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Final Report on Vaccine Refrigerator Testing

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ABSTRACT

For the Central American Health Clinic Project initiated in 1986, Sandia National Laboratories and the Florida Solar Energy Center recognized the need for a test and evaluation program for vaccine refrigeration systems. At the Florida Solar Energy Center, side-by-side testing of three photovoltaic powered vaccine refrigerators began in 1987. The testing was expanded in 1988 to include a kerosene absorption refrigerator. This report presents observations, conclusions, and recommendations derived from testing the four vaccine refrigeration systems. Information is presented pertaining to the refrigerators, photovoltaic arrays, battery subsystems, charge controllers, and user requirements.

This report should be of interest to designers, manufacturers, installers, and users of photovoltaic-powered vaccine refrigeration systems and components.

SECTION 1 INTRODUCTION AND BACKGROUND

Testing of three photovoltaic (PV)-powered vaccine refrigerators began in 1987 at the Florida Solar Energy Center (FSEC) as part of the Central American Health Clinic Project. This project was initiated in 1986 by the US Department of Energy and the Organization of American States, it was supervised by Sandia National Labs, and it was implemented by FSEC (1). The purpose of the project is to foster the fielding of PV-powered refrigerators in the rural areas of Central America, where improved health care is needed. This final report summarizes the side-by side test and evaluation of the vaccine refrigerators. It includes information from FSEC monthly progress reports and references 1 through 5.

1.1 Test Objectives

The testing at FSEC was established as a sub-task to the Photovoltaic Southeast Regional Experiment Station (SERES) project. The purpose of the testing program was to observe, characterize, and evaluate the performance of these systems under conditions as close as possible to actual field usage. In addition to testing the refrigerators, the tests at FSEC evaluated the PV arrays, the battery systems, the charge controllers, and the balance-of-system (BOS) components. This departs from the World Health Organization (WHO) test procedures that test only the refrigerator (6). All the refrigerators tested at FSEC had previously passed the WHO test criteria.

With an improved working knowledge of these systems, the system design, sizing methods, and operating strategies can be optimized more effectively. Ideally, this means less down time, less vaccine spoilage, and a more efficient and economical system. Major items of interest for the refrigerators include: energy consumption, temperature stability, ice making

capability, reliability, operating convenience, installation practices, and required operator knowledge. For the PV array and battery systems, items of interest include: ability to meet the refrigerator's energy needs, PV array and battery system characteristics, reliability and failure modes, maintenance needs, sizing methods, balance-of-system (BOS) characteristics, and operator requirements.

1.2 System Descriptions

The following PV-powered vaccine refrigerators were tested: (1) Marvel model 4STD, (2) Sunfrost model RFV-4, and (3) Polar Products model RR-2. These refrigerators use a conventional vapor-compression cycle for refrigeration and the temperature is thermostatically controlled. Danfoss hermetic compressors, either model BD2 or BD2.5, are used for the vapor-compression process. Unlike the Marvel and Sunfrost refrigerators, the Polar Products refrigerator uses two compressors, one for its freezer compartment and the other one for its refrigerator compartment. Twelve volt dc battery systems provide electricity for the brushless compressor motors. During the day, the PV arrays recharge the battery systems. Charge controllers for the Marvel and Polar Products systems prevent overcharging the batteries. The Sunfrost system, using nickel cadmium (ni-cd) batteries, does not use a charge controller. Table 1 lists the major components and specifications for the vaccine refrigerator systems. Some of the components in Table 1 are no longer commercially available. This includes the Marvel refrigerator, the Solavolt PV modules, and the Solavolt controller.

Table 1. Refrigerator System Components and Ratings

#	Refrigerator	PV Modules	Batteries	Controller
1	Marvel 4STD, 127 L Front Load	Solavolt MSVM4011 40 Wp, 6 ea	Exide GC-IV, 4 ea 6V @ 220 Ah	Solavolt (prototype) 12 Volt
2	Sunfrost RFV-4, 84 L Front Load	ARCO M55 53 Wp, 3 ea	NIFE Sunica SUN 31-3, 3 ea 4V @ 338 Ah	None
3	Polar Prod RR-2, 127 L Top Load	Solarex SX147 47 Wp, 5 ea	IBE Pwr-Plus, 2 ea 6V @ 369 Ah	Polar Prod. PCC 12V86 12 Volt
4	SIBIR S2325/PEV1ST 232 L Front Load	N/A	Kerosene	N/A

History as of 5/30/90:	Marvel	Sunfrost	Polar Prod	SIBIR
Began Operation:	Feb 87	Feb 87	Dec 87	Jun 88
Days Operational:	1042	1033	799	533
Compressor Hrs:	8263	5658	F3780/R1203	N/A

The kerosene powered vaccine refrigerator tested was a SIBIR model S2325/PEV1ST. Before the advent of PV-powered refrigerators, kerosene refrigerators were the only practical means for storing vaccines in many locations. This type of refrigerator uses an absorption cycle for refrigeration. Kerosene provides the energy and the refrigerator and freezer temperatures are regulated by manually adjusting the burner flame height. Either a change in ambient room temperature or a change in the quantity of ice being made requires adjusting the burner flame height in order to maintain the vaccines within

their proper temperature range. In addition to the kerosene burner, this refrigerator has a 115 Vac electrical heater. This permits operation from a generator or the electric utility.

1.3 Test Configuration

The refrigerators were installed in the garage of one of the PV grid-connected prototype houses at FSEC. This permitted the use of an existing data acquisition system. The instrumentation included transducers to measure the operating currents and voltages of the PV arrays, the battery systems, and the refrigerators. Using this data, power, energy, and ampere-hour (Ah) totals may be calculated. Thermocouples measured the ambient room temperatures, the refrigerator compartment temperatures, the freezer compartment temperatures, the vaccine vial temperatures, the icepack temperatures, and the PV array temperatures. For the PV-powered refrigerator systems, the solar energy received by their PV arrays was measured with a pyranometer. For the kerosene refrigerator, its energy requirements were determined by measuring the quantity of kerosene consumed.

Because of the strong effect of the ambient room temperature on the energy requirements of the refrigerators, a room temperature control system was installed in June, 1988. This permitted the room temperature to be maintained at stable temperatures during the different tests. The temperature control system consists of a small window type air conditioner, two 1500 watt floor heaters, and a temperature controller. The walls and ceiling of the room were insulated in order to minimize variations in temperature within the room and for energy efficiency. Figure 1 shows the test room and the four vaccine refrigerators.

