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SOLAR PUMP FIELD TESTS IN BOTSWANA --
PRELIMINARY TECHNICAL AND COST COMPARISONS

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ACRONYMS

AC	alternating current
AID	U.S. Agency for International Development
ALCC	annualized life-cycle cost
ARD	Associates in Rural Development, Inc.
BOS	balance of system
BRET	Botswana Renewable Energy Technology project
BTC	Botswana Technology Centre
DC	direct current
DWA	Department of Water Affairs
GOB	government of Botswana
IT Power	Intermediate Technology Power Ltd.
HP	horsepower
kWh	kilowatt-hour
LCC	life-cycle cost
LTPC	long-term performance characteristic
m	meters
Met Services	Department of Meteorological Services
MLGL	Ministry of Local Government and Lands
MMRWA	Ministry of Mineral Resources and Water Affairs
MPPT	maximum power point tracker
P	pula
PCU	power conditioning unit
PV	photovoltaics
RET	renewable energy technology
RPM	revolutions per minute
VDC	Village Development Committee
WMU	Water Maintenance Unit
Wp	watts peak

PREFACE

This report presents the results of a comparative testing and evaluation program for solar-powered water pumps conducted by the Botswana Renewable Energy Technology (BRET) project. Mr. Richard W. McGowan is senior engineer and Mr. Jonathan Hodgkin, a staff engineer for Associates in Rural Development, Inc. (ARD), the contractor implementing the BRET project for the U.S. Agency for International Development (AID) under contract number 633-0209-C-00-1024-00. This comparative photovoltaic (PV) pump testing program was undertaken in coordination with the Government of Botswana's (GOB) Ministry of Mineral Resources and Water Affairs (MMRWA). Substantial contributions to these activities were made by the Department of Water Affairs (DWA), Ministry of Local Government and Lands (MLGL), Botswana Technology Centre (BTC) and Rural Industries Innovation Centre (RIIC).

I. EXECUTIVE SUMMARY

Associates in Rural Development, Inc. (ARD), technical contractor to the Botswana Renewable Energy Technology (BRET) project, a joint effort of the U.S. Agency for International Development (AID) and the government of Botswana (GOB), conducted a series of long-term tests to compare the technical and economic performance of five solar photovoltaic (PV) water pumps at remote sites in rural Botswana. The tests were part of the more comprehensive water pumping comparative testing and evaluation program, which included tests of over 40 diesel, grid electric, wind, PV, hand-operated, animal-traction and biogas pumps. The objective was to provide detailed field-test results under the harsh operating conditions often encountered in developing countries, so that technical, economic and institutional comparative evaluations could be made of the various system alternatives.

This report gives the details of the PV pump testing program, including:

- discussion of currently available equipment options;
- system design;
- the technical and cost characteristics of each of the systems tested thus far;
- discussion of pertinent institutional issues, such as training needs and government policy, upon which wider dissemination may well hinge;
- needs for further research; and
- discussion of the potential for and realistic limitations of using PV pumps to meet village-scale water demand at remote sites in rural Botswana.

For the PV pump testing component, three Jacuzzi DC electric submersible pumps and two surface-mounted Honeywell DC electric motors driving Mono (progressive cavity, positive displacement) pumps were installed, monitored and evaluated. All PV arrays were fixed (non-tracking), ranging in size from 516 to 1,548 Wp (watts peak). The pumps were installed at sites in southeastern Botswana, and were used to provide water for village domestic consumption, small-scale irrigation and stock watering. Both production and prototype systems and components were tested. Some equipment sold as production was, in fact, prototype, leading to temporary outages in several systems.

Tests were divided into short- and long-term components. The short-term tests were designed to determine the maximum potential output of the pumps given the site and radiation conditions, and to determine the interactive performance of each of the system's components. The long-term tests were used to generate input data for a financial/economic analytical model by determining long-term technical performance parameters (e.g., component reliability and time-dependent output degradation) and the long-term recurrent costs of operation, maintenance and repair. The primary criterion for comparing the performance of each of the systems was the annualized life-cycle cost of water pumped per unit head per unit volume (or the unit cost in pula/m^3*m, where one pula equals US$0.57), hereafter called the "unit cost."

A life-cycle costing analysis was carried out wherein all costs (capital equipment, transportation, installation materials, labor, maintenance and repair) incurred or expected to be incurred over the economic lifetime of the system were included. Since the systems were monitored for periods varying from a month to nearly a year, it was necessary to extrapolate from the limited data base available thus far to estimate annual performance and cost figures. A simple computer algorithm calculated water output over the months not measured, using measured component efficiencies and estimated solar radiation levels for the periods for which no actual data had yet been collected. Estimated solar radiation levels were based in part on long-term measurements made at several relatively nearby locations in South Africa. These costs and water output data were then used to calculate the unit water cost, and the PV pumps' unit costs were compared to those measured and calculated for the other pumping systems (e.g., diesel, wind, etc.).

Mono pumps are the de facto standard pump in Botswana. Used on 85 percent of the boreholes in the country, they normally have relatively high starting torque requirements, making it necessary to use either batteries or a maximum power point (MPP) or constant voltage tracking (CVT) controller. One of the PV/Mono systems (at Otse) was an older battery system using eight ARCO 16-2000 modules. After the original charge controller failed, a new, locally manufactured controller was installed with a low-voltage disconnect that acted as the on/off switch. A recently developed low starting torque Nitrile stator Mono pump element was later installed for comparative purposes. Because a lack of proper battery maintenance (and the associated increased operating cost over the system lifetime) is not uncommon, the second Mono system (at Mmathubudukwane) used a BOSS solid-state CVT pump controller with a 1548 Wp array to provide the high starting torque. The CVT operation was problematic due to both design and manufacturing defects. It has since been redesigned and reinstalled at the site.

Of the three Jacuzzi submersibles tested, two were direct-coupled and the third was tested in two configurations: direct-coupled and with a CVT. The first two systems (at Molapowabojang and Mochudi) were identical, using 32 ARCO M53 modules for a total of 1,376 Wp. The third submersible (at Mahalapye) was originally configured with 12 M53s, and a fourth string was later added for 688 Wp. Although submersible centrifugal pumps do not strictly require controllers, the CVT was tested to see if the promised higher yields would justify the incremental cost to the system. This was not the case. The Mochudi pump, installed in a borehole with fairly saline water, failed after six months of otherwise trouble-free operation, due to excessive corrosion, and was replaced under warranty. While newer models are now routinely coated to protect against this problem, earlier models were not. Otherwise, the other submersible systems at Mahalapye and Molapowabojang ran without significant difficulty and required few repairs other than occasional replacement of vandalized modules.

Both short- and long-term measurements were made with a custom-designed data acquisition unit which recorded tilt radiation (silicon pyranometer), electrical output from the array (kWh sensor), electrical output to the pump (where a controller or battery bank was used), water output (positive displacement flow meter), elapsed time counter (on-board clock), and pump on-time. Return lines from the storage tanks to the boreholes were installed at most sites so that pump output would not be constrained by daily or seasonal demand variability.

The general results of each site's testing are given below. The Mono/battery system at Otse had the highest unit cost. The next most expensive system was the submersible at Mahalpye, which was improperly sized for the borehole conditions. An elevated tank that was to have been built by the water users never materialized, so the pump chosen for this site was operating off its design point. The unit costs of the submersible pumps at Mochudi and Molapowabojang and the CVT-driven Mono pump at Mmathubudukwane were approximately equal, assuming that initial operational difficulties with the Mono controller can be ironed out, and that the pump would perform over the long term at the level measured during short-term tests with the redesigned CVT. The unit costs for these three systems are approximatley equal to diesel pump unit costs for simailarly sized systems. No costs common to all systems were included in the analysis (e.g., borehole drilling, storage tanks, distribution piping, etc.). The issue of storage requirement differences for diesel, wind and PV was not specifically addressed in this phase of the study.

In estimating the recurrent operation, maintenance and repair costs, submersible pumps were assumed to require replacement every seven years, down-hole piping every five years, and solid state components every 10 years. Semi-annual

inspections of the system by Water Maintenance Units were assumed. A major assumption was that a pump attendant would have to be hired to inspect the aboveground components and storage/ distribution system on a weekly basis, based on the government's labor policies. While this does not affect the unit costs of the PV pumps compared to each other, it obviously affects their unit costs compared to diesels, since a large part of diesel operating cost is the cost of the pump attendant. Also, based on experience with the systems thus far, the periodic replacement of some modules due to vandalism was included in the recurrent costs. Previous analysis of PV pump costs often assumed that no components of the system would require replacement over the assumed 20-year lifetime (based on accelerated testing of the PV modules themselves). This assumption is unjustifiably optimistic and does not reflect the reality of harsh operating conditions encountered in the remote rural areas where these systems are most often installed.

Bearing in mind that Botswana has exceptionally high and annually uniform solar radiation levels, making PV more cost-effective, and that the GOB has been quite successful with its program to provide village water supplies primarily with diesel-driven Mono pumps (making diesel pumping a less expensive and more viable option than in many African countries), the general conclusions reached during the first phase of this study include the following:

- PV pumps (at 1984 module prices of about $8.50/Wp) are approximately cost-competitive with diesels for low- to moderate- head and flow conditions (greater than 120, but less than about 800 m^3*m/day, i.e., delivering either 20 m^3/day at 40 meters head or 40 m^3/day at 20 meters head), particularly at sites far removed from diesel support facilities;

- below this level of demand, hand pumps become more cost-effective if no labor charge for pumping is assumed;

- diesels are a better choice at heads greater than about 60 meters and for daily demands of more than 800 to 1,000 m^3*m/day, given present size limits on commerically available PV pumps;

- current (early 1986) module prices (at US$6/Wp or less) do not significantly alter these conclusions for systems larger than 2.2 kW, since the unit cost of diesel pumping drops off very quickly with increasing size above the smallest units--for systems less than 2.2 kW, PV pumps become increasingly cost-competitive with diesel as module prices continue to drop; and

- based on sensitivity analyses performed on all important cost assumptions in ARD's overall comparative pumping report (WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, 1986), the most sensitive cost assumption in all cases was the labor charge of the pump attendant.

The Department of Water Affairs (DWA) was particularly interested in whether the continued, nearly exclusive use of Mono pumps was desirable, or whether electric submersible pumps (powered by either PV, diesel generators or grid electricity) held sufficient promise that DWA should include more submersibles in its installation program. Based on the data gathered thus far, the choice between Monos and submersibles is unclear, with each having its own advantages and disadvantages depending on site conditions. An extensive discussion of the relative merits of each of the system types is given in this report. In general, it is recommended that equipment not be chosen primarily on a least-cost basis, but that careful consideration also be given to system and component simplicity and robustness, the level of technical skills required in system design, installation, operation and repair, and the level of institutional support required.

The testing program has been extended for an additional 15 months to strengthen the performance and cost data base, both in terms of the number of systems monitored (several Grundfos AC submersibles and a variety of other PV/Mono configurations are being installed) and the length of data collection for each system. This will allow for more accurate determination of recurrent costs and component reliability. In particular, the systems driven by renewable energy require measurements of long-term energy resource levels (e.g., wind distribution and solar radiation) that reflect seasonal and annual variations. Solar radiation measurements now being made by the Meteorological (Met) Services Department will complement the measurements taken at the PV pump sites, refining the solar radiation data base for more accurate and cost-effective pumping system design.

Other research that would further strengthen the conclusions of this study are:

- a study of storage costs for PV pumps;

- a study of the costs of developing the infrastructural support network that would be a necessary part of any extensive dissemination of PV pumps in Botswana; and

- compilation of a list of GOB boreholes where demand for water is less than 40 m^3 per day and heads are less than 50 meters, to help quantify the size of the potential market for PV pumps in Botswana.

II. INTRODUCTION

Water is a critical constraint to development. In the developing world, much donor emphasis has traditionally been placed on large-scale water projects aimed at benefiting the greatest population concentrations. Rural areas have normally been left to make do with whatever resources they had available to secure reliable and safe sources of water for drinking, stock-watering, and small-scale irrigation. Village-level water supply systems, which often do not have access to the national electrical grid, have typically been either gravity-fed (where possible), or supplied by a wide variety of water pumping or lifting equipment. This has traditionally included pumps driven by human, animal, wind and diesel power.

In the arid areas of Africa, few sites are fortunate enough to have gravity-fed systems, and thus require pumps. All pump equipment requires outlays of inherently limited financial resources, and all require varying degrees of periodic maintenance and repairs to keep them running successfully. Each type of pumping system has a particular niche of usefulness which is a function of the magnitude of the water demand, water source constraints, locally existing infrastructural support (such as technical skills and spare parts inventories), and funds available for purchasing equipment.

With the advent of lower-cost solar photovoltaic (PV) cells, water supply engineers have begun to examine PV as a serious alternative to diesel pumps for small-scale, low-head (lift) systems. Diesels are normally the de facto standard pumps in developing countries and are often considered the least-cost option. While diesel, wind and PV pumps are all considerably more expensive than human- and animal-driven pumps, the latter are normally unable to meet typical water requirements except when demand is very small (less than five m3/day at low to moderate head).

PV water pumps are now supplying water for irrigation and village drinking water in many areas around the world, including Africa, Asia, the Pacific islands, and Central, South and North America. These systems range in size from an experimental 25 kWp (kilowatts peak, see below) unit using a 25-HP pump to irrigate grain fields installed in Nebraska in 1978, to 280 Wp arrays with 1/2-HP motors pumping water for small vegetable plots in Botswana and Zimbabwe. There are now an estimated 2,000 to 4,000 PV water pumps currently in use around the world.

The purpose of this report is to present the results of a study of the comparative technical and economic performance of a number of PV pumps installed in Botswana and operated by the Botswana Renewable Energy Technology (BRET) project, with

technical support from Associates in Rural Development, Inc. (ARD). While the project tested and evaluated a wide variety of water pumps as part of its comparative testing program, this report specifically addresses only the PV pumps.

Several previous studies have examined PV pumping, but there has been a dearth of practical field experience with the use of this newest water pumping technology. While manufacturers' data on their products are useful in performance estimation, they are often not especially reliable for system design. This is because the pump performance curves are measured under ideal operating conditions in the laboratory, pumping very clean (non-corrosive, not sandy) water, with a multitude of researchers nearby to attend to the system. Field-test results are crucial to the sizing and design of real systems. It is hoped that this report will aid other system designers with future projects, as well as give an indication of the real costs of PV water pumping.

A. Brief Project History

Prompted by a perception of the increasingly acute energy crisis in rural Africa, the U.S. Agency for International Development (AID) began to fund a series of 24 renewable energy technology (RET) projects in Africa in the late 1970s. As part of an overall evaluation of the results of this effort, a study funded by AID in late 1982 examined various RETs that were part of donor development programs in seven countries, and reported its findings on the technical performance of these systems (see TECHNICAL FINDINGS ON THE PERFORMANCE OF RETS IN AFRICA: RESULTS FROM 55 PROJECTS IN SEVEN SAMPLE COUNTRIES, J. Ashworth and G. Burrill, ARD, 1984). Among the technologies investigated were various types of RET water pumps--in particular, wind and photovoltaics. Some of the major technical findings included the following:

- there were long periods of inoperation of all types of pumps due to a shortage or complete lack of adequate spare parts and technical skills to keep the pumps running;

- insufficient training in proper maintenance and operations skills had been characteristic of many of the projects involving water pumps;

- RET pumps were frequently found to have been poorly designed, in terms of matching various components of the systems (e.g., pump and motor) and using unreliable or unproven components; and

- many donor agencies, in spite of previous problems with RET pumps, still felt that there was tremendous

potential for using PV for potable water pumping, in spite of its high capital cost, because of its promised high reliability for such a critical load.

Due in part to the findings of this report, the BRET project, after its mid-term evaluation, refocused some of its efforts to develop what has since become a comprehensive comparative testing and evaluation program for a wide range of water pumping systems, including diesel, PV, wind, biogas, animal- and human-traction pumps, and hand pumps. The overall results of this program are given in the summary report (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986).

Although the technical performance of the first generation of PV pumps is well documented (see SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS, THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank/UNDP, 1983), the rapidly maturing technology and the continually decreasing cost of PV modules caused BRET project planners and AID advisors to feel that a detailed field comparison of currently available PV pumps would provide valuable information to government decision makers and water resources development specialists about costs and reliability. Project staff decided to initially test five or six PV pumps instead of the two units suggested in the original project paper. Procurement and installation of these pumps was delayed at first by a lack of agreement between BRET and Botswana Technology Centre (BTC) staff on which types of pumps to test. The program was further delayed by the initial reluctance of the Department of Water Affairs (DWA) to release boreholes to the BRET project for the pump tests.

This report discusses the results of the detailed field testing of the first group of PV pumps purchased during 1984-85. Comparative technical and economic assessments of each of the PV pumps monitored by the project are given. While these results should not be considered conclusive because of the limited data on the relatively small number of pumps (five) monitored thus far, the information base will be significantly increased during the extension of the testing program through 1986. In addition to longer-term data on the recurrent costs and reliability of the presently monitored systems, this extension will allow monitoring of the performance of a second group of PV pumps, which had already been purchased and was in the process of being installed as the overall BRET project drew to a close in September 1985.

A World Bank mission to Botswana in 1984, while suggesting that previous analyses (see AN ANALYSIS OF WATER LIFTING DEVICES IN BOTSWANA, N. Davidson, BTC, 1984) of the potential for PV water pumping in Botswana should be viewed with caution, stated that PV pumps could possiblly be competitive with diesel pumps,

but only in certain situations. They would have to be used 1) for village drinking water supply, not irrigation; 2) at sites where diesel-pumping recurrent costs were higher than average (i.e., at more remote sites where the transport costs of fuel and spare parts were high); and 3) where the static lift was less than 30 meters (see BOTSWANA: ISSUES AND OPTIONS IN THE ENERGY SECTOR, draft, World Bank/UNDP, 1984). According to DWA personnel and a cursory examination of drilling records for boreholes in many areas of Botswana, average static lifts (depth from surface to water level) are in the 70- to 80-meter range over much of the country. However, along the eastern border (where much of the population lives), static lifts average 40 meters or less. It was mainly in such low- to moderate-head boreholes where the BRET PV pumps were installed.

B. Previous Comparative Evaluations

A very detailed study commissioned by the World Bank in 1978 examined the technical, economic performance and social acceptance considerations of the first generation of solar pumps (see SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS, THE TECHNOLOGY, ITS ECONOMIC AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank/UNDP, 1984). Other studies since then* have given, in varying detail, analyses of the performance of solar pumps under a variety of conditions in Africa and Central America. Nearly all of these studies have concluded that there are certain circumstances under which PV can be cost-competitive with diesel and windmill water pumps, but that relative position will be dramatically improved as the cost of the PV modules themselves (typically 80 to 85 percent of total installed system cost) continues to drop.

These studies have analyzed the technical field performance of the PV pumps in considerable detail, and have noted that there is still considerable room for improvement in the balance of system (BOS) components such as pumps, motors and controllers. As more research and development work on better matching of components proves fruitful, the annualized unit water costs of PV pumping will continue to improve relative to diesels, assuming constant fuel costs. Since diesel pumping is a mature technology, it is unlikely that further technical advances will dramatically alter its cost structure. Since the majority of the life-cycle cost (LCC) of operating a diesel lies in its long-term recurrent costs (for fuel, operators and periodic overhauls),

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*See HANDBOOK ON SOLAR WATER PUMPING, Sir William Halcrow and Partners and IT Power Ltd., World Bank/UNDP, 1984; EVALUATING THE TECHNICAL AND ECONOMIC PERFORMANCE OF PHOTOVOLTAIC PUMPING SYSTEMS: A METHODOLOGY (final draft), J. Kenna et al, IT Power and LESO for USAID, 1985.

reducing capital equipment costs will have little significant effect on the LCC.

However, diesels have the distinct advantage of being the most commonly used type of pump in the developing world. As such, the support infrastructure is already in place to some degree with respect to maintenance, spare parts availability, trained mechanics, fuel transport and equipment distribution networks. The use of PV will have to hold significant promise of realizable savings in order to justify the expenditure of scarce resources on establishment of a similar support infrastructure. The magnitude of these savings is discussed in detail in the overall comparative testing report (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986).

III. OVERVIEW OF SOLAR WATER PUMPING TECHNOLOGY

Photovoltaic pumps have been in use all over the world since the late 1970s. The initial pumping equipment used in the early systems consisted of off-the-shelf pumps and motors which were, in most cases, not specifically designed to be used with the PV array's electrical output. This lack of proper load matching between the power source and the motor/pump resulted in generally low system efficiencies, necessitated oversized arrays, and significantly increased the unit cost of water pumped ($\$/m^3$ per meter of head). Since that time, considerable research and development, coupled with some field-testing efforts, have resulted in water pumping equipment and controls that are more efficient, more reliable and less costly. This section describes the types of equipment currently used as well as recent developments in the field.

Solar pumps are used primarily for drinking water supply, stock watering and, to a lesser extent, for small-scale irrigation. Since the water output of a given pumpset (motor and pump) is directly proportional to the elevation plus pipe friction and velocity losses (i.e., the total pumping head) in the system, it is useful to talk not only in terms of the water output but also total head. For a given energy input, the higher the head, the lower the output, and vice versa. As an example of a small-scale irrigation application, consider the following. In some countries in Africa, many of the small farms are 1/2- to two-hectare (ha), intensively farmed plots (see HANDBOOK ON SOLAR WATER PUMPING, Sir William Halcrow and Partners and IT Power Ltd., World Bank/UNDP, 1983). For a total pumping head of 30 meters, a commercially available, 2.2 kW solar pump would provide approximately 40 m^3/day under good solar radiation conditions (20 MJ/m^2/day). Since irrigation water requirements are between about 20 and 80 m^3/ha/day, this PV pump could be used to irrigate 1/2 to two hectares. Similarly, for drinking water supply to a rural village, assuming that each person consumes 30 liters per day (the current minimum per capita demand used by the DWA in Botswana), the same pump would provide for the needs of about 1,300 people. If the pumping head were half of that initially assumed, the water output would approximately double, as long as the head and flow were within the particular pump's design operating range, and the borehole yield was sufficient.

Most of the PV pumps currently in use are located in developing countries. This is largely because international donor agencies have realized the considerable potential for these systems in isolated areas in those countries which do not yet, and may never, have access to grid electricity with which to pump water. Since national electrical grids cover most areas of developing countries, PV pumps (under current cost structures) would likely be cost-competitive at only the most remote sites,

or when their use is subsidized. Consequently, much of the comparative field-testing work has also taken place in developing countries. The logistics of gathering accurate experimental data when systems are installed at remote sites are formidable indeed.

A. Advantages and Disadvantages

PV pumps are normally characterized by relatively high initial capital costs and low long-term recurrent costs (annualized unit water costs are discussed in detail in Section VII). The principal reason for these low recurrent costs is the very long useful lifetime of PV cells, which use no fuel other than sunlight and have no moving parts. Anyone who is familiar with diesel engines in the field can appreciate the great advantage of having no moving parts that require lubrication, frequent overhauls and constant attention. PV manufacturers now routinely offer 10-year waranties on their modules against loss of rated performance. The cost of modules has dropped dramatically in the last five years, and there is every indication that price decreases will continue, since considerable research and development efforts are currently underway on a number of different PV cells in the United States, Japan and Europe. During the BRET project, module costs decreased from about P17.5/Wp to a current tender price of P10.5/Wp (from $10/Wp to $6/Wp, as of December 1985).

PV system reliability is no longer the concern it once was. As a result of field experience with the several thousand PV pumps now in use, manufacturers have developed high-quality systems and components that are generally much more reliable than the first-generation equipment, which did little to establish consumer confidence in photovoltaics. PV electrical generating systems have developed to the point that their outage rate is less than that of most electric utilities in developing countries, and their growing reputation for high reliability has led to their use as power supplies for critical loads (such as remotely sited telecommunications) for which power outages cannot be tolerated.

PV systems are also modular, which allows a user to increase the water ouput from the water system simply by increasing the number of modules in the array (subject, of course, to the constraints of the pumpset and the borehole yield). This modularity allows for more exactly meeting the site hydraulic energy requirements, rather than simply running an oversized pump, as is commonly the case with diesel applications. PV systems are most competitive with base-case diesel pumps in the low capacity range (less than three HP, or 2.2 kW--the current limit of standard off-the-shelf PV pumps) of the water pumping market, since diesel costs per installed kilowatt increase

markedly for small horsepower units (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986).

Most of the diesel systems in Botswana are Listers, the smallest model of which is a nominal 7.5 horsepower. Smaller gasoline-driven pumps from Japan are becoming available. These are high-speed units generally considered to be much less robust than Listers, and would likely have to be replaced approximately every three years. This frequent replacement would have an obviously adverse effect on the LCCs of the system. In addition, the gasoline engines require unleaded gasoline, which is not readily available in Botswana.

Since solar radiation is usually highest during the hottest part of the year, solar pump output is usually highest during the periods of highest water demand (during the dry season). PV pumps, as users frequently comment, run virtually silently. PV systems also require very little, if any, operator interaction, since electronic controls allow for unattended operation. Thus, recurrent costs are reduced because the skilled labor necessary for the successful long-term operation and maintenance of diesel engines is not required. Finally, PV pumps are not inherently dependent (as are diesels) upon the vagaries of rural transportation networks for a continuous fuel and spare parts supply.

In summary, the advantages of PV pumps are:

- long-term reliability of power supply;
- low long-term recurrent costs;
- unattended operation made possible by electronic controls;
- modularity;
- independence from vagaries of fuel supply;
- high potential for further decreasing cost;
- typical coincidence of output with highest demand period; and
- silent operation.

The primary disadvantage of using small-scale PV water supply systems is the comparatively high initial capital cost, coupled with the expenditure of often scarce foreign exchange. This has resulted in the impression that the upfront costs of PV will make the delivered cost of water unacceptably high. However, people are often not aware of the true magnitude of the

long-term recurrent costs of diesel (or other fossil-fueled) pumps, much of which are also hard currency for fuel and parts.

PV pumps are not "on-demand" systems, like diesels, that can deliver as much water as the available fuel supply will permit. PV pump output is limited by available solar radiation, as well as by the size of system components. Therefore, provision must be made for storage so that energy (electrical or hydraulic) can be accumulated during off-peak periods in order to satisfy peak demands. The size of storage required depends on the variability of demand, solar radiation uniformity, and the array size relative to peak demand. The optimum mix of module size and storage is a complex, cost-driven function. The size limits on currently available PV pumping equipment have already been mentioned and, for all practical purposes, restrict the use of PV to low- to moderate-demand sites at relatively low heads.

While a common goal in developing countries is the generation of rural employment, use of PV has exactly the opposite effect. Pump attendants are seldom required, except to attend to the reticulation network, if any. In Botswana, while the Government of Botswana (GOB) seeks to reduce the recurrent cost of water pump operation, it would prefer to concurrently increase its labor-intensity.

Since PV is a relatively new and unfamiliar technology, it has the disadvantages of a general lack of public awareness of potential applications, and little or no existing institutional support infrastructure. A potentially large, as yet unquantified cost of the more widespread use of PV (for pumping, village electrification, etc.) is the cost of developing a support infrastructure for system design and installation, equipment and spare parts supply networks, and the training of technicians. For diesel pumps, this infrastructure already exists in both the private and public sectors in Botswana.

B. Typical Commerically Available Systems

The range of available off-the-shelf PV pumps has increased dramatically in the last three years. In the United States alone, where there was only one manufacturer of submersible pumps specifically for PV applications in 1982, there are now at least five manufacturers (Jacuzzi, Grundfos, A. Y. MacDonald, Franklin, Trusty Warns). In addition, manufacturers have adapted several other types of pumps for use with PV as their perception of the potential market has risen, including jack (or reciprocating piston) pumps, surface-mounted centrifugal pumps, and jet pumps, all of which have specific applications (see Section III.B.3 below).

1. System Configurations and Components

PV pumping systems normally consist of the following components: PV modules, array support structures, controls or battery charge regulators, pump/motor set, wiring and, frequently, some form of energy storage--either electrical storage (batteries) or hydraulic storage (water tanks). The simplest systems consist only of PV modules mounted on the array support structure and connected directly to the pump motor without any controls, regulators or power conditioning units (see Section III.B.4 below). Water is delivered directly from the well with no intervening electrical storage device. While this is the least expensive configuration, it does not necessarily result in the lowest cost per unit of water delivered.

Since few sites have sufficiently uniform solar radiation to ensure water availability on a daily basis throughout the year, PV systems normally include some form of storage for periods of low radiation. Water storage tanks are the less expensive means of storage for the volumes of water normally required by small villages for drinking water and stock watering, or for small-scale irrigation. If batteries are used (where on-demand pumping is desired, or to provide high starting surge current to the pump motor), then a regulator must be wired between the array, the batteries and the load. This will ensure that the batteries are neither deep-discharged by overloading, nor have their electrolyte boiled away by overcharging from the array due to insufficient load. Either of these conditions will significantly shorten the life of the lead-acid batteries that are most commonly used with PV, thereby requiring unnecessarily frequent and expensive replacement of the battery bank, and considerably increasing the LCC of the system.

Some types of pumps (see below) require a large surge current to the motor during startup. Batteries used for energy storage can also supply this starting current. Under certain circumstances, discussed below, certain types of controllers (power conditioning units, or PCUs) can be used to supply starting current if batteries are not desired for reasons of maintenance or cost.

2. Modules and Mounting Hardware

Several types of PV cells are commonly used. At present, single crystal cells (e.g., ARCO) are most widely used for power applications, followed by semicrystalline (e.g., Solarex), amorphous silicon (ASi), and polycrystalline cells. ASi cells have been used primarily for powering small appliances, such as pocket calculators, and have only recently been manufactured in sizes appropriate for power production. Hence, this discussion

concerns the other three cell types, and ASi cells are only mentioned in the section on future developments. There are differences in the performance characteristics as well as costs of the cell types, but these are not examined here. At the present time, the price per installed peak watt for single cell, semicrystalline, and polycrystalline cells are nearly identical. The PV pumps used in the tests thus far have all been ARCO single-crystal cells assembled in 36-cell M-53 modules. The next set of pumps installed will also use Solarex SX-146 modules.

