RESEARCH AND DEVELOPMENT ✦ RECHERCHE ET DÉVELOPPEMENT

DEFENSIO PER SCIENTIAM

# INVESTIGATION OF A PHOTOVOLTAIC/BATTERY HYBRID SYSTEM FOR POWERING THE HIGH ARCTIC DATA COMMUNICATIONS SYSTEM

## FINAL REPORT

by

C.L. Gardner

Research & Development Branch

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CRAD REPORT
NO. 2/89



Canada

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## 1.0.0 INTRODUCTION

The High Arctic Data Communications System (HADCS) was established to provide reliable communication between CFS Alert and Ottawa. This system includes a ground link from Alert to Eureka and a satellite link from Eureka to Ottawa. The ground link is necessary because Alert is over the horizon with respect to suitable satellites in stationary orbit.

HADCS includes six unmanned microwave repeaters that are located on the top of mountains between Alert and Eureka. Typical power requirements for these sites are given in Table 1. These repeater stations are powered at the present time using SAFT 608Z 2000 Ah air depolarized (zinc-air) primary cells. Each repeater has two banks of batteries; one prime and one backup with 8 to 10 battery boxes of 14 cells in each box. Cell and battery data are given in Table 2.

Annual battery maintenance is required. Each summer the prime battery bank is removed, the existing back-up bank is taken into active service (i.e., becomes the prime bank) and a fresh set of batteries is installed as the back-up bank. The old set of batteries has to be removed for disposal. Because of the remoteness of the HADCS sites and the weight of the battery system (about 2 tons per site), replacement of the batteries is a major operation. It takes about 3 weeks and involves approximately 25 people as well as the use of one or two Chinooks and two twin Huey helicopters during this period.

**TABLE 1**

**HADCS POWER REQUIREMENTS**

| | |
|---|---|
| NOMINAL VOLTAGE: | 15V (10V MIN TO 18V MAX) |
| CURRENT DRAIN: | 2 A CONTINUOUS |
| OPERATING TEMPERATURE: | -55°C to +30°C |
| DURATION: | MINIMUM 1 YEAR UNATTENDED |

## TABLE 2

## CHARACTERISTICS OF EXISTING BATTERY SYSTEM

| | | |
|---|---|---|
| 1. | CELL DATA: | (608Z ZINC-AIR) |
| (A) | Manufacturer: | SAFT, |
| (B) | Capacity: | 2000 AH |
| (C) | Voltage: | 1.2 V |
| (D) | Weight: | 14 kg (WET)<br>9.5 kg (DRY) |
| (E) | Volume: | 12.3 $dm^3$ |
| 2. | BATTERY SYSTEM DATA | |
| (A) | Configuration: | 10 Parallel Strings of 14 Cells in Series |
| (B) | Battery Weight: | 1960 kg |
| (C) | Battery Volume: | 1722 $dm^3$ |
| (D) | Cost: | $10 K |

An analysis of the cost of battery replacement at the HADCS sites has been made by DCEM (1). A summary of these findings is given in **Table 3**. From these results it is seen that the capital cost of the batteries is less than 10% of the total battery replacement costs.

## TABLE 3

### ANNUAL HADCS POTASH BATTERY REPLACEMENT

### SUMMARY OF COSTS (1983 $)

| | | | | |
|---|---|---|---|---|
| 1. | PURCHASE OF BATTERIES | | $ 60 K | |
| 2. | DELIVERY OF BATTERIES | | $ 66 K | |
| | | | SUB-TOTAL | $126 K |
| 3. | SUPPORT AIRCRAFT | | | |
| | (A) FLYING TIME | | | |
| | | (I) CHINOOK | $350 K | |
| | | (II) HUEY | $214 K | |
| | | (III) TWIN OTTER | 20 K | |
| | (B) DELIVERY OF FUEL | | 13 K | |
| | (C) LANDINGS AT EUREKA | | 24 K | |
| | | | SUB-TOTAL | $621 K |
| 4. | BATTERY EQUIPMENT MAINTENANCE | | | 3 K |
| 5. | SUPPORT CAMP | | | 80 K |
| | | | TOTAL | $830 K |

The high cost of using the air depolarised cells as a power supply for HADCS resulted in DREO being tasked by DCEM in 1983 to look at alternative, less expensive options. A summary of the Aim and Work Plan of this task (DCEM 58), which updates a previous DREO study done in 1978(2), is given in Table 4.

The initial studies at DREO covering Phases I and II have been reported previously (3). These studies indicated the feasibility of using a photovoltaic/rechargeable battery hybrid system to power the HADCS system during the six summer months. In order to demonstrate the feasibility of this concept it was recommended that the work outlined under Phase III of this task (Table 4) be carried out.

## TABLE 4

## UNATTENDED ARCTIC POWER SYSTEMS

**AIM:** To investigate, procure or develop and finally test an alternative power source to the current Potash Batteries which, while meeting all existing operational and equipment requirements, will allow for realization of savings in overall operating/maintenance costs.

**WORK PLAN**

PHASE I Review previous study (DREO Report # 787) and update the report to include new power sources that have become available since that time.

PHASE II Make recommendations for the procurement or development of an alternate system.

PHASE III

a. Evaluation of a Photovoltaic/Battery System for HADCS.

1. Installation and evaluation of a 7.5 watt (continuous) photovoltaic system at Alert. The performance of the solar panels, batteries and other components will be monitored closely at this experimental site. Ambient Temperature and incident solar radiation data will also be collected.

2. Installation of a 30 watt (continuous) photovoltaic system at one of the project Hurricane sites. The system will be monitored using existing telemetry or possibly by the installation of amp-hour meters.

3. Evaluation of the low temperature performance of Willard DH-5 pure lead batteries.

b. Evaluation of the low temperature performance of 608Z zinc-air batteries after prolonged storage.

The performance of aged 608Z zinc-air cells will be monitored at the test site at Eureka. These evaluations will be designed to test the ability of the 608Z cells to provide a 4 year shelf life the operating conditions of HADCS. Cells will be tested during the winter season and left on open circuit during the summer.

PHASE IV

a. Installation and evaluation of a power transfer switch at the HADCS site on Blacktop Ridge.

b. Evaluation of the performance of a 400 watt photovoltaic/ battery system at Blacktop Ridge.

This report describes the results of experiments carried out to address these questions during the period from 1984 until 1988 and represents the final report for Task DCEM 58.

# 2.0.0 EXPERIMENTAL

## 2.1.0 Photovoltaic/Battery Installations

### 2.1.1 General Considerations

Photovoltaic panels coupled with a lead-acid battery storage system have been used successfully to power many remote installations. The Canadian Coast Guard now has about 2000 such installations in service in Canada. These systems have proven to be extremely reliable and cost effective. For applications in the Arctic a photovoltaic system can only be used during the summer season. The solar radiation data (4) for Alert given in Figure 1 demonstrates this vividly. Solar energy has, however, been used successfully (5) by the Coast Guard to power seasonal range lights at Resolute. This system has operated reliably for 9 years without significant degradation. The system is turned on April 15 and off September 28.

Resolute, which is located at 74°40'N, has environmental conditions very similar to Alert and Eureka. Summer temperatures rarely rise above +10°C and, in winter, temperatures down to -50°C are not uncommon. Blowing snow and ice storms are frequent in winter accompanied by strong winds. The Coast Guard range lights are in an exposed location and are subjected to these extremes.

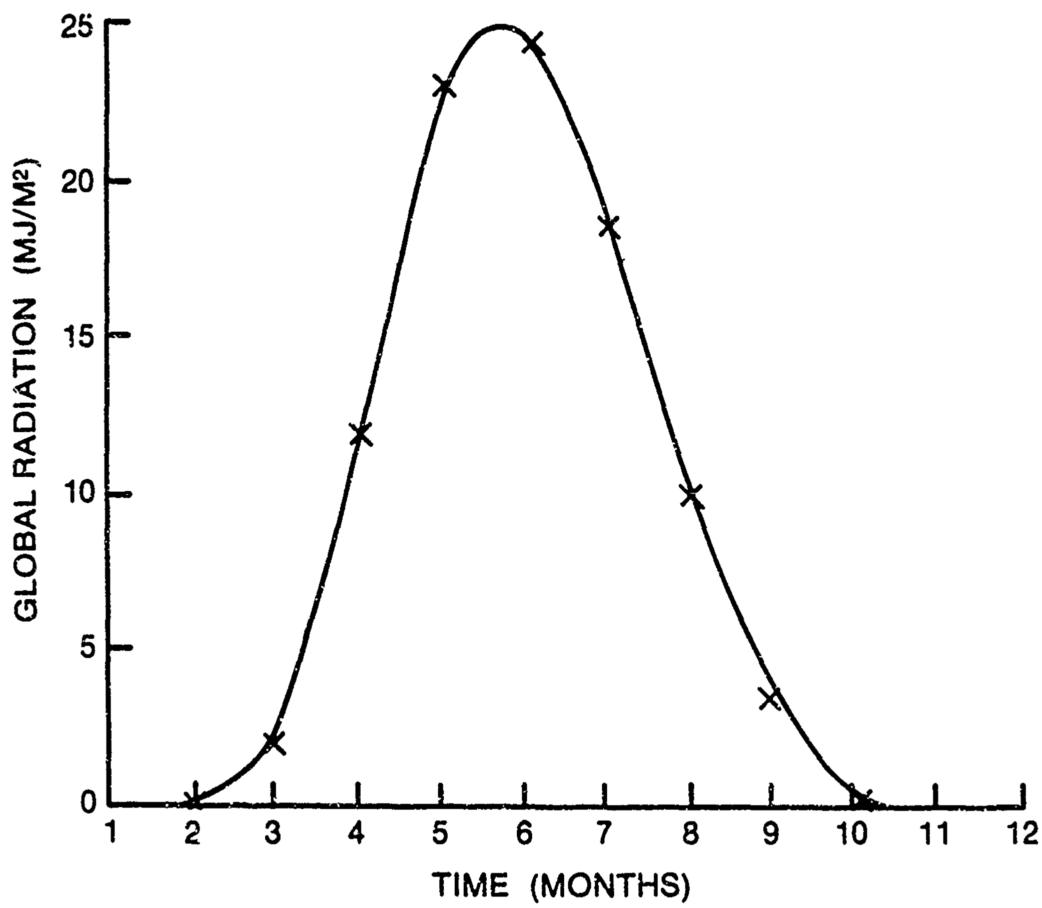


Figure 1. Intensity of Solar Radiation at Alert

In order to meet their requirements, the Coast Guard have written rigorous specifications and demand that manufacturers qualify their products before they are used. Solar panels and regulators are covered by Coast Guard Specifications MA 2055. Amongst other things, the specification requires an operating temperature range of -60°C to +40°C, that the panels and mountings be designed to withstand wind loadings of up to 175 km/h from any horizontal direction and a guaranteed life of 5 years although normally 10 or more years are expected. At the present time only 3 solar panel manufacturers have demonstrated the ability to meet this specification. These manufacturers are Solarex, ARCO, and Solar Power Corp. At the present time, only Solarex manufactures a regulator incorporating the fail-safe features required by the specification.

The requirements for the lead-acid rechargeable batteries for photovoltaic system are defined in Coast Guard Specification MA 2072. The only battery that has been qualified at the present time is the Exide DH-5 Charge Retaining Battery. This battery has a self-discharge rate of less than 1% per month at 25°C.

Discussion with Mr. S. Leung, Marine Aids Division, Canadian Coast Guard, and with Mr. R. Gibson of Solarex Corp. indicated that it should be possible to power the HADCS system for six months of the year (15 March to 15 September) using a solar photovoltaic system.

The size of the system needed to provide 30 watts continuous during this six-month period was estimated by S. Leung (5) to be 320 watts (peak) output of the panels with 2000Ah lead-acid battery storage capacity and to be 400 watt (peak) output with 670Ah storage capacity by Solarex (7,8). The estimate made by Solarex was based on the assumption that the battery could be allowed to drop as low as 30% of its capacity. Because of the extremely low temperatures that will be encountered this is considered unacceptable. At -40°C, the battery electrolyte, will freeze when more than 30% of the capacity is removed (i.e. $<$ 70% state of charge). For this reason a much larger capacity was considered essential.

Based on the estimates given above, a 400 watt (peak) solar array with a 2000Ah battery was selected for initial evaluation for the HADCS sites. This system is considered to be conservatively sized; however, it is important that the capacity of the array be sufficient to bring the batteries back to a near fully charged state before the end of the solar season to prevent the lead-acid batteries from freezing during the winter.

