COMPARATIVE TESTING FOR WATER-PUMPING SYSTEMS INSTALLED IN BOTSWANA

General Research Methodology and Specific Field Implementation Instructions

Prepared by:

Richard McGowan and John Ashworth
Associates in Rural Development, Inc.
362 Main Street
Burlington, VT 05401
(under USAID contract number 633-0209-C-00-1-24-00)

Date: July 9, 1984

CONTENTS

PREFACE

The Botswana Renewable Energy Technology (BRET) project is jointly funded by the Government of Botswana (GOB) and the U.S. Agency for International Development (AID). The BRET project is a part of the Ministry of Mineral Resources and Water Affairs (MMRWA). Technical assistance and project management are being provided by Associates in Rural Development, Inc. (ARD), of Burlington, Vermont, under AID contract number 633-0209-C-00-1024-00.

Mr. Richard McGowan and Dr. John Ashworth developed the conceptual design and specific data items for this paper as part of ongoing consultancies to the BRET project for the collection of field data on the economic and technical performance of a number of renewable energy technologies (RETs).

Our thanks to Margaretha Wilcke and Laurie Gee for the preparation of the final manuscript, as well as to Modise Motshoge and Mmasekgoa Masire, who read and critiqued earlier versions of the data collection sheets. Thanks also go to Mr. Peter Hawken of the Canadian National Research Council, who provided a thorough technical critique of the paper.

1.0 INTRODUCTION

1.1 Background

During the first two years of the BRET project, a number of major energy needs were defined through the use of village-level surveys and by holding discussions with major energy-using institutions. Data were also collected on the availability of indigenous renewable resources to provide power or fuel to meet the needs that were deemed to be highest priority. Among the institutional energy needs, water pumping was clearly among the most significant for villagers and GOB officials alike. In a country with an average rainfall of only 400-700 mm/year (and below-average rainfall for the past several years), clean drinking water for the local population and their herds is a constant and pressing need.

Many of the villages of Botswana are not connected to the national electric grid. Therefore, power for water pumping is provided by small, stand-alone power generators normally powered by diesel fuel. At the request of the MMRWA, the BRET project has undertaken the selection and field testing of various non-fossil fuel power sources which could conceivably displace diesel engines for water pumping in remote sites. While most of BRET's attention and resources will be directed toward the field testing and monitoring of pumping systems powered by wind-energy systems and photovoltaic (PV) arrays, an effort will be made to monitor existing or planned installations powered by animals, by human traction, by hand and by anaerobic digestors (coupled to a modified diesel engine to burn the resulting biogas). To provide the baseline against which these alternative pumping strategies will be tested, BRET and MMRWA will also closely monitor the cost and performance of a number of small diesel pumpsets.

It is important that the reader keep in mind two basic facts about the comparative water-pumping testing methodology described in the following report. First, it is part of a long-range technology-delivery process being implemented in Botswana by ARD and the BRET staff. The water-pumping systems being tested in 1984 and 1985 are those that remain from a multi-year, needs-driven technology selection program begun in 1982. The basic size and performance of the pumps were based on the measured water needs of sample villages. Water has to be available at certain times and during certain seasons, determined by the consumption habits of the local population and their livestock. Technologies which did not meet these needs-based requirements were dropped from consideration.

The local energy resource base for each alternative technology was also examined to determine if it could provide the energy needed with only a modest amount of water storage. Other technologies were dropped from consideration at this point as not

being appropriate to Botswana's resource base. The comparative testing methodology will carry this winnowing of technological alternatives one step further. It will indicate those energy systems which are not only technically feasible but also cost effective, reliable, durable and easily maintained in the field.

Second, the comparative testing methodology outlined in this report is designed to provide information to government decision makers who are interested in the delivery of water, and not necessarily interested in the intimate details of the technical performance of the energy systems themselves. Based on discussion with MMRWA and AID staff, as well as on previous discussions with decision makers in a variety of government and donor agencies, ARD has designed this comparative testing methodology to answer their information needs first, followed by the information requirements of the renewable energy firms and energy technology research community. Therefore, the major emphasis will be on condensing the information collected to a small number of comparable benefits and costs, as well as providing detailed information on operating problems, maintenance requirements and the training required to operate and maintain the systems. Emphasis will not be placed upon questions of energy conversion efficiencies, performance losses due to elevated ambient temperatures, etc. (although these problems will be addressed), but rather on how much water is produced, at what cost, and with what reliability.

1.2 Experimental Objectives

1.2.1 Statement of the Problem

At many sites in Botswana which do not have access to electric power from the grid, diesel engines drive Mono positive displacement (progressive-cavity type) pumps to provide water. Because of the expense and considerable downtime associated with these diesel engines, alternative pumping methods will be examined to determine their respective reliability and cost.

The most important criterion in choosing a water supply system is its reliability in insuring some minimally acceptable level of availability of water. If it does not meet this criterion, then its cost is irrelevant. Reliability is a function of the frequency of breakdowns, the frequency of necessary maintenance, the availability of spare parts, and the technical expertise required to keep the system in proper operating condition. The second most important criterion is cost. A complete economic analysis incorporates the costs associated with each of the above requirements, as well as the initial capital cost and recurrent operating costs (such as fuel), and compares alternatives capable of meeting similar needs based on a life-cycle costing technique. This and other economic figures of merit will be examined in detail below.

1.2.2 Purpose of the Experiment

In order to determine which of the water-pumping devices available are most appropriate for use in Botswana, each alternative's technical performance must be examined as a function of reliability and cost. The purpose of this comparative testing program is to determine the performance of several representative types of windmills and solar photovoltaic pumps, and compare their performance characteristics with several similarly sized diesel pump sets. Pump performance will be characterized by output curves which give water pumped as a function of total pumping head (see Section 3.2.1 below) and the strength of the resource base (e.g., wind regime or solar insolation level). The systems as a whole will be characterized by detailed information on expected maintenance and unexpected downtime due to breakdowns, ease of installation, maintenance and repairs (if any), and the costs associated with each, based on actual operating conditions in Botswana. In addition, any training required for technicians to adequately install and operate these systems will be documented.

1.2.3 Experimental Hypothesis

The hypothesis of this experiment is that, in many situations, at least one of the alternative pumping systems being tested will prove to be a cheaper and more reliable method of meeting village water supply requirements than conventional diesel-powered pumps. The information generated from the experiment will allow decision makers to choose the most appropriate system for the site under consideration, based on some knowledge of the renewable energy resources available on site. Combined with data being collected by Meteorological (MET) Services in Botswana, both through the existing and expanding anemometry program, and the solar radiation data collection program now in the procurement phase, Department of Water Affairs (DWA) engineers and technicians will be able to determine whether a PV pump, a windmill, or any of the other alternatives available in Botswana is the most reasonable choice for a given site.

1.3 Principles of Comparative Testing

The following are general guidelines for the use of BRET and MMRWA staff on what to look for when selecting energy systems and sites for a comparative testing program. In the detailed description of the experiment given later in this report, specific guidelines for water-pump testing and well selection will be given. It should be recognized, at the start, that certain of these principles will be difficult to follow entirely, because of a scarcity of funds and a relative paucity of pumping systems available for monitoring. Nevertheless, it is important to keep the following rules in mind at all times in order to maximize the usefulness of the information collected to MMRWA and AID decision makers.

Rule 1: Select systems that have approximately equal annual output.

In comparative testing, there is only limited value in comparing systems of greatly dissimilar size. They have different performance characteristics, different maintenance needs and different capabilities to affect the development process as a whole. Water-pumping systems that can service same- or similar-sized communities should be selected. A windmill that is capable of pumping 9000 cubic meters per year (or an average of 25 cubic meters per day) at a particular site should be matched with a diesel or PV system of similar output capacity. While this will have to be compromised in practice (certain systems such as hand pumps or human traction pumps have only very limited output capability under the best of conditions), output comparability should be a major consideration in the selection of systems. If there are major differences in output among the systems selected, then, for purposes of analysis, they should be divided into separate categories based on output range. Comparisons should only be made within these categories.

Rule 2: Allow all systems to perform at maximum output.

A common error in comparative testing procedures is to unintentionally constrain one or more systems, so that their measured output is less than what it might have been. This has the effect of making these systems appear to be more costly per unit of output than they really are. In some cases, systems are installed at locations where there is little or no demand for their output. They are then required to perform only to meet this limited demand. For example, a lighting system at a clinic may only be operated one evening a week. Those hours of operation are all that is recorded as system output, even though the energy system is capable of providing lighting six hours a night, seven days a week.

It is important that the comparative testing procedure be designed so that all systems operate where there is a sufficient energy resource available to drive the system, even if it means dumping excess output. When the wind is blowing above the windmill's cut-in speed, the wind water pumper should be pumping even if the storage tank is already full. This is the only way to get accurate data on the system's capability.

Rule 3: Do not allow site limitations to constrain system output.

A corrolary to the principle explained above is that the testing procedure should be structured so that inadequacies of the testing site do not have an adverse impact on the system performance. If there are obstructions at a well site that reduce windflow to a windmill, they should be removed (or a higher tower installed), so that the true measure of the system potential can be taken. One common problem with water-pumping system tests is that the underlying aquifer may have a low recharge rate, which can limit the amount of water that can be taken from the well each hour. If this is so, then an aquifer recharge system will have to be built into the well for the purposes of the test. This is so that energy system can pump at its maximum possible rate, but then return part of the flow to the well to avoid excessive draining of the well. This will then measure the true performance potential of the pumping system, rather than the well yield.

Rule 4: Monitor all systems for the same performance information.

When doing a comparative testing program, it is crucial that information for all units be collected in the same way. The same data should be collected for each system, at the same time intervals, preferably using the same type of data-acquisition system. If water flowrates for one water-pumping system are collected on a monthly basis, then this should be done for the other systems being tested as well. Also, remember that the precision of the total comparative testing program is determined by the level of the least precise monitoring system. It makes little sense to use sophisticated computer-based monitoring devices for the performance testing of PV water-pumping systems, if the wind energy availability of a another site is made by simply asking local residents what their estimation of average annual windspeed is.

1.4 Training Workshops

This report contains the essential reference material for project technicians and data analysts who will be working on the comparative testing program. While this report should not be construed to be a stand-alone reference on the physical principles of windmills, photovoltaic and diesel pumping systems, it does address the basic considerations with which system designers of RET-based pumping systems should be familiar. Readers with other than engineering backgrounds need not concern themselves with the engineering sections of this report, but should consider these sections as background for the more important, comparative economic sections which are sketched in this report and given in more detail elsewhere (see Ref.7).

The engineering, technical and economic principles mentioned here will be discussed in detail at a series of workshops to be given in Botswana both for persons directly involved in the comparative testing program as well as for those interested in certain general aspects of it. These workshops will range from specific hands-on training for instrument installation for technicians, to discussions with Ministry and other interested persons focusing on the analytical methodology and goals of the program; in particular, the potential impact of RET-based pumping systems on the economy of Botswana.

2.0 DESCRIPTION OF EXPERIMENTAL APPARATUS

2.1 Water-Pumping Windmills

A wide variety of windmills will be tested during the comparative testing program. They vary considerably in both cost and performance capability. The economic comparisons which will be made after the completion of data collection normalize cost as a function of annual output. The most important measure of performance in this experiment will be the average annual cubic meters of water pumped per unit cost, based on life-cycle costing methods. Cost figures thus include all costs incurred over the expected lifetime of the device. Water output will be indexed to the total pumping head of the site (see the Appendix for an illustration of the definition of different types of head).

Shadow costs for the foreign-manufactured machines will be accounted for as well. For instance, purchasing Botswana-made machines generates local employment, helps reduce foreign exchange costs and, presumably, guarantees that the technical expertise necessary to fabricate spare parts and make subsequent repairs will be available in-country. However, certain of the foreign-made machines hold the promise of very high water-pumping capacity, which, in the long run, might make them more cost effective. Thus, it is appropriate to examine the entire range of available wind pumpers to determine which is most appropriate for Botswana.

There are two water-pumping windmills which are manufactured in Botswana, the Windmill Technical Group Serowe (WTGS) machine, and the Rural Industry Innovation Center (RIIC) machine, the latter developed and tested in a joint effort by RIIC and BRET. They are both low-solidity (relatively few blades) machines whose rotary drives are used to run the commonly used Mono progressive-cavity pumps. Since they approach the drive train problem in different ways (WTGS: centrifugal clutch coupling; RIIC: variable step-up transmission), it is reasonable to make tests of each of the machines.

The two foreign-made "high performance" machines are the U.S.-manufactured Wind Baron and the Kenyan Kijito. Both are high-solidity (many blades) machines which are able to provide relatively high outputs even in areas of relatively low windspeeds. Both have high initial capital costs, which are further increased by shipping costs. However, if their pumping performance does in fact meet their manufacturer's claims, these high up-front costs may be offset by long-term reliability and high-volume output.

A number of conventional, commercially available machines will also be tested. The South African-made Climax and Southern Cross machines have been used with some modicum of success in

Botswana for years. While wind tunnel tests have been done on the Climax machines, neither machine has been carefully monitored under field conditions to determine output as a function of cost. These machines will act as the reference against which the newer foreign and experimental domestic models are compared.

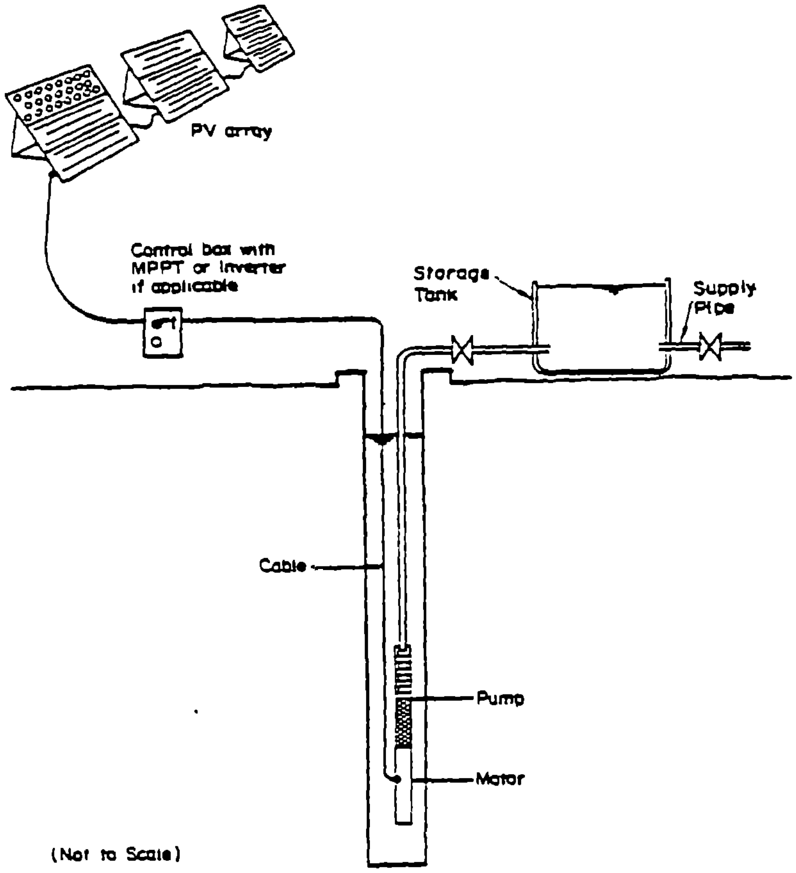
2.2 Solar Photovoltaic Pumps

Many types of photovoltaic pumping systems are now commercially available. A typical system is shown in Figure 1. Each has its best use, depending on the characteristics or tne water source. In field situations, the different pump types are normally used in the following applications, listed in general order of increasing total pumping head:

- Surface-mounted, direct current (DC), centrifugal pumps, for low head suction lifts (0-6 meters) and low to very high output.
- Surface-mounted, DC jet pumps, low to medium head (7-20 meters) with medium output.
- AC or DC submersibles, low to medium-high head (7-100 meters) and low to medium-high output.
- Surface-mounted jack (reciprocating) pumps, for medium to very high head (20-200 meters), but low output.
- Progressive-cavity (such as Mono) pumps, with surface-mounted motor and downhole pump, medium to high head (20-200 meters) with medium output.

Obviously, there is a great degree of overlap of appropriate applications between the different pump types. However, in addition to required head and flow, there are a number of other design constraints which must be considered. These include overall efficiency (which can vary considerably from pump to pump), water conditions such as salinity or solids content, extent of expected (and unexpected) maintenance and repairs, and cost per delivered unit or water. Also, certain of these pumps have only recently become commercially available. So, long-term reliability has yet to be ascertained.

In general, the simplest proven system which can accomplish the task within the cost constraints or tne project is the wisest choice. However, additional components, such as power conditioning equipment (see PCUs below), can significantly increase the output from certain types of systems. So, in some systems, simplicity has been sacrificed to achieve higher performance.



Typical Configuration for a PV Pump (6)
Figure 1

Initially, economic analyses were performed on various types of pumps fitted to typical boreholes with pumping heads of 30 and 100 meters. The holes actually picked by the DWA have ranged from 12 meters head with a required annual average output of 15 cubic meters per day to 70 meters head at an output of 25 cubic meters per day. This range effectively eliminated the possibility of using any suction pumps (maximum lift 5-7 meters). The relatively high levels of salinity and sand content make it inadvisable to use standard jack pumps, whose leathers can be worn out by pumping too much sand.

Since a new generation of relatively high efficiency DC motors has become available, there seemed, given the financial contraints of the project, little point to testing AC systems. The latter have relatively efficient motors but require a DC (PV panel output) to AC (current required by pump motor) inverter, which decreases efficiency, increases cost and thus far has been a notoriously troublesome component of AC systems. Several new AC systems have recently become commercially available (Grundfos, Franklin). Should the range of the testing program be extended, it would be useful to test AC systems for comparison with DC.

The following pumps have been chosen to fit the site constraints (borehole yield, total pumping head, user demand, etc.) of the boreholes picked by BRET and DWA:

- Two Jacuzzi submersibles with DC brush-design motors pumping approximately 30 cubic meters a day at 30-meter pumping heads, directly coupled to PV array output.
- One Jacuzzi submersible with a DC brush-design motor pumping approximately 15 cubic meters per day against a 12 meter total head, coupled to a PCU (see below).
- Two Honeywell DC brush-design, surface-mounted motors and PCUs driving conventional Mono pumps. The PCU allows for earlier morning start-up against the high starting torque of the Mono pump, obviating the need for an expensive degradable battery bank. One system is a 1.5 Hp (1.1 kW) motor driving an ES-10 mono, pumping about 20 cubic meters/day against a 62-meter head. The second system will couple a 3.0 Hp (2.2 kW) motor with a Mono pump to get 34 cubic meters/day against a 72-meter head.

In addition, several other pumps are being considered:

- An A.Y. MacDonald Brushless DC submersible. The testing prototypes of this design are now available. The first production run is scheduled for June 1984. The two advantages of a brushless submersible motor are: 1) no need to pull pump/motor set to replace brushes (this will be necessary on Jacuzzis after 6000-8000 operating hours); 2) increased efficiency since there is no voltage drop across brushes (however, additional electronic power conditioning equipment will reduce overall system efficiency in a different way).
- A jack (reciprocating piston) pump. This would be appropriate in less sandy and saline water sources for low flow at high head.

Since the introduction of PV pumping systems into common use, there has been an increased awareness of certain design flaws in the coupling of commonly available DC motors with PV array output. The most troublesome of these was the mismatch between the operating point of the DC motor and that of the PV array. If these two operating points (a particular current and voltage combination) are not at least close to each other, the system as a whole operates very inefficiently. Some typical operations curves are given in Figure 2, for resistor and motor loads. Note the high surge current when the motor starts.

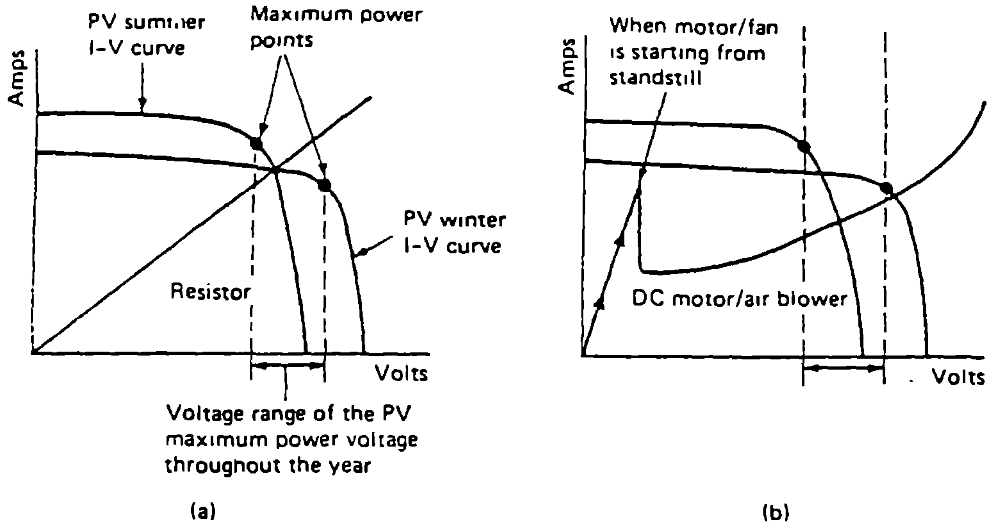


Figure 2 - Typical operating curves for PV loads (3)

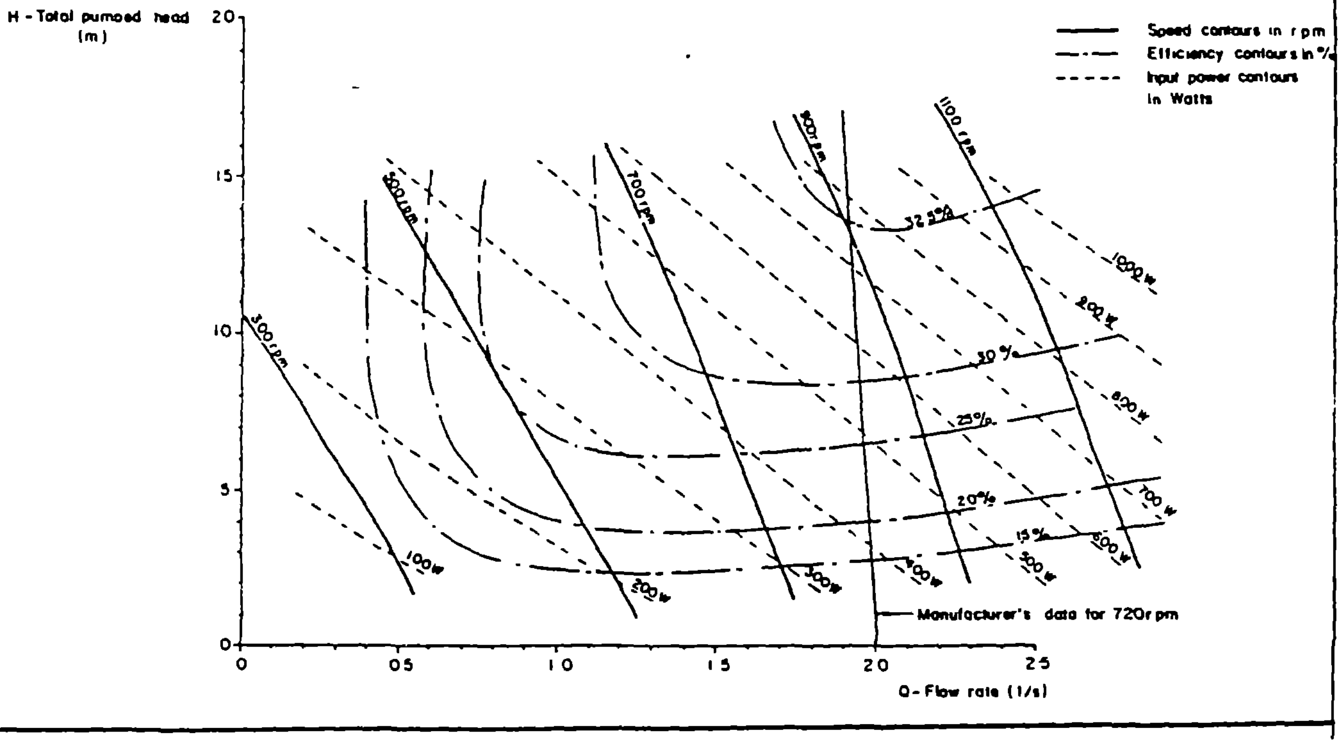


Figure 3 - Typical rotary positive displacement pump performance (6)

In order to deal with this problem, a number of companies have developed more efficient DC motors with operating curves which better match those of PV arrays. In addition, an electronic device known as a power conditioning unit (PCU) has been developed. This forces the PV array to operate at its maximum power (current x voltage) point at any level of solar insolation. It also can vary current and voltage from the array to allow earlier starting of a high torque pump, such as the Mono. Torque is directly proportional to current. Rotational speed (RPM) is directly proportional to voltage. Up to the point of maximum allowable voltage to the pump motor, the higher the RPM (and consequent power consumption) the higher the water output (see Figure 3).