Since extensive accelerated testing has been performed on all commercially available modules, it is generally accepted that, under normal conditions of use, they are likely to have lifetimes of up to 20 years, with less than a 10 percent degradation in power output over that period. Ten-year manufacturer warranties against undue degradation of output are becoming standard. This expected lifetime, however, does not apply to the balance of system (BOS) components such as pumps, motors and controllers. Batteries, if used in the system, do degrade over time and have to be replaced several times during a normal system lifetime.

Modules are mounted on the array support structure at a fixed angle roughly equal to the latitude (to maximize the average annual output of the array), or at an angle chosen to maximize the array output during the critical design month where the ratio of electrical demand to available solar radiation intensity is highest. The modules are wired in series and parallel to match the electrical demand of the pump motor. In some systems, provision is made for seasonal adjustment of the tilt angle to increase the output from the array. Unless the user fully understands the benefits of such a strategy, it is unlikely that the angle adjustment will be performed as the system designer envisioned, and the net result will be a reduced, rather than increased average annual output. While sun-tracking array mounts are available, for the sake of system simplicity, all arrays in these tests were fixed (see Section III.B.6 below).

3. Pumps and Motors

Six types of pumps are normally used in PV systems. They are listed below, along with a brief description of their use, advantages and disadvantages. All comments are made with regard to commerically available, commonly used system and component sizes (i.e., less than 2.2 kW). There are several very large capacity PV pumps in operation, but these are not regarded as competitive with similarly sized diesel pumps, since they must be custom-engineered and do not enjoy comparative economies of scale.

- <u>self-priming centrifugal</u>: surface-mounted for easy access and repair; for high-volume, low-head applications; limited suction head of five meters; relatively inefficient compared to submersibles that have flooded inlets.

- <u>jet</u>: surface-mounted motor; can be used beyond suction limit, but relatively inefficient hydraulics increase array size and therefore system cost; least expensive intermediate-head pump, but economically restricted to <25-meter head; very reliable.

- <u>submersible centrifugal</u>: downhole multi-staged pumpset, not restricted to suction limit; efficient hydraulics (compared to jets and jacks); brushless DC submersibles still in the development stage, so present DC submersibles require pulling pump for periodic brush replacement; inverter losses with AC submersibles; pumpset requires replacement every four to seven years, depending on water quality; capacity limitation since the DC solar submersibles currently available are all nominal one kW; sandy or highly saline water can cause rapid degradation.

- <u>jack (reciprocating piston)</u>: downhole piston and cylinder, driven by sucker rod from surface; can pump low flows against very high heads; beyond 70 meters, used with low flows instead of submersibles; requires batteries or PCU (see below) for high starting current; requires leather and cylinder replacement periodically, more expensive than same-sized centrifugals; relatively inefficient as leathers degrade.

- <u>positive displacement rotary</u>: Mono or Moyno pumps, high starting surge of standard units requires battery or PCU; sand or very hard water can cause premature degredation if rubber stators are used; electrically mismatched with PV array output characteristics, so requires additional controls; can overload and destroy motors if downstream valves are inadvertently closed; not confined to suction limit, no priming problems; newly developed nitrile stators have lower starting torque.

- <u>vertical turbine</u>: surface-mounted motor for ease of maintenance; downhole pump driven by rotary shaft; shaft losses reduce efficiency compared to submersibles; not confined to suction limit, no priming problems; high capacities available.

- rotary vane: low-flow, shallow well and high-discharge head applications; uncommon.

Irrigation systems that normally require high flows at low heads use centrifugal pumps because of their high capacity, reliability and ease of maintenance. Surface-mounted centrifugals are used for high capacity at low head, and vertical turbine centrifugals for deeper wells, because they are both relatively inexpensive and their motors are easily serviced. Drinking water supply systems are more likely to use submersibles or positive displacement pumps, which are more efficient but have lower capacities.

4. Controls, Power Conditioning Units (PCUs), Batteries

As mentioned previously, some PV pumping systems are simply modules connected directly to the pump motor. Controls, batteries and PCUs can be used to increase the ouput of the system as an alternative to using a larger, more expensive array. All of these devices exact a price in terms of both power consumption and system cost. Battery losses reduce system efficiency by up to 25 percent, PCUs by five to 15 percent, and battery charge regulators by about two to five percent. Inverters used with AC motors normally have about 10 percent energy losses. The ideal system is not necessarily the most efficient, but rather that which uses the proper combination of components to give the lowest annualized unit water cost. Low unit costs are a direct function of the robustness of the equipment given the borehole water conditions and locally available technical skills for maintenance and repair.

Controls are used to increase system efficiency and safety of operation. Battery charge controllers or regulators are used to prevent overcharging by the array as well as over-discharging by the load, which can result in motor damage during long-term, low-voltage operation. Some PCUs (maximum power point trackers, or MPPTs) force the array to operate at its maximum power point which significantly increases system efficiency and output, and can also supply starting surge current to certain high starting torque pumps.

Batteries are used in PV systems for both control and storage. Since they are essentially a constant voltage source, the pump motor runs at a constant voltage and consequently higher efficiency. Batteries are also used to supply high starting current when required. Ideal battery characteristics include low maintenance, low cost, long life, high energy efficiency, low self-discharge, good cycling capability, and the ability to store energy efficiently at high temperatures, such as those encountered in Botswana, without adversely affecting battery life expectancy. Existing batteries approach these ideals to varying

degrees, depending on the type of battery. Generally speaking, the closer the battery type approximates these ideal operating characteristics, the higher its cost. If used in a PV pumping system, batteries are the system component that require most frequent and expensive replacement during the useful lifetime of the system.

5. Evolution of PV Pumps

Many of the first-generation PV pumps did not perform as well as expected due to immature technology (see Section VI.B on the Otse pump). Systems were often designed knowing little about the solar resource of the intended site. Since solar radiation monitoring is now occurring in many countries, designers of future systems will not be similarly hampered.

The best sites for solar pumps (assuming seasonally constant loads, such as drinking water supply) have both high and seasonally uniform solar radiation levels, so system design requires little extrapolation from existing data. Systems are sized based on the worst-case "design month," when the ratio of water demand to energy supply (solar radiation) is highest. For village water supplies, demand is usually fairly constant throughout the year, so the month of lowest radiation on the array plane is the design month. For irrigation systems, annual radiation data are not as important as solar radiation levels during the irrigation season(s). The PV system is then sized so that irrigation demands can be met under worst-case conditions. Borehole data on yields and depths are critical. If the water level in a borehole drops 10 meters during the dry season, when irrigation is required, a low-head pump designed using wet-season borehole data will perform dismally. To compensate, designers can over-design a system, but this will adversely affect unit water cost. It is important to know seasonal variations in borehole yields and drawdown rates to properly design a system.

Another major design problem with early PV pumps was the impedance mismatching of the power supply and the BOS. PV operation is characterized by a current/voltage (IV) curve (see Figure 1). Maximum system output occurs when the system operates at the maximum power point (MPP) on the IV curve, when the impedance of the array and the load are properly matched. The early French Pompes Guinard in Africa were particularly plagued by impedance mismatching, and their output was well below expectation. As awareness of the gravity of this problem spread throughout the industry, pump manufacturers began to design their DC pumpsets with PV array output characteristics in mind, which significantly increased system performance.

Operation and maintenance problems also included premature battery degradation, due either to underestimating battery

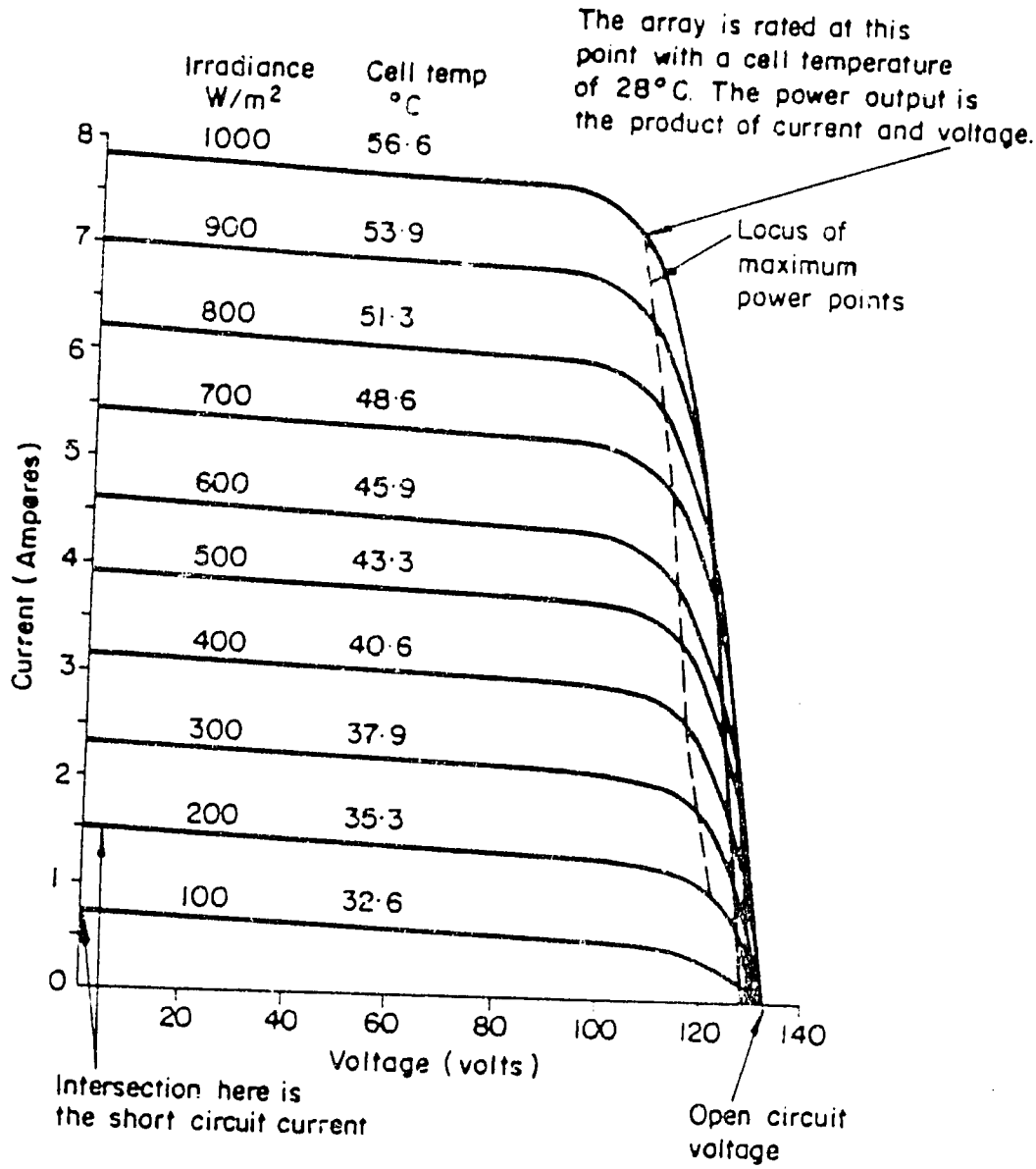

Figure 1. A typical relationship between current and voltage for a PV array.

requirements and consequent deep-discharging and rapid deterioration, or to charge controller failure and subsequent boiling away of the electrolyte. Early versions of some power conditioning units had quality control problems. Some systems have experienced varying degrees of performance degradation due to vandalized modules, and goats have shorted more than one circuit due to their taste for inadequately protected wire insulation. Typical pump maintenance problems such as seal/impeller degradation and brush replacement occur in PV pumps with the same frequency as standard pumps. Compared to diesel installations, however, PV systems generally have much less downtime caused by equipment failure or operator error, due primarily to the exceptional reliability of the power modules.

PV modules are by far the most expensive component of a pumping system. Significant cost reductions have occurred over the last eight years since PVs have been used for water pumping. Modules are rated by peak watts (Wp), which is the module output under certain solar radiation, loading and operating temperature conditions. Modules that cost P35/Wp ($20/Wp) in 1978 are now selling for P10.5/Wp ($6/Wp). The cost of modules is still dropping, albeit more slowly than was earlier expected. For single crystal cells, cell efficiencies in the laboratory are now approaching 20 percent, and commerical module efficiency is currently 12 percent. Semicrystalline module efficiency is 10 percent. Amorphous (ASi) modules are now available for small-scale power generation and have module efficiencies of about five to six percent and bulk costs of P26-32/Wp ($15-18/Wp). The first-generation commercial PV systems experienced some significant module degradation problems, but these have been solved by the major manufacturers.

Considerable effort has been made by several pump and motor manufacturers (e.g., Jacuzzi, A. Y. MacDonald, Franklin Electric, Grundfos, Honeywell, KSB, AEG Telefunken) to develop higher-efficiency pumpsets for use with PV. Some of their efforts have met with considerable success. Pumpsets now on the market are considerably more efficient and reliable than the typical pumps reviewed in (see SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS, THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank/UNDP, 1983). Efforts have been directed toward the development of brushless submersible DC pumps, which would eliminate maintenance costs associated with pulling a downhole pump every 10,000 hours or less to replace brushes. Thus far, product development has not met manufacturers' expectations. This has led some manufacturers (e.g., Grundfos) to turn to synchronous AC motors with DC to AC inverters for submersibles, which have thus far achieved an enviable reputation for reliability and simplicity of installation.

6. New Components and Approaches for Cost Reduction

More power can be obtained from the same size array by several different strategies. PV systems work best when operating at their maximum power point (MPP). There are several PCUs that force the array to operate at or near the MPP, thereby considerably increasing the array output. Their cost varies considerably, from P351 to P6,140 ($200 to $3,500). The more expensive PCUs follow the MPP very precisely, while the less expensive ones merely approximate it by forcing the array to operate at a pre-set constant voltage. Manufacturers claim annual output increases of up to 15 percent. These increases must be balanced against the incremental cost of the devices, their added complexity and the subsequent potential for failure, as well as compared to the cost of simply adding more modules to increase the array output.

Another way to increase power production is to physically move the array so that it is always oriented perpendicular to incoming solar radiation. Very large PV arrays use one- or two-axis, computer- or optically-driven, continuous-tracking devices, which are quite complex and expensive. For small, remotely sited systems, manual seasonal adjustment of arrays has met with little success because users fail to stick to the adjustment schedule, so the array is left at a less than optimal tilt angle and annual array output actually drops.

A third, more promising approach is a passive, gravity-driven freon tracker which tracks the sun continuously throughout the day, then returns to its east-facing position in anticipation of the morning sun. These single-axis trackers are mechanically very simple, and have been used on a small scale for several years of trouble-free operation, increasing array output as much as 40 percent. They are particularly useful for irrigation, since the greatest additional output occurs during the summer.

Concentrators multiply the amount of solar energy falling on individual cells, thereby increasing electrical output. The cost of the concentrator can sometimes offset the cost of additional modules to generate the same amount of power. At the simplest level, concentrators are reflecting mirrors surface-mounted alongside standard modules, effectively doubling the incident radiation level. Alternatively, Fresnel lenses integrally mounted in a module above the cells also concentrate solar radiation. The popularity of this type of module is evidenced by its sales rate. Although still only a small fraction of sales compared to standard flat, non-concentrating modules, sales of concentrating modules are steadily increasing.

For all of these devices, the critical issue is whether or not the increase in system performance has greater value than the

consequent increased cost and complexity. In remote applications in developing countries, system longevity has been found to be inversely proportional to complexity. In comparing the economics of different system options, some value must be assigned to simplicity of operation and consequent reliability. Every additional component represents an additional opportunity for failure.

C. PV Pumps Tested in Botswana

Five PV pumps were initially selected for testing on a variety of boreholes. Several factors went into site selection. First, a cross section of the typical borehole conditions encountered in Botswana was sought. Second, different types of pumps (e.g., submersible, rotary positive displacement) were to be tested. Finally, the desires of DWA, or of the various Councils in cases where pumps were installed on Council boreholes, needed to be accommodated.

Site selection was less than ideal from a designer's perspective. Since the technology itself was unfamiliar to decision makers, they were understandably reluctant to use any but the less desirable boreholes (low yield, crooked, or where there was no real demand), or those in areas where water demand was critical and immediate, and no standard diesel equipment was immediately available. In some cases, user groups agreed to invest in the new system by, for instance, building a larger elevated tank. At Mahalapye, this did not happen as agreed upon, meaning that the pump chosen was not running at design head, which adversely affected its performance.

The sites, with a general description of the equipment installed (detailed descriptions can be found in Appendix D) are as follows:

- Mahalapye: Jacuzzi S4XP-4 DC submersible with a 12-module ARCO M-53 array (516 Wp), a BOSS constant voltage tracker (later removed), mounted in a sand river cistern, pumping water for garden-plot irrigation, later increased to 688 Wp;

- Mmathubudukwane: Mono ES-10S pump (being replaced with a nitrile version) with a Honeywell 1.5-HP DC motor, BOSS constant voltage tracker, 36-module M-53 array (1,548 Wp), in a borehole, for village water supply;

- Mochudi: Jacuzzi SJ1E-7 DC submersible, direct coupled to a 32-module M-53 array (1,376 Wp), in a borehole, pumping water for irrigation and stock watering;

- Molapowabojang: Jacuzzi SJ1E-7 DC submersible, direct coupled to a 32-module M-53 array, (1,376 Wp), in a borehole, for village water supply;

- Otse: Moyno (later replaced with Mono) pump with 0.5-HP Honeywell motor, eight-module ARCO 16-2000 array (initially 280 Wp, since replaced with M-53s, so 344 Wp), in a borehole, pumping water for a community garden--this system is being upgraded with a 0.75-HP motor driving a Mono ES-15S with a nitrile stator, and a BTC battery charge controller manufactured in Botswana; and

- several other PV pumps (three Grundfos AC submersibles, and several more Mono pumps with Honeywell one-HP motors and controllers) have been purchased and are currently being installed by BRET, but data collection has not yet begun for these systems.

IV. DATA COLLECTION METHODOLOGY

The data collection methodology for determining the performance of the BRET PV pumps was first outlined in COMPARATIVE TESTING FOR WATER-PUMPING SYSTEMS INSTALLED IN BOTSWANA (R. McGowan and J. Ashworth, ARD, 1984). Revisions of the original methodology were made as the field testing proceeded, reflecting the constraints of time, skill levels of available technicians, and various equipment malfunctions that occurred over the testing period. In general, the program managed to assemble a large data base on the detailed performance and cost of PV pumps, but it was not as comprehensive as initially planned. The institutional, managerial, logistic and technical constraints that hampered data collection are mentioned under the operating histories of each of the sites in Section VI.A below.

A. Criteria for Comparing Pumping Systems

In order for PV pumps to be taken seriously by development professionals, water resources specialists must be convinced of two things. They must be assured that the potential LCC savings associated with PV pumps can balance the considerably higher initial capital costs, and that the equipment will perform as well as manufacturers claim, both in terms of daily water output and long-term reliability. Determining whether to embark on a program encouraging widespread, or even limited, use of this relatively new technology involves several considerations. An accurate determination of costs and technical skills required for the design, installation, operation and routine maintenance of the system; availability of replacement parts; and social acceptance of the devices at the user level must be made. In the following two sections, technical and economic criteria are listed, as well as the reasons for choosing these criteria. The questions of social acceptance are discussed in the site histories of each pump in Section VI.A.

1. Technical Performance Criteria

The technical criteria used to characterize PV pumps revolve around two major questions: how much water does the pump provide, and when?; and what are the pump's operation and maintenance requirements? The first question is answered by measuring both the short- and long-term output of the pump over the entire range of expected operating conditions. Since system output is contingent upon proper operation of each system component (PV array, wiring harness, controls, motor, pump and storage system), the performance of each component must be

measured, and the effects of each component's operation on the others examined.

The PV array can be characterized by current voltage (IV) curves which give electrical output as a function of solar radiation level (Whr/m^2 or MJ/m^2) incident upon the array surface and cell operating temperature. The pump motor also has a characteristic IV curve, and the better the match between the two, the higher the efficiency of the system and the greater the water output. Certain types of control devices can improve this match, but at a cost. For instance, some PCUs (see Section III.B.3), while improving the match between the array and the pump motor, consume a certain amount of power, and their effect must be measured to determine the overall effect on system performance.

The overall system performance can be characterized by the efficiencies of the various subsystems. Therefore, the following efficiencies were examined:

- <u>array efficiency</u>: electrical energy output of array divided by solar energy incident upon it, both instantaneous and monthly average daily values;

- <u>hydraulic efficiency</u>: hydraulic output (in terms of head and water volume) of pump/motor divided by electrical input from array (or from controller, if the system has one), instantaneous and long-term average values--hydraulic efficiency is given as a function of the solar radiation level; and

- <u>overall system efficiency</u>: hydraulic energy output from pump (instantaneous and long-term average values) divided by solar radiation incident on array.

While a reasonable knowledge of the various efficiencies just described is useful for properly sizing a system, the bottom line is how much water the system can produce at a given head and radiation level for a given cost. Therefore, water output is presented in the Section VII.B as a function of solar radiation on the array.

The site history summaries discuss general technical issues, social acceptance and institutional concerns, including:

- problems encountered during both installation and operation of the pump;

- a subjective evaluation of advantages and disadvantages of the particular pump in terms of simplicity of installation, functional complexity (a

good indicator of long-term reliability), and probable reliability based on previous experience with similar pumps;

- technical skills necessary to design, install and maintain the pumps in proper running condition;

- spare parts availability and use of locally manufactured components (e.g.,locally made controls);

- possible accommodation of backup systems to supplement the output of the PV pump during extended low radiation periods (e.g., Mono pumps that can be belted to either diesel or PV power supplies); and

- problems peculiar to a specific component of certain types of systems (batteries, for instance).

In addition, the monthly average daily values of solar radiation in the plane of the array (30 degrees above horizontal at all sites) was calculated based on both the data actually measured during the tests and extrapolations from longer term meteorological data measured in Botswana and the Republic of South Africa. This value will aid in the design of future systems (see Appendix C) by enlarging the long-term solar radiation data base being accumulated by MET Services in Botswana and the Weather Bureau in South Africa.

2. Financial/Economic Selection Criteria

Life-cycle costing techniques are commonly used to compare the relative unit water costs of equipment alternatives. By taking into account all costs incurred over the system's useful lifetime, and assigning a time value to the occurrence of these costs, a single comparative criterion (the unit water cost) can be calculated. This reflects capital equipment expenditures, recurrent maintenance and operating costs for parts, labor and transportation, and any other costs associated with the system.

A number of assumptions were made when performing this analysis. Variables such as discount rates, expected price increases above the general rate of inflation, assumed or measured system lifetimes, shadow-pricing of labor and foreign exchange, and availability of financing can dramatically affect the outcome of the analysis, either individually or synergetically. However, since changes in these variables do not greatly affect the relative ranking of similar systems (e.g., several PV systems compared to each other), sensitivity analyses were confined to the overall comparative pumping report (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin,

ARD, 1986). To clarify what values should be used as base-case assumptions, most of the reasonable possibilities were reviewed in a discussion with MMRWA engineers and economists. Among the decisions arrived at were the following:

- The primary comparative criterion was to be the annualized life-cycle (unit) cost per cubic meter of water delivered (pula/m^3) and the unit cost per unit volume per unit head (pula/m^3*m). Although a benefit/cost ratio, net present value, or internal rate of return could also have been chosen, they all require the knowledge or assumption of a benefit value, which can vary widely. MMRWA also requested that the unit cost be calculated both in terms of discounted and non-discounted water <u>volume</u>, so both are shown in the spread-sheets.

- As mentioned above, unit costs were calculated in terms of pula/m^3 as well as P/m^3*m (the volume*head product). However, the authors consider the pula/m^3 to be an oversimplified formulation. The energy required for pumping water (and, hence, the size and consequent cost of the PV system required) is directly proportional to the volume of water pumped and the head (or lift) through which it is pumped. Hence, pump comparisons normally give pumping costs in terms of flow (in m^3) times head (in meters). This tends to normalize the performance of pumps at different sites, and reflects the additional energy input required to pump water from a deeper borehole.

- Since the government was assumed to be the primary purchaser of PV pumps, no import duties were assessed against the equipment. Sensitivity analyses were performed to determine the effect of bulk buying on individual system cost (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986).

- Local labor would be shadow-costed at a rate of 0.5, and foreign exchange at a rate of 1.1.

- Customarily, the GOB industrial class regulations require the hiring of a full-time pump attendant (pumper) for diesel pump installations. While PV pumps do not require this level of user interaction, it was decided for sociopolitical reasons to include a part-time pumper's salary (one day a week at P6/day) in the baseline operation and maintenance costs of the PV pumps. Sensitivity analysis on this assumption are included in the comparative pumping

report (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986).

- Loan interest charges were not included in the financial cost analysis. While there appears to be excess liquidity in commercial banks (at typical 13.5 percent interest rates), banking institutions are typically very conservative, making loans difficult to obtain. This issue should be examined in the project extension.

- While incremental training costs for PV pump technicians should somehow be factored into the recurrent operation and maintenance costs of the systems, the magnitude of this incremental cost is difficult to evaluate and was not specifically included in the analysis given here. The extension report should examine this cost in some detail.

- Salvage values for BOS components were assumed to be zero, reflecting the assumption that components will be used until they no longer function, at which point they will be discarded rather than repaired (except where very minor repairs are required, in which case they will be reinstalled after local repair). Since there will be periodic replacement of some modules due to vandalism, some modules will have less than 20 years of service. These modules were therefore assigned a nominal salvage value.

- Because of the lack of on-demand water delivery with PV pumps, it is reasonable to assume that storage tanks in PV systems should be larger than those in diesel systems of similar capacity. However, because of the inherent variability in diesel delivery to remote sites, tanks used with diesel systems are already larger than normal--in fact, about the size one would expect to use with PV. Therefore, the tank costs were considered essentially equal for both types of systems and consequently not included in the analysis. This assumption will be examined in the project extension.

- Discount rates and real cost increases of equipment and labor above the general rate of inflation were taken to be six and zero percent respectively, reflecting the gvernment's standard assumptions. Currently, Botswana has a relatively high annualized inflation rate, due in part to the fluctuating values of the U.S. dollar and the South African rand, and their impact upon the value of the pula.

Thus, it is difficult to make reasonable assumptions about discount and inflation rates. Also, because the private sector in rural Botswana does not have extensive experience with the use of credit, it could be argued that a higher, social-preference-based discount rate should be assumed, which would reflect other than simply the opportunity cost of capital.

- For the ARD report WATER PUMP FIELD TESTS IN BOTSWANA (R. McGowan and J. Hodgkin, 1986), sensitivity analyses were performed on the following parameters:

  --discount rates (six, nine and 12 percent);
  --real fuel cost inflation (zero, two and four percent, and assuming GOB bulk purchasing);
  --amortization period (15, 20 and 25 years);
  --probable decrease in the price of PV modules based on past and current cost reductions and efficiency increases ($7.5/Wp, $6/Wp and $4/Wp); and
  --variations on requirement for operator charges (one day/week, three days/week and full-time).

  None of these significantly changes the relative ranking of the different PV systems compared to each other, and so are not repeated here.

In the original comparative testing program evaluation methodology, the concept of specific capital cost was discussed. This is a very quick, yet much oversimplified method for comparing the costs of PV pumping systems to each other based only on initial installed cost and rated capacity. It takes no account of recurrent costs or time value of money, which were assumed to be about equal for PV pumps of similar capacity. Since this rough estimate cannot be applied to the comparison of diesel, wind or any other type of pump whose recurrent costs are not the same as PV, it has not been included in this report.

B. Data Collection Requirements

In order to adequately characterize the unit cost of a pump, both the installed cost and long-term recurrent costs must be determined. For renewable energy systems, this means determining the output of the pump on a monthly basis over the year, because of possible monthly variations in the strength of the renewable energy resource at the site. Solar radiation levels, as well as wind speeds, can and do vary considerably throughout the year. It is important to know the measured output of a particular pump over the range of solar radiation levels likely to be encountered, as well as to know with some assurance what the

long-term expected average daily radiation levels will be at the site, in order to predict annual pump output.

Solar pumps are sized based on both site-specific solar radiation levels and hydraulic energy demand of the design month (see Appendix C for a detailed PV pump sizing algorithm). To properly size a pump, the solar radiation level, array output, average hydraulic efficiency of the pump, water demand, and total pumping head of the system must be known, at least approximately. From this information, and certain expectations about the longevity of each component and periodic maintenance requirements, the long-term recurrent costs and benefits can be calculated.

Collecting this information is not, however, an easy task. Data collection difficulties during field testing were exacerbated by the fact that the BRET PV pumps in Botswana have been installed at relatively remote sites. This significantly increased the efforts required not only to install the pumps, but to make sure that proper data collection procedures were being followed, and that the pumps were working properly during the data collection periods. This did not always turn out to be the case.

1. Monitoring Instrumentation

After discussions with manufacturers of electronic data-logging equipment, ARD technical staff concluded that off-the-shelf instrumentation that adequately addressed the data recording requirements of the BRET program did not exist. Although manufacturers were willing to custom design and build integral units capable of measuring all the parameters mentioned above, the costs quoted for the units were prohibitively high (quotes of up to $10,000 per unit were received). Several designs included microcomputer-based data-loggers capable of analyzing the data on-site. A technician would have to visit the site periodically to retrieve the analyzed data for transfer into a central computer for later review. This approach was exceedingly costly and required highly trained technicians (mainly for programming the data-loggers). Thus, given the BRET project's previous difficulties with data-loggers in passive solar building performance monitoring, the approach was rejected.