Positioning of the solar array in high Arctic is not completely straight forward. To minimize the size of the system, it should be oriented to optimize solar energy collection in the spring and the fall. Using hourly solar energy data for Alert (4) it can be shown that most of the solar energy is received from the southerly quadrant. From this observation it was concluded that the solar array should face due South.

The maximum altitude of the sun above the horizon is about 10° for March and September. It is therefore concluded that the solar array angle should be 80° (i.e., angle from the horizontal) to optimize energy collection during the spring and fall. It should be pointed out that an 80° array angle does not optimize total energy collection over the entire solar season. Solarex have calculated (8) this angle to be about 60°.

### 2.1.2 80 Watt Photvoltaic/Battery System

An 80 watt photovoltaic/battery system consisting of two Solarex SX-120 40 watt solar panels built to CCG Specification 2055, seven Exide DH-5 500 Ah lead-acid cells and a Solarex CCG014-80 shunt regulator was installed (Fig 2) at the HADCS shelter at Alert in June 1984. The array was installed at an angle of 80° to the horizontal and facing due south.

Although the solar panels were nominally rated at 12V it was decided to run this system as a 14V system because the normal cut-off for the HADCS system is 12.8V. To accomplish this, minor modifications were made to the voltage regulator following advice from the manufacturer and a string of seven lead-acid cells was used. Because the voltage of solar panels increase with decreasing temperature, no problems were anticipated in running the photovoltaic system at this higher voltage in view of the low ambient temperatures encountered at the HADCS sites.

Instrumentation was installed to monitor the performance of the system as completely as possible. The data collected is shown in Table 5. All of the data was

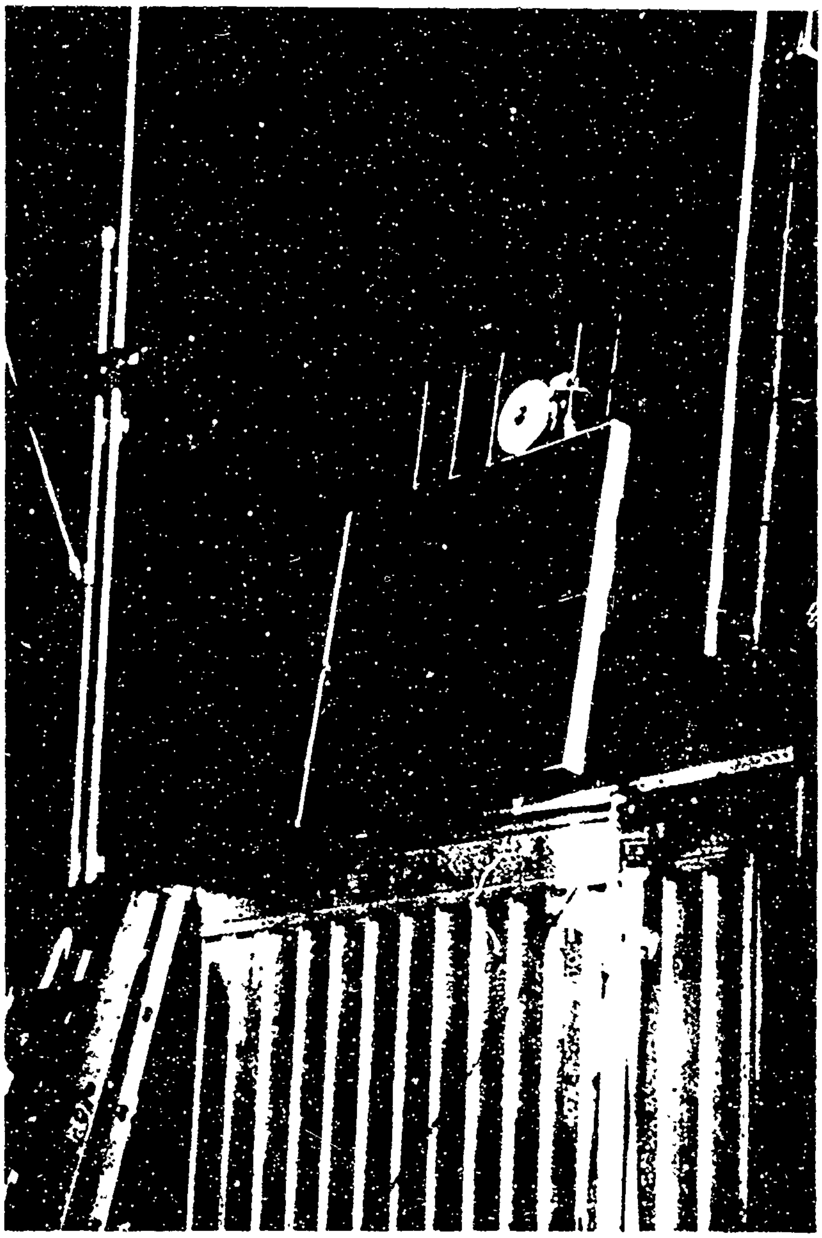

Figure 2 80 Watt PV/Battery System

sampled every 5 minutes using a Fluke 2280A data logger and hourly averages were stored on magnetic tape. For the three year period from June 1984 until June 1987, data tapes were removed and replaced each month by the technical staff at CFS Alert and sent to Ottawa for analysis. All of the equipment operated reliably during this period with minimal loss of data. During the period from March 15 to Sept 15 each year the lead-acid battery was discharged into a 30.9ohm resistive load or at about 0.5A. During the winter period from Sept 15 to March 15 each year the resistive load was disconnected. The timing circuit resulted in a small discharge (approximately 13mA) during this period.

TABLE 5

PARAMETERS MEASURED - 80 WATT PV/BATTERY SYSTEM

1. Ambient Temperature
2. Battery Temperature
3. PV Array Temperature
4. Wind speed
5. Solar radiation intensity - horizontal surface
6. Solar radiation intensity - plane of array
7. PV Array Voltage
8. Current out of array
9. Power out of array
10. Battery voltage
11. Current into battery
12. Power into battery

### 2.1.3 400 Watt Photovoltaic System (Mt Grant)

A full sized 400 watt photovoltaic system was installed on the side of the microwave tower **(Figure 3)** at the HADCS site on Mt. Grant in June 1984. This system was operated until June 1986 when it was dismantled. The main purpose of this installation was to test the capability of the photovoltaic system to withstand the environmental conditions encountered at the remote sites. It was known that extremely high winds and very low temperatures are sometimes encountered.

Figure 3    Mt Grant Solar Installation -

Limited monitoring of this system was also carried out. No battery s orage was included with this system and the output of the a ay was connected directly to a 2 ohm load. Since the max. am voltage of the array is about 20 volts, this limits tne output of the array to about 200w. The total output of the array was measured using an AGA 481.001.000 amp-hour meter. As this meter does not operate when the input voltage is less than 10 volts, the output of the array was also not measured for output powers less than about 50 watts. The output measured by the amp-hour meter is expected to be significantly lower than the true output. Readings of system output were taken each year during visits for site maintenance.

**2.1.4 400 Watt Photovoltaic/Battery System. CFS Alert.**

A 400 watt photovoltaic system consisting of 10 Solarex SX-120 40 watt solar panels, a 2000 Ah battery bank consisting of 4 parallel strings of seven Exide DH-5 500 Ah cells and two Solarex CCG012-250 regulators modified to give a charging voltage of 16.8V at 20°C was installed **(Fig 4)** at the HADCS shelter at CFS Alert in June 1985. This system was installed primarily to examine the interfacing of a full sized PV system with the radio repeaters at the Alert end of the HADCS microwave link. Operational data was collected using the Fluke 2280 A data logger for the period from June 1985 until June 1987. This 400 watt system was dismantle in June 88.

The system was designed to power the radio repeater system using the PV/battery system during the period from March 15 to September 15 and switch back to AC power provided by the CFS Alert utility system during the period from September 15 to March 15.

**2.1.5 400 watt photovoltaic/battery system. Blacktop Mt.**

A 400 watt photovoltaic/battery system consisting of the 400 watt array that had previously been installed on Mt Grant, a 2000Ah battery bank consisting of 10 parallel 14V strings of Exide DD-5 cells and custom built shunt regulator and switching electronics built under contract by Diversitel Commmunications was installed in June 1987 (Fig 5 & 6).

This system was designed to address the difficult problem of integrating a PV power system with the existing primary battery power supply without compromising reliability.

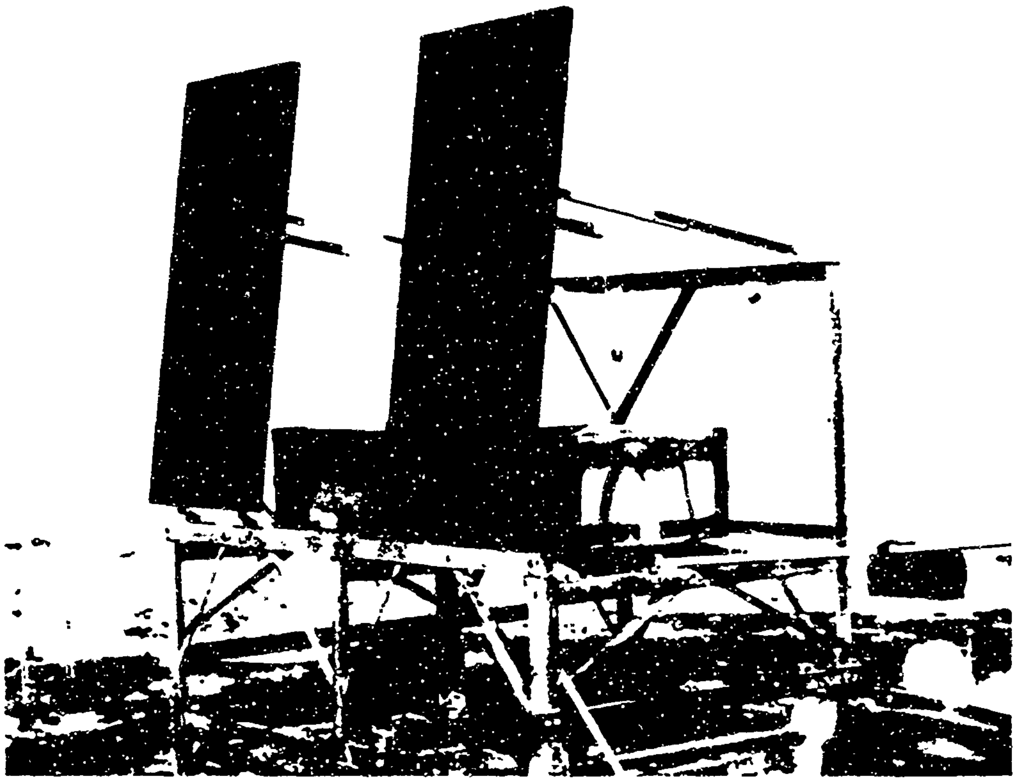

Figure 4 400 Watt PV/Battery System at Alert

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FIGURES 5, 6

In the interface system that was installed (9) a simple switch selects the solar or primary battery power source. All timing is derived from a microprocessor and clock/calendar. The control strategy is based on the date and indications of shunt current and low-battery voltage. The power switch requires a continuous stream of pulses in order to connect the load to the photovoltaic system. In the absence of this pulse stream, the power source reverts automatically back to the primary power source.

This power supply system was installed in June 1987 and has supplied all of the power consumed by the repeaters from 13 Jun to 07 Oct 87 and from 19 Feb 88 to 7 Jun 88.

Data were formated by the microprocessor and transmitted to Eureka using an FM telemetry system operating at 164 MHz. The telemetry receiver and Hyperion computers were installed in a heated shelter located at the south-east corner of the battery building at Eureka. Data transmitted includes date, time, storage battery voltage, pyranometer voltage, hours since last shunt current and status bits which indicate shunt current, low battery voltage and season. All of the data was stored on floppy disks which were removed by AES staff and sent to Diversitel Communications for analysis each month.

### 2.2.0 Discharge Characteristics of Aged SAFT 608Z Zinc-Air (Air-Depolarised) Batteries.

The use of a photovoltaic/battery hybrid system for powering the HADCS remote sites for 6 months during the summer will extend the life of the zinc-air batteries from one to two years. If the present practice of providing a back-up battery system is continued, then the SAFT 608Z cells would be on standby for two years before being taken into service and they would be four years old before being completely discharged. This period is beyond the manufacturers claim of a three-year shelf life after activation. Because of the low ambient temperatures at the HADCS sites, it was considered likely that the batteries would remain operational for the four year period.