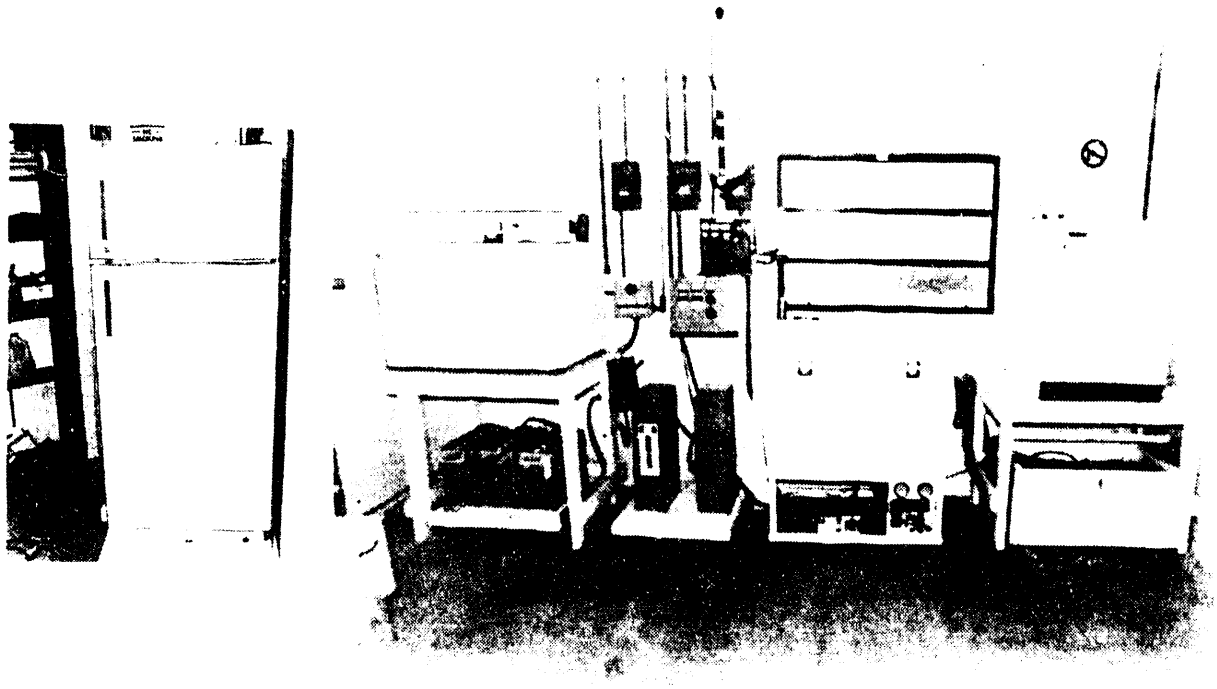

Figure 1. Inside of Vaccine Refrigerator Test Room. Left to Right: SIBIR, Sunfrost, Polar Products, and Marvel Refrigerators.

SECTION 2 REFRIGERATOR OPERATION AND ENERGY CONSUMPTION

The vaccine refrigerators tested were designed by their manufacturers to maintain the vaccine vial temperatures within the designated temperature range and to make ice for the purpose of maintaining vaccine temperatures when the vaccines are transported away from the health clinics to treat patients. For the PV-powered vaccine refrigerators, their daily energy use is important because it dictates the size of the PV array and the battery system needed. This section of the report presents an energy consumption model for each of the PV powered vaccine refrigerators. It also discusses the temperature stability of the vaccine refrigerators, their ice making capability, their holdover times, their ease of installing and operating, and their operator requirements and reliability.

2.1 Energy Consumption Model

Results from testing the systems have yielded a method for modeling the daily energy consumption of the refrigerators (2). The model is based on calculating the heat conducted through the refrigerator walls, the latent heat of fusion of water for making ice, and the heat gain from air changes during door openings.

Although usually not considered for a vaccine refrigerator, a cold product load may also be added to the model. The cold product load accounts for nonintended use of the refrigerator. An example is putting room temperature beverages in the refrigerator. Once the contents of the refrigerator have reached the refrigerated space temperature, the amount of the contents stored makes little difference in the energy consumption. Energy consumption tests with empty and full configurations confirmed this.

For the model, the energy consumption is dependent on the room air temperature (Trm), the amount of ice to be made (Kg), and the door opening time (Md). These variables together with the specific refrigerator constants (size, insulation, etc) are used to calculate the daily electrical load in watt-hours (Wh) with the set of equations shown in Table 2. In the equations, the numerator is the thermal load and the denominator is the refrigeration system coefficient of performance (COP). To convert the daily Wh load to a daily ampere-hour (Ah) load, the daily Wh load may be divided by the average system battery voltage (Vbat). Depending on the PV system sizing method preferred, either the daily Wh load or the daily Ah load may be used by a system designer to determine the required size of the PV array and the battery system.

Table 2. Refrigerator Load Model Equations

WHempty =	(k/l)*A*24*(Trm-5)/COP	(Eq 1)
WHice =	(98.6+1.16*Trm)*Kg/COP	(Eq 2)
WHair =	0.3292*Vol*Ac*Md*(Trm-5)/COP	(Eq 3)
WHcold =	1.16*(Trm-5)*Ww/COP	(Eq 4)
WHtotal =	WHempty + WHice + WHair + WHcold	(Eq 5)

where WH = electrical energy per day (Wh/day)
k = wall thermal conductivity (W*m/(m^2*deg C)
l = wall thickness (m)
A = outside wall surface area (m^2)
Trm = daily average room temperature (deg C)
COP = refrigeration coefficient of performance
Kg = mass of ice (kg)
Vol = refrigerator internal volume (m^3)
Ac = number of air changes per minute
Md = daily door open time (minutes)
Ww = water mass to be cooled (kg)

Table 3. Constants for the Refrigerator Load Model Equations

Constant	Marvel	Sunfrost	Polar Products
k	0.025	0.025	0.025
l	0.060	0.114	0.106
A	2.595	3.120	3.193
Vol	0.127	0.084	0.133
Ac	4.03	2.48	1.73
COP	1.0	1.5	1.0

Improved values derived from measured data.

Marvel COP = 1.10*(1.0 + 0.015*(30-Trm))

Polar Products COP = 1.11*(1.0 + 0.010*(30-Trm))

Examples of the refrigerator load model are shown in Figures 2 through 4. They were obtained with the set of constants shown in Table 3. Actual Wh measurement values are also shown for comparison. Agreement between the modeled and the measured values is generally good for the Marvel and the Polar Products refrigerators. However, for the Sunfrost refrigerator, the modeled values are higher than the measured values at the lower and upper room temperature regions. This is because the model assumes ice is completely frozen within a 24 hour period. For this refrigerator, the actual energy usage is less due to icepack supercooling (see paragraph 2.3). The model for this refrigerator can be improved by multiplying by the ratio of 24 divided by the actual hours required to freeze the icepacks. For the example presented, an extra hour of freezing time is assumed for each one degree C above or below 32 degrees C. This allows the calculated values to better approximate actual measurements.