ARD decided instead to purchase custom-built "Modulogs" from Beckman American. While there have been some sensor calibration problems, the Modulogs have proven reliable under harsh operating conditions. The Modulogs are powered by standard "D" cell batteries, and were designed to collect cumulative totals of the measured parameters for display on low-power-consuming liquid crystal diodes (LCDs) on the face of the data-logger. These values were then periodically recorded on a data collection sheet

(DCS) by a BRET technician or other person hired to record data. This approach was a compromise between the accuracy and computational ease of a computer-based data-logger operating under harsh environmental conditions (high temperatures and blowing sand), and the traditional method of hiring untrained individuals to read and record analog meters on a periodic basis. This requirement has not been a serious drawback, as literate readers seem to be available at all sites thus far.

The parameters measured were the following:

- solar radiation in the plane of the array (Whr/m^2);
- water output of the pump (liters);
- total elapsed time of the test (minutes);
- running time of the pump (minutes);
- electrical energy output of the array (Whr); and
- where power conditioning units were used, the electrical energy to the pump (Whr).

The sensors used to make these measurements were frequency-encoded pyranometers; oscillating-piston, positive-displacement flow meters; on-board clocks; and standard watt-hour meters. In addition, the total pumping head was measured with a combination of well dipper for the static head and drawdown, and a pressure gauge mounted in the discharge line to measure the discharge head. Velocity head was calculated and found to be negligible compared to total pumping head in all cases. Return lines from the tanks to the boreholes were installed so that any excess water pumped to the tanks and not used by the villagers would be returned to the boreholes. This allowed the pumps to operate unconstrained by float valves in the tanks. Overall, the instruments have a combined error of about 10 percent. Unfortumately, since the systems are still collecting data in the field at the pump sites, recalibration has not yet been possible for all the instruments. This will be performed in the testing program follow-on activity.

The Modulog integrated all of the parameters, until it was manually reset to zero after values were manually recorded, at which time it began integrating the measured values again. Remote sensors for measuring each of the parameters (except time, which was measured by an on-board clock) were wired to the main Modulog unit. The sensors have not proven to be as reliable as the Modulog itself (in particular, the pyranometers and watt-hour meters). After examination of the data collected, it became apparent that sensors on some of the systems were giving spurious readings and had to be replaced. Since the sensors are isolated

electronically, only data on the channel with the bad sensor were lost. However, this did result in some holes in the data at some sites.

In addition to the Modulogs, various hand-held instruments were used to measure instantaneous values for solar radiation (instantaneous and integrating pyranometers), array voltage and amperage (multimeters and clamp-on ammeters), pump voltage and amperage (same), and ambient and module temperature (mercury thermometers and multimeter-driven thermocouples). Tachometers were used to measure the rotational velocity of the Mono pumps and surface-mounted motors. These measurements were made both to expand the data base for later analysis, and to make occasional checks on the reliability and accuracy of the Modulog measurements. The instantaneous measurements were very helpful in the identification of inoperable or failing sensors in the main instrumentation.

2. Data Collection Procedure

Although the data collection procedure is essentially the same as that given in COMPARATIVE TESTING FOR WATER-PUMPING SYSTEMS INSTALLED IN BOTSWANA (R. McGowan and J. Ashworth, ARD, 1984), it was modified somewhat as a result of field experience with the custom-developed instrumentation, as well as to reflect constraints on the technical skills available for data collection. Thus, it is summarized again here for the reader's convenience.

Short-Term Tests

The main purpose of the short-term tests was to monitor system performance over a full day to develop pump curves of water output as a function of total head at a given solar radiation level. From this information, the hydraulic efficiency of the pumpset as a function of radiation level could be determined. These curves were generated by collecting data over a full operating day at each operating site, recording the Modulog readings at 15-minute intervals. In addition to this, instantaneous values for voltage, current, back-of-module temperature and solar radiation were also measured at each interval.

Ideally, these short-term tests were to be performed on cloudless days when all sensors were operating properly. In fact, on several occasions the sky clouded up during the day and provided less-than-ideal monitoring conditions. Occasionally other problems, such as dead batteries in an instrument, inhibited proper data collection. The remoteness of many of the sites made the experimental conditions considerably less than

ideal. Given the magnitude of the data collection task and the dearth of available skilled technicians, time was the greatest constraint. (In addition to collecting data on the solar pumps, tests on windmills, diesels, grid electric pumps, and a variety of human- and animal-traction pumps were being conducted concurrently). It was not always possible to return to a site to collect more data as scheduled if, for some reason, the opportunity was missed. In spite of these limitations, much useful information was collected.

The short-term tests took advantage of one of the most useful features of the Modulog, the capability of temporarily "freezing" the integrator displays while internal integration continued. This allowed a technician to stop the display at the end of the 15-minute measurement interval so the data could be recorded on the DCS provided. After recording the information and checking for accuracy, the LCD displays were then "unfrozen" to their real time values to continue the tests.

Long-Term Tests

Data collection for the long-term tests relied primarily on the help of people living near the sites to record the data on a daily or monthly basis. These recorders were local residents who were among the beneficiaries of the water pumped. At each of the pump sites, daily readings were taken over monthly (or longer) periods. At some sites, several consecutive months of data were collected. Potential recorders were selected on the basis of local recommendations, and their aptitude for properly recording the data was checked before they were hired. If an individual seemed appropriate, he or she was given a book of data collection sheets and asked to take readings every day for 30 days, at the same time each day (preferably early in the morning or late in the afternoon, but at least once a day, at any rate). This procedure worked reasonably well, except at one site where data were collected at three different times of the day depending on the recorder's work schedule. Since the Modulogs were not reset until a BRET staff member had time to check the final monthly readings, under worst-case conditions, monthly blocks of data were collected. At best, detailed values of inputs and outputs each day were collected.

In addition to these procedures, at the Mochudi site, data were collected on a weekly basis, and at Otse, where the storage was small and the pump was switched on and off manually in response to demand variations, data were collected both when the pump was turned on and turned off. After March, when the majority of the pump and instrumentation installation work had been completed, regular monthly visits to each site were made by at least one of the BRET technical staff. Also, whenever any of the BRET staff traveled by any of the pump test sites, they

stopped to take readings and check the systems. These random visits helped to keep track of any operation or maintenance problems with pumps or instrumentation, and helped to further improve the quality of the data being collected.

Collection of Detailed Cost Data

Determining the cost of the equipment used in the PV pumps is not as simple as it seems. Since the BRET project was funded by AID, most of the high-capital-cost items had to be purchased in the United States from U.S. suppliers. This had a variety of effects on the actual equipment purchased and prices paid. On the one hand, it meant that the pump testing project had access to state-of-the-art technology not yet commonly available in Africa. In addition, much of the equipment was purchased in bulk, reducing the cost below that which would be paid retail for a single system.

Questions arose as to whether it was appropriate to use the prices actually paid for the systems, or whether it made more sense to use the current prices for the same or similar equipment commercially available in Botswana. As it happens, the retail unit price for ARCO Solar modules (the bulk of the modules used in the testing thus far) in Botswana is essentially equivalent to bulk U.S. prices. This is because U.S. PV manufacturers--painfully aware of the current artificially strong U.S. dollar, yet vitally interested in maintaining their market share in an extremely competitive industry--must offer their products below cost to foreign buyers, at least in the short run. For this reason, the prices used for this analysis are local market prices. It is, of course, possible that if the DWA were to purchase a relatively large number of modules, or if exchange rates were altered significantly, the module price, FOB Gaborone, would vary somewhat. Since module cost alone accounts for up to 80 percent of the total installed system cost it was clear that a sensitivity analysis of varying module prices was necessary (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986). While initial capital cost of modules was based on local prices as of July 1985, replacement modules (necessitated by vandalism or failure) were costed at $6/Wp, the cost as of December 1985.

For the remainder of system costs, DWA tender prices were used, largely because DWA is the largest purchaser of pumping equipment in Botswana, the BRET project came under MMRWA, and it is likely that only government groups would be in a financial position to seriously consider widespread purchase of PV pumps in Botswana. For solar pumps, this assumption was not critical since the BOS cost was small compared to the array cost. Some of the equipment (such as the constant voltage trackers) was not commercially available in Botswana. The purchase price of these

items was used in the analysis, with the exchange rate assumed to be P1.00 equal to $0.57.

The PV pump at Otse was already installed when purchased by BRET. It was an older design which, while installed in several countries in Africa, has not gained widespread acceptance among PV water supply specialists (see site history). To use its actual cost (from 1982) would bias the financial analysis severely against it, due to the significantly higher cost of modules at that time. Therefore, the current replacement cost of this system has been used.

V. ANALYTICAL METHODOLOGY

The analytical methodology used for this program seeks to incorporate the approaches of similar past efforts* so that results can be presented in a common format for easy comparison. When testing the performance of PV pumps, there are certain parameters that must be measured so that long-term output can be predicted, and upon which the cost analysis is based. The principal questions that arise in the different approaches to testing are the level of effort involved, technical skills of those collecting the data, number and type of systems involved, and amount of time and money available to perform the tests.

Previous efforts have focused principally on either laboratory tests or simple computer modeling based on manufacturers' data for pump output. This program focused specifically on field tests as the best determinant of the actual costs that will be incurred by PV pump users in the developing world, where precise system design, an adequate spare parts supply, or sufficient technical skills for the proper installation, maintenance and repair of the pumps may be the exception rather than the rule. For a given system, site-specific conditions can affect water output, equipment lifetime, and the subsequent unit costs of water delivery. Since the primary focus of this project was to determine relative costs of equipment alternatives, the emphasis was on longer-term data collection rather than determination of detailed short-term pump characteristics.

A. Pump Curves

The single most important technical characteristic of a pump's operation for predicting long-term output is the pump curve, which describes the pumping capacity in terms of head and flow (and voltage and current, for submersible pump sets). When operating at a given point on the curve, the pump will deliver a certain volume of water at a certain head. When the pumping head is increased (by adding an elevated tank to the system, for example), the volume of water pumped decreases (for a given sized system), since it takes more energy to pump to the additional height. For PV pumps, an additional parameter that specifies

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*See SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS, THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank/UNDP, 1983; EVALUATING THE TECHNICAL AND ECONOMIC PERFORMANCE OF PHOTOVOLTAIC PUMPING SYSTEMS: A METHODOLOGY (final draft), J. Kenna et al, IT Power Ltd. and LESO for USAID, 1985; and AN ANALYSIS OF WATER LIFTING DEVICES IN BOTSWANA, N. Davidson, BTC, 1984.

system performance is the solar radiation level on the plane of the array. For a certain radiation level, a point on the curve indicates how much water the pump will deliver at a given head.

To predict the long-term output based on the limited measurements collected thus far, it was necessary to determine the average subsystem (or hydraulic) efficiencies of each system for use in the simple PV pump output algorithm given in Appendix C. The three kinds of efficiencies with which designers are most concerned (discussed in Section III.A.1), are the array (N_a), subsystem (N_s), and overall system (N_o) efficiencies. N_a indicates how effectively the array converts solar radiation into electrical energy (about eight to 11 percent for the BRET arrays). N_s indicates how effectively the motor and pump convert electrical energy into water delivered at a given head (10 to 40 percent, depending on how well the pumpset is matched to the site conditions). N_o indicates how effectively the overall system converts solar radiation into water delivered at a given head (two to five percent). Since N_o is not needed in the pump output algorithm, it will not be dealt with further.

The boundaries of the subsystem efficiency change somewhat for systems with battery charge controllers (regulators), batteries, or PCUs such as constant voltage trackers. Since each of these components has a certain efficiency, the subsystem efficiency of a system with either controller or battery (or both) would include the controller and/or battery losses. Other things such as wiring losses affect the performance of the system, hence the overall system efficiency. Using too small a wire size can cause relatively large voltage drop in the power cable to the pump. Examples of the magnitude of wiring losses can be seen in the example system sizing given in Appendix C. Using too narrow a wire gauge with a submersible pumpset at 50 meters can noticeably reduce the system efficiency. Since the electrical energy measurements are made at the top of the power cable going into the borehole, the subsystem (pump/motor) efficiency will appear less than specified by the manufacturer's pump curves.

The performance of PV modules themselves is fairly well known under given solar radiation and cell operating temperature conditions; thus, measured array output was not so critical an input to the algorithm. However, solar radiation is not constant over a day or over a year, so short-term measurements over the range of radiation levels likely to be encountered can be used to generate a curve of pump output as a function of solar radiation level, which is then combined with known (or estimated) average solar radiation levels over "standard solar days" to determine volume output over any day of the year. This procedure can be repeated for each day, thereby generating monthly average output predictions. The results can be confirmed by actual measured values as the data become available, thus iteratively refining

the subsystem efficiency used in the algorithm. A simpler, though less accurate procedure is to estimate an average daily subsystem efficiency by de-rating the measured N_s under peak operating conditions (i.e., at noon) to reflect the fact that at low radiation levels (in the morning and afternoon) the system is operating away from its design point and therefore less efficiently.

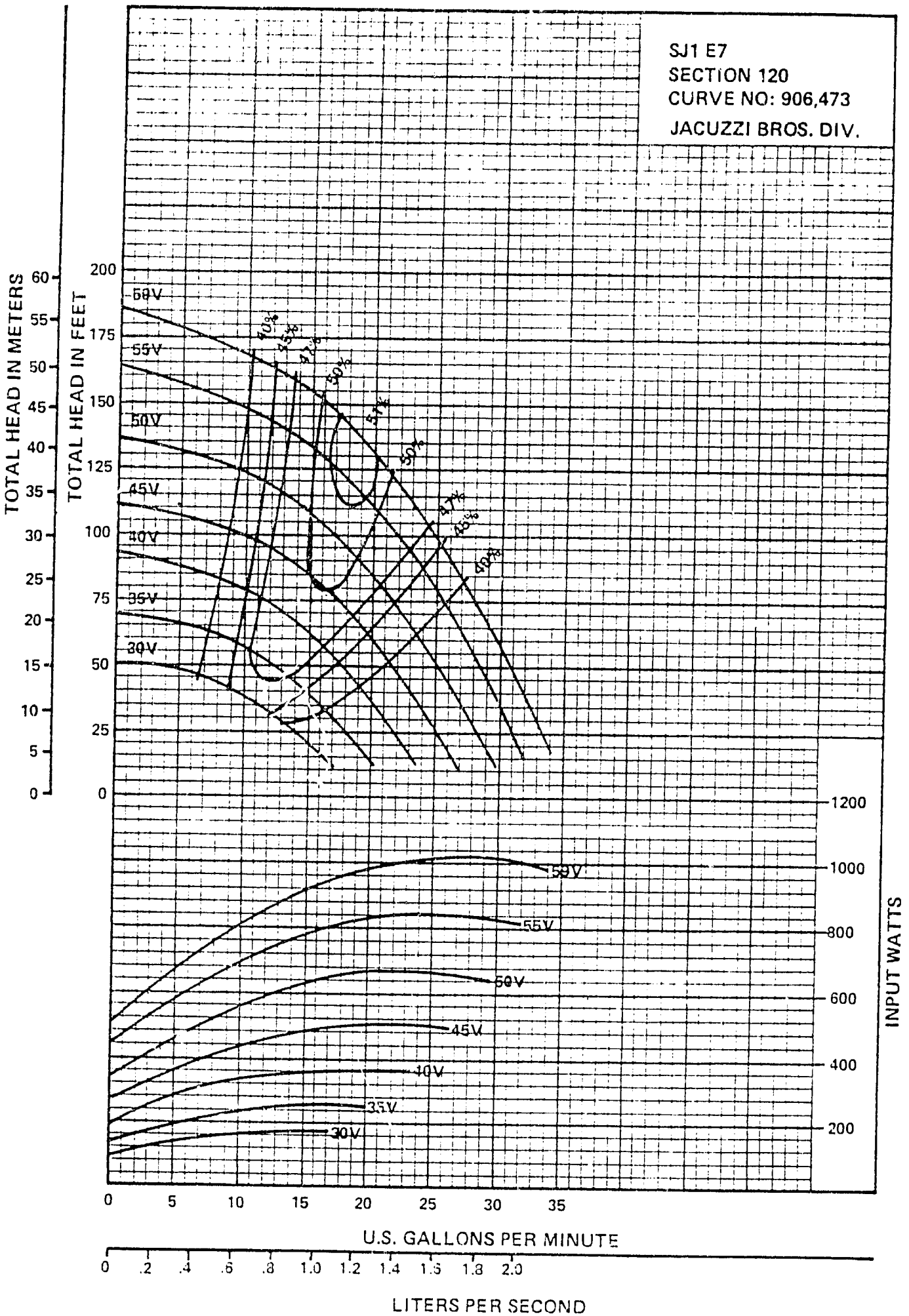
For a given site, assuming that there is sufficient borehole yield throughout the year, the pump will operate at a nearly constant head. During dry seasons, the borehole water may drop somewhat, thereby increasing the head and decreasing the water output. If the pumping capacity approaches the borehole yield, drawdown will occur, also reducing the water output. For most of the PV pumps tested here, adequate borehole yield resulted in little drawdown (<2 m in most cases), so that the pumps could be assumed to operate at approximately a constant head. If the head did vary seasonally, it could still be easily accommodated in the algorithm. Examples of manufacturers' pump curves for submersible pumps used during the tests are given in Figure 2. Actual operating data measured during the field tests, including solar radiation level, water flow rate, and subsystem efficiency, are given in Section VI.B.

While system and component efficiency are important in comparing systems, the cost per unit of output is the most important characteristic. A pump user does not really care what the efficiency of the system is, except insofar as the cost of the system goes up as the overall efficiency goes down for given head and flow conditions. The main reason that system designers are concerned with efficiencies is that they must be able to describe different pump types adequately in order to be able to predict performance at other sites. To do this, the system designer must have a good estimate of solar radiation levels throughout the year, the depth of the borehole, the overall pumping head, the size of storage required, and an estimate of the fluctuations in demand (particularly if irrigation is being considered.

B. Long-Term Performance Characteristics (LTPCs)

LTPCs are important as means of validation of output estimation from algorithms such as the one described in Appendix C. Where holes exist in data (e.g., daily radiation levels for a particular month), estimates of LTPCs can be extapolated from pump curves and estimations of radiation levels for other sites for that month. Also, since solar radiation levels are being recorded at each PV pump site, a reliable solar radiation data base throughout the country is growing.

Figure 2.


SJ1 E7
SECTION 120
CURVE NO: 906,473
JACUZZI BROS. DIV.
TOTAL HEAD IN METERS
TOTAL HEAD IN FEET
60V
55V
50V
45V
40V
35V
30V
40%
45%
47%
50%
51%
50%
47%
45%
40%
INPUT WATTS
U.S. GALLONS PER MINUTE
LITERS PER SECOND

The most important LTPCs are maintenance and repair requirements, from which a determination of both recurrent costs and manpower training needs can be made. A major input into the cost analyses given in Section VI is the recurrent cost of operation, maintenance and repair. All system components are replaced at certain intervals over the system economic lifetime. The lifetime is assumed to be 20 years, based on the component with the longest lifetime--the PV modules. Replacement times are a strong function of proper installation and operation procedures, as well as site constraints such as water quality. Boreholes with highly corrosive water can cause rapid deterioration of equipment, necessitating much more frequent repair than normal. Crooked boreholes can quickly ruin Mono pump shafts and cause rapid deterioration of the drop pipe connections as well.

LTPCs are by nature the most difficult to quantify, because they are so site-specific, and adequate measurement requires unacceptably long testing periods. Issues such as social acceptance, use patterns, annual and seasonal fluctuations in demand, and the problems associated with infrastructural development can only be adequately measured over several years. Preliminary estimates based on past experience are therefore necessary at this stage of the testing program. These will be further refined during the project extension.

VI. TECHNICAL PERFORMANCE RESULTS

Section VI.A details the experience with the first set of solar pumps installed by the BRET project. It is important to keep in mind that these pumps were installed as part of a testing program. All of the systems installed by BRET were state of the art at the time of their installation, and most still are. Some were prototype systems (the Mono/Moyno pumps) that had not been subjected to extensive development, so there were the inevitable bugs in both system design and operation. Performance characteristics were constantly reviewed, and the systems were continually adjusted to obtain the best possible performance from the components specified in the initial system design. If this had not been the case, many of the less obvious problems would not have been noticed, let alone fixed. This approach led to more down time than normal, since prototype systems have, by definition, components that have not been subjected to extensive field tests (see Mmathubudukwane below). The expression "the only trouble with working at the cutting edge, is staying ahead of the blade," comes to mind.

As discussed below, Mono (and Moyno) pumps have certain characteristics which make them less than ideal for use with PV systems. However, since about 85 percent of the boreholes in Botswana use Mono pumps, the decision was made to adapt PV power supplies to the particular characterisitcs of Monos. A second generation of these systems will no doubt perform much better, both in terms of water output and reduced maintenance and repairs. Mono Pumps (South Africa) has been working on the development of new, lower starting torque Nitrile pumps, as well as power conditioning units specifically designed for use with photovoltaics (see Mmathubudukwane and Otse below). Successful development of these devices will make the use of progressive-cavity pumps with PV much more attractive.

On the other hand, there have been very few problems with the submersible pumps (except at one site where the water quality was poor). The simplicity of their system design has surely contributed to this situation. Submersible pumps do not require battery storage because of their low starting torque requirements, nor do they require a separate controller. Data on all of these systems are still preliminary, since less than a year has elapsed since the first system was installed. Nevertheless, the project extension will provide a much more refined view of the capabilities of this first set of PV pumps, as well as of the group currently being installed, whose performance has not yet been carefully measured.

A. Site Histories

Test results to date, while indicative of the performance capabilities of PV pumps, cannot be termed conclusive. There simply has not been sufficient time to complete a full testing program as originally envisioned. The first pumps were only instrumented fully at the beginning of 1985, and problems with several of the pumps (most notably the one at Mmathubudukwane) have meant that only limited data are available to date. A brief history of each site is given below, followed by analyses of the data.

Mahalapye

This pump was installed at a garden near Mahalapye in September 1984. The system consists of 12 ARCO Solar M-53 modules coupled to a Jaccuzzi submersible pump, mounted on a cement cistern in a shallow hand-dug well in the river bed. A constant voltage tracking controller (CVT) was also installed as part of this system. Formal monitoring did not begin until mid-February because there was insufficient water storage at the site (the tank which the user agreed to install had not been installed), and the pump was not being used full time. A return line to return unused water from storage to the well was installed at this time, and full-time monitoring was begun on February 16, 1985. To measure the effect of the BOSS CVT on the system (which does not strictly require a CVT), the CVT was removed from the system in early April and data were collected for an additional month. In late May, two consecutive days of intensive short-term testing were undertaken, one day with the CVT in place and one without. These tests showed that the significantly reduced head (from 15 to seven meters), due to the unexpected lack of an elevated storage tank, caused the system to deliver only a third to a half of its design efficiency. The additional elevation head would have resulted in the pump operating at a much more favorable point on the performance curve, thereby significantly increasing the subsystem efficiency.

The water output results for March, April, May and June were 14.5, 14.6, 12.8, and 15.1 m^3/day respectively. The April and May data were collected without the CVT in the system. It appeared that the CVT used in this system is of limited value at best. The efficiency of the device varied widely over the day, and it neither significantly increased water output nor was required for providing starting current to the relatively low starting torque motor. During the peak sun hours of the day, the CVT reached a peak (not average) efficiency of more than 95 percent, but it is precisely during this part of the day that the electrical characteristics of solar array best match those of the pump motor, precluding the need for any controller. During the morning and afternoon hours, the device would be most useful to

aid in load matching, but potential increases in energy production during these hours were lost because of the CVT's decreased operating efficiency. Thus, while the controller did not significantly affect the system's overall performance, it was judged to be of no significant value to the system due to its unnecessary incremental cost.

Mmathubudukwane

Installation of this pump was begun in December 1984. There have been several problems with this pump and site. The system was designed to use a 36-module (1548 Wp) ARCO Solar M53 array driving a Honeywell 1.5-HP, DC, permanent magnet motor connected to a Mono pump. A BOSS PCC180 CVT was used as the controller, to eliminate the need for storage batteries and to provide the high starting current required to start the Mono. However, the CVT would not start the pump as it was designed to. While this particular model CVT was supposed to have been a production model, it was in fact a prototype. As it turned out, not only was there a manufacturing defect in the current limiting switch, but the capacitors were undersized to deliver the required surge current specified during procurement. After long consultations with the manufacturers in the United States, a redesigned controller was installed, and it performed well in preliminary tests.

This process took until mid-April 1985. During these preliminary tests, it became clear that the solar pump was over-pumping the borehole, due to a decrease in the borehole yield since DWA's initial test-pumping. Fortunately, the borehole was due for a cleaning and an additional test-pumping by DWA. This was completed by early June. Although the yield of the borehole after cleaning was still less than when originally drilled, BRET technical staff felt that the solar pump would probably not unreasonably tax the yield, since it would only be pumping six to eight hours a day on a continuous basis.

During this period, Mono Pumps (South Africa) expressed an interest in assisting the project, since they had become involved in PV pumping as well. They kindly donated a Nitrile (as opposed to their standard natural rubber composition) stator ES-10 fitted with a foot valve for this borehole. This type of Mono has a much lower starting torque requirement, reducing peak power requirements and resulting in cost savings in PV modules. After the cleaning and test-pumping had been completed, the new pump was installed and testing was begun in early July.

After preliminary data had been gathered and the pump seemed to be operating satisfactorily, the crew left it on automatic control. However, after several days another problem cropped up which pointed out one of the disadvantages of operating with a

positive displacement pump such as a Mono. With a submersible pump, if head is increased beyond the normal operating range of the pump, the flow rate will be reduced in proportion to the increased head. Eventually, if head continues to increase, it will reach a point where there is no flow at all, but the power absorbed by the motor will not change dramatically.

However, a positive displacement pump is essentially a constant flow device at a given RPM, and will continue to absorb more power as the head is increased. The result is that if head is increased beyond the capacity of the motor, the motor will overheat (if no overload protection is built into the motor) and, if the situation is allowed to continue for even a relatively short time, the windings will be destroyed. The fastest way to over-range the pumping head in this type of system is to shut off a gate valve in the discharge line when there is no pressure relief valve (or PRV, which had not yet been installed in the discharge line during the preliminary tests). Unfortunately, it is common practice to put gate valves (rather than backflow valves) in discharge lines in order to shut off flow between the storage tank and the borehole for maintenance or repair purposes.

This happened at Mmathubudukwane, where the pumper apparently closed at least one of the three gate valves in the system while the pump was operating, although he had been specifically warned about this because of the lack of a PRV. The motor was rewound at a repair shop in Gaborone (it was reassuring that such repairs are available in Botswana), and was reinstalled after the gate valves were removed and replaced with backflow and pressure relief valves. Further data are forthcoming.

While long-term data are not yet available, some short-term data were collected as a part of the acceptance tests, and have been used to estimate the actual performance of the system. While the original design criteria specified an expected total pumping head of 62 meters, this was later measured to be about 45 meters. During short-term testing in mid-December, the solar pump, as installed, would not start on its own. While the CVT was unable to provide the necessary starting surge, there was ample power available for running the pump. The pump was started with a manual boost, and it pumped at an instantaneous rate of 0.53 liters per second at a solar insolation level of 600 watts/m^2. During similar testing on April 24th, the output was 0.61 liters per second when the insolation level was 900 watts/m^2 (easily reached on almost any sunny day in Botswana). Using similar spot data over the range of radiation levels, the PV pump output algorithm predicted an annual output of about 6570 m^3/year, with a worst-case design month output of 16 m^3/day. This was used in the cost analysis. This prediction was based on solar radiation measurements at Mmathubudukwane and several nearby sites where solar radiation is being recorded on an

ongoing basis. Obviously, longer-term data are required for this site.

Mochudi

This site is equipped with a Jacuzzi submersible pump directly coupled to an array of 32 ARCO Solar M-53 modules, operating at a head of about 36 meters, installed in September 1984. At this site, as at most of the other sites, the original storage tank capacity was inadequate. Under the favorable solar radiation conditions normally encountered in Botswana, a two-day storage capacity (or about 40 m^3) would be sufficient. At most of the PV pump sites, the beneficiaries of the water had agreed to provide the labor and funding for properly sized cement, steel or ferrocement tanks as their contribution to the water supply system. However, since this did not occur, two nine-cubic-meter galvanized-steel tanks, intended to be temporary, were installed until the permanent tanks were to have been built.

The horticultural group that had requested the pump had not properly established their plot as agreed upon, so the water demand was initially less than the pump's capacity. Initially, users would turn off the pump when the tanks were full, and, although they were discouraged from doing so, this practice did not immediately stop when an overflow return line from the tanks to the borehole was installed. Finally, it became necessary to lock the switch box so that it was certain that the pump was operating at design capacity.

Monitoring began in early December and data were initially collected on a weekly basis. A full day of short-term, intensive tests was conducted in late December. In February, the pump was turned off for a protracted period, as the temporary storage tanks were leaking so badly that the area around the pump became flooded. The tanks were repaired, and the system was operating properly by the end of the month.

In mid-April, the pump stopped operating. When it was removed and examined, it was found to be badly corroded. Subsequent investigation led to the conclusion that the water in this borehole has an unusually high lime content. Although specially coated submersible pumps that can tolerate these conditions are now standard from the manufacturer (and should always be specified if they are not), this submersible pump was not properly coated. The manufacturer replaced the pump under warranty. In the meantime, in the interest of collecting continuous operating data, a spare pump was installed in the borehole. The present pump will be replaced with the coated pump when it arrives. This problem has, however, demonstrated the need to test the water quality in a borehole before choosing a pump.

