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PHOTOVOLTAIC ELECTRIFICATION OF HEALTH CLINICS AND VILLAGE SCHOOLS IN BOTSWANA

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Appendices:

ACRONYMS

AC	alternating current
AH	amp hours
AID	U.S. Agency for International Development
ARD	Associates in Rural Development, Inc.
BEDU	Botswana Enterprise Development Unit
BHC	Botswana Housing Corporation
BREAC	Botswana Renewable Energy Activities Committee
BRET	Botswana Renewable Energy Technology project
BTC	Botswana Technology Centre
CDC	Center for Disease Control
DC	direct current
DCS	data collection sheet
DEE	Department of Electrical Engineering
DPS	Deputy Permanent Secretary
DWA	Department of Water Affairs
GOB	Government of Botswana
IDM	Institute of Development Management
LCC	life-cycle cost
MFDP	Ministry of Finance and Development Planning
MLGL	Ministry of Local Government and Lands
MMRWA	Ministry of Mineral Resources and Water Affairs
NASA	National Aeronautics and Space Administration
NDP-5	Fifth National Development Plan
PCV	Peace Corps volunteer
PEC	Project Executive Committee
PP	project paper
PV	photovoltaic
RECC	Rural Extension Coordinating Committee
RET	renewable energy technology
R/F unit	refrigerator/freezer unit
RHC	retained heat cooker
RIIC	Rural Industries Innovation Centre
RIO	Rural Industrial Officer
RMO	Regional Medical Officer
RWL	resting water level
SIDA	Swedish International Development Agency
TESIE	technical, economic, sociocultural, institutional or energy (assessment model)
USDA	U.S. Department of Agriculture
VDC	Village Development Committee
VET	Village Extension Team
VHC	Village Health Committee
VTF	Village Technology Facility
WHO	World Health Organization
WSR	Western Solar Refrigeration
WTGS	Windmill Technology Group Serowe
YWCA	Young Women's Christian Association

PREFACE

This report discusses some of the activities of the Botswana Renewable Energy Technology (BRET) project, which is jointly funded by the U.S. Agency for International Development (AID) and the government of Botswana's (GOB) Ministry of Mineral Resources and Water Affairs (MMRWA). Technical assistance and project management for the BRET project were provided by Associates in Rural Development, Inc. (ARD), of Burlington, Vermont, under AID contract number 633-0209-C-00-1024-00. This report was written by Mr. Richard McGowan, ARD's senior engineer, and Mr. Jonathan Hodgkin, ARD staff engineer in Botswana.

One of the BRET project's goals was to demonstrate and evaluate the use of solar photovoltaic (PV) cells for stand-alone electricity generation at remote sites. The end-uses included water pumps, health clinic electrification for refrigeration and lighting, school lighting, radio communications and weather instrumentation at remote sites. This report discusses the project's experiences with PV electrification of health clinics and village schools from 1982 through 1985. This work involved the cooperation of MMRWA, the Ministry of Health (MOH) and Ministry of Local Government and Lands (MLGL).

A number of people contributed greatly to gathering the information for this report. Mr. James Sentle, a BRET technician, and Mr. Stewart Bentley, a Peace Corps volunteer and BRET engineer, were primarily responsible for both installing the PV systems and initiating the monitoring process. ARD consultant Jack Shields also contributed substantially to the program. The efforts of all these individuals represent just the first step in an ongoing process of bringing the benefits of electrification to many rural areas of Botswana.

I. EXECUTIVE SUMMARY

The Botswana Renewable Energy Technology (BRET) project conducted a demonstration program of solar photovoltaic (PV) electrification installations for rural health clinics and schools. Four PV lighting systems were installed in rural schools that did not have access to mains (national electrical grid) electricity. Three rural health clinics were electrified for lighting and cold-chain vaccine storage.

As part of the efforts of the Ministry of Local Government and Lands (MLGL) to improve the quality of life in rural areas, interest was expressed in school lighting systems. The systems were intended to be used for educational purposes (e.g., teachers preparing lessons, students studying for examinations, general reading) as well as to provide a place for evening community meetings. Both MLGL and the Ministry of Health (MOH) were also interested in clinic electrification to improve the quality of medical services in rural areas, particularly at small clinics and health posts where the potential electrical load did not warrant purchase and operation of even small diesel generators. The project paper for the BRET project mandated installation of several clinic electrification systems. Installation of lighting systems for the clinics was agreed upon as well. The BRET project was also involved in PV electrification for meteorological data collection, water pumping, radio communications and powering test instrumentation, so small-scale PV electrification demonstration installations were a natural complement to these efforts.

The school lighting systems were designed and installed sequentially, with each new system design based on information on lighting loads and use patterns derived from the previous installations. Three direct current (DC) and one alternating current (AC) systems were installed. Based on this limited experience, the DC systems are simpler and more cost effective.

The lighting levels used at the BRET project installations were not up to current Department of Electrical Engineering (DEE) specifications for mains systems. However, after interviews with system users and discussions among DEE and BRET technical staff, it was generally accepted that reduced lighting levels were warranted for rural installations. While definite standards have not yet been agreed upon, BRET staff feel that a general lighting level of 50 lux, and a reading area level of 100 lux, are sufficient. Greater lighting levels can certainly be obtained using PV equipment, but system costs are proportionally greater.

Measured use patterns (in terms of actual on-time and the number of lights used) for the lighting systems were considerably less than those designed for. Long-term system monitoring should be continued to more closely define actual use patterns as well as user expectations, both of which will be useful in designing more cost-effective systems.

The clinic electrification program did not go as far as planned due to institutional difficulties associated with site procurement, limited availability of technical personnel and equipment procurement delays. Further efforts should involve all interested parties in all directly concerned government of Botswana (GOB) agencies, as well as potential users and installation personnel, in the selection of additional sites and equipment to preclude the recurrence of these institutional difficulties. BRET technical staff focused their efforts on the water pumping and solar building design programs; thus there was not sufficient staff time left for more than installation and preliminary monitoring of the PV electrification installations.

The cold-chain vaccine storage units performed reasonably well, with the notable and unfortunate exception of the first unit installed. The failure of this first-generation unit caused decision makers to be skeptical of further installations, which caused significant delays in the program. The costs of the units are given in detail in this report, but the long-term recurrent costs of the alternative systems--paraffin (kerosene) or propane refrigerators--are not well known, so a comparative analysis is not given here.

The main obstacle to the widespread dissemination of PV electrification systems is their relatively high initial capital cost. However, a preliminary comparative life-cycle cost analysis based on the data recorded thus far indicates that the costs of providing electricity for small lighting systems with PV and petrol generators are quite similar, using 1984 costs. The price of PV has dropped 20 percent since that time, which puts the PV systems in a favorable light with regard to annualized life-cycle cost and low maintenance requirements. The costs associated with developing a support infrastructure for widespread dissemination of PV systems was not included in the analysis.

Since both the clinic and school electrification programs were oriented toward demonstration rather than testing, accurate and complete long-term data are not yet available to make careful cost comparisons among the alternative power supply systems. While the capital equipment and installation costs of the PV systems are known, and long-term recurrent costs can be estimated with some degree of accuracy, this is not necessarily the case with petrol generators. Other interested groups should continue the current data monitoring efforts, assist DEE and MOH in the selection of sites for the remaining cold-chain vaccine storage equipment, and assist in the furtner monitoring and analytical efforts necessary to give a more comprehensive overview of the PV electrification efforts. This report lays out the methodology for economic analysis of the alternative systems and presents the data collected and analyzed thus far.

II. INTRODUCTION

One of the most critical needs in remote rural areas of the developing world is facilities for the storage of medical vaccines. Since health clinics in these areas seldom have access to mains (grid) electricity, until recently this need has been met by propane- or paraffin- (kerosene-) powered refrigerator/ freezer (R/F) units. While the development of these units has progressed to the point where currently available units are usually quite well designed, they nonetheless have a highly variable history of reliability under harsh operating conditions in the field. They have been plagued by problems with unreliable fuel supply networks, lack of adequate local maintenance and repair capability, and high long-term operational costs due to constantly rising fuel costs.

To address the need for a cold-chain vaccine R/F unit that is reliable, cost-effective, and easy to use and maintain, organizations in several countries began work on the development of a solar PV-powered R/F unit. This approach was due to the rapid decrease in the cost of PV modules during the late 1970s, which dramatically reduced overall system cost, as well as to the general perception that PV systems had the potential for extremely reliable long-term operation with minimal maintenance requirements. Researchers and development professionals at that time assumed that module prices would continue to drop as the demand for PV devices increased, which would result in cost-effective systems in the near future. This has indeed been the case under some circumstances.

Lighting in areas without mains electricity was also becoming a priority. At rural health clinics, the need for lighting is obvious. Although surgery is not normally performed, the clinics have maternity wards which require lighting for nighttime deliveries. Night emergency procedures also require adequate lighting. The conventional lighting sources have been kerosene lamps and torches (flashlights).

In addition to clinic lighting, there has been increasing interest in lighting in the evenings for rural classrooms, so that teachers can prepare lessons, students can read and study, and evening classes and community activities can be held. Quantifying these benefits compared to the costs of providing lighting is admittedly difficult, and depends heavily on site-specific use patterns. Given the problems associated with the use of diesel or petrol generators (e.g., lack of fuel, heavy maintenance requirements, spare parts availability), PV modules are being examined more closely to determine their potential for powering such lighting systems.

Approximately 35 of the 62 secondary schools in Botswana are not connected to the national electrical grid, and hence are candidates for PV electrification (figures from BRET/BTC PV Workshop, August 1985, Gaborone). At off-grid sites where diesel generators are not being used, lighting is currently provided by white gas or paraffin lanterns, which are expensive and potentially dangerous. Another increasingly popular use of PV-generated electricity is charging small 1.5-volt, dry-cell batteries. Although this can be among the most economically favorable uses of PV, it was not specifically addressed in this program.

Initially, the direct current (or DC, the type of electricity generated by PV arrays) lighting and refrigeration equipment used was that developed for marine or recreational vehicle use, where energy efficiency was not a great concern. The increased use of PV throughout the world has given small-appliance manufacturers incentive to develop new, more efficient DC lighting and other electrical appliances to satisfy this market. These energy-efficient appliances allow the use of fewer PV modules in the power supply, thus significantly reducing system costs. As a result, PV remote-site electrification is becoming increasingly interesting to many areas of the developing world, including Botswana. There are currently some 600 PV refrigeration units installed worldwide. Another 100 units are planned for installation in Zaire, where they will be produced through a joint venture with a local manufacturer.

A typical clinic electrified with PV has a vaccine storage unit, several lights and a power supply, a part of which is the PV array, consisting of individual modules wired together with batteries and a charge controller. School PV systems most often simply provide a few hours of lighting a day to allow evening use of classrooms. They could also occasionally support a small radio so that broadcasts of educational programs could be received.

Typical system configurations and costs vary, but the PV modules themselves represent the majority of the initial capital equipment cost of the system. PV modules are normally rated in terms of their peak power production capability. For instance, a typical module might be capable of producing 40 watts of power under certain specified conditions of solar radiation intensity and ambient temperature (40 Wp, or watts peak). While PV module prices have not continued to drop as rapidly as researchers in the late 70s assumed, they have dropped from $20/Wp in the late 70s to $6/Wp currently. However, PV systems still have a considerably higher initial capital cost than fossil-fuel-based systems such as propane or kerosene. Thus, to be cost-effective, it must be shown that the reduction in long-term recurrent costs associated with the use of PV more than makes up for the higher initial investment in equipment.

While cost is an important consideration in the use of stand-alone PV electrification systems, the long-term reliability of the systems is of much greater importance. Reliability of operation is particularly critical in the cold chain since vaccines exposed to high ambient temperatures, even for relatively short periods, lose their potency. Also important is user acceptance and ease of local maintenace and repair, without which no system will achieve long-term operational reliability.

Little field testing has been done on small-scale lighting systems for schools. Thus, while extensive laboratory testing of some of the currently available PV R/F units has occurred (see Section II.C), there is still a need for comparative testing of different systems under actual field operating conditions. The interaction of the lighting and refrigeration subsystems has hardly been examined. PV vaccine storage R/F units in particular are a relatively immature technology. Several new manufacturers entered the market over the life of the BRET project, and several others dropped out. The same is true for much of the 12-volt lighting equipment now coming on the market. This new equipment holds considerable promise for favorably changing the economics of PV clinic electrification, mainly due to lower equipment prices and increased energy efficiency, allowing for reduced array costs. Much of this new equipment has yet to be evaluated under actual operating conditions in developing countries. The clinic and school electrification subcomponents of the BRET project's overall PV demonstration and evaluation program were conceived to address the need for a critical technical, social and economic analysis of these systems in small health clinics and schools in rural Botswana. This effort complements the GOB's efforts to maximize use of economically viable, indigenous energy resources and, wherever possible, to reduce dependence on imported fuels, in particular petroleum and its derivatives.

A. History of BRET Project PV Lighting in Schools

One of the more common uses of photovoltaics was for small-scale lighting systems designed to provide limited light for evening activities in remote locations. Most were designed as single-module systems with a battery and one or more lights, a model commonly used in many countries. Lighting was one of the first uses of PV energy in Botswana as well. The Botswana Technology Centre (BTC) has been involved in a program to install and evaluate small-scale PV lighting systems in houses in several low-income neighborhoods of Gaborone, neighborhoods which were not served by mains electricity. This experience convinced the BTC that PV lighting on a small scale had potential and was a technology that could be successfully disseminated. BTC committed time and effort to developing a controller that could be built in Botswana. This was part of its attempt to overcome two of the primary obstacles to successful adoption of the technology, cost and local repairability. BTC also published two documents about PV lighting, Power from the Sun--Light at Night and A Reliable Controller for Small Solar Powered Lighting Systems. These activities led to an increased awareness of the potential for PV lighting systems. In the private sector, PV distributors report small but steady sales of lighting systems to wealthier Batswana and expatriates. The Department of Electrical Engineering (DEE) is also interested in PV lighting systems. DEE is currently designing PV lights and contracting to have them installed at two rural branch libraries (Bobonong and Letlakeng).

No school electrification plans were specifically mentioned in the BRET project paper. However, as the project developed and the potential for providing light at reasonable cost became better known, MLGL expressed an interest in installing PV lighting in rural schools, and the BRET project got involved. Relatively late in the project, a pilot project to install lights in one classroom in each of four schools was outlined and approved. While a detailed testing program per se was not undertaken, the intent of the activity was to gain experience from several installations and to approximately evaluate the costs and benefits of such systems.

MLGL's interest in lighting grew out of the idea that lighting in rural primary schools could serve multiple purposes, i.e., improve the quality of life in rural areas and benefit the rural population. First, lighting would increase the ability of schools to fulfill their responsibilities--teachers would have more time for preparing lessons and marking papers, students would have more time for studying or reading, and evening sessions could be held, particularly prior to examinations. Second, lighting would mean that community activities such as PTA meetings, Village Development Committee (VDC) meetings and other community events could take place.

The BRET pilot/demonstration program outlined involved four rural schools and was designed to determine whether the provision of basic PV lighting in rural schools was a cost-effective use of government funds. To answer this question, the four systems were iteratively designed based on experience with the designs used thus far. The first installations provided both technical and nontechnical information which was used in later designs. As a result, each was designed somewhat differently to reflect site-specific use patterns and availability of progressively better equipment. The four schools that currently have PV lighting systems installed are Oodi (Kgatleng District), Ditshegwane (Kweneng District), Shoshong (Central District) and Molapowabojang (Southern District). The systems were installed, in that order, between February and August 1985.

B. History of BRET Project PV Clinic Electrification

The rationale for the BRET project's involvement in clinic electrification comes from the project paper, which called for installation of six PV-powered vaccine R/F units at six health posts and complete electrification (lights and R/F units) of three rural health centers. Health centers are typically larger and have more facilities than health clinics, which serve smaller populations and are primarily concerned with health education, some degree of maternity care, collecting statistics and giving immunizations. Health posts, further down the list, are not normally staffed by people trained to give injections. With the effort to upgrade all health care facilities, these descriptions are changing.

Based on a series of site visits to several clinics by ARD consultants in 1981, and discussions between BRET project staff and MMRWA officials, ARD/BRET technical staff made the decision to work with health clinics instead of health centers. A set of criteria was developed by ARD/BRET staff for choosing proper sites for the demonstration installations of these institutional-level renewable energy technologies. Since the initial discussions were with district-level personnel in the Kweneng District, it was natural to pick the first clinic out of Kweneng, so Lensweletau was chosen. Shoshong was selected because the BRET project already had a presence there with the Village Technology Facility (VTF), a rural technology training location. This would enable the BRET project's activities to be concentrated geographically, allowing for better technical and logistical support.

Not all of the refrigeration units purchased by the BRET project have been installed in the field. There were several reasons for this. The primary reason was the lack of sufficient technical staff to devote enough time to the clinic and school demonstration/evaluation components of the overall BRET project effort in the area of photovoltaics. The comparative testing of water-pumping systems and the passive solar building design programs received primary emphasis, and thus absorbed much of the time and effort of the technical staff. Second, there were many institutional difficulties encountered, particularly in the PV refrigeration program, where one of the greatest difficulties was simply the procurement of sites. In addition, because of overlapping responsibilities of MLGL and MOH (MOH supplies medical equipment to MLGL for the health clinics), two bureaucracies (which did not necessarily have the same agendas) had to be dealt with instead of one.

After the problems encountered with the first PV refrigerator installation (see Section V), MLGL requested an evaluation of that unit before assigning other sites for future PV R/F unit installation. This evaluation was not performed in a timely manner, so delays in assigning additional sites inevitably resulted. Another unit was promised to Ditshegwane on the basis that the BRET project already had a presence there (a VTF had already been established there). The unit has not been installed partly because MLGL officials would not approve the site prior to receiving the above-mentioned evaluation. This unit should be installed by DEE, which is absorbing responsibility for the continuation of the BRET project's initial PV electrification efforts.

The involvement of Dr. Sieben of the MOH, a supporter of the BRET project's PV electrification efforts, would probably have been helpful in the earlier phases of the project. Dr. Sieben expressed enthusiasm for the continuation of BRET's clinic electrification efforts and gave BRET technical personnel a list of sites to consider for immediate installation. DEE should consult with Dr. Sieben as part of its continuation of the clinic electrification program.

C. Previous Refrigeration Evaluations from Other Projects

Several experiments sponsored by the NASA Lewis Research Center and the Center for Disease Control (CDC) in the United States examined in detail the laboratory performance of several early PV-powered R/F units.[1,2] The units were tested in isolation rather than with any lighting systems. The first phase of the NASA/CDC project consisted of development by participating contractors of several PV R/F units that would meet World Health Organization (WHO) specifications, as well as several operating constraints dictated by NASA. The second phase was to include comparative testing of the units developed based on the WHO Standard Test Procedure for Refrigerators and Freezers for Use in the Cold Chain and modified somewhat by NASA. While contractors were urged to consider cost-effectiveness in system design, an economic evaluation giving detailed comparisons of the PV R/F units to standard propane or kerosene was not part of these tests.

