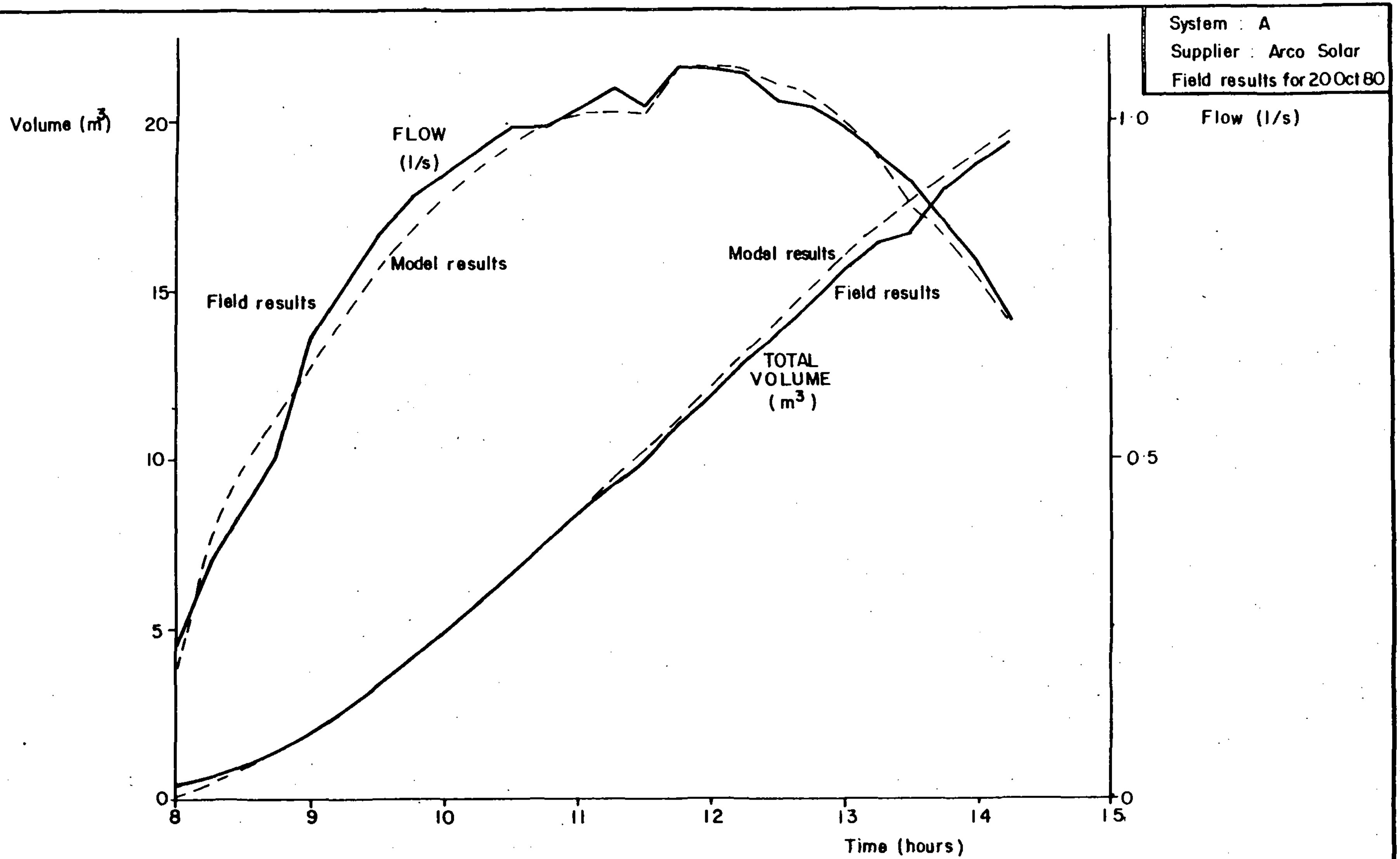


Figure 38 Validation of PV system model (pump output)

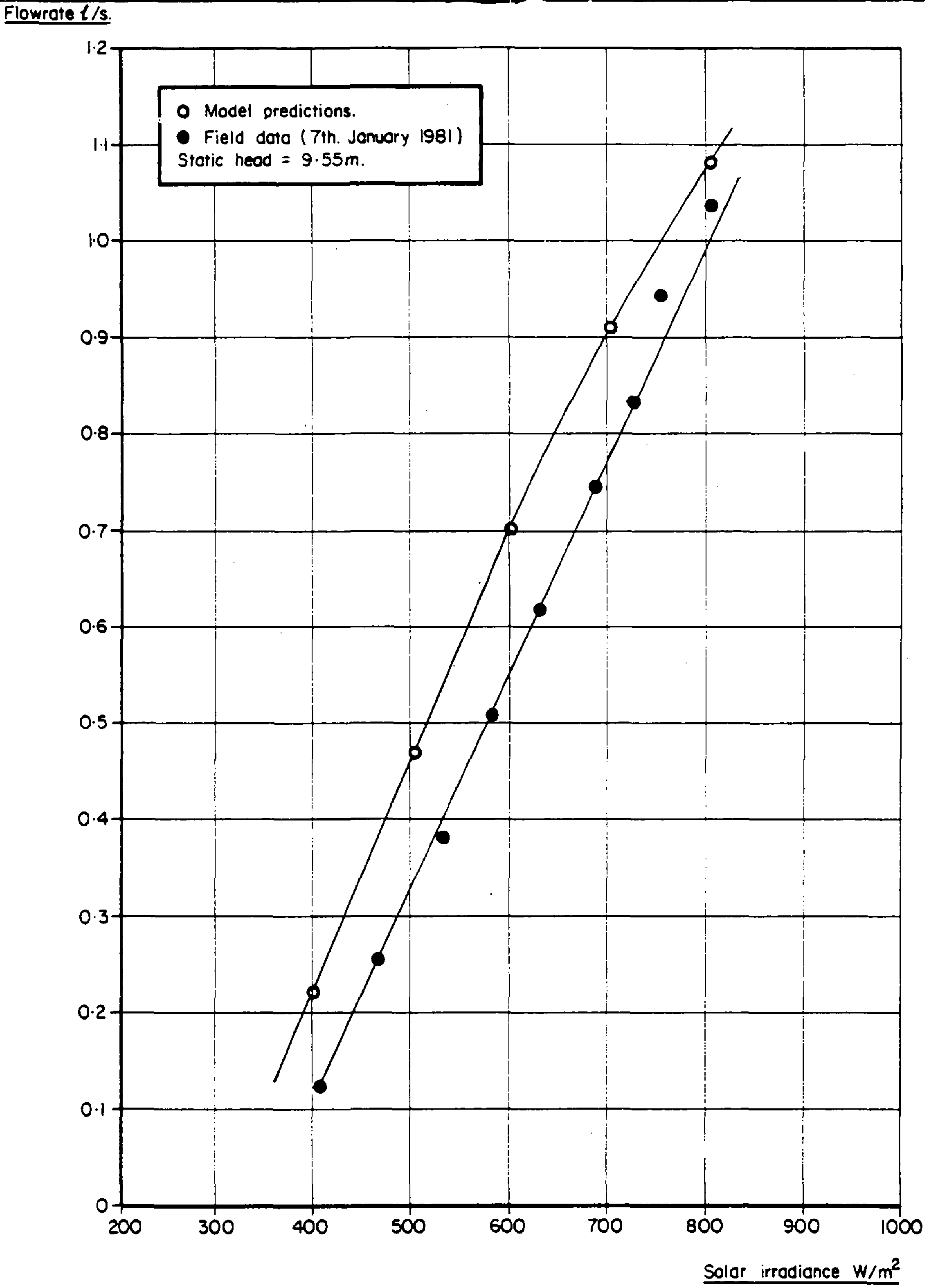


Figure 39 Validation of PV system model (flowrate)