To test the ability of the zinc-air batteries to operate over a four-year period, a battery made up of 14 SAFT 608Z cells that had been activated in 1982 and then left on open circuit were discharged into 74.3 ohm resistive load during the period from 15 Sep 84 to 15 Mar 85 and from 15 Sep 85 until 17 Jan 86 when the battery voltage had dropped to 3.0V. Voltage readings were taken weekly by technical staff from the AES weather station at Eureka. The battery was placed outside at the rear of the battery building at Eureka.

## 2.3.0 Low Temperature Recharge of Exide DH-5 Lead-Acid Cells

Because of concern regarding the ability of the lead-acid batteries to store the output from the solar panels at the low temperatures encountered in the spring (March) when the system becomes operational following the winter period, the low temperature performance of the Exide DH-5 cells was measured at -40°C. This work was carried out by Cominco Research Centre under Contract (10).

In these tests the specific gravities, cell voltages and plate potentials of four test cells were measured as received. The cells were then given a boosting charge at 2.30V for 60 hr and 2.5V for 5 hrs following which they were discharged at 6.4A to 1.9V to determine initial capacities. Three of the cells were then cooled to -40°C and the cells were then cycled according to the conditions shown Table 6.

**TABLE 6**

**Cycling Test Conditions for the Four Exide DH-5 Cells**

| Cell # | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Cycling Temperature, °C | -40 | -40 | -40 | 20±2 |
| Charging Period | | | | |
| Voltage, V | 2.65 | 2.70 | 2.75 | 2.40 |
| Maximum Current, A | 4.0 | 4.0 | 4.0 | 4.0 |
| Time, h | 8 | 8 | 8 | 8 |
| Discharging Period | | | | |
| Current, A | 1.0 | 1.0 | 1.0 | 1.0 |
| Time, h | 12 | 12 | 12 | 12 |

NOTE: There was a rest period of 5 minutes after each charge and discharge period.

## 3.0.0 RESULTS

### 3.1.0 Performance of the Photovoltaic Systems

#### 3.1.1 80 Watt PV/Battery System

As outlined previously, this system operated reliably during the three year period from June 1984 to June 1987. The battery voltage and power delivered to the load during this period are illustrated in Fig 7 and 8. These results show that the voltage has remained in the 14.0-17.0V range and that the power of approximately 7.5 watts has been delivered reliably during the summer periods. The charge remaining in the battery during this period can be calculated using the data for the current being put into the battery and the current being taken out by the load. These results are shown in Fig 9. In making this calculation a charging efficiency of 96% was assumed.

Fig 9 shows that, for most of this three- year period, the battery has remained more than 80% charged. The capacity remaining dropped to about 250 Ah at the end of the first winter (March 85). While this decrease is larger than one would like it should be noted that the array is smaller than one quarter of the recommended full sized array (400w) while a one quarter load has been used. In addition the solar radiation received in the summer of 1984 was abnormally low. This is seen in Table 7 which compares the solar radiation data received during this three year period with the 30 year averages recorded by AES at Alert. From this table, it is seen that in 1984 all months except August were below average and that July and September were more than two standard deviations below the 30 year average.

A summary of the overall performance of the 80 watt system is given in Table 8.

From the data presented it has been shown that the 80 watt PV/battery system worked reliably during this three year period in- spite-of the fact that the solar panel was 25% undersized and that exceptionally poor weather was encountered. It should also be noted that solar radiation intensities at Alert are expected to be lower than at the remote HADCS sites. Advection fog is a common phenomenon in the Alert area during the summer months (June to-August) when open water occurs. The remote HADCS sites are not generally subject to these foggy conditions as they are at higher altitude and further in land.

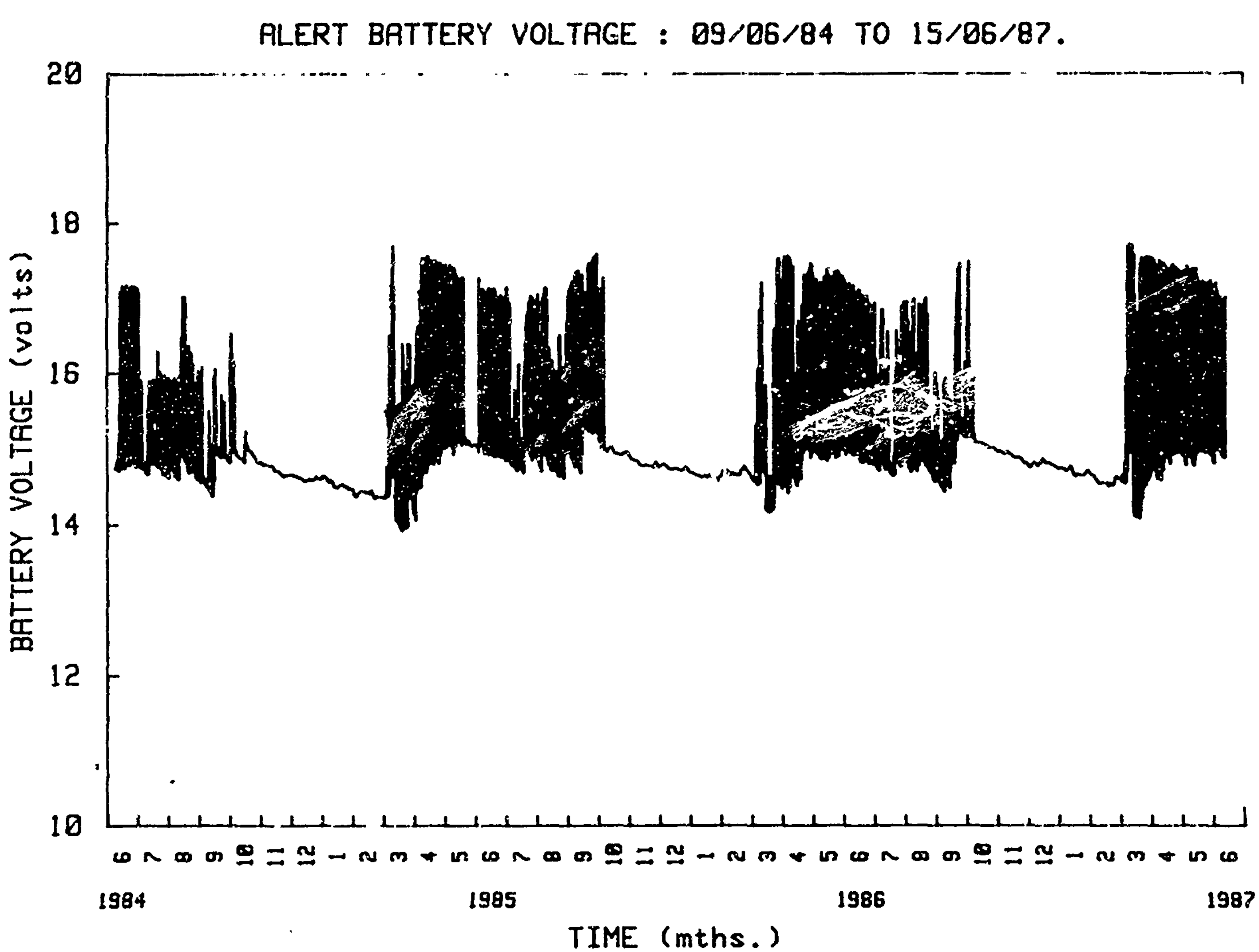



Figure 7 Battery Voltage: (80 Watt System)

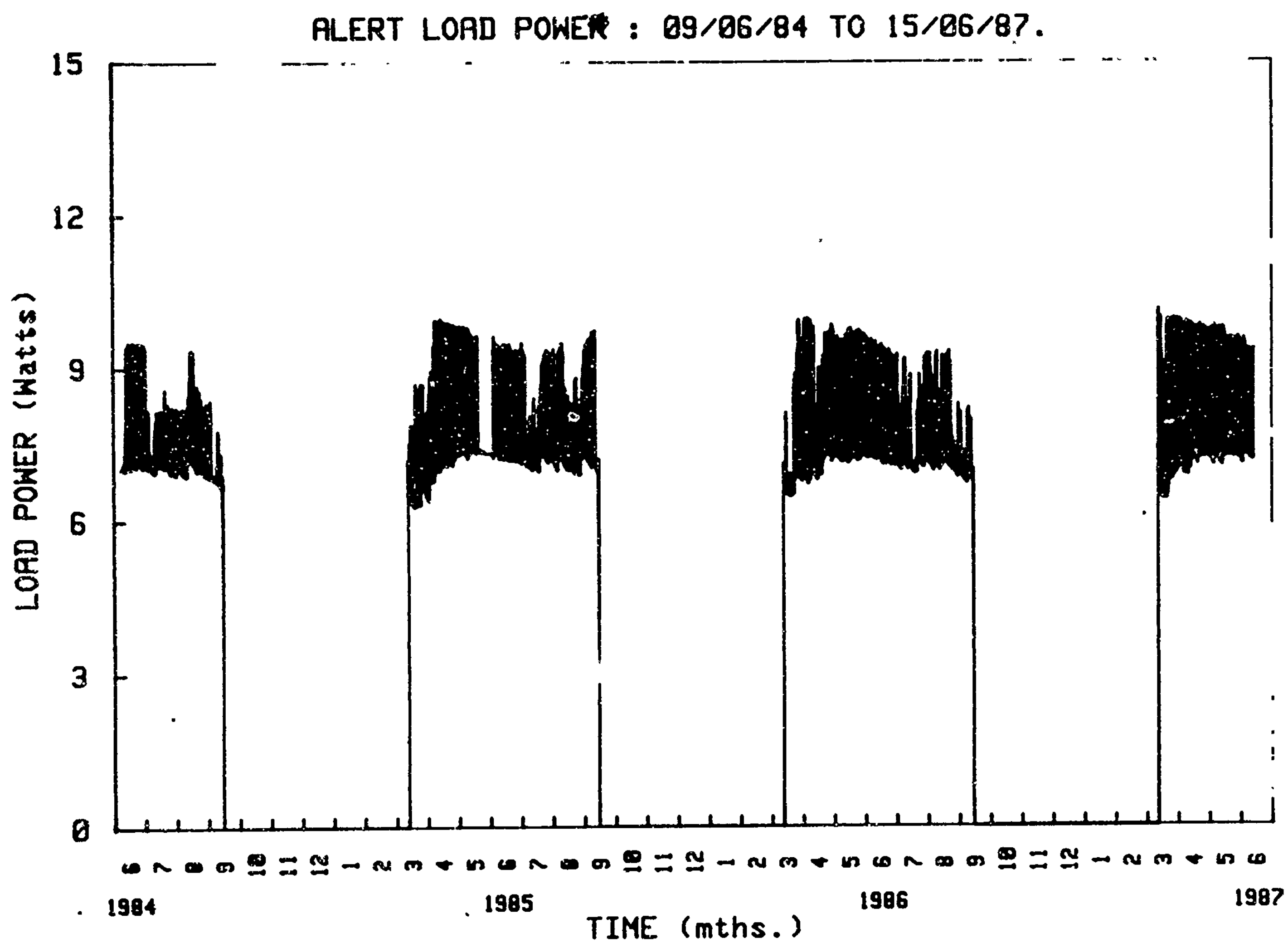



Figure 8 Load Power: (80 Watt System)