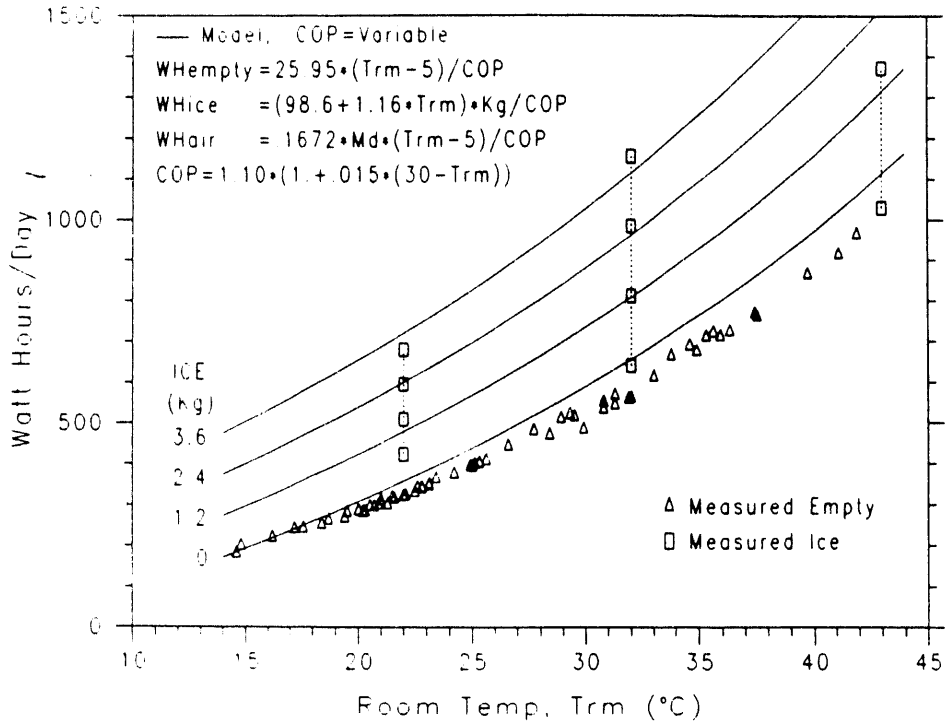

Figure 2. Daily Energy Load Model for the Marvel Refrigerator.

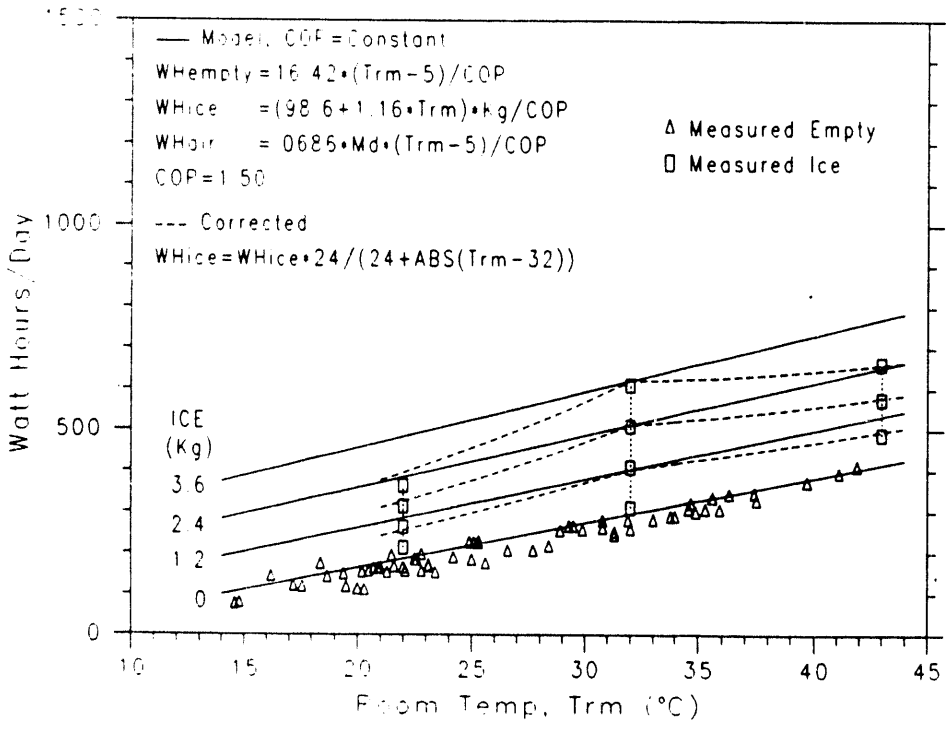

Figure 3. Daily Energy Load Model for the Sunfrost Refrigerator.

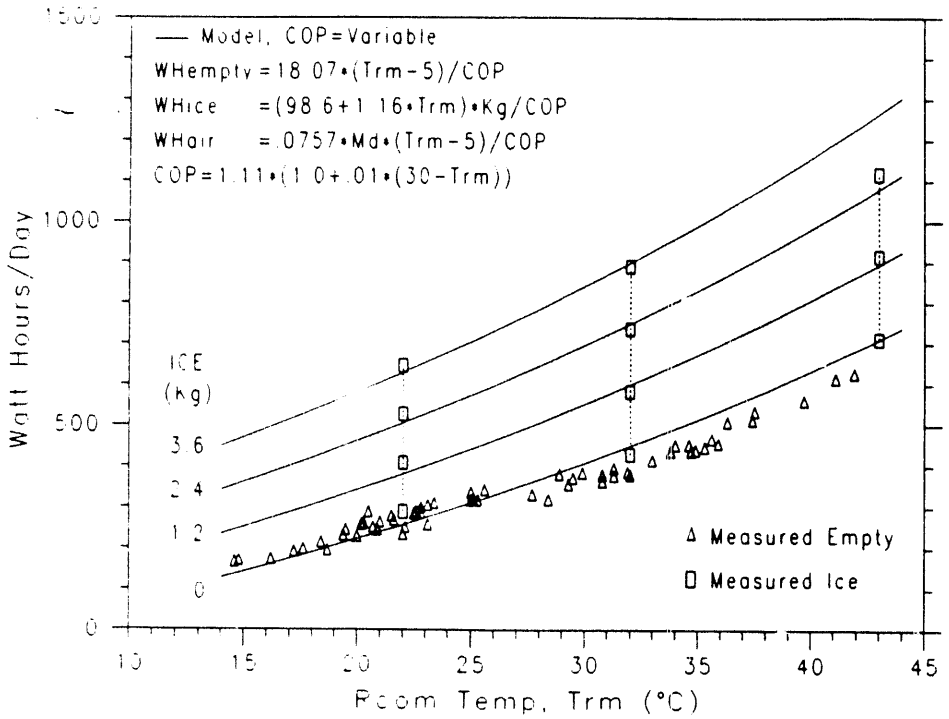

Figure 4. Daily Energy Load Model for the Polar Products Refrigerator.

Once the constants are obtained for a given refrigerator, the load can be computed for any desired set of conditions. Note that the refrigeration system COP is also a variable and is refrigerator dependent. It is best obtained from measurements made on a working unit (2); however, in lieu of this, it can be estimated as a constant from Danfoss compressor specifications.