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[1] Darkazalli, G. and G. Hein. "Solar Photovoltaic Powered Refrigerator/Freezers for Medical Use in Remote Geographic Locations." NASA Lewis Research Center. NASA CR 168268. October 1983.

[2] Kaszeta, William. "Qualification Testing of Solar Photovoltaic Powered Refrigerator Freezers for Medical Use in Remote Geographic Locations, Final Report." Solavolt International, for NASA Lewis Research Center. NASA CR 168181. December 1982.

Generally, these tests were designed to measure:

- ability of the R/F unit to maintain uniform temperatures within a specified range in both the refrigerator and freezer sections;
- power consumption, which is directly proportional to required array size, and hence the cost of the overall system;
- ice-making capability; and
- cycling time, or percent of time the compressor is running out of the total elapsed test time--the longer the compressor running time, and the more frequently it turns off and on, the shorter the expected lifetime of the compressor.

Several of the R/F units developed successfully passed the acceptance tests. Many of these units were then distributed to remote health clinics in many parts of the world. Extensive field-testing and examination of user acceptance issues have not taken place to any appreciable degree.

III. OVERVIEW OF REFRIGERATION AND PV LIGHTING TECHNOLOGY

The need for availability of vaccines at remote sites has led to development of various storage technologies with very site-specific applicability. Successful vaccine storage requires an extremely reliable storage device that is capable of continuously maintaining interior temperatures within a narrow band of acceptability. Some vaccines (see below) must remain frozen, so freezing capacity is often required. Most vaccines cannot be frozen, but rather must be maintained at a temperature between 4 and 8°C. In addition, since vaccines are frequently stored in centrally located clinics in remote areas, provision must be made for ice production so that trips to surrounding villages can be made to vaccinate villagers. This requires the use of small portable vaccine-carrying containers that are cooled by ice. This ice is normally in the form of "cold-dogs," small plastic containers of water (e.g., the "blue ice" commonly used in the United States) that can be placed in the vaccine storage unit at the central clinic for periodic refreezing.

PV lighting technology has also advanced rapidly in the last several years. System components currently available are far superior to their predecessors in terms of efficiency (greater lumens per watt) and long-term reliability. Controllers for both refrigeration and lighting systems have advanced as well. While the first-generation controllers used in the early systems installed by the BRET project were plagued with failures, the newer-model replacements have performed flawlessly thus far and show every indication of continuing to do so.

A. Advantages and Disadvantages of PV Electrification

To some extent, PV R/F units are still a developing technology, although this is not the case with lighting systems. There are (at last count) four U.S. manufacturers of DC refrigerator/freezers designed specifically for use with PV, as well as several European manufacturers. Due to increasing competition among manufacturers and a spreading awareness among development professionals in the health field that PV generation of electricity can be a viable alternative under certain site-specific conditions, manufacturers are redesigning their equipment to optimize mechanical efficiency and cost. Incorporating feedback from users of the units in the field has led to more useful design features and better documentation. It is hoped that this report furthers that feedback/redesign process (see Section V.C).

The primary advantage of using PV to power R/F units and lighting systems is the high reliability of the power supply. PV modules have been in use in extraterrestrial applications for nearly three decades, and terrestrial applications are expanding in inverse proportion to the reduction of PV cell costs. Some manufacturers of PV modules (the integral units in which the cells themselves are mounted) now offer 10-year warranties against significant (greater than 10 percent) decreases in module power output over time. Accelerated testing procedures have indicated that modules are very likely to last for 20 years of service. Thus there is little question as to the long-term reliability of the modules themselves. However, there are many other components in the overall system. These will probably have to be replaced (batteries in particular--see Section III.B) or repaired at some point during the useful lifetime of the system. In addition to reliability, the use of PV gives a degree of independence from the vagaries of fossil fuel supply and increasing costs.

At many, if not all, of the remote clinics where use of PV R/F units would be considered, lighting would also be desired. As mentioned previously, lighting is the primary load in schools. Usually, after several lights are installed as part of the initial system, requests come in from the system users for additional lighting. This points up an additional advantage of PV--its modularity. Additional lights can be handled by the base system simply by adding modules to the array, up to the limit of the current handling capability of the controller. Above that level, a larger-capacity controller must be added to the system, which normally represents a fairly small incremental equipment cost.

The principal disadvantage of PV is its high initial cost. In order to be strictly cost-competitive with fossil-fueled R/F units, they must be amortized over a relatively long period of time (approximately 10 to 15 years, see Section VI). Other disadvantages include foreign exchange requirements and a general lack of familiarity with the technology on the part of technicians (thus requiring training of field technicians) as well as government decision makers (thus requiring demonstration and awareness programs on the part of either system manufacturers or donor agencies).

The costs of training and maintaining the entire support infrastructure for design, installation, operation and long-term maintenance and repair of stand-alone PV power generation systems is not often considered when listing the obstacles to the widespread dissemination of PV electrification. This question has been addressed to some extent in the ARD report, "Training Needs Assessment for RETs" (by George Burrill, June 1985), although the costs of such training have yet to be adequately quantified.

B. Typical System Configurations and Components

PV electrification systems typically consist of the following components:

- for refrigeration, the R/F unit, which includes the cooling compartments, compressor, condenser, evaporator and controls;
- battery regulator/controller, if it is not contained within the R/F unit;
- battery bank and wiring harness; and
- PV array, including modules, array support structures, wiring harness and power cable to the battery regulator.

Some systems (such as the Polar Products RR-2) have two compressors, one for the refrigerator and one for the freezer. While this increases the overall reliability of the system by allowing one compressor to cool both freezer and refrigerator in the event of failure of the other compressor, it also significantly increases the system cost.

Photovoltaic R/F units vary in capacity from 50 to 127 liters. Some units are simply for refrigeration, others only for freezing, but most have both capabilities. While 50 liters may seem quite small, it is more than adequate for storing sufficient vaccines to supply the needs of many of the smaller rural health care facilities in Botswana. While units larger than the 127-liter size could certainly be built, many field trials have shown that excess capacity often encourages use of the R/F units for purposes other than those for which they were designed. Such uses (e.g., storage of food and cold beverages) can dramatically increase the device's energy consumption beyond its design limits (since they presumably result in significantly more frequent door opening and subsequent heat losses) and adversely affect the primary purpose of the unit. Manufacturers feel that R/F units with greater capacities would probably only be needed at larger facilities. Since such facilities would be likely to have access to grid power (or have other electrical energy end-uses that might dictate use of a diesel generator), manufacturers perceive the market for larger units to be quite small.

PV lighting systems are similar to refrigeration systems except in end-use devices. PV lighting systems consist of the following components:

- the lights themselves, which are usually DC fluorescent tubes but can be AC (alternating current) fluorescent or even AC incandescent if other system components (inverters) are in place to allow conversion of the electricity from DC to AC;

- the wiring system, complete with conduit, if necessary, along with all associated connectors, circuit breakers and junction boxes;

- the system controls, which include the light switches and a battery charge controller to prevent battery over-charge or over-discharge;

- one or more batteries to store electrical energy generated during daylight hours for use at night; and

- the PV array, including the modules, frame, wiring and power cable to the controller.

Normally, small-scale lighting systems use one or two modules and batteries and are DC systems throughout. One larger AC system was tested as part of the BRET program.

In addition to any instrumentation that is supplied with the battery regulator (sometimes volt and amp meters), other instrumentation is sometimes mounted on the R/F units themselves. For systems without some minimal level of monitoring instrumentation, a special monitoring package was installed to measure the relevant performance parameters. Details of the instruments used in the BRET project tests are given in Section IV.B.1.

C. Systems Tested in Botswana

Ten R/F units were purchased by the BRET project. Of these, five were installed in rural health clinics (three on a permanent basis, two temporarily). The reasons for this difference are given in Section V.B. Various types of R/F units were used so that differences in use patterns, performance and cost could be documented and analyzed, and so that their acceptability could be evaluated from the standpoint of ease of use and size, for example. This provided information so that recommendations could later be made as to the general reliability and cost-effectiveness of each type. The models purchased by the BRET project were:

- one Western Solar Refrigeration (WSR) unit;

- three SunFrost Vaccimax;

- one Polar Products RR-2 and three RR-50L; and
- two Marvel 4RTD, a modified version of the WSR unit.

All of these units except the SunFrost and the modified Marvel units have been tested according to the NASA/CDC/WHO procedures mentioned in Section II.B. The SunFrost units were developed after the NASA testing project, but were subject to independent testing, which maintained that their very low energy consumption made them very competitive with other currently available R/F units.

Although PV R/F units can be purchased as refrigeration units, freezing units or both, all those purchased by the BRET project had both refrigeration and freezing capability. This was due to the need to store polio and measles vaccines, as well as the practice in Botswana (common in many countries) of storing vaccines in a centrally located clinic in a remote area and making periodic trips to surrounding villages to vaccinate residents. This practice requires short-term storage of vaccines in small, insulated, portable, ice-cooled boxes. The reusable ice packs are placed in the clinic R/F unit for periodic refreezing.

According to Dr. Sieben at the MOH, who is the UNICEF representative in Botswana, UNICEF normally supplies village and regional health clinics with units that are capable of both refrigeration and freezing. Vaccines typically used in Botswana are listed below by preferred storage method:

- must be frozen (i.e., between -8° and -10°C, or WHO requirement of -20°C): polio/measles;
- must be refrigerated (0°-8°C), but when frozen, potency is not adversely affected: BCG (tuberculosis), DT, T (D=diptheria, T=tetanus); and
- must be refrigerated and cannot tolerate freezing: DPT (P=pertussis).

In Botswana, therefore, both refrigeration and freezing capability are required for storage reasons (storage time averages approximately one month). In addition, ice packs are used about once a month to refrigerate the portable vaccine carriers when trips are made from the regional health centers to the villages under their jurisdiction. Although 210-liter R/F units are normally supplied, they are really not sufficient for use by the larger regional health centers that require more storage space.

Dr. Sieben has recently ordered 47 more R/F units from UNICEF, and delivery is expected in six or eight months. He said that MOH would be glad to use additional BRET units, and suggested the following possible sites: Selibe-Phikwe; Mahalapye, where the BRET project currently has a PV pump installed; and Ramotswa, where there are maintenance problems with the current gas R/F unit. Mission hospitals in the area (e.g., Bamalate Mission Hospital) might well serve as additional demonstration sites.

Four school lighting systems were installed for testing and evaluation by the BRET project, all in slightly different configurations. The systems, locations and installation dates are given below.

In Oodi, the system was installed in February 1985 in a 50-square-meter classroom. The system consisted of six 15-watt DC fluorescent lights (switched sets of two); two 100-amp-hour, shallow-cycle batteries; two Arco Solar M-63 modules; and one analog voltmeter.

The Ditshegwane system was installed in May 1985. A 50-square-meter classroom was outfitted with 14 15-watt DC fluorescent lights (four switches); three 100-amp-hour, shallow-cycle batteries; three Arco Solar M-53 modules; and one BTC charge controller.

In May 1985, a 95-square-meter classroom in Shoshong was outfitted with six 50-watt AC fluorescent lights (switched sets of three); six 100-amp-hour, shallow-cycle batteries; eight Arco Solar M-63 modules; two BTC charge controllers; and two 300-watt inverters.

Finally, in Molapowabojang, the system was installed in May 1985 in a 50-m^2 classroom. Nine 15-watt DC fluorescent lights (four switches); three 100-amp-hour, shallow-cycle batteries; two Arco Solar M-53 modules; and one BTC charge controller made up the system.

In some cases, component choices were dictated by product availability and convenience. This was true in the decision to use ARCO M-63 self-regulating modules in the Shoshong and Molapowabojang systems. Shallow-cycle batteries were used largely because they were available locally and were less expensive than deep-cycle batteries. The controller, used for its low-voltage cut-out capability, was designed for use with these batteries. A locally available inverter was used because of the warranty and service by local dealers. In light of the work completed thus far, it appears that these lighting systems were overdesigned. These issues are discussed in more detail in Section V.

IV. DATA COLLECTION METHODOLOGY

The PV electrification component of the BRET project was principally conceived as a series of demonstrations rather than a rigorous comparative testing program, and the amount of effort and time put into the comparative evaluation data collection program reflects this. The data collection methodology for monitoring and evaluation of the various clinic and school electrification installations was not rigorously developed prior to the installation of the equipment, as was the case with, for instance, the comparative water-pump testing program. Although considerable technical performance data were gathered over the life of the project, much of the information was in the form of data collection sheets distributed to the various sites and recorded by equipment users. Since the machines used were production models rather than prototypes, the emphasis was on user interaction and long-term reliability, rather than specific technical performance in the sense of energy efficiency or optimized system design. Short-term, intensive tests were performed on some of the refrigeration units at the BRET workshop to roughly quantify some of these parameters. The results are given in Appendix A.

A few remarks must be made on the logistic difficulties associated with any broad-based field-testing and evaluation program. While field tests are a critical stage in the development and dissemination of any new technology, such tests invariably present problems in data gathering which often far exceed the expectations of project planners. While the actual installation of a particular piece of equipment might take two people two days on-site, field tests often involve driving an additional day merely to reach the site. One can imagine the difficulties that ensue when technicians neglect to bring a single required tool. Lack of adequate communications at remote sites further aggravates this sort of problem.

The importance of training equipment users is often not sufficiently emphasized in demonstration programs. What may appear on the surface to be a simple set of instructions often becomes incomprehensible to people completely unfamiliar with the equipment. If breakdowns occur (as they often do with unfamiliar equipment, simply because users are not fully aware of proper operation procedures, however simple), one crucial piece of information is often forgotten--where to go and whom to talk with to get the equipment fixed. If the site is fairly remote, it might be (literally) weeks before technical support staff even find out that problems have occurred, let alone begin to address those problems. All too often, the emphasis of research and development projects is on the equipment itself. There is insufficient technical support to pay sufficient attention to the details that keep equipment in proper operating condition.

A. Criteria for Evaluating Refrigeration Units

There are several criteria for evaluating the performance of R/F units based on cost, temperature stability, long-term reliability, and ease of installation, use and repair. Temperature stability is crucial to the preservation of vaccine potency; hence, it is the most critical issue. For certain types of vaccines (e.g., polio-measles) that must be frozen, if the storage temperature of the vaccine gets above freezing for any length of time, the vaccine loses its potency. The same is true with vaccines that must be kept refrigerated below 8°C. If the refrigerator compartment temperature rises above that level, potency is lost. These temperature changes can easily happen without the eventual user's knowledge. A ruined vaccine might be administered anyway, with the recipient assuming protection against the particular disease. This can happen even if temperature-sensitive labels are used. If exposure to high temperatures occurs, which causes the label to change color to indicate an impotent vaccine, it is conceivable that health personnel might either forget to check the label or choose to ignore it due to lack of a suitable replacement.

1. Technical Performance Criteria

In the past, evaluations of the technical performance of R/F units have principally been concerned with issues of capability for local repair, temperature stability and long-term reliability. Only recently has the issue of energy efficiency arisen as a matter of concern. This was due in large part to the fact that long-term recurrent costs, such as those for paraffin or propane fuel, were not seen as a large part of the overall system cost. The rate of fuel consumption, which is inversely proportional to energy efficiency, was a matter of concern only insofar as a high rate of fuel consumption meant that the clinic or hospital had to be supplied more frequently with fuel. Large-scale, on-site fuel storage could result in theft problems, and regularly scheduled fuel delivery at many facilities could often be very difficult due to unreliable transportation networks, washed-out roads, or simply the unavailability of supplies at major distribution centers.

Although these problems have not been experienced to any great degree in Botswana, the general reliability of kerosene refrigeration has been low. This has been due in large part to the temperamental nature of kerosene refrigeration and the need for well-trained, attentive users who are able to adjust and care for the units. This has led, in recent years, to a movement toward gas refrigeration systems, which have proved much more reliable. However, this trend has not eliminated the problems of fuel delivery, need for local repair capability and adequate training of end-users.

The major advantage of using PV to supply energy for clinic electrification is that it obviates the need for and cost of conventional fuel supplies. However, this application of PV also forces system designers and purchasers to pay considerably more attention to the energy efficiency of the R/F units being used and to the size of R/F unit required. The more efficient the R/F unit, the fewer PV modules required to meet electrical energy demands, and the less expensive the system. Since PV systems are typically characterized by very high initial capital equipment costs, and very low long-term recurrent costs (low maintenance, zero conventional fuel consumption), the comparative economics of such systems are strongly driven by the energy consumption of the R/F unit (and lights, where used in conjunction with the R/F unit). Thus, it is particularly important to size the power supply so that the minimum number of modules is used to deliver the required amount of energy.

The energy use of a vaccine refrigerator depends heavily on whether or not it must make ice daily, because ice-making takes considerably more energy than merely maintaining the low temperatures required under normal use conditions. However, health clinics often require ice-making because of the need to periodically take vaccines to remote sites. For small R/F units, freezing several "cold dogs" on a daily basis can easily double daily energy consumption. Also, many models are available as a refrigerator/freezer or either refrigerator only or freezer only. Thus, actual site conditions and use patterns must be carefully considered when choosing the type of R/F unit and sizing the PV array.

Long-term temperature stability is critical for safe vaccine storage. Recent refrigerator/freezer designs make better use of eutectic (latent heat storage) plates that help ensure temperature stability over longer periods, even if the unit is inoperable for short periods. In one short-term test conducted at the BRET workshop (see Appendix A), when the temperature in the freezer compartment was initially at -9°C, it took two days for the temperature to rise above 0°C after the unit had been turned off (the door was not opened during this period). This fact, and the uniformly high solar radiation levels encountered in Botswana tend to increase the reliability and security of vaccine storage.

In other experiences with PV R/F units (with some notable exceptions), the capability for local repair was heretofore considered an expensive luxury. When R/F units broke down, replacement was more common than on-site repair. Units in need of repair were usually put in a warehouse in the country's capital, where one or two well-qualified, but overburdened, refrigeration mechanics repaired them, as time and the necessary spare parts became available. Since this approach is very costly in terms of equipment as well as net downtime (the time elapsed between the initial malfunction and notification of the proper authorities and actual replacement or repair of the unit), simple, modular design is now considered an important evaluation criterion because local repair (or at least, the replacement of suspect parts) is possible to a much larger extent. Standardization of spare parts and repair procedures is an important, yet often unrecognized, strategy that can significantly improve the success of local repair efforts.

2. Use Evaluation

Ease of installation and operation are very important features whose evaluation is unavoidably somewhat subjective. For instance, an installation manual that is quite clear to an experienced technician may be of little use to a layperson. Since nurses and medical technicians in rural health clinics typically have little or no technical expertise in either PV or refrigeration, manuals must be written so that installation and simple repair procedures are clear to nontechnical staff members. If they are not, repair or maintenance problems will very likely arise that will result in the unit being out of service for considerable periods of time, even though, theoretically, the problem may be easily solved. Not only will the vaccines lose their potency, but both clinic staff and MOH decision makers will lose confidence in the technology.