Vandalized modules were another problem at this site. In the 10 months since the system was installed, three modules have been vandalized, apparently by children throwing stones. The site is not near any settlement, and control of the children in the area may be difficult at first. An interesting observation has, however, been made as a result of this vandalism. Short-term tests conducted for BRET by technical staff at BTC have confirmed that the output of the cracked modules was not significantly degraded, at least not in the short term. The IV curves for a new module and for a broken one that had been operating (while damaged) in the field for five months were measured concurrently by BTC's testing apparatus, and little discernible difference in performance was noted. These IV curves are shown below in Figure 3.

Test results to date have been marred by some lack of confidence in the measurement of electrical energy consumed by the pump (the Modulog kWh sensor), and an apparent deterioration of the pyranometer prior to its failure on May 25th. These problems involved only the instrumentation and did not interfere with pump performance. The system operated without any required maintenance until the pump replacement in April.

In the meantime, another full day of short-term data was collected, and a month of daily values (in addition to the monthly long-term data collection) were also recorded. During the seven-month testing period to date, this pump has produced an average of 14.5 m^3/day (not including the non-operational periods). The monthly average output was 16.1, 15.3, 15.6, 13.1, and 12.6 m^3/day in December, January, March, May and June respectively. February and April are not included since a full month's data were not collected during these months.

Short-term tests indicate that the average subsystem efficiency reaches about 32 percent at the peak daily solar radiation period between 11 a.m. and 1 p.m. Extrapolating from these monthly figures measured thus far (and based on measured radiation values for the rest of the year), the output in the design month (likely to be December) in an average year would be about 16 cubic meters per day.

Molapowabajang

This was the first PV pump installed by the BRET project, in early September 1984. For some period of time, the pump operated without a return line, and the users continued to turn the pump off when the storage tanks were full. Although short-term tests were performed during the initial operating period, formal, long-term monitoring was not begun until the middle of January 1985, after a return line had been installed. Four sets of day-long intensive tests have been conducted thus far.

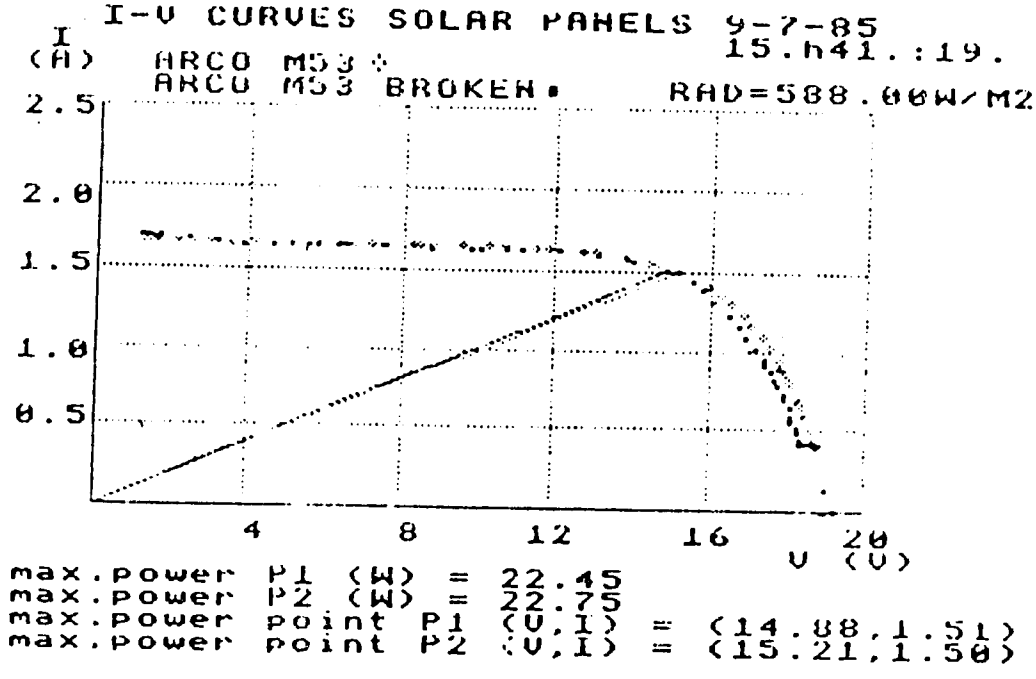


Figure 3.

I-V curves for M53 and broken M53 modules when facing sun.

During the first month of daily monitoring, review of the data collected showed that there was a problem with the return line, since the pump output was not as high as expected, even though the pump was turned off by the pumper after sufficient water had been delivered. During late April, this problem was solved and another month of data was collected. During this time, a full day of intensive, short-term testing took place. When the data were examined, it appeared that the pump output was still somewhat lower than expected. A careful examination of the wiring scheme revealed a minor installation oversight which, when corrected, increased output to the design level. Two days of intensive, short-term tests were performed, and another month of daily data collection was begun in early July. Review of the intensive test data indicated much improved performance. Over a three-day period in early July, the daily average pump output was 26.2 m^3/day. Prior to that, it had been pumping less than 20 m^3/day. There have been no outages whatever on the system thus far.

Otse

This system was the oldest tested. It was first installed in early 1982 by Taurus Batteries, the local distributor for ARCO Solar. The system was owned by Taurus until purchased by the BRET project in late 1983. Prior to this, there had been no problems reported except for two vandalized modules. However, the water storage capacity was quite limited (2.5 m^3), thus the use of the pump was very limited. The system consisted of eight ARCO Solar 16-2000 modules (no longer manufactured), a 0.5-HP Honeywell motor driving a Moyno pump (similar to Mono, except turning clockwise), and a timer and battery charge controller. In May 1984, two of the four batteries were replaced because they had worn out, and it was discovered that the regulator and timer were not functioning properly, so they were removed from the control circuit. Since the load approximately matched the deliverable power from the system, the system was run temporarily without controls (no controllers were immediately available). This temporary arrangement was, however, not acceptable for long-term operation since it was just a matter of time before the batteries were over-discharged. Partial monitoring was begun in October, measuring all variables except solar radiation, since there was not a sufficient number of pyranometers at that time.

With this type of timer-controlled battery storage system, it is important to understand that short-term tests have limited value for predicting long-term performance, since the batteries act as a constant current and voltage source, thereby evening out the water output over the short term. The short-term output of the pump will not be a strong function of the solar radiation intensity during pumping, as was the case with all of the other systems. This means that optimum use of the pump requires

balancing the fixed pump's on-time with the system's power supply capacity and solar radiation levels over the long term. Since the demand has been so variable at the site (and only recently has a large enough storage tank been constructed), measurement or estimation of long-term performance of this system was difficult. Recently, the Village Development Committee (VDC) built a larger storage tank (38 m^3). In the effort to fill this new tank, the batteries have been drained. A proper controller which does not require a separate timer (and is locally manufactured and therefore locally repairable by BTC) has been installed to alleviate the problem.

The output of the pump, monitored over nearly nine months, has been measured at 747 m^3, or 2.8 m^3/d. This is hardly representative of the system's capacity, as can be seen by the graph of water output and pump use during a two-month period (see Figure 4). It is obvious that the pump was only used every second or third day, which hardly taxed its capacity. During this period, the total head fluctuated somewhat as the pump was started, but stabilized at eight meters after the initial well draw-down level was reached. During this period the pump/motor efficiency averaged a dismal 10 percent, largely due to the slow speed at which the Moyno pump was designed to operate. The 1800-RPM motor, with a combined pulley-gearbox reduction ratio of 6.43:1, drove the pump at less than 280 RPM. In this range, the manufacturer specifies a pump efficiency of about 20 to 30 percent (compared to up to 70 percent when the pump operates between 700 and 1200 RPM).

During short test periods, the pump output ranged between 1.2 and 1.6 m^3/hr. Results of several tests showed the output, as expected, to be directly proportional to battery voltage. At 24 volts, the output was 1.5 m^3/hr. As battery voltage dropped to 22 volts (as it sometimes did after the failure of the early voltage regulator), output dropped to 1.3 m^3/hr. The pump could therefore easily deliver eight m^3/day under normal solar radiation levels in Botswana, if the array and batteries were properly matched.

Since storage capacity limited the actual output of the pump, the efficiencies and the instantaneous flow rates from the short-term testing were used in a simple PV output model to predict the potential of the pumping system. The model predicts that the average annual output for this pump would be 6.2 m^3/day, and in the worst-case design month of December, 5.4 m^3/day.

The same model was used to predict the output with a similar system configuration using different components. This exercise showed that the potential for this type of system was much greater than that realized in the Otse system, as designed. If a similar pump running at higher RPM (i.e., at a more efficient operating point) and better matched to the motor characteristics

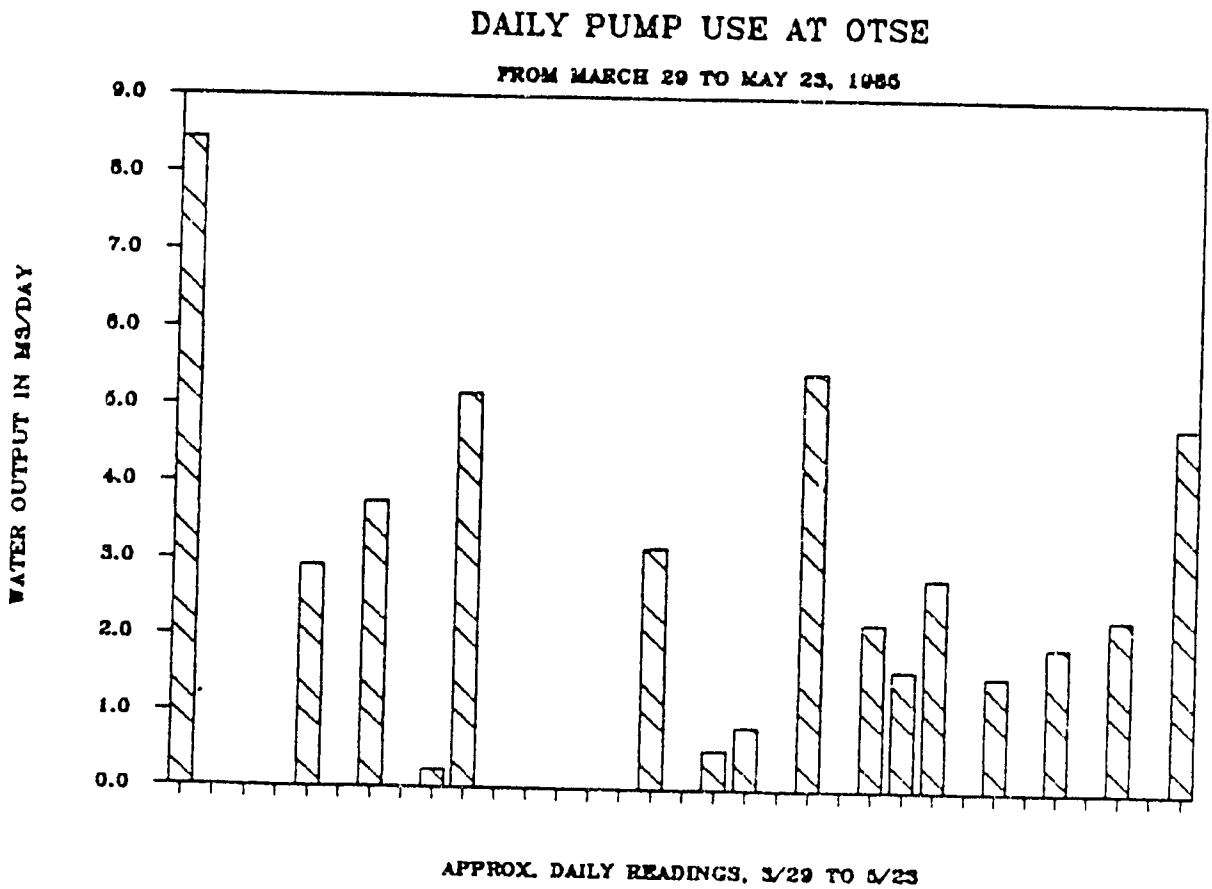

DAILY PUMP USE AT OTSE
FROM MARCH 29 TO MAY 23, 1986
WATER OUTPUT IN M3/DAY
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
APPROX. DAILY READINGS, 3/29 TO 5/23

Figure 4.

was used, the annual average output would be 13.2 m^3/day (or 11.4 m^3/day in December). This configuration will be tested as a part of the extension of the comparative pumping program, and will help to meet the greatly increased water demand at the site. The major lesson learned from testing this pump was that the design of solar pumping systems has come a long way since this pump was first installed in early 1982.

B. Comparative System Performance

Two main types of PV pumps were tested in this study-: DC centrifugal submersibles, with both pump and motor contained in a single integral unit, mounted down the borehole; and progressive-cavity Mono pumps, with the pump itself mounted down the borehole, connected by a rotating steel shaft through a belt drive and/or gearbox to the surface-mounted motor. These are two fundamentally different designs, each of which has its own advantages and disadvantages in terms of capital equipment cost, maintenance and repair schedules, ease of installation, and technical performance characteristics. While the relative merits of the two types of pumps are discussed in Section IX.A, this section of the report compares the technical performance results for each of the individual pumps.

Mahalapye

The 516 Wp ARCO/Jacuzzi system at Mahalapye did not perform as well as expected. When using submersible pumps, particular care must be taken to choose a model that is specifically designed for the head and flow conditions of that site. At Mahalapye, the design head was 15 meters, based on the construction of a new tank eight meters above the present one. Since the tank was never built as agreed upon, the pump used was not the proper choice for that site. At the design head, the pump would deliver about 2.5 liters/sec under peak operating conditions, and would provide about 20 m^3/day on an average annual basis.

The pump has operated without any maintenance so far. Although the system delivered approximately 30 m^3/day at seven meters' head, a different pump with the same number of modules would be capable of delivering considerably more than that. Also, since at low head the water delivery was greater than that planned for, it was turned on and off as the water demand varied, so it was not able to pump to full potential. The pump is going to be moved in the near future to another site (for political reasons), and the site will be more carefully chosen so that the pump will operate nearer its design point.

Graphs of one of the short-term tests of the Mahalapye pump are shown in Figures 5a through 8. Water output, solar radiation level, and hydraulic efficiency over the day are shown in Figures 5a and 5b. These are the results of two consecutive days of testing. The sharp variations in output in the afternoon are due to partly cloudy conditions. On one day (May 29th), the CVT was wired out of the system. The next day it was inserted to test its effect on the pump. On May 29th, the radiation level (and therefore pump output and hydraulic efficiency) increased very steadily until about 12:30 p.m. when some clouds rolled in. The flow rate peaks at 0.63 liters/sec, and the hydraulic efficiency at a very low 11 percent. On May 30th, when the afternoon was also very cloudy, the flow rate peaked at 0.61 liters/sec and the hydraulic efficiency at 13 percent. Although more water was pumped on May 30th, the radiation levels varied from day to day. Thus, simply based on these data, one cannot say that the pump performed better without the controller. However, based on longer-term output projections and further testing, use of the CVT with submersible pumps is not recommended (see Section VII.B).

Figures 6 and 7 show water output as a function of instantaneous radiation level over the day. Although the pump output bounced around considerably due to the variable clouds, the pump performance was very linear in relation to the radiation level. Because of the relatively low head, the pump starts up very early (around 7:30 a.m.) at a radiation level of about 200 W/m^2. Figure 8 shows the hydraulic efficiency versus radiation level for May 29th only. The one very high efficiency calculation is a result of instrumentation error. While the radiation and water outputs are fairly smooth curves, the jaggedness of the hydraulic efficiency lines suggests inaccuracy in the electrical power measurement. To account for this, later tests made use of multimeters and amprobes to directly measure the electrical energy transfers.

Data from the short- and long-term tests have been used to estimate system output in Table 1. Over the long term, the output from the system will average about 21 m^3/day, with the worst month (December) output about 17 m^3/day. In the economic analysis, it was assumed that the pump used was properly sized for the site, so that output averaged 30 m^3/day at the actual seven-meter pumping head.

Mmathubudukwane

The Mono-coupled system here has thus far been the most troublesome of the prototype systems, so long-term data are not yet available. Mono pumps operate more efficiently as the head increases. They are currently the only type of pump being considered for Botswana (although jack pumps could be used under

Figure 5a.

OUTPUT/SOLAR RADIATION/HYD.EFFICIENCY

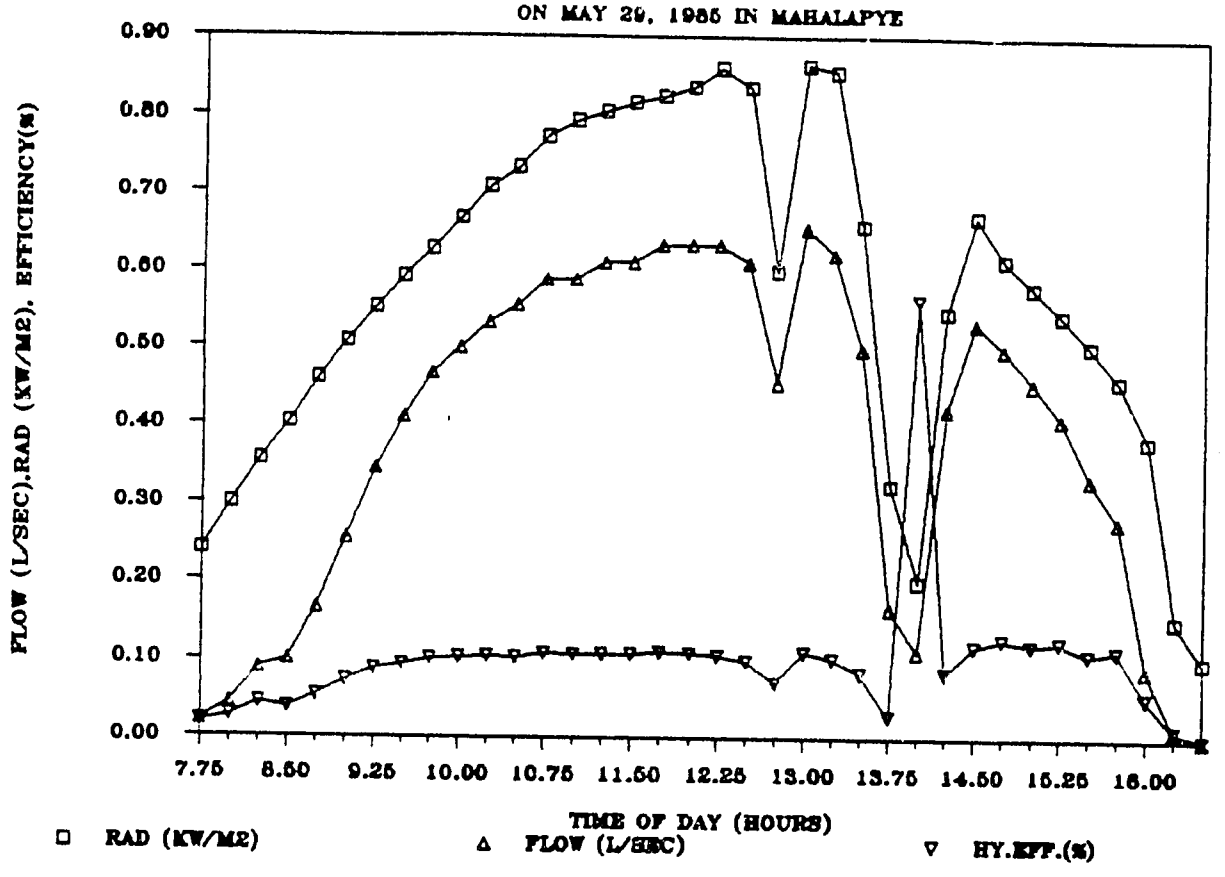


Figure 5b.

OUTPUT/SOLAR RADIATION/HYD.EFFICIENCY

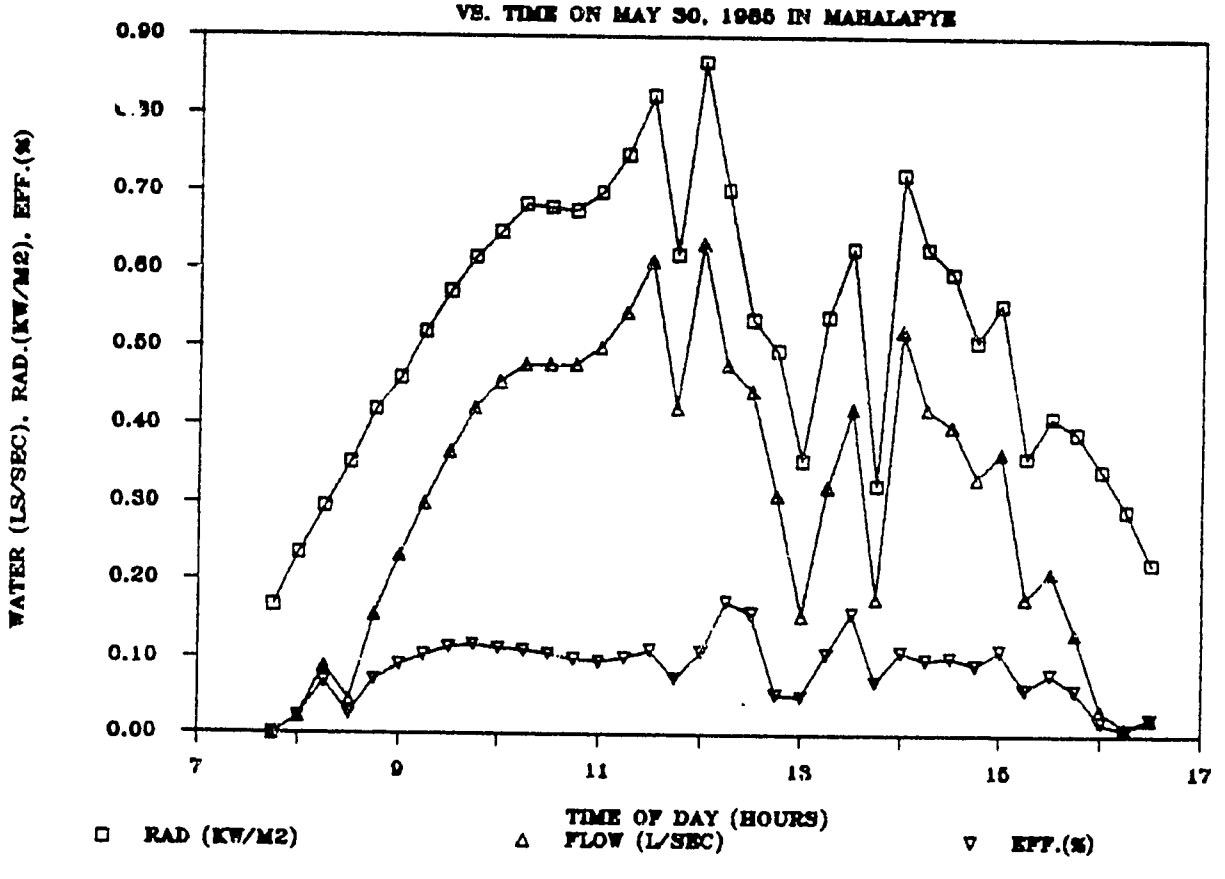


Figure 6.

WATER OUTPUT VS. SOLAR RADIATION LEVEL

ON MAY 29, 1986 IN MAHALAPYE

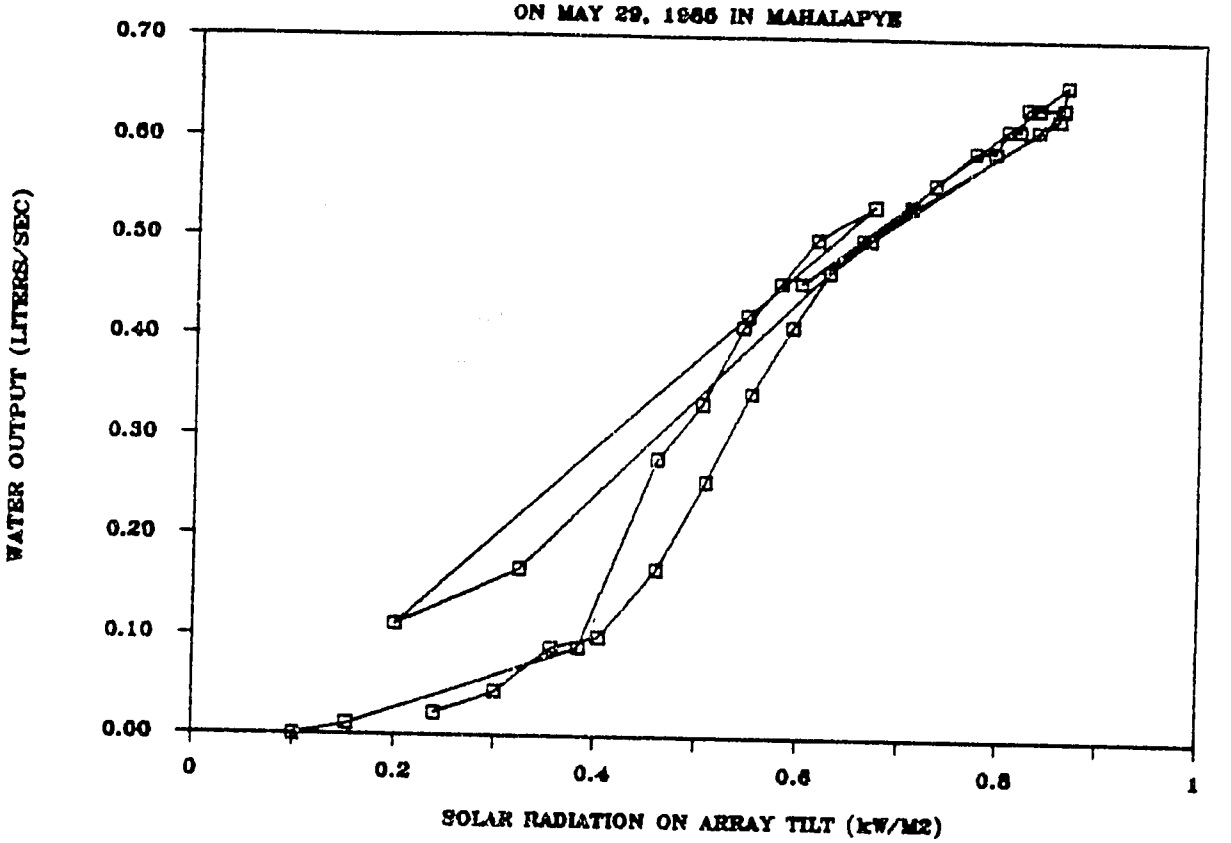


Figure 7.

WATER OUTPUT VS. SOLAR RADIATION

ON MAY 30, 1986 IN MAHALAPYE

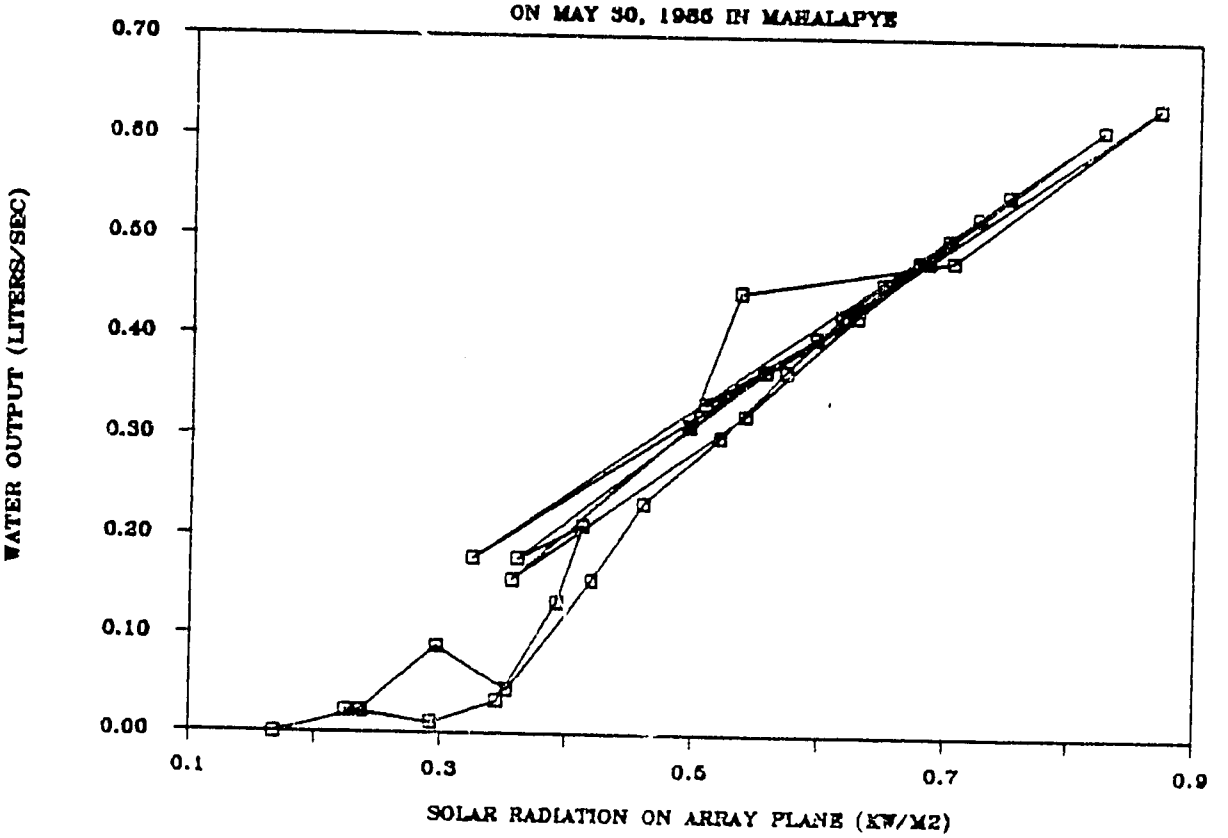


Figure 8.