Differences in the energy consumption of the refrigerators can be attributed to the wall insulation thickness, the refrigerator size, and the compressor location. The Sunfrost refrigerator used the least energy because it is the smallest size, it has thick walls, and its compressor is mounted on top for good air circulation. The Marvel refrigerator used the most energy because it is a larger size, it has thin walls, and its compressor is enclosed at the bottom of the refrigerator where

heat from the compressor adds to the thermal load.

For all the refrigerators, the room ambient temperature is the most important parameter in the energy consumption of the refrigerator. The second most important parameter is the amount of ice making performed. Both the room ambient temperature and ice making have a much greater affect on the energy consumption than does a reasonable amount of door opening. The Polar Products refrigerator, which has a door that opens from the top, was less affected by door-open time than were the other refrigerators that have a door that opens from the front. When the door of the Polar Products refrigerator is opened, the cool air does not rise.

2.2 Temperature Stability

One of the most important characteristics of a vaccine refrigerator is whether it can maintain the vaccine vial temperatures within the designated temperature range from 0 to 8 degrees C (6). Temperature stability is affected by thermostat characteristics, refrigerator construction, ice making, door openings, room temperature, operator awareness, etc. Vaccine vial temperatures over a three month period during which ice was frequently being made are shown in Figure 5. In general, all of the PV-powered refrigerators have the capability to maintain proper vaccine temperatures better than the kerosene refrigerator. Thermostat control of the PV-powered refrigerators is the main factor which allows improved temperature stability and less operator monitoring.

The Polar Products refrigerator, with its dual compressors and electronic thermostats, had the most stable vial temperatures for both with and without ice making. However, the temperature settings are more difficult to adjust in the field. This is intentional to reduce user tampering. The Marvel and

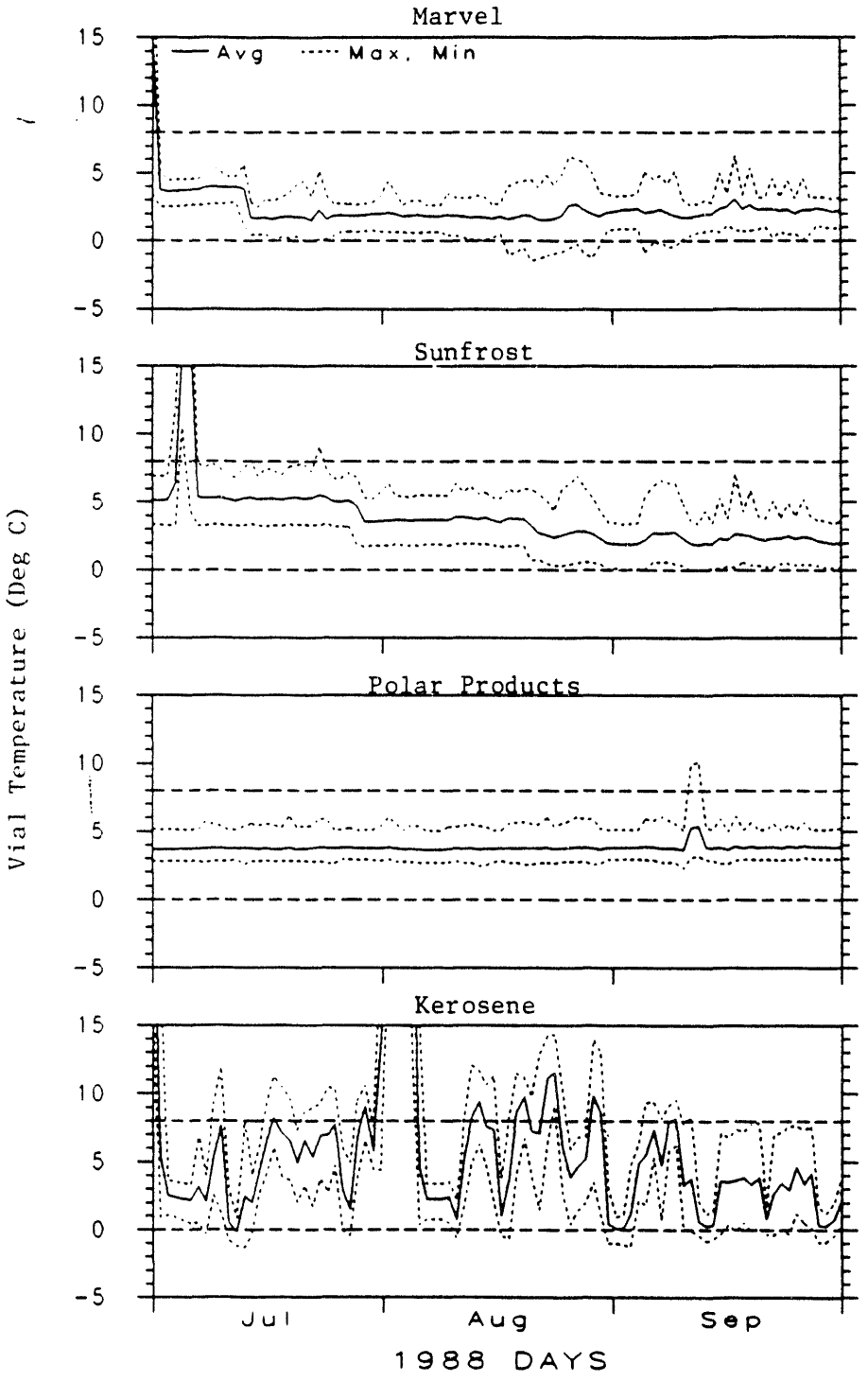

Figure 5. Vaccine Vial Temperatures Over a Three Month Period During Which Ice Was Being Made

the Sunfrost refrigerators each have single mechanical thermostats, and are somewhat affected by the level of ice making in progress. For high levels of ice making, the thermostat usually must be lowered to obtain the colder temperatures necessary for freezing icepacks within 24 hrs. The lower thermostat settings cause the vaccine vial temperatures to approach the 0 degree C lower limit. These thermostats are easy to adjust and replace should the need arise, provided spare parts are available.

The kerosene refrigerator does not use a thermostat. A manual adjustment of the burner flame by the operator is required to maintain the proper temperatures. The time lag between a flame adjustment and when the steady state temperature is reached may exceed 12 hours. Therefore, the operator must anticipate changes in the refrigeration load and be available to monitor the progress. Two changes per day are usually required. For this refrigerator, the vaccine section is closely coupled with the freezer section. During ice making sessions, vaccine vial temperatures may rise above 10 degrees C for several hours when warm icepacks are placed into the freezer. A higher flame (more heat) is required at this time. Then, as the icepacks freeze, the flame must be reduced to prevent the vaccine vial temperatures from becoming too cold.