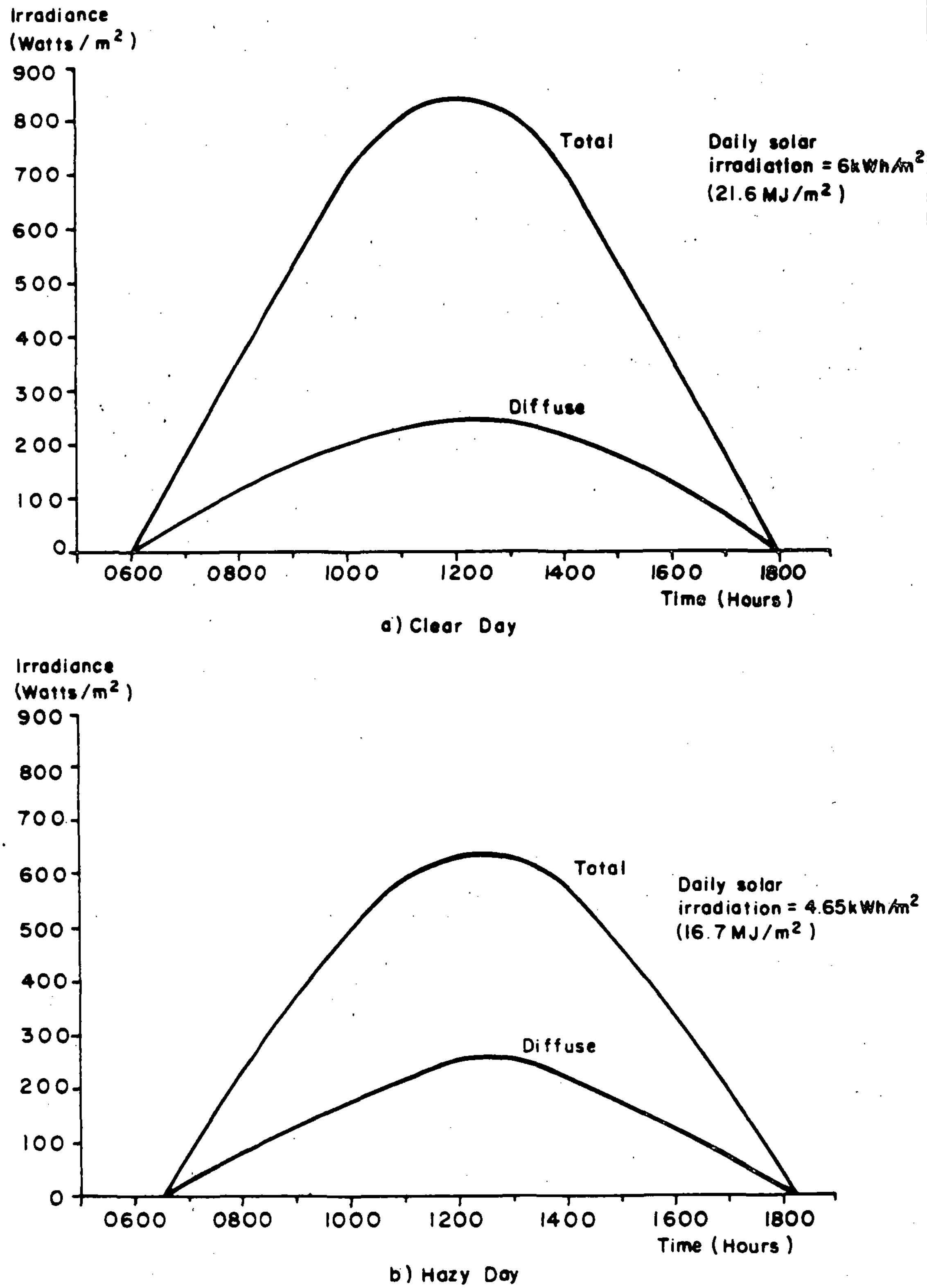


Figure 40 Standard solar days - clear and hazy

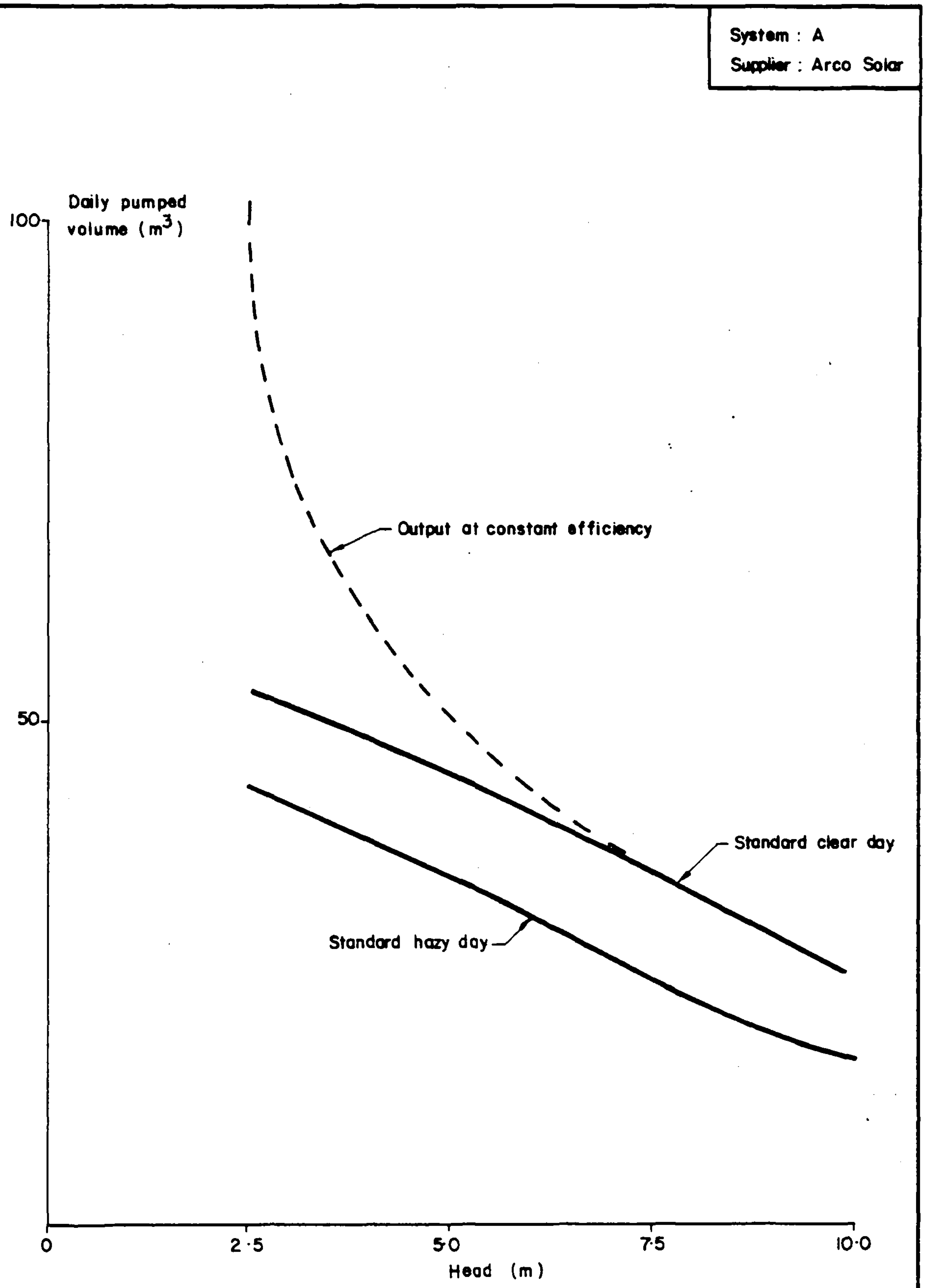


Figure 41 Variation of output with head for PV system

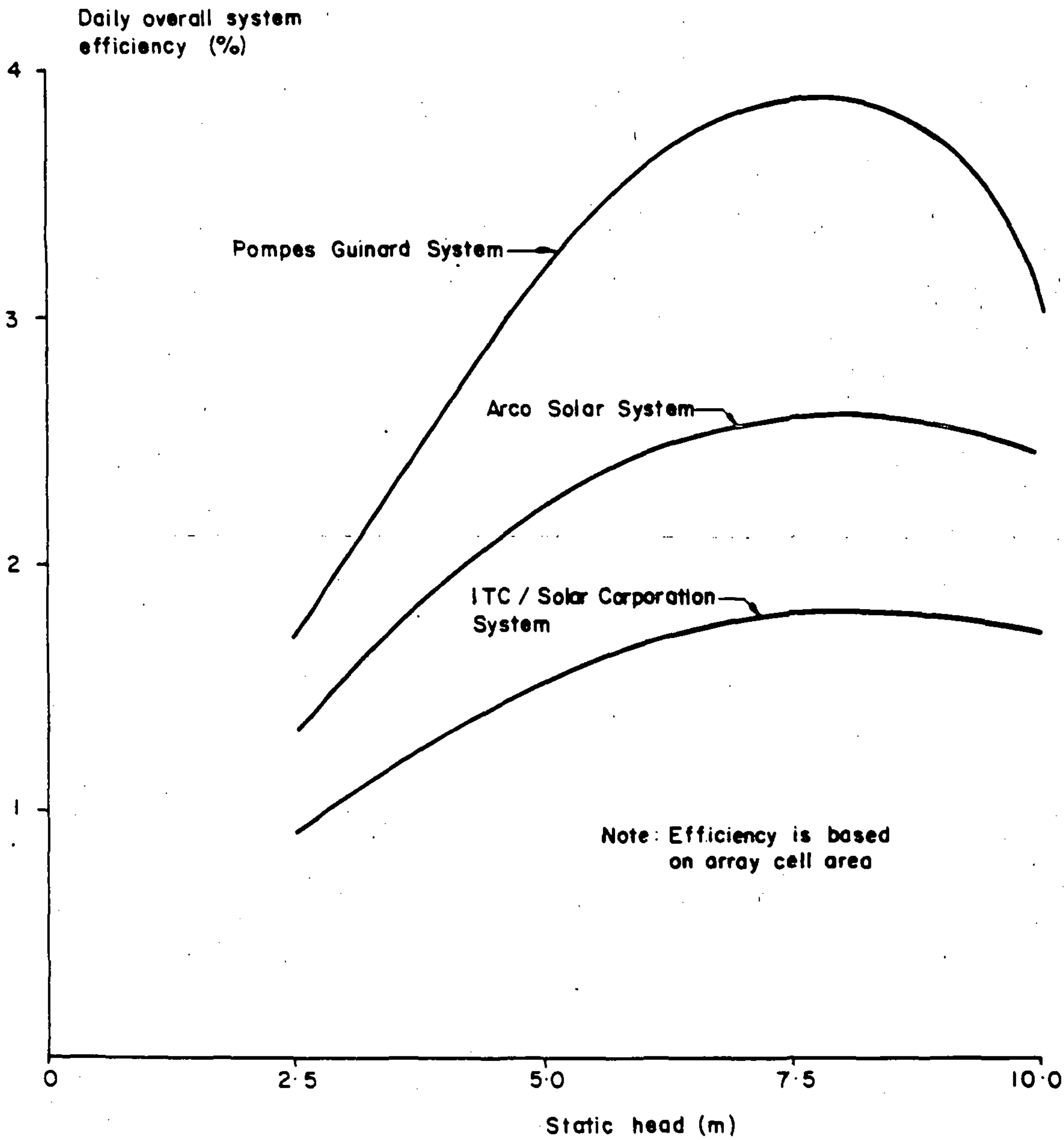