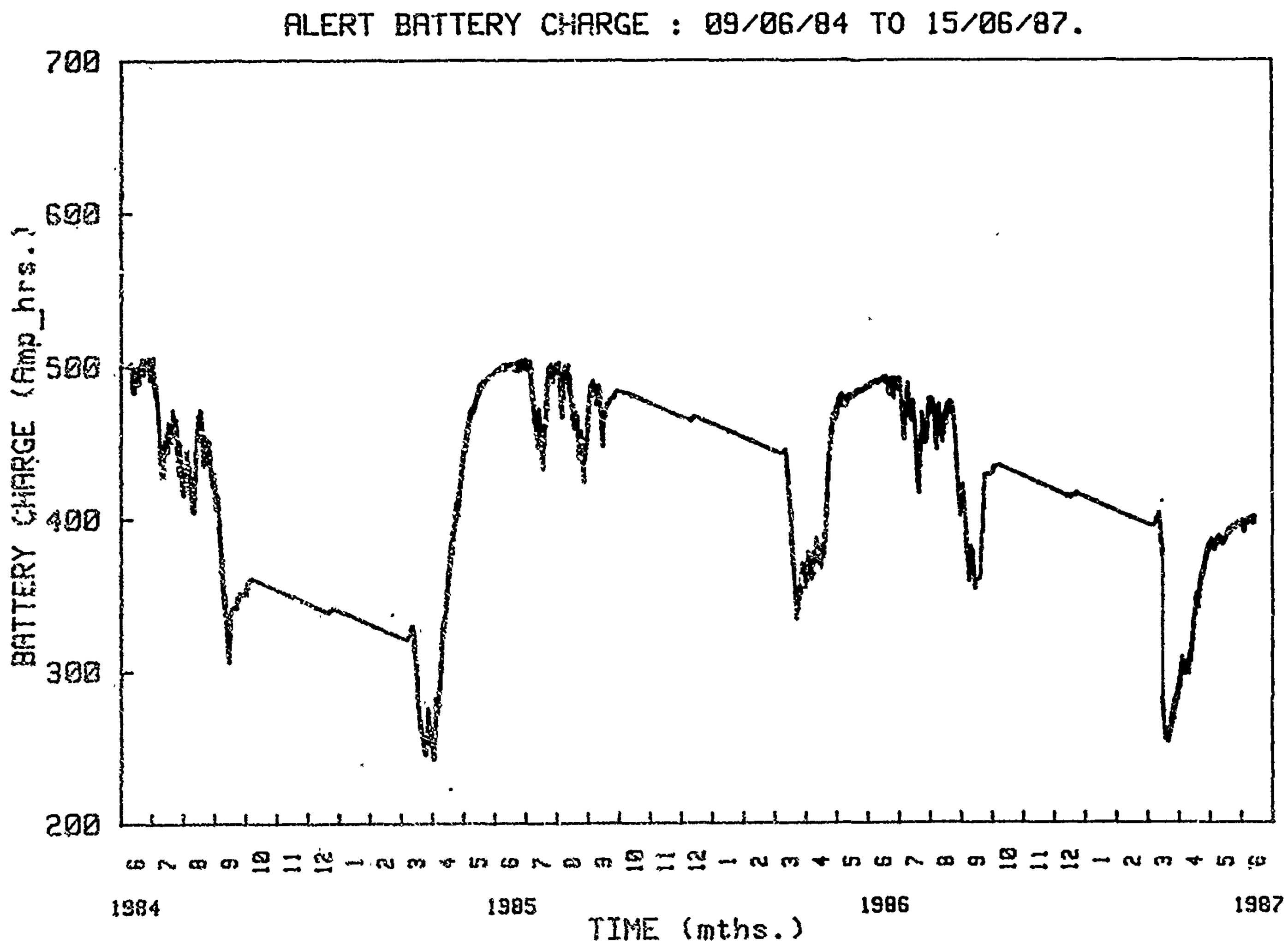



Figure 9 Battery Charge: (80 Watt System)

## TABLE 7

## SOLE RADIATION INTENSITIES: 1984-1987

| MONTH | EXPERIMENTAL MEAN ($KW/m^2$) | 30 YEAR MEAN ($KW/m^2$) | 30 YEAR STD. DEV. | DELTA EXP. - 30 YEAR |
|---|---|---|---|---|
| 1984 | | | | |
| JUNE | 0.253 | 0.287 | 0.022 | -0.052 |
| JULY | 0.185 | 0.220 | 0.021 | -0.035 |
| AUGUST | 0.133 | 0.124 | 0.019 | 0.009 |
| SEPTEMBER | 0.036 | 0.042 | 0.006 | -0.006 |
| OCTOBER | 0.003 | 0.004 | 0.001 | -0.001 |
| 1985 | | | | |
| MARCH | 0.018 | 0.024 | 0.002 | -0.006 |
| APRIL | 0.138 | 0.138 | 0.009 | 0.000 |
| MAY | 0.277 | 0.265 | 0.014 | 0.012 |
| JUNE | 0.299 | 0.287 | 0.022 | 0.012 |
| JULY | 0.232 | 0.220 | 0.021 | 0.012 |
| AUGUST | 0.138 | 0.125 | 0.019 | 0.013 |
| SEPTEMBER | 0.054 | 0.042 | 0.006 | 0.012 |
| OCTOBER | 0.002 | 0.004 | 0.001 | 0.002 |
| 1986 | | | | |
| MARCH | 0.027 | 0.024 | 0.002 | 0.003 |
| APRIL | 0.132 | 0.138 | 0.009 | -0.006 |
| MAY | 0.243 | 0.265 | 0.014 | -0.022 |
| JUNE | 0.268 | 0.287 | 0.022 | -0.019 |
| JULY | 0.201 | 0.220 | 0.021 | -0.019 |
| AUGUST | 0.137 | 0.125 | 0.019 | 0.012 |
| SEPTEMBER | 0.039 | 0.042 | 0.006 | -0.003 |
| OCTOBER | 0.002 | 0.004 | 0.001 | -0.002 |
| 1987 | | | | |
| MARCH | 0.023 | 0.024 | 0.002 | -0.001 |
| APRIL | 0.132 | 0.138 | 0.009 | -0.006 |
| MAY | 0.263 | 0.265 | 0.014 | -0.002 |

## TABLE 8

## PERFORMANCE SUMMARY - 80 WATT PV SYSTEM

| Month | Load power (Watts) | Array Power (Watts) |
|---|---|---|
| **1984** | | |
| JUNE | 7.603 | 12.114 |
| JULY | 7.292 | 7.525 |
| AUGUST | 7.310 | 8.761 |
| SEPTEMBER * | 6.888 | 2.451 |
| **1985** | | |
| MARCH ** | 6.763 | 3.213 |
| APRIL | 7.724 | 16.812 |
| MAY | 8.383 | 24.150 |
| JUNE | 8.063 | 17.352 |
| JULY | 7.553 | 11.973 |
| AUGUST | 7.428 | 9.422 |
| SEPTEMBER * | 7.672 | 7.669 |
| **1986** | | |
| MARCH ** | 7.018 | 3.007 |
| APRIL | 7.628 | 13.603 |
| MAY | 8.176 | 17.746 |
| JUNE | 8.038 | 15.774 |
| JULY | 7.389 | 9.461 |
| AUGUST | 7.456 | 9.618 |
| SEPTEMBER * | 6.996 | 4.864 |
| **1987** | | |
| MARCH ** | 7.126 | 4.843 |
| APRIL | 8.007 | 19.120 |
| MAY | 8.231 | 21.852 |
| JUNE | 8.098 | 19.623 |

** calculated from the 15th though the 30th.

* calculated from the 1st through the 15th.

During the three-year period that this system was in operation regular maintenance checks were made on the battery. These checks consisted of a measurement of the electrolyte level and the specific gravity. A summary of these results is included in Table 9. During the period of operation electrolyte loss was minimal and no water addition to the electrolyte was needed. The specific gravity readings indicated that stratification of the battery electrolyte took place during operation. Initial specific gravity readings were always considerably lower than those taken after agitation to mix the electrolyte. This indicates that the amount of gassing is insufficient to keep the electrolyte stirred.

TABLE 9

ELECTROLYTE SPECIFIC GRAVITY AND LEVEL MEASUREMENTS

| Cell #2 | Specific Gravity | Electrolyte Level |
|---|---|---|
| Jun 84 | 1.30 (20°C) | -0.25 |
| Jun 85 | 1.28 (1°C) | - |
| Jun 86 | $1.28^{5}$ (1°C) | -0.25 |
| | $1.29^{5}$ (after stirring) | |
| **Cell #5** | | |
| Jun 84 | 1.30 (20°C) | -0.25 |
| Jun 85 | 1.28 (1°C) | - |
| | 1.30 (after stirring) | - |
| Jun 86 | 1.28 (1°C) | -0.25 |
| **Cell #4** | | |
| Jun 84 | 1.30 (20°C) | -0.25 |
| Oct 84 | 1.25 (20°C) | - |
| Jun 85 | 1.28 (1°C) | - |
| Jun 86 | $1.28^{5}$ (1°C) | -0.25 |

### 3.1.2 400 Watt Photovoltaic System - Mt Grant

Installation of a 400 watt array on Mt. Grant demonstrated that the mounting recommended by the manufacturer was simple to install onto the microwave tower and rugged. The array withstood the environmental extremes without any signs of deterioration. Limited monitoring of the system was also carried out. This consisted of an annual reading of the output current from the array. The results of these measurements are shown in Table 10. This table also includes the calculated output (Ah) per hour of operating time which is defined as the number of operating hours during the period from March 15 to September 15. Based on these results it is seen that the array output over the two-year period that the system was installed was approximately 3.6 Ah per operational hour. This can be compared with a requirement for powering the microwave repeaters of about 2Ah/hour assuming a system voltage of 15V.

TABLE 10

PERFORMANCE OF 400 WATT PHOTOVOLTAIC SYSTEM - MOUNT GRANT

| Date | Time | Operational Hours | Total Amp-Hours | Ah/ Operational Hour |
|---|---|---|---|---|
| 15-06-84 | 14:25 | 0 | 0 | 0 |
| 01-07-84 | 23:30 | 393 | 1420 | 3.61 |
| 05-06-85 | 11:07 | 4148 | 12840 | 3.09 |
| 03-06-86 | 14:18 | 8495 | 30250 | 3.56 |

As mentioned previously, because of the limitations of the monitoring electronics, not all of the array output is being measured. It is thus concluded that the 400 watt array should be adequate to meet the power requirements of the HADCS sites for a 6-month period during the summer.

### 3.1.3 400 Watt Photovoltaic/Battery System - Alert

A number of problems were encountered with the operation of the 400 watt system that was installed at Alert in June 1985. This included loss of voltage regulation for the period from June 1985 June 1986 and the loss of load from July 1985 to September 1985. These problems resulted in considerable overcharging of the battery during the period from installation until June 1986. As shown in **Figure 10** this corresponded to an excess charge of almost 3000 Ah being put into the battery. Battery voltage and load power for the period from June 1985 until July 1986 are shown in **Figure 11 and 12** respectively. The effect of repairs that were made to the regulator on June 18, 1986 is clearly visible in all of the results. While the system remained operational until June 1988 data was not recorded for most of this period.

Measurement of the specific gravity and electrolyte levels made in June 1986 and August 1987 indicated that the battery was fully charged (SG=1.30-1.31) and that minimal water loss had occurred.

Measurements in June 1988 indicated that the electrolyte levels were still alright but that the specific gravity was low (1.27). This is probably related to stratification of the electrolyte although poor weather conditions may also have contributed to battery discharge.

### 3.1.4 400 Watt PV/Battery System - Blacktop Mt

The 400 watt PV/battery power system that was installed in June 1987 has supplied all of the power consumed by the repeaters on Blacktop Ridge from 13 June to 07 October 1987 and from 29 February 88 to 7 June 1988. Operational data **(9)** for this system was recorded for much of this period; however, problems with both the receiver and transmitter resulted in some loss of data during the first year of operation.

Analysis of the data received showed that power was being dissipated by the shunt regulator more often than expected. This was attributed to the relatively large voltage drop along the wires connecting the regulator to the battery (#18 gauge). The effect of the high resistance of these wires was to limit the rate that the batteries could be charged and to give a false indication that the battery was