2.3 Ice Making Ability

The World Health Organization (WHO) requires that vaccine refrigerators be able to make 2.4 kg of ice per day while still maintaining proper vaccine temperatures (6). Ice is usually made in 600 ml plastic icepack containers. With its larger capacity and -20 degrees C freezer (steady state), the kerosene refrigerator can make double this amount. However, when making ice at this level for several consecutive days, vial temperatures may exceed 10 degrees C for extended periods.

Kerosene usage in this high ice making mode is about 0.9 liter/day, which is slightly above the normal 0.75 liter/day value.

For the PV refrigerators, the two refrigerators with exposed evaporator plates (Marvel and Polar Products) froze the icepacks the best. This is because the icepacks can be placed in direct contact with the cold evaporator surface and are more likely to be pulled through the supercooling region of 0 to -5 degrees C. When making ice with the Marvel and Polar Products refrigerator, the ice packs should be placed in direct contact with the evaporator. If frozen ice packs are present, they should be located in the freezer such that the unfrozen ice packs can be placed in direct contact with the evaporator. Otherwise, the unfrozen icepacks may not freeze.

Supercooling is a phenomena where icepack water remains in a liquid state at temperatures below 0 degrees C. It only occurs in sealed icepacks when freezer temperatures are just below 0 degrees C, and frequently causes freezing times to exceed 24 hrs. Since the water remains a liquid, there is no latent heat generated. This accounts for the lower energy consumption shown for the Sunfrost refrigerator in Figure 3 at the upper and lower Trm regions. Because of the difficulty in freezing sealed icepacks, the temperature of the freezer evaporator plate should be a minus 10 degrees C or colder.

The Marvel and the Polar Products refrigerator can both handle up to 3.6 kg/day of ice making for periods of from 2 to 4 days. However, the energy requirements are considerably higher than the PV array and the battery system were sized for and battery depletion can be expected, thereby running the risk of rendering the refrigerator inoperative.

At room temperatures below 10 degrees C, it was noticed on

several occasions that the single compressor units tend to have a problem in their ability to make ice. At these low room temperatures, it takes very little compressor 'on' time to maintain proper vial temperatures, and therefore the freezer does not have a chance to achieve and hold the necessary -10 degrees C.

2.4 Holdover Time

The holdover time is defined by WHO as the period of time for which all of the vaccine temperatures being monitored remain below 10 degrees C when the energy source to the refrigerator is turned off. At FSEC, three different holdover tests were performed at a room temperature of 32 degrees C: one with the freezer filled with icepacks, one with the freezer empty (per WHO specifications), and one with the icepacks transferred from the freezer to the refrigerator section. At the start of the holdover tests the vaccine temperatures ranged from 2 to 5 degrees C. The results of the holdover tests are shown in Table 4.

For the holdover test with the freezer full, 14 frozen icepacks (8.4 kg) were present in the freezer section at the start of the test. Except for the kerosene refrigerator, 7.5 kg of vaccine (water in vaccine vials) was in the refrigerator compartment. The kerosene refrigerator's larger size permitted 20 kg of water in the refrigerator. For this test, the Marvel refrigerator had the longest holdover time. This is because the thermal resistance between the Marvel's freezer and refrigerator compartments is less than for the other refrigerators.

Because it is well insulated, the Sunfrost refrigerator had the longest holdover time when tested with the freezer empty. The other refrigerators with less insulation had shorter holdover times.

Table 4. Holdover Time in Hours

Refrigerator	Freezer Full	Freezer Empty	Icepack Transfer
Marvel	36.5 - 38	5.8 - 6	29.7 - 30
Sunfrost	14 - 16	9 - 13	56 - 60
Polar Products	8 - 10	7 - 8	44 - 45
Kerosene	8	6	14

The last holdover test, transferring frozen icepacks to the refrigerator section when the power is shut off, demonstrates an effective technique to increase the time before the permitted vaccine temperature is exceeded. For this test, 6 of the 8 icepacks in the freezer were removed and then placed in the refrigerator section. Except for the Marvel refrigerator, this method gave the longest holdover times. We recommend keeping 10 to 12 extra icepacks in the freezer to use for this purpose. Once frozen, the icepacks do not add to the daily energy requirements of the refrigerator and in the case of a loss of power, the extra holdover time may prevent vaccine spoilage while attempts are made to restore power to the refrigerator.

The range of holdover times in Table 4 reflect minimum and maximum times depending on when the power is turned off in relation to the compressor on-off cycle. For the Sunfrost refrigerator, the longer interval between compressor cycles gives a wider range in holdover times. As indicated by the lower and upper holdover times, the type of holdover test being performed can also influence the time between compressor cycles. Because the kerosene refrigerator cycle is continuous, only one time is given for each holdover test for this refrigerator.

2.5 Operating Convenience and Installation Practices

As long as the batteries for the PV-powered refrigerators are charged, these refrigerators require only an occasional thermostat adjustment. The Polar Products refrigerator has a top opening door, which cannot be left open unless it is propped open with a rod. This is an intentional design feature to limit door opening time. However, it makes this refrigerator less convenient to use than the other refrigerators that open from the front.

The refrigerators should be installed in the coolest possible location to reduce the energy consumption and to minimize component deterioration from high temperatures. The installation of the PV-powered systems also requires the placement of the PV array, the battery system, and the charge controller. The appropriate wiring between these components must also be performed. With properly trained personnel and a favorable site, these activities can be completed within a day. For installing systems in remote areas, thorough advance planning and preparations are needed to ensure that all the necessary equipment and tools are available during the installation.

For the kerosene refrigerator, the operator is required to ensure that the burner flame is always lit, properly adjusted, and that an adequate fuel supply is present. The flame should be checked at least twice per day, and the wick should be cleaned commensurate with the fuel quality. This is usually once per week for high grade fuel, and as often as every other day for poor or dirty fuel.

Other than having to assemble the burner, there is very little that has to be done in the way of installation for the kerosene refrigerator. There appears to be an initial break-in

period of about a month before interior temperatures began to stabilize. The most critical item to be concerned with is that this refrigerator should be located in a well ventilated area. The kerosene and exhaust fumes coming from this unit are noxious and should be kept away from patient areas, if at all possible.

2.6 Operator Requirements

For the PV-powered refrigerators, the most important operating requirement is that the battery be adequately charged to support the load. This means that the operator must know and understand that if the electrical load of the refrigerator exceeds the energy output of the PV array for extended periods, the battery state-of-charge (SOC) will decrease to the point where the refrigerator will cease operation. The operator must also realize that during periods of consecutive cloudy days the amount of battery charging can be negligible. Therefore, ice making during these times should be kept to a minimum or avoided all together.

The operator should be aware that the doors to the refrigerator must be tightly closed except when placing or retrieving vaccines and icepacks. On two occasions at FSEC, the door to the Sunfrost refrigerator was shut, but not latched, and air was free to enter and exit the refrigerator. Consequently, the compressor ran more than normal and the batteries were depleted causing the refrigerator to shut down.