Figure 42 Variation of daily system efficiency with head

System : A
Supplier : Arco Solar

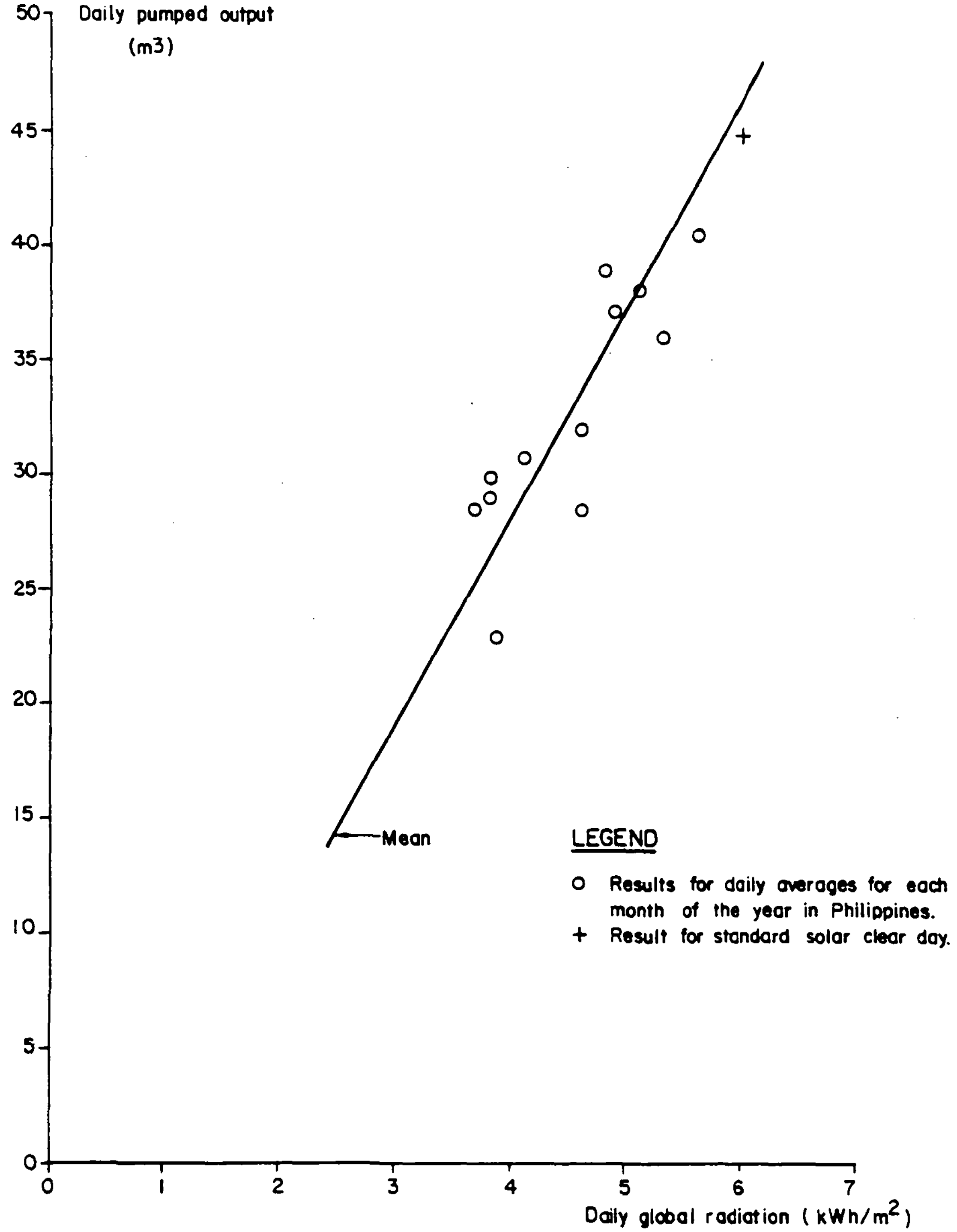


Figure 43 Daily system pumped output as a function of solar irradiation for Philippines condition