In the morning, the PCU reduces the voltage from the array and increases the current output. This allows the motor to generate enough torque to overcome the frictional resistance of the pump stator and start the pump rotating. The PCU then sets the array output at its maximum power point once the pump is running and its high starting current demand is diminished.

In the past, it was necessary to have a large battery bank for overnight storage. The high starting current could then be drawn from the battery bank. Batteries are expensive (in comparison to PCUs) and rapidly degrade unless treated very carefully. The PCU obviates the need for battery use. This increases the long term reliability of the system and decreases its initial capital cost.

In the pump listing given above, not all the pumps are coupled to the array through a PCU. For smaller systems, or for pumps which have low starting-torque requirements, it can be less expensive to simply add a few more panels than to include a PCU in the system. This was done in some cases.

2.3 Diesel Pumps

Since diesel pumping is the baseline against which all alternatives must be compared, it is important that some diesel installations be monitored for both cost and performance data. The performance monitoring of diesel pumps is considerably simpler (from a theoretical perspective) than RET-based pumping systems. There are only three system parameters to be measured on a long-term basis in the operating mode: fuel input, water output, and pump on-time. For short-term testing, the pump and engine RPM should be measured since output is a strong function of both. As with all pump system measurements, the static and total pumping head must be determined as well.

More difficult to measure in practice, however, are the maintenance and repair costs associated with running a diesel system. A detailed outline of the recommended procedure is included in the appendices. The sites chosen for monitoring should be of similar-size output to the wind and PV systems being monitored. They should also be chosen on the basis of the experimenters' assurance that the operators of the diesel systems can be relied upon to make note of all maintenance and repair procedures necessary during the operation of the diesel. Since expected maintenance costs, in addition to repair costs for unexpected breakdowns, represent (along with fuel consumption) a very large portion of the expense of diesel pumping, these should be recorded in detail.

In order to reduce the number of variables in the experiment as much as possible, only diesels driving Mono pumps should be chosen for monitoring. Since most of the diesel-driven pumps in Botswana fit this requirement, this is not an undue constraint on the experiment.

2.4 Instrumentation

The experiment is divided into three major sections: PV pumps, windmills and diesel-driven mono pumps. PV, wind and diesel experimental design and procedures will be discussed separately.

Instrumentation will be installed at each site to measure the relevant experimental parameters. Two types of data will be collected. The first type is continuous long-term (monthly). This data will be collected from the instruments on a monthly basis by project staff, and taken to Gaborone to be analyzed in detail by BRET technicians. While on-site, the data collection technicians will run a series of short-term tests over a one or two day period. These tests will generate output versus resource availability (wind or solar radiation) as a function of total pumping head. These curves will be particularly useful when designing similar systems for future sites.

In addition to the hard data collected, interviews will be conducted with the system end-users to determine their subjective impressions of the overall quality and reliability of the various machines. Often, this information can be used to explain unexpected breakdowns in the machinery. For instance, windmills require periodic lubrication. If users can be convinced of the usefulness of a pumping device in terms of its need for periodic maintenance procedures, they are more likely to perform these procedures on schedule. If this awareness is not present, and the machine goes down, it will simply be perceived as an inherent machine fault about which nothing could be done anyway. Educating end-users to the machine's capabilities and its limitations can only be helpful to both experimenters and end-users.

2.4.1 Wind Instrumentation

The instrumentation for the water pumping windmills will measure three variables: windspeed, pump strokes (or revolutions per minute with the Mono-coupled systems) and water output. The windspeed will be measured with a compilator which "bins" the windspeed. This means that a histogram (bar chart) will be generated which gives the overall wind distribution for the site. Each bar of the histogram represents the amount of time that the wind blew in that particular windspeed range over the recording period. The data recorder accumlates the minutes of wind in each windspeed "bin."

There are 16 bins, calibrated in km/hr. Bin No. 1 counts all minutes when the wind is blowing 0-2 km/hr, bin No. 2 counts 2-4 km/hr, etc., up to bin No. 16 which counts all times when the windspeed was greater than 30 km/hr. Since average windspeeds at the better sites in Botswana are in the range of 10-14 km/hr, this range of bins will give the windspeed distribution over the range of greatest interest.

Knowledge of the wind distribution is much more valuable than simply knowing the average windspeed. This is because the power available in the wind is equal to the cube of the windspeed (see Ref. 1 and 2). For example, let us assume that the average site windspeed is 10 km/hr. Further, for simplicity, imagine that the wind blows 12 hrs/day at 20 km/hr and the other 12 hours it doesn't blow at all. By the cubic relationship, if the wind blows constantly at the average windspeed, the power in the wind is proportional to 1000 (10 cubed) times a constant. However, in reality (for this example), half of the time there is no power available, but the other half of the time power proportional to 8000 (20 cubed) times a constant is available. Since energy is power times time, using the average windspeed to estimate the energy in the wind over the hypothetical day underestimates the actual value by:

$$\frac{8000 \times 12 \text{ hours}}{1000 \times 24 \text{ hours}} \text{, or } 75\% \text{ of the actual value}$$

This example is, of course, an oversimplification. It does, however, give some indication of the usefulness of knowing the wind distribution at a site, rather than simply the average windspeed.

2.4.2 PV Pump Instrumentation

In order to adequately characterize the performance of the photovoltaic pumping systems, it is necessary to measure six experimental parameters. These are: solar radiation in the plane of the array; power out of the array; power to the pump (assuming that there is some power conditioning device between the array and the pump, such as a PCU or a battery bank); water pumped; elapsed pump on-time; and total elapsed time since last reset (normally, the beginning of the experiment). Since array output is also a function of cell temperature, this should be measured occasionally during the short-term tests. Discharge head will be measured with calibrated pressure gauges mounted in the discharge line upstream of the flowmeter. Suction head, or static water level plus drawdown, will be measured with the well sounder carried to each site.

Solar radiation will be measured by a global pyranometer in the plane of the array (rather than horizontally) so that a more accurate determination of the array and system efficiency can be made. Power measurements will be made using standard DC kWh transducers. Flow measurements will be made with a positive displacement flowmeter placed one meter downstream of the wellhead. All sensor channels will have transient surge protection between the sensors and the data logger. This will help prevent instrument damage from electrostatic discharge.

2.4.3 Diesel Instrumentation

Four parameters will be measured on a continuous basis on diesel pump sets: fuel usage with an in-line flowmeter between the fuel tank and the engine; water output with a positive displacement flowmeter; pump on-time; and total elapsed time since reset (normally, since the beginning of the experiment. Pump on-time can be measured by a timer driven by the flowmeter. A hand-held tachometer can be used to measure pump RPM so that correlations may be made between RPM and flowrate. In addition, the short-term tests will also include measurements of static and dynamic (i.e., while the pump is running) head, using both the pressure gauge on the discharge side and the well sounder for the downhole measurements.

Particular care should be taken to insure that the instruments mounted on the diesel lines (the fuel flowrate measuring device, in particular) be chosen to be particularly resistant to damage caused by vibration. It may be necessary to use mechanical integrating flowmeters rather than the electronic pulsers used in the wind or PV instruments. It is particularly important to guard against contamination with dirt, dust, and diesel fuel. In addition, most of the diesels used in Botswana have both a supply and a return fuel line. Instead of using two flowmeters to measure the fuel consumption, a single flow measurement will be made on a feeder line from the storage tank to a small tank which contains both supply and return lines as well as appropriate filters to allow the exhaust gases in the return line to escape. This will also obviate the need for dealing with the problem of measuring two phase (liquid/gas) flow in the return line from the engine.

2.5 Data Collection Sheets

Data Collection Sheets (DCS) (see the Appendices) will be provided for the field technicians so that data are easily retrieved from the instrumentation. To provide some degree of redundancy and prevent loss of data, all measurement registers will also be photographed with a Polaroid camera. A picture of all the registers should be taken immediately upon arrival at the site, before any of the short-term testing is begun.

The DCS will be filled out completely by the field technicians during each site visit. Spaces are provided to record all pertinent experimental parameters, as well as details on any necessary maintenance or repair procedures. In addition, space for any information gathered from discussions with the water end-users will be provided. A series of questions in an interview format will facilitate the exchange of information between the villagers and the BRET technicians.

It is particularly important that any downtime for the systems be carefully documented and explained. Since system reliability is a crucial variable in the choice of a pumping system, this documentation should include: when the system stopped working; how many hours of work were required to restore it to working order; the total amount of time the system was not operating, and the spare parts (if any) required to restore the system to working order. Also, if the system is in working order but does not operate due to an insufficient resource base (e.g., a very cloudy day), this should be noted and explained. The related issue of training requirements for pump technicians should also be reviewed in the on-going analysis of the project.

Costing sheets for each type of pumping system are also given in the Appendix. These were developed by ARD and initially presented in the Financial and Social Cost/Benefit Analysis Consultancy Report. These should be filled out for each system after procurement and installation. Duplicate lists of all maintenance and repair procedures and their associated costs will be maintained at the BRET office. These should make careful note of both parts and labor costs for each system. This includes travel time, per diem costs for repair crews, and any other costs associated with the operation of the system.

There are currently 15 wind-monitoring instrumentation packs and five for PV pumps. The number of diesel pump sets to be monitored has yet to be decided. It is assumed that at any given point in time, approximately 18 of these packs will require monthly data retrieval. Since some sites are far removed from each other, two technicians should be assigned the task of data collection. Since the data collection procedure requires about one and a half days of on-site testing at each location (plus a half day travel to each site, on the average) if 18 instrument packs are in use, there will be 36 days per month of on-site testing and travel.

3.0 EXPERIMENTAL PROCEDURE

3.1 Choice of Site and Specific Borehole

3.1.1 Availability of On-Site Energy Resources

Siting a pump powered by renewable energy resources is not as simple a matter as siting a diesel pump. The system designer must have some minimal level of knowledge about the site-specific availability of these energy resources. In this experiment, these would include solar radiation, daytime temperature ranges, and wind regime.

While available power in the wind increases with the cube of windspeed, wind-pump water output is roughly proportional to the square of the windspeed at the height of the blades. Performance at higher windspeeds is less than theoretically expected, due to increased frictional losses in pumps, piping, gears, etc. Since windspeed normally increases logarithmically with height, characterization of the local wind regime must specify at what height the data were taken. Solar electric-pump output increases in direct proportion to the solar insolation level, and decreases in proportion to higher PV-cell temperature above the rated output at 25C. Some knowledge of these microclimatic parameters is thus crucial to system and component sizing.

Frequently, resource information is not readily available, and estimates must be made. In the case of solar insolation, especially in an ideal solar climate like that of Botswana (with both high and relatively constant insolation over the year), estimation of annual average monthly insolation levels can be made from extrapolations from data gathered in South Africa and Namibia. As the Meteorological Services solar data-gathering efforts begin to yield long-term reliable data, this will become the preferred climatological data base.

Wind data are not so easily extrapolated from data taken at other sites, since wind availability is a strong function of topography and other geographical site-specific characteristics. Fortunately, MET Services, DWA and the BRET project have been collecting data on wind regimes at many sites throughout Botswana. Before any specific site is chosen, however, an anemometry test should be made on-site and at the same height as the nearest MET Services site anemometer (assuming that MET Services data are being taken at a 10-meter height, otherwise at the height of the prospective windmill). Since this is normally done for a relatively short time (ideally, a full year, since windspeed is normally very seasonal), the site data can then be compared to the nearest available MET Services site data.

The procedure is as follows. First, the data collected at the prospective site should be compared with MET Services data for the same time period. For example, let us assume that the average daily windspeed recorded by the anemometer erected at the prospective site was 12.4 km/hr in July, and in August it increased somewhat to 13.5 km/hr. Data collected by MET Services (at not quite as ideal a site in town) during the same period was 10.6 km/hr in July and 11.2 in August. The long-term averages (over, say, a ten-year period) from the MET Services site indicate that the average windspeed in July is 9.9 km/hr in July and 10.5 km/hr in August. Thus, this July and August, the wind was blowing somewhat more than usual. The data for the prospective pumping site should thus be adjusted slightly downward (by proportions) to 11.6 km/hr in July and 12.7 km/hr in August. The site data can be corrected in this way to take advantage of longer-term data gathered at a relatively nearby site.

3.1.2 Water Resources and End-Use Requirements

The second major constraint on the choice of the wind or solar pumping site is the suitability of the borehole. The borehole yield must be within range of the pumping device planned for the site. Its recharge rate must not be less than the expected pumping rate of the windpumper, otherwise it would not be a true test of the machine's capabilities. To increase the usefulness of the comparative pumping data, one would prefer that the range of sites chosen have similar total pumping heads and well yields. Given the available well sites, this is a difficult requirement to fulfill. It would also be helpful to estimate each system's performance at a common head, such as 30 meters, for more apt comparisons of each system's performance. This will be done in the data analysis.

If wells with insufficient yields are all that is available, then one possibility is to dump much of the output back into the well so that excessive drawdown does not occur. This arrangement should be avoided if possible. It is likely that the increased availability of water will simply increase the demand, so that end-users would not respond well to dumping the water. Another solution is to put a timer on the system and restrict the number of pumping hours in a day, allowing the well to recharge between pumping cycles. From the data thus collected, the actual potential of the pumping system, when mounted on a well with sufficient yield, could then be extrapolated.

Ideally, the system designer would like to have detailed driller's data on water rest level, pumping water level at various flowrates, the size of the well casing at all depths, overall depth of the well, and some indicator of salinity and solids content (sand mostly) of the water. PH of the water is a good indicator or corrosiveness of the water. This will aid in the appropriate choice of pump and/or impeller material. Pumps vary in their ability to deal with highly saline or very sandy water. This is especially important when choosing among the wide variety of PV-powered pumps. Wind pumps normally use reciprocating cylinders, although some of the windpumpers being tested in this program will drive progressive-cavity (Mono) pumps.

3.2 System Design and Component Sizing

According to the principles of comparative testing in the introduction, only the performance and economics for systems or roughly equivalent size should be directly compared. Accordingly, most of the RET-driven pumping systems used in this experiment will have an output of 15-30 cubic meters/day at heads ranging from 15-80 meters. Systems with lesser capacities (e.g., handpumps) should be examined separately. Similarly, diesel engines with capacities of greater than 50 cubic meters/day should only be included for comparative purposes if no smaller diesel systems can be found to monitor.

3.2.1 Wind Systems

Once a borehole is chosen whose yield and site-specific wind regime indicates that it would be appropriate both in terms of economics and reliability of output (see Section 4.3), the choice of the rotor diameter is the next step. In this experiment, with the windmills chosen for testing, there is a constraint on the variety of sizes available from the various manufacturers (there is only one size Wind Baron, for instance). Normally a designer would do rough economic calculations to determine the rotor diameter most appropriate for the site. Then, with the rotor diameter chosen, fine tuning the design by sizing the cylinder is the next step. Cylinder sizing has traditionally been an art more than a science. Normally, manufacturers specify a particular cylinder size at a particular head (total effective height against which the water is pumped) which results in a certain flowrate at the specified average windspeed. This information is frequently presented in tabular form in the manufacturer's literature, and is frequently overly optimistic. Often, the windspeed data are completely omitted, making any attempt at cylinder (or rotor) sizing impossible.

The larger the cylinder size, the more water that will be pumped for a given rotational velocity of the blades. However, the power delivered by the blades to the gearing mechanism must be able to supply enough power to lift the column of water in the drop pipe (or to turn the progressive cavity pump shaft, if torque is being applied to the drive shaft). If not enough power is supplied by the blades, nothing moves, and no water is pumped. It is better to have a small cylinder pumping less water, than a large one which is not pumping any water at all.

A compromise must, therefore, be made between a relatively large cylinder which pumps much more water than a small cylinder when the available wind is high, and the small cylinder which pumps much more frequently, providing water on a more reliable day-to-day basis, with a lower overall output. Research has been done on a variable stroke device which, in effect, simulates a smaller cylinder at lower windspeeds and a larger cylinder at higher windspeeds. This device is not yet commercially available (see Ref. 11).

The correct cylinder-sizing procedure is to pick a minimum acceptable level of output (i.e., worst-case average wind conditions over a month) and size the cylinder to meet the daily output requirements. The end-users of the water from the wind pump will then be fairly well assured or water on a regular basis. Of course, if there is no wind for extended periods of time, there will be no output. Judicious site selection and storage sizing should prevent this. Storage is normally sized at three to six days of normal daily demand. There is an obvious tradeoff between the higher cost of a larger water storage tank and the resultant increased availability of water supply.

In order to determine the output under the worst-month conditions, one is forced to rely on manufacturers' data, or to base sizing decisions on actual data for the machine being considered under a variety of wind conditions, or to use a computer simulation model to determine output under the wind conditions which have been measured on the site during the pre-installation anemometry measurements (see Figure 4 for a sample output from such a model). A further complication occurs when different gear ratios are available for each size rotor diameter.

If manufacturer's data are available (see Figure 5 for an example chart) which give output as a function of average windspeed, total pumping head, rotor diameter and cylinder size, and the data are determined to be somewhat reliable, component sizing proceeds as follows:

a. De-rate all outputs by 80 percent to account for overly optimistic predicted flows, and periods of less than normal wind availability.

b. If output is given as a function of a number of different average windspeeds, chose the windspeed closest to that of the worst month at the proposed site. Be conservative.

c. Decide the minimal acceptable level of water supply during the worst month period, and convert that into the units on the table (usually liters/hr or gal/day).

d. Calculate the total pumping head for the installation (see the illustration of different definitions of head in the Appendices). This includes the static water level (depth

```
0
JRUN
INTEGRATION OF MULTIBLADE WINDMILL WITH WEIBULL WIND DISTRIBUTION


INPUT ROTOR DIAMETER IN METERS
?4 27
INPUT WINDMILL GEAR RATIO
?3
INPUT TOTAL PUMPING HEAD IN METERS
?30
INPUT CYLINDER DIAMETER IN METERS
? 102
INPUT PUMPING STROKE IN METERS
? 305
INPUT PUMP MECHANICAL EFFICIENCY
? 6
INPUT PUMP VOLUMETRIC EFFICIENCY
? 9
INPUT TRANSMISSION EFFICIENCY
? 9
INPUT PUMP ROD MASS (BUOYED). IN KG
?30
INPUT WIND PUMP RATED WIND SPEED. IN M/S
?8 5
INPUT WINDMILL SHUTDOWN SPEED. IN M/S
?22
INPUT INTEGRATION INTERVAL. IN M/S
? 5
INPUT MEAN WIND VELOCITY.IN M/S
?2
INPUT WEIBULL SHAPE FACTOR. K
?2
INPUT AIR DENSITY IN KG/M3
?1 2
INPUT TIME PERIOD(IN HOURS) OVER WHICH THE INTEGRAL IS TO BE CALCULATED
?24

 .
DO YOU WANT A_FULL OUPUT (INPUT 1) OR JUST THE FINAL WATER OUTPUT (INPUT 0)
?0
TOTAL WATER OUTPUT OVER 24 HOURS = 1 52873958 CUBIC METERS


  YOU CAN RESET ANY OF THESE VARIABLES:
          1) ROTOR DIAMETER
          2) GEAR RATIO
          3) TOTAL PUMPING HEAD
          4) CYLINDER DIAMETER
          5) STROKE
          6) PUMP MECH  EFF
          7) PUMP VOL  EFF
          8) TRANSMISSION EFF
          9) BUOYED ROD MASS
          10) WINDMILL RATED SPEED
          11) WINDMILL SHUTDOWN SPEED
          12) INTEGRATION INTERVAL
          13) MEAN WIND SPEED
          14) WEIBULL K FACTOR
          15) AIR DENSITY
          16) INTEGRAL TIME PERIOD

ENTER HOW MANY VARIABLES TO BE CHANGED  (0 TO QUIT)
?1
INPUT THE NUMBER ASSOCIATED WITH THE VARIABLE TO BE CHANGED
?13
MEAN WIND SPEED =
?3
TOTAL WATER OUTPUT OVER 24 HOURS = 10 9496597 CUBIC METERS


  YOU CAN RESET ANY OF THESE VARIABLES:
          1) ROTOR DIAMETER
          2) GEAR RATIO
          3) TOTAL PUMPING HEAD
          4) CYLINDER DIAMETER
          5) STROKE
          6) PUMP MECH  EFF
          7) PUMP VOL. EFF
          8) TRANSMISSION EFF.
```

Dempster 30m Head
$\bar{V} = 2$
Q = 560 m³/yr

Dempster 30m Head
$\bar{V} = 3$
Q = 4000m³/yr.

Wind Baron Mark IV 150 High Performance Wind Machine

For shallow well and water transfer applications (to 650')

The ability to produce large volumes of water at low wind speeds places the Wind Baron Mark IV 150 High Performance Wind Machine in a class by itself for limited irrigation, water transfer and other shallow well applications.

With a gearbox ratio of 1.5 to 1, the Mark IV 150 can pump nearly 1200 gallons per hour from a 36-foot deep well – in winds of 5 mph. At 20 mph, at the same well depth, this Wind Machine can pump over 4400 gallons per hour.

Ideally suited for locations that need large volumes of water at an economical cost, the Mark IV 150 out-produces conventional water pumping wind mills – particularly at low wind speeds.