Most PV systems are designed to protect the battery from excessive deep discharges, as repeated discharges will result in a shortened battery life. The controller protects the battery by cutting off the refrigerator, which more than likely means vaccine spoilage. The operator must be aware of these facts and regulate usage accordingly.

There is little operator knowledge required for a kerosene refrigerator. Other than keeping a clean burner and a properly adjusted flame, the main item of concern is ice making. If excessive ice making occurs, then vial temperatures may exceed safe limits and the risk of vaccine spoilage increases.

As a final point, which applies to all medical refrigerators, operators should be familiar with the holdover times for their particular unit. This is the elapsed time from when a power outage or flame blowout occurs until vaccine temperatures exceed the safe limit (usually 10 degrees C). Holdover times are predominately a function of insulation properties (R value). Units tested with an empty freezer yielded holdover times between 6 and 13 hours. A method for increasing this time is to maintain a stockpile of 10 to 12 frozen icepacks in the freezer for when such 'emergencies' may occur. The energy usage for maintaining icepacks in a frozen state is no greater than the energy used by an empty unit. When a power failure does occur, the icepacks are manually transferred from the freezer to the cold section. Holdover times can then be increased by a factor of up to 6 (total of 30-60 hours), which can buy valuable time to correct the problem, to recharge the batteries, or to install a new burner.

2.7 Reliability

After nearly three years of testing, the PV-powered refrigerators have amassed a combined total of over 18,900 hours of compressor 'on' time. During this time no compressor related problems have been observed. Problems with these refrigerators have been confined to the thermostats. Faulty thermostats in both the Marvel and the Sunfrost refrigerator required replacement. The Marvel thermostat was replaced after 22 months of operation and the Sunfrost thermostat was replaced after 40 months of operation.

SECTION 3 PV SYSTEM COMPONENTS

This section discusses the operation and the interaction of the PV arrays, the battery systems, and the controllers.

3.1 PV Array

Throughout the test period, the PV arrays have operated reliably and their power output has not degraded. For performance measurements, the module operating power and current values are obtained by dividing the daily array Ah (or Wh) totals by the daily insolation used and the number of parallel modules in the array. When these values are plotted versus the daily insolation for a whole year as shown in Figure 6, the average module operating current (Iop) or power (Pop) values can be determined.

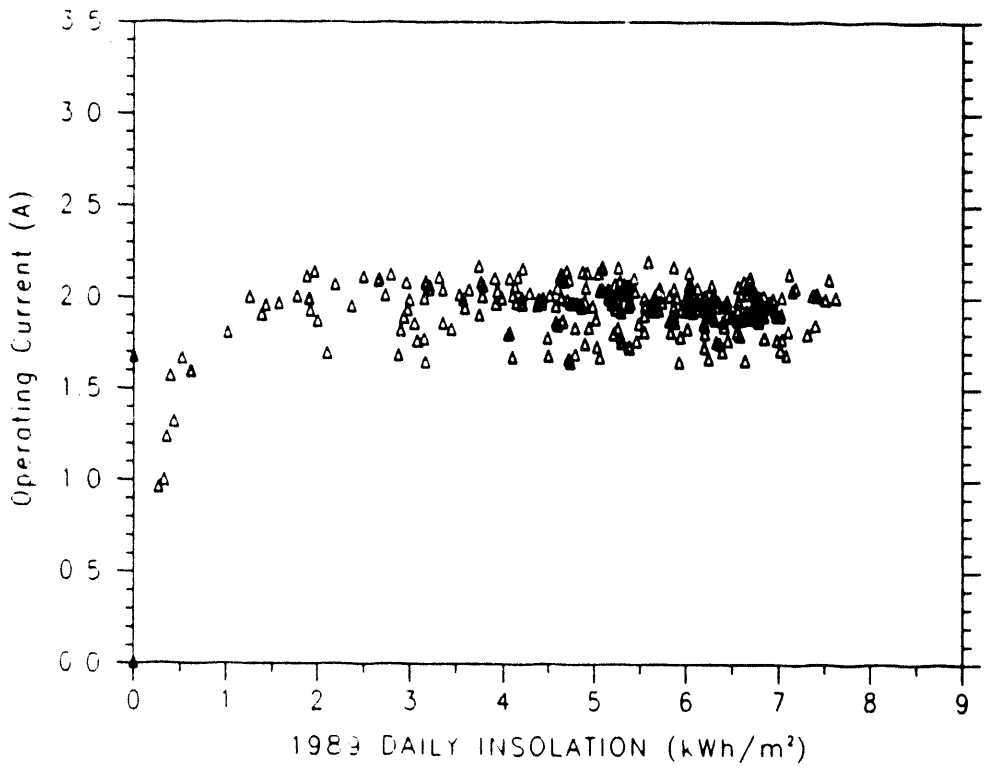

Figure 6. Iop of Solavolt Module versus Daily Plane-of-Array Insolation for 1989.

Table 5. Rated and Measured PV Module Performance

	Rating Method	Isc	Imax	Vmax	Pmax	%Eff
Solavolt	Rated, STC	2.74	2.45	16.5	40.4	8.7
MSVM4011	Rated, SOC	2.80	2.50	14.7	36.7	7.9
	Measured, SOC	2.50	2.16	14.2	30.7	6.6
	Avg Operating	----	2.10	14.3	30.0	6.5
ARCO	Rated, STC	3.27	3.05	17.4	53.0	12.2
M55	Rated, SOC	3.33	3.10	15.5	48.0	11.0
	Measured, SOC	2.93	2.59	14.9	38.7	8.9
	Avg Operating	----	2.90	13.5	39.0	9.0
Solarex	Rated, STC	2.76	2.56	18.4	47.0	9.8
SX147	Rated, SOC	2.81	2.51	16.7	42.0	8.7
	Measured, SOC	2.79	2.48	15.6	38.6	8.0
	Avg Operating	----	2.60	14.6	38.0	7.9

STC - Standard Test Conditions (1 kW/m^2, 25 deg C)
SOC - Standard Operating Conditions (1 kW/m^2, NOCT)

Table 5 shows a comparison between the manufacturers' rated module performance values and those obtained from actual measurements. While the differences can be partly attributed to wiring losses, spectral effects, mismatch, and temperature degradation, they are mainly due to module overrating by the manufacturers. If possible, system designs should be based on the measured module power at the nominal operating condition.

3.2 Batteries

For any PV-powered refrigerator system (or for that matter,

any PV stand-alone system), the battery is the stabilizing entity that stores the energy generated by the array and keeps the refrigerator running through the night and during periods of extended cloud cover. However, unlike the array which has a predictable and stable output, battery electrical characteristics change with use and age. This is because they are dependent upon a chemical reaction.