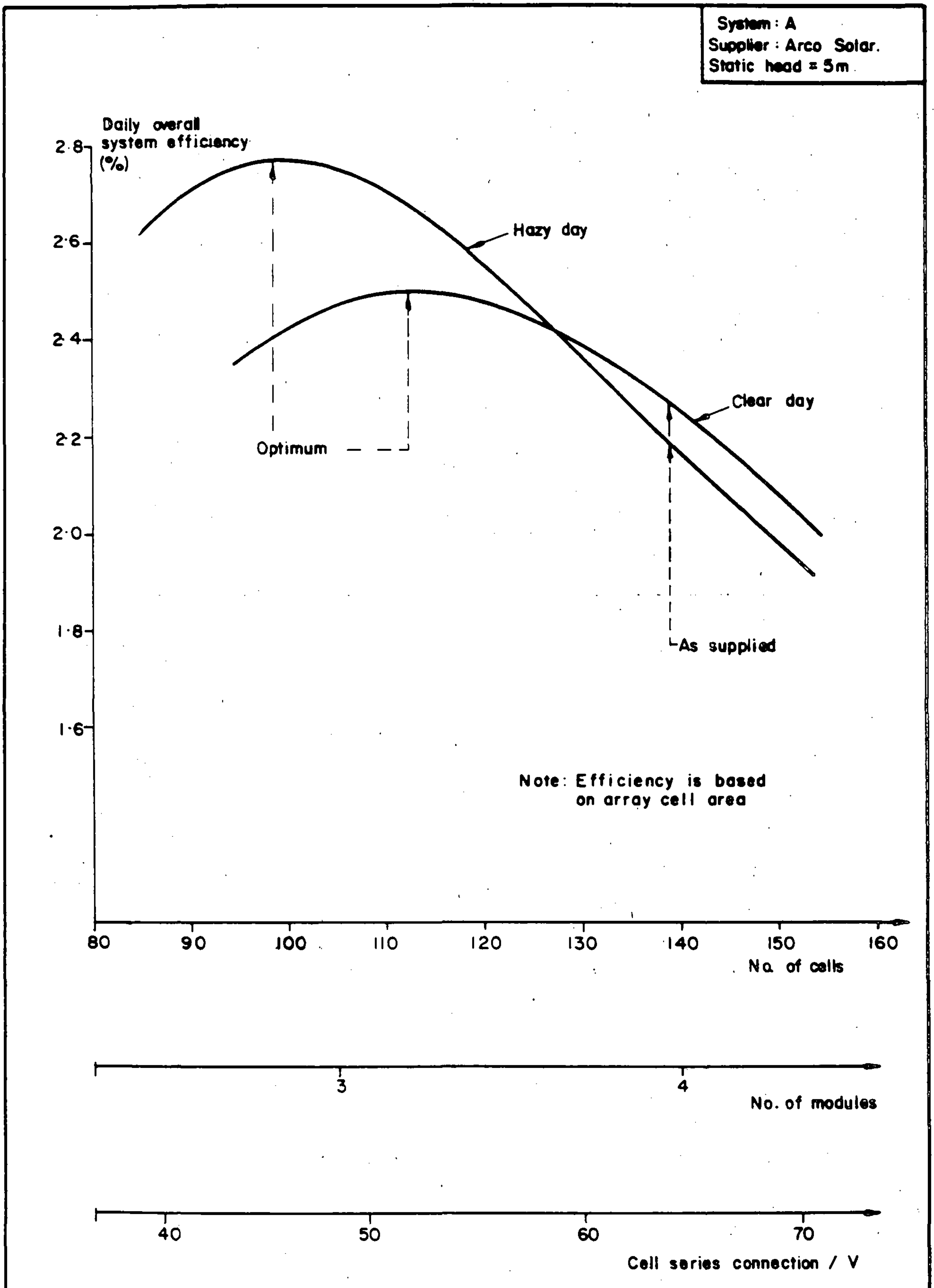


Figure 44 Sensitivity of daily overall system efficiency to array voltage

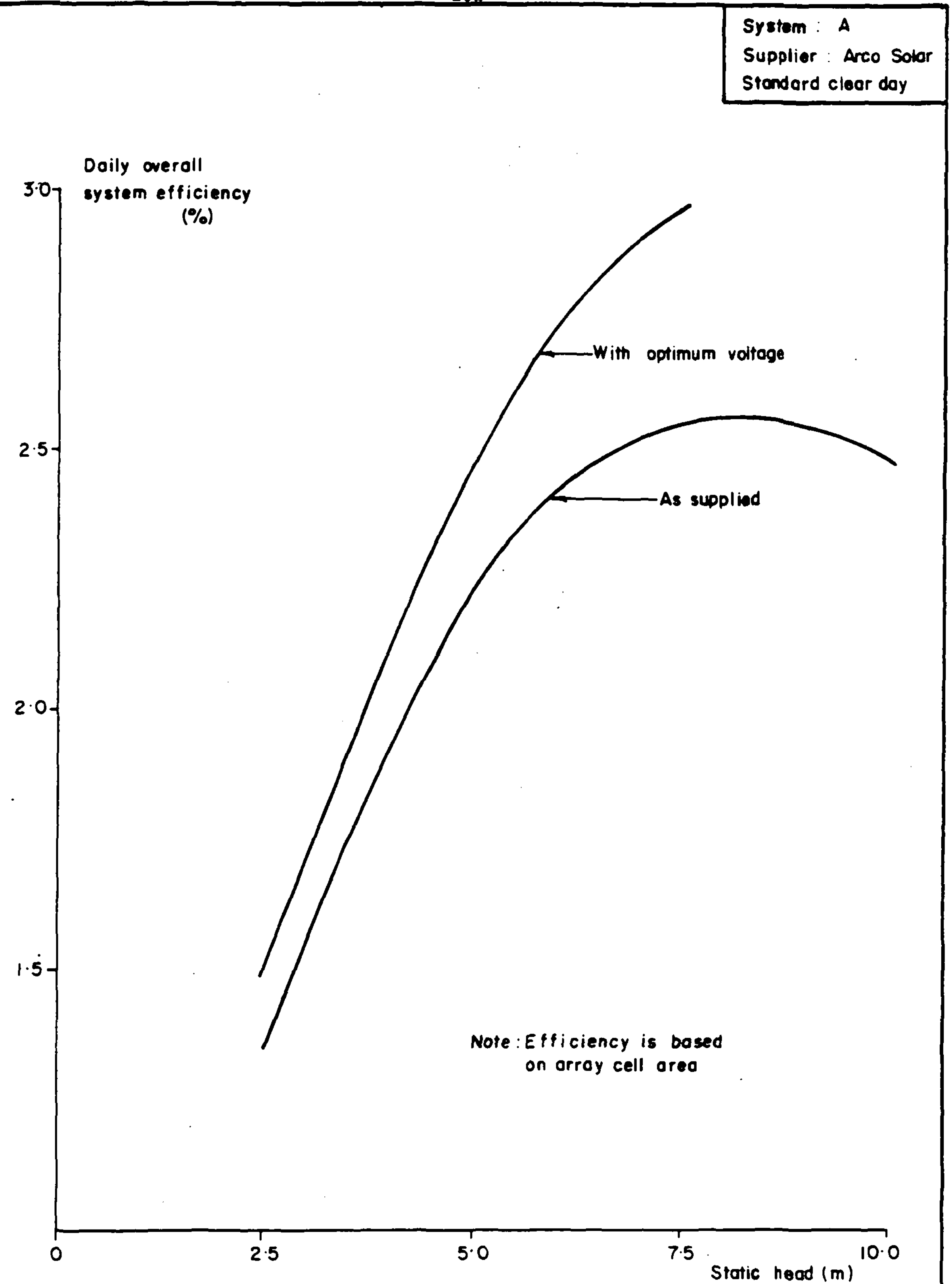


Figure 45 Variation of daily overall system efficiency with head for array optimised system