To determine the utility of both the equipment supplied and its accompanying documentation, interviews were conducted with clinic staff members and the BRET project technicians who were responsible for installing the equipment. Comments from these interviews are presented in Section V.B, and a synopsis of the lessons learned from the interviews as well as recommendations for further design improvements are provided in Section V.C.

3. Financial/Economic Criteria

As mentioned previously, although cost is certainly an important criterion in the selection of any piece of equipment, for purposes of clinic electrification, the issue of reliability assumes paramount importance, as impotent vaccines are worse than none at all. Accurate life-cycle costing analysis requires accurate estimation of long-term reliability (in terms of operation, maintenance and repair costs), which is a very difficult parameter to accurately quantify. It is a function not only of the unit's original design, but also its proper maintenance in the field. To a large extent, the latter is a function of the users' level of technical expertise, ease with which the machine can be operated, availability of spare parts, distribution and technical support infrastructures, and frequency and complexity of necessary periodic maintenance procedures.

When a new technology is introduced, investments in support infrastructure, which can prove to be considerably more costly and time-consuming than the procurement and installation of the equipment itself, have costs that are very difficult to estimate. For instance, projecting the cost of training an adequate pool of technicians in system design, installation, maintenance and repair for a certain number of PV-electrified rural clinics in an area where such training has not been carried out previously can be little more than an educated guess. Although issues of the training and necessary skills required to perform certain of these tasks have been dealt with to some extent (see "Training Needs Assessment for RETs," by George Burrill, ARD, June 1985), the associated costs have not been quantified. Even the costs of developing the existing support infrastructure for the gas-driven refrigerators currently used by MOH are not easily determined. The costs of developing this support infrastructure would be an integral input into comparative life-cycle costing analyses.

The life-cycle costing method discussed in Section VI is thus restricted to the comparison of known capital equipment and installation costs, and estimates of the long-term recurrent costs for the operation and maintenance of the equipment tested. The costs of developing support infrastructures of each of the competing technologies can only be estimated to be of the same order of magnitude, although the cost of developing the infrastructure for the existing technology (propane or kerosene) is obviously a sunk cost. Determination of the detailed costs, maintenance schedules, fuel consumption rates, and useful equipment lifetimes for gas and kerosene vaccine refrigerators were not a part of this demonstration program, but would have to be determined to perform an adequate comparative analysis.

B. Data Collection Requirements for Refrigeration Units

The data collection requirements for this project can be divided into three groups: technical performance, cost and user interaction.

For technical performance, the most important characteristics were:

- temperature maintenance and stability,
- ease of installation and maintenance (where users did not perform necessary maintenance themselves), and

- long-term reliability of component parts and of the R/F unit as a whole.

The cost category included determination (or estimation) of:

- capital equipment costs (a strong function of the energy efficiency of the equipment chosen),
- long-term recurrent costs of operation and maintenance,
- infrastructural support costs for equipment distribution and transportation,
- spare parts costs, and
- labor costs for technically skilled personnel.

User interaction parameters included:

- simplicity of operation,
- frequency and complexity of required periodic maintenance procedures,
- design features that contributed to ease of operation and repair (such as reactions to size and top- versus front-opening models), and
- aesthetic and functional attributes.

Although this last item may seem trivial, a frequent comment from users of the PV R/F units was that one model in particular "just didn't look like a proper refrigerator," and that they sometimes avoided using it for just that reason. This is just another example of how important social considerations can become in the adoption of (or aversion to) a new technology. People will often reject an unfamiliar technology simply because of the way it looks, no matter how energy efficient it might be. Technical development professionals would do well to bear in mind such potential pitfalls.

The PV refrigeration evaluation methodology was an evolving process (for reasons given below), so that the instrumentation used during different periods of the project varied somewhat. During the entire monitoring period, refrigerator and freezer temperatures were recorded by standard mercury thermometers placed in both freezer and refrigerator sections of the R/F units. Some of the units were also equipped with maximum/minimum thermometers which recorded the limits of temperature variation over the recording period. Finally, some were also periodically monitored with recording thermographs, devices that record the track of temperature variation on a paper tape. All of these measurements were made to verify manufacturers' claims of temperature stability within a certain acceptable range under a variety of operating conditions.

The electrical energy consumption measurements were by far the most problematic. Initially, two instrumentation packages (Curtis Integrators) for R/F unit monitoring were obtained from the manufacturer of the original R/F unit purchased by the BRET project (Western Solar Electric). These devices were designed to measure and accumulate (integrate) the current input from the PV array (AH) and current output to the R/F unit (AH), and to measure the total time the R/F unit had been operating. In addition, there was an on-board analog meter that had three settings: array current, compressor current and system operating voltage.

Because the monitoring devices were not off-the-shelf items, but were custom-made specifically to monitor the performance of PV R/F units, and because they were not accompanied by well-written field operation and repair manuals, they did not provide the trouble-free use promised by their manufacturer. After a period of unsatisfactory operation, the units had to be sent to South Africa and eventually the United Kingdom for repairs, and the turn-around time was nine months. Less sophisticated monitoring equipment (separate analog volt and amp meters, and a DC-driven clock on the compressor), which would have involved the use of manual record keeping, would have been a better choice, in retrospect. Such equipment was, in fact, installed on R/F units purchased later in the project.

Measurements were recorded on data sheets (for example, see Appendix B). The measurements recorded at both the Lensweletau and Shoshong clinics (and eventually, but for a much shorter period of time, at Mabule) were:

- refrigerator temperature (dial thermometer),
- freezer temperature (dial thermometer),
- ambient air temperature (maximum/minimum thermometer), and
- system voltage (integrally mounted voltmeter).

The data were recorded by the resident nurse twice a day, in the morning when she got to work, and in the afternoon just before she left. In addition, the items in the R/F unit (vaccines, ice packs, cold drinks, etc.) and general weather conditions (cloudy, sunny, etc.) were noted. This information represents most of the data base on the use of PV R/F units. Measurements were made over a one-year period at Shoshong and several months (thus far) at Lensweletau. The data collection at Mabule was inhibited by the misunderstanding discussed in a later section, but is now underway.

C. Criteria for Evaluating Lighting Systems

Many of the comments on the advantages and disadvantages of using PV power supplies, whether for refrigeration or for lighting, have already been mentioned in the previous sections and will not be repeated here. Since lighting in schools is a desirable but certainly not critical provision (as is the need for vaccine refrigeration), the reasons for evaluating the school lighting systems differ somewhat from those for the refrigeration systems. The principal reason for conducting the rural schoolroom lighting pilot project was to try to determine whether the benefits were worth the costs. To completely answer this question, it would be necessary to measure all the benefits that accrue to the users of the lights. This might go so far as to include measuring the increase in exam scores for students who had access to the lights (as opposed to those who did not), or quantifying the benefit to a community that had lights available for evening community meetings. Such estimates were clearly beyond the scope of the demonstration program. What seems to be undisputed is that definite benefits (albeit difficult to quantify) do accrue to villages with lighting systems, and that these systems are a step in fulfilling the GOB's expressed goals of increasing the standard of living in rural areas.

The concerns addressed in the demonstration program thus far begin to answer the cost-effectiveness question by refining suitable system designs for circumstances normally encountered in rural Botswana, and thereby getting a better idea of the range of system costs. Through interviews with system users, initial steps were made to determine who would use these lighting systems, for what purpose, and for an average of how many hours per day. These three related questions have significant implications for the evaluation of whether PV lighting in rural schoolrooms is worth the cost. In the final analysis, any decision about cost-effectiveness based on additional work by other investigators will be largely subjective because of the inherent difficulty of quantifying the benefits. The BRET demonstration program, in conjunction with ongoing work at BTC and DEE, should be viewed as the first step in gathering the necessary data to make such a determination.

1. Technical Performance Criteria

The technical performance criteria for lighting systems revolved around three issues:

- lighting level requirements as a function of GOB lighting standards (see below) as well as efficiency of the lights in terms of lighting output (lumens of illumination) per watt of power input, which determines the overall system cost for a given lighting level;

- skills (and subsequent training) required for successful long-term operation, maintenance and repair of the systems (often a strong function of system complexity); and

- reliability of system components, particularly active units such as charge control regulators.

Less important questions involved uncertainties about the electrical wiring standards (developed specifically for AC installations) currently accepted by the DEE, and their application to low-voltage DC PV systems. Since there are special considerations for small DC systems (such as battery storage safety issues) and the system voltages are so low (12 V), it can be argued that a separate code for DC systems should be adopted. The AC wiring codes were not strictly adhered to for the BRET project installations, nor was it necessary to do so from an engineering perspective. However, standard PV wiring practice was followed, such as choosing wire sizes to keep voltage losses below five percent and using DC-rated circuit breakers and connectors where possible.

There was considerable debate over appropriate lighting levels for the rural schools. It should be emphasized that, although there are standards for lighting levels used throughout the world for mains electric lighting systems, these are subjective to some degree. If the current standard of 400 lux used for reading areas where mains electricity is available were applied to PV systems in remote rural sites, those systems would become prohibitively expensive. However, it was generally accepted by BRET staff and DEE that a lower level would be adequate for school lighting for the purposes discussed above.

There has not been general agreement on exactly what that reduced lighting level should be, however, and the issue remains unresolved. A study on minimally acceptable lighting levels, based on interviews with users in the field, should be the basis for the revised standards. Photometric (lighting level) data on the 15-watt DC lights used in three of the installations was not available, thus guesses had to be made initially as to the lighting levels that could be provided.

Skills required for installation and operation of the various systems do not differ dramatically from standard electrician's skills. Familiarizing installation and maintenance technicians with the differences between AC and DC electrical wiring practice is a relatively simple matter. Since these technicians were not expected to perform actual maintenance on the components, but rather to replace units that they determined to be defective, extensive additional training was not required.

The reliability and maintenance/repair requirements of the lighting systems are important to their acceptance from both recurrent cost and social acceptance perspectives. Components of the DC systems were generally trouble free, with the possible exception of the controllers used in the early systems, several of which had to be replaced after failures occurred. As a result, one system was installed using self-regulating modules that did not strictly require a battery charge controller. DEE representatives felt that if the AC systems were found to be reliable and reasonably priced, the problems with different (AC and DC) codes and additional training requirements for their technicians would be reduced. Therefore, one demonstration system with a DC/AC inverter was installed.

Generous assistance in the above evaluations was provided by DEE staff. They provided guidance in defining installation requirements and instrumentation (lux meters) to allow measurement of the lighting intensity provided at each site.

2. Use Evaluation

The size (hence cost) of a PV electrification system is directly proportional to both the lighting level and the number of hours per day that lighting is provided. The benefits depend on who uses the lighting and for what purpose. The value of the benefits will vary considerably depending on whether the lights are used by a few individuals reading an hour or two an evening, or if that hour or two of system use provides lighting for village meetings, as well as for a number of students and teachers using the space for school-related activities.

User interviews to determine these unknowns were therefore an integral part of the demonstration program. When the first systems were designed, it was unclear how many hours of use they would get, there being no precedents. Since the power modules represent 50 to 80 percent of the cost of the lighting systems, a smaller load (in terms of either hours per day or lighting levels) would result in significant savings in capital equipment costs. On the basis of these ex post facto interviews, and on monitoring the daily hours of use to determine frequency and duration, it appeared that the systems were somewhat oversized for the actual demand (which may increase as user expectations rise), and the same level of service could therefore be provided at less cost.

3. Financial/Economic Criteria

A full-scale financial and economic evaluation is beyond the scope of this program. This would require a more complete evaluation and quantification of the benefits over the life of the system, as well as a careful evaluation of the alternatives (such as diesel or petrol generation, or grid extension to sites near mains service) for providing the same level of service to the rural classrooms. However, the costs for installation of the PV lighting systems are given below. An estimate of the costs of providing power using the type of petrol generator currently available in Botswana is given for comparison, and a life-cycle cost analysis based on these estimates is given. Consideration of wider dissemination of this technology warrants more careful analysis of the costs of alternative systems, based on experience in the field rather than estimates. Implications of the use patterns recorded thus far are discussed below.

D. Data Collection Requirements for Lighting Systems

The data collection requirements for lighting system evaluation consisted of a short-term visit (at which time light intensity readings were taken with a lux meter), and longer-term monitoring using a two-fold approach. First, data sheets (for example, see Appendix B) were given to the individual (the head teacher or principal) responsible for the lights. After receiving that person's permission, users were given data sheets on which to record purpose of use, number of people present, time the lights were turned on and off, and any remarks or problems encountered. The user evaluation was based on this information. Second, monthly site visits were conducted to collect data sheets and make certain that there were no equipment problems. As users become more familiar with their systems, the monthly visits will be reduced. However, it was felt that regular visits were required initially to show outside interest in the results, and to make sure that data were being collected properly and that users understood the proper use of the lighting systems. The results are given in Section V.C.

V. RESULTS

The results of the BRET demonstration and testing program for clinic and school PV electrification are given below. Section V.A provides the results of R/F unit system performance at each of the clinics. Information on the relative energy consumption of each of the models tested (and the effect on power supply size) is provided. Discussion is included of those technical and institutional problems encountered during testing which affected the testing procedures themselves, or were problems with either installation or equipment design and resulted in the unsatisfactory performance of some of the systems.

Section V.B contains comments on design features of the R/F units that significantly added to or detracted from their usefulness. This section was based on comments made by users as well as on observations made by BRET technicians during installation and operation of the various systems.

Finally, Section V.C discusses the performance of the school lighting systems, including brief discussions on the equipment and any problems with the components, the lighting levels measured at each site, use patterns, and user response to the systems.

A. Performance of Clinic Electrification Systems

The technical performance results given in this section are based primarily on two sources of data. The first was the long-term temperature stability maintenance data that were recorded on the data collection sheets by users of the equipment at the rural health clinics where it was installed. The second source of data was a series of short-term tests, performed at the BRET workshop in the winter of 1985, which measured the electrical energy consumption of several of the R/F units used by the project. The detailed experimental procedure for this series of tests is given in Appendix A.

As mentioned above, because this was a demonstration rather than rigorous comparative testing program, and because of the severe constraints on the availability of trained technical personnel, particularly at the outset of the program, the testing and evaluation program received little emphasis during the first two years of the BRET project. At that time, there were very few electric R/F units designed specifically for use with PV (although DC electric refrigerator/freezers had certainly been used for quite some time because of their extensive use on recreational vehicles in the United States). Those in existence were mainly prototypes and not yet production models.

Given this situation, the first R/F unit purchased by the project was a Western Solar Refrigeration unit which had undergone some comparative testing during a NASA-funded program in the United States, along with similar units from Polar Products Corporation and Adler-Barbour.[3,4,5] This unit contained both a refrigerator and a freezer section (since ice-making capability was required at the site). It was installed at the Lensweletau health clinic in June 1982.

1. Lensweletau

In December, six months after installation, BRET technicians were informed by the nursing staff at Lensweletau that the WSR R/F unit was not freezing properly, and that the refrigerator temperature was too warm. After technicians examined the unit and decided that field repair or adjustment was not possible, the unit was taken to a private local refrigeration repair facility in Gaborone (J&R Refrigeration). The J&R technicians felt that the difficulty lay in the compressor control unit. However, since they were unfamiliar with that specific unit, attempts at repair simply aggravated the situation. The unit was then taken to the Meteorological (MET) Services repair shop. The compressor unit was repaired to the point where it ran, but was not able to reach freezing temperatures in the freezer section. MET Services personnel attempted to fix the compressor controller, but felt that the problem lay rather in the freon loop, and gave up the attempt. The R/F unit had been at MET Services four months by this time. The unit was then taken to a second local refrigeration firm (Coolcare), where further attempts at repair were stifled by a lack of replacement parts. They suggested the R/F unit be rewired for 220 volts and "used properly."

After six months of continuing repair efforts, the BRET project received a letter from the Kweneng Council inquiring after the status of their R/F unit. The BRET response was to replace the WSR unit with a new Polar Products RR-50L (50-liter) unit that had recently been received. Although this unit functioned completely satisfactorily after its installation, the users had (with apparent good reason) lost faith in the reliability of the PV R/F units. When MOH operations personnel (who were unaware of the existence of the now-functioning BRET unit) offered them a gas-driven R/F unit, they accepted. It was

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[3] Darkazalli, 1983.

[4] Kaszeta, 1982.

[5] "Photovoltaic Powered Refrigerator/Freezer Systems for Storage of Medical Supplies," Statement of Work from RFP No. 3-142887. NASA Lewis Research Center. Contract DEN3-238. 1981.

the gas-driven unit that was then primarily used for vaccine storage. The BRET unit was used mainly for cold beverage and food storage by the clinic staff (there were three bottles and 11 eggs in the PV R/F unit, according to the last data collection sheet filled out).

The lighting system (see Appendix C for a detailed description) installed in conjunction with the PV R/F unit at Lensweletau has had very few problems. Due to the failure of the early ARCO Solar battery protector charge control units at other installations, a much more reliable SCI controller was installed and the ARCO unit removed. The battery system has not yet required any maintenance, but it is likely that the battery bank will have to be replaced approximately every five years, assuming proper periodic maintenance procedures are performed on a regular basis. Several of the light bulbs needed replacement also. Due to lack of availability of the 20-watt bulbs needed for the original fixtures, and the significantly lower energy consumption of recently available 15-watt fixtures, the 20-watt fixtures have been replaced.

2. Shoshong

The PV R/F unit and lighting system were installed at the Shoshong clinic in early 1984. A top-loading Polar Products RR-2 was used. This system worked without problems until several days before Christmas. At that time, it was reported that although the refrigerator compartments were cool, they were not cool enough for vaccine storage. A trip was made to Shoshong to determine if repairs could be made easily. A spare R/F unit (a Marvel) was taken along in case repairs could not be made. The problem with the refrigerator was not obvious, so the Marvel R/F unit was installed at the clinic, and the Polar Products returned to the shop for repairs. Interestingly, when tested at the shop, the Polar Products unit operated properly, indicating an installation problem rather than an equipment failure. However, the Marvel remained in Shoshong.

During March and April, the Marvel R/F unit began to blow fuses at the rate of one every several weeks. Just prior to this, the final shipment of refrigerators arrived in Gaborone after having been in transit for well over six months. It was decided that rather than try to repair the problem with the fuses or to reinstall the Polar Products RR-2, a newly arrived SunFrost would be installed for comparative testing purposes. BRET technicians felt that they could provide useful user response to the SunFrost, since the Shoshong clinic staff had been very supportive and helpful in this project, and had already been exposed to the Polar Products and Marvel models. This turned out to be the case (see Section V.B).

The lighting system at the clinic has functioned well. Occasional fixture replacement has been necessary due to burned-out bulbs and the non-availability of spares. As at the other clinics, the rechargeable torches have not been a success. The reasons for this were not determined, but they could have been due to a number of causes (e.g., user unfamiliarity with their proper operation, faulty charging circuits, failure to replace the torches often enough to give them sufficient recharge before further use).