Main items of interest, like the full charge or rated capacity, state of charge (SOC), and the energy and charge efficiencies, are dependent on such factors as battery temperature, age, SOC, plate quality and sulphation, electrolyte level, concentration, and purity, etc. Since it is doubtful these batteries will receive proper maintenance, it is inevitable battery capacity will decrease with time, and herein lies the main limiting factor for the successful long-term uninterrupted operation of these systems.

One of the most useful items for an operator to know is the battery SOC. This can aide him in determining if it is advisable to make additional ice or if ice production should be stopped due to a low battery. Unfortunately, SOC is difficult to determine, especially under field conditions. A standard method is to use the battery open circuit voltage (Voc) as a reference to estimate battery SOC. Periodic battery discharge tests during the project have yielded the following simple formula, which can be used to estimate the SOC for nominal 12 volt dc lead acid batteries:

$$SOC(\%) = (Voc-11.46)*71.$$

The SOC relationship for several different batteries is shown in Figure 7. The advantage of this relationship over Ah counting is that it is not dependent upon knowing the battery capacity. This means that the battery voltage versus SOC

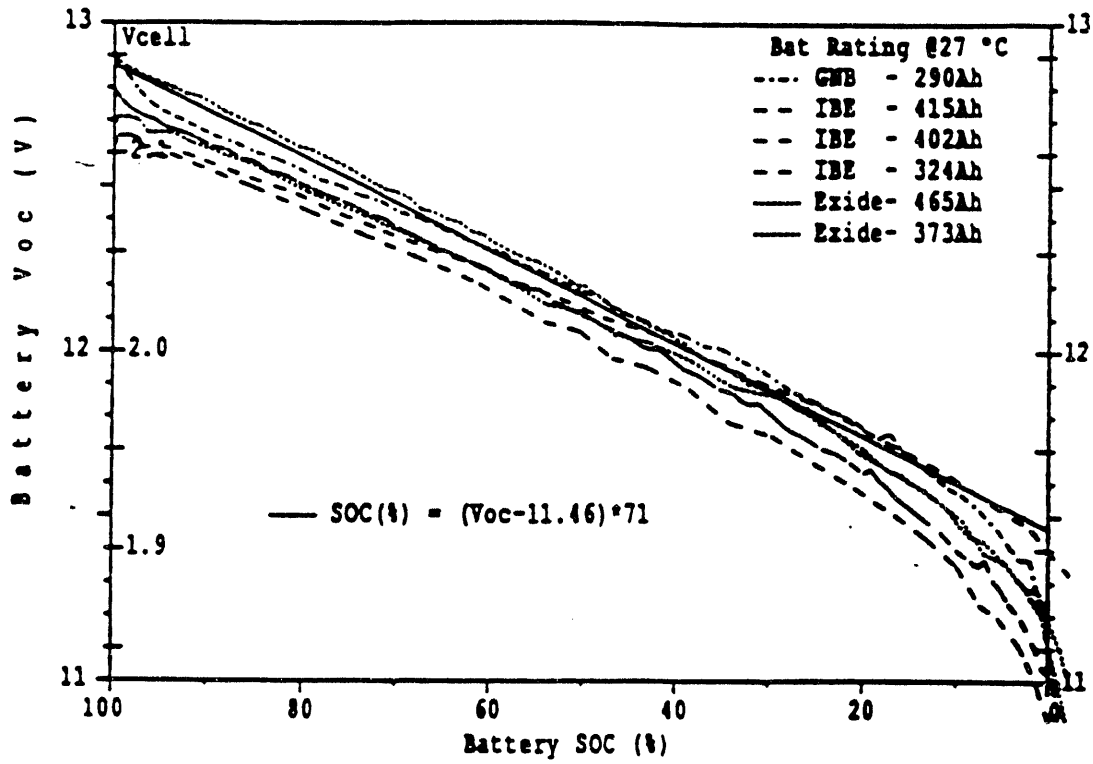

Figure 7. Battery State-of-Charge as a Function of the Battery Open-Circuit Voltage for Several Lead-Acid Batteries.

relationship can be used even as the battery capacity changes and decreases with time. Note, it may not yield valid SOC readings when individual battery cells begin to fail (i.e., when the battery voltage drops rapidly).

When making battery voltage measurements for determining SOC, they should be taken at night (or when the PV is off), when the battery is near room temperature, and when the compressor has been off for at least 1 hour. If the compressor cycle period is less than this time, the unit should be turned off in order to allow the battery voltage to stabilize. If measurements can only be made between cycles, the battery voltage may not be fully recovered and the operator should be aware of skewed values on the low side.

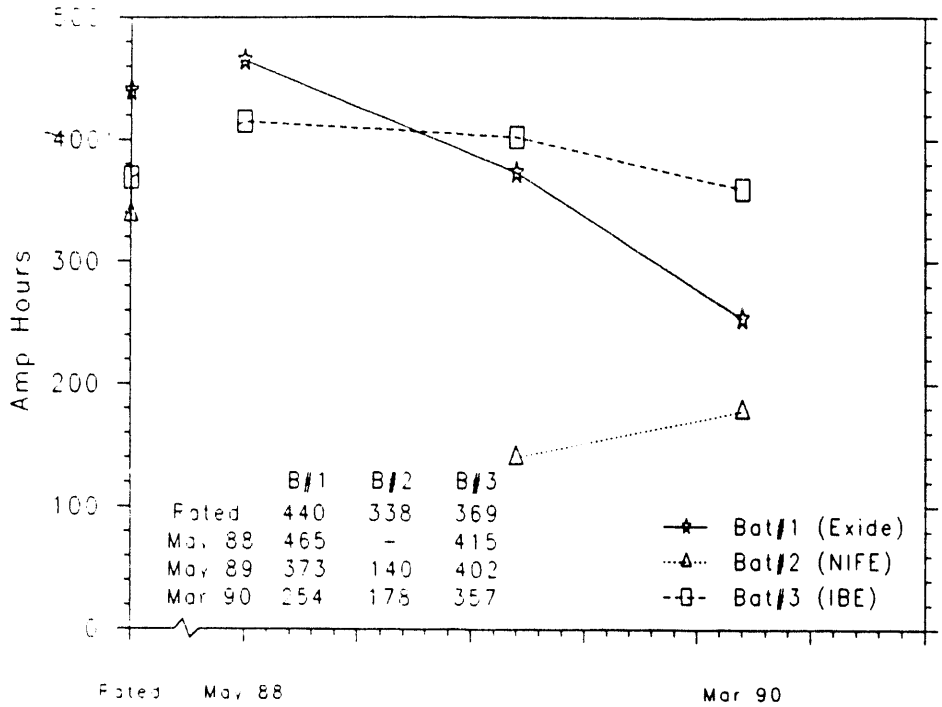

Figure 8. Battery Amp-Hour Capacities as Measured During the Last Two Years.