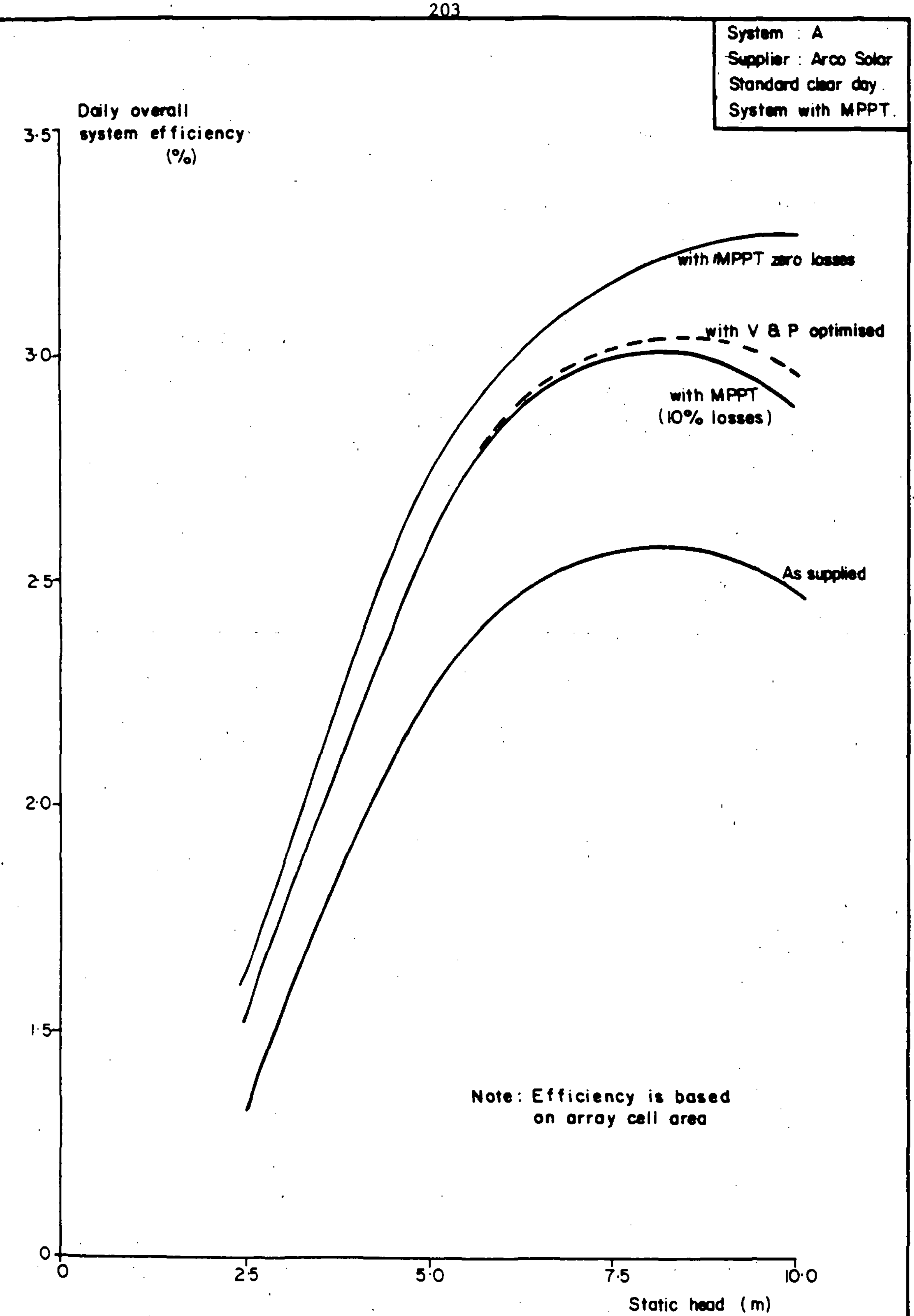


Figure 46 Variation of daily overall system efficiency with head for system with maximum power point tracker