3. Mabule

The problems encountered at the Mabule health clinic typify the institutional complexities often encountered during the introduction of new or unfamiliar technologies. There was an apparent overlap of responsibilities between MLGL and MOH in the administrative hierarchy for health care facilities. Health posts (the smallest and least well-equipped facilities) are the responsibility of MLGL. Health clinics are also administered by MLGL. However, health centers are under MOH, as are the several government hospitals in the more densely populated areas. Thus, MOH does not directly administer health care facilities at the most remote sites, where the use of PV systems would presumably be most appropriate. It does, however, provide health care-related equipment to MLGL for health posts and clinics.

Due to shipping delays and the consequently late arrival of the R/F unit purchased for Mabule, the lighting system was installed in Mabule about six months before the vaccine R/F unit. The Regional Medical Officer (RMO, under MOH) had been approached by the BRET project and offered the use of a PV lighting and refrigeration system for one of the clinics under his (apparent) jurisdiction. He accepted the offer and suggested that Mabule would be an appropriate site.

Unbeknownst to BRET technicians, the public health nurse (responsible for all clinics in the region) had not been informed by the RMO about the arrangement with the BRET project. She had been instructed on neither the existence nor the proper use of the unit. On her first visit after the installation of the R/F unit, the nurse said that the unit (a Polar Products RR-50L, a 50-liter model designed only for vaccine storage) was too small, allowed for no air circulation (it was uncertain what was meant by this statement), and she consequently instructed the staff at the clinic not to use it for vaccines. The R/F unit was therefore only being used for food and drinks.

After this situation was brought to the attention of the BRET technicians, they spoke with the public health nurse and found her to be very uncooperative. Although the BRET project had gone through the proper channels (i.e., the RMO), the public health nurse had apparently not been contacted by her superiors regarding the installation. BRET staff then wrote a letter to the RMO making him aware of the situation. This apparently had the desired effect, since the PV R/F unit was in use by the time BRET technicians visited the clinic again.

Additional data collection sheets (DCS) were given to the RMO at this time, for delivery to the clinic. However, the technicians found that DCSs were not being filled out by clinic staff after the R/F unit started being used for vaccines. Apparently, the DCSs first left by the BRET installation crew with the senior staff person on-hand at the time of the installation were never shown to any other staff members, so data were not being recorded. When this was discovered, the clinic staff was instructed in the use of the DCSs, with the accordance of the senior nurse. Another visit to the clinic was to take place shortly, at which time the procedures for data collection were to be reviewed again if any difficulties had arisen in the interim.

This installation, as well as those at the Shoshong and Lensweletau health clinics, the lighting systems at Shoshong, Oodi and Ditshegwane schools, and the Shoshong VTF were done by BRET technical staff and the Madiba Brigade. At the time of installation, staff at each of the sites were told to whom they should refer any requests for repairs or other questions that might arise about the operation and maintenance of the systems.

However, when breakdowns did occur, for instance, when a light stopped working at Mabule, the clinic staff apparently did not know where to turn for a replacement. They did not contact the BRET project (perhaps Gaborone was simply too far away). They eventually spoke with the Regional Medical Team on its next visit, and then with MOH officers, neither of whom knew what the BRET project was or how to contact it. Eventually, the Mabule clinic staff talked to the RMO with whom BRET representatives had initially spoken during the site procurement phase of the program. The RMO found out that two (by then) lights were not working and called the BRET project office from Lobatse. It turned out that a switch needed to be replaced between the battery charge controller and one section of lights, a simple enough problem to diagnose, but one that the users were not made aware of at the time of the installation. This incident pointed out the need for some sort of accessible users' manual for the systems as installed, which would allow the users, with a few simple tools, to troubleshoot and fix at least some common problems that might occur under normal conditions of use. This would be a useful project to undertake during any extension of the PV electrification efforts on the part of DEE.

Other social and institutional issues presented obstacles to successful augmentation of the program. For example, due to the poor performance of the WSR R/F unit, the first one installed by BRET technicians, other clinics were hesitant to rely on the other PV R/F units, even though they were from different manufacturers and were far superior units technically. Another problem that arose on several occasions was the lack of good supporting technical data on the operation and maintenance of some of the units. The WSR might well have been repairable in Botswana had the manufacturer included proper documentation. Other units, such as the SunFrost (which performed quite acceptably in most cases) had only a four-page manual. Since it was a relatively recently developed unit at the time the BRET project purchased it, this was perhaps understandable. But, nevertheless, much more detailed supporting documentation should be included with all units to facilitate repair in the field.

B. Utility of R/F Unit Design Features

The following remarks draw heavily on comments made by users during the BRET technical staff's visits to the various sites, as well as on observations made by BRET staff during the installation and monitoring phases of the project. The user comments are simply presented as legitimate responses to a new product, which may or may not be of importance to future design development of the machines.

1. User Comments

The WSR, Marvel, and Polar Products RR-2 appeared to users to be quite similar designs, except that people did not like the fact that there was no way to easily keep the door open on these top-loading units. This was, of course, by design, to prevent people from leaving the doors open and prevent consequent damage to vaccines. However, this also makes it difficult to clean the interior compartments, or to use both hands to pick up several vaccine vials at once. They also made several references to the fact that the inside storage room was smaller than they would prefer. Since the top of R/F units also serve as de facto shelves, people sometimes said that they would prefer a front-opener, with a flat top (unlike the SunFrost, with the compressor and condenser coils mounted on the top side) to store equipment that would not then have to be removed before opening the door.

The staff at Lensweletau felt that the Polar Products RR-50L was too low. It was designed to be mounted on a waist-high shelf for easy access, and they had not done this. They had previously had the WSR unit installed there, which was considerably larger, but did not work. The RR-50L has a dimpled surface which discouraged its use as shelf. It was not apparent why this was incorporated into the design. Nor, it was mentioned, was it a comfortable seat (sitting on the R/F unit door tends to slightly bend the hinges, which loosens the door seal, allowing air to enter and significantly degrading the performance of the refrigerator).

With the Marvel and the WSR, the door apparently became more difficult to close with increased use since the seal seemed to flatten out after a while, and the toggle arm had to be shoved very hard to close it completely. On the RR-50L (and other Polar Products units as well), there were unusual locking mechanisms which people apparently had difficulty in operating. People commented that there should be arrows to show the direction of opening, and that it was not necessary to have such a complicated locking mechanism. They also mentioned that the Polar Products units could not be locked, as could the SunFrost and Marvel. They felt it should be possible to lock the units to prevent theft and unauthorized use.

People liked the front-opening feature of the SunFrost and the fact that there are horizontal shelves, which made it look like the refrigerators they were familiar with. Comments were received that the Sunfrost model was too small. They commented that the other units (top loaders) "look like freezers."

2. Comments from BRET Technicians

For the Marvel and WSR, the wiring connections were underneath, making access difficult. The terminals are marked only with "+" and "-" on both sides, which does not readily indicate which terminals are for the controller and which are for the battery leads (however, this information is in the fairly complete manual which accompanied the Marvel unit). The units have a compartment for battery storage, and it was agreed that this was a good design feature. However, because of the difficulty in putting the batteries in the compartment and the fact that some of the batteries were too large for this storage area, they were frequently left on the floor next to the R/F unit. The rollers on the bottom (but not on the SunFrost units) were very helpful. The on/off switch on the bottom front panel was not clearly marked, nor were the indicator lights. The plexiglass covers over the refrigerator and freezer compartments were very awkward to use. The meaning of the terms "pull down" and "maintenance" on the switch on the back of the unit was unclear and poorly explained in the manual. This should certainly be clarified in future versions.

The SunFrost unit was unique in that it was a front-loading as opposed to top-loading unit. This was not in accordance with WHO specifications (see Appendix D). However, the manufacturer felt that this specification was not reasonable because the relatively minor incremental heat losses associated with a front-loading unit (due largely to the cool interior air falling out and being replaced by warmer ambient air) would likely be more than compensated for by the increased ease of use and flexibility of placement of the unit. Indeed, WHO documentation suggests that top-loading units be de-rated by dividing the actual volume by 1.4 to get an effective volume to account for not being able to functionally use all the space in top-loaders.

The SunFrost does not have an on/off switch, and one should be added on future units. In the current design, the only way to turn the machine on and off was by disconnecting wires. A larger terminal barrier strip should be used to accommodate large wires to reduce voltage drop. A much more detailed operation and maintenance manual should be written. The spring-loaded ball door-locking mechanism sometimes became very stiff, which made it difficult to open the door. That the tension of the ball was adjustable was not mentioned in the manual, nor was it at all obvious. Rollers should be installed on the bottom to make it easier to clean underneath the unit. One disadvantage of the front-loading feature was that people tended to lift up the unit by a corner of the door, which over the long run will bend the hinges to the point where the door will not seal properly. This could also be caused by people sitting on the door if the unit was not mounted off the ground as was recommended. A different type of handle should be used for the freezer door. The one that was used on the BRET models did not allow the user to exert enough leverage to open the door if the ball door-locking mechanism was too tight. The usefulness of the wire door rack was questioned, since it tended to hit articles stored on the main lower shelf. A design using separate doors for freezer and refrigerator compartments was suggested.

With the Polar Products RR-2, the removable screen was very difficult to get back on after connecting the wires. The holes provided in the screen for wire installation were not large enough, encouraging the installer to leave the screen off and components unprotected. The terminal connections were not marked to indicate which wires should be connected where. The battery compartment was useful, but it was not easy to get the batteries into the compartment, so users often left them out on the floor. An operation/maintenance manual was not shipped with the machine, but came several months later.

On the Polar Products RR-50L, the terminal connections were not marked for battery or array inputs. Polar Products only included a single-page installation instruction sheet with the unit. The manual, which was received later on, should have been supplied with the refrigerator. There were no holes for the wires to exit from the controller. The unit should have been equipped with rollers for ease of cleaning. The on-board controller was a helpful feature, but did not allow easy incorporation of a lighting system for low-voltage disconnect load management. The green and red indicator lights above the compressor should have been marked to show what they indicated.

The Polar Products units all had integral battery charge controllers. This was a very useful feature because it dramatically simplified the installation of the unit in the field by eliminating the need to wire an external charge controller into the system. However, on the Polar Products RR-50L unit, the barrier strip for connecting the PV array and batteries to the internal charge controller were not labeled, requiring an unnecessary tracing of the wires from the barrier strip back to the internal charge controller. The manual supplied with the unit applies specifically to the RR-2 and RR-1 units (although it says that it is for the RR-50L) and requires some interpretation on the installer's part. These shortcomings are perhaps due in part to the fact that the RR-50Ls purchased by the BRET project were among the very earliest ones produced, and users' reactions had not yet been incorporated to improve ease of installation and use. In spite of these small difficulties, the units performed very reliably once installed.

The following general comments and suggestions are applicable to all of the units:

- It would be very helpful to installers (and solve most installation problems) if there were some standard convention on wire color coding for the positive, negative and ground wires. This can be very confusing to new or semi-skilled installation crews. Unfortunately, international color conventions differ from U.S. conventions, so care must be taken to label connections carefully.

- It would help if thermostatic controls were installed by manufacturers in hard-to-reach areas so that casual readjustment of the controls (and possible resulting equipment malfunctions) would not happen. People tend to play with easily accessible controls. The thermostats used on nearly all the R/F units could be adjusted down as low as $-35^{o}C$. This would cause abnormally high energy consumption and possibly deep-discharge the battery bank. Controls that can be adjusted this far out of the normal operating range should not be used by manufacturers.

- All R/F units should be ordered with spare control boards as minimal replacement parts. Since compressors seldom fail, one extra compressor should be purchased for every five or so units in the field.

- It would be helpful both for installation crews and users to have simple analog volt (and possibly amp) meters as standard equipment on the R/F units. These would help considerably in preventing battery deep-discharge by advising users on the battery's state of charge, as well as aiding users in performing simple troubleshooting procedures. Their inclusion would be a negligible increment to the overall system cost.

- Manuals should provide the layperson with some minimum level of understanding of the system's operation, as well as contain basic troubleshooting procedures for repairing simple breakdowns. Illustrations should be used lavishly. Manuals should also contain detailed information on where to get spare parts and how to contact equipment manufacturers. Telephone and telex numbers should be included. A detailed shop repair manual should be available for optional purchase. This should be sufficiently detailed so that trained technicians could use it to do any necessary repairs.

C. Performance of School Lighting Systems

The results of the rural school lighting and demonstration activity are given in this section. Because the designs evolved as lighting systems were installed, system results are presented chronologically by installation.

1. Oodi

Since this was the first system designed and installed, it was decided that it would be as simple as possible. Fifteen-watt DC lights (requiring no inverter) and self-regulating modules (Arco Solar M-63, requiring no controller) were used. A simple voltmeter was installed that could be checked by users to insure that the battery voltage did not drop too low. Lack of photometric data limited the ability to predict the lighting level that would be achieved. After discussion with DEE personnel, it was decided to install six lights and then test to determine the lighting level. The design assumption was that the lights would be used an average of three hours per day, with no extra battery storage for cloudy periods. The lights were installed as switchable pairs from different points in the room. This would tend to keep people from using all the lights when two or four would be sufficient.

The results of the lighting intensity tests revealed the light level was on average just under 50 lux. A subjective evaluation by those present at the test indicated that the lighting level was sufficient for reading, at least for a short while, but a higher level of lighting would be preferable. It was pointed out that the gray and light blue walls of the room lowered the lux level on the surfaces measured, and the distance from the fixture to the working surface could be reduced to improve conditions as well. After DEE representatives mentioned that the wiring did not meet DEE standards for AC systems, it was agreed that 12-volt DC systems do not present the same hazards as 220-volt AC systems.

Over the first several months of use, there were no problems with the equipment. Although there was some concern about the lack of a low-voltage disconnect feature (which would automatically disconnect the lights from the battery, preventing deep-discharge) in the system, there were no faults. This may be due to the limited use that the lights get as compared to the design condition. Over the first several months of operation, the lights were used about every third day for an average period of slightly more than 1.5 hours. The overall average use was 0.6 hours per evening or one-fifth of the three-hour-per-day design capacity. It is difficult to say if this level of use reflects use over the long term. The novelty of having lights may mean that use is initially high and will taper off. Alternatively (and more likely this case), use is still low since people have not yet realized the full implications of having light available at night. In either case, it is not clear that a three-hour-per-day design is the proper choice.

There were several other interesting observations. Thirty percent of the time, there were more than 10 people present, and in 20 percent of the cases the room was used for village meetings of one sort or another (PTA, Village Development Committee, etc.). It appeared that users do not turn on all of the lights all of the time, but use fewer when fewer people are present. However, this is a limited sample, and more data collection is necessary to arrive at more solid conclusions.

2. Ditshegwane

This and the Shoshong system were designed at the same time. The Ditshegwane design evolved from the information available from the Oodi school. This system is also DC, but Arco M-53 (not self-regulating) modules and a battery charge controller were used. The BTC charge controller was chosen since it was locally manufactured and serviceable, a distinct advantage since controllers have been the most troublesome component of small PV lighting systems. In order to correct the less than ideal lighting levels at the Oodi school, the information collected there was used to try to design for a 100-lux lighting level. This required that 14 (rather than six) lights be used in the same size space. The average hours of use for which the system was designed were also reduced from three to 2.5. This resulted in a three-module design.

Over several months' use, this lighting system performed well, and there have been no reports of any difficulties. Tests conducted to determine if the illumination level reached the design goal showed that the lux level averaged just under 100 lux, indicating that design extrapolations from the Oodi tests seemed reasonable. It was also interesting that the initial reaction of the villagers was that if 14 lights were to be provided to the school, then perhaps they could be more efficiently used by dividing the lights between two rooms. This response seems to imply that a lighting level of under 100 lux would be acceptable to the villagers.

The data collected and examined so far represent less than one month of system use. So far, all schoolroom use seems to have been for evening study with an average attendance of nearly 12 individuals for almost 1.5 hours per evening nearly every weekday evening. This use pattern reflects the enthusiasm and initiative of at least one teacher in Ditshegwane. However, it appeared that this use level was higher than it would normally be over the long run, and a stable and predictable use pattern has most probably not been established yet. Interestingly, the average duration of use for this school is very nearly the same as at Oodi, about an hour and a half. Note that this is based on the limited data available thus far.

3. Shoshong

This village is quite a bit larger than the other sites, so a larger classroom was chosen for lighting. DEE had expressed interest in testing an AC system, and this village appeared to be the best candidate. Extrapolating from the Oodi and Ditshegwane measured data, and assuming a lighting level of 100 lux, the initial design was completed as if the DC lights were to be used and called for 30 of the 15-watt lights. By using 50-watt (40-watt nominal) AC fluorescent fixtures (1.2 meters long) with known photometric data, only six lights were required. This implied the use of a 300-watt inverter. Since the input to a 300-watt, 220-volt output inverter is 12 volts, and the amperage draw on the DC side is 25 amps at full load (not including inverter losses), one 20-amp BTC charge controller was not sufficient. Two of these controllers in parallel do not work either, as was learned the hard way. The imbalance in the two controllers caused one to pass most of the required current, blowing the fuse on that controller and almost instantly on the other as well.

The system is now divided into two completely separate systems consisting of three lights, an inverter, a charge controller, four batteries and four modules. A total of eight modules is required, as there are significant losses in the inverter and in the ballasts of the AC lights. As of this writing, the lighting system is still not operating properly at all times. Even though there were still intermittent and as yet unresolved problems with this system, tests to measure the lighting intensity level were conducted and showed 100 lux had been attained. This was at least in part because the photometric data for these lights were known. No user response data have yet been collected at this site.

4. Molapowabojang

This village was the last to be equipped with schoolroom lights in August 1985, very near the end of the BRET project. Unfortunately, time did not permit any testing or monitoring of the system in this school. The lighting design for this schoolroom also benefited from the previous experiences. At Ditshegwane, 14 lights and three modules were used to achieve an average lighting intensity of nearly 100 lux, with a design duration of use of 2.5 hours per day. This was more extravagant than necessary, given the use pattern experienced to date. In order to try to cut down on the cost and still provide good service, it was suggested that the lighting be divided into general lighting and task lighting. This was achieved by locating the lights in an unbalanced array, with an area of the room having a denser concentration of lights. The lights are switched in such a way that for general use six lights are used.

For reading or more concentrated work, two of the general lights are turned off and three additional lights, placed within the remaining four lights, are turned on. This strategy reduces the total number of lights to nine. Due to the experience in Oodi and Ditshegwane, the design use was further reduced to two hours, reducing the number of modules from three to two and significantly reducing system cost. Self-regulating ARCO M-63 modules were used because they were in stock, and a BTC controller was used for its low-voltage disconnect capability.

At the time of this writing, no light intensity tests have been done, nor have any longer-term use data been collected.