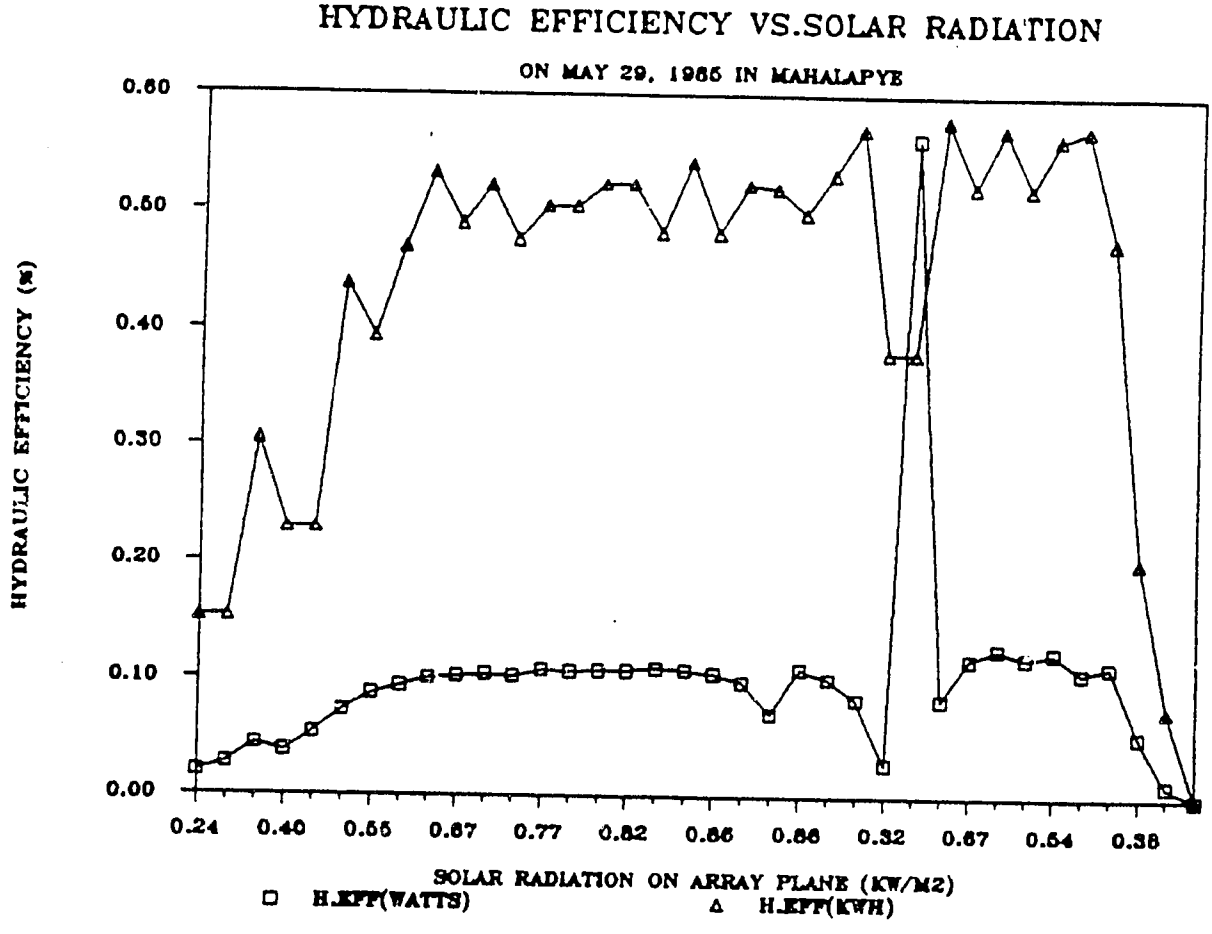

HYDRAULIC EFFICIENCY VS.SOLAR RADIATION
ON MAY 29, 1985 IN MAHALAPYE
HYDRAULIC EFFICIENCY (%)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.24
0.40
0.55
0.67
0.77
0.82
0.86
0.86
0.32
0.67
0.54
0.38
SOLAR RADIATION ON ARRAY PLANE (KW/M2)
H.EFF(WATTS)
H.EFF(KWH)

Table 1.

SOLAR PUMP SIZING ALGORITHM (IT Power/Halcrow, McSowan)
01-Aug 03:10 PM

Location: MAHALAPYE Latit: 22.5 Degrees
Array Tilt Angle: 30 Degrees

Min.Output based on hypothetical system satisfying min.hydraulic energy req'
Act.Output based on series modules in actual array for motor voltage req'd.

Month	Volume (m3/day)	St.Head (m)	Dyn.Head (m)	Tt.Head (m)	H.En.Rqd. (MJ/day)	ItrT.Rad. (MJ/m2-d)	Clear Index	Horz.Rad. (MJ/m2-d)	Tilt Factor	Arr.T.Rad (MJ/m2-d)	Max D/S Ratio	Min.Out. (m3/d)	Act.Out (m3/d)
January	15.0	7.0	0.0	7.0	1.03	39.6	0.60	23.8	0.83	19.7	0.052	15.6	18.4
February	15.0	7.0	0.0	7.0	1.03	38.0	0.60	22.8	0.92	21.0	0.049	16.5	19.5
March	15.0	7.0	0.0	7.0	1.03	34.4	0.60	20.6	1.07	22.1	0.047	17.4	20.6
April	15.0	7.0	0.0	7.0	1.03	30.4	0.60	18.2	1.27	23.2	0.044	18.3	21.6
May	15.0	7.0	0.0	7.0	1.03	25.7	0.62	15.9	1.48	23.5	0.044	18.6	22.0
June	15.0	7.0	0.0	7.0	1.03	23.7	0.63	14.9	1.59	23.7	0.043	18.7	22.1
July	15.0	7.0	0.0	7.0	1.03	25.0	0.64	16.0	1.55	24.8	0.042	19.5	23.1
August	15.0	7.0	0.0	7.0	1.03	28.7	0.65	18.7	1.36	25.4	0.041	20.0	23.6
September	15.0	7.0	0.0	7.0	1.03	33.4	0.65	21.7	1.15	25.0	0.041	19.7	23.2
October	15.0	7.0	0.0	7.0	1.03	37.4	0.63	23.6	0.96	22.6	0.046	17.9	21.1
November	15.0	7.0	0.0	7.0	1.03	39.0	0.61	23.8	0.85	20.2	0.051	16.0	18.8
December	15.0	7.0	0.0	7.0	1.03	39.6	0.60	23.8	0.80	19.0	0.054	15.0	17.7

DESIGN MONTH PARAMETERS

Design Month	December
Hydraulic Energy Requirement	1.0 (MJ/day)
Design Month Total Head	7.0 (meters)
Global Radiation on Array	19.0 (MJ/m2-day)
Avg.Subsys.Energy Efficiency	16%
Avg.Subsys.Power Efficiency	18%

Max Ratio	0.054	
Ann. Average Outpu	17.8	21.0
Ann. Minimum Outpu	15.0	17.7
Ann. Maximum Outpu	20.0	23.6

EQUIPMENT SIZING

	Min. Array Siz	Actual Array Size
Elect. Energy Req'd:	6.36 (MJ/day)	
PV Array Size :	437 (Wp)	515 (Wp)
Derated Motor Power:	335 (Watts)	395 (Watts)
Derated Hydr. Power:	60 (Watts)	71 (Watts)
Derated Pk.Flowrate:	0.88 (ls/sec)	1.03 (ls/sec)
Cell Operating Temp:	55 (deg.C)	55 (deg.C)

SPECIFIED COMPONENTS	Rated Efficiency
Motor : Jacuzzi SJ1	60%
Pump : Jacuzzi E7	30%
Battery : None	100%
PV Mods : ARCO M-53 (3s x 4p)	10%

certain circumstances as well) that can handle the larger, three-HP (2.24 kW) motors, which are the largest commercially available motors specifically for use with PV. Currently, this system configuration is the only one that holds promise for use at sites with over 60 meters' total pumping head. This situation will change shortly, however, since Grundfos (the other major U.S. manufacturer of solar submersibles besides Jacuzzi) is currently developing a series of five-HP (3.73 kW) DC submersibles to be used in just such situations.

Based on the short-term data gathered thus far, estimates of the performance of the Mmathubudukwane system are shown in Table 2 and Figure 9. It appears capable of pumping about 19 m^3/day at 45 meters head. The borehole yield at Mmathubudukwane is still of some concern, however. Even after its recent cleaning, it was again test-pumped at only 1.7 cubic meters per hour. However, this is based on continuous pumping for several days at a very high rate, and this will never occur using the solar pump. It remains to be seen whether the borehole yield will be an actual constraint on the system output.

Mochudi

The Jacuzzi SJ1-E7 at Mochudi performed, on the whole, nearly as expected, with the exception of the effect of the highly corrosive water conditions discussed in Section VI.A. This did not, however, significantly reduce the water output of the pump while it was operating. Some short-term tests conducted in December indicated that on a typical, fairly sunny day (19.8 MJ/m^2-day insolation on the array plane) in December, the pump delivered 19.8 m^3/day. The results of short-term tests done on June 11th are shown in Figures 10 through 12. Figure 10 shows the water output, solar radiation level, and hydraulic efficiency over the day. Figure 11 shows the water output as a function of solar radiation level, and Figure 12 shows the hydraulic efficiency versus solar radiation. This was a very good radiation day, as seen by the smoothly rounded curve over the day, and the smooth water output and hydraulic efficiency curves. Peak flow on that day was 0.92 liters per second, and the hydraulic efficiency was about 29 percent.

As the longer-term data were analyzed, it became apparent that output had been dropping off somewhat over time between December and April. After inspecting the pump, it turned out that the effect of the hard water in the borehole was to clog the pipes, thereby increasing effective head and reducing output below what would ordinarily be expected. Taking into account some reduction in the output over time, the sizing model predicted an annual average output of 18.2 m^3/day at the 36-meter head as shown in Table .

Table 2.

SOLAR PUMP SIZING ALGORITHM (IT Power/Halcrow, McSowan)
01-Aug-85 05:05 PM
Location: MMATHUBUD Latitude:24.4 Degrees
Array Tilt Angle: 31 Degrees

Min.Output based on hypothetical system satisfying min.hydraulic energy req'd.
Act.Output based on series modules in actual array due to motor voltage req'd.

Month	Water Vol. (m3/day)	St.Head (m)	Dyn.Head (m)	Tt.Head (m)	H.Eng.Rqd. (MJ/day)	XtrT.Rad. (MJ/m2-d)	Clear Index	Horz.Rad. (MJ/m2-d)	Tilt Factor	Arr.Tot.Rad (MJ/m2-d)	Max D/S Ratio	Min.Out. (m3/d)	Act.Out. (m3/d)
January	12.0	45.0	0.0	45.0	5.30	39.8	0.60	23.9	0.83	19.8	0.267	12.5	16.7
February	12.0	45.0	0.0	45.0	5.30	38.0	0.60	22.8	0.92	21.0	0.253	13.2	17.6
March	12.0	45.0	0.0	45.0	5.30	34.2	0.60	20.5	1.07	22.0	0.241	13.8	18.5
April	12.0	45.0	0.0	45.0	5.30	29.4	0.60	17.6	1.27	22.4	0.236	14.1	18.8
May	12.0	45.0	0.0	45.0	5.30	25.4	0.62	15.7	1.48	23.3	0.227	14.6	19.5
June	12.0	45.0	0.0	45.0	5.30	23.4	0.63	14.7	1.59	23.4	0.226	14.7	19.7
July	12.0	45.0	0.0	45.0	5.30	24.6	0.64	15.7	1.55	24.4	0.217	15.3	20.5
August	12.0	45.0	0.0	45.0	5.30	28.4	0.65	18.5	1.36	25.1	0.211	15.8	21.1
September	12.0	45.0	0.0	45.0	5.30	33.2	0.65	21.6	1.15	24.8	0.213	15.6	20.9
October	12.0	45.0	0.0	45.0	5.30	37.2	0.63	23.4	0.96	22.5	0.235	14.1	18.9
November	12.0	45.0	0.0	45.0	5.30	39.0	0.61	23.8	0.85	20.2	0.262	12.7	17.0
December	12.0	45.0	0.0	45.0	5.30	39.8	0.60	23.9	0.80	19.1	0.277	12.0	16.1

DESIGN MONTH PARAMETERS

Design Month :December
Hydraulic Energy Requirement: 5.30 (MJ/day)
Design Month Total Head : 45.0 (meters)
Global Radiation on Array : 19.1 (MJ/m2-day)
Avg.Subsys.Energy Efficiency: 31%
Avg.Subsys.Power Efficiency : 35%

Max Ratio : 0.277

Ann. Average Output =	14.0	18.8
Ann. Minimum Output =	12.0	16.1
Ann. Maximum Output =	15.8	21.1

EQUIPMENT SIZING

	Min. Array Size	Actual Array Size
Elect. Energy Req'd:	16.90 (MJ/day)	
PV Array Size :	1156 (Wp)	1548 (Wp)
Derated Motor Power:	885 (Watts)	1184 (Watts)
Derated Hydr. Power:	324 (Watts)	434 (Watts)
Derated Pk.Flowrate:	0.73 (ls/sec)	0.98 (ls/sec)
Cell Operating Temp:	55 (deg.C)	55 (deg.C)

SPECIFIED COMPONENTS

		Rated Efficiency
Motor :	Honeywell 1.5 Hp (180V DC)	80%
Pump :	Nitrile ES-10 Mono pump	70%
Battery :	Boss Inc CVT controller	95%
Belt Drv:	Pulleys 1:2 red.to 900 RPM	90%
Wiring :	100 m. 4 mm @ 3 amps	97%
PV Mods :	ARCO M-55 (12s x 3p)	10%

Figure 9.

PROJECTED ANNUAL WATER OUTPUT (M3/DAY)

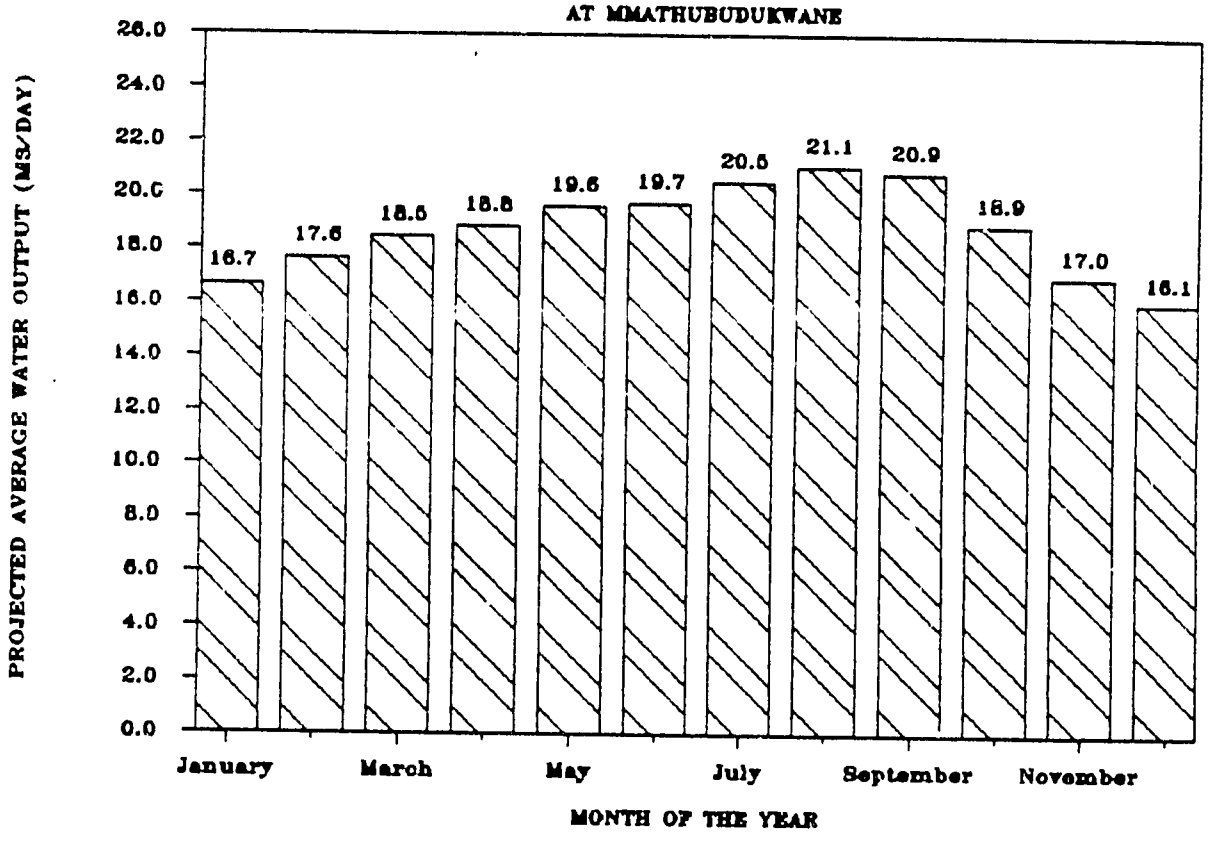


Figure 10.

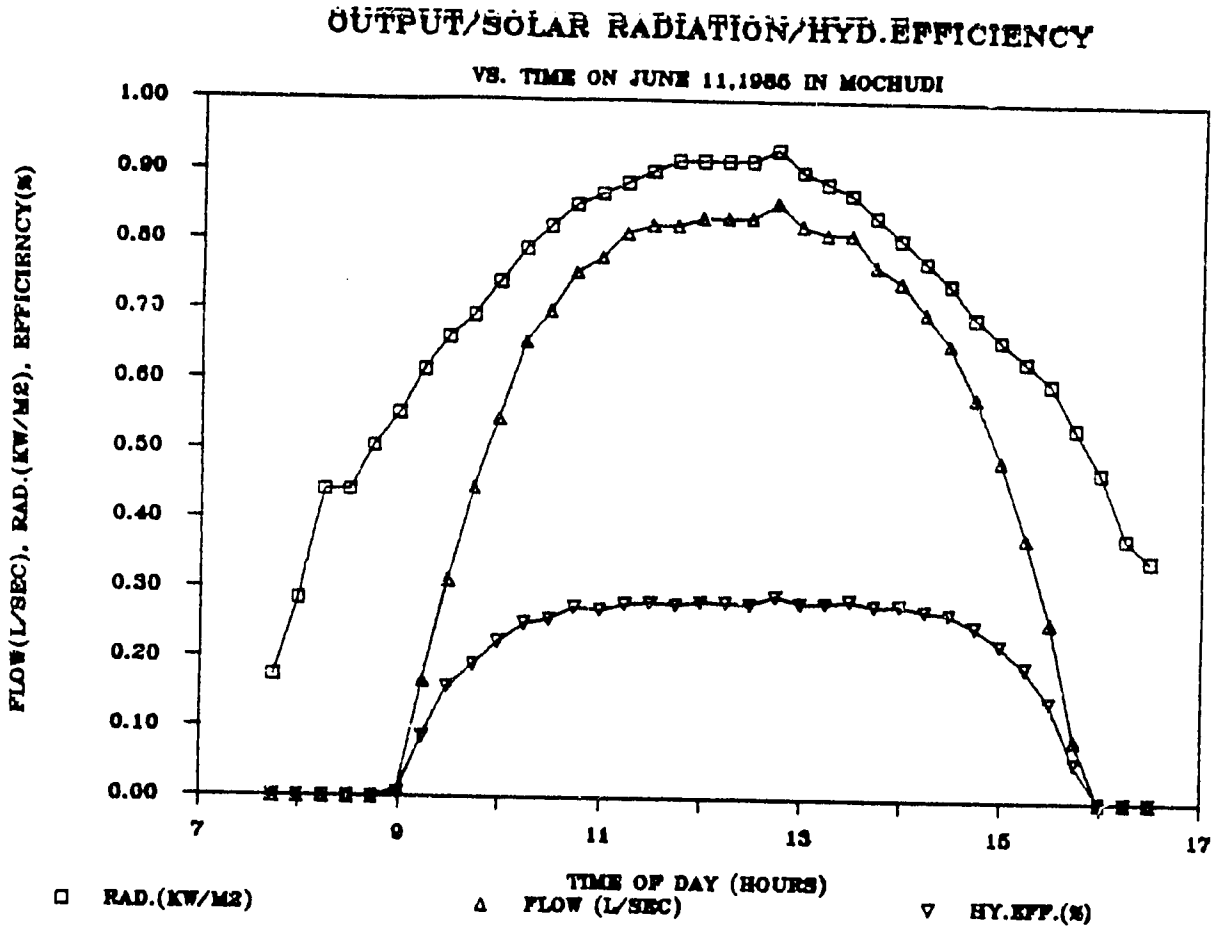


Figure 11.

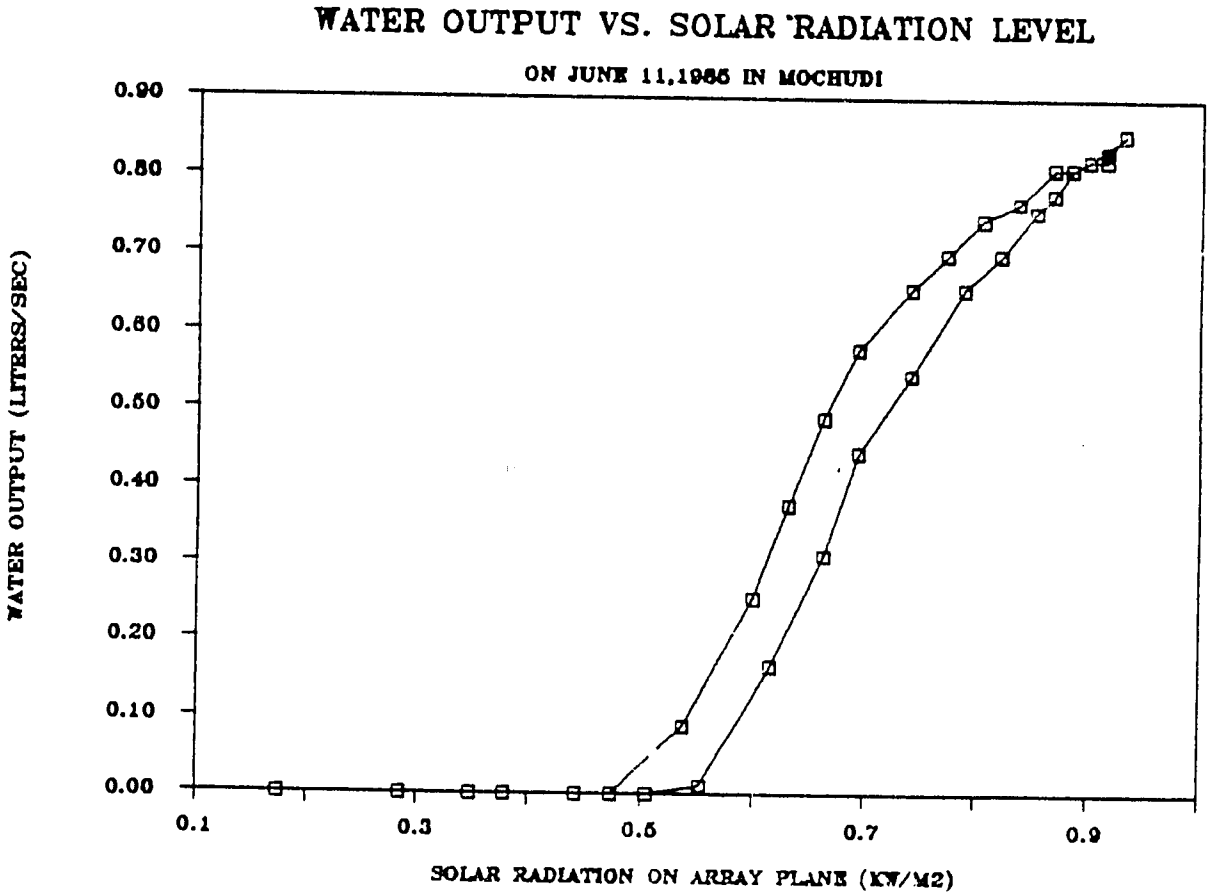


Figure 12.

HYDR.EFFICIENCY VS. SOLAR RADIATION

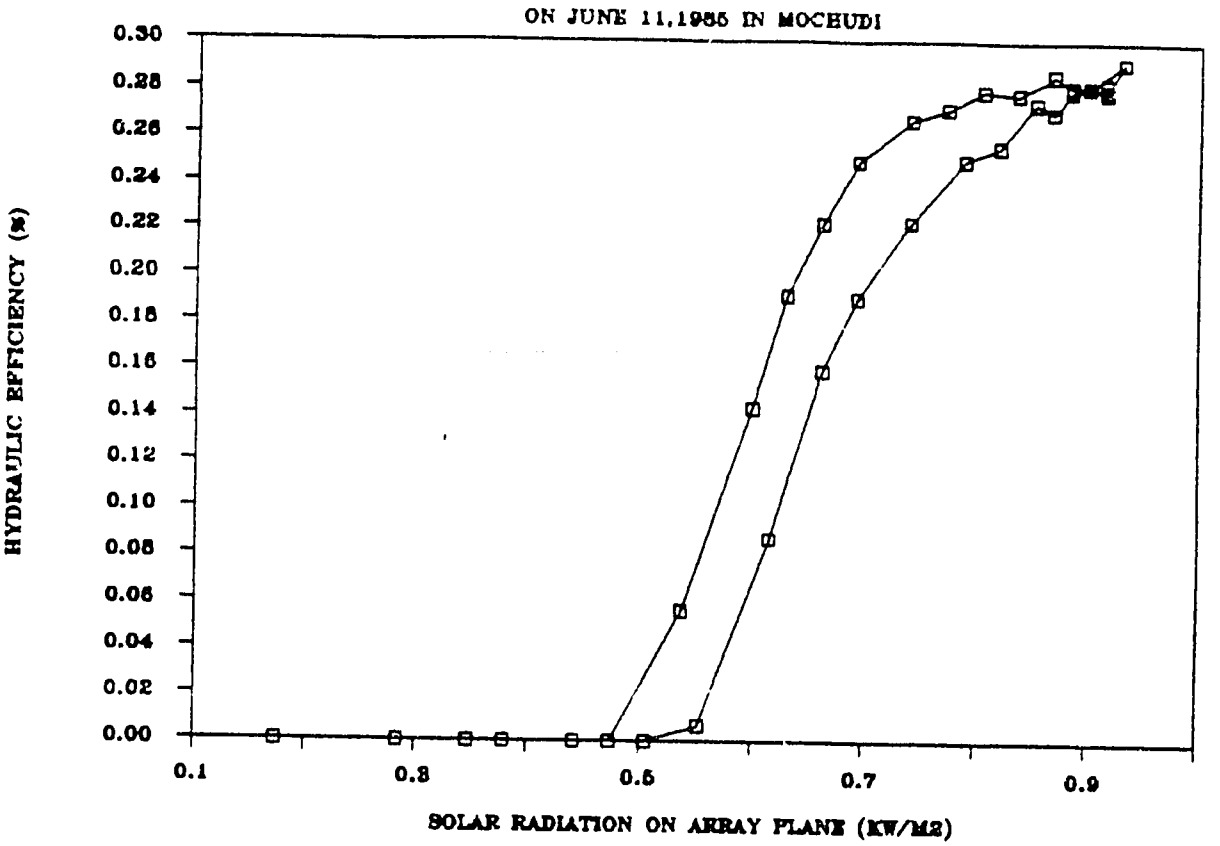


Table 3.

SOLAR PUMP SIZING ALGORITHM (IT Power/Halcrow, McGowan)
01-Aug-95 06:53 PM
Location: MOCHUDI Latitude:24.4 Degrees Min.Output based on hypothetical system satisfying min.hydraulic energy req'd.
Array Tilt Angle: 29 Degrees Act.Output based on series modules in actual array due to motor voltage req'd.