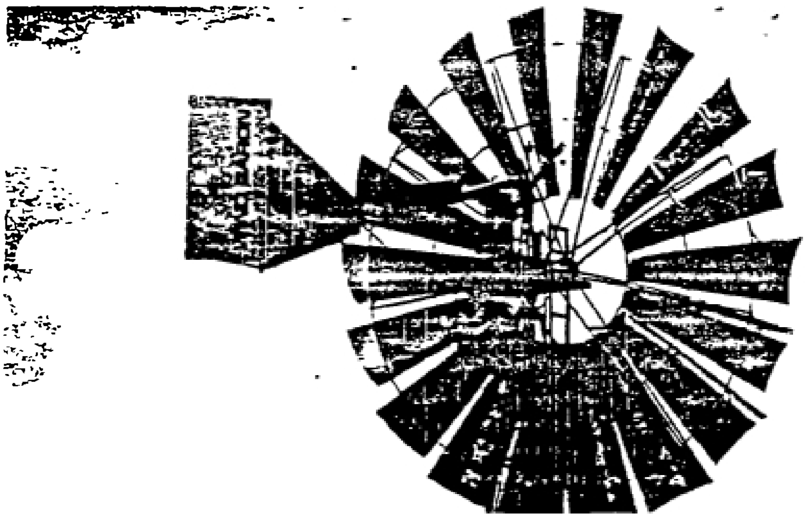
Because the Mark IV 150 uses a bolt-on differential gearbox that can be replaced with a higher or lower ratio gearbox – it can adapt to changing water tables with a minimum of effort and cost.

Wind Baron Performance Standards

Performance Table #3 – Water Pumping @ Sea Level
Mark IV 21 ft. Diameter Counterbalanced High Performance System
1.5 : 1 Gear Box Ratio x 17 in. Stroke

Cylinder Size		Maximum Pumping Head		Discharge Capacity in Gallons Per Hour and Liters Per Hour at Various Wind Speeds							
				5 MPH	8 KM/HR	10 MPH	16 KM/HR	15 MPH	24 KM/HR	20 MPH	32 KM/HR
IN	MM	FEET	METERS	GAL/HR	LITERS/HR	GAL/HR	LITERS/HR	GAL/HR	LITERS/HR	GAL/HR	LITERS/HR
1⅝	41	666	203	64	242	131	496	189	717	238	900
1¾	44.5	574	175	74	281	151	575	220	832	276	1 045
1⅞	47.6	500	152	85	322	174	659	252	954	[illegible]	1 198
2¼	57	347	106	123	465	251	950	364	1,377	457	1 729
2¾	70	232	71	183	682	375	1,419	542	2,051	682	2,581
3	76	195	59	218	825	446	1 688	646	2 445	816	3 089
3¼	82.5	166	51	256	969	523	1 980	757	2 865	951	3 599
3¾	95	25	38	341	1,290	697	2 638	1 008	3 815	1 267	4 785
4	102	110	34	388	1 468	794	3 005	1 145	4 349	1 443	5 462
5	127	70.5	21.5	605	2,290	235	4 674	1 788	6 767	2 246	8 501
6	152	49	15	874	3 308	1784	6,752	2 583	9 777	3 245	12,282
7	178	36	11	1189	4,500	2428	9 193	3 515	13 304	4 415	16 711
8	203	28	8.5	1554	5,882	3175	12 017	4 595	17 392	5 772	21 847
9	229	22	6.7	1967	7 445	4015	15,197	5 812	21 998	7 301	27 634
10	254	18	5.5	2428	9,190	4959	18,770	7 179	27,172	9 017	34 130
11	279	15.5	4.5	2936	11 113	5997	22,699	8 682	32,861	10 904	41,272
12	305	12	3.7	3494	13,225	7139	27 021	10 333	39 110	12 979	49 125
13	330	10.5	3.2	4103	15,530	8383	31,730	12 134	45 927	15 241	57,687
14	356	9	2.7	4746	17,964	9695	36,695	14 035	53,122	17 628	66,722
APPROX. STROKES PER MINUTE				7		14.3		20.7		26	

NOTE: Capacity values in table are based on theoretical cylinder displacement. In reality the actual capacity will vary between 80-95% of these values depending upon the cylinder design, condition and setting and should be taken into consideration when sizing your system.



Features:

- Oil well-type counterbalancing unit.
- High torque, multi-blade wind wheel.
- Bolt-on differential gearbox.
- Ball bearing-mounted pivots
- Built-in, automatic furling system
- High traction mainframe safety platform.
- Fully galvanized – right down to the bolts – for corrosion protection
- Heavy duty tower made from 4" x 4" x ⅜" galvanized angle iron.
- 40', 50' and 60' tower heights.
- Tower access "window" for easier down-hole maintenance.

For more information about Wind Baron Wind Machines, contact your nearby distributor. Or, contact:

Wind Baron Corporation
3702 West Lower Buckeye Road
Phoenix, Arizona USA 85009
Telephone (602) 269-6900
Telex. 683 5005, INTELEX

FORM 0106-0883
PRINTED IN U.S.A.

WIND BARON IS A REGISTERED TRADE MARK OF WIND BARON CORPORATION

THE WIND BARON WIND MACHINE IS COVERED BY U.S. PATENTS
OTHER PATENTS PENDING

from surface to standing water level), the drawdown (increase in depth to water when pumping), the dynamic or friction head (friction losses in <u>all</u> piping from pump to delivery), and any static discharge head from the wellhead to the storage tank top. Any pressurization in the tank should also be added to the total head.

e. Locate the total head calculated in Step "d" on the output chart and move over to the column where required rate or delivery is listed. This will give the rotor diameter needed. If the machine has a single rotor size and there are multiple tables for different gear ratios, then pick the gear ratio at the required head which gives the most output.

f. Frequently the manufacturer will give a recommended cylinder size associated with a given rotor diameter and pumping head. If no other sizing method is available, use the specified cylinder. If computer simulation programs are available, run the windmill using wind data similar to those for the site under consideration. Vary the cylinder size to larger and smaller than that recommended, and see what the effect on the output is. Remember, in higher windspeeds, output will always be increased with a larger cylinder. In lower windspeeds, however, the windmill will not pump as frequently with a large cylinder. The output from a small cylinder will be more consistent on a day-to-day basis, but will likely have a smaller annual average output in lower wind regimes. Pick the largest cylinder that will produce the minimum required otuput on a regular basis.

g. The tower height should be chosen so that the windmill will be well above any nearby obstructions. An industry rule of thumb is that the tower should be no less than eight meters higher than any obstructions (trees, buildings, etc.) within 100 meters of the mill in all directions. In practice, the choice of the tower is a function of what sizes are commericially available, unless the tower is custom built. In that case, care should be taken that the tower is structurally engineered to be able to withstand well in excess of the highest recorded wind gust ever experienced near the site.

3.2.2 <u>PV Systems</u>

Since the pump type for a particular application is, to a large extent, dependent upon head and flow requirements, the first task is to determine the total pumping head. The flowrate will be constrained by both the demand at the site chosen and the availability of solar insolation. Data on solar insolation levels in Botswana are scant at this time. System designers

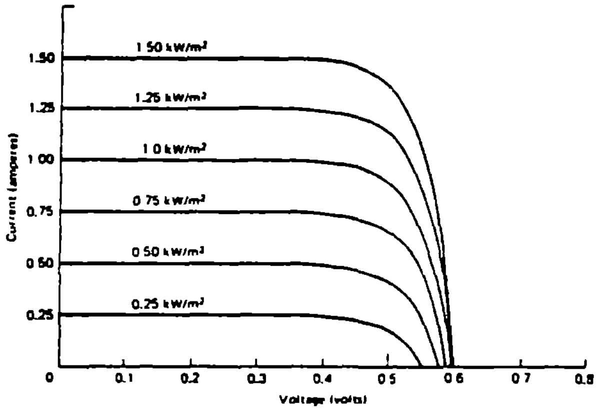


Figure 6 - Changing current with changing insolation (11)

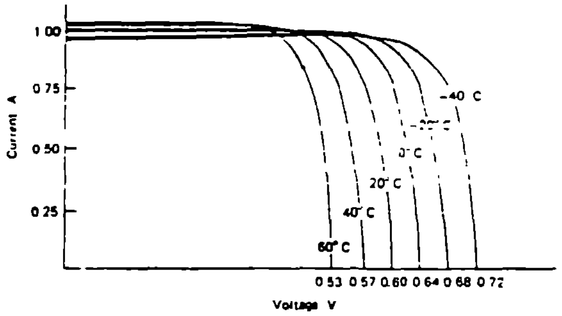


Figure 7 - Changing voltage with changing temperature (11)

should refer to Section Three--Climatic Factors, in the Passive Solar Design Workbook (available from the BRET office) for recommendations for the estimation of insolation levels in different parts of the country. MET Services data should be used as it becomes available.

Arrays are sized using insolation (irradiance over time) units of kilowatt hours per square meter per day (kWh/m^2-day). The maximum power available from the array increases with an increasing level of insolation (see the knee of the power curves in Figure 6). All calculations for the pump power supply should be made based on the minimum acceptable volume of water delivered during the worst solar radiation month. Fortunately, heaviest water demands usually occur during the summer, when insolation levels are normally the highest.

PV panel specifications are normally given under test conditions of 1 kW/m^2 at a cell temperature of 25C. This level of radiation over an hour period is one hour of "peak sun," or 1 kWh/m^2. While the PV cell output current is directly proportional to irradiance, increasing the cell temperature will decrease the operating voltage of the cell (see Fig. 7,Ref.11). An average correction factor of a 0.5 percent drop in power output per degree Centigrade increase in cell temperature above 25C should be incorporated into array sizing (see Ref. 12).

For example, a nominal 40-watt module rated at 25C, but operating at 45C, under 1 kW/m^2 solar insolation, will have a power output of (40 watts) x (1-(45-25)x(.005)) = 36 watts under these conditions. This means that the array will have to be about ten percent larger if its normal operating temperature is 45C. Systems in Botswana should be assumed to operate at about this temperature on an average annual basis. Actually, the output will decrease somewhat in the summer and there will be more power output in the cooler winter, per unit irradiance.

There are, on an average annual basis in Botswana, about six peak hours of sunlight per day. The rough system sizing, then, proceeds as follows. Flowrate in liters per second times the total pumping head in meters times 9.81 (conversion constant) gives water watts. This is the theoretical power required to pump that amount of water through that head. For example, to pump 3000 liters (3 cubic meters) per hour against a total head of 62 meters would take about:

$$\frac{3000 \text{ liters/hr}}{3600 \text{ second/hr}} \times 62 \text{ meters} \times 9.81 = 507 \text{ water watts}$$

However, electric pump/motor sets are usually only about 50 percent efficient. Therefore, double the water watts to get the actual required motor (hence, array) size. In this example,

$$507 \text{ water watts} \times 2 = 1014 \text{ motor watts}$$

Motor ratings are normally given in horsepower (Hp). 745 watts equal one horsepower. Motors available in this range are 1.0 HP and 1.5 HP (1118 watts). Rounding these requirements up to the next largest available motor requires choosing the 1.5 Hp motor. If panels with a derated output of 39 watts are used:

1118 watts / 39 watts per panel = 29 panels

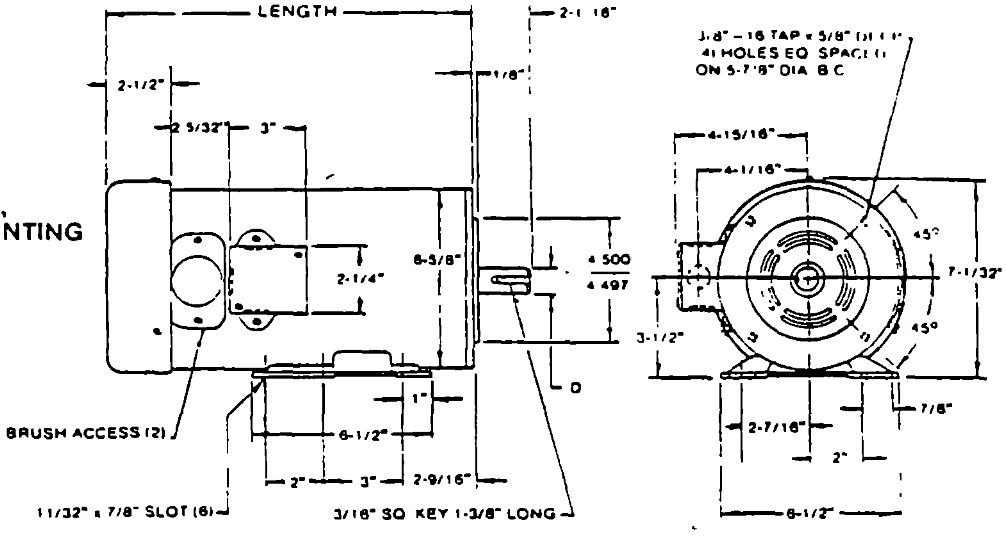
However, another requirement is that the panels provide the correct voltage to operate the pump motor. The motor in this case is nominally 180 volts. Since voltage increases as panels are wired in series, and the rated single-panel voltage is about 17.3 volts (derated to about 15 volts because of the expected high temperature operation in Botswana), three parallel strings of 12 panels each (180/15=12), or a total of 36 panels, are required.

If the pump has a high starting torque (like a Mono), one must ensure that the motor can supply enough torque to overcome the pump's frictional resistance to starting against a load. Motor specifications give inch pounds of running torque. (See Figure 8 for sample DC permanent magnet motor specifications.) Stall torque (when the motor cannot turn against the load) is normally 4-6 times the running torque. Hence, a motor with a running torque of 25 inch pounds can deliver over 100 inch pounds of torque to start the pump shaft rotating. The Mono pump in this example has a starting torque requirement of 60 inch pounds. Commercially available 1.5 HP motors have running torques in the range of 37 to 78 inch pounds, which is more than adequate.

Power conditioning units are able to supply the relatively high surge current necessary to start the shaft rotating by reducing the voltage to the motor. Since power equals current times voltage, for a given power level, increasing (decreasing) the current decreases (increases) the voltage. This reduces the RPM (revolutions per minute) of the pump, hence the volume output. As soon as the pump is rotating, current requirements are reduced, so (for a constant power level) the pump voltage increases, thereby increasing RPM and consequently the water flowrate. PCUs are sized according to the maximum current they can carry at a given nominal system voltage.

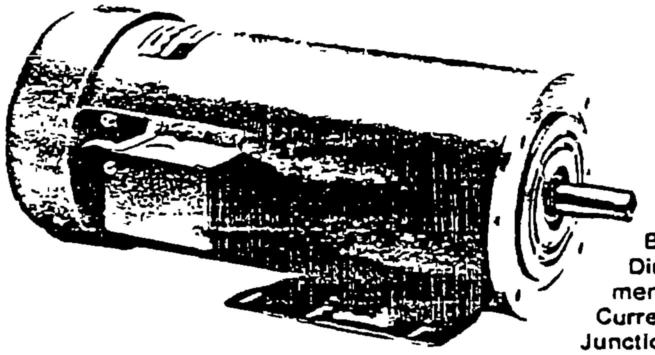
The pump instantaneous output can be estimated from pump capacity curves, which are given as water output as a function of total pumping head. Sometimes the pump power requirements are also given for the particular head and flowrate. Another important parameter sometimes included in pump curves is the family of efficiency curves (see Figure 9). If these curves are not given, they can be calculated by the theoretical power determination procedure given above. Pumps normally operate most efficiently (i.e., at maximum output per unit power input) near the middle of the pump curve. Efficiency decreases moving

MODEL SR53 TEFC, 56BC or 45BC MOUNTING



STANDARD MOTOR SIZES—Continuous Duty

MOTOR PART NUMBER	Enclosure	RATED					Allowable Peak Amp	CONSTANTS			DIMENSIONS			WT LBS
		Volt	HP	RPM	Amp	Lb. In		R_A	J	mh	Lgth. In.	D In.	NEMA	
SR5332-2501	TENV	90	3/4	1200	7	39 3	71	9	18.8	15 7	10¾	⅝	56	41
SR5332-3301	TENV	180	3/4	1200	3 5	39 3	36	3 6	19	62 7	10¾	⅝	56	41
SR5348-2318	TEFC	180	1-1/2	1200	7	78.7	52	1.95	23	18.8	14⅝	⅞†	145T	61
SR5320-2292	TEFC	90	3/4	1750	7 1	27	62	1.1	14 3	6.4	11⅝	⅝	56	32
SR5320-2286	TEFC	180	3/4	1750	3 6	27	31	4 3	14 3	25 6	11⅝	⅝	56	32
SR5324-2212	TEFC	90	1	1750	9 5	36	76	73	16	5 1	11⅝	⅝	56	34
SR5324-2287	TEFC	180	1	1750	4 7	36	38	2.95	16	20 3	11⅝	⅝	56	34
SR5332-2423	TENV	90	1	1750	9	36	99	61	22 4	8	11¼	⅝	56	41
SR5332-2545	TENV	180	1	1750	4 5	36	49	2 4	22 4	32	11¼	⅝	56	41
SR5348-2293	TEFC	180	1-1/2	1750	7	54	76	1 30	23	10 1	14⅝	⅞†	145T	61
SR5320-3005	TEFC	90	1	2500	10	25.2	90	57	14	6	11⅝	⅝	56	32
SR5320-3006	TEFC	180	1	2500	5	25 2	44	2.3	14	11 2	11⅝	⅝	56	32
SR5332-2491	TEFC	180	1-1/2	2500	6 5	37 8	73	1 21	22.4	6 5	13⅞	⅞†	145T	41
SR5340-2696	TEFC	180	2	2500	9 8	50 4	90	68	22.4	5 3	14⅝	⅞†	145T	49
SR5316-2546	TEFC	90	1	3450	10	18 3	99	46	12 4	4	11⅝	⅝	56	26
SR5316-2332	TEFC	180	1	3450	5	18 3	51	2 35	12 4	6 7	11⅝	⅝	56	26



For mounting specification add suffix to part numb
56C—NEMA 56C face (5/8" dia shaft)
56B—NEMA 56-145 base
56BC—NEMA 56C face & 56-145 base
45C—NEMA 145TC face (7/8" dia. shaft)
45BC—NEMA 145TC face & 56-145 base
†—Shaft length 2-1/8"

Construction: TEFC (open, drip-proof model giv economical package at 2 HP).
Brush Design: Negator spring
Direction of Operation: Can be run in either direction b merely reversing terminal polarity
Current Limiting: Required.
Junction Box Location: 10-cubic inch junction box for ea wiring Equipped with welded mounting feet

Figure 8 - Typical DC motor specifications
(courtesy Honeywell Corp.)

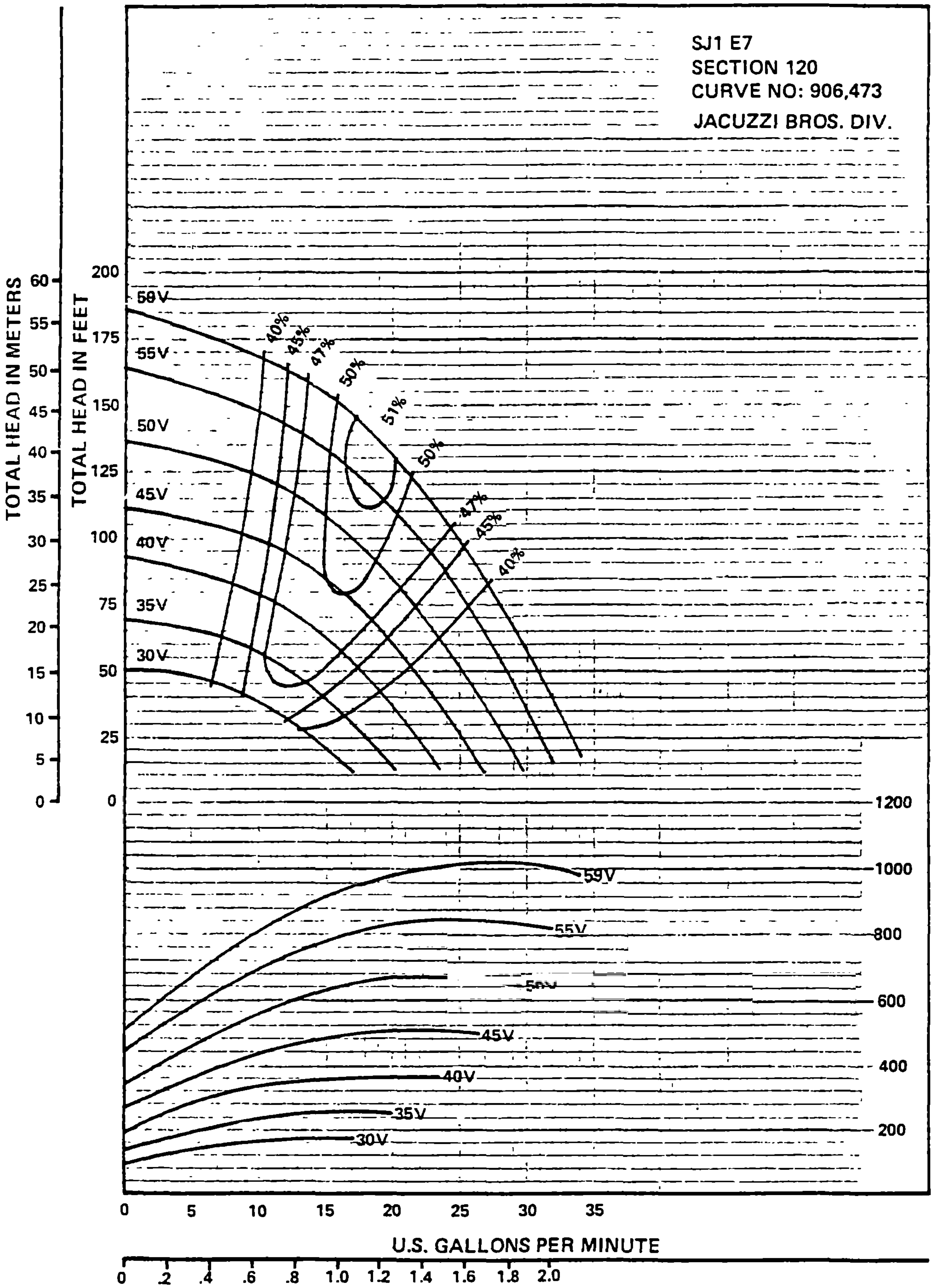


Figure 9 - Pump Performance Curves (courtesy Jacuzzi Bros.)