VI. FINANCIAL/ECONOMIC ANALYSIS

A. Vaccine Storage Units

For the R/F units, the de facto standard currently in use in Botswana was the gas- or propane-powered unit. While the costs of the PV R/F systems and an estimate of probable recurrent costs are given in the table below, the current study did not include the determination of the costs of the various alternatives, so that a comparative life-cycle cost analysis between the two types of systems could not be performed. Further research should investigate the recurrent costs of using propane vaccine refrigerators. Then the costs given here for PV units can be compared directly. AC R/F units should not be compared directly, because if reliable mains power were already available at any site, the obvious choice would be an AC electric refrigerator. If health clinics were located within close proximity of power lines, grid connection charges, any costs for step-down transformers, and variations in electricity tariffs (expected when the Morupula Power Plant comes on line) should all be considered in these analyses.

Location	Modules	R/F Unit	Other	Labor	Transport	Total
Shoshong	P4560* (8)	P4050 (PP-RR2)	P1750	P1300	P100	P11,760
Lensweletau	P5130 (9)	P1930 (PP-50L)	P1300	P 850	P150	P 9,560
Mabule	P6840 (12)	P1930 (PP-50L)	P1700	P1500	P500	P12,470

*P1.00 = US $0.57

The R/F unit costs given above include shipping to Botswana. For reference, the actual cost and interior volume of each of the units (FOB U.S.) are:

Marvel 4RTD (127 liters):	P 2006
Polar Products RR-50L (50 liters):	P 1930
Polar Products RR-2 (127 liters):	P 4050
SunFrost Vaccimax (56 liters):	P 2085

The cost differences depend largely on the components included in each model. The Marvel and SunFrost do not have on-board battery charge controllers, which must be purchased separately at a cost of about P150 to P300. The Polar Products RR-2 has two compressors, while the other brands have one. While this provides a backup should one of the compressors fail (an unlikely event), it is an expensive option. Size variation is considerable. However, the smallest units are more than ample for the vaccine storage required at the sites used in this program.

Recurrent costs in the comparative economic analysis should include annual visits for system inspection and replacement of any parts. This cost should be partially attributed to the lighting system at the clinic. The batteries will require replacement every four or five years, and the modules might require an occasional replacement due to vandalism, should it occur. The controllers are solid state and unlikely to need replacement. If the wiring, circuit breakers and switches are adequately protected when installed, it is unlikely that they will require replacement. These comments apply to the lighting systems discussed below as well.

B. School Lighting Systems

A standard life-cycle costing technique was used to estimate the comparative performance of the PV lighting systems installed by the project. Because of the relatively small size of the load for the school electrification systems, a petrol generator driving an AC lighting system was considered the most reasonable alternative at the sites where PV would be considered for use. Kerosene lights do not really supply adequate illumination for reading, so were not considered. Mains electricity system costs were not compared because it is, by definition, not available at remote rural sites.

The spreadsheet given on the following page compares the costs of a typical petrol generator-based lighting system with the BRET-installed PV-based systems. The spreadsheets are in the standard format used in other ARD reports, but the categories will be briefly explained here:

- initial capital cost--including such items as the major system components (PV modules, support structures, batteries, controller, lights, etc.) as well as wiring, crimp connectors, cable ties, etc.;
- installation cost--all labor and transportation costs incurred during the installation;
- PV of recurrent costs--present value of all expected operating and maintenance costs over the lifetime of the system, including any spare or replacement parts or labor and transportation charges which will be incurred;

FINANCIAL ANALYSIS OF SCHOOL LIGHTING SYSTEMS

Site Location :	OODI	DI[illegible]	SHOSHONG	MO[illegible]A	Petrol
Design watt-hrs/day :	260	570	1040	260	900
Observed watt-hrs/day :	75	200			270
Amortiz'atn. Period (yrs.):	20	20	20	20	20
System Life	'20	20	20	20	20
Discount Rate (%) :	6%	6%	6%	6%	6%
COSTS					
Initial Capital Cost :	1,560	2 660	6,510	1,950	900
Installation Cost :	360	610	240	400	300
Total Installed Cost :	1,920	3,270	6,750	2,350	1,200
PV of Recurrent Costs :	989	1,484	3,255	1,805	6,170
Life Cycle Cost ([illegible]) :	2,909	4,754	10,005	4,155	7,370
BENEFITS					
Design Annual kw-hrs :	95	208	380	95	329
Observed Annual kw-hrs :	27	73	N/A	N/A	99
Annualized LCC (P/kw-hr): (Design condition) :	2.7	2.0	2.3	3.8	2.0
Annualized LCC (P/kw-hr): (Observed condition) :	9.5	5.7	N/A	N/A	3.8

- life-cycle cost (LCC)--present value of all costs incurred in the purchase, installation, operation, maintenance and repair over the system lifetime;

- annualized LCC--the LCC divided by the present worth factor for the discount rate and system lifetime assumptions, and divided by the estimated annual kilowatt hours generated.

For this analysis, it was necessary to make certain assumptions that are difficult to quantify. The uncertainty involved in estimating the useful lifetime of new equipment has already been mentioned. More reliable conclusions would have been made, had more of the units logged operating time. This particularly applies to long-term recurrent costs of maintenance and repair, which have to be rather grossly estimated because of the relatively short period of data collection for most of the units. The recurrent cost assumptions were:

- one trip per year, to replace one broken or burned-out light, and general inspection of the PV system;

- transportation costs from Gaborone (less than ideal, but reflects actual conditions);

- no replacement of major components over the life of the PV systems;

- replacement of the generator after 10 years (long lifetime, but generator running at very low loading condition); and

- recurrent costs for generator include on-site replacement of filters by local operator, periodic overhauls as required, and two trips per year for fuel delivery and expected maintenance--no operator labor costs were assumed, since users would likely operate the generator themselves.

The results of the financial analysis given here should be viewed as tentative, pending completion of longer-term data collection, particularly with regard to the estimates of recurrent costs. The petrol generator delivers power at a relatively high cost because of the fact that it is being run at part load (60 percent assumed, but probably lower in actuality), and thus is not running very efficiently. However, this low load also penalizes the PV system because a controller has to be used whether two or 10 modules are used. The modules were assumed to generate 130 wh/day and 190 wh/day for the M-63 and M-53 respectively. These values are based on tests done by G. Jacobs at BTC and data measured during the PV pump tests. The "observed condition" energy consumption is calculated from the measured hours of use times the power consumption of all lights, and assumes 25 percent battery losses.

Looking at the spreadsheet, there are two values for the annualized life-cycle cost given at the bottom. The first calculates the kilowatt-hour cost based on what the system was designed to deliver. As previously mentioned, the systems are not being used to anywhere near their actual capacity. This therefore increases the unit cost of delivered energy, so that the unit cost (for the "observed condition") is considerably greater than the design annualized LCC. Since the majority of PV system costs is mainly sunk capital costs, any increase in the system demand (up to its capacity limit) will decrease the unit energy cost. With the petrol generator, this is not so true, since increases in demand, while amortizing out the capital costs over a greater number of kilowatt hours generated, will also significantly increase both fuel costs and the frequency of necessary maintenance.

The "observed condition" annualized LCC for Shoshong and Molapowabojang are not given because the use patterns have not yet been determined. However, since these systems were designed using the data from the previous two systems, it is hoped that their annualized LCC will be lower than either Oodi or Ditshegwane. For Shoshong, it will likely be greater than Molapowabojang because of the higher cost for an AC system. Annualized LCC is sensitive to system size, and is generally higher for smaller systems.

Much of the difference among the four PV systems is due to variations in use patterns and the distances inspection and repair crews must travel. If use patterns change, the actual cost of power could vary considerably. The general conclusion suggested by this spreadsheet is not that the Ditshegwane system is cheaper than the one at Molapowabojang (which is much further away, so has greater recurrent transportation costs), but rather that the comparative costs for petrol and PV generation are quite close using 1984 costs. The cost of PV modules has dropped 20 percent since then, and the cost of petrol is about the same. If this situation continues, the use of PV for such systems becomes a better and better choice, for reasons of cost as well as reduced maintenance requirements.

Any financial or economic evaluation of the potential for use of PV lighting systems in rural schools can only be preliminary because it is not yet clear what the size of the load will be in terms of hours of use per day. The most recently installed system at Molapowabojang begins to approach a reasonable design, but only interviews with users after the system has been in place for some time will determine this.

Below is the cost breakdown for the major cost components of BRET lighting systems. Following that is a discussion of why these costs differ and how they might be reduced in future PV lighting installations.

Location	Modules	Inverter	Other	Labor	Transport	Total
Oodi	P1140*		P 420	P300	P 60	P1920
Ditshegwane	P1710		P 950	P330	P280	P3270
Shoshong	P4560	P840	P1110	P160	P 80	P6750
Molapowabojang	P1140		P 810	P300	P100	P2350

*P1.00 = US $0.57

As can be seen from the above figures, the costs of the systems as installed range from just under P2000 to over P6700, with the module cost making up about 50 to 70 percent of the total cost. The Shoshong classroom is almost twice as large as the others, so a cost comparison cannot be based on total cost alone. Since the Shoshong system is also unique because it is an AC installation, it is discussed separately below.

From the data collected thus far, it appears that the Oodi school PV array is larger than it needs to be. The system could be used almost three times as much as it is and still only require one module (albeit at only the 50-lux level). If only one module were used, then the system cost would be less than P1400. Alternatively, at the current level of use (in terms of hours per day), additional lights could be added to increase the lighting level, and one module would still be sufficient. A system of this size could probably be installed for about P1500.

At Ditshegwane, there are three modules. At the current use level, it would be possible to reduce the number of modules to two because the users are using only eight of the 14 lights on most occasions. This would reduce the cost to P2700 and still allow all 14 lights to be used an average of 1.3 hours per day.

The Molapowabojang design incorporated these observations in a design that is more cost-effective while still addressing the lighting intensity needs for various uses. If those using the lights are careful not to use more lights than necessary (i.e., six lights for general use and seven for reading or studying), it may be possible to reduce the array to one module and still provide more than an hour of light per evening on average. More information on use patterns at this and the other schools is needed before reliable use patterns can be established.

Shoshong is a special case for several reasons: the room is about twice the size of the others, and it is an AC system. It is not true that the cost of providing AC lighting in a room half the size of the Shoshong classroom would cost half as much. First of all, only one controller and one inverter would be needed in either design. Second, the transportation costs would remain the same in either case. However, using AC power rather than DC results in cost savings for some components and additional costs for others. The AC lights cost less than DC, and there will be fewer AC fixtures (since they are higher wattage units). The labor cost will be reduced, as it takes less time to install fewer fixtures. On the other hand, the inverter and the greater number of modules required (to allow for inverter and ballast losses) increase the cost.

In order to get some idea of the differences between the AC and DC designs, a design was completed for this room using DC fixtures. This system would require four modules and 30 (15-watt) lights, and would cost about P4200, or roughly 60 percent as much as the current installation. The current AC system could well have been designed more carefully (to meet a lower actual demand, and using a more efficient inverter), which would have reduced the cost somewhat. However, the losses (inverter and ballast) in an AC system and the resultant increase in the number of PV modules required would still result in a higher cost for the AC system. This assumes that the reliability record for the AC system matches the DC one, which has not been the experience of the BRET project. Although this is but a single example of an AC system, and not necessarily representative, other users' collective experience worldwide suggests that small-scale lighting systems are most cost-effective when they are DC.

A comparison of PV costs to the cost of other systems designed to provide similar service was not a part of the current work. While an estimate of petrol generation costs is given in the economic analysis spreadsheet, this is based on assumptions, not on actual measured data. Detailed measurements of alternative system costs should be made before any longer-term commitment to PV electrification in schools is made. This kind of work has been done in several other places, notably in Papua New Guinea. In that study, small household systems were compared. PV was shown to out perform kerosene lights in terms of light quality and intensity as well as cost over a five-year period, given prices in Papua New Guinea.

It is important to note that many potentially economic PV installations are located near national electrical grid transmission lines. Since the Botswana Power Corporation normally charges its actual cost to connect a customer to the grid, these service connection charges can be substantial. Thus, when comparing the cost of PV versus grid electrification for a site that does not currently have a grid connection, it is very important to include the hook-up charge as an "initial capital cost" item. This charge is largely a function of the proximity of the prospective site to the grid, as well as the availability of nearby step-down transformers.

Other costs that are difficult to quantify are those associated with creating a support infrastructure for PV, including equipment distribution networks, repair facilities, spare parts stocks and training. Refrigeration and PV mechanics must be trained so that systems are kept in a proper state of repair. Consideration of the benefits of employment generation and environmental impacts are similarly beyond the scope of this report.

Many of the advantages of PV electrification systems are difficult to quantify. For instance, what is the benefit value of a PV refrigeration unit that maintains temperature stability so that potent vaccines are always available, compared to a fossil-fueled refrigerator which loses power, not due to malfunction, but due to late delivery of fuel? This sort of situation can be analyzed using risk analysis techniques, but the data required for any meaningful analysis would be extremely difficult to collect. What, for example, are the odds that a storm will wash out a particular section of road, thus prohibiting the fuel delivery vehicle from reaching the health clinic? Such data would be based on an educated guess at best.

VII. OBSTACLES TO WIDESPREAD USE OF PV FOR RURAL LIGHTING AND REFRIGERATION

Based on the limited experiences with clinic electrification and schoolroom lighting thus far, the greatest obstacles to widespread use of PV power supplies are high capital equipment costs, difficulty of obtaining repair parts and current lack of adequately trained technicians. Although the high system capital cost of PV R/F units (compared to gas or kerosene units) certainly weighs against their widespread adoption, the very high reliability of the PV power supply might well adjust this balance in favor of PV. This has been shown to be the case in a similar project in the Gambia.

Other users of PV power in Botswana have come to the same conclusion. For example, the Botswana Telecommunications Corporation has converted many of their units at remote sites from diesel to PV generators. Microwave repeater stations, VHF radios, rural high-frequency radios, carrier repeaters, and multi-access radios are currently installed or are planned for installation using PV power throughout Botswana. Telecommunications personnel claim that the "lower ongoing costs of transport, fuel, staff time, and the lower risk of outages make solar systems viable" for their expanded installations. Since telecommunications require a very high power supply reliability, the comment attests to PV's growing reputation as an extremely reliable power supply.

As more PV installations occur in Botswana, it is likely that the support infrastructure, in both the private and public sectors, will grow as well. For a successful maintenance program, spare parts and trained technicians must be available. While the private sector (e.g., Taurus Batteries) and the public sector (e.g., Botswana Telecommunications Corporation) have provided much of this support thus far, further development will be necessary to support any widespread dissemination efforts. Information is being made available to potential consumers (both public and private) through BRET project publications as well as through the BTC, and this effort should be continued.

Further private-sector involvement in supplying equipment and spare parts, skilled technicians and perhaps even financing for private purchases should be encouraged. While most of the PV electrification equipment currently used in Botswana thus far has been purchased by the GOB or supplied by international donor agencies, there is a growing private-sector demand, particularly for radio communications and small lighting systems. At this point, a public awareness campaign would at least make the populace aware of the existence and potential benefits of PV electrification.

A. Training

The training requirements for development of a support infrastructure to provide system design, installation, operation, maintenance and in-country repair capability for PV systems for clinics and schools have been examined elsewhere.[6,7] The specific skills required include:

- electrical engineering expertise, including specific familiarity with DC electricity and PV power systems;
- solar resource evaluation capability (although this is currently being performed by MET Services to a large extent);
- familiarity with battery selection and maintenance;
- installation and routine maintenance experience for technician personnel;
- for refrigeration, a familiarity with electrical controls commonly used in refrigerators, as well as experience with mechanical refrigeration components such as compressors; and
- understanding of and experience with simple (conceivably computer-based) sizing algorithms for design stand-alone (or hybrid systems with backup diesel or gas generators) PV power systems and sizing components.

B. Maintenance

Maintenance requirements for PV electrification systems are quite minimal under normal operating circumstances. General maintenance procedures include the following:

- regular cleaning of arrays to remove accumulated dust, which tends to slightly degrade electrical output;

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[6] Burrill, George. Training Needs Assessment for RETs. ARD, Burlington, VT. June 1985.

[7] "Evaluation of International Photovoltaic Projects--Interim Report." Meridian Corporation. October 1985.

- occasional checking of connections and terminals for possible corrosion (normally quite low in Botswana due to low relative humidity there, but can be a problem in other areas) and consequent voltage drops in the wiring; and

- checking of battery banks (specific gravity) for degradation or excessive boiling of electrolyte, which would require topping off of the cells.

Longer-term maintenance would include the checking of the system components for long-term degradation, such as proper operation of controllers (low and high voltage cut-outs), the need to apply an equalizing charge to the different battery cells, or the possibility of having to replace modules damaged by vandalism. Obviously, these maintenance requirements are much less than those of diesel electric generators. This low maintenance feature of PV power systems is one of its most desirable characteristics, and one for which some users (notably telecommunications) are more than willing to make the trade-off of higher initial capital investments in the power supply equipment. Some users, who lack access to funding, are not, however, in a position to avail themselves of this opportunity.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Petroleum consumption in Botswana increased an average of 3.8 percent per annum during the period between 1980 and 1984. The GOB is concerned by the increasing dependence on imported fossil fuels and would welcome alternatives to this trend (remarks by Mr. J. Diphaha, Deputy Permanent Secretary of MMRWA, at BRET/BTC PV Workshop on August 6, 1985). The GOB is addressing this issue as part of the Sixth National Development Plan. PV-generated electricity can be and is being used in Botswana for a wide variety of applications, including water pumping, telecommunications, health clinic electrification for lighting and vaccine storage, school lighting systems, and military applications. The high and uniform solar radiation conditions characteristically found in Botswana suggest that PV electrification in remote rural areas might well be competitive with the common alternatives of petrol or diesel-driven generators on the basis of both cost and system reliability.

The conclusions and recommendations derived from BRET project experience with small-scale, remote-site PV electrification in Botswana can be conveniently grouped into technical and economic/institutional categories. The technical recommendations directly concern the type of equipment used (and recommendations for future use), improvements on equipment and installation practice which could improve system performance and reduce costs, and suggestions for standards by which to choose equipment. The economic/institutional recommendations are very interrelated, particularly because the choice of technology (in the case of vaccine refrigeration, in particular) should not be made merely on the life-cycle cost of the system alternatives. Rather, technology selection should include some evaluation of the long-term reliability of the cold-chain equipment and its impact on vaccine availability and potency at rural health care facilities.

Conclusions

Comments on specific features of the R/F units used during the BRET project with regard to specific design features are given in Section V.B and not repeated here. In general, the units used by the project (with the notable exception of the Western Solar Refrigeration unit) were quite reliable and lived up to promises made by their manufacturers. Most of the minor problems that cropped up during the monitoring of these units were due to installation errors on the part of crews initially unfamiliar with the equipment, or users who were unfamiliar with the proper care, maintenance and limitations of the equipment. The fact that users sometimes did not know whom to turn to for maintenance on their equipment has already been mentioned. The need for more effective user/installer interaction must be emphasized.