Month	Water Vol. (m3/day)	St.Head (m)	Dyn.Head (m)	Tt.Head (m)	H.Eng.Rqd (MJ/day)	XtrT.Rad. (MJ/m2-d)	Clear Index	Horz.Rad. (MJ/m2-d)	Tilt Factor	Arr.T.Rad (MJ/m2-d)	Max.D/S Ratio	Min.Out. (m3/day)	Act.Out. (m3/day)
January	15.0	36.0	0.0	36.0	5.30	39.8	0.60	23.9	0.83	19.8	0.267	15.6	16.1
February	15.0	36.0	0.0	36.0	5.30	38.0	0.60	22.8	0.92	21.0	0.253	16.5	17.1
March	15.0	36.0	0.0	36.0	5.30	34.2	0.60	20.5	1.07	22.0	0.241	17.2	17.9
April	15.0	36.0	0.0	36.0	5.30	29.4	0.60	17.6	1.27	22.4	0.235	17.6	18.2
May	15.0	36.0	0.0	36.0	5.30	25.4	0.62	15.7	1.48	23.3	0.227	18.3	19.0
June	15.0	36.0	0.0	36.0	5.30	23.4	0.63	14.7	1.59	23.4	0.226	18.4	19.1
July	15.0	36.0	0.0	36.0	5.30	24.6	0.64	15.7	1.55	24.4	0.217	19.2	19.9
August	15.0	36.0	0.0	36.0	5.30	28.4	0.65	18.5	1.36	25.1	0.211	19.7	20.5
September	15.0	36.0	0.0	36.0	5.30	33.2	0.65	21.6	1.15	24.8	0.213	19.5	20.2
October	15.0	36.0	0.0	36.0	5.30	37.2	0.63	23.4	0.96	22.5	0.235	17.7	18.3
November	15.0	36.0	0.0	36.0	5.30	39.0	0.61	23.8	0.85	20.2	0.262	15.9	16.5
December	15.0	36.0	0.0	36.0	5.30	39.8	0.60	23.9	0.80	19.1	0.277	15.0	15.6

DESIGN MONTH PARAMETERS

Design Month :December
Hydraulic Energy Requirement: 5.30 (MJ/day)
Design Month Total Head : 36.0 (meters)
Global Radiation on Array : 19.1 (MJ/m2-day)
Avg.Subsys.Energy Efficiency: 27%
Avg.Subsys.Power Efficiency : 30%

Avg.Rad.MJ/m2d= 20.2

Max Ratio 0.277

Ann. Min. Output =	15.0	15.6
Ann. Max. Output =	19.7	20.5
Ann. Avg. Output =	17.5	18.2

EQUIPMENT SIZING

	Min. Array Size	Act. Array Size
Elect. Energy Req'd:	19.38 (MJ/day)	
PV Array Size :	1326 (Wp)	1376 (Wp)
Derated Motor Power:	1014 (Watts)	1053 (Watts)
Derated Hydr. Power:	308 (Watts)	320 (Watts)
Derated Pk.Flowrate:	0.87 (ls/sec)	0.91 (ls/sec)
Cell Operating Temp:	55 (deg.C)	55 (deg.C)

SPECIFIED COMPONENTS

	Rated Efficiency
Motor : Jacuzzi SJ1	70%
Pump : Jacuzzi E7	45%
Battery : None	100%
Wiring : 30 m 4 mm @ 17 amps	96%
PV Mods : ARCO M-52 (4s x 8p)	10%

Wiring Losses (assuming copper wire @ 25C)

Wire Length (m):	30	Approx.Volt.Loss:	2.0 volts
Wire Diam. (mm):	4	Wiring Effic. (%):	96%
Av.Running Amps:	17		
System Voltage :	55		

Molapowabojang

In spite of the fact that this was the first PV pump installed during the project, it was the best performer in terms of water output per installed capacity. More importantly, it has been trouble-free since its installation. The results of one of the short-term tests on July 28th are given in Figures 13 through 15. The water output was directly proportional to the solar radiation level, and the hydraulic efficiency was fairly constant over most of the operating day. The peak flow rate approached 1.3 liters per second, and the hydraulic efficiency hovered around 30 percent. The total output for that day was 25.8 m^3/day at about 24 meters' head. The reason for the slight jump in output at about 12:30 p.m. was a slight tune-up of the wiring at that time. As a result of this, you can see that that output for a given radiation level was slightly higher in the afternoon, particularly at the lower end of the range.

Data from all short-term tests and the accumulated results of the long-term measurements were used with the model to estimate an annual average output of 24.3 m^3/day, assuming a constant 24-meter head. The model results and graph are shown in Table 4.

Otse

The original design of the Otse system was characteristic of the first generation of PV pumps, meaning that the pump and motor were not particularly well-matched electrically, and were constrained in output by the very small storage tank at the site. The site was recently retrofitted with a new standard Mono ES-15S pump. The older ARCO 16-2000 modules have been replaced with the more powerful M53s. The VDC chairman in Otse, who is also responsible for the borehole, had requested that the capacity of the system be increased to take into account greater water demand. This was done.

Short-term testing done on several occasions showed that the orignal system was pumping about 0.9 liters per second at a head of about 13 meters. The erratic use profile of the pump was shown in Section VI.A. The estimated long-term average output from the new system components are shown in Table 5 and Figure 16. However, these predictions should be regarded with caution until further testing results during the project extension can be used to validate the assumptions used in the projection.

Figure 13.

Output/Solar Radiation/Hyd.Efficiency

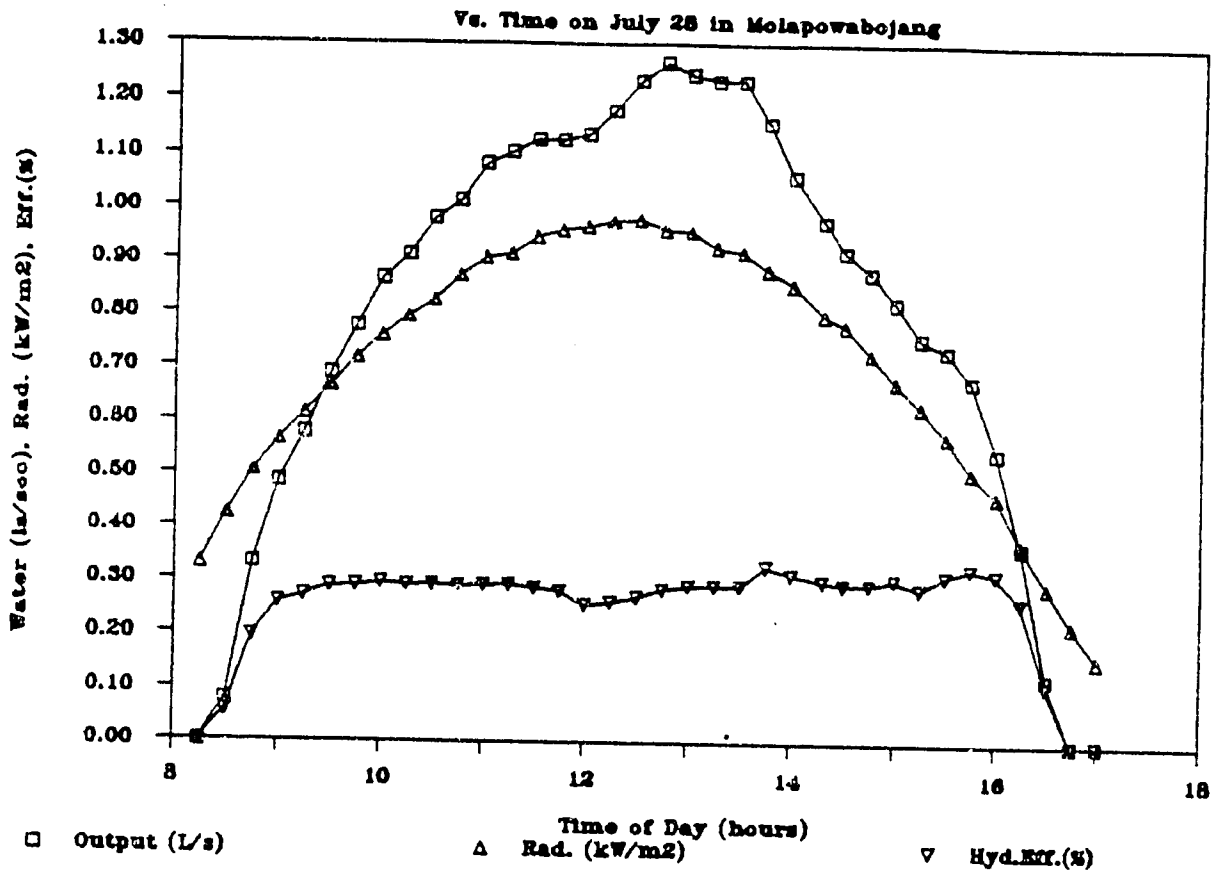


Figure 14.

Water Output Vs. Solar Radiation

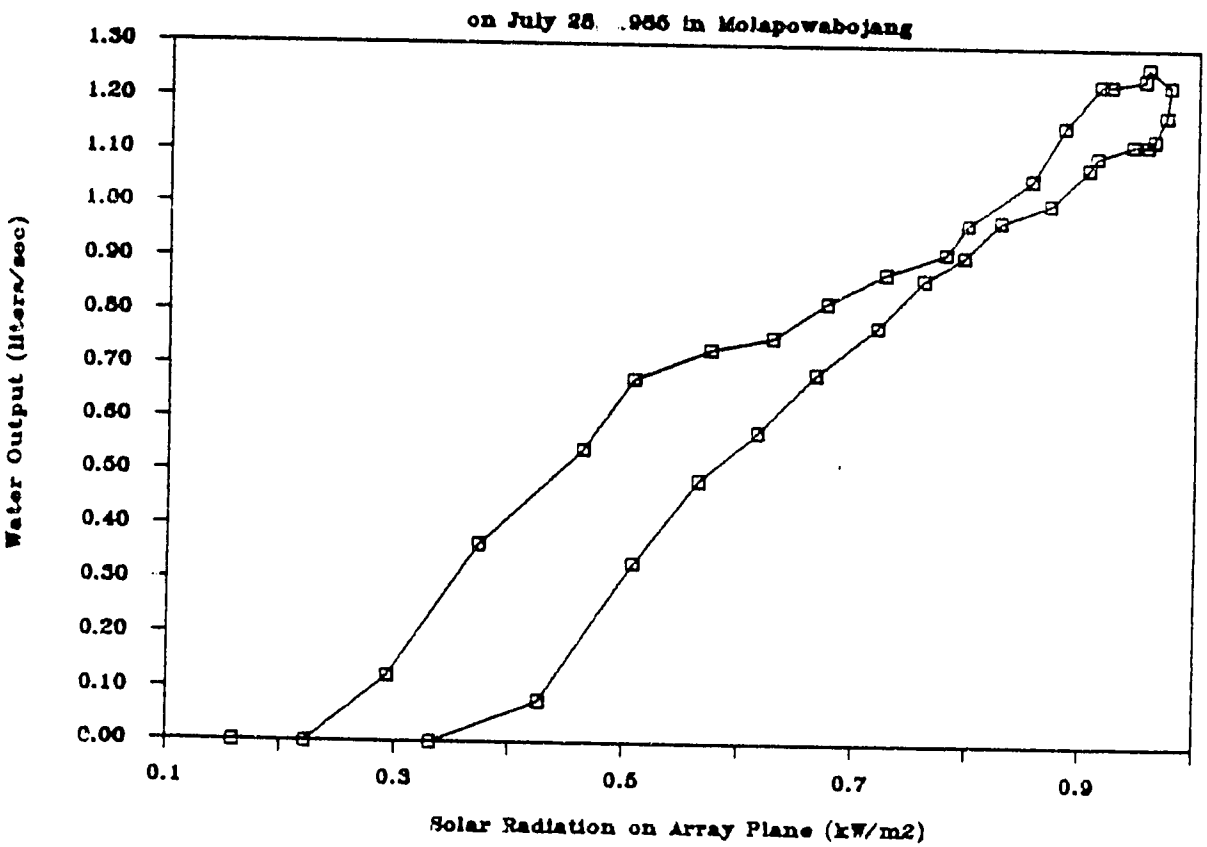


Figure 15.

Hydraulic Efficiency Vs.Solar Radiation

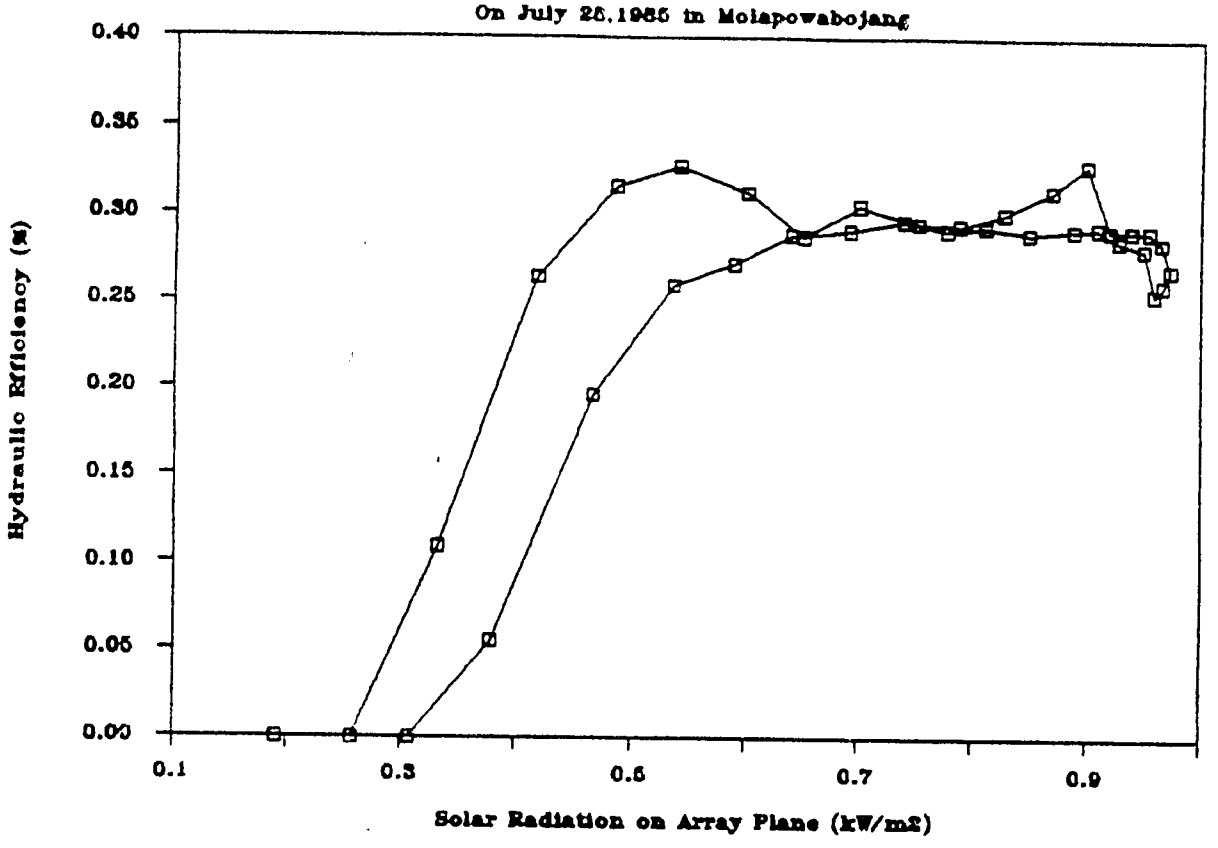


Table 4.

SOLAR PUMP SIZING ALGORITHM (IT Power/Halcrow, McGowan)
02-Aug-85 09:04 AM
Location: MOLAPOWAB Latitude:24.4 Degrees
Array Tilt Angle: 29 Degrees

Min.Output based on hypothetical system satisfying min.hydraulic energy req'd.
Act.Output based on series modules in actual array due to motor voltage req'd.

Month	Water Vol. (m3/day)	St.Head (m)	Dyn.Head (m)	Tt.Head (m)	H.Eng.Rqd (MJ/day)	XtrT.Rad. (MJ/m2-d)	Clear Index	Horz.Rad. (MJ/m2-d)	Tilt Factor	Arr.T.Rad (MJ/m2-d)	Max.D/S Ratio	Min.Out. (m3/day)	Act.Out. (m3/day)
January	20.0	24.0	0.0	24.0	4.71	39.8	0.60	23.9	0.83	19.8	0.238	20.8	21.5
February	20.0	24.0	0.0	24.0	4.71	38.0	0.60	22.8	0.92	21.0	0.224	22.0	22.8
March	20.0	24.0	0.0	24.0	4.71	34.2	0.60	20.5	1.07	22.0	0.214	23.0	23.9
April	20.0	24.0	0.0	24.0	4.71	29.4	0.60	17.6	1.27	22.4	0.210	23.5	24.3
May	20.0	24.0	0.0	24.0	4.71	25.4	0.62	15.7	1.48	23.3	0.202	24.4	25.2
June	20.0	24.0	0.0	24.0	4.71	23.4	0.63	14.7	1.59	23.4	0.201	24.5	25.5
July	20.0	24.0	0.0	24.0	4.71	24.6	0.64	15.7	1.55	24.4	0.193	25.5	26.5
August	20.0	24.0	0.0	24.0	4.71	28.4	0.65	18.5	1.36	25.1	0.188	26.3	27.3
September	20.0	24.0	0.0	24.0	4.71	33.2	0.65	21.6	1.15	24.8	0.190	26.0	27.0
October	20.0	24.0	0.0	24.0	4.71	37.2	0.63	23.4	0.96	22.5	0.209	23.6	24.4
November	20.0	24.0	0.0	24.0	4.71	39.0	0.61	23.8	0.85	20.2	0.233	21.2	22.0
December	20.0	24.0	0.0	24.0	4.71	39.8	0.60	23.9	0.80	19.1	0.246	20.0	20.8

DESIGN MONTH PARAMETERS

Design Month :December
Hydraulic Energy Requirement: 4.7 (MJ/day)
Design Month Total Head : 24.0 (meters)
Global Radiation on Array : 19.1 (MJ/m2-day)
Avg.Subsys.Energy Efficiency: 24%
Avg.Subsys.Power Efficiency : 27%

:Avg.Rad.MJ/m2d= 20.2

Max Ratio 0.246

Ann. Min. Output =	20.0	20.8
Ann. Max. Output =	26.3	27.3
Ann. Avg. Output =	23.4	24.3

EQUIPMENT SIZING

	Min. Array Size	Act. Array Size
Elect. Energy Req'd:	19.4 (MJ/day)	
PV Array Size :	1326 (Wp)	1376 (Wp)
Derated Motor Power:	1014 (Watts)	1053 (Watts)
Derated Hydr. Power:	274 (Watts)	284 (Watts)
Derated Pk.Flowrate:	1.16 (ls/sec)	1.21 (ls/sec)
Cell Operating Temp:	55 (deg.C)	55 (deg.C)

SPECIFIED COMPONENTS

		Rated Efficiency
Motor :	Jacuzzi 5J1	70%
Pump :	Jacuzzi E7	40%
Battery :	None	100%
Wiring :	30 m 4 mm @ 17 amps	96%
PV Mods :	ARCO M-55 As x 36	10%

Wiring Losses (assuming copper wire @ 35C)

Wire Length (m):	30	Approx.Volt.Loss:	2.0 volts
Wire Diam. (mm):	4	Wiring Effic.(%):	96%
Av.Running Amps:	17		
System Voltage :	55		

Table 5.

SOLAR PUMP SIZING ALGORITHM (IT Power/Halcrow, McBowan) 27-Jul-85 13:00

Location: OTSE Latitude: 25 Degrees Min.Output based on hypothetical system satisfying min.hydraulic energy requirement
Array Tilt Angle: 30 Degrees At.Output based on modules in series in actual array due to motor voltage requirement

Month	Water Vol. (m3/day)	St.Head (m)	Dyn.Head (m)	Tot.Head (m)	H.En.Rqd. (MJ/day)	XtraT.Rad. (MJ/m2-day)	Clear Index	Horiz.Rad. (MJ/m2-day)	Tilt Factor	Arr.Tot.Rad (MJ/m2-day)	Maximum D/S Ratio	Min.Output (m3/day)	At.Output (m3/day)
January	10.0	9.0	0.0	9.0	0.88	40.0	0.60	24.0	0.83	19.9	0.044	10.4	11.8
February	10.0	9.0	0.0	9.0	0.88	38.0	0.60	22.8	0.92	21.0	0.042	10.9	12.5
March	10.0	9.0	0.0	9.0	0.88	34.0	0.60	20.4	1.07	21.8	0.040	11.4	13.0
April	10.0	9.0	0.0	9.0	0.88	29.0	0.60	17.4	1.27	22.1	0.040	11.5	13.1
May	10.0	9.0	0.0	9.0	0.88	25.0	0.62	15.5	1.48	22.9	0.038	11.9	13.6
June	10.0	9.0	0.0	9.0	0.88	23.0	0.63	14.5	1.59	23.0	0.038	12.0	13.7
July	10.0	9.0	0.0	9.0	0.88	24.0	0.64	15.4	1.55	23.8	0.037	12.4	14.1
August	10.0	9.0	0.0	9.0	0.88	28.0	0.65	18.2	1.36	24.8	0.036	12.9	14.7
September	10.0	9.0	0.0	9.0	0.88	33.0	0.65	21.5	1.15	24.7	0.036	12.8	14.[illegible]
October	10.0	9.0	0.0	9.0	0.88	37.0	0.63	23.3	0.96	22.4	0.039	11.7	13.[illegible]
November	10.0	9.0	0.0	9.0	0.88	39.0	0.61	23.8	0.85	20.2	0.044	10.5	12.[illegible]
December	10.0	9.0	0.0	9.0	0.88	40.0	0.60	24.0	0.80	19.2	0.046	10.0	11.4

DESIGN MONTH PARAMETERS

Design Month : December
Hydraulic Energy Requirement: 0.88 (MJ/day)
Design Month Total Head : 9.0 (meters)
Global Radiation on Array : 19.2 (MJ/m2-day)
Avg.Subsys.Energy Efficiency: 19%
Avg.Subsys.Power Efficiency : 22%

Max Ratio : 0.046

Ann. Average Output = 11.5 13.2
Ann. Minimum Output = 10.0 11.4
Ann. Maximum Output = 12.9 14.7

EQUIPMENT SIZING

	Min. Array Size	Actual Array Size
Elect. Energy Req'd:	4.56 (MJ/day)	5.20 (MJ/day)
PV Array Size :	301 (Wp)	344 (Wp)
Derated Motor Power:	237 (Watts)	271 (Watts)
Derated Hydr. Power:	68 (Watts)	78 (Watts)
Derated Pk.Flowrate:	0.77 (l/s/sec)	0.88 (l/s/sec)
Cell Operating Temp:	50 (deg.C)	50 (deg.C)

SPECIFIED COMPONENTS Rated Efficiency

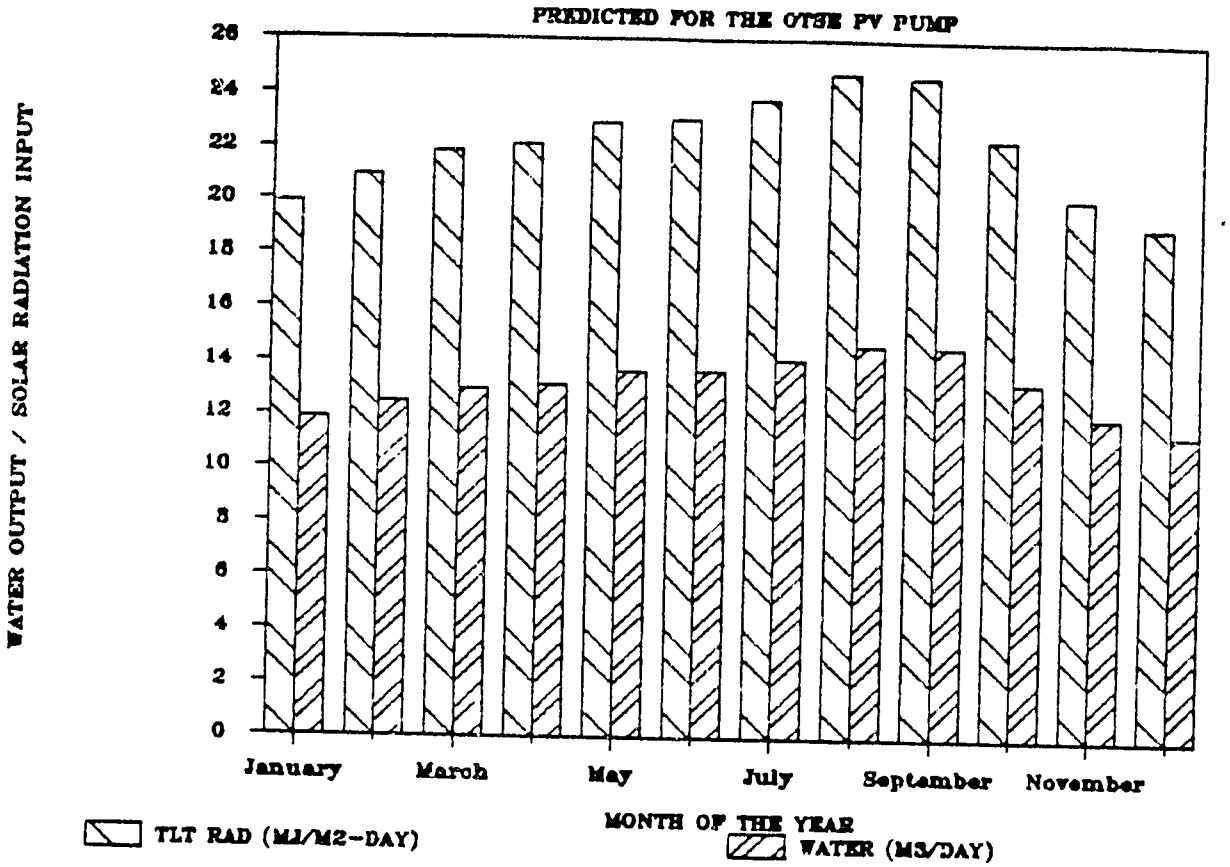
Motor : Honeywell 0.5 Hp (24V DC) 70%
Pump : Mono ES15S (STrq(10 ft-lbf) 41%
Battery : 4 Batteries (400 AH @24V) 75%
PV Mods : ARCO M-53 (2s x 4p) 10%

BATTERY REQUIREMENTS (if used)

System Operating Voltage: 24
Single Battery AH Rating: 200
Days of Storage Desired : 1
Max. Depth of Discharge : 20%
Bats.in Parallel Req'd: 2.0

Figure 16.

Water Output and Solar Radiation Input



VII. FINANCIAL AND ECONOMIC ANALYSIS

A. Methodology

Life-cycle costing analysis, which calculates the present worth of all costs, capital, operation and maintenance, and replacement parts over the lifetime of the system, is a common method used for financial and economic comparison of water pumping alternatives. This method is used here. A cost/benefit ratio is also calculated, although it has the limitation of requiring that a benefit value per unit of water pumped be assumed, and this can be highly site-specific.

The costs considered in this analysis do not include the costs of well drilling or development, the water distribution system, or storage tanks, except where specifically noted. Since it is standard practice in Botswana to use storage tanks with a two-day capacity with diesel pumps, the equivalent tank size would likely be the same for the PV system, given the high and relatively uniform solar radiation conditions prevailing in that country. However, this issue is far from resolved, and storage sizing will be further examined during the extension of the testing program (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986). Any system components which are common to both systems are not included in the costing.

Economic Cost Considerations

Economic analyses attempt to place a "true" value (cost to the national economy) on various cost components, which is not necessarily what these costs would be in the marketplace. They attempt to quantify such real costs to the overall economy such as the cost of government subsidies (hidden or otherwise), anomalies in the marketplace, imbalances in exchange rates, or scarcity in the availablity of foreign exchange. While the real economic cost of subsidies would not be taken into consideration by the average private-sector consumer, it should be taken into account by government planners who are particularly concerned about foreign exchange shortages, many of which are caused by importing fossil fuels.

However, PV pumps also require considerable foreign exchange. It is not reasonable to suggest spending more scarce foreign exchange on PV modules and components than would be spent on a diesel system alternative. While extensions of the electrical grid have also been suggested as a possible alternative to diesel or PV for water supply, several studies have indicated that, in many rural areas, the low load factors often encountered in rural electrification schemes make the cost per kWh generated much more expensive than initially planned for

(see ENERGY ALTERNATIVES FOR IRRIGATION PUMPING, AN ECONOMIC ANALYSIS FOR NORTHERN INDIA, R. Batia, International Labor Office, 1984). Stand-alone systems, whether PV, diesel or wind (where sufficient wind occurs), merit closer examination under such circumstances.

Since the purpose of this report is just to give the results of the PV pumping study, the comparative results with diesel, wind, animal and human traction, and hand pumps is reserved for the overall comparative pumping report. Sensitivity analyses were performed on all the major assumptions for this analysis, including discount rate, fuel cost inflation, system economic lifetime, future cost of PV modules, labor costs for pump attendants, etc. Since these calculations are most useful when compared to the unit water costs of alternative types of systems, they have been included in the overall comparative testing report as well (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986). The detailed breakdown of all cost assumptions used in this analysis are given in Appendix A.

B. Results of the Analysis

Table 6 summarizes the results of the comparative economic analysis of the five systems tested using the assumptions discussed in Section IV.A.2 and elaborated below. To a varying degree, each system's output involves some uncertainty in that it was based on extrapolation from the actual data collected during the pumping program thus far. The costs of the Mono-coupled systems involve the most extrapolation, for the reasons already discussed.

While the upper portion of the spread-sheet is fairly self-explanatory, the sections at the bottom, which summarize the annualized life-cycle costs calculated for each case, deserve some explanation. Table 7 summarizes all recurrent costs for each system by year over the assumed 20-year (module) lifetime. The five categories are:

- Pumper Cost: This is the stipend paid to the pump attendant or, in the case of PV, the reticulation network attendant. This job involves making weekly checks of the system to make sure it is running properly, keeping records of the system's performance (water output), and advising the Water Maintenance Unit (WMU) repair crews if any maintenance or repairs are necessary.

- Constant Annual Recurrent Costs: These are the costs for annual inspection trips from the WMU (for example, to replace worn drive belts for the Mono systems) and general system inspection. They

Table 6.

ECONOMIC ANALYSIS OF SOLAR PUMPS

Pump Site	Mahalapye	Mmathab.	Mochudi	Molapow	Otse
Avg. Output (m3/dy):	30.0	16.1	15.6	20.8	13.0
Total Pump Head (m):	7	45	36	24	9
Amort. Per. (yrs) :	20	20	20	20	20
Array Peak Watts :	516	1548	1376	1376	280
Discount Rate (%) :	6%	6%	6%	6%	6%
COSTS					
Init. Cap. Cost (P):	11839	28171	24584	24440	8941
Installation Cost :	428	164	140	141	147
Install. Cost-Labor:	420	420	350	370	350
Tot. Installed Cost:	12687	28755	25074	24951	9438
Recurrent Costs PW :	6756	8317	8578	8511	7008
Life Cycle Cost (P):	19443	37072	33652	33462	16446
BENEFITS	(Assumed Water Value =			0.30 Pula/m3)	
Annual Flow (m3/yr):	10950	5877	5694	7592	4745
Discount. Ann. Flow:	6280	3370	3265	4354	2721
Head*Flow (m3*m/yr):	76,650	264,443	204,984	182,208	42,705
Benefits @P.30/m3 :	3285	1763	1708	2278	1424
Benefit Stream PW :	37679	20221	19593	26124	16327
Benefit/Cost Ratio :	1.94	0.55	0.58	0.78	0.99
Unit Cost (P/m3) : (Water Discounted):	0.27	0.96	0.90	0.67	0.53
Unit Cost (P/m3) : (Water Undiscount.):	0.15	0.55	0.52	0.38	0.30
Unit Cost (P/m3*m) : (Water Undiscount.):	0.022	0.012	0.014	0.016	0.034

Table 7.