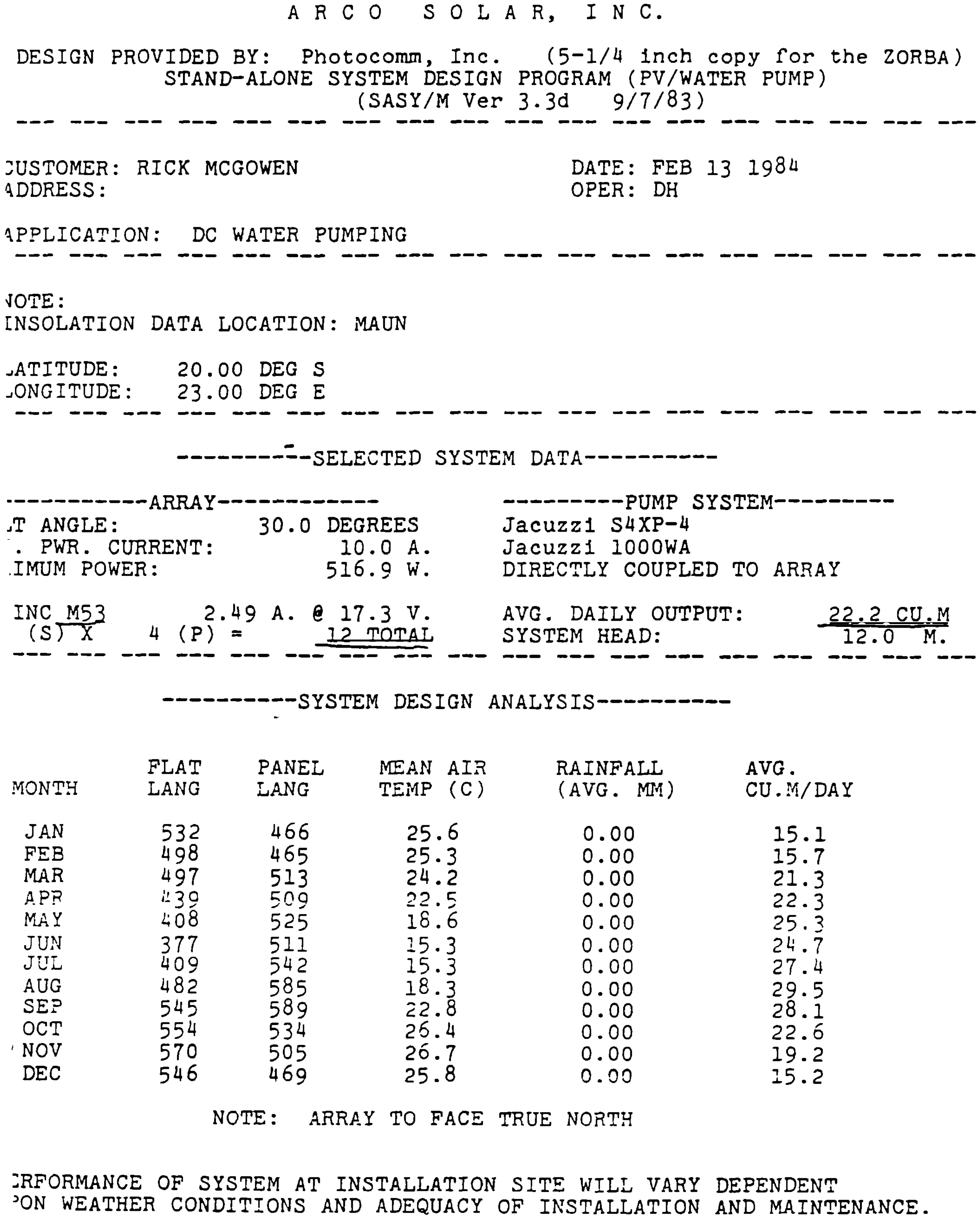
in either direction away from the middle of the capacity curve. Efficient system design is crucial in PV applications.

Average daily water output can be estimated by taking the flowrate from the pump capacity curve, then multiplying this by the number of hours the pump will be running with peak insolation on the array. If the pump output is three cubic meters per hour when the motor is receiving its rated watts from the panel, and the motor is correctly sized to match the pump and array, and if there are six hours of peak (level at which panel is rated) sunlight, then there will be about 18 cubic meters pumped per day.

As was the case with windmill sizing, manufacturer's claims of output are frequently overstated, and power requirements are understated. They tend to give output under absolutely ideal conditions, ignoring increased losses due to less than ideal field conditions. These factors should be accounted for when sizing the system. Wire-to-water efficiency (WWE) is the actual volume of water pumped divided by the theoretical volume which could be pumped if there were no losses in the system. Another way of saying this is that the WWE equals the theoretical power required to pump a certain volume or water divided by the actual power required to pump the same volume of water. Assuming a 50% WWE will account for most of the losses under normal conditions.

Battery bank sizing will not be addressed here since PCUs will be used instead to optimize panel/load matching and to supply sufficient surge current for starting. Similarly, since AC motors and their required DC/AC inverters will not be used (at least in the initial phase of the project), inverter sizing will not be examined here.

Other system sizing methods are sometimes provided in PV manufacturers's literature. Another method is to use computer sizing techniques. They give average daily output per month using the solar radiation level at the site as an input. These programs can indicate whether or not a PCU device would be of use (since the designer could merely increase the number of panels to get the same power output), at what optimum angle the array should be tilted, the effect of temperature-caused degradation of performance, etc. A sample output from such a program is given in Figure 10.



```
                    A R C O   S O L A R,  I N C.

 DESIGN PROVIDED BY:  Photocomm, Inc.   (5-1/4 inch copy for the ZORBA)
            STAND-ALONE SYSTEM DESIGN PROGRAM (PV/WATER PUMP)
                          (SASY/M Ver 3.3d   9/7/83)
 --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- ---

USTOMER: RICK MCGOWEN                     DATE: FEB 13 1984
DDRESS:                                   OPER: DH

PPLICATION:  DC WATER PUMPING
 --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- ---

OTE:
INSOLATION DATA LOCATION: MAUN

ATITUDE:     20.00 DEG S
ONGITUDE:    23.00 DEG E
 --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- ---

             ----------SELECTED SYSTEM DATA----------

-----------ARRAY------------          ---------PUMP SYSTEM---------
T ANGLE:              30.0 DEGREES    Jacuzzi S4XP-4
. PWR. CURRENT:            10.0 A.    Jacuzzi 1000WA
IMUM POWER:               516.9 W.    DIRECTLY COUPLED TO ARRAY

 INC M53        2.49 A. @ 17.3 V.     AVG. DAILY OUTPUT:        22.2 CU.M
  (S) X     4 (P) =      12 TOTAL     SYSTEM HEAD:               12.0  M.
 --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- --- ---

            ----------SYSTEM DESIGN ANALYSIS----------


          FLAT     PANEL     MEAN AIR     RAINFALL      AVG.
 MONTH    LANG     LANG      TEMP (C)     (AVG. MM)     CU.M/DAY

  JAN      532      466        25.6         0.00          15.1
  FEB      498      465        25.3         0.00          15.7
  MAR      497      513        24.2         0.00          21.3
  APR      439      509        22.5         0.00          22.3
  MAY      408      525        18.6         0.00          25.3
  JUN      377      511        15.3         0.00          24.7
  JUL      409      542        15.3         0.00          27.4
  AUG      482      585        18.3         0.00          29.5
  SEP      545      589        22.8         0.00          28.1
  OCT      554      534        26.4         0.00          22.6
  NOV      570      505        26.7         0.00          19.2
  DEC      546      469        25.8         0.00          15.2

               NOTE:  ARRAY TO FACE TRUE NORTH

RFORMANCE OF SYSTEM AT INSTALLATION SITE WILL VARY DEPENDENT
ON WEATHER CONDITIONS AND ADEQUACY OF INSTALLATION AND MAINTENANCE.
```

Figure 10 - Computer simulation program output for PV pumping (courtesy ARCO Solar, Inc.)

3.3 Pumping Equipment and Instrumentation Installation

All of the installations will be surrounded by a protective fence so that the pumping equipment and the instrumentation will not be disturbed. For the PV pumps, the fence will also serve the purpose of keeping people and animals away from the high-voltage lines (up to 180 volts) which can cause serious injury. All PV arrays will be mounted on concrete pads or footings, according to the recommendations in the references.

3.3.1 Windmills

Windmills will be installed using standard procedures contained in the references in the Appendices. In addition, Wind Baron is supplying a detailed ass bly and installation manual for its machines. Gin poles will be used for erection if no cranes are available on-site. Water storage tanks should be capable of storing the equivalent of at least four days supply. No float valves should be used on the storage tanks to shut off the flow of water, as this would constrain the pumping system performance. If output is greater than demand, the excess water should be piped back into the well from the tank. This applies to the solar electric water systems as well.

The anemometers should be placed at the same height as the windmills so that no extrapolation of the wind data will have to be performed. The anemometers can either be placed on booms extending well out to the side of the towers or on separate poles. They should be situated such that the wind turbulence caused by the machine and tower affects the readings as little as possible.

Pump stroke counters or RPM counters for the Mono-coupled machines will be mounted on the slowest moving shaft for ease of measurement. For reciprocating pumps, a magnetically driven microswitch mounted on the stuffing box will pulse each time a magnet mounted on the pump or sucker rod moves past. For the rotational pumps, RPM will be counted by a metal disc mounted on the drive shaft rotating past a similar type or switch supported from the tower.

The water flow meters should be placed in the delivery pipe downstream of the pressure gauges, after the discharge head of the well. The meter and gauge should be placed at least three feet away from any angles in the pipe to assure a smooth flow through the instruments. The sensor terminal box with the battery power supply will be mounted in an accessible position on the tower so that the regular monthly readings and pump and power curve generation tests will be facilitated for the monitoring technicians. Detailed instructions for instrument installation will be given in the instrumentation manuals and installation workshops.

3.3.2 Photovoltaic Pumps

All of the photovoltaic arrays should be set as close as possible so that the tilt angle of the array from the horizontal is the same as the latitude of the site (about 30 degrees). This will insure the most constant monthly delivery of water to the end-users, since the systems are to be used for drinking water rather than irrigation. If they were to be used for irrigation, the arrays should be set at a lower angle (15-20 degrees up from horizontal) to maximize the water output in the summer when the sun is high in the sky. All arrays should face due north.

Mono-Coupled Honeywell 1.5 HP Motor

The Mono-coupled, PV-driven motor will be the simplest retrofit, since the pump is already installed. After the array support structures are assembled on a concrete base within a fenced enclosure, the panels will be wired 12 in series by 3 in parallel. The power out of the array will be connected directly to the PCU. Output from the PCU will go to the 1.5 HP motor, which will be mounted on a standard electric motor discharge head. The 1750 RPM motor will have a 4.5 inch double "V" belt pulley which will reduce the pump RPM to 800. This is in the range of most efficient operation of the pump.

Jacuzzi Submersible with PCU

These two systems will be installed in hitherto unused boreholes. Well casings for these two pumps must be at least five inches in diameter for installation of the pumps. This involves simply screwing the pumps onto the drop pipe sections, attaching the power cable and lower water-sensing switch, and lowering additional pipe sections until the required depth is reached. The two-wire power cable is then attached to the PCU mounted on the array support structure on a concrete slab within a fenced enclosure. The array power cable is then connected to the PCU "array-in" terminals, and the pump turned on.

Jacuzzi Submersible without PCU

Installation is essentially the same as above, except that the array is connected directly to the pump power cable. The pump then runs directly off the array output.

PV Instrumentation Installation

Instrumentation installation for these systems differs only slightly. In all cases, there will be a flowmeter in the discharge pipe after the wellhead, with the pressure gauge upstream of it. Again, this meter should be place at least one meter downstream of any angles or turbulence-producing fittings in the flow path. Also, in all cases, there is a power transducer measuring the power output directly out of the array. In the systems where there is power conditioning equipment, there will be a second transducer measuring the power output from the PCU to the pump.

The fourth, fifth and sixth measurements will be common to all systems. These are the "pump-on" elapsed timer (driven by the flowmeter output), the total elapsed timer, and the radiation measurement in the plane of the array (using a global pyranometer). The pyranometer will be securely mounted on top of the array structure and well away from any possible shading by obstructions.

3.3.3 Diesel Pumps

Since all of the diesel pumps are already in place, no installation is required. Diesel pump parameters to be measured are the rate of fuel consumption, the water output or the pump (at a measured RPM of the diesel and pump rotor), pump-on time, and total elapsed time since reset (beginning of the experiment). The fuel consumption will be measured by a single flowmeter on a feeder line to the tank apparatus described in Section 2.4.3. The water flowmeter will be placed in its normal configuration downstream of the discharge pressure gauge and downstream of the wellhead. The timers will be contained in the main instrument display box mounted near the diesel engine but on a separate mount to eliminate degradation from vibration.

All the sensors will be connected through a transient protection module, which helps guard the electronics against static discharge or nearby lightning strikes. Any direct strikes will destroy the equipment, and guaranteed safeguards against this eventuality are simply not available. However, a careful grounding strategy will protect the equipment under most conditions likely to be encountered. The transient proctection module, as well as the panels and array support structures, should be grounded using a three-stake arrangement with two-meter solid copper ground stakes located at the points of an equilateral triangle at least 10 meters apart.

The instrument packs should be mounted inside a well-ventilated enclosure which has screening over the ventholes to prevent any unwanted inhabitants. The enclosure should be painted white to reduce unwanted heat absorption, since the instruments are subject to heat damage above about 50C. The enclosure should be locked down to prevent theft. Bolts on the interior weatherproof box around the instruments have tamper-resistant bolts as well.

4.0 ANALYTICAL PROCEDURE FOR DATA COLLECTION AND ANALYSIS

The two types of data being recorded during the comparative testing program will be treated differently. The short-term data will be used to generate pumping-system capacity curves, as discussed in the Instrumentation subsection of Section 2.4. These curves can be viewed as representing the potential capacity of the given system. They will be used to determine the output of a similar system on another site, given a description of the energy resources available at the other site.

The long-term continuous data will characterize in detail the performance of the system at that particular site. This will be used to generate economic analyses which contain data covering operation and maintenance costs, a measure of downtime resulting in water unavailability, and the costs of a backup system to operate during the periods when the RET pumping system is not meeting the minimum water supply requirements.

4.1 Technical Comparison of Wind Systems

4.1.1 Data Collection Procedure

On a monthly basis, a technician trained in the use of the instrumentation will visit each site for a full two-day period. The following equipment should be taken along on each site visit:

- replacement battery pack for instruments,
- dessicant (drying) pack for replacement, if required,
- multimeter for troubleshooting,
- hand-held tachometer for measuring RPM,
- well-sounder and extra cable (in case of breakage),
- Data Collection Sheets for windmill data collection,
- hand calculator for efficiency checking calculations,
- Polaroid camera for back-up data retrieval, and
- a copy of this report for reference.

During each site visit, the technician will perform the following tasks (these procedures will be revised as necessary depending on their suitability in the field):

- On the Data Collection Sheet (Wind DCS, see Appendices), the technician will record all the variables for the complete description of the site and wind machine: location, borehole number, name and model of the windmill, rotor diameter, cylinder size and length of stroke (or Mono pump description as appropriate), tower height, etc.

- Then, take several pictures of the face of the instrumentation pack, making sure that all LCDs (liquid crystal displays) are clearly visible in the photograph. On the back of each photograph, list the site name, the date, and your initials.

- The totaled values for accumulated time in each of the 16 windspeed bins will be recorded on the DCS. After having recorded all 16 values, check to make sure that the values correspond to the correct bins.
- The accumulated values of total water volume pumped, total strokes, total pump on-time, and total elapsed time will then be recorded.
- With the well-sounder carried to the site, the technician will record the water rest level (if the windmill is not pumping at some point during the visit). At a time of relatively high windspeed, the pumping water level will be recorded on the DCS along with the average windspeed at which the depth reading was taken. Both the rest water level and the pumping water level should be recorded twice, at different times during the site visit. The pressure gauge is read and recorded concurrently with pumping water level readings.
- Beginning early in the morning, when windspeed is usually low, the technician will conduct a series of short-term tests to generate "instantaneous" points of flow versus windspeed. Each test will last from one to two minutes (depending on what seems a more reasonable value based on the variability of the wind and water flows). In order to generate the most useful data, a wide range of wind speeds should be tested. Technicians can refer to the instantaneous windspeed LCD display to judge when the tests should be begun.
- To perform the "instantaneous" tests, the technician must first "freeze" the display (by touching the magnet to the appropriate spot on the instrument box) and record on the DCS the individual values for total wind run, total elapsed time, total flow, and total strokes (or rotations). After writing down and re-checking these four values, "unfreeze" the display and watch the total elapsed time counter. When one (or two) minutes have passed, "freeze" the display again. In the same way as before, write down the values of the same four variables. After checking for recording accuracy, then "unfreeze" display.
- On the DCS, subtract the two values of total wind run. This gives the wind run for the period. Now subtract the two elapsed time values. Divide the wind run for the period by the elapsed time value to get the average

windspeed during that time. Subtract the two values for flow. Divide that number by the elapsed time just calculated. This gives average flowrate at the average windspeed which was just calculated. Repeat this test and calculations 30 times during the site visit, using as wide a windspeed range as possible.

- If windmill start-up occurs during the site visit, record the start-up windspeed on the DCS. Each time the machine stops and then starts up again, record the average windspeed at which this took place. This will allow more accurate determination of the actual cut-in (start-up) windspeed. Note stroke count or RPM at rated windspeed if it occurs.

- If the wind machine being tested is one of the RIIC or WTGS machines driving a Mono pump, use the tachometer during the short-term tests to determine the average RPM of the pump shaft, and record it in the stroke columm of the DCS.

- The technician, having gathered all the necessary data, will then do a brief series of calculations to determine overall system efficiency (see Data Analysis below) to make sure that the readings taken are reasonable. System efficiency should be between 5 and 20 percent. If this is not the case, re-check the calculations. If no explanation is apparent, then check the equipment and question the water-users to see if the system has been operating properly. In any event, a thorough visual inspection of all the equipment should be made to determine that it is in satisfactory condition and working properly.

- Perform the service procedures discussed in the instrumentation manual, including battery exchange, dessicant cannister checking, inspection of all cables and wire connections, and inspection of the instrument box to make sure that the weather-tight seal is intact.

- The water end-users at the site should be consulted and any operation anomalies discussed. The short interview questions on the back of the DCS should be asked. If they have any reason to believe that the system is working improperly, or not working at all, the technician should attempt to ascertain the reasons involved. If possible, the technician should troubleshoot the system to determine if simple repairs can put the system back in operation. No repairs of electronic components should be attempted in the field by unqualified persons. Any relevant comments which might be helpful to repair crews should be recorded on the back of the DCSs. That will conclude data collection for that visit.

4.1.2 Data Analysis

After the data have been gathered from the field sites, they should be brought to the BRET Office and immediately duplicated. This will help prevent undue loss or data. After duplication, one copy of the DCSs, as well as the photographs taken on-site, should be stored in a locked cabinet. The remaining copy will be analyzed by BRET technicians in the following way:

- First, the monthly accumulated compilator data for the site wind regime will be graphed according to the procedure outlined in the BRET Wind Consultancy Report, where histograms of wind duration in each of the compilator bins, in addition to the available power in the wind, are calculated and graphed.

- The average values for water pumped and strokes counted (or total revolutions in the case of the Mono pumps) over the month will be determined, on a monthly as well as daily basis. Since it is unlikely that the data will be recorded exactly on a monthly basis, it should be normalized to that basis as follows:

$$AP = TP \times 31/TD$$

where: AP = average monthly water pumped
TP = total water pumped since last recording
31 = number of days in average month
TD = total number of days since last recording

- Knowing the number of strokes it took to pump a certain volume of water enables the determination of the cylinder volumetric efficiency (VE). Determine the actual cylinder internal volume by referring to the Appendix table of "Amount of Water Discharged Per Stroke. Convert this volume to liters by dividing gallons by 3.785. Multiply this volume by the number of strokes recorded. Divide the actual recorded flow over the period by the calculated strokes x cylinder volume. This gives the value for VE. VE will probably decrease over the period of the experiment as the rubber pump stator (for Mono pumps) or the leathers (for reciprocating piston pumps) become worn. In the latter case, a dramatically reduced VE might indicate the need to replace the cylinder leathers. VE should be greater than 80%.

- To determine the instantaneous points of system efficiency, it is necessary to calculate the hydraulic power represented by the water actually pumped by the windmill against the total pumping head (not including friction head) of the system. From the short-term testing data, select average points over the range of the output versus windspeed curve. For each of the points, compute the system efficiency by taking the hydraulic power represented by actual water pumped at this head and dividing by the power available in the the wind at the windspeed for that point.

For example, at a wind speed of 14 km/hr (3.89 m/sec), with an air density of 1.01 kg/m3 and using a six-meter diameter rotor,

$$\text{Power} = 0.5 \times \text{air density} \times (\text{windspeed})^3 \times \text{rotor area}$$

$$= 0.5 \times 1.01\ \text{kg/m3} \times (3.89\ \text{m/sec})^3 \times \text{pi} \times 9\ \text{m2}$$

$$= 840\ \text{watts}$$

NOTE: The Standard Atmosphere assigns a value of 1.225 kg/m3 to the density of air at sea level. The average altitude in Botswana is approximately 1000 meters. From the Table of Properties of the Atmosphere, (see the Appendices) at this altitude, the atmospheric density is 0.9075 as much as at sea level. Therefore, for efficiency calculations, use either 1.112 kg/m3 or the appropriate corrected value.

Now, let us assume that the windmill is pumping 2.0 cubic meters per hour against a total vertical head of 31 meters. From the formula given in Section 3.2.1 for the determination of hydraulic power (flow x head x 9.81), this is equivalent to:

$$\frac{2.0\ \text{m}^3/\text{hr} \times 1000\ \text{liters/m}^3 \times 31\ \text{m} \times 9.81}{3600\ \text{sec/hr}}$$

or 169 watts.

The system efficiency is then:

$$\text{Efficiency} = \frac{\text{Hydraulic Output}}{\text{Power Available in the Wind}} = \frac{169}{840} = 20\%$$

- Plot overall system efficiency versus windspeed over the range of windspeeds for which the short-term data were recorded. Since it is likely that the technician will not be able to record windspeed (and associated flow-rates) over a wide range during each site visit, the range of the data will increase with each additional month's readings.

- From the results of the short-term testing, plot the points of water output as a function of windspeed. There should be 30 points on this graph. If it happens that a particular range of windspeed has no points in it, try to specifically fill in these blank areas during the next site visit. Graph these data after each site visit and determine if there is any change with time.

- Having calculated the total power available in the wind in kWh over the last data collection period (according to the BRET Wind Consultancy, above), the overall average system efficiency can be readily calculated. First, determine the hydraulic energy represented by the volume of water pumped since the last data retrieval. This is the total liters pumped times total head (<u>not</u> including friction losses) times 9.81 (gravitational constant) and divided by 3,600,000 to get kWh. Then divide the total hydraulic energy by the total energy available in the wind over the data collection period. This gives monthly average system efficiency.

- Drastic reductions in system output at a given windspeed would indicate either faulty pumping equipment, instrumentation or incorrect data retrieval procedures. If this occurs, it should be thoroughly investigated and corrected as soon as possible. Since gradual decreases in output will not likely be noticed by the system users, <u>DATA ANALYSIS SHOULD BE PERFORMED ON AN ONGOING BASIS. DATA SHOULD UNDER NO CIRCUMSTANCES BE ANALYZED MORE THAN ONE MONTH AFTER RETRIEVAL.</u>

- A number of other calculations can be made from the data collected. The appropriateness and necessity of additional calculations can be made as the experiment progresses.

4.2 Technical Comparison of PV Systems

4.2.1 Data Collection Procedure

In the same manner as the windmill data collection, PV pump data will be collected on a long-term continuous basis as well as from short-term intensive studies. The latter will be used to generate pump capacity curves as a function of the incident radiation on the photovoltaic array. For each site visit, the technician will take the following equipment:

- replacement battery pack for instruments,
- dessicant (drying) pack for replacement, if required,
- multimeter for troubleshooting,
- hand-held tachometer for measuring RPM,
- well-sounder and extra cable (in case of breakage),
- Data Collection Sheets for PV pump data collection,
- hand calculator for efficiency checking calculations,
- Polaroid camera for back-up data retrieval, and
- a copy of this report for reference.