There continues to be an active interest in PV lighting in general, and PV lighting in rural schools has become a particular focus for some. Several organizations in Botswana have specific interest in the information this program can provide on the design aspects and use of PV lighting in rural schools. Among these organizations are DEE, BTC, MLGL and the Energy Section of MMRWA. Much work remains to be completed, due in part to the late start on installing the first system, and to other pressing demands on BRET staff, as well as on DEE staff, who lent valuable assistance to the program. The conclusions that can be drawn from the work to date are:

- As envisioned at the outset of the program, provision of lighting in rural classrooms results in the rooms being used for educational activities as well as community meetings, providing increased services to the rural population.

- While it is agreed that acceptable lighting levels for rural installations will be substantially less than those for mains-connected systems, a consensus needs to be reached on exactly what that level is so that PV systems can be sized properly. A general lighting level of 50 lux, and 100 lux for reading areas, seems acceptable in rural schools. User surveys should be initiated to clarify this issue.

- The long-term data collection process for determination of use patterns for lighting systems is incomplete. The data collected thus far may well be skewed by early enthusiasm about having lights or, conversely, by lack of a full appreciation of their potential uses. It appears that the average duration of use is about 1.5 hours, but frequency of use is much more variable.

- The cost of providing PV lights in rural schools is highly dependent on the resolution of the preceding two issues. A reasonably designed PV lighting system costing approximately P2000 would be capable of providing an acceptable level of general lighting (about 50 lux) for public meetings and a higher level of lighting (100 lux) in a smaller area for the purposes of reading, studying and lesson preparation.

- There have been no problems with any aspect of the physical installation for any of the DC school lighting systems thus far. Worldwide experience with small PV lighting systems is much the same, so there is little reason to believe that significant problems will be encountered. The batteries will need replacing at three- to five-year intervals, and light bulbs will need replacement periodically. Use of BTC controllers should ensure that any problems with these can be rectified locally. However, the same cannot be said about the AC installation in Shoshong. There have been problems, most of which can be traced to the fact that the system is AC rather than DC.

- Although there are a number of PV lighting installations in place in both the public and private sectors, an installation code has not been agreed upon. It is generally understood that 12-volt DC systems are not as hazardous as 220-volt AC installations, and that codes should take this into account. However, there are areas where special care should be taken with DC, particularly battery safety.

- The clinic electrification work done thus far shows considerable promise for PV-driven R/F units. There have been some problems with first-generation equipment, but newer equipment seems to be better designed, more reliable, more efficient and less expensive.

- Preliminary tests show significant differences in the power consumption of the various R/F units. Since this directly affects system cost, further tests and review of recent testing data from other sources are warranted before additional equipment purchases are made.

- Clinic electrification systems installed early in the program suffered from defective equipment, and insufficient understanding of the operation and maintenance of the systems by users and installation crews. This situation presented an obstacle (justifiable reluctance on the part of MOH) to finding additional sites for later installations, so that all of the equipment was not installed by the end of the program.

- Not enough information is yet available to do reasonable life-cycle cost comparisons of PV and propane R/F units. The costs of the latter need to be carefully measured, and the longer-term recurrent costs of the former need more precise determination before such an analysis can be adequately undertaken.

Recommendations

Prior to presentation of overall recommendations, several very specific technical recommendations are given below. These should be incorporated into the GOB electrical supply regulations under the appropriate sections pertaining to low-voltage or PV system design. These recommendations draw heavily on discussions held during the BTC Photovoltaic Workshop held in Gaborone in August 1985, for which the authors particularly thank Nikki Davidson of the BTC. For papers that expand on the general recommendations listed here, please refer to the bibliography. From a system designer's perspective, then, the following points should be carefully considered during system design:

- When installing PV electrification for clinics, the lighting and refrigeration systems should be separated so that possible overuse of the lights cannot adversely affect the operation of the R/F unit. This can be done either by installing totally separate systems with separate battery banks, or by connecting the R/F unit directly to the single battery bank, and connecting the lighting system through a low-voltage disconnect switch on the controller. When the disconnect is set high enough (12.5 volts, for instance), during periods of high energy demand the lights will cut out well before the energy supply to the R/F unit is drawn down excessively.

- All PV systems should use electrical conduit rather than unprotected wiring. Not only does this protect the wiring from damage by animals, children or insects, but it is an important safety feature for system users.

- Wiring should be sized to meet the highest expected ampacity under design peak operating conditions. This will not only prevent possible degradation of the insulation due to overheating, but will increase system performance by reducing voltage losses in the wires.

- All connections should be carefully made with respect to electrical losses (use crimp connectors and avoid loose or dirty connections), safety (seal and protect connections from inquiring fingers), and utility (keep wiring and connections well out of the way of traffic in the building).

- Proper selection of components is critical to long-term system reliability. There was a considerable difference between the reliability of the first and second generation of PV components. Older first-generation equipment should be avoided (particularly early battery charge controllers).

- Deep-discharge batteries should be used in systems as soon as they become available through local distributors. Shallow-discharge batteries are somewhat less expensive, but the long-term recurrent costs are considerably higher than the deep-discharge variety because of their greater chance of damage due to overuse. Batteries should be protected by being mounted in a vented box to prevent hydrogen buildup.

- Arrays should be carefully roof-mounted (to reduce the chance of vandalism or other damage), where possible, using proper mounting procedures and equipment. Particular attention should be paid to proper grounding of the array for safety purposes.

- Self-regulating modules should only be used where the array consists of one or two modules (with one 100-amp-hour battery per module). With larger systems, output per unit investment is higher using standard modules and a battery charge controller. In general, the greater system simplicity (external controllers are not required) does not make up for the lower power output per unit cost of these modules.

General recommendations about the vaccine refrigeration effort include:

- DEE, which now has responsibility for the remainder of the PV R/F units, should initiate discussions with MOH representatives on site selection and eventual installation of these units.

- Provision should be made for monitoring the new units using the same data collection sheets the BRET project used. Users can easily complete these after a minimum of explanation. Later examination of the forms, as well as interviews with the users (as discussed in this report), will provide much needed data on the comparative performance of those units which have not yet received sufficient field testing.

- Before embarking on system installations, crews should be more carefully trained in the fundamentals of PV electricity as well as its specific application to the cold chain. This will make for better physical installations as well as enable crews to better communicate proper operation and maintenance procedures to eventual users.

- MOH and MLGL should be involved as much as possible in site selection and local user training procedures, so that misunderstandings among any parties do not hinder further dissemination efforts.

- Users should be more involved during site selection and system installation, and should be given specific training in proper operation and simple maintenance procedures before the installation crew leaves the site. Periodic visits to the site should be made, with decreasing frequency, to make sure that the system is operating properly and users are becoming familiar with proper procedures and system limitations.

The purpose of the PV school lighting demonstration program was to show interested GOB agencies and individuals that the technology would work. This report gives recommendations based on the four systems installed thus far. It also attempts to answer some questions about use of PV lighting systems so that informed decisions can be made in the future. The possible implementation of any further dissemination efforts must be left to MLGL and the responsible District Council officials. The general recommendations given below are limited to aspects of the work in progress.

- Tests of the lighting intensity level at the Molapowabojang school should be completed. The results would show whether, as anticipated, the task lighting/general lighting approach to school lights is a good one.

- DEE should continue to monitor use of the classrooms over the next year. This is not a time-consuming activity and will yield valuable information about longer-term use patterns of the lights and help in designing more cost-effective school lighting systems.

- Short-term user surveys should be conducted to learn how users feel about the lighting intensity levels. This would help to determine if the currently used levels are acceptable or possibly greater than those required for the common uses of the schoolrooms.

- DEE, possibly with assistance from BTC, should develop standards for installation of PV systems in GOB buildings. Work in this area should begin with a search for 12-volt DC standards used for boats and caravans. Contact with organizations in other countries involved in public-sector use of PV systems is also recommended.

- An evaluation of other lighting system alternatives in rural schools should be undertaken. The costs of AC lights powered by a small generator set or gas lights providing the same level of service should be measured. A life-cycle costing analysis could then be performed using the PV systems cost data provided in this report.

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APPENDIX A

Description of BRET Workshop Experiment Comparing Performance of PV Refrigerators

Purpose of the Experiment

The purpose of this experiment was to determine the energy consumption of the several brands and models of PV R-F units purchased by the BRET project. Ideally, this would have been done in actual installations at rural health clinics over both the short and long term. However, due to difficulties detailed in the main report, only three clinics currently have PV R/F units installed. Therefore, it became necessary to perform a short-term experiment at the BRET workshop as well as at another location in Gaborone to collect some of the necessary data.

R/F Units and Power Supply Equipment Tested

- Marvel 4RTD, SunFrost, and Polar Products RR-2 and RR-50L R/F units at BRET workshop; a second SunFrost at another site in Gaborone.
- Five-module array of Solarex SX-146 modules at BRET workshop; a second array of four ARCO 16-2000s at the other site.
- Battery banks for each R/F unit (two or three batteries, shallow-discharge, 110 AH each).

Power Supply Instrumentation

- Marvel: Curtis integrator with array and load AH measurements, as well as compressor on-time.
- SunFrost (at BRET): load amp-hour (AH) integrator.
- SunFrost (at site 2): Curtis Integrator.
- Polar Products RR-2 (at BRET): Curtis Integrator.
- Polar Products RR-50L (at BRET): load amp-hour integrator.
- Voltage and current meters for instantaneous readings at all sites.

Temperature Instrumentation (at All Sites)

Mounted next to the R/F units was a thermograph (0-60°C scale) which recorded the fluctuations in the ambient air temperature. Inside the refrigerator compartment of each of the R/F units was an identical thermograph to measure the variations in the refrigerator compartment temperature. There was also a maximum/minimum thermometer in the freezer, and a mercury thermometer in the refrigerator compartment with which to make instantaneous readings whenever the amp-hour integrators were read.

Data Collection Sheets

All data were recorded on data collection sheets (see sample DCS at end of this appendix). Recorded data varied somewhat from system to system because of the limited instrumentation available. But, for all systems, the amp-hours of electrical energy consumption, maximum and minimum ambient air temperatures, freezer and refrigerator compartment interior air temperatures, and number of openings of the R/F unit main door (equal to the number of readings made) were recorded. For systems equipped with the Curtis dual integrators, the array amp-hours were also recorded, although this variable was not of critical interest, since the R/F units' energy consumption, not the arrays' energy output, was being examined.

System Descriptions .

The R/F units were powered as follows: A five-module array at the BRET workshop was split into two panels, a two-module panel for the SunFrost and a three-module panel for the Marvel (based on previous experience with the average energy consumption of each of the R/F units). The three-module panel was connected to an SCI1 charge controller and then to two 110-amp-hour batteries. The Marvel 4RTD unit was wired directly to the batteries, rather than through the low-voltage disconnect load circuit on the controller. These load terminals would normally be used for connecting lights as a secondary load, and were not used for this experiment.

The power supply for the SunFrost was identical except that only two modules were connected to the charge controller. The SunFrost system at Site 2 was connected in the same manner, except that a different array and three batteries were used for convenience (the modules had lower power output so more had to be used, as was the case with the batteries). Since the R/F unit power consumption was the important variable here, the size of the power supply (as long as it was sufficient) was not a critical issue.

Performance Tests

Due to time constraints, only two of the three standard tests were performed: pull-down and maintenance level energy consumption rates. These tests were performed as follows:

Pull-Down Test--The battery banks were charged in an unloaded mode for three days to bring them to full charge. During this period, all of the R/F units were allowed to equilibrate to ambient temperature and then were loaded with a standard load (two six-packs of Castle). The units were then switched on simultaneously. All of the temperatures and power supply parameters were recorded every 15 minutes until the refrigerator and freezer compartment maintenance temperatures of 8°C and -5°C respectively were reached. Total amp-hours of electrical energy consumed and time to reach maintenance temperature were the primary performance criteria.

Maintenance Test--With the R/F units at equilibrium temperature and containing both the refrigerator and freezer standard loads, the amp-hour integrators were simultaneously reset and energy consumption over a period of several days was noted, with data being recorded several times a day. After that, the recording period was reduced to once every several days, and data collection continued for about two weeks. The long-term ability of the units to hold the temperatures stable was also noted.

A more detailed testing procedure would have included the following ice-making test. Lack of time precluded the performance of this procedure.

Ice-Making Test--Starting from a common maintenance temperature, and having been loaded with the standard refrigerator load described above, each R/F unit freezer compartment should be loaded with two liters of water in open containers to simulate six "cold dogs" (plastic liquid containers frozen for short-term cold storage of vaccines). Time and amp-hour consumption needed to freeze the containers of water should be noted, as well as the ability of the unit to maintain uniform temperatures within the specified ranges (+2°C to +8°C for the refrigerator compartment, -5°C to -15°C for the freezer).

There were not sufficient array and load amp-hour integrators to measure all of the array outputs. Since the module output was being measured in other tests for PV systems in Botswana, it is not necessary to duplicate these data here.

Results and Conclusions

Given the limited amount of time to conduct these tests, the results must be viewed as tentative. All of the units performed reasonably well, although there was a problem in the control circuit in one of the units after several weeks of trouble-free operation. The origin of the problem is as yet unresolved, and similar units have had no problems.

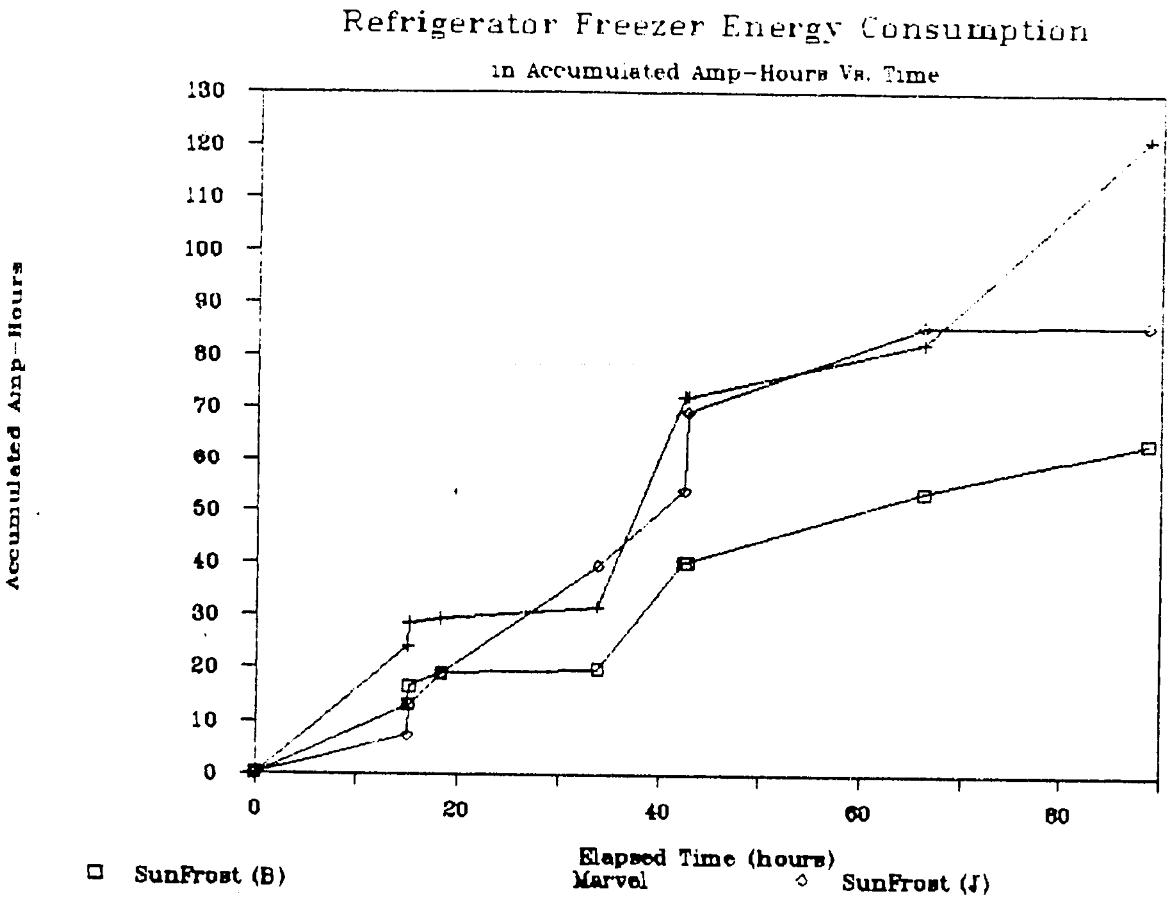
In general, all units successfully completed the pull-down tests described in the last section, easily reaching the required temperatures (-4°C in the freezer and +8°C in the refrigerator) very quickly. However, the ambient temperature was not 43°C, but rather in the 15° to 25°C range. Thus, all results discussed here should not be considered as absolute values, but values for each of the machines relative to each other. The machines easily froze equal-sized containers of water in several hours.

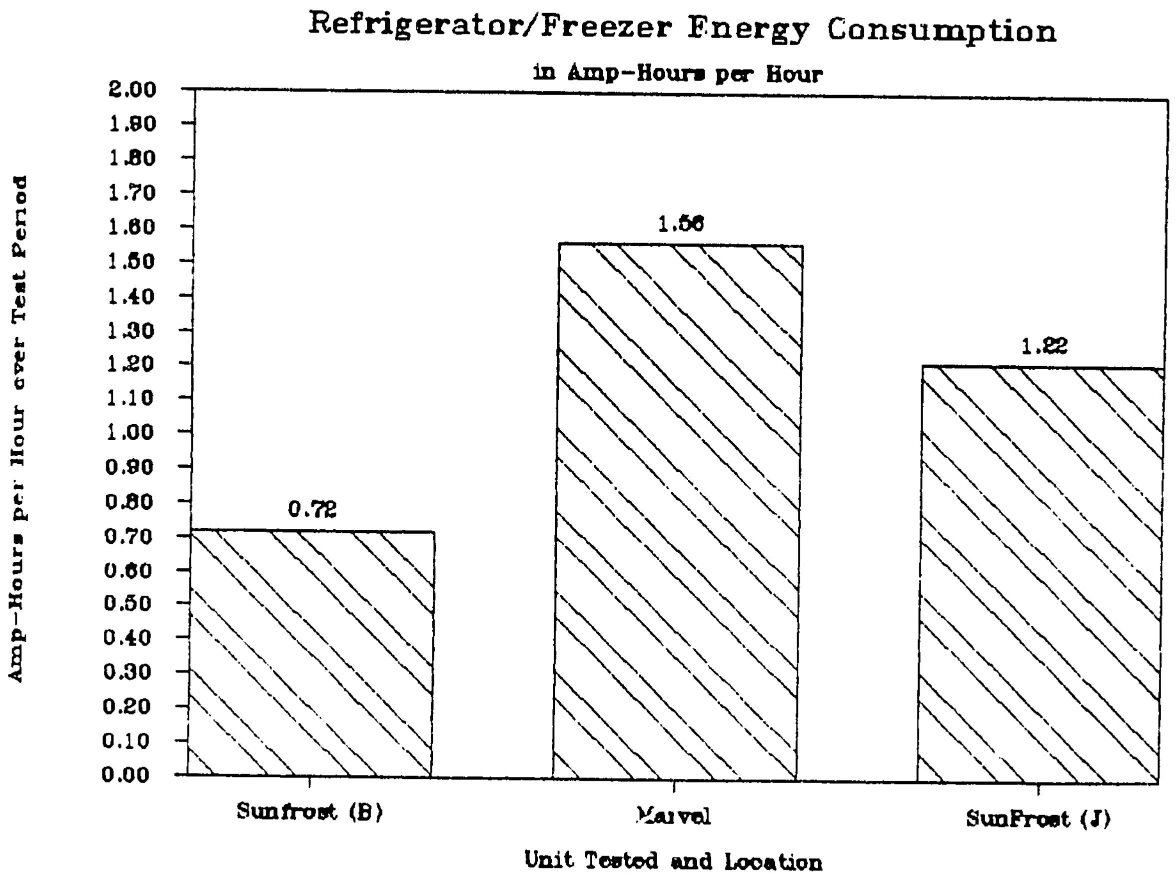
Two graphs of the preliminary data collected are given on the following page. The first shows accumulated energy consumption with time for the first three R/F units tested. The SunFrost(B) and the Marvel were side by side in an outdoor enclosure at the BRET workshop and thus were exposed to the same ambient temperature. The SunFrost(J) was installed in a house where the indoor air temperature was generally higher than ambient. Thus, the SunFrost(J) had somewhat higher energy consumption because it was in a warmer environment. Nonetheless, it was still less than the Marvel.