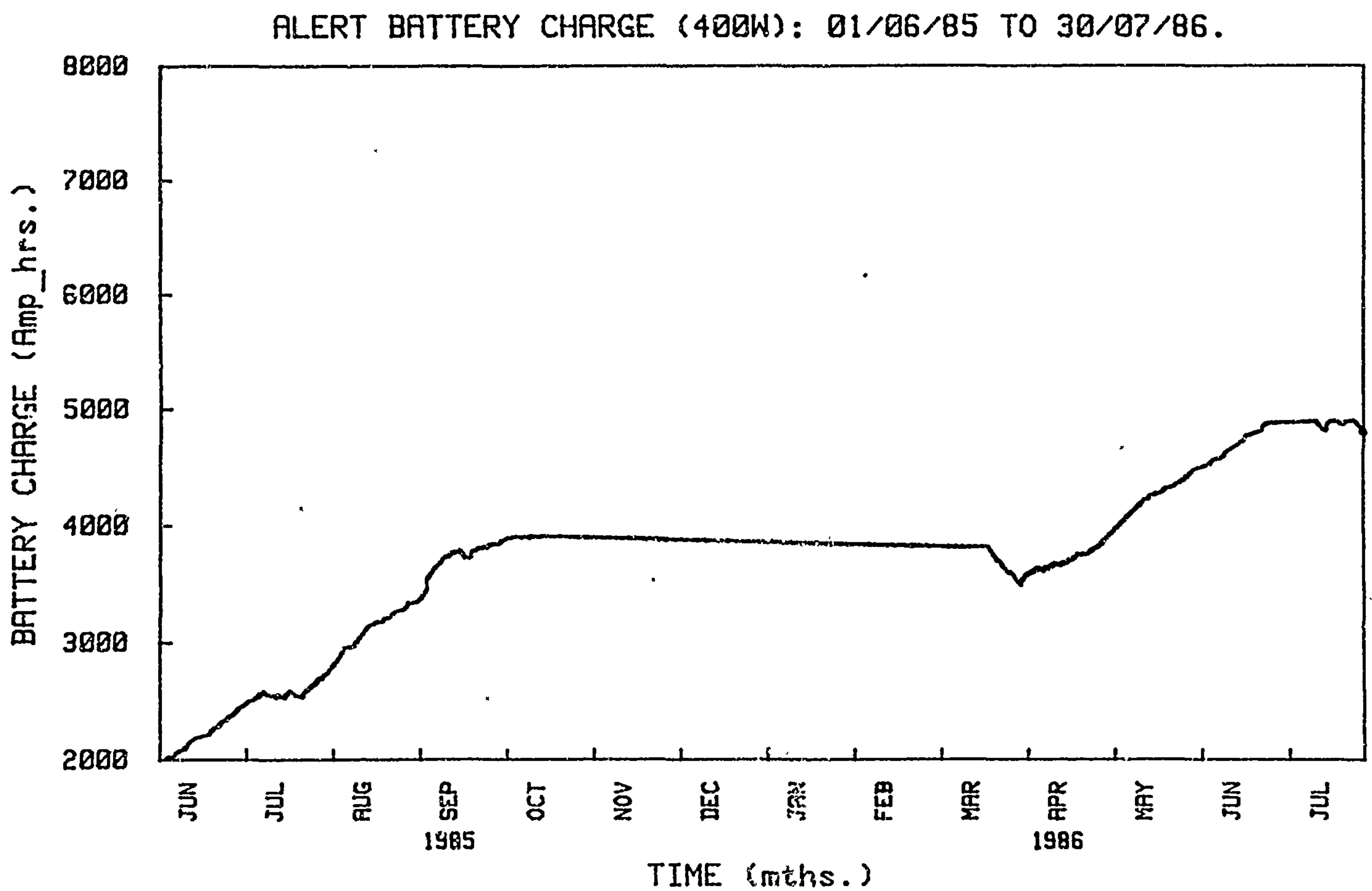



FIGURE 10 BATTERY CHARGE (400W SYSTEM)

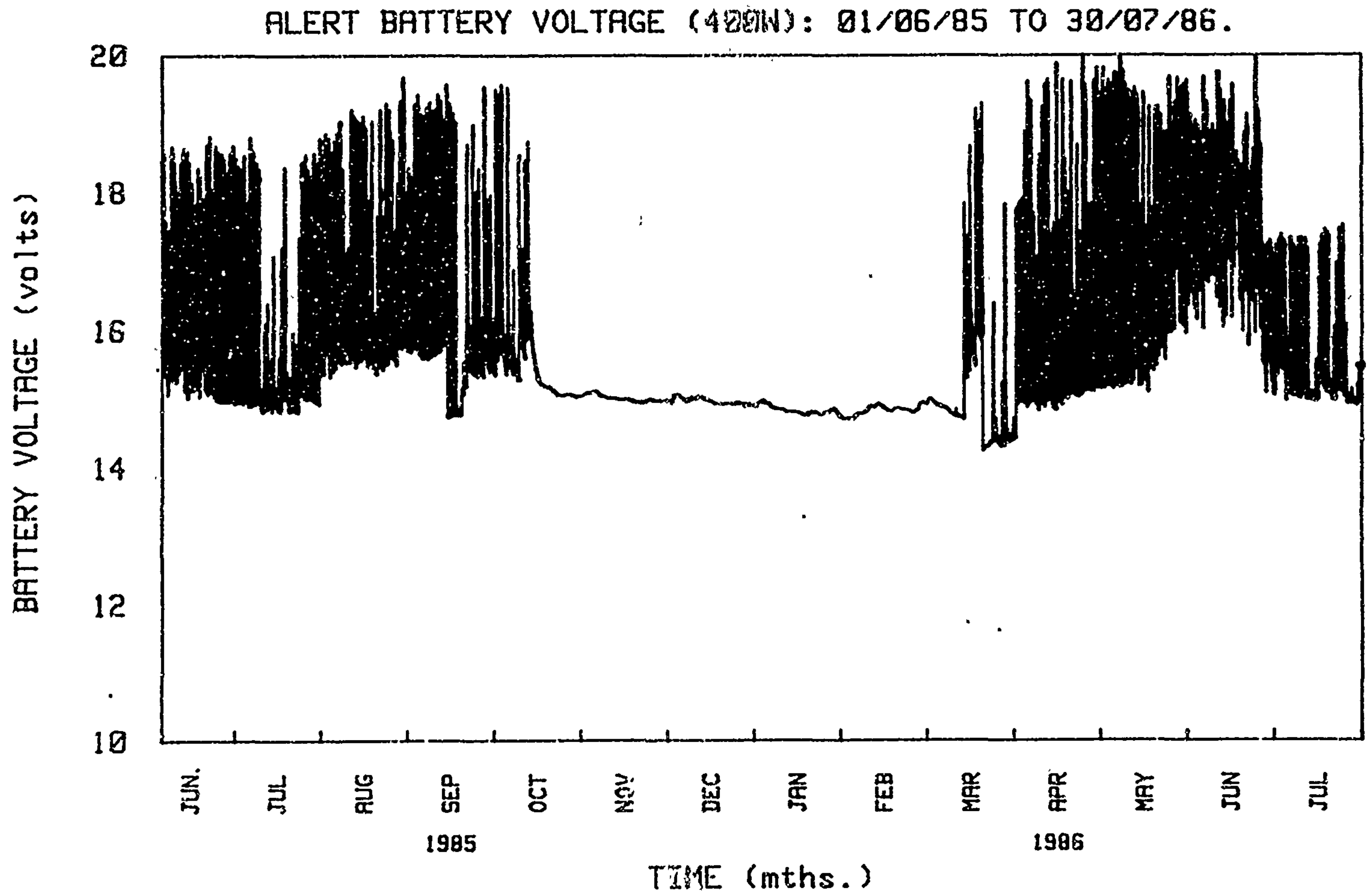



FIGURE 11 BATTERY VOLTAGE (400 WATT SYSTEM)

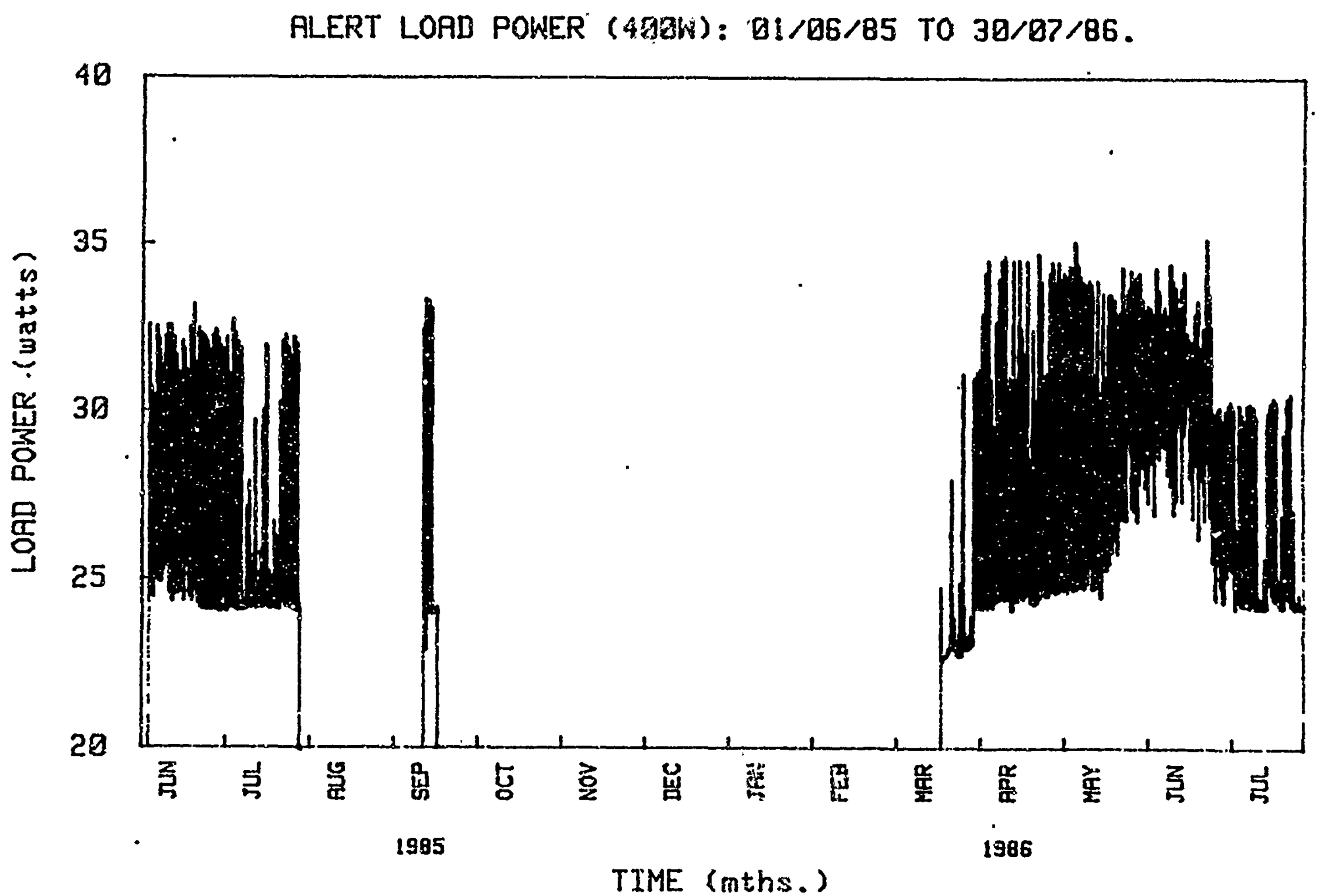



FIGURE 12 LOAD POWER (400 WATT SYSTEM)

fully charged. This resulted in the solar/battery system being turned off later (07 October) than was probably desireable and being turned on (29 Feb 88) prematurely. In spite of this difficulty, the PV system provided reliable power during the first year of operation. To prevent this difficulty in the future, the connecting wires to the battery were changed to #8 gauge in June 1988. This will minimize IR drop during charging.

### 3.2.0 Discharge Characteristics of Aged SAFT 608Z Zinc-Air Cells

The results of the discharge of a set of aged SAFT 608Z zinc-air cells during the winters of 1984/85 and 1985/86 are shown in **Figures 13 and 14** and **Tables 11 and 12**. The results show that this set of cells delivered 1508 amp-hours to a 12.8V cut-off. This represents a loss of capacity of almost 25% from the manufacturers rating of 2000 Ah. It should be remembered however that this set of cells almost four years old in the activated state and that the temperature during discharge was below -40°C for much of the time.

### 3.3.0 Charge Acceptance of Exide DH-5 Cells

All four test cells underwent 40 charge-discharge cycles under the experimental conditions listed in **Table 6** and the results are given in **Tables 13 to 18**. After the 40th charge under the experimental conditions, the cells at low temperatures were removed from the freezer and all allowed to warm up to room temperature. All the test cells were discharged at room temperature without any further charge to determine their after-cycling capacities (states of charge). They were then fully charged and discharged again. The results obtained are presented in **Table 19**.

### 3.3.1 Cell at Room Temperature.

As shown in **Table 16**, the charge accepted by the cell at room temperature was about 105% of that discharged in the previous cycle for the first few cycles; then it decreased to a constant level of 102% and remained at this level to the end of the test. At the end of the charging period, the current was very low: less than 80mA for all but the first six cycles. The end-of-discharge voltage decreased (**Table 16**). Acid concentration was slightly reduced to ca 1.300 sp. g. at the end of the test. However, the capacity determined after the cycling test did not show any observable change compared with that before the test. Thus, it may be concluded that, at 22°C, the cell did not suffer any measurable capacity loss under the test conditions.