During each site visit, the technician will perform the following tasks (these procedures will be revised as necessary depending on their suitability in the field):

- On the DCS for PV systems, the technician will record all pertinent site description information such as location, borehole number, the manufacturer's name, model number of PV pump and other system components (PCUs, panels), etc.

- Then, the technician will take several Polaroid pictures of the LCDs (liquid crystal displays), making sure that all the experimental quantities can be readily seen.

- Record the six parameters on the LCD displays: total radiation, total power from the array, total power to the pump, total water output, total pump on-time, and elapsed time since the last site visit.

- With the well-sounder carried to the site, the technician will record the rest (static) water level in the well early in the morning before the pump turns on. Near noon, with the pump running at near full capacity, record the pumping water level at two different times. Then, after the pump shuts down in the evening, record the water rest level again. Record the pressure gauge readings both times the pumping water level is recorded.

- When the pump starts in the morning, record the value of the incident radiation on the DCS. Try to schedule the site visit so that this can be done on two consecutive mornings.

- Near noon, when the pump is running near full capacity, take three separate readings of pump RPM with the hand-held tachometer, and record them on the DCS.

- To begin the short-term tests, with the pump running, record dynamic head, pressure, then freeze the display. Record all of the parameter values except the pump on-time counter on the DCS. Unfreeze the display and wait for one to two minutes to pass on the elapsed time counter. Freeze the display again and record all the values a second time. Determine and record the pump RPM with the hand-held tachometer if a Mono pump is being tested. Repeat this test 30 times during the day, making note of the time of day each test was performed. Try to perform the tests over a wide range of radiation intensities, both in the morning and the afternoon.

- Having gathered all the necessary data from the instrumentation, perform the necessary calculations to make sure that the data are reasonable (see Data Analysis below). If the efficiency calculations give unexpected answers, redo them. If this doesn't work, carefully check the pumping equipment and instrumentation to try and determine the source of the problem.

- Perform the service procedures for the instrumentation package which are explained in the instrument manual, including battery check and replacement, dessicant cannister inspection and possible replacement, etc.

- Finally, perform a thorough inspection of all the pumping equipment and instrumentation to make sure that all equipment is operating properly. This should include an inspection of all cables and wires for loose connections, and a careful inspection of the instrumentation box to see that the water and dust seal are intact.

- The water end-users near the site should then be interviewed according to the format given in the DCS and any operational anomalies of the system should be thoroughly discussed. If there is any reason to believe the system is working improperly, or not at all, the technician should try to ascertain the possible reasons involved. If possible, the technician should troubleshoot the system to determine if some simple repair, like tightening a connection, might solve the problem. No repairs or electronic equipment should be attempted in the field by unqualified personnel. Any relevant comments which might be helpful to repair crews should be noted on the back of the DCS. This concludes the site visit procedure.

4.2.2 Data Analysis

After the data have been collected from the sites, it should immediately be brought to the BRET office in Gaborone and duplicated. This will help to prevent undue loss of data. After duplication, one copy of the DCS, along with the photographs taken during the site visits, should be filed in chronological order in a locked cabinet. The other copy will be analyzed by BRET technicians in the following way:

- First, take the total radiation on the collector plane since the last site visit and divide by the number of days (converted from the minutes on the elapsed time counter) to get an average daily radiation value. Do the same for the power out of the array, the power to the pump (although these will sometimes be equal for the directly coupled systems), and the water output.

- Determine the PV array efficiency by first calculating the total area of the array (area of a single panel x number of panels). Multiply the daily incident radiation value obtained above by the area of the array. This gives total incident radiation on the array on an average daily basis. Divide this value into the average daily power out of the array to get the daily array efficiency.

- Determine the overall system efficiency by first determining the hydraulic energy represented by the volume of water pumped since the last site visit. Energy in kWh equals volume times head times 9.81 (the gravitational constant) divided by a constant (3.6-E6, i.e, 3,600,000 when volume is in liters and head in meters). For example, assume the system has pumped 900,000 liters against a 30 meter head (total head but <u>not</u> including friction losses). The hydraulic energy to do this is:

  $$E(h) = \frac{900{,}000 \times 30 \times 9.81}{3{,}600{,}000} = 73.6 \text{ kWh}$$

  Now divide this by the total amount of energy (in kWh) incident upon the array over that period (this was calculated in the Daily Array Efficiency above). This gives the monthly average total system efficiency. It should be on the order of four to seven percent.

  Continuing the example, assume that the array is 11.9 square meters. If the radiation measurement for thirty days was 130 kWh per square meter. The overall system efficiency is then:

  $$\%\,\text{Eff} = \frac{73.6 \text{ kWh}}{11.9 \times 130} = 4.8\%$$

- The pumping subsystem efficiency can be calculated in the same way as the overall system efficiency. After having calculated the theoretical energy required to pump the monthly total water volume (as described above), instead of dividing by the energy incident on the array, divide by the total energy delivered to the pump.

- To determine the percentage loss due to the PCU, divide the energy delivered to the pump by the total energy out of the array. This number should be 70-95%.

- After several monthly data sets have been taken, make plots of the following relationships:

  —monthly average daily radiation (kWh) on the array plane vs. time (i.e., by month);
  —array output (kWh) vs. time (i.e., by month);
  —array efficiency (%) vs. time (i.e., by month);
  —monthly average daily water volume pumped (cubic meters) vs. monthly average daily total radiation on the array (kWh); and
  —monthly average daily overall system efficiency (%) vs. monthly average daily radiation on the array (kWh).

- From the short-term data, generate plots of instantaneous water output as a function of instantaneous radiation on the array plane. Each month the newly generated curves should be compared with those drawn previously to see if there is any degredation in system performance over time.

- Also from the short-term data, generate curves of instantaneous water output as a function of power to the pump. In the case of the Mono-coupled system, these should be given as a family of curves at fixed RPM levels (see Figure 3). These curves should also be compared to determine any pump performance degredation over time.

- Drastic reductions in system output at a given level of irradiance would indicate either faulty pumping equipment, instrumentation or incorrect data retrieval procedures. If this occurs, it should be thoroughly investigated and corrected as soon as possible. Since gradual decreases in output will not likely be noticed by the system users, DATA ANALYSIS SHOULD BE PERFORMED ON AN ONGOING BASIS. DATA SHOULD UNDER NO CIRCUMSTANCES BE ANALYZED MORE THAN ONE MONTH AFTER RETRIEVAL.

- Several other relationships might prove to be of interest as the experiment progresses. These can be determined from the data already collected and graphed as deemed appropriate.

4.3 Technical Comparison of Diesel Systems

4.3.1 Data Collection Procedure

On a monthly basis, a technician trained in the use of the instrumentation will visit each site for a full two-day period. The following equipment should be taken along on each site visit:

- replacement battery pack for instruments,
- dessicant (drying) pack for replacement, if required,
- multimeter for troubleshooting,
- well-sounder and extra cable (in case of breakage),
- hand-held tachometer for RPM measurements,
- Data Collection Sheets for diesel data collection,
- hand calculator for efficiency checking calculations,
- Polaroid camera for back-up data retrieval, and
- a copy of this report for reference.

During each site visit, the technician will perform the following tasks:

- On the Data Collection Sheet (DCS, see Appendix), the technician will record all the variables for the complete description of the site and wind machine: location, borehole number, name and model of the diesel engine, Mono pump type and model number, etc., as indicated.

- Then, take several pictures of the face of the instrumentation, making sure that all digital or mechanical counters on the fuel and water flowmeters are clearly visible in the photograph. On the back of each photograph, list the site name, the date, and your initials.

- The accumulated values of total water volume pumped, total fuel consumption, total pump on-time, and total elapsed time will then be recorded.

- With the well-sounder carried to the site, the technician will record the water rest level at a time when the diesel engine is not running. Later, when the engine is running the pump at full speed, record the pumping water level. Both the rest water level and the pumping water level should each be recorded twice, at different times during the site visit. Read and record the pressure gauge reading at the same time as the pumping water level readings.

- During pump operation, the technician will conduct a series of short-term tests to generate "instantaneous" points of water output as a function of fuel consumption. Each test will last from one to five minutes (depending on what seems a more reasonable value based on the variability of the fuel and water flows).

- To perform the short-term tests, first warm up the engine to normal operating temperature. With the pump running, record on the DCS the individual values for total elapsed time, total fuel consumption, and total water flow. After writing down and re-checking these three values, take two separate readings with the tachometer to get the revolutions per minute (RPM) of the pump shaft and the diesel shaft. Watch the total elapsed time counter as you do this, noting when five minutes have passed since the test began. When it has, write down the values of the same three variables just as you did at the start of the test.

- On the DCS, subtract the two values of total elapsed time. Similarly, find fuel consumption and water flow over the five minute period by subtracting their respective values. Write down the pulley ratio (pulley on diesel shaft diameter over pump shaft pulley diameter). This will serve as a check on the diesel shaft and pump shaft RPM readings, which later will be used to check against the manufacturer's output specifications or power output at a given RPM and fuel consumption rate.

- Divide total water flow by the difference in elapsed time (close to five minutes) to get the average water flowrate during the test. Similarly, divide the total fuel consumption for the test by the difference in elapsed time to get the fuel flowrate during the test. Repeat this test and calculations 15 times during the site visit. Not as many tests are required as the PV and wind pumping tests because, presumably, the diesel will have an approximately constant power (hence water) output at a given fuel consumption rate, which itself will be approximately constant.

- The technician, having gathered all the necessary data, will then do a brief series of calculations to determine overall system efficiency (see Data Analysis below) to make sure that the readings taken are reasonable. The total system efficiency (fuel input to hydraulic output) should be between 4 and 15 percent. This comes from the multiplication of the efficiencies of each of the system components: diesel engine (15%); drive shaft (90%); Mono pump (50%); and line shaft (80%), i.e., as low as 5% for the whole system. If this is not the case, then re-check the calculations. If no explanation is apparent, then check the equipment and question the water users to see if the system has been operating properly. In any event, a thorough visual inspection of all the equipment should be made to determine that it is in satisfactory condition and working properly.

- Perform the service procedures discussed in the instrumentation manual, including battery exchange, dessicant cannister checking, inspection of all cables and wire connections, and inspection of the instrument box to make sure that the weather-tight seal is intact. Wipe off any grease, fuel or dirt on the instruments.

- The water end-users and the diesel operator(s) at the site should be consulted and any operation anomalies discussed. The short interview questions on the back of the DCS should be asked. If they have any reason to believe that the system is working improperly, or not working at all, the technician should attempt to ascertain the reasons involved. If possible, the technician should troubleshoot the system to determine if simple repairs can put the system back in operation. No repairs of electronic components should be attempted in the field by unqualified persons. Any relevant comments which might be helpful to repair crews should be recorded on the back of the DCSs. That will conclude data collection for that visit.

4.3.2 Diesel Data Analysis

After the data have been gathered from the field sites, they should be brought to the BRET Office and immediately duplicated. This will help prevent undue loss of data. After duplication, one copy of the DCSs, as well as the photographs taken on-site, should be stored in a locked cabinet. The remaining copy will be analyzed by BRET technicians in the following way:

- The average values for water pumped and fuel consumed over the month will be determined, on a monthly as well as daily basis. Since it is unlikely that the data will be recorded exactly on a monthly basis, it should be normalized to that basis as follows:

  $$AP = TP \times 31/TD$$

  where: AP = average monthly water pumped
  TP = total water pumped since last recording
  31 = number of days in average month
  TD = total number of days since last recording
  Substitute FC (fuel consumed) for TP to get normalized monthly fuel consumption. To determine average daily water pumped, divide each of the monthly values by 31.

- Knowing the number of revolutions it took to pump a certain volume of water enables the determination of the pump rotor and stator degredation due to the wearing action of sand and grit in the well water. The volume of water pumped at a given RPM will decrease somewhat with time as the rubber stator becomes worn. Plot the water flowrate versus RPM as a function of time to determine if there is a reduction in the volumetric efficiency of the pump.

- To determine the overall pumping system efficiency, it is necessary to calculate the theoretical power it takes to pump water against the total pumping head of the system. Head determination was outlined in Section 3.2.1d.

- Now determine the energy available in the fuel being consumed by the diesel. From the Diesel DCS, at a fuel consumption rate of one liter per hour, assuming that each liter of diesel has an energy content of about 38 MJ (10.5 kWh) the energy being delivered to the engine at 2000 RPM is 10.5 kWh per hour.

- Now, let us assume that the diesel is pumping 10.0 cubic meters per hour against a total pumping head of 24 meters. The hydraulic energy required to pump the water is 10.0/3.6 x 24 x 9.81 = 0.654 kWh. Hence, the system efficiency is:

$$\%\ \text{Eff.} = \frac{\text{Hydraulic Energy Required}}{\text{Energy Available in the fuel}} = \frac{0.654\ \text{kWh}}{10.50\ \text{kWh}} = 6\%$$

- Plot water output as a function of fuel consumption over the range of fuel flowrates recorded during the short-term testing. Increased fuel consumption per unit of water pumped will be an indicator that the system efficiency is dropping, indicating a need for maintenance procedures, or possibly an overhaul.

- Drastic reductions in system output at a given rate of fuel consumption would indicate either faulty pumping equipment, instrumentation or incorrect data retrieval procedures. If this occurs, it should be thoroughly investigated and corrected as soon as possible. Since gradual decreases in output will not likely be noticed by the system users, DATA ANALYSIS SHOULD BE PERFORMED ON AN ONGOING BASIS. DATA SHOULD UNDER NO CIRCUMSTANCES BE ANALYZED MORE THAN ONE MONTH AFTER RETRIEVAL.

- A number of other calculations can be made from the data collected. The appropriateness and necessity of additional calculations can be made as the experiment progresses.

4.4 Economic Intercomparisons of PV, Wind and Diesel Pumping

From the cost data collected over the experiment, the system performance calculated from the monitoring equipment and the DCS can be expressed in terms of water output per unit cost. Besides a feel for the probable long-term reliability of each type of system, output per unit cost is the most important indicator of the desirability of one system over another.

Since there has been a precedent set in the case of economic analysis of PV pumping systems (see Appendix B), the concept of Specific Capital Cost (SCC) will be applied to make comparisons between the various PV systems tested. By definition:

$$SCC = \frac{C \times 1000}{rho \times g \times V \times H}$$

where:

SCC = specific capital costs, in terms of dollars per unit pumping energy per day (\$/kJ-day)
C = total installed capital cost of the system
1000 = units conversion constant
rho = density of water being pumped (kg/m3)
g = gravitational acceleration constant (9.81 m/sec^2)
V = water flowrate (cubic meters per day)
H = total pumping head (meters)

For example, let us assume that a particular PV system requires twelve \$345 PV panels, costs \$2650 for the balance of the system, and has shipping and installation costs of \$850. It pumps 22.2 cubic meters per day against a 12 meter head. Thus,

$$SCC = \frac{(12 \times \$345 + \$2650 + \$850) \times 1000}{1000 \frac{kg}{m3} \times 9.81 \frac{m}{s2} \times 22.2 \frac{m3}{day} \times 12 \ m} = \$2.92 \text{ per kJ/day}$$

There are obvious limitations to using SCC to compare with other types of pumping systems, other than photovoltaics. There are no operation and maintenance costs taken into consideration. Neither are general discount, inflation or fuel-cost inflation rates considered. However, for comparing PV systems which have identical expected lifetimes and are purchased concurrently, this method does provide a quick and easily computed factor for relative cost comparisons. It is recommended, therefore, that SCCs be computed and compared for the various PV pumping systems purchased and monitored for this experiment.

For the purpose of intercomparison between the various types of systems being tested (PV, wind, and diesel), the Life-Cycle Costing (LCC) technique, as presented in previous ARD consultancies for the BRET Project (see Ref. 7 and 8), should be used. Two examples of this procedure are given in Figures 11 and 12, one for a prototype RIIC windmill at 75 meters head

Machine: RIIC prototype #2 with mono ES-15 progressive cavity pump

Total pumped head: 75 m/ 100 m

Wind duration: 24 hours/day at $\bar{v}$

	Average ~~WIND SPEED~~ ($\bar{v}$)	
COSTS	13.6 km/hr (75 m)	13.6 km/hr (10
1. Initial capital cost (year 0):	8,500 (1)	8,500
2. Annual operating costs:	200	200
3. Present value of additional discounted capital costs @ 15% discount:	150	150
(replacement cylinders in years 5 and 10) @ 25% discount:	87	87
BENEFITS		
4. Water pumped - cubic meters/year :	2,956 (2) (3)	2,100
5. Annual value of water pumped, valued at $1.00/$m^3$:	2,956	2,100
6. Net annual benefits (water value minus operating costs; line 5 minus line 2) :	2,756	1,900
7. Net present value of benefit stream (years 1-10) @ 15%:	13,832	9,536
@ 25%:	9,840	6,794
8. Net present value of benefits minus costs (years 1-10) @ 15%:	5,182	886
@ 25%:	1,253	-1,803
9. Value of water that makes benefits minus costs (line 8) equal 0 @ 15%:	0.65	0.92
@ 25%:	0.88	1.24

(1) Projected cost (prototypes only available thus far).

(2) Extrapolated from 2 months' (March-May) field trials.

(3) During periods of very low $\bar{v}$, a diesel pump provided back-up power. Diesel-pumped water not included in output figure given.

NOTE: Figures for this machine given in Pula.

Figure 11 - Economic Analysis of a Windmill

Machine: Jacuzzi S425-10 submersible pump with 32 ARCO M53 modules

Total pumped head: 30 m

Solar radiation average: 5.7 $\frac{\text{Kwh}}{\text{m}^2\text{-day}}$ on the horizontal (i.e., approximates annual radiation in Gaborone)

COSTS

1. Initial capital cost (year 0)	12,000
2 Annual operating costs:	50
3. Present value of additional discounted capital costs @ 15% discount: (replacement cylinders in years 5 and 10)	1,000
@ 25% discount:	

BENEFITS

4. Water pumped - cubic meters/year :	11,060 (1)
5. Annual value of water pumped, valued at $1.00/$\text{m}^3$:	11,060
6. Net annual benefits (water value minus operating costs; line 5 minus line 2) :	11,010
7. Net present value of benefit stream (years 1-10) @ 15%:	55,259
@ 25%:	39,311
8. Net present value of benefits minus costs (years 1-10) @ 15%:	42,259
@ 25%:	26,311
9. Value of water that makes benefits minus costs (line 8) equal 0 @ 15%:	0.24
@ 25%:	0.33

(1) Output based on computer simulation, personal communication from David Harris.

Figure 12 - Economic Analysis of a PV Pump

(based on experimental performance data) and the other for a Jacuzzi PV pump (based on a computer simulation). The method is relatively simple and can easily be programmed for use on a hand calculator. One version of it is also available on the BRET microcomputer.

The method attempts to take account of all costs throughout the useful lifetime of a system (except for intangibles such as social impact). Several relative performance factors are calculated: Net Present Value (NPV) of Benefits Minus Costs (which includes an assumption of the value of water); Value of Water which makes NPV equal to zero (which removes an inaccuracy due to the water value assumption); and the Benefit/Cost Ratio (which, as it implies, is the ratio of all benefits accrued by the investment over the total costs incurred over the useful life of the system, again assuming a certain value for water pumped).

All of the systems monitored during the experiment should have their costs recorded on the Cost DCS given in the Appendices. From these data, LCC parameters should be computed and compared. In determining the cost figures to be included in the analysis, any relevant shadow prices (such as the cost of foreign exchange) should be factored into the financial calculations. Presentation of the results should be in the format of the examples shown.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 General Criteria for System Choice

This section of the final Comparative Testing Program should present the general criteria acording to which decision makers can choose a water pumping system for a particular site, given some knowledge of the constraints of demand on the system, borehole limitations, available capital resources, availability of renewable enrgy resources on site (e.g., wind/solar regimes), and the reliability and cost effectiveness of each of the different types of systems being considered.

The recommendations should be put into a simply understood matrix format. Given the parameters just mentioned, the choice of one or another system will fall out of a flowcharted series of programmed questions. Short- and long-term costs typically encountered for each system type will be given so that the final system choice can be made with some measure of confidence.

5.2 PV/Wind Pumping Applications in Botswana

The systems performing best in each category (deep well - greater than thirty meters, or shallow well - less than thirty meters, wind/PV/diesel) will be listed with their most important performance characteristics. These are: expected downtime per year, output as a function of total pumping head, initial capital cost, and probable annual operation/maintenance repair costs.

5.3 Wind and Solar Resource/Application Maps

Based on the data being collected by BRET, DWA and MET Services, regional maps of Botswana will be drawn up which will give estimates of renewable energy resources for all of Botswana. Decision makers will be able to tell at a glance, for instance, whether the site under consideration has a reasonable potential for windmill water pumping. If the maps do indicate this possibility, then the site should be further investigated by the installation of an anemometer before any final decision to purchase a wind machine is made.

These maps will also allow quick elimination of sites where the likelihood of a sufficient wind resource is low. Since the output of most pumps is also a function of pumping head, the maps will also give the maximum reasonable head that one could expect a wind machine to pump against, given the wind regime typical in that area.

Similar maps for proper siting or PV pumps will also be drawn up. It is expected, however, that the available solar radiation in Botswana does not vary significantly enough that there will be great differences between sites. This assumption will be investigated in the upcoming BRET/MET Services national radiation monitoring program.

6.0 SUGGESTIONS FOR FURTHER STUDY

As the results of the Comparative Testing Program are analyzed, it is likely that certain of the pumping systems being tested will perform much better than others. Certain parameters may prove themselves to be much more important than others in the system design process. As lessons are learned about the applications and limitations of the various system types to the specific conditions in Botswana, it may prove necessary to investigate other commercially available pumps which come on the market during the experiment. If further funding of this program becomes available, the data base attainable from further investigation will prove valuable not only to Botswana, but to all countries in Sub-Saharan Africa.

APPENDICES

BIBLIOGRAPHY

1. E. H. Lysen, 1983, Introduction to Wind Energy, Steering Committe for Wind Energy, the Netherlands.

2. J. Park, 1983, The Wind Power Book, Chesire Books, Calif.

3. M. Buresch, 1983, Photovoltaic Energy Systems, McGraw Hill Company, New York.

4. R. W. Fox and A.T. McDonald, 1978, Introduction to Fluid Mechanics, John Wiley and Sons, New York.

5. K. E. Anderson, 1981, Water Well Handbook, Missouri Water Well and Pump Contractors Association, Belle, Missouri.

6. W. Halcrow et al, 1983, Small-Scale Solar Powered Pumping Systems: The Technology, Its Economics and Advancement, ITDG, London.

7. J. A. Ashworth, 1983, Financial and Social Cost/Benefit Analysis of Renewable Energy Technologies in Botswana, A Consultancy Report, BRET.

8. R. Smith, 1983, Wind Energy Technology for the BRET Project, A Consultancy Report, BRET.

9. R. McGowan and J. Ashworth, 1983, Data Collection Handbook for Energy Systems Installed in Developing Countries, BRET.