The second graph shows the average amp-hour consumption per hour of elapsed time over the two-week experiment. Again, the SunFrost average energy consumption was less than half of that of the Marvel. However, the Marvel was a larger unit, with a slightly greater expected cooling load. Nonetheless, taking this into consideration, the SunFrost design certainly showed promise, particularly for an early production model.

During the initial tests, all of the units needed some adjustment to stabilize temperatures in both the refrigerator and the freezer compartments. Both the Marvel and the SunFrost had quite acceptable temperature stability after these initial adjustments were made. If anything, the units were both running colder than necessary, so that energy consumption was greater than would be expected under other circumstances. However, the tests were done during the cool season in Botswana, so the tentative results should not be considered as characterizing the annual daily energy loads. They should only be viewed relative to each other to compare the various units' relative energy demand under the test conditions.

Initial energy consumption tests on the Polar Products units have not yet been completed. Longer-term tests should be


Refrigerator Freezer Energy Consumption
in Accumulated Amp-Hours Vs. Time
Accumulated Amp-Hours
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
Elapsed Time (hours)
□ SunFrost (B)
Marvel
◇ SunFrost (J)


Refrigerator/Freezer Energy Consumption
in Amp-Hours per Hour
Amp-Hours per Hour over Test Period
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.72
1.56
1.22
Sunfrost (B)
Marvel
SunFrost (J)
Unit Tested and Location

conducted on all of these units. This could be done simply by installing the integrators with the units in the field and adding an extra column to the data collection sheet where the daily energy consumption could be recorded on the sheet. Longer-term data would lead to much more reliable conclusions about the relative merits of each of the machines.

Recommendations

There are many design parameters which need to be considered in the selection of a PV, or any other R/F unit for use in rural clinics. These include system reliability, ease of use, availability of technical skills and materials for system sizing, installation and repair, and the cost of the system. The capital equipment cost of a PV system is directly proportional to the energy consumption. The greater the energy consumption, the more PV modules are required, and the greater the cost of the system. For propane or kerosene R/F units, this increased cost is expressed in terms of higher long-term recurrent costs of the fuel supply. For PV R/F units, the increased cost is the incremental capital cost of additional modules and batteries.

Capital equipment cost alone should not be the single criterion used in the selection of an R/F unit, but it should certainly be considered as an important input into the system life-cycle cost calculations. This experiment, by providing some tentative information on the energy consumption of PV R/F units, will help designers of clinic electrification systems to more accurately size the power supply, thereby reducing system cost to a minimum. Further tests, over longer periods, under actual conditions of use in clinics, would greatly increase the utility of this information.

PV Refrigerator Comparative Testing At BRET Workshop
27-Jul-85 08:21 PM

System: SunFrost at BRET Workshop

Date and Time	Compressor Clock	Refrig Volts	Compressor Amps	Array Amp-Hours	Load Amp-Hours	Ambient Temp (C)	Refrig Temp (C)	Freezer Temp (C)	Compress On-Time	Elapsed Time	Comments
31240.5	103.5	13.9	4.9	0.00	0.00	10	11	12	0.0	0.0	SF dial thermometers way off compared to thermographs, mercs and max/mi
31240.6	107.5	12.8	4.7	0.00	13.04	12	7	-21	4.0	4.0	frig dial sez #2, max/min sez #5 in refrigerator.
31240.6	108.6	12.2	4.2	0.00	16.62	11	5	-22	5.1	4.1	freezer dial therm sez -1, merc sez -15.
31240.8	109.5	8.6	0.0	0.00	19.12	10	4	-15	6.0	7.2	Thermostat reset from -30 to -20 at 1515 7/12/05
31241.4	109.7	10.9	4.6	0.00	19.95	8	4	1	6.2	22.8	load disconnect light on charger not lighting when it should, even thoug
31241.8	116.2	8.2	0.0	0.00	40.31	13	4	-16	12.7	31.4	after this reading, changed batteries 1830-1845, thermostat changed from
31241.8	116.2	12.1	4.6	0.00	40.31	13	4	-16	12.7	31.7	charge mode light still on
31242.8	120.0	12.3	0.0	0.00	53.74	17	3	-18	16.5	55.1	reset thermostat to -8, charging lights both off
31243.7	122.8	12.1	4.4	0.00	63.63	19	1	-11	19.3	77.6	reset frig thermostat 10 degrees toward "W"
											CycTime= 0.248711
31255.8 Marvel at BRET Workshop											
31240.5	491.4	13.0	0.0	0.00	0.00	11	11	11		0.0	something weird w/SF BRET AH/hr= 0.82
31240.6	495.4	13.0	7.4	1.59	24.07	12	12	-6		4.0	" Marvel AH/hr= 1.56
31240.7	496.5	11.0	?	1.59	28.63	11	11	-5		5.1	" SF Jimmy'AH/hr= 1.22
31240.8	498.8	10.4	4.9	1.59	29.51	10	9	-4		7.4	controller sez charging mode "o".
31241.4	514.2	11.5	4.9	1.59	31.80	10	3	-7		22.8	
31241.8	523.2	10.4	0.0	8.42	72.30	13	4	-6		31.8	charge mode light on after dark
31241.8	523.2	10.4	0.0	8.42	72.30	13	4	-6		31.8	
31242.8	546.5	13.0	0.0	16.14	82.47	17	3	-7		55.1	
31243.7	569.2	13.0	0.0	22.59	121.54	19	3	-10		77.8	max/min ambient since beginning 20/2. reset frig thermo from 1:30 to 12:
SunFrost at Jimmy's											
31240.6	2188.2	12.7	0.0	0.00	0	12	12	12		0.0	
31240.7	2189.7	12.0	5.2	8.32	7.21	21	10	?		1.5	
31240.7	2191.0	11.9	?	11.69	13.05	21	9	?		2.8	
31240.8	2192.6	12.1	0.0	11.94	19.07	16	9	-15		4.4	
31241.4	2207.5	12.0	?	16.14	39.57	5	2	-15		19.3	
31241.8	2216.0	12.2	0.0	67.18	53.99	20	-1	-20		27.8	reset freezer thermostat from -20 to -10
31242.8	2240.6	12.4	0.0	117.78	69.29	22	-1	-13		52.4	reset freezer thernostat from -10 to -8, turned ref thermo 10 degrees to
31243.4	2254.9	12.9	?	120.32	85.67	16	0	-11		66.7	
31243.4	2256.0	12.2	?	126.07	86.06	18	0	-10		67.8	
31243.5	2257.5	13.2	?	137.00	87.22	21	0	-10		69.3	
31243.5	2258.1	12.6	?	140.00	88.10	22	0	-10		69.9	
31243.6	2259.2	13.0	?	147.20	88.73	23	0	-9		71.0	
31243.7	2263.6	12.5	0.0	158.22	91.71	21	1	-11		75.4	ambient thermog sez 21, red merc sez 25, ref photo dial sez 1, on b sez

APPENDIX B

Examples of Clinic and School Monitoring Sheets

MONTORING SHEET

Week of 16th
to 22nd
Month July

Days	Time	Temperature inside Refrigator	Temperature Outside	Voltage	How much is in the Refrigator ? Full, ¾, ½, ¼, Empty	Control Box Light On	Patients in Ward	Fuses	Big Clouds	Used the Torch	Regular Cycle	Pull Down Cycle	Comments
Monday	9.10am	-3	17	14	Vaccines	off	Nil	–	No	No	–	–	
	5.10pm	+3	19	13	Vaccines	off	Nil	–	No	NO	–	–	
Tuesday	9.11am	-3	16	14	Vaccines	off	Nil	–	Nil	No	–	–	
	5.10pm	+4	16	14	Vaccines	off	Nil	–	Nil	No	–	–	
Wednesday	8.10am	+3	15	15	Vaccines	on	Nil	–	Nil	Nil	–	–	
	5.00Pm	+2	18	15	Vaccines	off	Nil	–	Nil	Nil	–	–	
Thursday	8.10Am	+3	16	13.8	Vaccines	on	Nil	–	Nil	Nil	–	–	
	4.50P	+4	20	13	Vaccines	off	Nil	–	Nil	Nil	–	–	
Friday	8.10Am	+3	16	13.8	Vaccines	on	Nil	–	Nil	Nil	–	–	
	5-05Pm	+2	20	13	Vaccines	off	Nil	–	Nil	Nil			
Saturaday	10am	+3	18	14	Vaccines	OFF	Nil	–	Nil	Nil	–	–	
	4 am	+3	18	13	"	OFF	Nil	–	Nil	Nil	–	–	
Sunday	9 am	+4	16	15	Vaccines	OFF	Nil	–	Nil	Nil	–	–	

(Stays)

DITSHEGWANE SCHOOL LIGHTS

PAGE: 1

NAME	DATE	PURPOSE OF USE	TIME ON	WEATHER ON DAY OF USE				NO. OF LIGHTS USED			NO. OF PEOPLE PRESENT	TIME OFF	REMARKS:	
				RAIN	CLDY	P.CLDY	SUN	2	6	6				
Mr. B. MHETE	5-6-85	PREPARING & MARKING	7.15 p.m				✓		8		1	9.15 p.m	Good.	2
Mr. B.M. MHETE	4-6-85	MARKING & READING	7.10 p.m				✓		8		19	9.05 p.m	Good.	2
Mr. B. M. MHETE	5-6-85	MARKING & READING	7.00 p.m				✓		8		15	9.15 p.m	Good.	2
Mr. B MHETE	6-6-85	MARKING & READING	8.50 p.m				✓		8		8	9.50 p.m	Good.	1
Mr. B MHETE	7-6-85	READING	7.10 p.m				✓		8		12	8.40 p.m	Good	1½
Mr. B. MHETE	10/6/85	PREPARING & MARKING	7.00 p.m				✓		8		10	8.50 p.m	Good	2
Mr. B. MHETE	11/6/85	PREPARING & MARKING	7.00 p.m				✓		8		10	9.15 p.m	Good.	2¼
Mr. B. MHETE	12/6/85	MARKING & PREPARING	7.00 p.m				✓		8		14	9.00 p.m	Good.	2
Mr. B. MHETE	13/6/85	MARKING & PREPARING	7.00 p.m				✓		8		19	9.00 p.m	Good.	2
Mr. B. MHETE	14/6/85	READING	7.05 p.m				✓		8		4	9.00 p.m	Good	2
Mr. B. MHETE	17/6/85	READING & MARKING	7.25 p.m				✓		8		8	9.00 p.m	Good	2
Mr. B. MHETE	18-6-85	READING & MARKING	7.05 p.m				✓		8		21	9.00 p.m	Good	2

APPENDIX C

Detailed Descriptions of Clinic Systems

Since the components of the school lighting systems have already been listed in the text, only the clinic electrification system components are listed here. They are:

Lentsweletau: One Western Solar refrigerator/freezer, nine ARCO Solar 16-2000 modules, four 110-AH shallow-cycle batteries, ARCO BP-12 battery charge controller. Initially, there were five 20W fluorescent lights (delivery, maternity, surgery, etc.). After the R/F unit had problems and was exchanged for a Polar Products RR-50L, the BP-12 was exchanged for an SCI-1 controller. Three 15W lights were added, as well as a 37.5W high-intensity light for the delivery room, and a rechargeable torch (flashlight) for emergency use.

Shoshong: Polar Products RR-2, 12 ARCO 16-2000 modules, six 110-AH batteries, nine 20W fluorescent lights, one rechargeable torch, high-intensity light, ARCO Universal Charge Controller (UCC), which was later replaced with an SCI-1 battery-charge controller after the UCC showed evidence of impending difficulties. The RR-2 was later replaced with a Marvel 4RTD because the RR-2 was not operating in the correct temperature range, and was temporarily taken back to Gaborone for testing. This was very likely an operator misunderstanding about setting the thermostat correctly, since subsequent examination showed no obvious problem with the RR-2. The Marvel was test-operated with few difficulties for two months, except for occasional and as yet unresolved problems that resulted in blown fuses, which were easily replaced. The Marvel was then replaced by a SunFrost for test-operation, which had no difficulties and was still operating as expected at the conclusion of the project.

Mabule: Polar Products RR-50L refrigerator/freezer, 12 ARCO 16-2300 modules, six 110-AH batteries, seven 15W fluorescent lights, ARCO UCC controller, 37.5W high-intensity light, rechargeable torch, radio communications. The modules were wired directly to the controller terminals of the UCC, and the R/F unit was wired directly to the batteries. The lighting system was wired to the load terminal of the UCC.

APPENDIX D

WHO/NASA Performance Specifications for PV Refrigerators

The R/F unit shall be a top-opening, chest-type unit.

The R/F unit, the compressor/motor/condenser, battery complement, controls, regulator and instrumentation shall be assembled as an integral unit.

The R/F unit assembly shall be packaged to provide maximum personnel safety. The design of enclosures and arrangement of components shall provide good ventilation of the battery compartment and compressor, and ease of servicing.

The compressor motor shall be a DC type and operate at a nominal 12 volts.

The dimensions of the R/F unit assembly shall conform to the following:

- total maximum height of assembly: 100 cm;
- total usable storage volume: minimum--60 liters, maximum--100 liters; and
- freezer compartment usable volume: minimum--20 liters, maximum--one-third total refrigerator/ freezer unit volume.

The materials used for the R/F unit inner and outer liner jackets shall be durable, easily cleaned, and resistant to deterioration from exposure to foods and vaccines. The inner and outer R/F unit liners shall be sealed together to minimize moisture penetration due to atmospheric and/or temperature-induced vapor pressure differences between the environment and the insulation cavity.

The material for insulation shall be foamed-in-place polyurethane type and shall be of sufficient thickness to provide adequate cold retention, minimize compressor energy requirements and, in general, provide the greatest overall system economic benefit.

The R/F units shall have a single outer lid which is hinged, self-closing and lockable. The outer lid gasket shall be capable of withstanding normal medical use and provide the necessary sealing to minimize heat leaks.

The R/F units shall have separate interior lids for the freezer and refrigerator compartments. The interior lids shall be hinged and designed to reduce heat transfer between the compartments and the outer lid.

With the R/F unit empty and the complete assembly stabilized in a 43°C ambient environment, the assembly shall be capable of achieving refrigerator compartment temperatures in the range of 4° to 8°C within 24 hours after compressor startup.

The R/F unit shall be capable of continuously maintaining refrigerator compartment temperatures in the range of 4° to 8°C when the refrigerator compartment is filled with a uniformly distributed water load in the ratio of one-third liter liquid per liter of refrigerator compartment volume, with an empty freezer compartment, and with the complete R/F unit assembly in a 43°C environment. Further, the R/F unit shall be capable of meeting this requirement with 70 percent or less compressor run (on) time.

The R/F unit shall be capable of freezing a minimum of two kilograms of water every 24 hours with the initial water temperature being 43°C and with the R/F unit operating in a stable cycling mode in a 43°C ambient environment.

Source: Kaszeta, W. Qualification Testing of Solar Photovoltaic Powered Refrigerator Freezers for Medical Use in Remote Geographic Locations, Final Report. Solavolt International, for NASA Lewis Research Center. NASA CR 168181. December 1982.

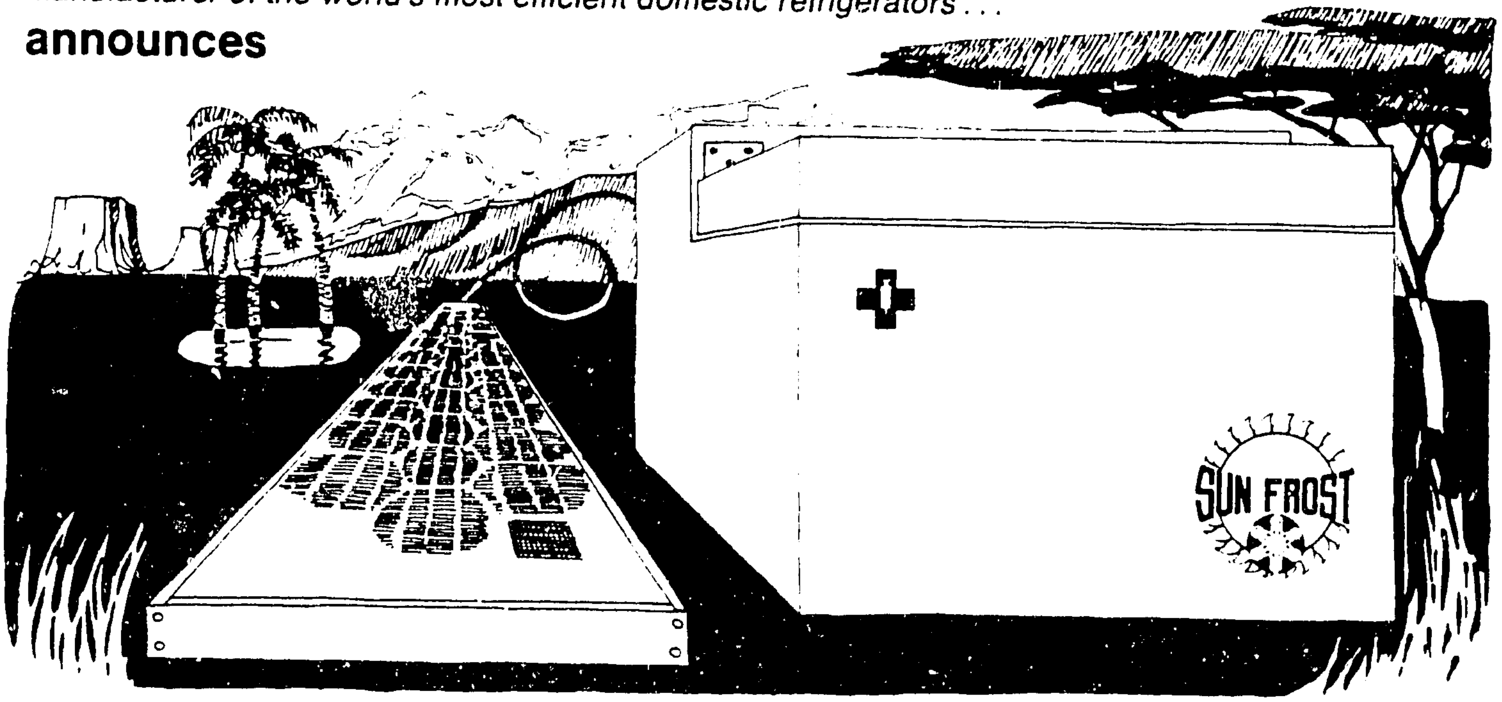
APPENDIX E

Manufacturers' Literature

SUN FROST . . .

manufacturer of the world's most efficient domestic refrigerators . . .

announces



Vaccimax — a 2 cubic foot 56 liter refrigerator freezer which can typically be powered by one photovoltaic panel.