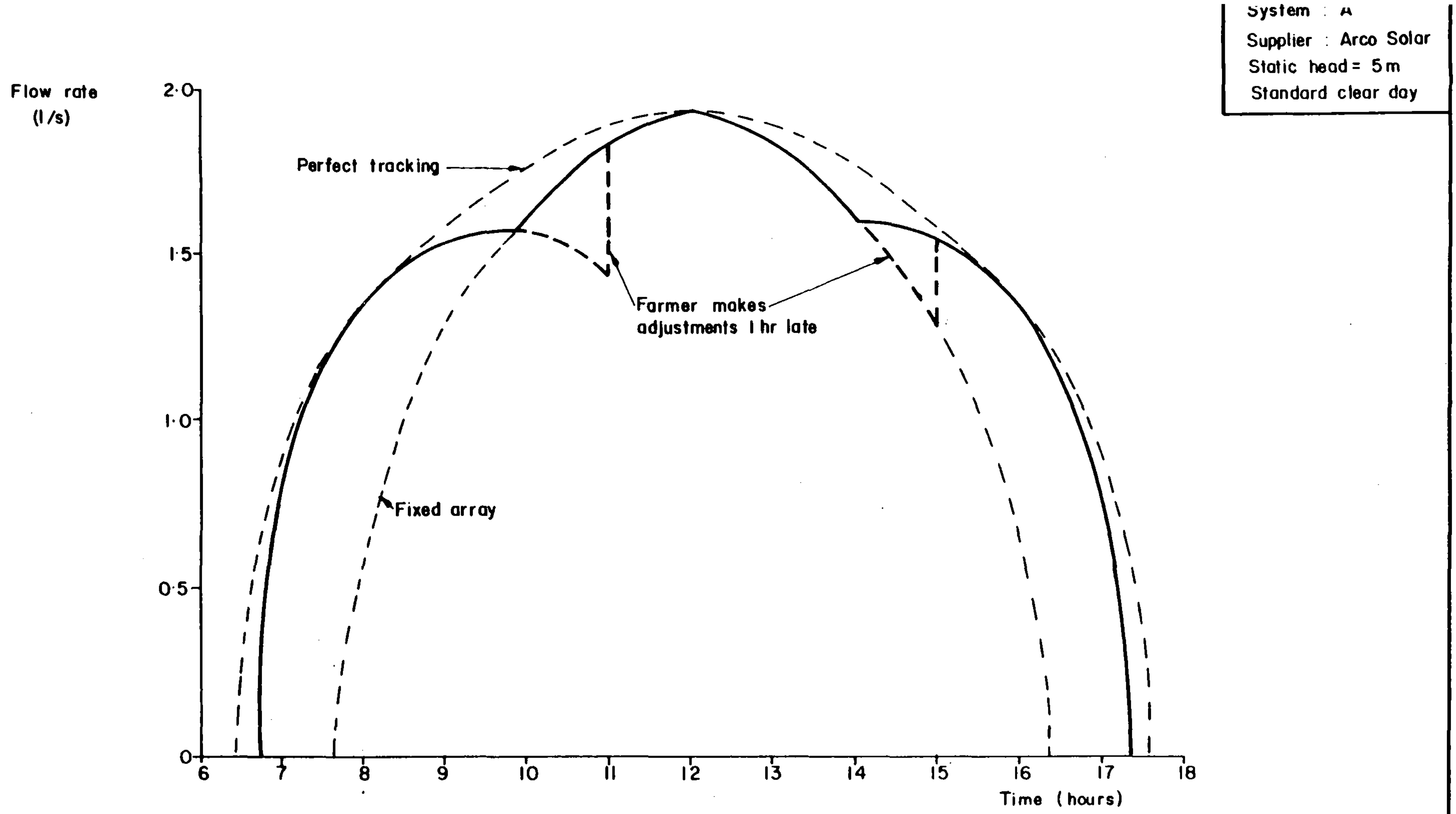


Figure 47 System performance with manual sun tracking - two adjustments per day

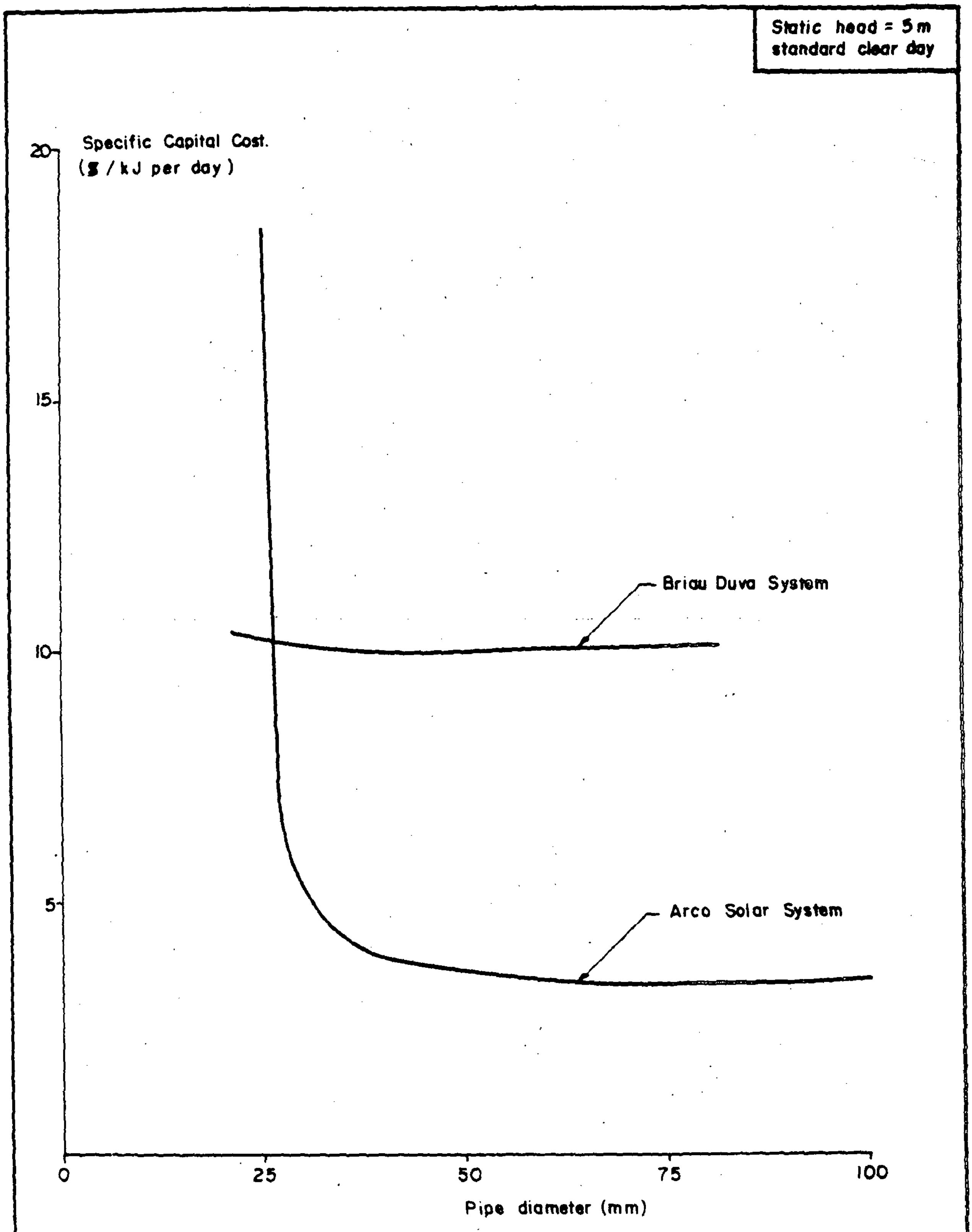
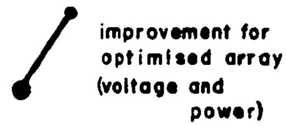


Figure 48   Effect of pipework changes on Specific Capital Cost

SYSTEM	SUPPLIER
A	Arco Solar
B	Briau (Duva)
C	Briau
D	ITC / Solar Corp
E	Omera Segid
F	Photowatt Int
G	Pompes Guinard
J	Solar Electric Int



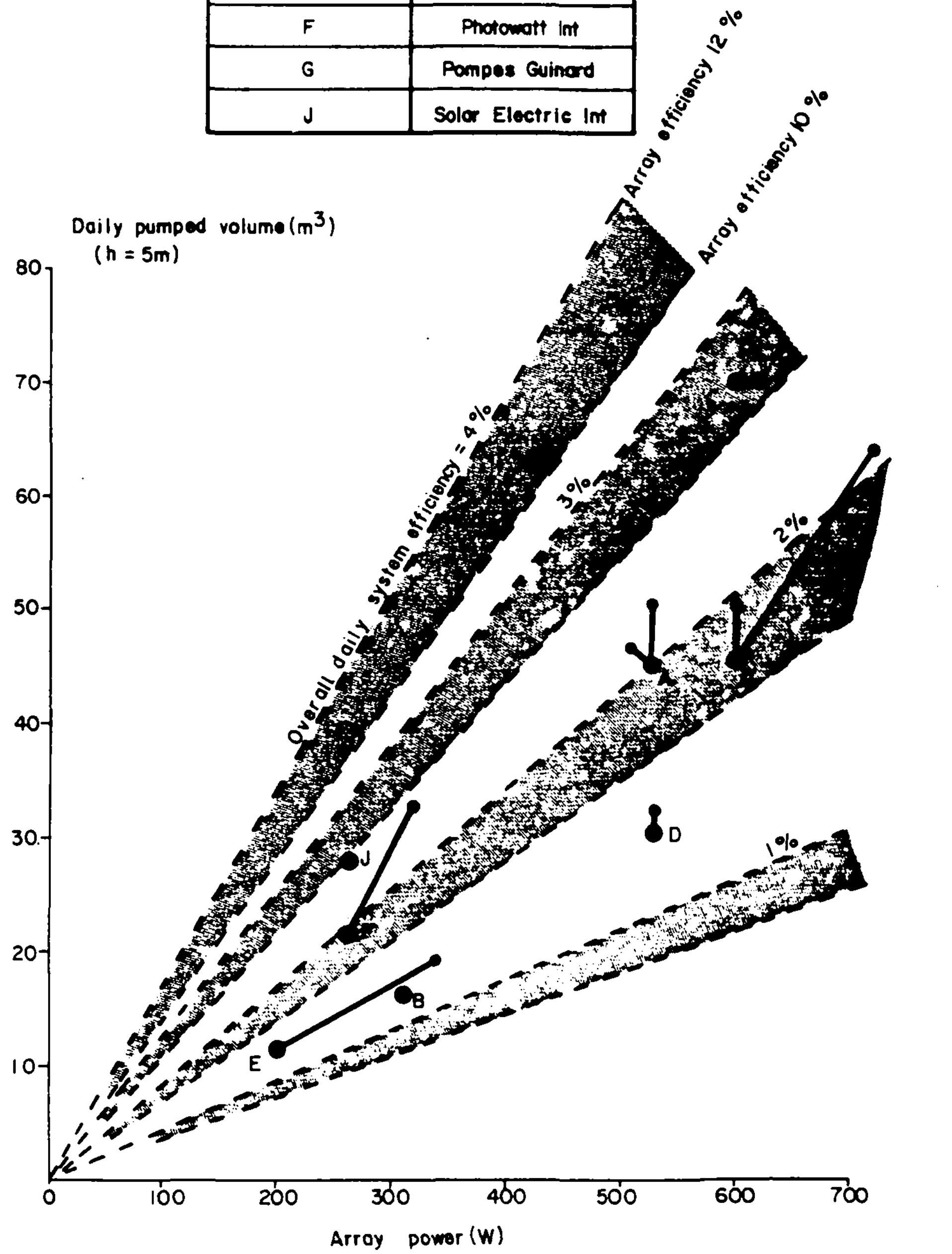


Figure 49 Comparison of systems based on water output as a function of array rated power