10. L. B. Hamilton, D. Norris and B. Sachs, 1984, Passive Solar Design Workbook, BRET.

11. C. C. Gonzalez, G. M. Hill, and R. G. Ross, 1982, Photovoltaic Array - Power Conditioner Interface Characteristics, JPL, US DOE Flat Plate Solar Array Project.

12. IT Power, Ltd., 1983, Wind Technology Assessment Study, Volume One, Wind Study Report, the World Bank, Reading, UK.

13. W. Halcrow and Partners, 1984, Handbook on Solar Water Pumping, IT Power Ltd., London.

14. W. Halcrow and Partners, 1983, Small Scale Solar Powered Pumping Systems: The Technology, Its Economics and Advancement, Main Report, IT Power Ltd., London.

PART ONE
PERFORMANCE DATA COLLECTION SHEETS

WINDMILL WATER PUMPING SYSTEM DATA COLLECTION SHEET

1. Site Description: Location: ______________________________
Site Latitude: _____; Longitude: _____; Altitude: _____ m
Describe the terrain near the site (flat, hilly, trees, etc.)
____
____

2. Windmill Description (from manufacturer's literature)
Manufacturer and Model No.: ______________________________
Rotor Diameter: ___ m; Number of Blades: _______
Rotor RPM ____ at Rated Windspeed of: ____ km/hr
Maximum Rotor RPM: _____ at ______ km/hr
Cut-In Windspeed: ____ km/hr; Furling Windspeed: ____ km/hr
Survival Windspeed: ____ km/hr; Ground to Rotor C-Line: ____ m
Axis Orientation: __ Horizontal or __ Vertical (check one)
Mechanical Power Transmission (gear or belt): ______________
Gear or Pulley Ratio: ____________

3. Borehole and Pump Description (fill in A and either B or C)

A. Borehole No.:________; Recorded Rest Water Level: _____ m
Pumping Water Level: ______ m; Discharge Head: _____ m
Dynamic Head of ____ m of Pipe of ____ mm Outside Diameter
Measured at Flowrate of: _______ liters/sec
Pipe Type (galvanized steel, PVC, etc.): ________________
Outside Casing Diameter: ____ mm; Tank Size: _____ m3

B. Cylinder: Cylinder Type and Material (tube/rod type, bronze leathered or O'Bannon type, etc.)____________________
Length of Stroke: ____ m; Cylinder Diameter: ____ m;

C. Mono Pump: Model No.(ES-10, ES-15S,etc.):________________
Break-out Torque: _______ (ft-lbf or N-m, circle which)
Rated Output: _____ liters/min @ _____ RPM @ _____ m head
Absorbed Power at Rated Output: ______ kW

4. Continuous Data Measurements Since Last Site Visit

A. Accumulated Windspeed Bin Values (minutes per bin)

Bin 1: ______ (0- 2 km/hr)
Bin 2: ______ (2- 4 km/hr)
Bin 3: ______ (4- 6 km/hr)
Bin 4: ______ (6- 8 km/hr)
Bin 5: ______ (8-10 km/hr)
Bin 6: ______ (10-12 km/hr)
Bin 7: ______ (12-14 km/hr)
Bin 8: ______ (14-16 km/hr)
Bin 9: ______ (16-18 km/hr)
Bin 10: ______ (18-20 km/hr)
Bin 11: ______ (20-22 km/hr)
Bin 12: ______ (22-24 km/hr)
Bin 13: ______ (24-26 km/hr)
Bin 14: ______ (26-28 km/hr)
Bin 15: ______ (28-30 km/hr)
Bin 16: ______ (> 30 km/hr)

B. Total Water Volume Pumped: ______________________ liters
Total Wind Run: ______________________ km
Total Strokes Recorded: ______________________ strokes
Total Pump On-Time: ______________________ minutes
Total Elapsed Time: ______________________ minutes

5. Short-Term Testing

A. Display Freezing for "Instantaneous" Tests

	Elapsed Time (minutes)	Wind Run (km)	Flow (liters)	Strokes
Test 1 - Start				
Stop				
Difference				

$\frac{\text{Wind Run x 60}}{\text{Elapsed Time}}$ = ______ km hr; $\frac{\text{Total Flow}}{\text{Elapsed Time}}$ = ______ liters/min

Test 2 - Start				
Stop				
Difference				

$\frac{\text{Wind Run x 60}}{\text{Elapsed Time}}$ = ______ km hr; $\frac{\text{Total Flow}}{\text{Elapsed Time}}$ = ______ liters/min

Test 3 - Start				
Stop				
Difference				

$\frac{\text{Wind Run x 60}}{\text{Elapsed Time}}$ = ______ km hr; $\frac{\text{Total Flow}}{\text{Elapsed Time}}$ = ______ liters/min

Test 4 - Start				
Stop				
Difference				

$\frac{\text{Wind Run x 60}}{\text{Elapsed Time}}$ = ______ km hr; $\frac{\text{Total Flow}}{\text{Elapsed Time}}$ = ______ liters/min

Test 5 - Start				
Stop				
Difference				

$\frac{\text{Wind Run x 60}}{\text{Elapsed Time}}$ = ______ km hr; $\frac{\text{Total Flow}}{\text{Elapsed Time}}$ = ______ liters/min

Test 6 - Start				
Stop				
Difference				

$\frac{\text{Wind Run x 60}}{\text{Elapsed Time}}$ = ______ km hr; $\frac{\text{Total Flow}}{\text{Elapsed Time}}$ = ______ liters/min

Test 7 - Start				
Stop				
Difference				

$\frac{\text{Wind Run x 60}}{\text{Elapsed Time}}$ = ______ km hr; $\frac{\text{Total Flow}}{\text{Elapsed Time}}$ = ______ liters/min

B. Well Sounding
Rest Water Level: Test 1: ____ m; Test 2:____ m
Pumping Water Level:
Test 1: ____ m @ ____ km/hr windspeed @ ____ PSI pressure
@ flowrate of: ______ liters/sec after: ___ minutes
Test 2: ____ m @ ____ km/hr windspeed @ ____ PSI pressure
@ flowrate of: ______ liters/sec after: ___ minutes

C. Windmill Start-Up Windspeed (km/hr): 1)____ 2)____ 3)____

D. Overall Pumping System Efficiency

Calculate the total lift by adding the pumping water level (m) to the discharge head (convert pressure reading in PSI to meters by multiplying by 0.703 m/PSI). See the worked example of the following procedure in Section IV.1.2, Data Analysis.

Rotor Area = pi/4 x (rotor diameter)^2 = _____ m^2

Point for Calculation: Take a representative point from the short term tests for flowrate and windspeed: ______ liters/min @ ______ km/hr.

Theoretical Power Available in the Wind: First divide windspeed in km/hr by 3.6 to get m/sec:_____. Then,

$$\frac{\text{Power}}{\text{Unit Area}} = 0.5 \times 1.01 \text{ kg/m3} \times (\_\_\_\_\_ \text{m/sec})^3 \times 3.1416$$

$$\text{Theor. Power Avail.} = \frac{\text{Power}}{\text{Area}} \times \text{Rotor Area} = \_\_\_\_\_\_ \text{ watts}$$

Determine system instantaneous efficiency from the example in the text, Section 4.1.2.

Your answer should be between 10-25%. If it isn't, try another data point. If this also gives a spurious answer, carefully check the numbers you are using to make sure that they are the correct ones for the calculations being done. If they are, then see "System Inspection" below. Also, check to see if the last site visit calculations gave similar answers.

6. PERFORM THE SERVICE PROCEDURES ON THE INSTRUMENTS (see the manual included with the instruments.

7. Operations Log: On a separate sheet of paper, indicate any problems you may have encountered during system testing procedure. List any actions you took to remedy these problems. List routine maintenance procedures required and time taken these procedures. Write down any observations you have which you think are appropriate to the evaluation of the

system.

8. Ask the local villagers the following questions and make note of any relevant responses. Ask them if they have any other comments or questions on how well or poorly the system is working. List responses on the back of this sheet.

   1. Does the windmill pump water every time the wind is blowing harder than just a light breeze?

   2. Have there been any shortages of water since my last visit?

   3. Have there been any unusual noises coming from the machinery?

   4. Is the quality of the water acceptable for drinking?

This report completed by: ______________________; Date: _________

PHOTOVOLTAIC WATER PUMPING SYSTEM DATA COLLECTION SHEET

1. Site Description: Location: ______________________________
Site Latitude: ______; Longitude: ______; Altitude: _____ m
Describe the terrain near the site (flat, hilly, trees, etc.)
____
____

2. Power Supply System Description

A. Panel Manufacturer/Model No.: ____________________
Number of Panels in Array: ____ panels
Rated Output per Panel: _____ watts at 1000 watts/m2
Physical Dimensions of each Panel: ____ m by ____ m
No. of Panels in Series ____ by ____ in Parallel
Total Array Area (TAA): ________ m2
Nominal Output Voltage of Each Panel: ____ volts
Nominal Array Ouput: _____ amps at _____ volts
Tilt Angle of Array: ____ Degrees Up from Horizontal
Azimuth: ____ Degrees ____ (east/west) of True North

B. Battery Storage (if any): ___ in Series by ___ in Parallel
Manufacturer and Model No. of Batteries: _________________
Rated at ____ amp-hours at Discharge Rate of ___ amps for
____ hour period.

C. AC/DC Inverter (if any) Manufacturer/Model No. ___________
Type (rotary, solid state, synchronous): _________________
Efficiency: ____ % at Rated Capacity: ____ watts

D. Regulator/Controller: Manufacturer/Model No: _____________
Nominal Voltage: ___ volts; Max Charging Current: ___ amps
Rated Capacity: ____ watts

3. Borehole and Pump Description

A. Borehole No: ______; Recorded Rest Water Level: ______ m
Pumping Water Level: ______ m; Discharge Head: _______ m
Dynamic Head of ______ m of Pipe of ______ mm diameter
Measured at Flowrate of: _____ liters/sec for: ____ min
Pipe Type (galvanized steel, PVC, etc.): ________________
Well Casing Diameter: ____ mm; Storage Tank Size: ____m3

B. Pump/Motor Manufacturer/Model No. _______________________
Pump Type (submersible DC, shaft turbine, progressive
cavity, jack, etc.): ___________________________________
Break-out torque: _________ (ft-lbf or N-m, circle which)
Rated Output: ____ liters/min @ ______ m head @ ____ RPM
Nominal Voltage: _____; Running Amps: _____;
Absorbed Power at Rated Output: _____ watts

4. Continuous Data Measurements Since Last Site Visit

Total Radiation On Array: ______________________ Wh/m2
Total Energy from Array: ______________________ Wh
Total Energy to Pump: ______________________ Wh
Total Water Volume Pumped: ______________________ liters
Total Pump On-Time: ______________________ minutes
Total Elapsed Time: ______________________ minutes

5. Pump Turn-On Radiation Value (W/m2)
Day One: _____; Day Two: _____

6. Pump RPM at High Insolation (rev/minute, from tachometer)
Test 1: ______ RPM @ ______ W/m2
Test 2: ______ RPM @ ______ W/m2
Test 3: ______ RPM @ ______ W/m2

	Elapsed Time (minutes)	Radiation (kWh/m2)	PV Energy (kWh)	Pump Energy (kWh)	Flow (liters)
Test -Start					
Stop					
Difference					

If Mono pump being tested, shaft speed for this test is: ____ RPM

Incident Radiation on Array = $\frac{\text{TAA x Radiation x 60}}{\text{Elapsed Time}}$ = ______kW.

Power to Pump = $\frac{\text{Pump Energy x 60}}{\text{Elapsed Time}}$ = ______kW

Test -Start					
Stop					
Difference					

If Mono pump being tested, shaft speed for this test is: ____ RPM

Incident Radiation on Array = $\frac{\text{TAA x Radiation x 60}}{\text{Elapsed Time}}$ = ______kW

Power to Pump = $\frac{\text{Pump Energy x 60}}{\text{Elapsed Time}}$ = ______kW

Test -Start					
Stop					
Difference					

If Mono pump being tested, shaft speed for this test is: ____ RPM

Incident Radiation on Array = $\frac{\text{TAA x Radiation x 60}}{\text{Elapsed Time}}$ = ______kW

Power to Pump = $\frac{\text{Pump Energy x 60}}{\text{Elapsed Time}}$ = ______kW

Test -Start					
Stop					
Difference					

If Mono pump being tested, shaft speed for this test is: ____ RPM

Incident Radiation on Array = $\frac{\text{TAA x Radiation x 60}}{\text{Elapsed Time}}$ = ______kW

Power to Pump = $\frac{\text{Pump Energy x 60}}{\text{Elapsed Time}}$ = ______kW

8. Well Sounding
Rest Water Level: Test 1: _____ m; Test 2: _____ m
Pumping Water Level:
Test 1: ____ m @ ____ W/m2 insolation and ____ PSI pressure
Test 2: ____ m @ ____ W/m2 insolation and ____ PSI pressure

9. Overall System Efficiency

Calculate the total lift by adding the pumping water level (m) to the discharge head (convert pressure reading in PSI to meters by multiplying by 0.703 m/PSI). See the worked example of the following procedure in 4.2.2., Data Analysis. Choose a point from the short term measurements with which to check the overall system efficiency: ____ liters/min at _____ W/m2 of radiation and with ____ watts of power being delivered to the pump. Calculate the hydraulic power needed to pump that flow to that head exactly as was done for the windmill calculations.

To get the total system efficiency, divide the hydraulic power determined above by the total radiation incident on the array. The total system efficiency (TSE) is then:

$$\text{TSE} = \frac{\text{hydraulic power required}}{\text{total incident radiation on array}} = \_\_\_\_\_ \%$$

This answer should be between 2-6%. Check your calculations again if it is not. Now check the pumping subsystem eficiency (PSE) by doing the following:

$$\text{PSE} = \frac{\text{hydraulic power required}}{\text{power delivered to pump}} = \_\_\_\_\_ \%$$

This answer should be in the range of 30-60%. As above, check your calculations if it is not. If, after trying another data point, you still get a spurious answer, carefully check the numbers you are using to make sure that they are the correct ones for the calculations being performed. If they are, a careful equipment and instrumentaion system check is required. You should also check the efficiency calculations from the previous visit to this site for comparison.

6. PERFORM THE SERVICE PROCEDURES ON THE INSTRUMENTS (see the manual included with the instruments).

7. Operations Log: On a separate sheet of paper, indicate any problems you may have encountered during the data collection procedure. List any actions you took to correct these problems. List routine maintenance procedures required and time taken for these procedures. Write down any observations

you made which you feel are appropriate to the evaluation of the system.

8. Ask the local villagers the following questions and make note of any relevant responses. Ask them if they have any other comments or questions on how well or poorly the system is working. List responses on the back of this sheet.

   A. Does the PV system pump water whenever the sun is shining near midday?

   B. Have there been any shortages of water since my last visit?

   C. Have there been any unusual noises coming from the machinery?

   D. Is the quality of the water acceptable for drinking?

This report completed by: ______________________; Date: __________

DIESEL WATER PUMPING SYSTEM DATA COLLECTION SHEET

1. Site Description: Location: ______________________________
   Site Latitude: ______; Longitude: ______; Altitude: _____ m

2. Diesel Description (from manufacturer's literature)
   Manufacturer and Model No.: ______________________________
   Number of Cylinders: _____ ; Bore: ____ mm; Stroke: ____ mm
   Cylinder Capacity: _____ cc;
   Rated Brake Horsepower (BHP): _____ HP @ _____ RPM
   Mechanical Power Transmission (gear or belt): ______________
   Gear or Pulley Ratio: ___________

3. Borehole and Pump Description

   A. Borehole/Pipe Description (from Driller's records and
   Installation records): Borehole No: ______________
   Pumping Water Level: _______ m; Discharge Head: ______ m
   Dynamic Head of ______ m of Pipe of _____ mm Diameter
   @ Flowrate of: _____ liters/sec after: ____ minutes
   Outside Casing Diameter: ____ mm; Tank Size: ____ m3
   Pipe Type (galvanized steel, PVC, etc.): ______________

   C. Mono Pump: Model No.(ES-10, ES-15S,etc.):______________
   Break-out Torque: __________ (ft-lbf or N-m, circle which)
   Rated Output: _____ liters/min @ _____ RPM @ _____ m head
   Absorbed Power at Rated Output: ______ kW

4. Continuous Data Measurements Since Last Site Visit

   Total Water Volume Pumped: ______________________ liters
   Total Fuel Consumption: ______________________ liters
   Total Pump On-Time: ______________________ minutes
   Total Elapsed Time: ______________________ minutes

/ Elapsed Time / Fuel Consumption / Water Flow /
(minutes) (liters) (liters)

Test - Start /_______________/____________________/_____________/
Stop /_______________/____________________/_____________/
Difference /_______________/____________________/_____________/
Measured Pump Shaft RPM: _____ RPM
Pulley Ratio _____ x Pump RPM _____ = _____ Diesel Shaft RPM

$\frac{\text{Total Water Flow}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

$\frac{\text{Total Fuel Consumption}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

---

Test - Start /_______________/____________________/_____________/
Stop /_______________/____________________/_____________/
Difference /_______________/____________________/_____________/
Measured Pump Shaft RPM: _____ RPM
Pulley Ratio _____ x Pump RPM _____ = _____ Diesel Shaft RPM

$\frac{\text{Total Water Flow}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

$\frac{\text{Total Fuel Consumption}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

---

Test - Start /_______________/____________________/_____________/
Stop /_______________/____________________/_____________/
Difference /_______________/____________________/_____________/
Measured Pump Shaft RPM: _____ RPM
Pulley Ratio _____ x Pump RPM _____ = _____ Diesel Shaft RPM

$\frac{\text{Total Water Flow}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

$\frac{\text{Total Fuel Consumption}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

---

Test - Start /_______________/____________________/_____________/
Stop /_______________/____________________/_____________/
Difference /_______________/____________________/_____________/
Measured Pump Shaft RPM: _____ RPM
Pulley Ratio _____ x Pump RPM _____ = _____ Diesel Shaft RPM

$\frac{\text{Total Water Flow}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

$\frac{\text{Total Fuel Consumption}}{\text{Elapsed Time}} = \_\_\_\_\_$ liters/min

---

B. Well Sounding
Rest Water Level: Test 1: ____ m; Test 2:____
Pumping Water Level:
Test 1: ____ m @ ____ liters/minute @ ____ PSI pressure
Test 2: ____ m @ ____ liters/minute @ ____ PSI pressure

C. Overall Pumping System Efficiency

Calculate the total lift by adding the pumping water level (m) to the discharge head (convert pressure reading in PSI to meters by multiplying by 0.703 m/PSI).

Choose a point from the short term measurements with which to measure the overall system efficiency.
fuel flowrate: ______ liters/hour of fuel
water flowrate: ______ liters/sec of water

Power Available in the Diesel Fuel: Assuming a heat content of 10.5 kWh/liter, then the power available to the engine can be calculated from the fuel flowrate as follows:

Power (kW) = 10.5 kWh/liter x fuel flowrate (liters/hr)

Now find the system efficiency from the hydraulic energy of water pumped divided heat energy from fuel consumed, as per the example in Section 4.3.2.

$$\text{System Efficiency} = \frac{\text{Hydraulic Energy Required}}{\text{Energy Available in Fuel}} = \_\_\_\_ \%$$

Your answer should be between 5-20%. If it isn't, try another data point. If this also gives a spurious answer, carefully check the numbers you are using to make sure that they are the correct ones for the calculations being done. If they are, then see "System Inspection" below. Also, check to see if the last site visit calculations gave similar answers.

6. PERFORM THE SERVICE PROCEDURES ON THE INSTRUMENTS (see the manual included with the instruments.

7. Operations Log: On a separate sheet or paper, indicate any problems you may have encountered during system testing procedure. List any actions you took to remedy these problems. List routine maintenance procedures required and time taken these procedures. Write down any observations you have which you appropriate to the evaluation of the system.

8. Ask the local villagers the following questions and make note of any relevant responses. Ask them if they have any other comments or questions on how well or poorly the system is working. List responses on the back of this sheet.

1. Has the diesel pump worked every time it was necessary to pump water?

2. Have there been any shortages or water since my last visit?

3. Have there been any unusual noises coming from the machinery?

4. Is the quality of the water acceptable for drinking?

This report completed by: ______________________; Date: _________

PART TWO
COSTING DATA COLLECTION SHEETS

PART ONE--COSTS

Key Assumptions

The following section assumes that the individual system being examined, be it diesel, PV or wind-powered, is one of several installations to be installed, repaired and maintained by a professional crew employed by the GOB, BRET project, or some other organization. Therefore, certain costs such as transportation and engineering labor are spread out over several sites. It is further assumed that replacement parts are carried by the repair crew during their routine visits, but that special re-supply runs will be required periodically for provision of fuel for diesel-powered systems. This will mean that a transportation cost will be figured in for fuel but not for spare parts.

I. Background data on installation site (referred to as "Site A"):

a. Distance to Site A from crew offices (city_______) _____ kilometers (Ia)

b. Number of workers on installation crew _____ workers (Ib)

c. Total number of sites to be visited during same visit by same crew _____ sites (Ic)

d. Total round-trip mileage to be covered during service visit _____ kilometers (Id)

e. Mileage attributable to Site A:

$\frac{Id}{Ic}$ OR 2 x Ia (use lower figure) _____ kilometers (Ie)

f. Cost per kilometer to rent small repair truck _____/kilometer (If)
thebe

g. Fuel cost for Site A: $\frac{\text{total fuel cost}}{Id}$ x Ie _____ pula (Ig)

h. Transportation cost to visit Site A (Ie x If x Ig) _____ pula (Ih)

i. Total number of person-hours to travel to all sites during one visit, make repairs/maintenance, and return to crew office (not including overnight hours unless staff is paid extra for these trips) _____ hours (Ii)

j. Labor cost for each service visit (total wages for all workers on crew for visit, including travel time) _____ pula (Ij)

k. Total expenses paid/allowed for entire crew for duration of service visit _____ pula (Ik)

l. Labor cost for visit to Site A = $\frac{Ij}{Ic}$ _____ pula (Il)

m. Expenses for visit to Site A = $\frac{Ik}{Ic}$ _____ pula (Im)

n. Total cost for visit to Site A = Ih + Il + Im _____ pula (In)

BENEFITS (ALL SYSTEMS)

I. Water pumped:

1. Maximum daily water output measured ________ liters/day
2. Minimum daily water output measured ________ liters/day
3. Annual average daily water output ________ liters/day

   Measured? _____ Estimated? _____ (check one)

II. Employment generated:

1. Average number of hours per month of labor required to operate/maintain the pumping system ________ hours/month
2. Average wage paid for operation/maintenance ________ pula/month
3. Other non-wage compensation paid to operator (lodging, food, etc.)--give estimated value ________ pula/month
4. Annual number of hours of labor required ________ per year

   How calculated? (check one)
   _____ direct employment record
   _____ monthly average x 12
   _____ other means

III. Additional benefits:

1. Increase in food production due to introduction of irrigation:

   a. Current annual production of ____________ = _____/year
   crop name kilos

   b. Annual production prior to introduction of irrigation
   \- ____________ = _____/year
   crop name kilos

   c. Difference between current and prior production (a-b) = ______/year
   kilos

   d. Value of crop output ____ pula/kilo

   e. Value of increased food production (c x d) = _____ pula/year

2. Other benefits (list nature and monetary value, if known)

   ____

   ____

PART TWO--COSTS (DIESEL PUMP)

Key Assumptions

It is assumed that the diesel pump will operate eight hours per day, 350 days per year. It is further assumed that there will be a full-time pump operator or "pumper" as well as a part-time operator for the pumper's weekly day off, holidays, and vacation. Diesel systems require major and minor maintenance at specific numbers of operating hours. The pumper will provide the monthly routine parts replacement required, following the recommendations of the manufacturer. Generally, this means the replacement of oil filters and air filters every 250 operating hours. The GOB maintenance crew will visit every three months for the first two years of the pumps, and then every two months thereafter. Every six months or every 1500 engine hours, the GOB team will change fuel filters, V-belts, head gaskets; conduct a major de-carbonization; & replace other parts as required. Every two years the diesel will be overhauled in Gaborone and the pump pulled for overhaul or replacement.