A NEW STANDARD IN ENERGY EFFICIENT REFRIGERATION

- energy consumption in a 90°F environment--about 10 amp hrs/day or 120 watt hrs/day
- in a 70°F room 7 amp hrs/day or 84 watt hrs/day
- excellent temperature control
- independent controls set the temperature in the refrigerator and freezer sections
- VACCIMAX has only one moving part
- a high quality DC compressor with less than a 10% duty cycle
- requires few heavy batteries & PV panels, reducing transportation and assembly problems.
- the condenser & evaporator of the VACCIMAX are extremely durable

> *The high efficiency of the*
>
> **Vaccimax**
>
> *refrigerator reduces system costs and greatly expands the potential market for vaccine storage PV powered refrigeration.*

Other SUN FROST products:

Refrigerator - freezer	10 cubic ft.	35 amp hrs/day or 420 watt hrs/day
Refrigerator	10 cubic ft.	14 amp hrs/day or 168 watt hrs/day
Freezer	8.5 cubic ft.	53 amp hrs/day or 636 watt hrs/day
Refrigerator - freezer	17 cubic ft.	42 amp hrs/day or ½ kwatt hrs/day

For more information, contact

SUN FROST

P.O. Box DD Arcata, CA 95521

Larry Schlussler, Ph.D. **(707) 822-9095**

POLAR PRODUCTS

February 10, 1984

Enclosed are 10 brochures on the RR-2, and a letter describing NASA's testing procedures on our refrigerators (I was mistaken about WHO doing the testing). This page contains the product description on the RR-50L.

Polar Products is announcing their new solar powered refrigerator, RR-50L. Deliveries will start this February. The specifications are as follows:

1. Total volume: 50 ltr; 20 liters for the freezer and 20 liters for the refrigerator.
2. It can produce a **maximum** of 3 kg of ice per day if sufficient power is available.
3. Recommended battery bank size is 200 to 300 amp hours.
4. Recommended array size for vaccine storage is 3 to 4 modules.
5. Energy consumption will range from 18 to 40 amp hours a day.
6. Constructed of molded ABS plastic.
7. 12.7 cm (5 inches) of polyurethane foam insulation on all sides.
8. Lid with double seals.

Pricing with voltage regulator is as follows:

Retail price	$995.00
Qty. 4-19	776.00
20-99	660.00
100-199	550.00
200+	445.00

Minimum order is 4 units; for smaller quantities use retail pricing ($995.00). Brochures will be available on the RR-50L and the RR-1 in April.

Yours truly,

Mary Swissler

NEW ADDRESS
POLAR PRODUCTS
2909 OREGON COURT BLDG. C-1
TORRANCE, CA 90503 U.S.A.
(213) 320-3515
TLX 703682 POLAR LSAUD

POLAR PRODUCTS

Thank you for your interest in solar and our products. Should you decide to purchase our products or not; your awareness of energy alternatives will help foster support which can diminish our dependence on fossel fuel and nuclear fission type power plants. In most areas throughout the world, refrigerators and freezers represent the single largest demand of electricity in the home.

To power your refrigerator and freezer from the sun is the first step in becoming independent of the utility companies. If you live in a rural area that is not serviced by a utility company there is no question regarding the cost effectiveness of our system over diesel and gas generators or having the utility company connect you to their grid.

COMPLETE SYSTEMS:

These systems include photovoltaic arrays, support structures, all wiring, (except conduit), 300 amp/hr battery bank and a RR refrigerator. We are sizing two arrays to fit most applications; a 105 to 110 peak watt array for locations with lots of sun or light useage refrigerator/freezer and 160 to 165 peak watt array for locations with lower amounts of sun or greater refrigerator/freezer usage. Extra PV modules can be added without rewiring or major modification to support structure. Generally we recommend oversizing the PV array because the surplus power can be used to power other load devices (appliances).

RR-2 is now available in a single compressor model, RR-1. The specifications of RR-1 are similar to RR-2; RR-1 weighs 64 kg., can store 4 batteries. We recommend RR-1 for home use and RR-2 for vaccine use.

Our RR refrigeration systems also can provide 12 Vdc electrical power to run lights, television, stereos, communications, water pumps, etc. The photovoltaic array is generally oversized in order to provide sufficient power during poor weather conditions or heavy refrigeration usage. Therefore when the sun is at its best, or when the refrigeration is used the least, the excess energy is automatically switched to power your other requirements.

	* Pw/80	Pw/105-110	Pw/120	Pw/160-165
RR-1 Complete System:	$2,595.00	$2,895.00	$3,120.00	$3,595.00
RR-2 Complete System:	$3,495.00	$3,895.00	$4,020.00	$4,400.00

All systems are supplied with voltage regulators, reverse polarity protection, battery charger, low voltage disconnect, and power diversion. To delete this circuitry; subtract $50.00 from the unit price.

REFRIGERATORS ONLY: (batteries, PV array not included)

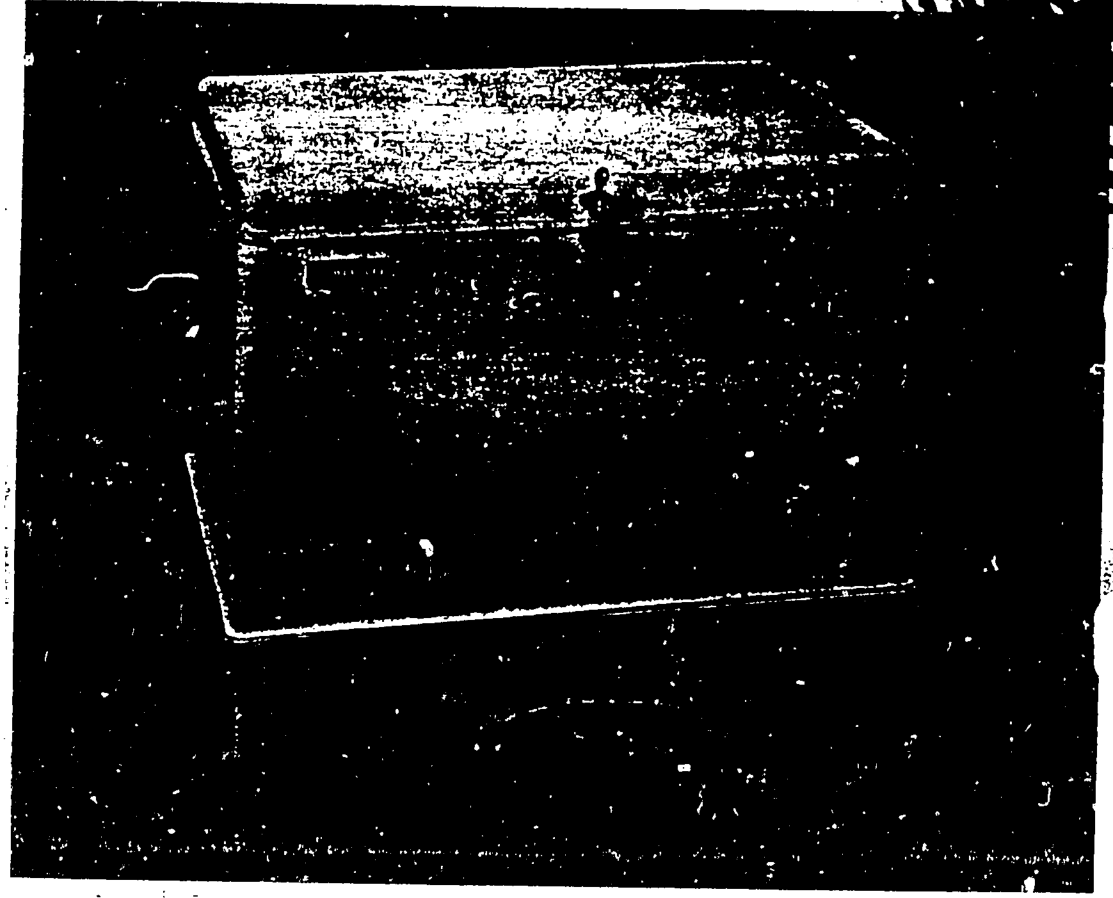
RR-2	Refrigerator only:	$1,995.00
RR-1	Refrigerator only:	$1,095.00

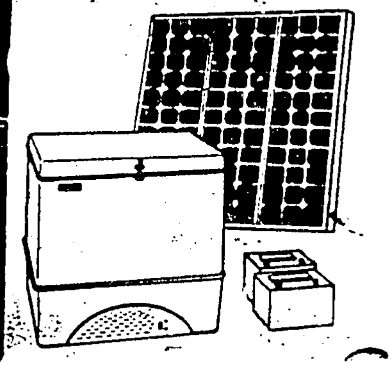
Pricing is in U.S. dollars, F.O.B. Bellingham, Washington.
Effective- June 7, 1983
*Peak Watt
EXPORT PRICE LIST

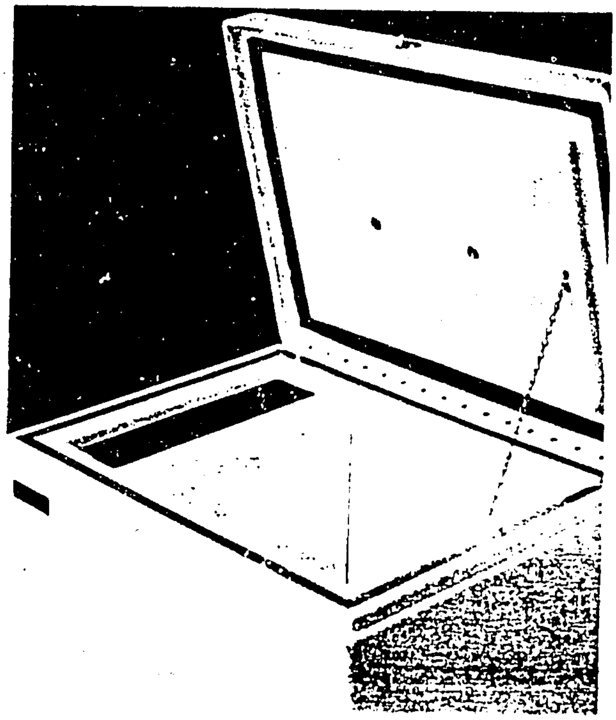
NEW ADDRESS
POLAR PRODUCTS
2909 OREGON COURT BLDG. C-1
TORRANCE, CA 90503 U.S.A.
(213) 320-3515
TLX 703682 POLAR LSAUD

MARVEL

Reliable Bio-Medical Refrigeration







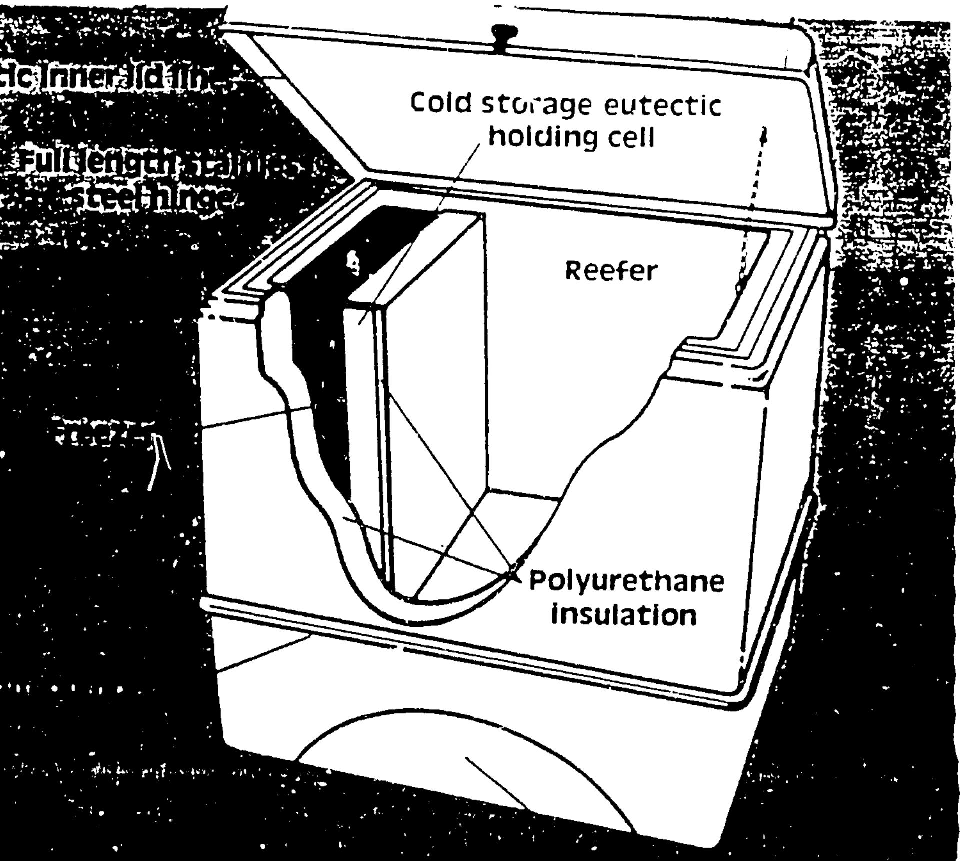
Model 4RTD

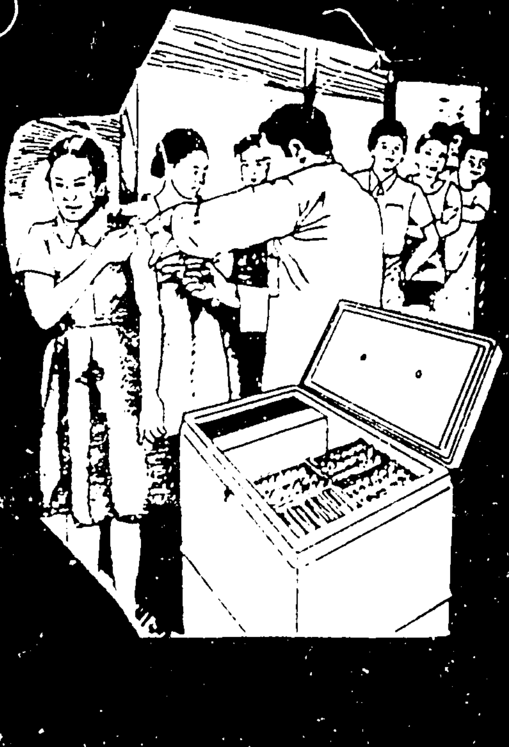
Solar 12-volt DC Power 4.0 cubic foot Refrigerator with Freezer, solar insulated for tropical installation, chest type.

The Marvel Model 4RTD Solar refrigerator provides long-term, highly efficient refrigeration for cold storage of bio-medical supplies or food products in areas where conventional grid power is unavailable or unreliable. The Model 4RTD has the most efficient power consumption factor of any refrigeration system available for its size. It is designed for commonly available photovoltaic 12-volt DC batteries. The rugged Model 4RTD is constructed of state-of-the-art non-ferrous materials for physical and performance reliability in harsh environments. It includes a cold storage cell for utmost efficiency. Marvel's 4RTD was designed to pass the rigid "cold chain" standards of operation set by the World Health Organization (WHO) and the Center for Disease Control. National Aeronautics and Space Administration, Lewis Research Center (NASA) tested the 4RTD on behalf of WHO.

Features

- Power Source: photovoltaic 12-volt DC batteries are rechargeable by solar array, diesel generators and 115-volt battery charger.
- Low power consumption
- Cold storage eutectic cell provides refrigeration for long periods of time with no compressor operation
- Self-contained battery storage compartment
- Foamed-in-place, thick-walled polyurethane insulation
- 3 cubic foot refrigerator compartment (85 liters)
- 1 cubic foot freezer compartment (28.3 liters)
- Can operate for years with preventive maintenance
- Tough fiberglass-reinforced ABS plastic refrigerator cabinet and top door
- Chromed brass and stainless steel hardware
- Rugged, efficient and reliable





Specifications

Dimensions

Capacity

Weight

Materials

Electrical Protection

Refrigeration System

Performance Requirements

MARVEL DIVISION

D.C. MODEL MARINE AND SOLAR

Model No.	Description	Retail	Dealer	Dist.	5 or more Stocking Dist.
6RFD	6.1 cu. ft. ref/freezer, forced air, DC 12 volt	898.00	718.40	538.80	484.92
6STD	6.1 cu. ft. ref/freezer, static condenser, DC 12 volt	767.00	613.60	460.20	414.18
4RFD	4.5 cu. ft. ref/freezer, forced air, DC solar insulated	1020.00	815.00	610.00	549.00
4STD	4.5 cu. ft. ref/freezer, static condenser, DC solar insulated	920.00	735.00	550.00	495.00
4NFD	4.5 cu. ft. Normal temp., all refrig., forced air, DC solar insulated	1020.00	815.00	610.00	549.00
4NSD	4.5 cu. ft. Normal temp., all refrig., static condenser, DC solar insulated	920.00	735.00	550.00	495.00
4RTD	4.5 cu. ft. ref/freezer, top opening, chest type, DC solar insulated	2007.00	1605.00	1200.00	1080.00

CONVERSION KITS

I6AC	Ice device conversion kit, 6 tray, AC 115 volt	429.95	344.96	257.97	232.17
I6DC	Ice device conversion kit, 6 tray, DC 12 volt	627.00	501.60	376.20	338.58
MADC	Mechanical assembly, DC 12 volt	550.00	440.00	330.00	297.00