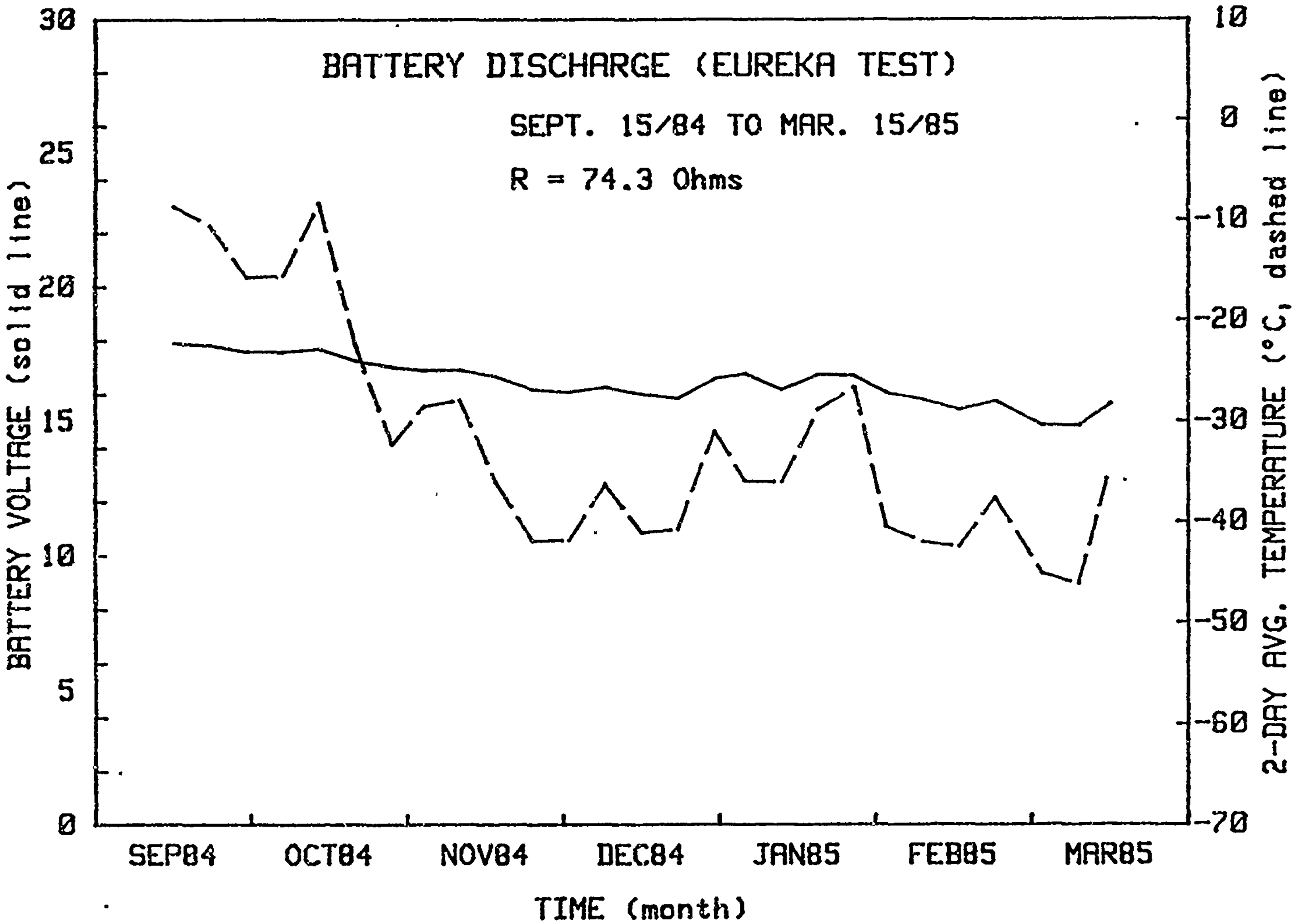



FIGURE 13 DISCHARGE OF ZINC-AIR BATTERY: 1984/1985

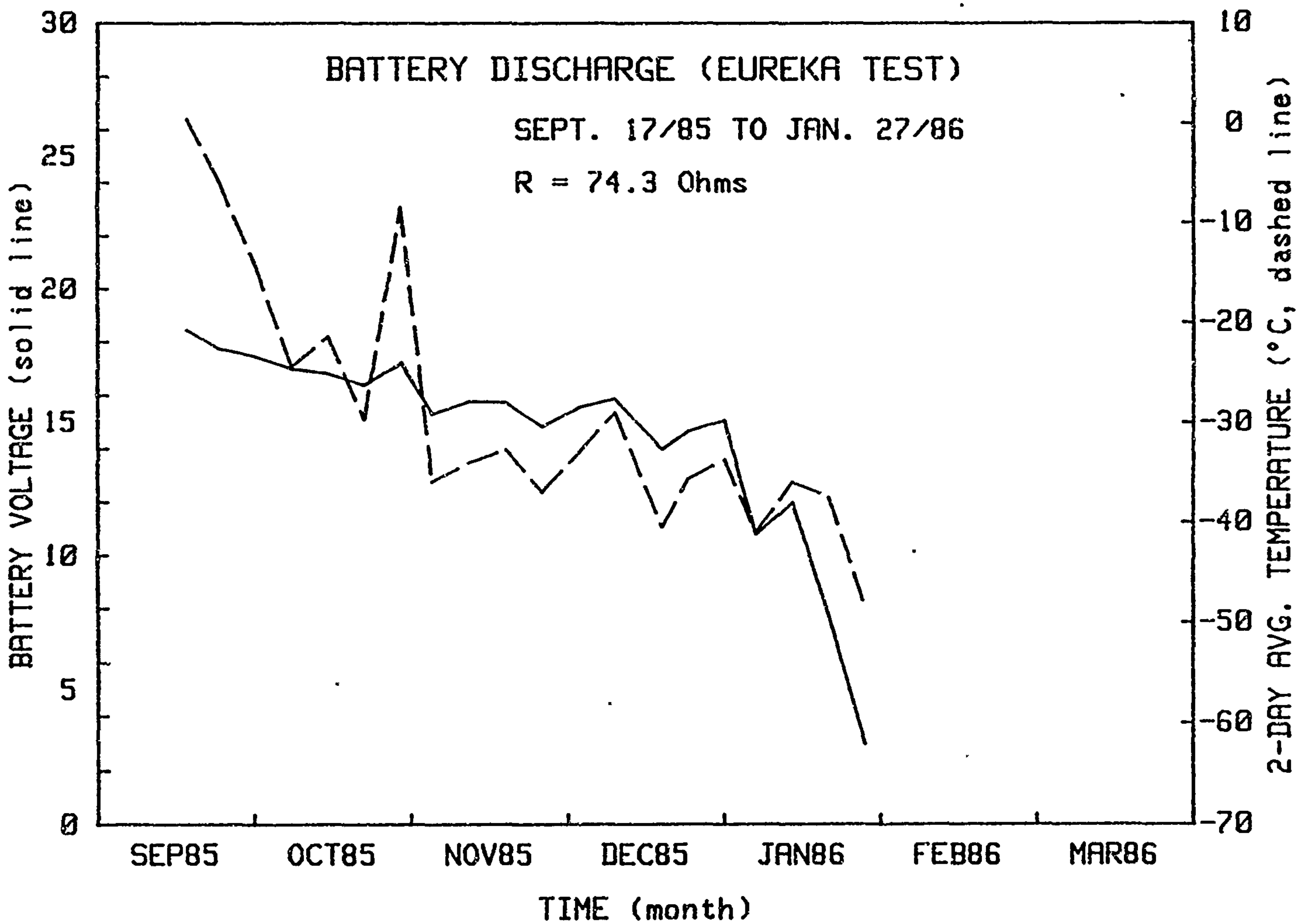



FIGURE 14 DISCHARGE OF ZINC-AIR BATTERY: 1985/1986

## TABLE 11

## CUMULATIVE AMP HRS DURING WINTER DISCHARGE AT EUREKA

## WINTER 84/85

| YEAR | MONTH | DAY | VOLTAGE | AMPHR |
|---|---|---|---|---|
| 84 | 9 | 15 | 17.88 | 0.00 |
| 84 | 9 | 22 | 17.82 | 40.29 |
| 84 | 10 | 29 | 17.56 | 80.00 |
| 84 | 10 | 6 | 17.57 | 119.73 |
| 84 | 10 | 13 | 17.70 | 159.75 |
| 84 | 10 | 20 | 17.22 | 198.68 |
| 84 | 10 | 27 | 16.99 | 237.10 |
| 84 | 11 | 3 | 16.86 | 275.22 |
| 84 | 11 | 17 | 16.65 | 351.06 |
| 84 | 11 | 24 | 16.17 | 387.62 |
| 84 | 12 | 1 | 16.07 | 423.96 |
| 84 | 12 | 8 | 16.27 | 460.75 |
| 84 | 12 | 15 | 16.00 | 496.92 |
| 84 | 12 | 22 | 15.84 | 532.74 |
| 84 | 12 | 29 | 16.57 | 570.21 |
| 85 | 1 | 5 | 16.76 | 608.10 |
| 85 | 1 | 12 | 16.16 | 644.64 |
| 85 | 1 | 19 | 16.74 | 682.49 |
| 85 | 1 | 26 | 16.67 | 720.18 |
| 85 | 2 | 2 | 16.06 | 756.50 |
| 85 | 2 | 9 | 15.80 | 792.22 |
| 85 | 2 | 16 | 15.40 | 827.04 |
| 85 | 2 | 23 | 15.76 | 862.68 |
| 85 | 3 | 2 | 14.82 | 896.19 |
| 85 | 3 | 9 | 14.83 | 929.72 |
| 85 | 3 | 15 | 15.64 | 960.03 |

## TABLE 12

## CUMULATIVE AMP HRS DURING WINTER DISCHARGE AT EUREKA

## WINTER 85/86

| YEAR | MONTH | DAY | VOLTAGE | AMPHR |
|---|---|---|---|---|
| 85 | 9 | 17 | 18.45 | 960.03 |
| 85 | 9 | 23 | 17.74 | 994.41 |
| 85 | 9 | 30 | 17.45 | 1033.87 |
| 85 | 10 | 7 | 16.98 | 1072.26 |
| 85 | 10 | 14 | 16.80 | 1110.25 |
| 85 | 10 | 21 | 16.37 | 1147.26 |
| 85 | 10 | 28 | 17.23 | 1186.22 |
| 85 | 11 | 4 | 15.30 | 1220.82 |
| 85 | 11 | 11 | 15.79 | 1256.52 |
| 85 | 11 | 18 | 15.74 | 1292.11 |
| 85 | 11 | 25 | 14.83 | 1325.64 |
| 85 | 12 | 2 | 15.56 | 1360.82 |
| 85 | 12 | 9 | 15.89 | 1396.75 |
| 85 | 12 | 18 | 13.98 | 1437.39 |
| 85 | 12 | 23 | 14.66 | 1461.07 |
| 85 | 12 | 30 | 15.09 | 1495.19 |
| 86 | 1 | 6 | 10.79 | 1519.59 |
| 86 | 1 | 13 | 12.00 | 1546.72 |
| 86 | 1 | 20 | 7.76 | 1564.27 |
| 86 | 1 | 27 | 3.00 | 1571.05 |

3.3.2 Cells at -40°C.

At the beginning of the cycling test the charge acceptance for the three cells was very low, as shown in Tables 13 to 15. It increased, however with cycling. After 20 cycles, it remained basically unchanged with further cycling.

The number of ampere-hours returned increased slightly when the charging voltage was raised from 2.65 to 2.75V, as shown in Tables 13 to 15.

The specific gravities were measured and the results are presented in Table 17. The data show that the concentration decreased gradually from 1.31 to about 1.28 sp.gr. at the 20th cycle, after which there was no significant change with further cycling. The specific gravity-cycle curves for the three cells at -40°C can be regarded as identical to one another, taking into account the considerable spread within each data set. The data, as shown in Table 16, also indicate that stratification of the electrolyte in the test cells was not appreciable.

After the 40-cycle test, the capacities of the cells were determined and the data obtained are given in Table 19. The cells were then fully charged, and their capacities were again measured. The data obtained are also presented in Table 19. A capacity loss of about 120Ah, or about 34% of the capacity before the test, had occurred during the cycling, as shown in Table 17. No appreciable difference among the three test cells was indicated by the experimental data, even though the cells were charged at different voltages (Tables 6).

The averaged coulombic charging efficiencies of the cells in the cycling test were calculated and the results are entered in Table 18. The calculation showed that the average coulombic efficiency was about 90% for a cell being charged at 2.65V. Increasing the charging voltage to 2.75V might have lowered the coulombic efficiency.