A. Capital cost (in Gaborone)

	imported	local	total
diesel engine			
diesel fuel storage tank(s)			
drop pipe			
pump			
replacement parts for diesel (year's supply)			
replacement parts for pump (year's supply)			
other			
Total	(IIA1)	(IIA2)	

B. Installation cost
(Assumption is that the installation visit to Site A is just for this one installation. If several units are to be installed consecutively at different sites during one trip, then total costs for each item should be divided by number of sites, as was done in Part One.)

1. Site preparation (including concrete pad) _____ pula
2. Shelter for diesel engine _____ pula
3. Local unskilled labor _____ pula
4. Labor cost for installation team (Ij) _____ pula
5. Living expenses for installation team (Ik) _____ pula
6. Transportation cost for installation (fuel & truck) _____ pula

Total _____ pula (IIB)

C. Operating costs

1. Annual fuel consumption _____ liters (IIC1)
2. Cost of each liter of fuel (in Gaborone) _____/liter (IIC2)
   pula
3. Annual cost of fuel in Gaborone = IIC1 x IIC2 _____ pula (IIC3)
4. Annual cost to deliver fuel to Site A (Note: This assumes that a special fuel resupply run to all sites is made two times a year and that fuel is also delivered during the routine visits every three months.) _____ pula (IIC4)
5. Annual oil usage for diesel engine (12 oil changes per year, plus oil consumption during operation) _____ liters (IIC5)
6. Cost of oil (in Gaborone) _____/liter (IIC6)
   pula
7. Total annual cost of oil = IIC5 x IIC6 _____ pula (IIC7)
8. Daily wages for pumper _____ pula (IIC8)
9. Number of work days for pumper (does not include days off, holidays, leave) _____ days (IIC9)
10. Annual salary for pumper = IIC8 x IIC9 _____ pula (IIC10)
11. Annual wages for relief pumper (about 80 days/year x wage/day) _____ pula (IIC11)
12. Total operator wages = IIC10 + IIC11 _____ pula (IIC12)

D. Annual replacement parts

1. Oil filters = # used/year x cost/unit _____ pula (IID1)
2. Air filters = # used/year x cost/unit _____ pula (IID2)
3. Fuel filters = # used/year x cost/unit _____ pula (IID3)
4. D-C gasket sets = 2 sets/year x cost/unit _____ pula (IID4)
5. V-belts = cost/belt x 2 per set x 2 sets/year
   OR 4 x cost/belt _____ pula (IID5)

E. GOB routine site visits for maintenance/repair

1. Cost of each visit = Ih + Il + Im _____ pula (IIE1)
2. 4 visits (Years 1&2) OR 6 visits (Years 3-5) _____ visits (IIE2)
3. Annual cost = IIE1 x IIE2 _____ pula (IIE3)

F. Cost for major overhaul (according to manufacturer's specifications, but normally every 3000 hours or 2 years) _____ pula (IIF)

DIESEL COST SUMMARY

Capital cost:

imported (IIA1 x 1.1)[a] _____ + local (IIA2) _____ = ________ pula

Installation cost (IIB) = ________ pula

Annual Operating Cost Summary

Fuel (IIC3 + IIC4) _____ + Oil (IIC7) _____ +
Local wages (IIC12) _____ + Annual replacement
parts (IID1 + IID2 + IID3 + IID4 + IID5) _____ +
Routine GOB site visits (IIE3) _____ = ________ pula

Total annual operating costs ________ pula

Periodic Recurrent Costs

Major diesel engine overhauls (IIF) every ____ months = _____ pula

Major pump overhaul every ____ months = _____ pula

---

[a] Government of Botswana attaches a 1.1 multiplier on foreign exchange costs.

PART THREE--COSTS (WIND-POWERED PUMP)

Key Assumptions

It is assumed that the wind-energy powered water pump will operate for a minimum of four and a maximum of eight hours a day, 325 days a year (Acually, data on wind velocities at individual sites are available in-country from the compilators used in the national wind-energy monitoring program.). It is further assumed that each wind system will be installed by a GOB or BRET project team, and will receive routine service and lubrication from a local "pumper" who will be paid for a certain number of hours of service and monitoring. The GOB team will also visit several other wind systems during the routine service calls every three months. Every six months the GOB team will do a more extensive servicing of the windmill and pump, and the pump will be replaced every three to four years, depending on the manufacturer's specifications.

A. Capital cost (in Gaborone) (Note: All costs include delivery to Gaborone, import duties, etc.)	imported	local	total
wind turbine			
sucker rods/drop pipe			
tower			
fencing around tower (if required)			
pump			
water tank			
plumbing (pipes and valves)			
replacement parts for windmill (year's supply)			
replacement parts for pump (year's supply)			
other			
Total	(IIIA1)	(IIIA2)	

B. Installation cost
(Assumptions: The installation visit to this site (Site B) is just for this single system and this one site. All supplies, including the tower, can be delivered from Gaborone to Site B in a single trip. Do not include costs for anemometry equipment.

1. Site preparation _____ pula
2. Footings or tower tie-down anchors _____ pula
3. Local unskilled labor _____ pula
4. Labor cost for Gaborone-based installation crew _____ pula
5. Living expenses for installation crew _____ pula
6. Transportation cost for carrying wind turbine, tower, installation equipment and crew (fuel and truck) _____ pula
7. Other _____ pula

Total _____ pula (IIIB)

C. Annual Operating Costs

1. Number of hours per week for local pumper _____ hours (IIIC1)
2. Hourly wage for pumper _____ pula (IIIC2)
3. Annual wage for pumper = IIIC1 x IIIC2 x 52 _____ pula (IIIC3)
4. Lubricants/oil for oil bath (annual total cost) _____ pula (IIIC4)
5. Other (specify ____________________) _____ pula (IIIC5)

Total = IIIC3 + IIIC4 + IIIC5 _____ pula (IIIC6)

D. Annual replacement parts

1. V-belts _____ pula (IIID1)
2. Pump leathers or seals _____ pula (IIID2)
3. Other (specify ____________________) _____ pula (IIID3)
4. Other (specify ____________________) _____ pula (IIID4)

Total = IIID1 + IIID2 + IIID3 + IIID4 _____ pula (IIID5)

E. GOB routine site visits for maintenance/repair

1. Cost of each visit = Ih + Il + Im _____ pula (IIIE1)
2. 3 visits (Year 1) OR 4 visits (Years 2-10) _____ visits (IIIE2)
3. Annual cost = IIIE1 x IIIE2 _____ pula (IIIE3)

F. Cost for major wind turbine overhaul (according to specifications of manufacturer, but normally every 3-5 years) _____ pula (IIIF)

G. Cost for major pump overhaul (if manufacturer recommends, in addition to routine maintenance and routine parts replacement) _____ pula (IIIG)

Wind pump cost summary

Capital cost:

imported (IIIA1 x 1.1)[b] _____ + local (IIIA2) _____ = ________

Installation cost (IIIB) = ________

Annual operating costs = IIIC6 + IIID5 + IIIE3 = ________

Costs of major overhauls -- wind turbine (IIIF) = ________

Costs of major pump overhauls -- pump (IIIG) = ________

[b] Government of Botswana attaches a 1.1 multiplier on foreign exchange costs.

PART FOUR--COSTS (PHOTOVOLTAIC-POWERED PUMP)

Key Assumptions

It is assumed that the PV-powered pump will operate for six to eight hours per day, 365 days a year. It is further assumed that each PV pumping system will be installed by a GOB or BRET project team, and that the only routine maintenance required will be for the storage battery and pump (if surface mounted). A local "pumper" will be employed to monitor and service the unit once a week (including washing the panels) and to call in a service team in the event of interruption of pumping. A GOB or BRET project team will visit this site and several other PV installations every three months. Every six months, a thorough check will be made of the PV system, storage batteries, water tank and pump. The batteries will be routinely replaced according to manufacturer specification (every 18-30 months normally), and the pump will be replaced routinely as well (normally every three to four years).

A. Capital cost (in Gaborone) (Note: All costs include delivery to Gaborone, import duties, etc.)	imported	local	total
PV panels (with mounting hardware, racks and wiring harness)			
control panel/voltage regulator (if any)			
storage batteries (if any)			
enclosure for control panel and batteries			
fencing for PV array			
pump			
replacement fuses and parts for control panel and wiring harness (year's supply)			
replacement parts for pump (year's supply)			
water tank			
other			
Total	(IVA1)	(IVA2)	

B. Installation cost
(Assumptions: The installation visit to this site (Site C) is just for this single system and this one site. It is further assumed that all supplies, including the fencing and panels, can be delivered from Gaborone to Site C in one trip. Costs do not include expenditures and labor for solar monitoring equipment or insolation data collection.)

1. Site preparation (including erecting fence) _____ pula
2. Concrete pad _____ pula
3. Local unskilled labor _____ pula

4. Labor costs for Gaborone-based installation crew _____ pula

5. Living expenses for installation crew _____ pula

6. Transportation cost for carrying PV system, pump, fencing and crew to Site C and back to base (fuel and truck) _____ pula

7. Other _____ pula

Total _____ pula (IVB)

C. Annual operating costs

1. Weekly wage for local "pumper" _____ pula (IVC1)

2. Annual wage for pumper = IVC1 x 52 _____ pula (IVC2)

3. Lubricants/oil bath for pump (if required) _____ pula (IVC3)

4. Other (specify ____________________) _____ pula (IVC4)

Total = IVC1 + IVC2 + IVC3 + IVC4 _____ pula (IVC5)

D. Annual replacement parts

1. V-belts (if required) _____ pula (IVD1)

2. Pump leathers or seal (if required) _____ pula (IVD2)

3. Fuses and replacement diodes _____ pula (IVD3)

4. Other (specify _________________________) _____ pula (IVD4)

Total = IVD1 + IVD2 + IVD3 + IVD4 _____ pula (IVD5)

E. GOB routine site visits for maintenance/repair

1. Cost of each visit = Ih + Il + Im _____ pula (IVE1)

2. 3 visits (Year 1) OR 4 visits (Years 2-10) ____ visits (IVE2)

3. Annual cost = IVE1 x IVE2 _____ pula (IVE3)

F. Cost for major pump overhaul (if manufacturer recommends in addition to routine maintenance and routine parts replaement) _____ pula (IVF)

G. Cost of replacement batteries (normally every 18-30 months) _____ pula (IVG)

PV pump cost summary

Capital cost:

imported (IVA1 x 1.1)[c] _____ + local (IVA2) = _______

Installation cost (IVB) = _______

Annual operating costs = IVC5 + IVD5 + IVE3 = _______

Periodic recurrent costs:

pump overhaul every ___ months = _______

replacement batteries every ___ months = _______

---

[c] Government of Botswana attaches a 1.1 multiplier on foreign exchange costs.

PART THREE
GENERAL REFERENCES

1. DISCOUNTING THE FLOW OF COSTS AND BENEFITS
2. SPECIFICATION SHEET FOR ARCO M-53 PV MODULES
3. PROPERTIES OF THE STANDARD ATMOSPHERE
4. TECHNICAL SPECIFICATIONS OF A TYPICAL SMALL DIESEL ENGINE
5. ILLUSTRATION OF DIFFERENT TYPES OF HEAD
6. WATER DISCHARGED PER STROKE BY SINGLE ACTING CYLINDERS, CONTENTS OF ROUND TANKS IN US GALLONS FOR EACH FOOT DEPTH
7. FRICTION OF WATER IN PIPES
8. UNIT CONVERSION TABLE

B. Discounting the Flow of Benefits and Costs

A traditional problem for development planners and project administrators is comparing alternative investment opportunities to determine which should be funded. This is particularly difficult when alternatives' initial capital costs, operation and maintenance requirements, and benefit streams differ widely. The analyst's task is to reduce the stream of benefits and costs to a set of economic values that can easily be compared.

In the case of water pumping technologies, the net discounted present value of the stream of benefits was calculated, as well as the economic value for each cubic meter of water required to equate the streams of benefits and costs over the project's life. In the first instance, the net benefit of a water pumping system in any given year is the economic value of the water produced minus maintenance costs, any capital investments and replacement parts installed during that year.

All benefits and costs are not considered to be of equal value. Benefits received later in a project are generally not valued as highly as those received today. Similarly, costs incurred in a project's tenth year are usually deemed less important than the initial capital investment. The discount rate is a measure of the time-related value of money, goods and services. If an individual or agency is indifferent to receiving 100 pula today versus 110 a year from now, the person or group is has an annual discount rate of 10 percent. Discount rates are specific to groups and individuals and may vary drastically within a society. Those without access to commercial credit or living in poverty may have very high discount rates (50 percent a year or more), while government institutions may use low rates (five percent) in comparing alternative investment opportunities.

An investment's net present value is the sum of net benefits for each year of the project, with each year's net benefit (or loss) reduced by a discount factor (r). To discount net benefits for one year, they are divided by one plus the discount rate $(1 + r)$. To do so for two years in the future, net benefits are divided by $(1 + r)^2$. Thus, net benefits are discounted n years into the future by dividing them by $(1 + r)^n$. At high discount rates, the value of future net benefits drops rapidly. Thus, 100 pula in net benefits to be received four years from today at a discount rate of 25 percent have a current discounted value of only 40.96 pula $((100 \text{ pula}/(1 + .25)^4)$.

In general, the net present value of an investment can be calculated using the following economic equation:

$$NPV = \sum_{i=1}^{n} \frac{(B_i - C_i)}{(1 + r)^i}$$

where NPV is net present value; i, the year; B_i, benefits in year i; C_i, costs in year i; r, the discount rate; and n, the life of the project in years.

This very simple, universally accepted methodology was deliberately chosen to compare alternative water pumping technologies. No factors were introduced to differentially weight various types of benefits and costs--the discount rate was applied equally to all costs and benefits. Different inflation rates for production factors (e.g., labor, money, energy, etc.) are difficult to justify without good data and often distort economic analyses. Such steps are warranted only if hard, empirical data are available on current price changes and there is reason to believe that present trends will continue in the future. For example, a forecasting methodology which assumed in 1980 that fossil fuel prices would rise at a higher rate than inflation would yield estimates for current fuel bills that are far too high for 1983. Similarly, no shadow prices were used for any of the major factors--labor, replacement parts or the initial capital investment. In addition, foreign exchange limitations were not factored into the analysis, since it was assumed that this is a separate issue for consideration by the government of Botswana (GOB).

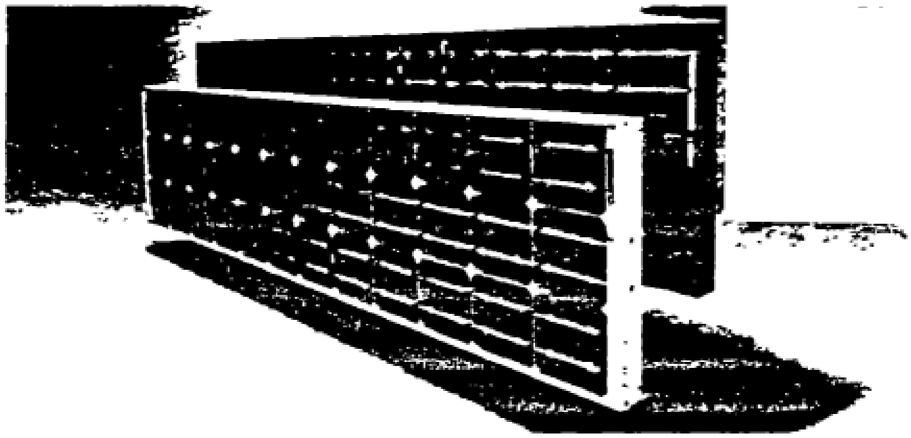
In the analysis that follows, two annual discount rates were used--15 and 25 percent. The first reflects the rate used by GOB ministries and agencies in making investment decisions, which is based on current GOB interest rates for development project capital, plus a modest amount for expected inflation. The second was chosen to represent a rate that characterizes the investment decisions of private firms and individuals, who are more uncertain about future investments and place a greater value on current, as opposed to future, receipts than government agencies.

In the calculations, water was valued at $1.00 per cubic meter, which while based on reasonable values from potable water systems installed at other locations, is not an empirically derived value for water in Botswana. The actual value of water could be higher or lower, depending on the site and preferences of local populace. However, since the same value was used for all the systems compared, changing that value would affect the net present value of benefits minus costs for each system, but not the relative ranking of the different systems.

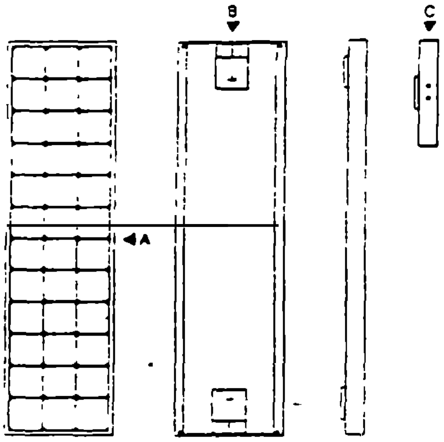
One way to deal with the problem of not having an actual observed value for pumped water is to solve the equation for this value. For each system examined, the value of a cubic meter of water was allowed to vary until the discounted stream of benefits equaled the costs for the life of the project.

ARCO Solar®

M53 Photovoltaic Module



A Length: 48 in/121 9 cm
B Width 12 in/30 5 cm
C. Depth: 1 5 in/3 8 cm
2 4 in/6.1 cm including
Junction Box



New High Efficiency Square Cells

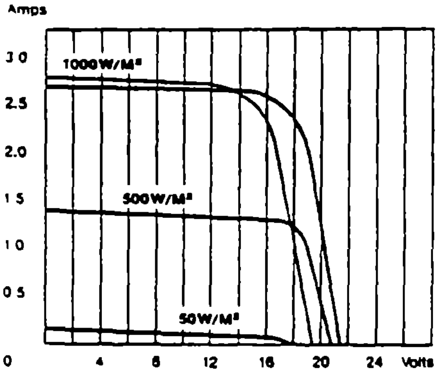
The ARCO Solar M53 is a nominal 43 watt photovoltaic (solar electric) module; i the first ARCO Solar module to utilize our high efficiency single-crystal silicon square cells. The M53 continues to maintain the quality and features that have e tablished ARCO Solar modules as an industry standard, and also incorporates new features. These innovations make it an even more efficient, reliable and du solar module, well suited for a wide variety of applications—large and small The M53 is available either with regular aluminum frame and white backing, or with black anodized aluminum frame and black backing. The M53 is physically and electrically compatible with existing ARCO Solar systems.

Each of the M53's 36 series-connected solar cells produces over 2.4 amps.* Ov all module efficiency is greater than 11.5% due to the denser packing allowed b the square cells. Multiple redundant connections on the front and back of each cell help assure module circuit reliability, and by using single-crystal silicon cel the module can produce power in as little as 5% of noon sun Two by-pass dioo are wired into each module to reduce potential power loss from partial shading a single module within an array

• Performance Characteristics

The IV curve (current vs. voltage) below demonstrates typical M53 power response to various light levels at 25°C cell temperature and at the NOCT (Nominal Cell Operating Temperature) 47°C

1000 w/m² @ 25°C	▬
1000 w/m² @ 47°C	▬



Specialized Construction

The M53 utilizes our highest standard of glass laminate construction This enab it to withstand some of the harshest environments and continue to perform efficiently This same standard of construction has allowed other ARCO Solar modules to meet the design, performance and durability requirements of the U Department of Energy and pass additional, more stringent, ARCO Solar tests. Solar cells are permanently laminated between special anti-reflective tempere glass and EVA, backed by multiple layers of polymeric protection. This weathe proof package is then sealed by a neoprene edge-gasket and supported by a rugged lightweight aluminum frame.

There are two environmentally sealed junction boxes on each module, one for positive and one for negative termination. Each junction box contains dual terminations, a wired-in by-pass diode and two additional non-active termination posts Designed for easy wiring access, the junction boxes accept standard ¾ flexible conduit or our Standard Interconnect Wire (SIW) and grommets Juncti boxes are securely attached to the module frame with screws and to the modu backing with adhesive.

ARCO Solar, Inc.
Subsidiary of Atlantic Richfield Company

ower Specifications

	1000 w/m², AM 1.5 spectrum and 25°C (±0.5°C) cell temperature
Open Circuit Voltage/Typical	*21.7 Volts*
Short Circuit Current/Typical	*2.7 Amps*
Voltage/Typical at Load	*17.3 Volts*
Current/Typical at Load	*2.49 Amps*
Module Efficiency/Typical	*11.5%*
Average Power/Typical Watts @ Test, ±10%	*43 Watts/P. Max*

odule Characteristics

Electrically matched single-crystal silicon solar cells.

Fault tolerant, multiple redundant contacts on each cell for circuit reliability.

Nominal operating cell temperature (NOCT) 47°C/50°C (black version)

Service Temperature conditions of −40°C to +90°C, 0 to 100 percent humidity.

Computer designed cell grid pattern for high conductivity.

Cells chemically textured for anti-reflection enhancement.

Two by-pass diodes. Each by-passes 24 cells, with 12 cell overlap.

Tempered anti-reflective glass front.

Specular reflection by inside of front glass.

Efficient conversion of both direct and diffuse light.

Polymeric encapsulant.

Multiple-layer protective coating behind cells

Interlocking aluminum side rails—(black anodized optional)

External grounding screw.

Module surface promotes self-cleaning by natural processes (rain, wind, etc.)

Junction boxes designed for easy wiring access.

Module leakage current of less than 50µA at 3000 VDC.

Ground continuity of less than 1 ohm for all metallic surfaces.