An historical plot of measured battery capacities is shown in Figure 8. The data points on the y-axis ordinate are manufacturer's ratings, not measured values. Initial measurements were not made because the emphasis at the start of the program was on testing the refrigerators. The figure shows that the lead-acid batteries (IBE and Exide) are showing a loss of capacity with age and that for the Exide batteries this loss of capacity is faster than for the IBE batteries. For the Marvel system, GNB absorbed electrolyte batteries were the original batteries. After 18 months, their measured capacity was about a third less than their rated capacity and they were replaced with Exide batteries. Therefore, the Exide batteries in Figure 8 have been in service 18 months less than the other two batteries shown.

The measured battery capacity of the ni-cd batteries (NIFE) was much less than its rated value. This may partially be the result of the series and parallel wiring of this battery system during its first 15 months of operation. As received, some of the jumper wires used to connect the battery cells in parallel were missing. This resulted in 6 of the 18 battery cells not being in the charge and discharge circuit. Once this was discovered, the proper jumper connections were made and the battery capacity tests were performed. Measurements in the following year showed only a slight change in the reduced capacity.

For the PV-powered refrigerators, this loss in battery capacity over time will require battery replacement at regular intervals to maintain the reliability of these systems. Further testing can more accurately determine the needed replacement interval, but it appears that this interval is less than 5 years for the lead-acid batteries tested. A replacement interval for the ni-cd batteries cannot be estimated from our test data.

An average, or round trip, battery Wh efficiency can be obtained by dividing the annual discharge Wh's by the annual charge Wh's. Based on the work performed to date, battery Wh efficiencies are about 75 percent and Ah efficiencies are about 85 percent.

3.3 Charge Controllers

Any PV-powered refrigerator system which uses a lead-acid battery must include a charge controller to protect the battery from excessive overcharging and deep discharges. Since there is a desire to limit the overall cost of a system, simple voltage comparator type controllers are typically used, which disconnect the array and the refrigerator at predetermined voltage setpoints. While no special effort was devoted to testing the

controllers, per se, it has been obvious that they generally do not perform as intended.

All of the controllers used in these systems base their disconnects on instantaneous voltage. Because these compressors use an ac motor with electronic dc commutation, significant ripple and surge voltages have been observed throughout these systems. This has caused (on numerous occasions) the arrays and the refrigerators to be cut off at inappropriate times, and has necessitated changes in the setpoints. This is a weak link in these systems, which should be addressed for improved system performance, for full battery utilization and proper protection, and to reduce the chances of unnecessary refrigerator disconnects.

The ni-cd battery bank has been stated as being able to take overcharging and deep discharges without damage, and therefore no controller has been used on the Sunfrost refrigerator system. However, based on the observed water usage (it has required annual watering), the use of a controller with the ni-cd batteries may be beneficial and warranted if the previously discussed controller problems are resolved.

SECTION 4 SUMMARY AND CONCLUSIONS

FSEC has completed the testing of three PV-powered vaccine refrigerator systems and one kerosene powered vaccine refrigerator. The PV-powered refrigerators were manufactured by Marvel, Sunfrost, and Polar Products. The kerosene refrigerator was manufactured by SIBIR.

The performance of the major components of these refrigerator systems was characterized and evaluated for a wide range of operating conditions. An energy consumption model was developed to accurately estimate the refrigerator electrical load. Using the electrical load given by the energy consumption model, designers and installers can optimize the sizes of the PV array and battery system.

From the testing and operation of these vaccine refrigerator systems, the following observations, recommendations, and conclusions are made:

1. All four refrigerators performed satisfactorily in fulfilling their primary function of vaccine refrigeration.
2. Room ambient temperature is the most important parameter in the energy consumption of the refrigerators. The second most important parameter is the amount of ice making performed.
3. Once the vaccine vials are cooled to the refrigerator temperature and the ice packs are frozen, the energy required by the refrigerators is practically independent of the quantity of vaccine in the refrigerator compartment or the quantity of ice in the freezer compartment.
4. Because the PV-powered refrigerators are thermostatically controlled, they have the capability to maintain proper vaccine temperatures with little or no operator intervention.

5. The PV-powered refrigerators were easier to maintain than the kerosene refrigerator. The flame height for the kerosene refrigerator required adjustment twice a day and its burner was cleaned weekly. Dirty kerosene may require the burner to be cleaned daily.
6. The kerosene refrigerator has the capability to make the most ice on a daily basis, but the flame height needs to be increased during ice making to prevent the vaccines from being warmed by the unfrozen icepacks.
7. The Polar Products refrigerator, with two compressors, performed the best in terms of maintaining vaccine temperatures, making ice, and operating under extreme environmental conditions.
8. The Sunfrost refrigerator was the most energy efficient, but it had difficulty making the WHO prescribed amount of ice on a daily basis.
9. Holdover times can be increased by up to a factor of 6 if frozen icepacks are stockpiled in the freezer and then placed in the refrigerator compartment when the refrigerator's power is lost.
10. The kerosene refrigerator needs to be installed in a well ventilated room. Even with good ventilation, the kerosene fumes and the exhaust fumes from the burner are noxious and make working and living conditions unpleasant.
11. With the exception of the their thermostats, the PV-powered refrigerators operated reliably. The Marvel thermostat was replaced after 22 months of operation and the Sunfrost thermostat was replaced after 40 months of operation.
12. The PV arrays have operated reliably and their power output has not degraded, but their power level was less than rated by the PV module manufacturers. Realistic module performance should be used for design purposes.

13. Experience with most of the batteries has been disappointing in terms of both capacity and expected lifetime. The IBE (forklift) batteries showed the best capacity and expected lifetime. Battery life is the main factor in limiting the successful long-term operation of these systems.
14. The reaction of the charge controllers to voltage fluctuations during compressor motor operation caused the disconnection of the PV arrays or the refrigerators at inappropriate times. Charge controller technology needs to be advanced and meaningful design and performance standards need to be established.
15. The PV-powered vaccine refrigerators have additional components that are new to operators. Consequently, operator training is important.

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Strategic Plan
Corporate Action Tracking Sheet

Action:

_____

_____

_____

Champion: _____ **Org:** _____ **Phone:** _____

Operational Plan: (Which of the 7 core teams/operational plans includes this action?)

_____

Description of Action to include What, Why, How and Benefits such as cost savings/avoidance, budget savings, reduce cycle time, increase federal direction, etc.

_____

_____

_____

_____

_____

_____

_____

_____

Team Members (Individuals responsible for completing this action)

_____	_____	_____
_____	_____	_____
_____	_____	_____

Strategic Plan
Corporate Action Tracking Sheet

Key Milestones (list all key steps necessary to successfully complete the action)

Milestone	Date

Issues/Concerns/Barriers to completing action

_____

_____

_____

_____

_____

_____

_____

Strategic Plan
Corporate Action Tracking Sheet

Metrics to track the completion of action (include metrics used in AL's Strategic Plan)

DATE

FILMED

7/13/94

END