## TABLE 13

Cycling Results for Cell #1, Which Was Tested at -40°C With a Charging Voltage of 2.65V

| Cycle No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.014 | 2.019 | 2.020 | 2.016 | 2.014 | 2.022 | 2.021 | 2.014 | 2.016 | 2.012 | 2.017 |
| End-of-Charge Current, A | 0.263 | 0.375 | 0.462 | 0.580 | 0.609 | 0.623 | (1) | 0.888 | 0.999(1) | 0.829 | 0.628 |
| Recharge, | | | | | | | | | | | |
| Ah | 3.67 | 4.16 | 5.77 | 7.05 | 7.91 | 7.60 | 1.10(1) | 9.80 | 4.85(1) | 9.55 | 6.17 |
| % Discharged Ah | 30.6 | 34.7 | 49.8 | 58.8 | 66.3 | 63.3 | 9.2(1) | 81.7 | 40.4(1) | 79.6 | 51.4 |

| Cycle No. | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.015 | 2.012 | 2.012 | 2.010 | 2.010 | 2.012 | 2.012 | 2.012 | 2.017 | 2.012 | 2.012 |
| End-of-Charge Current, A | 0.840 | 0.850 | 0.930 | 1.065 | 0.883 | 0.893 | 0.930 | 0.944 | 1.035 | 1.147 | 0.951 |
| Recharge, | | | | | | | | | | | |
| Ah | 10.05 | 10.61 | 10.50 | 10.45 | 10.06 | 10.25 | 10.75 | 11.00 | 11.99 | 10.95 | 10.66 |
| % Discharged Ah | 83.8 | 88.4 | 87.5 | 87.1 | 83.8 | 85.4 | 89.6 | 91.7 | 99.6 | 91.3 | 88.8 |

| Cycle No. | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.012 | 2.013 | 2.010 | 2.011 | 2.011 | 2.010 | 2.009 | 2.010 | 2.009 | 2.010 | 2.010 |
| End-of-Charge Current, A | 1.000 | 0.913 | 0.940 | 0.968 | 0.985 | 1.065 | 1.138 | 0.975 | 1.006 | 0.999 | 0.999 |
| Recharge, | | | | | | | | | | | |
| Ah | 11.7 | 10.30 | 11.40 | 11.25 | 11.86 | 11.55 | 11.88 | 10.68 | 11.40 | 11.28 | 11.33 |
| % Discharged Ah | 97.5 | 85.8 | 95.0 | 93.8 | 98.8 | 96.3 | 99.0 | 89.0 | 95.0 | 94.0 | 94.4 |

| Cycle No. | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.012 | 2.009 | (2) | 2.009 | 2.011 | 2.005 | 2.006 | 2.006 | 2.004 | 2.002 | 2.007 |
| End-of-Charge Current, A | 1.026 | 1.022 | (2) | 1.203 | 0.937 | 1.003 | 0.903 | 1.028 | 1.000 | 0.965 | 1.009 |
| Recharge, | | | | | | | | | | | |
| Ah | 11.40 | 12.12 | (2) | 11.40 | 11.90 | 10.90 | 11.05 | 11.65 | 11.20 | 11.26 | 11.42 |
| % Discharged Ah | 95.0 | 101.0 | (2) | 95.0 | 99.2 | 90.8 | 92.1 | 97.1 | 93.3 | 93.8 | 95.2 |

Notes: (1) Charging was terminated prematurely due to programming errors.
(2) Loss of record.

## TABLE 14

Cycling Results for Cell #2, Which Was Tested at −40°C With a Charging Voltage of 2.70V

| Cycle No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.016 | 2.018 | 2.014 | 2.022 | 2.023 | 2.021 | 2.020 | 2.022 | 2.019 | 2.011 | 2.019 |
| End-of-Charge Current, A | 0.342 | 0.407 | 0.565 | 0.580 | 0.637 | 0.633 | 0.682 | 0.733 | 0.913(1) | 0.859 | 0.635 |
| Recharge, | | | | | | | | | | | |
| Ah | 4.17 | 5.18 | 6.45 | 7.45 | 8.35 | 7.85 | 8.46 | 9.00 | 0.90(1) | 10.05 | 6.79 |
| % Discharged Ah | 34.7 | 43.2 | 54.0 | 62.1 | 69.6 | 65.4 | 70.8 | 75.0 | 7.5(1) | 83.8 | 56.6 |
| **Cycle No.** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **Average** |
| End-of-Discharge Voltage, V | 2.013 | 2.007 | 2.018 | 2.020 | 2.012 | 2.011 | 2.012 | 2.011 | 2.013 | 2.015 | 2.013 |
| End-of-Charge Current, A | 0.899 | 0.852 | 0.885 | 0.890 | 0.940 | 1.179 | 1.112 | 0.919 | 0.950 | 0.995 | 0.965 |
| Recharge, | | | | | | | | | | | |
| Ah | 9.90 | 10.20 | 10.75 | 10.80 | 11.05 | 10.50 | 10.90 | 10.25 | 11.0 | 11.35 | 10.67 |
| % Discharged Ah | 82.5 | 85.0 | 89.6 | 90.0 | 92.1 | 87.5 | 90.8 | 85.4 | 91.7 | 94.6 | 88.9 |
| **Cycle No.** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **29** | **30** | **Average** |
| End-of-Discharge Voltage, V | 2.019 | 2.012 | 2.011 | 2.011 | 2.010 | 2.011 | 2.015 | 2.011 | 2.013 | 2.011 | 2.012 |
| End-of-Charge Current, A | 0.960 | 0.980 | 1.090 | 0.950 | 0.980 | 0.974 | 0.985 | 1.000 | 1.040 | 1.227 | 1.018 |
| Recharge, | | | | | | | | | | | |
| Ah | 11.55 | 11.50 | 11.00 | 10.85 | 11.40 | 11.25 | 11.65 | 12.35 | 11.65 | 11.15 | 11.44 |
| % Discharged Ah | 96.3 | 95.8 | 91.7 | 90.4 | 95.0 | 93.8 | 97.1 | 103.0 | 97.1 | 92.9 | 95.3 |
| **Cycle No.** | **31** | **32** | **33** | **34** | **35** | **36** | **37** | **38** | **39** | **40** | **Average** |
| End-of-Discharge Voltage, V | 2.011 | 2.010 | (2) | 2.014 | 2.008 | 2.008 | 2.008 | 2.005 | 1.996 | 2.033 | 2.010 |
| End-of-Charge Current, A | 1.007 | (2) | 1.035 | 0.961 | 0.999 | 0.963 | 0.960 | (1) | 0.942 | 0.995 | 0.983 |
| Recharge, | | | | | | | | | | | |
| Ah | 11.30 | (2) | 11.60 | 12.12 | 10.96 | 11.56 | 11.20 | 2.40 | 18.55(3) | 11.00 | 11.41 |
| % Discharged Ah | 94.2 | (2) | 96.7 | 102.0 | 91.3 | 96.3 | 93.3 | 20.0(1) | 155.0(3) | 91.7 | 95.1 |

Notes: (1) Charging was terminated prematurely due to programming errors.
(2) Loss of record.
(3) Charging time was extended to make up for the previous undercharge.

# TABLE 15

Cycling Results for Cell #4, Which Was Tested at -40°C With a Charging Voltage of 2.75V

| Cycle No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.009 | 2.011 | 2.008 | 2.015 | 2.016 | 2.014 | 2.014 | 2.015 | 2.013 | 2.003 | 2.011 |
| End-of-Charge Current, A | 0.375 | 0.404 | 0.545 | 0.610 | 0.623 | 0.645 | 0.696 | 0.744 | 0.999(1) | 0.874 | 0.651 |
| Recharge, | | | | | | | | | | | |
| Ah | 4.60 | 5.55 | 6.94 | 8.00 | 8.40 | 8.15 | 8.80 | 9.30 | 1.15(1) | 10.50 | 7.15 |
| % Discharged Ah | 38.3 | 46.3 | 58.2 | 66.7 | 70.0 | 67.9 | 73.3 | 77.5 | 9.6(1) | 87.5 | 59.6 |

| Cycle No. | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.006 | 2.006 | 2.011 | 2.013 | 2.006 | 2.006 | 2.006 | 2.005 | 2.006 | 2.008 | 2.007 |
| End-of-Charge Current, A | 0.900 | 0.860 | 0.925 | 0.895 | 0.950 | 1.194 | 1.138 | 0.938 | 0.960 | 0.991 | 0.975 |
| Recharge, | | | | | | | | | | | |
| Ah | 10.31 | 10.50 | 11.00 | 11.15 | 11.50 | 10.85 | 11.26 | 10.55 | 11.25 | 11.60 | 10.99 |
| % Discharged Ah | 85.9 | 87.5 | 91.7 | 92.9 | 95.8 | 90.4 | 93.8 | 87.9 | 93.8 | 96.7 | 91.6 |

| Cycle No. | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.014 | 2.005 | 2.005 | 2.004 | 2.004 | 2.005 | 2.009 | 2.006 | 2.008 | 2.006 | 2.006 |
| End-of-Charge Current, A | 0.965 | 0.980 | 1.110 | 0.955 | 0.980 | 0.995 | 0.990 | 1.005 | 1.040 | 0.936 | 0.996 |
| Recharge, | | | | | | | | | | | |
| Ah | 11.85 | 11.95 | 11.40 | 11.15 | 11.65 | 11.55 | 11.95 | 12.72 | 11.88 | 9.96 | 11.60 |
| % Discharged Ah | 98.8 | 99.6 | 95.0 | 92.9 | 97.1 | 96.3 | 99.6 | 106.0 | 99.0 | 83.0 | 96.7 |

| Cycle No. | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.002 | 1.998 | (2) | 2.002 | 2.002 | 2.002 | 2.002 | 2.001 | 1.999 | 1.998 | 2.001 |
| End-of-Charge Current, A | 1.085 | (2) | 1.135 | 1.002 | 1.028 | 0.963 | 1.046 | 1.017 | 1.021 | 0.975 | 1.030 |
| Recharge, | | | | | | | | | | | |
| Ah | 8.76(3) | (2) | 12.00 | 13.08 | 11.56 | 12.00 | 12.00 | 11.70 | 11.90 | 11.80 | 12.01(4) |
| % Discharged Ah | 73.0(3) | (2) | 100.0 | 109.0 | 96.3 | 100.0 | 100.0 | 97.5 | 99.2 | 98.3 | 100.0(4) |

Notes: (1) Charging was terminated prematurely due to programming errors.
(2) Loss of record.
(3) Charging current was too low due to a faulty analog output unit in the system.
(4) Data from cycles 31 and 32 are excluded.

## TABLE 16

Cycling Results for Cell #4, Which Was Tested at 20±2°C With a Charging Voltage of 2.40V

| Cycle No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.139 | 2.139 | 2.146 | 2.135 | 2.133 | 2.132 | 2.132 | 2.133 | 2.133 | 2.132 | 2.135 |
| End-of-Charge Current, A | 0.183 | 0.151 | 0.120 | 0.097 | 0.084 | 0.082 | 0.071 | 0.068 | 0.070 | 0.073 | 0.100 |
| Recharge, | | | | | | | | | | | |
| Ah | 12.68 | 12.26 | 12.56 | 12.45 | 12.30 | 12.20 | 12.20 | 12.24 | 12.24 | 12.24 | 12.35 |
| % Discharged Ah | 105.4 | 102.1 | 105.8 | 103.8 | 102.5 | 101.7 | 101.7 | 102.0 | 102.0 | 102.0 | 103.0 |

| Cycle No. | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.129 | 2.129 | 2.131 | 2.131 | 2.131 | 2.130 | 2.129 | 2.132 | 2.129 | 2.130 | 2.130 |
| End-of-Charge Current, A | 0.068 | 0.072 | 0.074 | 0.077 | 0.071 | 0.072 | 0.079 | 0.079 | 0.066 | 0.061 | 0.072 |
| Recharge, | | | | | | | | | | | |
| Ah | 12.24 | 12.24 | 12.24 | 12.24 | 12.24 | 12.24 | 12.24 | 12.36 | 12.24 | 12.24 | 12.25 |
| % Discharged Ah | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 103.0 | 102.0 | 102.0 | 102.1 |

| Cycle No. | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.128 | 2.126 | 2.126 | 2.126 | 2.127 | 2.127 | 2.129 | 2.129 | 2.129 | 2.129 | 2.128 |
| End-of-Charge Current, A | 0.060 | 0.054 | 0.056 | 0.065 | 0.062 | 0.062 | 0.062 | 0.062 | 0.069 | 0.065 | 0.061 |
| Recharge, | | | | | | | | | | | |
| Ah | 12.12 | 12.12 | 12.24 | 12.24 | 12.12 | 12.12 | 12.24 | 12.12 | 12.24 | 12.24 | 12.19 |
| % Discharged Ah | 101.0 | 101.0 | 102.0 | 102.0 | 101.0 | 101.0 | 102.0 | 101.0 | 102.0 | 102.0 | 101.6 |

| Cycle No. | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End-of-Discharge Voltage, V | 2.127 | (1) | 2.125 | 2.129 | 2.127 | 2.128 | 2.127 | 2.125 | 2.123 | 2.122 | 2.126 |
| End-of-Charge Current, A | (1) | 0.065 | 0.055 | 0.057 | 0.060 | 0.058 | 0.057 | 0.055 | 0.052 | 0.052 | 0.057 |
| Recharge, | | | | | | | | | | | |
| Ah | (1) | 12.12 | 12.14 | 12.24 | 12.24 | 12.24 | 12.12 | 12.24 | 12.24 | 12.24 | 12.22 |
| % Discharged Ah | (1) | 101.0 | 101.0 | 102.0 | 102.0 | 102.0 | 101.0 | 102.0 | 102.0 | 102.0 | 101.8 |

Notes: (1) Loss of data.