RECURRENT COSTS SUMMARY BY YEAR (Economic)
Inf.Rate:0.00%

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Site: Mahalapye						**Jacuzzi Submersible**														
Pumper co	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156
ARC (M)	94	188	188	188	94	188	94	188	188	94	188	188	188	94	94	188	188	188	188	188
ARC (L)	6	12	12	12	6	12	6	12	12	6	12	12	12	6	6	12	12	12	12	12
MARC (M)	0	0	0	0	553	0	1958	0	0	553	0	0	0	1958	553	0	0	0	0	0
MARC (L)	0	0	0	0	30	0	30	0	0	30	0	0	0	30	30	0	0	0	0	0
SALVAGE																				-500
Tot.R.C.	256	356	356	356	839	356	2244	356	356	839	356	356	356	2244	839	356	356	356	356	-144
Site: Mmathubudukwane						**Honeywell motor w/Mono**														
Pumper co	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156
ARC (M)	94	203	203	203	109	203	109	203	203	109	203	203	203	109	203	203	203	203	203	203
ARC (L)	6	12	12	12	6	12	6	12	12	6	12	12	12	6	12	12	12	12	12	12
MARC (M)	0	0	0	0	1592	0	1191	0	0	2338	0	0	0	1191	1592	0	0	0	0	0
MARC (L)	0	0	0	0	48	0	6	0	0	48	0	0	0	6	48	0	0	0	0	0
SALVAGE																				-500
Tot.R.C.	256	371	371	371	1911	371	1468	371	371	2657	371	371	371	1468	2011	371	371	371	371	-129
Site: Mochudi						**Jacuzzi Submersible**														
Pumper co	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156
ARC (M)	94	188	188	188	94	188	94	188	188	94	188	188	188	94	188	188	188	188	188	188
ARC (L)	6	12	12	12	6	12	6	12	12	6	12	12	12	6	12	12	12	12	12	12
MARC (M)	0	0	0	0	1437	0	2114	0	0	1437	0	0	0	2114	1437	0	0	0	0	0
MARC (L)	0	0	0	0	60	0	60	0	0	60	0	0	0	60	60	0	0	0	0	0
SALVAGE																				-500
Tot.R.C.	256	356	356	356	1753	356	2430	356	356	1753	356	356	356	2430	1853	356	356	356	356	-144
Site: Molapowabojang						**Jacuzzi Submersible**														
Pumper co	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156
ARC (M)	94	188	188	188	94	188	94	188	188	94	188	188	188	94	94	188	188	188	188	188
ARC (L)	6	12	12	12	6	12	6	12	12	6	12	12	12	6	6	12	12	12	12	12
MARC (M)	0	0	0	0	1422	0	2114	0	0	1422	0	0	0	2114	1422	0	0	0	0	0
MARC (L)	0	0	0	0	60	0	60	0	0	60	0	0	0	60	60	0	0	0	0	0
SALVAGE																				-500
Tot.R.C.	256	356	356	356	1738	356	2430	356	356	1738	356	356	356	2430	1738	356	356	356	356	-144
Site: Otse						**Honewell motor w/Mono**														
Pumper co	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156	156
ARC (M)	94	188	188	188	94	188	188	188	188	94	188	188	188	94	94	188	188	188	188	188
ARC (L)	6	12	12	12	6	12	12	12	12	6	12	12	12	6	6	12	12	12	12	12
MARC (M)	0	0	0	0	1673	0	0	0	0	1917	0	0	0	708	1673	0	0	0	0	0
MARC (L)	0	0	0	0	30	0	0	0	0	36	0	0	0	10	30	0	0	0	0	0
SALVAGE																				-500
Tot.R.C.	256	356	356	356	1959	356	356	356	356	2209	356	356	356	974	1959	356	356	356	356	-144

include the cost of two technicians and light truck transport from the nearest WMU site.

- Non-Annual Benefits: A convenient place for recording the salvage value of equipment at the end of the system's useful lifetime. Here, it represents the value of the most recently replaced modules (due to anticipated periodic vandalism, see below).

- Non-Annual Recurrent Costs: For the submersibles, this includes the cost every fifth year of replacing the safety cable, all downhole pipes (due to expected corrosion) and two modules (per 30- to 40-module system) due to vandalism, and the labor and transport costs of doing so. Every seven years, the pump set will be replaced, so the seventh and fourteenth year costs include equipment, transport and labor costs of doing this. For the Mono system at Mmathubudukwane, these costs include replacing the Mono column (standard practice on diesel systems as well), shafts and bobbins every five years, and includes equipment, transport and labor charges. The motor itself is replaced every seven years. The controller is replaced after the tenth year (it is a solid state device). For Otse, the only difference is that the battery bank is also replaced every five years.

- Net Recurrent Costs: This is the sum of all the costs (minus the salvage value) in the rows above.

The net recurrent costs for each year at each site are then taken as a series of negative cash flows and, using the discount rate and the amortization period listed in the upper section of the main spread-sheet, the present value of the recurrent costs is calculated. This value is added to the total installed cost to give the life-cycle cost.

Benefits are calculated in a straightforward manner, using a value of P0.30/m^3 of water pumped as a typical water value. Since this value represents the actual tariff rate charged by the DWA at the sites it services throughout the country, it is not arbitrary. Nonetheless, the value might not accurately represent the actual cost of water delivery by DWA (an updated tariff study is currently underway). As such, the present worth of the benefit stream and the benefit/cost ratio calculated are necessarily based on a somewhat tenuous assumption.

The most useful comparative figures are the unit costs. The calculations are fairly standard, with two explanatory notes. As mentioned previously, MMRWA requested that the water volume be

discounted according to the discount rate assumed. A more common formulation in the literature is to calculate the unit cost without discounting the volume of water. Therefore, both of these formulations are presented separately as the "Unit Cost (P/m^3), Water Discounted" and the "Unit Cost (P/m^3), Water Not Discounted." As discussed in Section IV.A.2 (Financial/Economic Criteria), a much more useful quantifier of the comparative economics of the various types of systems is the unit cost per m^3*m, which takes into account the head through which the water must be pumped and the actual energy required to do so. This value is given in the row for "Unit Cost (P/m^4), Water Not Discounted." As can be seen in Figures 17 and 18, the relative comparison of the systems does not depend on which of the first two formulations is chosen. In this case, this is true because a constant value of the annual volume of water pumped is assumed in all cases. If this were not the case, and if different volumes were pumped some years, the relative ranking would not necessarily remain the same.

The unit cost (discounted) is represented by the bar on the left, and the unit cost (not discounted) is represented by the bar on the right for each of the sites. From these graphs, it appears that the system at Mahalapye is the best since it delivers water at the lowest cost. Next comes Otse, then Malopowabojang, Mochudi, and finally Mmathubudukwane. It works out that the systems are ranked according to increasing head. The higher the head, the less water pumped (even apart from the system array size, at least for this particular case).

However, look closely at the second graph of unit water cost per unit volume per unit head (P/m^3*m). The ranking of the systems is very different. The Mono-coupled system at Mmathubudukwane and the two Jacuzzi submersibles at Mochudi and Malopowabojang are in a very close tie for the most cost-effective system (ignore for a moment the operational problems at Mmathubudukwane, which are discussed elsewhere). The Otse system, which is the only battery system and has the most poorly matched components, is by far the least cost-effective system.

This latter comparison gives much more information on the comparative performance of the five systems. Saying that a system on a five-meter borehole is more cost-effective simply because it pumps more water than a similar system on a 40-meter borehole does not take into account actual energy costs. The cost of the system is directly proportional to the energy it produces. This is why the m^3*m (or m^4) formulation of the unit cost is a more useful criterion for comparing different pumping systems. In ARD's report, FIELD TESTS OF SMALL-SCALE WATER PUMPS IN BOTSWANA (R. McGowan and J. Hodgkin, 1986), the unit costs for diesel, wind, PV and hand-operated pumps are given for comparison.

Figure 17. Economic Unit Water Cost (P/m3)
OF SOLAR PUMPS

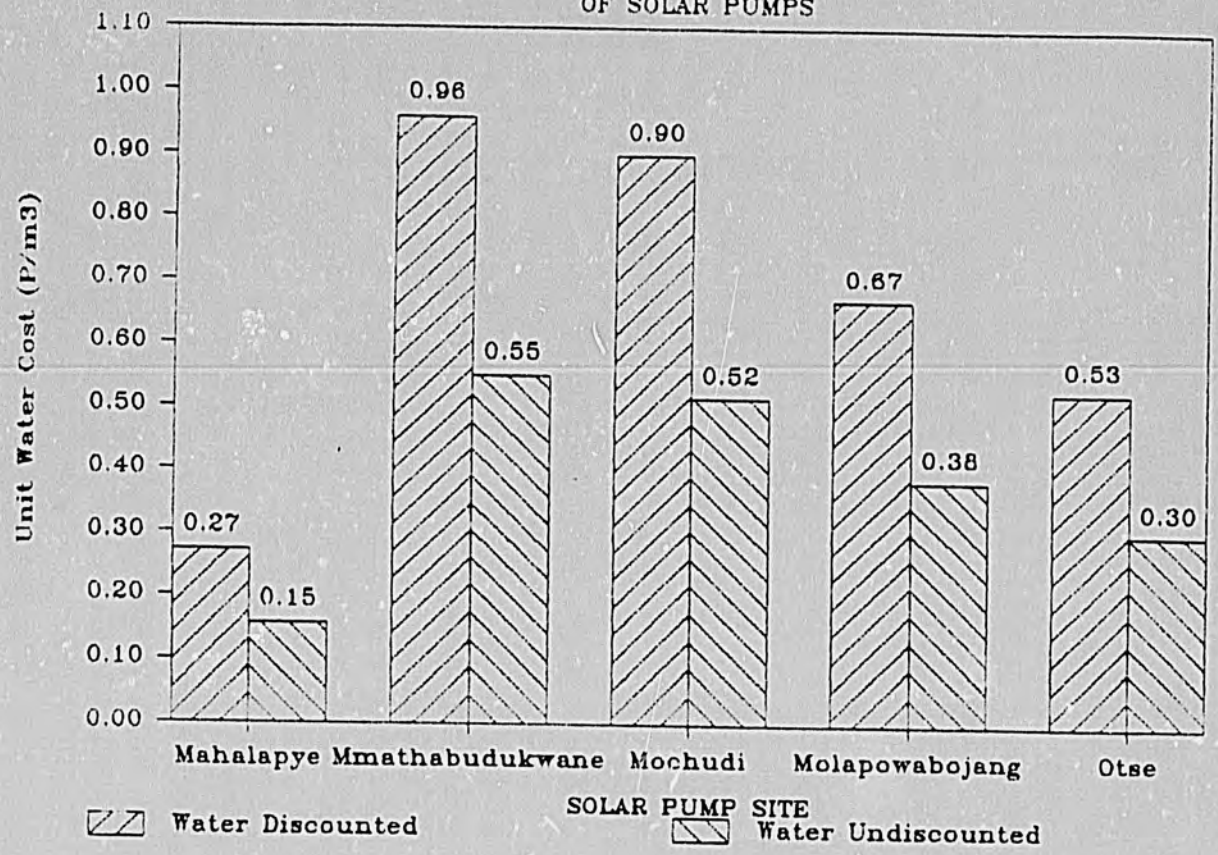
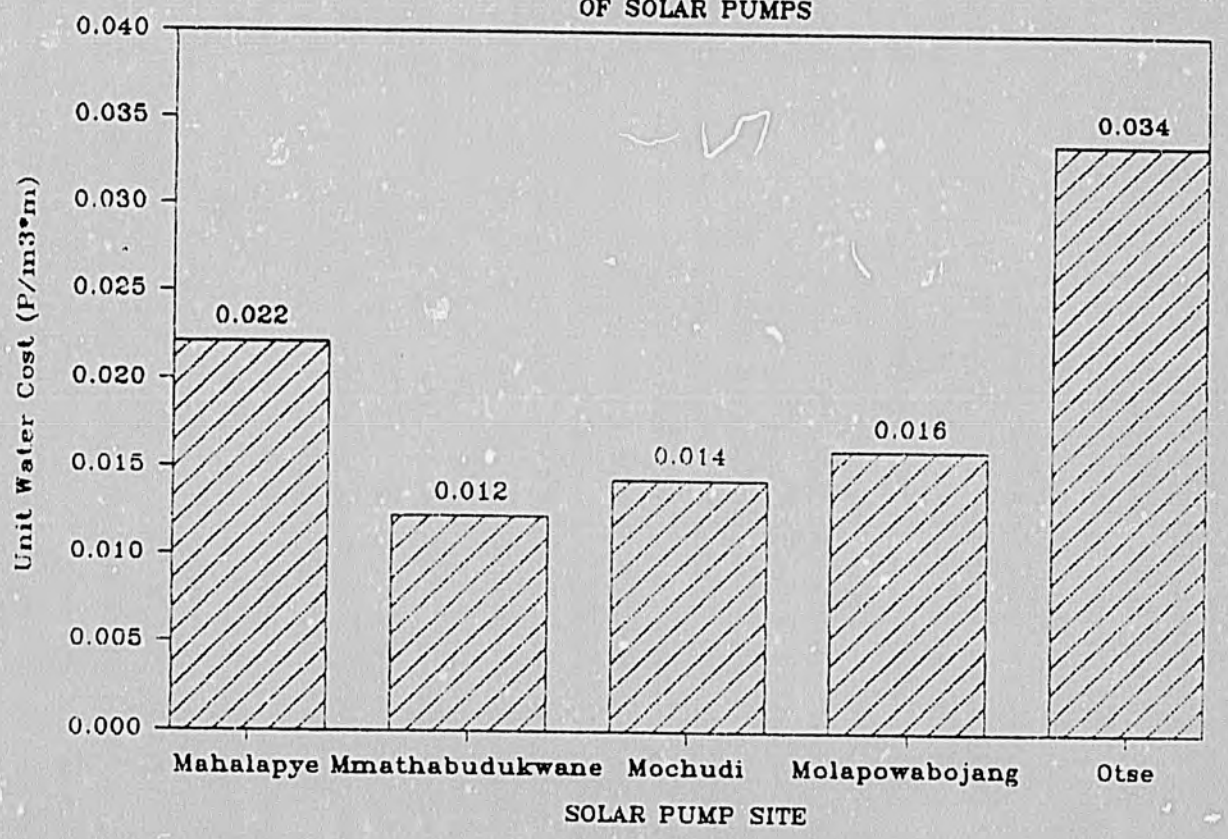


Figure 18. Economic Unit Water Cost (P/m3*m)
OF SOLAR PUMPS



For the small-scale PV systems discussed here, the module cost is about 80 to 85 percent of the entire system cost. While it is likely that the cost of modules will continue to decline, although not at as rapid a rate as had been forecasted over the last five years, it is unlikely that BOS costs will decrease at a similar rate. While there will be certain economies of scale as the number of units manufactured increases, BOS costs are spread over the array structures, pumps, motors, and regulation and control electronics. The technology for manufacturing these devices is relatively mature. Therefore, it is unlikely that the costs of any of these components will drop precipitously. Since BOS costs are a small fraction of the overall system cost, moderate decreases in BOS costs will have little effect on the life-cycle cost. Therefore, significant decreases in system costs will likely come only from continuing decreases in module costs, and to some extent from economies of scale in manufacturing as the worldwide demand for components increases (as it gives every indication of doing).

While local manufacture of PV modules has been suggested as a means of reducing end-user cost, this seems unlikely for two reasons. First, the PV cells themselves represent about 85 to 90 percent of the module manufacturing cost. While local labor rates would presumably reduce the size of the 15 percent labor cost, it would not significantly affect the total module cost. Also, PV module manufacturers in developed countries have the considerable advantage of economies of scale. Increasingly automated assembly lines are being used to further reduce manufacturing costs. It is unlikely that local manufacturers in developing countries could effectively compete in a market where wholesale prices are often below actual cost--subsidized in some countries (such as Japan) by the government, or in the United States by the companies themselves in hopes of winning a larger share of an ever-increasing market.

VIII. CONSTRAINTS TO WIDESPREAD USE OF PV PUMPS

A. Financial and Institutional Constraints

To address the problem of relatively high capital equipment cost, compounded by limited foreign exchange, several countries have begun local manufacture of some or all of the components for PV systems. Charge controllers, for example, are already being manufactured in Botswana. Entire PV pumping systems, including modules, batteries, controllers and small DC motor-driven jack pumps are being manufactured (with the help of extensive government subsidies) on a small scale in India.

At least one corporation (Spire Corp. in the United States) has begun to sell complete turnkey operations for the production of PV modules, from the cell materials to the lamination. Several countries have purchased these units and are now manufacturing their own modules. The cost of modules is approximately 10 to 15 percent labor. Thus, if production volume is high enough and local labor rates are lower than those in the United States, Europe or Japan--where most of the PV modules are currently being manufactured--some savings can be realized through local production of modules. This is only likely where much of the production is exported (e.g., if Botswana were producing modules for all SADCC countries). As mentioned previously, when there is little economy of scale, it would be difficult to successfully compete with larger manufacturers in developed countries, unless subsidies were involved. Added benefits of local manufacture are local employment generation and gross domestic product effects, which in turn affect GNP. However, turnkey operations are not inexpensive (starting around US$500,000), and careful market studies should be done before any such investment is made.

While the principal obstacle to the widespread use of PV for small-scale water supply is the high initial capital investment required, it is also necessary to overcome a general lack of awareness on the part of both the private and public sectors of the potential benefits of photovoltaics. Many potential users--private parties as well as governments and financing institutions--are unaware of the long-term benefits of this promising technology, or view it as an experimental technology that is many years away from commercialization.

Having limited access to or experience with long-term capital financing, individuals in developing countries often expect very short pay-back periods and implicitly high discount rates. Convincing potential users that it is reasonable to trade relatively high initial costs for reductions in long-term recurrent costs would require a carefully planned public awareness program, perhaps through mechanisms such as existing

government agricultural extension programs. Also, conflicts of interest may occur among various government agencies regarding the relative merits of this trade-off. For instance, while MMRWA (through DWA) is responsible for capital equipment purchasing for water delivery, MLGL is responsible for recurrent costs.

While the government of Botswana is not so concerned with the availability of financing for capital investments, private citizens who wish to take advantage of the potential savings of using PV for water pumping are faced with the difficulties of obtaining financing. At sites where PV is a reasonable choice, it is in the government's interest to make financing available to private parties, so some method of financing the purchase of PV pumps should be developed. The use of subsidies should be considered from an overall economic perspective. Alternative sources of financing to offset the relatively high capital equipment costs might include PV manufacturers and distributors, or perhaps agricultural cooperatives or syndicates.

Import duties, particularly on items with high capital costs, can significantly affect life-cycle cost analyses. While solar electric pumps have shown themselves to be cost-competitive in many situations in Botswana (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986), appreciable customs duty surcharges on pumps imported from outside the South African Customs Union (e.g., from the United States or Europe), could significantly increase the relative cost of solar, wind or other imported pumping systems compared to diesels manufactured in South Africa. This also points out the advantage of locally manufactured pumps such as the human traction pump and certain of the wind pumps purchased or made locally by the BRET project.

In some countries, import duties are levied based upon the end-use of the equipment. In Botswana, there is no import duty charged on agricultural equipment. It is reasonable to assume that equipment for purposes such as village water supply would receive similarly favorable treatment. Since diesel fuel is not heavily subsidized in Botswana, and since the unit water cost of pumping with diesels is much more dependent on recurrent operation and maintenance costs than on initial captial equipment costs, favorable import duty status would encourage the use of RETs over pumps fired by fossil fuels.

The artificially strong U.S. dollar over the last several years has not favored U.S. manufacturers. Since the equipment used for the BRET comparative testing program was mostly of U.S. origin, the actual system unit water costs in pula reflect the imbalance of exchange rates resulting from an unusually strong U.S. dollar. Now that this trend has slowly begun to reverse itself, the cost of PV in pula should drop accordingly. The Japanese have invested considerable time and effort in PV research (and surpassed the United States in module production

for the first time in 1986), and have begun to sell their modules worldwide, which has contributed to the decreasing cost of modules over the last two years. Due to South Africa's (the primary source of diesel fuel for Botswana) difficulties in obtaining oil, it is unlikely that the cost of diesel fuel in Botswana will drop greatly, in spite of the current drop in world oil prices. Also, there is often considerable lag time between changes in the world price and that which is paid by consumers. In remote rural areas, there may be no appreciable decrease whatsoever, since transportation and logistics represent an ever-increasing fraction of the cost paid by consumers there.

B. Technical Support Infrastructure Constraints

When the BRET testing program began, there was one distributor (Taurus Batteries, the local ARCO distributor) of solar modules in Botswana. Now there are several. When the program began, very few technicians had had any experience with system design, installation or troubleshooting. Only the Department of Telecommunications had given any serious attention to photovoltaics (and has since increased its use of PV dramatically; see EXPERIENCES WITH PV CLINIC AND SCHOOL ELECTRIFICATION IN BOTSWANA, R. McGowan, ARD, 1985). Now, in addition to personnel trained by the BRET project, staff from the BTC, DEE, DWA and several other private-sector groups have begun to accumulate considerable experience in the use of PV. This trend seems likely to continue.

However, to provide infrastructural support to any widespread dissemination of PV systems (whether for water pumping or remote-site power supply) throughout Botswana, significant investment in training will be necessary. These costs, as noted previously, have not been included in the financial/economic analysis since they have not been carefully examined and quantified. The actual training needs themselves have, however, been qualitatively examined (see TRAINING NEEDS ASSESSMENT FOR RENEWABLE ENERGY TECHNOLOGIES, G. Burrill, ARD, 1985). This assessment focuses on the short-term needs of the various GOB agencies that will continue to deal directly with PV applications, as well as the longer-term needs for supporting dissemination of various RETs. It was recommended that at least one graduate engineer with specific training in mechanical or electrical engineering, and experience with PV installations, would be required simply to continue the program at its present level. A solar pump installation crew and a separate maintenance crew would also be required. This would represent an installation capability of approximately 10 to 20 pumps per year at sites around the country. Maintenance training at the district level would also have to take place. Increasing the scope of government activities beyond this would require a similar increase in numbers of support technicians and engineers.

Under a similar program in Mali, technical staff have been trained and are currently maintaining more than 60 solar pumps. This program has met with considerable success.

Several manufacturers of PV-related pumping equipment (such as Mono and Jacuzzi) have already invested in South African manufacturing facilities for their PV-related equipment. Mono is in the midst of a program for the development of a new low-cost controller. As the market increases, it is likely that other entrepreneurs, as well as established companies, will find it profitable to become further involved in PV activities, and the increased competition in the field will prove favorable to consumers.

If the PV market sector continues to expand in Botswana, a significant private-sector technical support capability would be needed to insure a reliable supply of new equipment and spare parts, continuing awareness and implementation of technical advances, and constant upgrading of skill levels through training. Financial incentives for the development of this capability might include favorable import duty treatment, sales tax waivers or tax rebates where appropriate and, conceivably, outright subsidies, depending upon the magnitude of the benefits the GOB perceives in the increased dissemination of the technology. Since it is neither necessary nor desirable for the GOB to increase expenditures unnecessarily, thereby competing with the private sector, the GOB should encourage the establishment of these private-sector activities to provide support functions over time, rather than absorbing these functions into government agencies.

IX. CONCLUSIONS AND RECOMMENDATIONS

The overall comparative testing program undertaken by the BRET project had two purposes:

- to compare several typical systems of the same type (e.g., Monos and submersibles, both driven by PV); and

- to compare different types of systems (e.g., wind pumps, PV, diesel, etc.) on the basis of their technical and economic performance.

Recommendations could then be made on the best type of system for a given set of site-specific circumstances. This paper specifically addresses the first purpose as it pertains to PV pumps. The second purpose is covered in the overall pumping report, WATER PUMP FIELD TESTS IN BOTSWANA (R. McGowan and J. Hodgkin, ARD, 1986).

The two kinds of PV pumps tested were the Mono driven by surface-mounted motors, and Jacuzzi submersibles with both pump and integral motor submersed in the borehole. While additional PV pumps are being tested in the second phase of the program, only the two systems mentioned above are dealt with here. Section IX.A discusses the relative merits of each of these two types of PV pumps. Section IX.B gives the conclusions and recommendations, and Section IX.C discusses further research needs.

A. Comparative Advantages of Mono and Submersible Pumps

There are several important differences in the operation of Mono and submersible pumps which result in both advantages and disadvantages for the user. Mono pumps have proven to be very robust under the conditions of use normally encountered in Botswana. In sandy, saline, or otherwise corrosive water, Monos tend to last longer than submersibles. With the exception of the relatively high starting torque of Monos, their operating characteristics are quite favorable for some of the borehole conditions frequently encountered in Botswana, such as relatively high pumping heads and variable or uncertain water depths in some boreholes.

Monos perform well under these conditions because their efficiency is not particularly sensitive to total pumping head, as is the efficiency of submersibles. If a submersible is not carefully sized for a particular borehole, or if the actual head varies from the design head (see Section VI.A on Mahalapye), its hydraulic efficiency could drop significantly. Since the static

water level (i.e., depth from surface to water level) of boreholes can change over time, particularly under excessive drought conditions, this could be a significant limitation for submersibles.

Monos are manufactured locally in South Africa (as are some models of the Jacuzzi submersible) and Zimbabwe. As such, distribution and technical support are not generally a problem. People are familiar with the proper application and maintenance of Monos, and there is a considerable support infrastructure for marketing, distributing, installing and maintaining the pumps. Stocks of new units and spare parts are readily available in many areas of the country. Submersibles (whether PV-driven or otherwise) are just coming into use in Botswana, and as yet do not have this level of infrastructural support. The costs of developing this infrastructure have yet to be adequately quantified.

At present, the largest PV submersibles commercially available are nominal 0.75 kW pumpsets (which can deliver, for example, 25 m3/day at 25 meters head). However, permanent magnet DC motors of up to 2.2 kW are available for use with PV arrays to drive Monos, so the potential capacity of Monos is significantly greater. However, some submersible pump manufacturers (Grundfos) are currently developing five-HP (3.7 kW) units which will come on the market shortly.

Monos are more flexible than electric submersibles since they do not specifically require electric motors. For instance, several of the wind pumps tested by BRET used Mono pumps rather than reciprocating-piston pumps (of course, by far the greatest number of Mono pumps are diesel-driven). This would be a distinct advantage for use with hybrid systems, which could use a combination of PV, wind, diesel and even animal traction to drive the pump when the primary energy source was not available. For example, a wind pump driving a Mono could have a diesel backup (such as the RIIC wind pump at Mojogojogwe). The drive belt would simply be switched from the wind pump pulley to the diesel pulley during periods of low wind speed. This would not be possible with an electric submersible pump unless the mechanical shaft power from the backup unit was used to drive a generator.

Monos have surface-mounted motors which allow for ease of replacement and repair. Depending on the water quality in the borehole, surface-mounted motors, which are susceptible to vandalism (human and otherwise), may or may not last longer than down-hole motors.

Submersibles have certain advantages over Monos as well. It is much simpler to install a submersible pump because a smaller crew with fewer technical skills is required. Submersibles do not use a drive shaft or bobbins, as Monos do, so only the drop

pipe with the power cable attached must be installed in the borehole. Very straight boreholes are not necessary, as they are for Monos. The installation of a Mono in a slightly crooked borehole (not unusual in Botswana) can range from difficult to impossible. If such an installation is done, the bend in the drive shaft can accelerate wear and decrease mechancial efficiency. No drive belts, pulleys or weeping glands need be adjusted or replaced, since submersibles do not use them. Submersibles also do not require extensive concrete pads or pumphouses, nor will they blow out a discharge line if a valve is closed or a pressure relief valve defective.

Experience with submersibles in Botswana thus far indicates that they have less down time than Monos (probably due more to their diesel power plants than the pump elements themselves). When down-hole components must be replaced more frequently due to poor water quality, replacement costs for Mono shafts and bobbins are greater than simply the replacement of the drop pipe for submersibles. However, submersibles must be properly coated with corrosion-resistant materials so that their submersed motors will not wear out prematurely.

Monos (because of their relatively high starting torque) require the use of some type of controller or battery bank in the system; submersibles do not. Each of these devices has a cost in terms of power requirements, capital cost, and increased system complexity. Thus, while it is true that a submersible pump (i.e., the integral pump and motor unit) costs more than a Mono pump with a DC electric motor, the additional costs of controllers or batteries often negate this initial advantage. The recurrent costs of battery replacement can easily become a driving factor in the life-cycle costing, particularly when the batteries are not properly cared for, necessitating more frequent (and more costly) replacement.

Considerably more difficulties were xperienced with the PV-driven Mono pumps than the submersibles used in the first phase of the BRET pumping program. This was due in large part to the prototype controllers used, as well as to the fact that one of the systems was of a first-generation design, which was not well matched to the water demand and borehole constraints. As seen in the financial/economic analysis in Section VII, the best performers among the Mono and submersible systems had similar unit water costs (per m3*m), P0.11-0.12/m^3*m of water delivered. In addition, if the next generation of controllers (including the one currently under development by Mono) is as inexpensive and reliable as promised, the Monos would gain an edge (probably temporary, as larger submersibles become available). Another advantage would be the local manufacturability and subsequent repairability of those controllers.