CO Solar, Inc.
y of Atlantic Richfield Company

21011 Warner Center Lane
PO Box 4400
Woodland Hills, CA 91365
Tel 213 - 700-7390
Telex 674838
TWX 910-494-2791

Consult your dealer for full and complete details regarding the installation and use of ARCO Solar M53 photovoltaic modules

Specifications subject to change without notice

Properties of the *U.S. Standard* Atmosphere (4)

Geometric Altitude (meters)	Temperature (K)	p/p_0 (—)	ρ/ρ_0 (—)
−500	291.4	1.061	1.049
0	288.2	1.000*	1.000†
500	284.9	0.9421	0.9529
1,000	281.7	0.8870	0.9075
1,500	278.4	0.8345	0.8638
2,000	275.2	0.7846	0.8217
2,500	271.9	0.7372	0.7812
3,000	268.7	0.6920	0.7423
3,500	265.4	0.6492	0.7048
4,000	262.2	0.6085	0.6689
4,500	258.9	0.5700	0.6343
5,000	255.7	0.5334	0.6012
6,000	249.2	0.4660	0.5389
7,000	242.7	0.4057	0.4817
8,000	236.2	0.3519	0.4292
9,000	229.7	0.3040	0.3813
10,000	223.3	0.2615	0.3376
11,000	216.8	0.2240	0.2978
12,000	216.7	0.1915	0.2546
13,000	216.7	0.1636	0.2176
14,000	216.7	0.1399	0.1860
15,000	216.7	0.1195	0.1590
16,000	216.7	0.1022	0.1359
17,000	216.7	0.08734	0.1162
18,000	216.7	0.07466	0.09930
19,000	216.7	0.06383	0.08489
20,000	216.7	0.05457	0.07258
22,000	218.6	0.03995	0.05266
24,000	220.6	0.02933	0.03832
26,000	222.5	0.02160	0.02797
28,000	224.5	0.01595	0.02047
30,000	226.5	0.01181	0.01503
40,000	250.4	0.002834	0.003262
50,000	270.7	0.0007874	0.0008383
60,000	255.8	0.0002217	0.0002497
70,000	219.7	0.00005448	0.00007146
80,000	180.7	0.00001023	0.00001632
90,000	180.7	0.000001622	0.000002588

[*] $p_0 = 1.01325 \times 10^5$ N/m² absolute (= 14.696 psia)

[†] $\rho_0 = 1.2250$ kg/m³ (= 0.002377 slug/ft³)

SPECIFICATION

he Lister LT1 and LT2 diesel engines are available in a ariety of builds, designed for a comprehensive range f applications. The maximum continuous bhp is 7.5, T1 and 15.0, LT2 at 3000 and 3600 rev/min.

ooling: Flywheel mounted fan.

ubrication: Self-regulating plunger type pump aintaining constant pressure

overning: Class A2 or Class B according to build.

rankcase: Cast iron, robust design.

Starting: Hand starting. Detachable handle on the amshaft extension. Geared starting provision at the lywheel end depending on the build (LT1 only). lectric starting optional.

ower Take-off: Full power may be taken from the lywheel end or from a crankshaft extension at the earcase end (LT1 only).

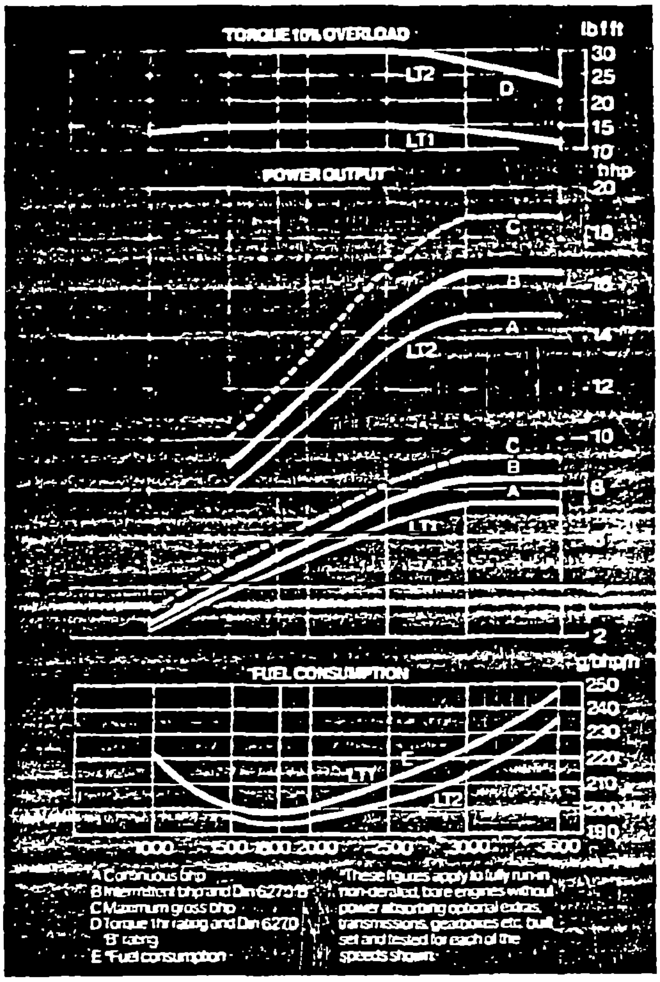
otation: Looking on the flywheel.
LT1 – Clockwise and Anticlockwise.
LT2 – Anticlockwise.

ECHNICAL DATA

ower output:

ngine speed rev/min	continuous bhp (BS 649.1958)		PS or CV (kW) (Din 6270 'B')	
	LT1	LT2	LT1	LT2
3600	7.5	15.0	8.36	16.73
3000	7.5	15.0	8.36	16.73
2500	6.7	13.4	7.47	14.95
2000	5.35	10.7	5.97	11.93
1800	4.8	9.6	5.35	10.70
1500	4.0	8.0	4.46	8.92
1000	2.5	-	2.79	-

MEP at 2000 rev/min: 85.1 lbf/in².
ore: 3.25 in
troke: 3.00 in.
mber of cylinders:– LT1. 1, LT2. 2.
der capacity: LT1 24.89 in³
LT2 49.78 in³
ubricating oil sump capacity: LT1 2.7 pints
LT2 6.3 pints
eight of engine: LT1 approx. 179 lb with standard equipment.
LT2 approx. 287 lb with standard equipment.



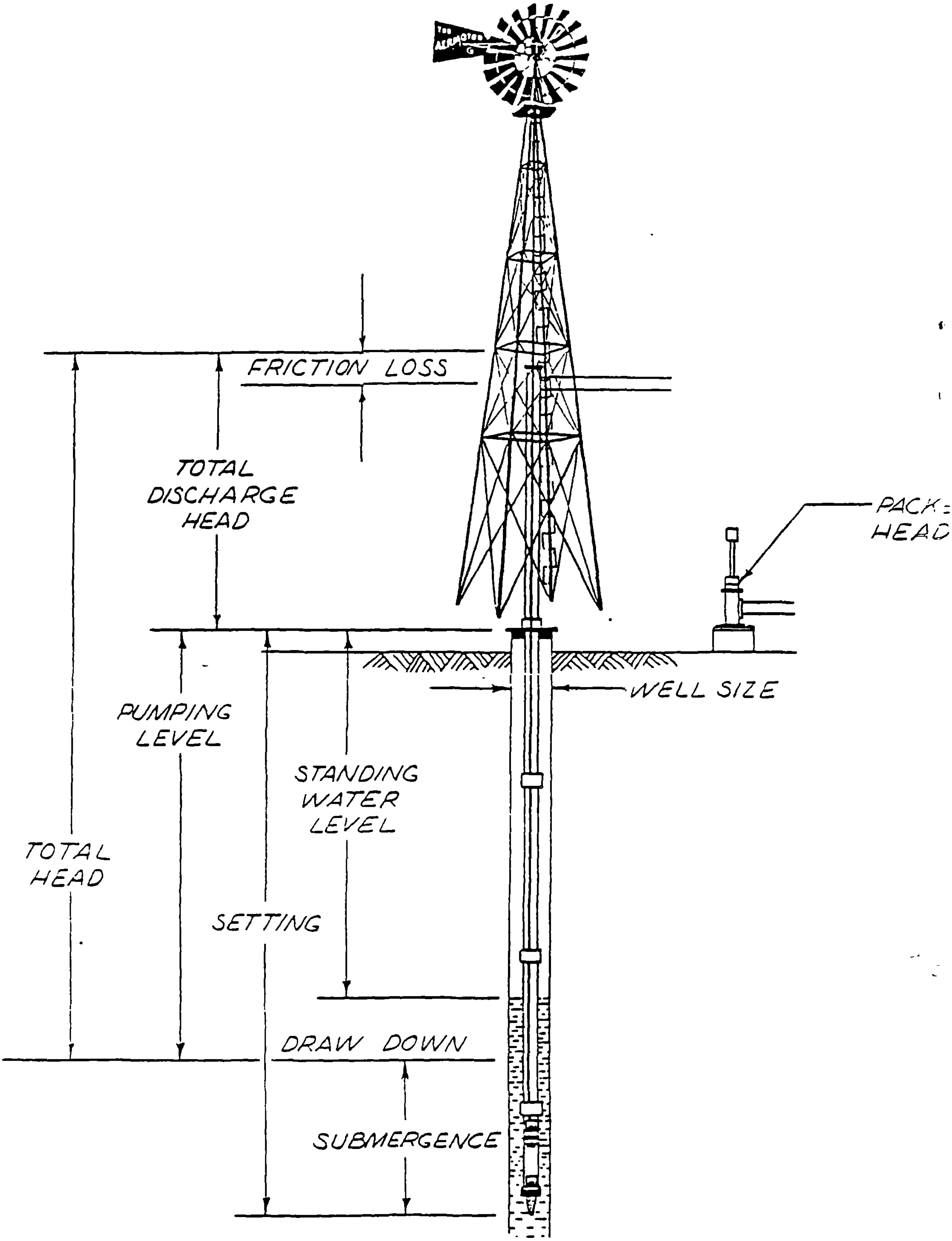
*These figures apply to fully run-in, non-derated, bare engines without power absorbing optional extras, transmissions, gearboxes etc. built, set and tested for each of the speeds shown.

RATING. BS 649: 1958 (and Din 6270).
This is the bhp which the engine is capable of delivering continuously at a stated crankshaft speed in accordance with the conditions specified in BS 649 1958 (Din 'A'). The engines shall be capable of satisfactorily providing an output 10% in excess of the BS continuous rating at the same speed for one hour in any period of twelve hours consecutive running (Din 'B') unless driving centrifugal water pumps, fans and other similar equipment when overload is not permitted.
Note that 10% overload and Din 'B' ratings apply only to a fully run-in engine. This is normally attained after a period of approximately 50 hours running

DERATING. BS 649: 1958.
Altitude: 3½% for every 1000 ft above 500 ft above sea level

Air inlet temperature: 2% for every 10°F above 85°F

Humidity: up to a maximum of 6%.


THE AERMOTOR CO
FRICTION LOSS
TOTAL DISCHARGE HEAD
PACK
HEAD
WELL SIZE
PUMPING LEVEL
STANDING WATER LEVEL
TOTAL HEAD
SETTING
DRAW DOWN
SUBMERGENCE

To obtain the capacity of a pump with diameter of cylinder given in table, but with a longer stroke than 24 inches, add or multiply the capacity to represent the required length of stroke.

To obtain the amount of water discharged per minute, multiply the capacity per stroke by the number of strokes per minute To obtain the amount of water discharged per hour, multiply this figure by 60

WATER DISCHARGED PER STROKE BY SINGLE ACTING CYLINDERS

Dia of (Pump Cyl) in In	Length of Stroke in Inches with Capacity Per Stroke in Gallons												Area of Circle (Pump Cyl in Sq Inches	Dia of (Pump Cyl In In
	1	2	3	4	5	6	7	8	10	12	18	24		
1⅜	0064	.0128	0192	0256	0320	0384	0448	0512	0640	0768	1152	1536	1 4849	1⅜
1½	0076	0153	0229	0306	0382	0459	0535	0612	0765	0918	1375	1832	1 7671	1½
1⅝	0090	0180	0270	0360	0450	0540	0630	0720	0900	1080	1620	2140	2 0739	1⅝
1¾	0104	0208	0312	0416	0512	0625	0729	0833	1041	1249	1872	2497	2 4053	1¾
1 13/16	0112	.0224	.0336	0448	0560	0672	0784	0896	1120	1344	2016	2688	2 5802	1 13/16
1⅞	0120	0240	.0360	0480	0600	0720	0840	0960	1200	1440	2160	2880	2 7612	1⅞
1 31/32	0132	0263	0395	0527	0659	0790	0922	1054	1317	1580	2371	3161	3.0440	1 31/32
2	0136	0272	0408	0544	0680	0816	0952	1088	1360	1632	2448	3264	3 1416	2
2 3/16	0163	0325	0488	0650	0812	0976	1137	1300	1625	.1952	2928	3904	3 7584	2 3/16
2¼	0172	0344	0516	0688	0860	1033	1205	1377	1721	2071	3104	4137	3 9760	2¼
2½	0212	0425	0637	0850	1062	1275	1437	1700	2125	.2550	3825	5100	4 9070	2½
2¾	0257	.0514	0771	1028	1285	1543	1800	2057	2571	3085	4628	6171	5 9395	2¾
3	0306	0612	0918	1224	1530	1836	2142	2448	3060	3672	5508	7344	7 0686	3
3¼	0359	0719	1078	1438	1795	2156	2515	2975	3594	4313	6469	8625	8 2957	3¼
3½	.0416	0833	1249	1666	2082	2499	2915	3332	4165	4998	7497	9996	9 6211	3½
3¾	0479	0957	.1435	1914	.2393	2871	3350	.3828	4785	.5743	8614	1 1485	11.044	3¾
4	0544	1088	1632	.2176	.2720	3264	3808	4352	5440	6528	9792	1 3056	12 566	4
4¼	0614	1228	1842	2457	3070	3685	4299	4913	6141	7370	1 1054	1 4739	14 186	4¼
4½	0688	1377	2065	.2754	3442	4131	.4819	5508	6885	8262	1 2393	1 6524	15 904	4½
4¾	0767	.1534	2301	3068	3835	4602	5369	6136	7670	9204	1.3806	1 8408	17 721	4¾
5	0850	1700	2550	3400	4250	5100	5950	6800	8500	1 0200	1 5300	2.0400	19 635	5
5½	1028	.2057	3085	4114	5142	6171	7199	8228	1 0285	1 2342	1 8513	2.4684	23.758	5½
5¾	1124	2248	.3372	4496	5620	6744	7868	8992	1 1240	1 3488	2 0232	2 6975	25 967	5¾

Capacities are given in American Gallons

- Area of circle = diameter squared × 7854
- Circumference of a circle = diameter × 3.1416
- Pressure in pounds per square inch of a column of water = head in feet × .434
- Head in feet of a column of water = pressure in pounds per square inch × 2 30947
- A U S gallon = 231 cubic inches
- A U S gallon of fresh water weighs 8.33 pounds
- A U S gallon of sea water weighs 8 347 pounds
- A cubic foot of water (1728 cubic inches) contains 7 481 U S gallons and weighs 62.355 pounds
- Feet head × 434 = pounds pressure per square inch
- Pounds pressure × 2.31 = feet head
- Meters × 3 28 = feet head
- U S gallons × 833 = imperial gallons
- Imperial gallons × 1 2 = U S gallons
- Cubic feet × 7 48 = U S gallons
- To convert inches vacuum into feet suction, multiply by 1 13
- To reduce pounds pressure to feet head, multiply by 2.3
- To reduce heads in feet to pressure in pounds, multiply by 434
- Friction of liquid in pipes increases as the square of the velocity

Contents of Round Tanks in U S. Gallons for Each Foot in Depth

Inside Diameter		Gallons One Foot In Depth	Inside Diameter		Gallons One Foot In Depth	Inside Diameter		Gallons One Foot In Depth	Inside Diameter		Gallons One Foot In Depth
Ft	In		Ft	In		Ft	In		Ft	In	
1	0	5.87	5	9	194.19	10	6	653 69	15	3	1365 96
1	3	9 17	6	0	211 44	10	9	678.88	15	6	1407 51
1	6	13 21	6	3	229 43	11	0	710 69	15	9	1457 00
1	9	17 98	6	6	248 15	11	3	743.36	16	0	1503.62
2	0	23 49	6	9	267.61	11	6	776.77	16	3	1550.97
2	3	29 73	7	0	287 80	11	9	810 91	16	6	1599 06
2	6	36 70	7	3	308.72	12	0	848.18	16	9	1647 89
2	9	44 41	7	6	330 38	12	3	881 39	17	0	1697 45
3	0	52.86	7	9	352.76	12	6	917 73	17	3	1747 74
3	3	62 03	8	0	375.90	12	9	954 81	-17	6	1798.76
3	6	73 15	8	3	399 76	13	0	992 62	17	9	1850 53
3	9	82.59	8	6	424 36	13	3	1031 17	18	0	1903.02
4	0	93 97	8	9	449 21	13	6	1070 45	18	3	1956.25
4	3	103.03	9	0	475.80	13	9	1108.06	18	6	2010.21
4	6	118 93	9	3	502.65	14	0	1151 21	18	9	2064 91
4	9	132.52	9	6	530 18	14	3	1192.69	19	0	2121 58
5	0	146 83	9	9	558 45	14	6	1234 91	19	3	2176 68
5	3	161 88	10	0	587 47	14	9	1277 86	19	6	2233.52
5	6	177 67	10	3	617 17	15	0	1321.54	20	0	2349 46

SPECIFICATIONS FOR STANDARD "AMERICAN MADE" STEEL PIPE

(Inside) Nominal Size Inches	Actual Outside Diameter	Nominal Weight per Foot Pounds	Number Threads per Inch	Outside Diameter Pipe Coupling	(Inside) Nominal Size Inches	Actual Outside Diameter	Nominal Weight per Foot Pounds	Number Threads per Inch	Outside Diameter Pipe Coupling
⅛	405	24	27	41/64	2	2 37	3 65	11½	2¼
¼	54	42	18	13/32	2½	2.87	5 79	8	3⁹/₃₂
⅜	675	56	18	57/64	3	3 5	7 57	8	4
½	84	85	14	1³/₁₆	3½	4 0	9 10	8	4¹¹/₃₂
¾	1 05	1 13	14	1⅜	4	4 5	10 79	8	5¹/₁₆
1	1 315	1 67	11½	1⁴³/₆₄	5	5 56	14 61	8	6¼
1¼	1 66	2.27	11½	2¹/₃₂	6	6 62	18 97	8	7⁷/₁₆
1½	1 9	2 71	11½	2¹¹/₃₂	8	8 62	28 55	8	9¾

FRICTION OF WATER IN PIPES

Loss of Head in Feet Due to Friction, Per 100 Feet of Ordinary Iron Pipe
(Based on Williams and Hazen Hydraulic Tables)

Gals Per Min	¼ inch Pipe	⅜ inch Pipe	½ inch Pipe	¾ inch Pipe	1 inch Pipe	1¼ inch Pipe	1½ inch Pipe	2 inch Pipe	2½ inch Pipe	3 inch Pipe	4 inch Pipe	5 inch Pipe	6 inch Pipe
	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.	Fric.
1	28.0	6.4	2.1	1 9									
2	103.0	23.3	7 4										
3		49 01	15 8	4 1	1 26								
4		89 0	27 0	7 0	2 14	0 57	0 26						
5		126 0	41 0	10 5	3 25	0 84	0.40						
10			147 0	38 0	11 7	3 05	1 43	0 50	0.17	0 07			
15				80 0	25 0	6 50	3 0	1 08	0.36	0 15			
20				136 0	42.0	11 1	5 2	1 82	0.61	0.25			
25					64 0	16 6	7 8	2.73	0.92	0.38			
30					89.0	23 5	11 0	3.84	1 29	0.54			
35					119.0	31 2	14 7	5.1	1 72	0.71			
40					152 0	40 0	18.8	6.6	2.20	0.91	0 22		
45						50 0	23 2	8.2	2 80	1 15	0.28		
50						60.0	28.4	9 9	3 32	1 38	0 34	0 11	
70						113 0	53.0	18.4	6 21	2.57	0 63	0 21	
75							60.0	20.9	7 1	3.05	0.73	0 24	0 13
100							102 0	35.8	12 0	4 96	1 22	0 41	0 16
120							143 0	50 0	16 8	7 0	1 71	0 58	0 23
125								54 0	18 2	7 6	1 86	0 64	0 30
150								76.0	25 5	10 5	2.55	0 88	0 39
175								102.0	33 8	14 0	3 44	1 18	0 48
200								129 0	43 1	17 8	4 40	1 48	0 62

Friction of Water in 90° Elbows

Size of Elbow, Inches.	½	¾	1	1¼	1½	2	2½	3	4
Friction Equivalent Ft. Straight Pipe.	5	6	9	8	7	8	11	15	16

Pressure of Water Per Square Inch and Feet Head

Feet Head of Water and Equivalent Pressure						Lbs Pressure and Equivalent Ft Head of Water					
Feet Head	Lbs. per Sq. Inch	Feet Head	Lbs. per Sq. Inch	Feet Head	Lbs. per Sq. Inch	Lbs. per Sq. Inch	Feet Head	Lbs. per Sq. Inch	Feet Head	Lbs. per Sq. Inch	Feet Head
1	43	60	25 99	200	86 62	1	2.31	40	92 36	170	392 52
5	2.17	100	43 31	300	129 93	5	11 54	80	184 72	225	519 51
10	4.33	150	64 96	600	259.85	10	23.09	125	288.62	350	808 13
20	8.66	160	69 29	700	303.16	15	34 63	130	300.16	375	865 89
30	12.99	170	73 63	800	346.47	20	46.18	140	323 25	400	922.58
40	17 32	180	77 96	900	389 78	25	57 72	150	346.34	500	1154 48
50	21 65	190	82 29	1000	433 09	30	69 27	160	369 43	1000	2308 00

Weight of Water Contained in One Foot Length of Pipe of Different Sizes

Size In.	Pounds	Size In.	Pounds	Size In.	Pounds
½	086	2	1 372	4	5.488
1	343	2½	2.159	4½	6 966
1¼	537	3	3.087	5	8 575
1½	774	3½	4 214	6	12.348

Multiply by number of feet high or head

UNIT CONVERSION TABLE

Speed

Miles per hour (mph) = Meters per second × 2 24
Meters per second = mph × 0 447

mph = Knots × 1 15
Knots = mph × 0 869

Knots = Meters per second × 1 94
Meters per second = Knots × 0 514

Kilometers per hour = Meters per second × 3 6

Length

Feet = Meters × 3.28
Meters = Feet × 0 305

Miles = Kilometers × 0 621
Kilometers = Miles × 1 609

Miles = Nautical miles × 1.15
Nautical Miles = Miles × 0 869

Kilometers = Nautical miles × 1 852

Area

Square feet = Square meters × 10 76
Square meters = Square feet × 0 093

Power

Watts = Kilowatts × 1,000
Kilowatts = Watts × 0 001

Kilowatts = Megawatts × 1,000
Megawatts = Kilowatts × 0 001

Btu/hour = Watts × 3 413
Watts = Btu/hour × 0.293

Btu/hour = Kilowatts × 3,413
Kilowatts = Btu/hour × 0 000293

Horsepower = Watts × 0 00134
Watts = Horsepower × 746

Horsepower = Kilowatts × 1.34
Kilowatts = Horsepower × 0 746

Energy

Watt-hours = Kilowatt-hours × 1,000
Kilowatt-hours = Megawatt-hours × 1,000

Btu = Watt-hours × 3.413
Watt-hours = Btu × 0.293

Btu = Kilowatt-hours × 3,413
Kilowatt-hours = Btu × 0 000293

Horsepower-hours = Watt-hours × 0.00134
Watt-hours = Horsepower-hours × 746

Horsepower-hours = Kilowatt-hours × 1.34
Kilowatt-hours = Horsepower-hours × 0.746