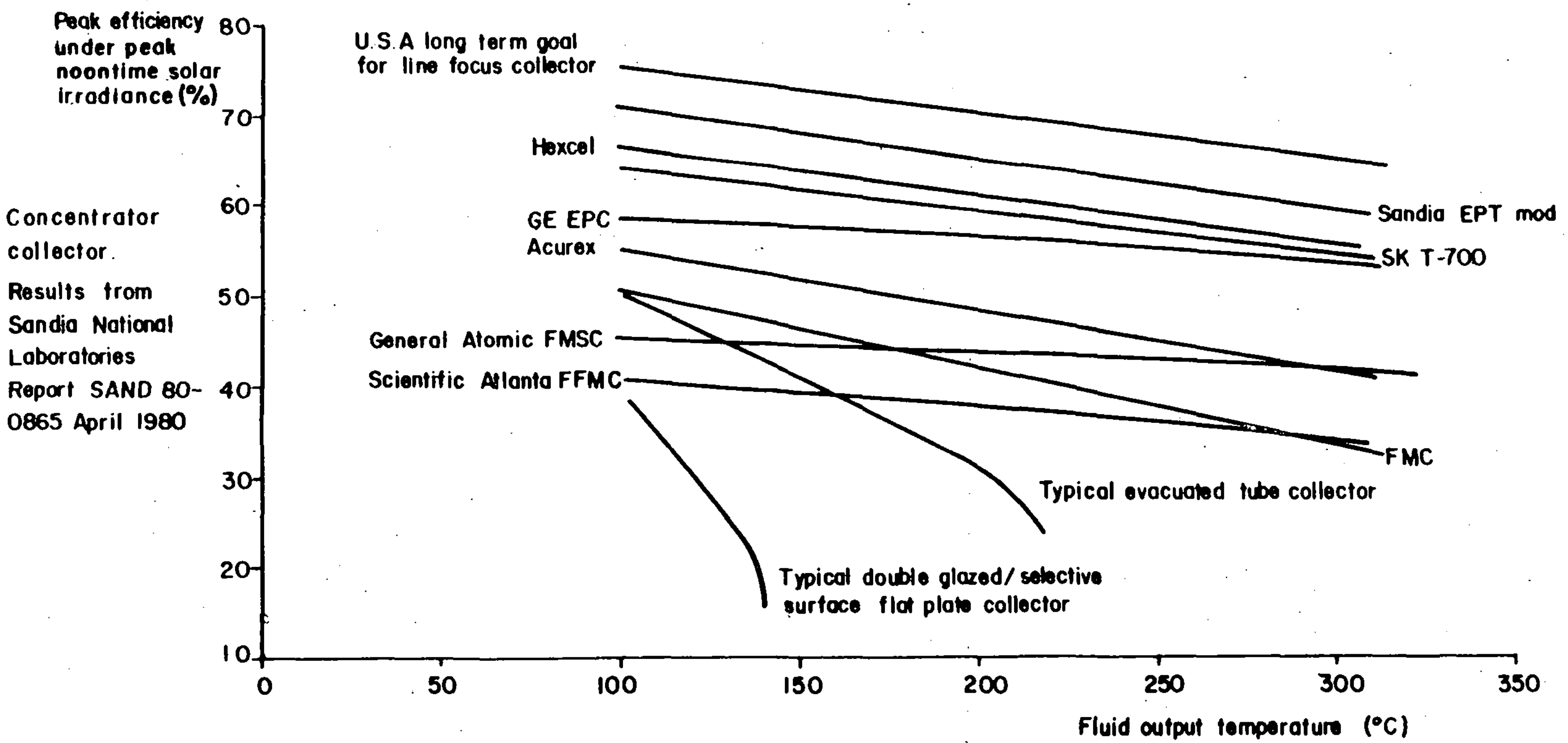


Figure 50 Comparison of solar collector performances

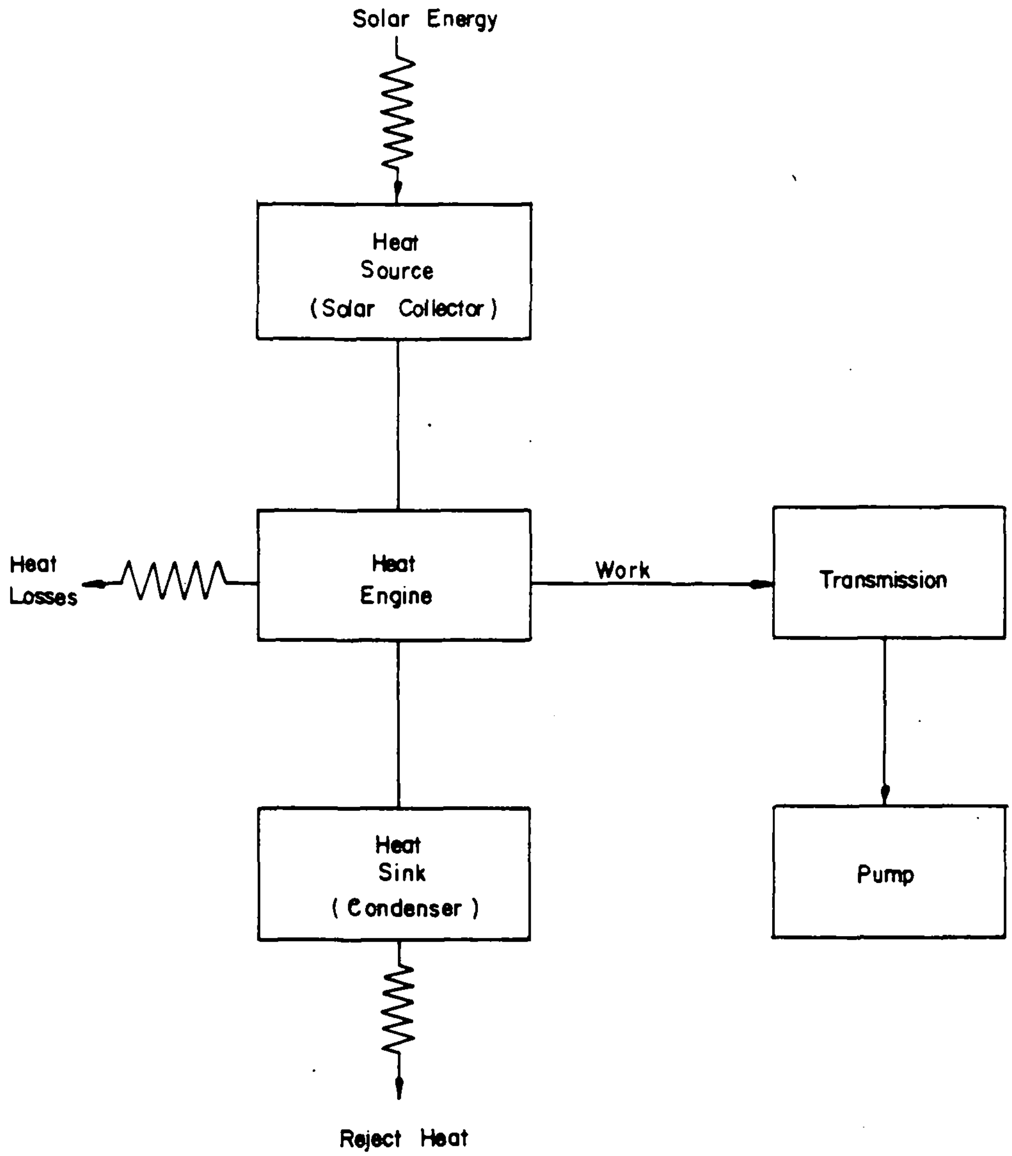


Figure 51 Thermal system block diagram