The greatest source of dispute among the advocates of each type of pump was hydraulic efficiency. The cost of water delivery for a PV pump is inversely proportional to its hydraulic efficiency, since a more efficient pump requires fewer PV modules to deliver the same quantity of water. The BRET tests found that the efficiencies were so similar that a generalization as to whether Monos or submersible systems were more efficient was not possible. Well-designed systems, whether Mono or submersible, ran at hydraulic efficiencies of slightly more than 30 percent. While Mono pumps can run at efficiencies of up to 75 to 80 percent (according to the manufacturer's laboratory tests), this does not include the motor or other losses. While an estimate is made of the losses due to bobbin and shaft friction as well as transmission losses in the drive shaft in the manufacturer's literature, in BRET's measurements, Mono system efficiencies are quite similar to submersible system efficiencies.

B. Conclusions

The most general conclusions that can be drawn at this stage of the comparative testing program are the following:

- Small-scale, stand-alone PV pumping systems, when well designed but using only standard, commercially available equipment, have been shown in most cases to be reliable, cost-effective means of delivering water to remote (i.e., off-grid) sites in Botswana (see WATER PUMP FIELD TESTS IN BOTSWANA, R. McGowan and J. Hodgkin, ARD, 1986).

- PV pumps are becoming increasingly cost-effective compared to the alternatives as the price of power modules continues to drop. PV module prices were nearly P15/Wp at the beginning of the project, dropped to P13/Wp at the end of the first phase, and are currently being quoted at P10.5/Wp. This represents a 43 percent decrease in price over three years.

- While there are significant differences between existing Mono-coupled and submersible PV pumps, each type of pump exhibits certain advantages and disadvantages that make it an appropriate choice under certain circumstances. Although the advantages of standardization of equipment are undoubtedly significant, neither type of pump should be dismissed as inappropriate for use in Botswana at this stage of development.

- While PV pumps do not require full-time pumpers, as do many alternative systems (especially diesels),

they still require part-time attendants to keep an eye on the system and to quickly notify pump maintenance units in the event of any necessary repairs.

- For properly designed systems, the larger the system is in terms of peak watts, the lower the unit water cost, up to the size limits of available equipment.

- Careful load and component matching is critical to achieving long-term low unit water costs. Proven, robust equipment should be used, rather than unfamiliar components that promise slightly higher efficiency or lower cost.

- The BRET comparative testing program has not yet gathered sufficient data (i.e., annual results on a monthly basis for each of the systems tested) to make definitive long-term conclusions about the long-term costs of PV pumps. This information will evolve out of the extension of the project. However, extrapolations from the data gathered thus far have confirmed other researchers' conclusions that PV pumps show considerable potential under existing pricing structures and should be deployed where technical (less than 50 meters' head, with water demand less than 40 m^3/day) and institutional conditions (a certain minimal level of technical infrastructural support) permit.

C. Recommendations

The following recommendations are made to give some specific direction to the PV component of the comparative pump testing program. They are:

- Continue to gather long-term data on the pumps currently being tested. This will yield much more reliable information on long-term costs, reliability and water availability, and make the technical performance results more statistically significant.

- Expand the range of equipment tested to include smaller-demand Mono systems, as well as other types of submersible pumps such as the Grundfos.

- Correlate the solar radiation data being gathered at the pump sites with the solar radiation data being gathered at the three Meteorological Services sites in Botswana, where more accurate instrumentation is being used.

- Examine more closely the costs of developing an infrastructural support network to design, procure, install, operate and maintain PV pumping systems, and incorporate these costs in the financial/ economic comparisons of unit water cost.

- Review DWA borehole records to determine the location and number of sites that might be appropriate for installation of PV pumps (i.e., sites where static heads are less than 50 meters, and where demand is less than 40 m^3/day). The number would give an indication of the size of the potential market for PV pumps in Botswana.

Specific technical recommendations for system designers and users include the following:

- Complexity should be avoided where possible in system design. If not strictly required, electronic tracking devices should not be used (i.e., with submersibles). Where necessary (i.e., with standard Mono pumps), electronic controllers (such as CVTs or MPPTs--see Section III.B.4) rather than batteries should be used to meet high starting torque requirements. Batteries are also the system component most susceptible to theft.

- If it is necessary to use batteries for energy storage (e.g., for slow pumping of low-yield boreholes), be sure that proper battery maintenance procedures are followed to minimize the need for frequent (and costly) battery replacement.

- Be sure to install pressure relief valves on all Mono systems, as well as thermal overload protection on the motors.

- All systems should include low-water disconnect devices to insure that the pump will be protected should the water level fall below the pump.

D. Further Research Needs

The BRET compartive testing program for PV pumps, while adding significantly to the increasing body of knowledge about the field performance of this promising technology, was not an exhaustive study of the existing range of photovoltaic pumps. Manufacturers' research is continually yielding new refinements on equipment to reflect the results of field tests such as those conducted by BRET. These refinements tend to decrease equipment cost, while increasing component and overall system efficiency

and reliability. Long-term field-testing yields information on the most elusive equipment operating characteristics--reliability and long-term operation, maintenance and repair costs--which can so dramatically affect life-cycle costs. As mentioned previously, widespread dissemination of this technology is dependent upon creation of the necessary technical support infrastructure. To refine life-cycle cost input parameters, detailed cost estimates for the training of skilled technicians must be determined. While these training needs have been ascertained, their costs remain to be adequately quantified.

RET-driven pumps normally have seasonally dependent variations in their power supplies. PV pumps are no exception. While design tools (see Appendix C) have been developed which can aid system designers in estimating the output of PV pumps during each month of the year, these are by necessity merely estimates. The water output of solar pumps is directly proportional to the amount of solar radiation incident upon the array. As yet, reliable, long-term solar radiation data have not been collected for most of Botswana. This program's data collection effort has added to the data base required for accurate predictions of pump output. The BRET-funded Meteorological Services solar radiation monitoring equipment will add significantly to this effort. However, these studies are only beginning.

Year-round monitoring of solar pumps is necessary to validate design tools. Fortunately, the extension of the BRET comparative testing program will allow annual data to be collected on a larger number of systems, resulting in more comprehensive and reliable design tools. The extension will also provide more reliable data on the long-term operation and maintenance costs that can so critically effect the life-cycle cost of a pumping system.

Water storage requirements, and the differences between the magnitude of these requirements for different types of pumps (diesel, wind, PV), were not addressed in this study. Since the cost of storage can significantly affect overall system cost, this should be examined in detail in further studies. Since diesel pumps can deliver water on demand (if fuel is available, and if the diesel works), diesels would presumably require less storage than PV pumps. However, the solar resource in Botswana is so uniform that it has not been found necessary to have included more than one day of storage in the systems installed thus far. Since the output of these systems was usually more than adequate for the water demands of the sites, storage was not a critical issue. In countries where solar radiation levels are neither so high nor so uniform, the costs of increased storage would be more of a concern. The storage issue remains largely unexamined.

In addition to these general needs for further research on the technical and economic performance of solar pumps, there are several pieces of information that could be collected by DWA which would prove very useful in both the use and evaluation of PV and other pumps. Improved data on borehole characteristics would be of particular benefit in the sizing of submersible pumps, given that their performance is so dependent upon the pumping head. In the BRET program, borehole yields were frequently found to be considerably less than specified in the drilling records, resulting in installation of pumps that were intially oversized for the borehole. It would be desirable (but expensive) to test-pump boreholes before installation of pumps, particularly if considerable time has elapsed since the initial drilling.

This study has attempted to incorporate the field research methodologies used by other researchers, and to improve upon those methodologies so that all these studies, when put into a common analytical format such as that presented here, will allow for easy comparison among their technical and economic conclusions. A common methodology and format for presentation of results would be very useful for the integration of all this information, and would make it accessible to decision makers of different backgrounds, whether economists, engineers or administrators. The development of a comprehensive testing methodology for water pumps of most common types has been funded by several donor agencies, and the methodology is coauthored by the authors of this paper. It will be available in mid-1986.

Field research programs in small-scale PV pumping are underway in several other countries. Economic and technical performance comparisons of diesel, wind and PV systems is going on in Africa, Southeast Asia, India and Central America. The World Bank has also funded extensive laboratory and field-testing programs for hand pumps, the preliminary results of which are now available. As the results and conclusions of this research become available, engineers, economists and water resources specialists will have a much larger data base from which to make decisions about allocations of inherently limited financial resources for development of rural water supplies. Photovoltaics can play an important role in this development. Government policy decisions that carefully weigh the advantages and disadvantages associated with the range of available pumping technologies, and take into account the true costs to the national economy associated with the use of each, will determine the magnitude of that role.

APPENDIX A

Detailed Costs Breakdowns for PV Systems

The following section describes in detail the rationale for assigning costs to each line item of the financial/economic analysis given on the spread-sheets in Section VII.B. Since there are two major types of costs (initial capital equipment and installation costs, and all recurrent operating, maintenance and repair costs), they are divided into two sections below.

Capital Equipment and Installation Costs

In calculating the costs for these PV pumps, every effort has been made to reflect the actual costs on a site-specific basis. The costs include all the necessary hardware to pump water at the site in question. Also included are such aboveground components as water meters, non-return valves and gate valves so that with the connection of piping to storage or reticulation system, the entire water delivery system would be complete. Except as noted, storage and reticulation systems are not included. Borehole drilling and well preparation are not included. This is because these costs do not vary when different pumping systems are used.

The cost of the array includes the costs of ARCO Solar M-53 modules used on all the BRET installations. It also includes the costs of manufacturer-supplied interconnects and support structures. In all cases, the current prices for these components as supplied by the Gaborone dealer (Taraus Batteries) were used. These prices seem to compare favorably with the international market prices at this time.

The pump/motor category includes the costs of the pump, motor, and gearboxes or belt/pulley units used to connect them. These are an integal unit in the submersible systems. For the Mono-coupled systems, this figure includes the cost of the motor, Mono pump and discharge head.

Piping is broken down into two categories, aboveground and below-ground. Below-ground piping costs are fixed by the required pump installation depth, which is directly related to the borehole rest water level and draw down. Below-ground components also corrode much more quickly than those aboveground; therefore, they must be replaced more frequently than the rest of the piping system. In the Mono-coupled cases, the Mono drive head (gearbox) is included in the aboveground components. The "other" category includes the costs of wiring (including submersible pump wire as appropriate), ground rods, switch boxes, switches, and circuit breakers or fuses as necessary.

The "other" category also includes all other capital costs not contained elsewhere, such as the cost of cement, crushed stone and sand to make the array support foundation, as well as reinforcing steel, foundation bolts, and borehole clamps. Since fencing is an integral part of a complete PV pumping system, and it is not an insignificant cost, it is broken out separately.

The standard DWA construction crew consists of six to 10 people, plus a driver and driver's assistant. The crew generally camps at the construction site on installation jobs and gets a per diem allowance in addition to regular pay. The crew that was available to the BRET project was a very capable crew of eight and a driver and helper. The cost of keeping this crew in the field is P140 per day, of which approximately 40 percent is wages and the rest the allowance. The crew comes supplied with a seven-ton truck. Since the crew was not initially familiar with the installation procedure for submersible pumps (even though it is simple compared to that for Mono pumps), a learning curve was involved. The second installation was much faster than the first, and the third faster than the second. Thus, the installation times assigned to each site are to some degree an estimated average, since the authors do not wish to bias the results by including the costs of the initial installation of a new and unfamiliar system. These costs are believed to be realistic when compared to diesel system installation costs as experienced by similar construction crews in Botswana.

Transport costs are calculated by the kilometer at different rates depending on the type of vehicle used. During installation, a seven-ton truck is used. This truck is used to ferry supplies to the site, carry the crew and its camping equipment, and haul stone and sand as required. In each case, the mileage includes a round trip from Gaborone to the site and a round trip from the nearest stone crusher to the site.

Recurrent Costs

Given that the comparative testing program has yet to run long enough for any normal major repairs to have become necessary, and that it is, by nature, a testing program, the true long-term operation and maintenance requirements have not yet been definitively established. Because of the data collection needs, the number of visits to each of the test sites has been far in excess of those required for smooth operation of the pumps. Manufacturers' claims for the lifetimes of these pumps is far in excess of the actual operation time of any of the pumps thus far. Therefore, it has been necessary to estimate the recurrent cost schedules, based on experience to date in Botswana.

The base-case assumption is that DWA will be the primary purchaser of these pumps, and that they would be installed as part of the village water supply program. This means that the installation would be done by DWA, and all recurrent costs would be born by the District Councils and their respective Water Maintenance Units or Water Departments. All transport costs are calculated from the location of the Water Maintenance Unit responsible for the pump to the actual site.

The recurrent costs have been broken down into several broad categories. The first of these is annual recurrent costs, which includes site visits for inspection, replacement of drive belts as necessary, and other related work done on an annual basis. Two site visits per year by a crew of two in a four-wheel-drive vehicle are planned. This vehicle was chosen because it is what is normally used for this type of activity at the council level. Two people would normally go on such light maintenance or inspection trips. The major question was how many such trips to include in a given year. The Water Maintenance Units are responsible for 20 to 70 boreholes and pumps each. It appears that each diesel pump site is visited between one and four times a month depending on location. These visits are often part of a tour of several sites that includes major work at one of them. Thus, it was considered reasonable to charge two trips per year to PV pump maintenance, although sites are likely to be visited more often.

The other major annual recurrent cost is that of a pumper. One of the advantages of photovoltaic pumping installations is that they can be operated without an attandent. However, for village systems, a pumper performs other tasks, such as taking care of the storage tanks and the piping system, keeping records and reporting any problems to the Water Unit. DWA feels that someone must be responsible at the local level for the system's operation. Therefore, for the base-case condition, a pumper is assumed to be required one day a week, at a rate of six pula per day. Financial and economic viability seems to be strongly affected by the use of pumpers. A sensitivity study examining this assumption is included in ARD's report, WATER PUMP FIELD TESTS IN BOTSWANA (R. McGowan and J. Hodgkin, 1986).

At five years, it was assumed that most below-ground piping components would be replaced. This figure will vary widely with water quality, borehole alignment (especially with Mono pumps) and depth. Although there are scant records of the time elapsed between replacements, a five-year replacement period seems reasonable. It was assumed that all piping and, in the case of Mono pumps, all bobbins and half of the shafts, would need replacing. This assumption will make little difference except to bias the results toward submersibles if the replacement period is too short, or towards Monos if the period is too long.

Also at the five-year mark, any batteries used in the systems would have to be replaced. However, one five-year expense that applies to all of these systems module replacement, based on a controversial assumption that there will be some module breakage. Based on experience thus far, a reasonable assumption is that the replacement of two modules every five years for 30- to 40-module arrays and one module every five years for arrays of fewer than 20 modules will be required.

DC electric submersible motor brushes are expected to last from 5,000 to 10,000 hours according to the manufacturers. At this point, having little else to go on, it is assumed that the motor itself has a lifetime of about 25,000 hours or seven years at six hours run time per day. The same assumption was made about surface-mounted DC motors.

It was assumed that the controllers, whether battery charge controllers or other power conditioning units, would be replaced at 10-year intervals. Except for breakage, the lifetime of the PV modules was placed at 20 years. This is based on numerous accelerated testing programs conducted by manufacturers, and reinforced by the fact that manufacturers are now giving module warranties based on a reduction of module power output of less than 10 percent over 10 years. The Mono pumps themselves were assumed also to last the full assumed 20-year system lifetime. At the end of 20 years, it was assumed that the modules would have a salvage value of 25 pula each, and the rest of the system would be scrap.

APPENDIX B

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APPENDIX C

Sizing Algorithm for Solar Pumps

There are a variety of methods used to size solar pumps, ranging from the simple to the sublime. The principal difficulty in the sizing of solar pumps is the general lack of good site-specific data on the magnitude of monthly average long-term solar radiation levels. In conjunction with adequate information on the year-round changes in well rest level and yield, this information is critical to a successful design.

PV systems, because of their modularity, are somewhat forgiving of underestimates of power requirements, since additional panels (groups of modules in series or parallel) can be added after initial system installation if the water output does not meet design specifications. However, if the output is overestimated, the unnecessary modules included in the initial purchase are a non-recoverable sunk cost, supplying water over and above the requirements specified by the purchaser. It is, therefore, useful to have as close an approximation as possible on what output can be expected before the system is actually purchased.

Computer sizing algorithms have been developed by most of the major PV module manufacturers as engineering support services for their distributors. When a customer approaches the distributor for a bid on a particular job, the distributor simply relays the information on well yield, pumping head, water supply requirements, and local radiation levels (if available) to the company. The system is then sized, specifying a certain number of modules wired in parallel and series, a motor and pump, various control options, and a prediction of water output by month for that site. Since most of these programs are proprietary, representing many hours of research and development, PV manufacturers are loath to distribute them to the general public. However, the design depth of detail provided by such programs is not necessary for most systems. In lieu of using these programs, simpler sizing algorithms have been developed by a variety of designers. One of these is described in detail in the Handbook on Solar Water Pumping (Sir William Halcrow and Partners and IT Power Ltd., 1984, henceforth referred to as "the Handbook"). Since even this level of calculation becomes tediously repetitive, the algorithm was written in spread-sheet form for convenience in the multiple system designs for the BRET project. An example using this algorithm is given in Table 4 in the body of this report.

This design tool incorporates additional features from the algorithm described in the Handbook. It is intended to be used by a person somewhat familiar with available PV equipment, and

requires the possession of reasonably accurate manufacturers' pump and motor output and efficiency curves, as well as some idea of the monthly solar radiation levels, fluctuations in well yield and depth, and the water demand for the particular site.

With that information at hand, the system design process proceeds as follows. Refer to Table 4 and follow along.

1. Fill in the second column (Water Vol.) with the monthly average daily water requirement. The third column is the static head, the fourth the dynamic head losses (insert a first estimate, or leave this blank for the time being, until the flowrate is calculated later on). These are then added together to get the total pumping head in the fourth column. The fifth column calculates the daily hydraulic energy demand from these preliminary data, using the formula:

$$\text{Hydraulic Energy (MJ)} = \frac{9.81 \times \text{head(m)} \times \text{volume (m3)}}{1000}$$

This formula only calculates the theoretical hydraulic energy demand necessary to pump the amount of water you specified through the given head. However, pump sets operate at less than 100 percent efficiency. Therefore, this number has to be divided by the pump subsystem efficiency to give the actual electrical energy demand.

2. From the Handbook, follow the procedure for determining the solar radiation on the array at the tilt angle chosen. This will entail filling in the columns on extraterrestrial radiation at your latitude, the clearness index (a measure of how much solar radiation actually gets to the ground at your site, having been attenuated by clouds, smog, etc.). The tilt factor is a geometric conversion of the radiation on the horizontal plane to the plane of the array at a certain tilt angle above the horizontal.

3. The tilt angle, for most purposes, should be approximately equal to the latitude of the site. This should be adjusted to maximize water pumped during peak demand periods, such as for irrigation needs, if applicable. This procedure is adequately explained in the Handbook and will not be repeated here. However, if actual measured radiation data are available for your site (or nearby), compare it with the estimates given by the Handbook procedure and adjust your results accordingly. Since the solar radiation maps given in the Handbook are estimates at best, any local data would likely significantly improve its accuracy by taking into account the local microclimate.

4. The column labeled "Max D/S Ratio" calculates the ratio of hydraulic energy demand (D) to solar radiation supply (S) for each month of the year, and then picks the month with the highest ratio (the "Max Ratio" below the column). This fixes the critical design month, which is the month where the hydraulic energy demand is greatest in comparison to the solar energy available. A macro command then picks off the name of the design month, total pumping head, hydraulic energy requirement, and global radiation on the plane of the array, and writes that information in the "DESIGN MONTH PARAMETERS" section.

5. Now look at the "SPECIFIED COMPONENTS" section. Tentative components (or their probable efficiencies at least) must be written in under "Rated Efficiency". If you are uncertain at this point about what to use, tentatively use a motor efficiency of 70 percent, and a pump efficiency of 50 percent. As you narrow the range of possibilities to actual pumps and motors to consider, replace these efficiencies with those from the manufacturers' performance curves.

6. If the system will have batteries, a common battery energy efficiency (watt hours out divided by watt hours in) is about 75 percent. However, you must be careful about using this algorithm to size battery systems, because the actual operation of the real system is probably such that the pump gets power directly from the array during much of the pumping day. This means that not all of the energy input will be derated by first having to be stored in the batteries. The spread-sheet will take these efficiencies and calculate the parameters listed in the "EQUIPMENT SIZING" section, which are the daily electrical energy requirement, minimum array size to supply this energy, etc.

7. From this information, the program will calculate the water pumped in the "Min. Output" column in the upper right hand corner of the spread-sheet. The array output is derated by several factors: the cell operating temperature, an assumed impedance mismatch loss of 10 percent, and an assumed difference between peak power efficiency and overall energy efficiency (the average subsystem operating efficiency over the day). The subsystem energy efficiency has been assumed to be 10 percent less than the peak power efficiency, but actual test results indicate that is, in fact, 15 to 20 percent less than the peak power efficiency. Remember, it is better to be conservative in your estimate of pump output. The "Min. Output" is calculated as follows:

$$m3/day = \frac{Wp \times N(sub) \times H(a) \times F(m) \times (1-.005(Tcell-25))}{9.81 \times h}$$

where: m3/day is the daily water output,

Wp is the peak watt rating of the array,

N(sub) is the subsystem energy efficiency,

H(a) is the total radiation incident on the array over the day in MJ/m2-day,

F(m) is the impedance mismatching factor (0.9),

Tcell is the actual operating temperature of the cell used to derate the cell output from its rated capacity (at 25C),

9.81 is the gravitational constant, and

h is the total pumping head, including elevation head, pipe friction losses, and velocity head in meters.

8. The "Min. Output" is the first step in an iterative process to focus in on the equipment you really need. It assumes an array of the minimum size necessary to meet the hydraulic energy requirement calculated previously. However, this does not reflect real equipment sizes and availability. For instance, a 371 Wp peak array does not exist. To begin the iterative choice of real equipment, pick an integral number of the type of modules you are planning on using (among the most common module peak watt ratings: ARCO M-53's are 43 Wp, Solarex SX-146's are 46 Wp) and insert the Wp rating of your possible array into the "Actual Array Size" PV Array Size cell. The program will then derate the module output (10 percent for impedance mismatching, and an additional derating for temperature compensation based on the specified nominal cell operating temperature), calculate a peak flow rate, and calculate the average daily outputs for each of the months. Make sure that the peak flow rate does not exceed the well yield. Use the peak flow rate to estimate the dynamic pumping head in the proposed system, and enter that dynamic head in column four. Revise this as you iterate.

9. Now, to narrow down the motor possibilities, pick a motor and pump that will accept the derated peak power output of the array (i.e., a 1/2-HP motor is rated for continuous duty at 746/2, or 373 Watts). Make sure that the motor you pick has a rated input power capacity that is at least as high as the "Derated Motor Power." This is about the maximum power the array will deliver to the motor at any given point. Normally motors have a load factor of about 1.2, meaning that they can take 20 percent more than their

rated capacity for short periods of time during operation (i.e., not continuous). Be sure that this is not exceeded in your design. Put in the actual motor and pump efficiencies from the manufacturers' pump and motor curves.

10. Check the motor's running amps and voltage requirements. The modules in the array must be wired in series to get the motor's required voltage. For instance, ARCO M-53's are considered to have an average voltage output of 15 volts under normal operating conditions. Therefore, you will have to wire six modules in series to get 90 volts, if that is what the motor wants to see. In order to make up the array, these six-module, 90-volt strings will then be wired in parallel until the required peak power requirement ("PV Array Size") is reached. The new number for the "PV Array Size" is the number of modules required by the motor voltage and amperage requirements, times the rated peak watts per module. Review the peak and monthly water volumes calculated in the spread sheet to see how they fit the site constraints and demand.

11. Continue this iterative process to see what effects are produced by using different pumps, motors, or array wiring combinations. Vary the cell operating temperature to reflect the ambient air temperature during pump operation. A formula for estimating the cell operating temperature is:

T(cell) = Radiation on array (MJ) * 0.75 + T(ambient)

12. It is wise to always be conservative in your estimates of efficiency for all components. Most manufacturers' curves give data under laboratory conditions reflecting the most favorable operating circumstances for their equipment. Since PV pumps do not normally operate under constant voltage and amperage conditions, the average subsystem energy efficiency is less than the peak power efficiency. The design month parameters reflect this by derating the energy efficiency by 10 percent. Also, dust, high cell temperatures, vandalized modules, voltage losses (which can be calculated by the spread-sheet if you know the approximate wire runs and sizes) in the wiring down to the pump (if a submersible is used), and deteriorated batteries will all reduce the output of the system. Do not overestimate the output of the pump by being overly optimistic. The choice of equipment should be based on cost, performance, ease of installation and maintenance, and frequency of expected repairs. Keep in mind the advantages and disadvantages of each type of pump set before making your final decision.

APPENDIX D

Detailed System Descriptions

Photovoltaic Pump Installations of the BRET Project

SITE:	MAHALAPYE
DISTRICT:	CENTRAL
B.H. NO.:	NONE, DUG WELL
TOTAL HEAD:	7 METERS
WATER USE:	COOP GARDEN
ARRAY SIZE:	12 PANELS
ARRAY OUTPUT:	516 WATTS PEAK
PUMP TYPE:	JACUZZI SUBMERSIBLE Model XP-3
MOTOR TYPE:	JACUZZI DC Model S4
CONTROLLER	CONSTANT VOLTAGE TRACKER
SYSTEM COST:	12,021 PULA

SITE:	MMATHUBUDUKWANE
DISTRICT:	KGATLENG
B.H. NO.:	977
TOTAL HEAD:	45 METERS
WATER USE:	AUGMENT VILLAGE SUPPLY
ARRAY SIZE:	36 PANELS
ARRAY OUTPUT:	1548 WATTS PEAK
PUMP TYPE:	MONO, ES-10
MOTOR TYPE:	HONEYWELL 1.5 HP DC
CONTROLLER:	CONSTANT VOLTAGE TRACKER
SYSTEM COST:	28,000 PULA (EST.)

SITE:	MOLAPOWABAJANG
DISTRICT:	SOUTHERN
B.H. NO.:	3327
TOTAL HEAD:	23 METERS
WATER USE:	VILLAGE SUPPLY
ARRAY SIZE:	32 PANELS
ARRAY OUTPUT:	1376 WATTS PEAK
PUMP TYPE:	JACUZZI SUBMERSIBLE Model E7
MOTOR TYPE:	JACUZZI DC Model SJ-1
CONTROLLER:	N/A
SYSTEM COST:	23,087 PULA

SITE:	MOTHEBE(MOCHUDI)
DISTRICT:	KGATLENG
B.H. NO.:	4234
TOTAL HEAD:	38 METERS
WATER USE:	COOP GARDEN (INTENDED)
ARRAY SIZE:	32 PANELS
ARRAY OUTPUT:	1376 WATTS PEAK
PUMP TYPE:	JACUZZI SUBMERSIBLE Model E7
MOTOR TYPE:	JACUZZI DC Model SJ-1
CONTROLLER:	N/A
SYSTEM COST:	23,229 PULA

SITE:	OTSE
DISTRICT:	SOUTH-EAST
B.H. NO.:	1233
TOTAL HEAD:	7 METERS
WATER USE:	COOP GARDEN
ARRAY SIZE:	8 PANELS
ARRAY OUTPUT:	250 WATTS PEAK
PUMP TYPE:	MOYNO, 1V12
MOTOR TYPE:	HONEYWELL, .5 HP, 24 V
CONTROLLER:	REGULATOR AND BATTERIES
SYSTEM COST:	8976 PULA (Replacement cost)

Proposed Photovoltaic Installations of the BRET Project

SITE:	MARAPONG
DISTRICT:	CENTRAL, TUTUME SUB.
B.H. NO.:	3906
TOTAL LIFT:	76 METERS
ARRAY SIZE:	48 PANELS
ARRAY OUTPUT:	2.1 KW PEAK
PUMP TYPE:	MONO ES-4
MOTOR TYPE:	D.C.
CONTROLLER	24 HRS/DAY W/ 18 BATTERIES
SYSTEM COST:	68,000 PULA (EST)
EXPECTED OUTPUT:	14 CUBIC METERS PER DAY
SITE:	MMADIKOLA
DISTRICT:	CENTRAL, BOTETI SUB.
B.H. NO.:	4673
TOTAL LIFT:	50 METERS
ARRAY SIZE:	35 PANELS
ARRAY OUTPUT:	1.5 KW PEAK
PUMP TYPE:	A.C. SUBMERSIBLE W/INVERTER
MOTOR TYPE:	GRUNDFOS SP2-18/35
CONTROLLER:	NONE
SYSTEM COST:	35,000 PULA (EST)
EXPECTED OUTPUT:	20 CUBIC METERS PER DAY
SITE:	MOOKANE KHUMALO
DISTRICT:	CENTRAL, MAHALAPYE SUB.
B.H. NO.:	2343
TOTAL LIFT:	30 METERS
ARRAY SIZE:	12 PANELS
ARRAY OUTPUT:	.5 KW PEAK
PUMP TYPE:	MONO ES-109
MOTOR TYPE:	D.C.
CONTROLLER:	6 BATTERIES
SYSTEM COST:	18,000 PULA (EST.)
EXPECTED OUTPUT:	13 CUBIC METERS PER DAY
SITE:	MONAGALWANA
DISTRICT:	KWENENG
B.H. NO.:	[illegible]
TOTAL LIFT:	50 METERS
ARRAY SIZE:	14 PANELS
ARRAY OUTPUT:	.60 KW PEAK
PUMP TYPE:	A.C. SUBMERSIBLE W/INVERTER
MOTOR TYPE:	GRUNDFOS SP1-18
CONTROLLER:	NONE
SYSTEM COST:	23,000 PULA (EST)
EXPECTED OUTPUT:	5 CUBIC METERS PER DAY