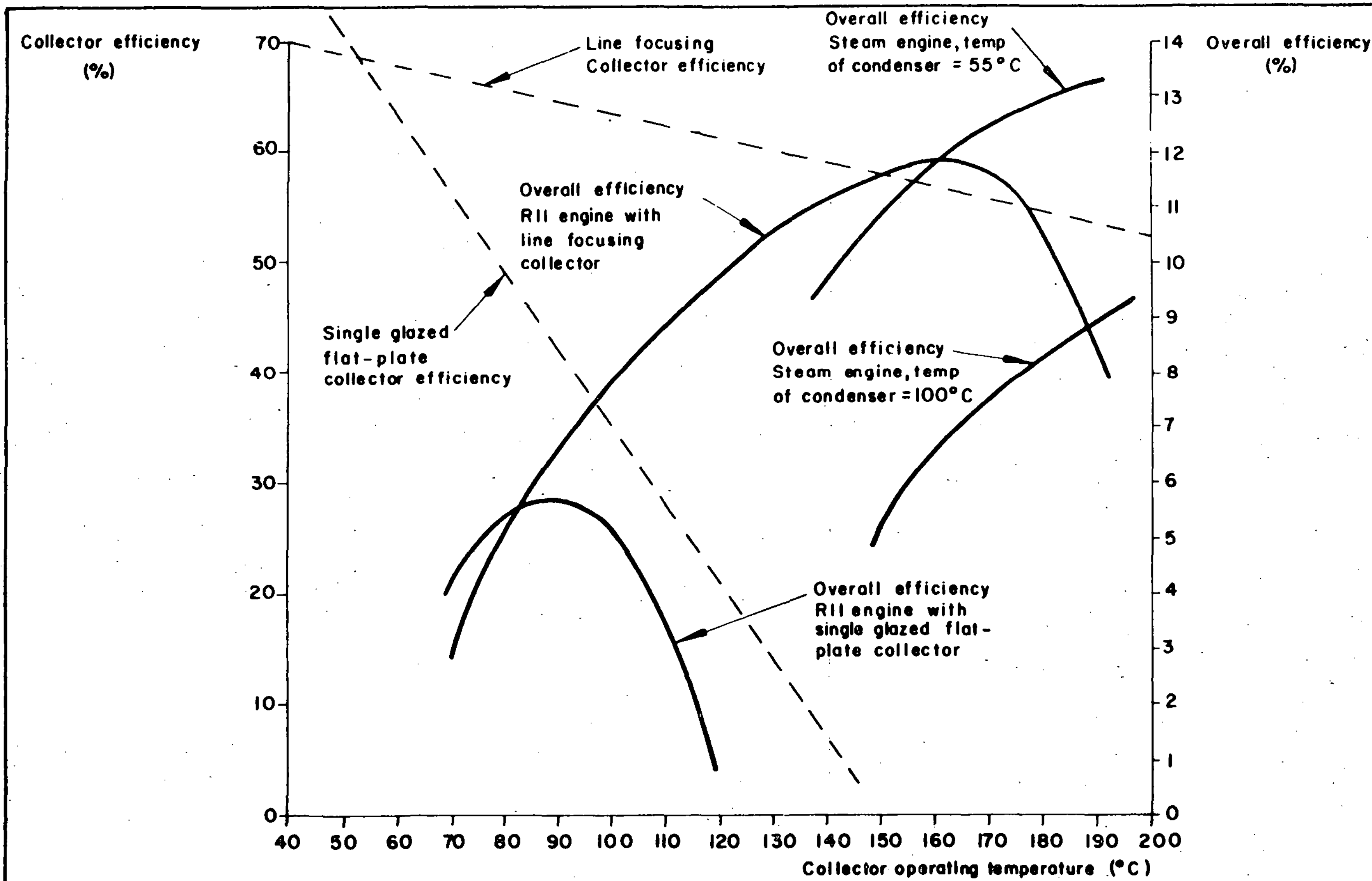


Figure 52 **Examples of thermal component and system efficiencies**

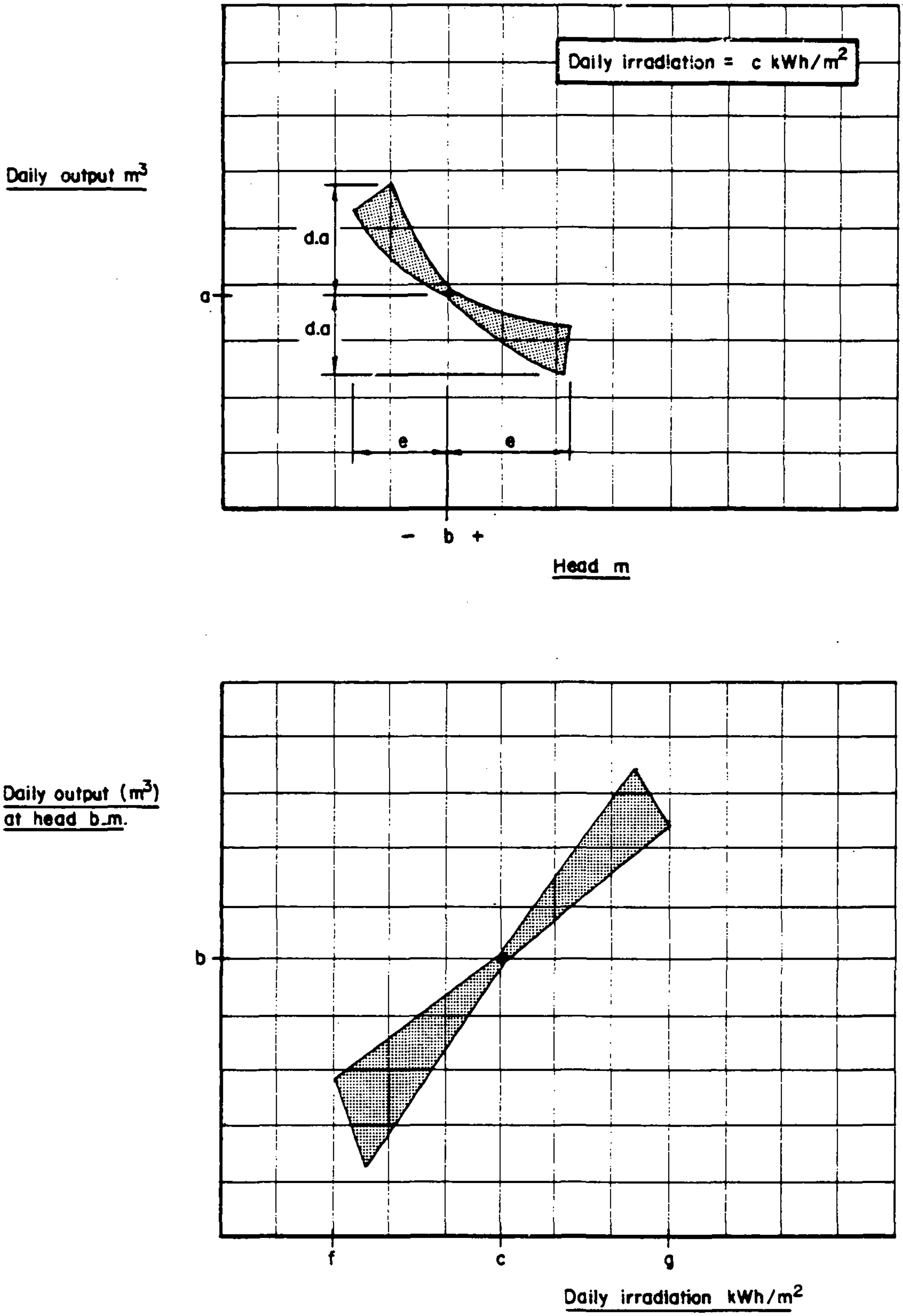


Figure 53 Specification characteristics for photovoltaic pump