## TABLE 17

### Specific Gravity of Acid in Cells at the End of Discharge During the Cycling Test

| Cycle # | | Cell No. 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 0 (charged) | | 1.312 | 1.311 | 1.307 | 1.312 |
| 5 | top | 1.291 | 1.297 | 1.295 | 1.299 |
| | bottom | 1.293 | 1.299 | 1.296 | 1.307 |
| 17 | top | 1.277(1) | 1.284 | 1.278 | 1.294(2) |
| | bottom | 1.278(1) | 1.280 | 1.275 | 1.300(2) |
| 25 | top | 1.273(3) | 1.277 | 1.273 | 1.298(4) |
| | bottom | 1.275(3) | 1.280 | 1.275 | 1.295(4) |
| 34 | top | 1.283 | 1.279 | 1.276 | 1.306(5) |
| | bottom | 1.288 | 1.282 | 1.282 | 1.312(5) |
| 40 | top | 1.285 | 1.279 | 1.277 | 1.297 |
| | middle | 1.287 | 1.283 | 1.280 | 1.300 |
| | bottom | 1.289 | 1.287 | 1.282 | 1.303 |

Notes: (1) 21st cycle; (2) 16th cycle; (3) 27th cycle; (4) 24th cycle; (5) 33rd cycle.

## TABLE 18

**Typical End-of-Charge Potentials, End-of-Discharge Potentials and Overpotentials of Positive and Negative Plates.**

| | | Cell No. | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Temperature, °C | -40 | -40 | -40 | 22 |
| **Open Circuit Before Discharge:** | | | | |
| Cell Voltage, V | ——— | 2.165 | ——— | 2.175 |
| Positive Plate Potential, V | ——— | 1.207 | ——— | 1.206 |
| Negative Plate Potential, V | ——— | -0.958 | ——— | -0.969 |
| **End-of-Charge:** | | | | |
| Cell Voltage, V | 2.650 | 2.700 | 2.750 | 2.400 |
| Positive Plate | | | | |
| Potential, V | 1.527 | 1.527 | 1.528 | 1.230 |
| Overpotential, mV | 320 | 320 | 321 | 24 |
| Negative Plate | | | | |
| Potential, -V | 1.114 | 1.165 | 1.214 | 1.170 |
| Overpotential, mV | 156 | 207 | 256 | 201 |
| **End-of-Discharge:** | | | | |
| Cell Voltage, V | 2.010 | 2.010 | 2.009 | 2.132 |
| Positive Plate Potential, V | 1.088 | 1.084 | 1.082 | 1.170 |
| Negative Plate Potential, V | -0.920 | -0.920 | -0.925 | -0.960 |

Note: The plate potentials were measured at about the 25th cycle against a $Hg/Hg_2SO_4$ reference electrode in 1.30 sp.gr. $H_2SO_4$ at the cell temperature.

## TABLE 19

### Discharge Capacities of the Cells After the Cycling Test

| | Cell No. | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| First Discharge to 1.90V at 22°C and 6.4A | | | | |
| Time Elapsed, h | 37.0 | 37.6 | 36.3 | 55.8 |
| Discharge Capacity, Ah | 237 | 241 | 232 | 357 |
| % Rated Capacity | 51.5 | 52.4 | 50.4 | 77.6 |
| Second Discharge to 1.90V at 22°C and 6.4A, after being fully charged at room temperature | | | | |
| Time Elapsed, h | 57.5 | 55.6 | 54.4 | 55.9 |
| Discharge Capacity, Ah | 368 | 356 | 348 | 358 |
| % Rated Capacity | 80.0 | 77.4 | 75.7 | 77.8 |

## 3.4.0 Sizing of Photovoltaic Systems in the Arctic - Solar Radiation Modelling

The output of a photovoltaic array is linearly dependent on the intensity of the solar radiation incident on the array. This relationship is demonstrated clearly in Fig 15 where the output of the 80 watt array at Alert is plotted against the radiation intensity measured by the Eppley pyranometer mounted in the plane of the array. In general, however, there is very little experimental data available for solar radiation intensity on inclined surfaces so it is usually not possible to use this simple relationship to determine the size of photovoltaic array needed to meet a specific requirement.

Because of the limited availability of solar radiation data on inclined surfaces, it is desireable that the irradiance of the inclined surface be modelled from solar radiation data for a horizontal surface. Global radiation on a horizontal surface is much more readily available being recorded at twelve Atmospheric Environmental Service Sites in the Yukon and North West Territories. To be of practical use in the Arctic, it is desireable that the models use only parameters that may be easily measured or acquired from existing data bases. The use of global radiation as a sole parameter to determine sky condition is convenient as it is often available or easily measured.

In our studies, two well developed radiation models (those of Hay (11) and Klucher (12)) have been used to compare the results calculated from these models with the experimental results for radiation intensity on a south facing 80° inclined surface at Alert. This comparison was carried out to assess the capability of these models to calculate the irradiance on tilted surfaces under the severe radiation regime encountered at high latitudes. This regime is characterised by 24-hour solar days and nights, and low solar elevations for most of the year.

The results of these calculations (Figure 16 and 17) showed that both the models of Hay (11) and Klucher (12) give reasonably accurate estimates of slope irradiance from April to August when the sun is reasonably high in the sky (above 6 to 8 degrees). During March and September, however, when solar elevation is very low, the models seriously over estimate the radiation available on inclined surfaces. The failure of these models to adequately predict irradiance at low solar irradiance at low sun angles is related to a breakdown of the commonly used relationship (13) between sky condition as defined by the ratio of

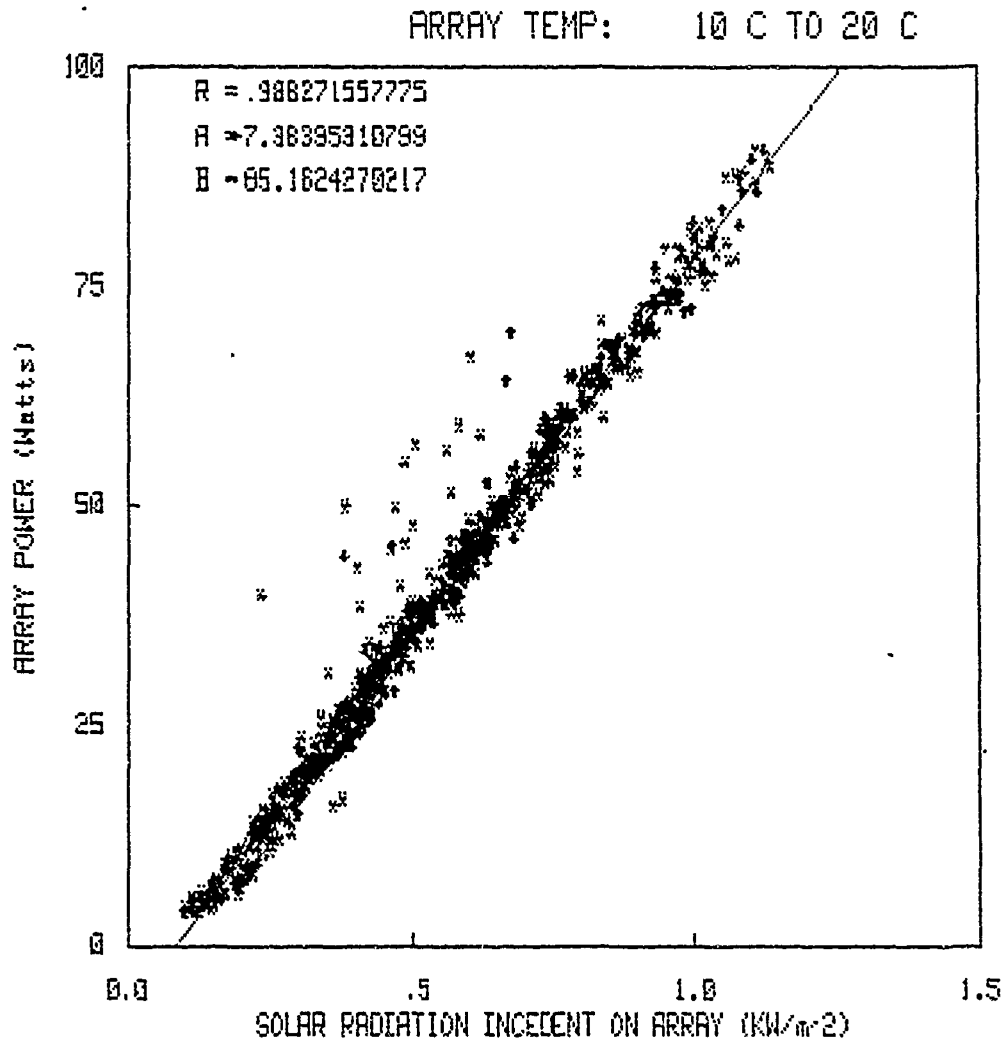



FIGURE 15 PV ARRAY OUTPUT VS RADIATION INTENSITY

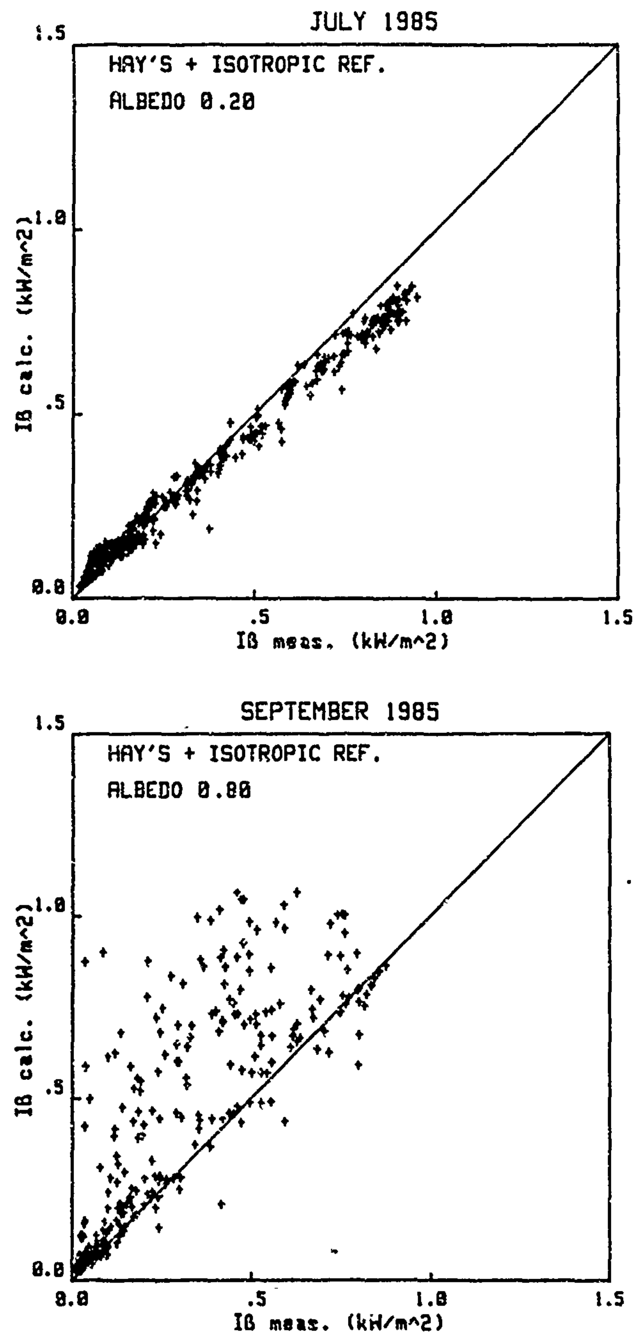



FIGURE 16 COMPARISON BETWEEN MEASURED AND CALCULATED RADIATION INTENSITIES - HAY'S MODEL

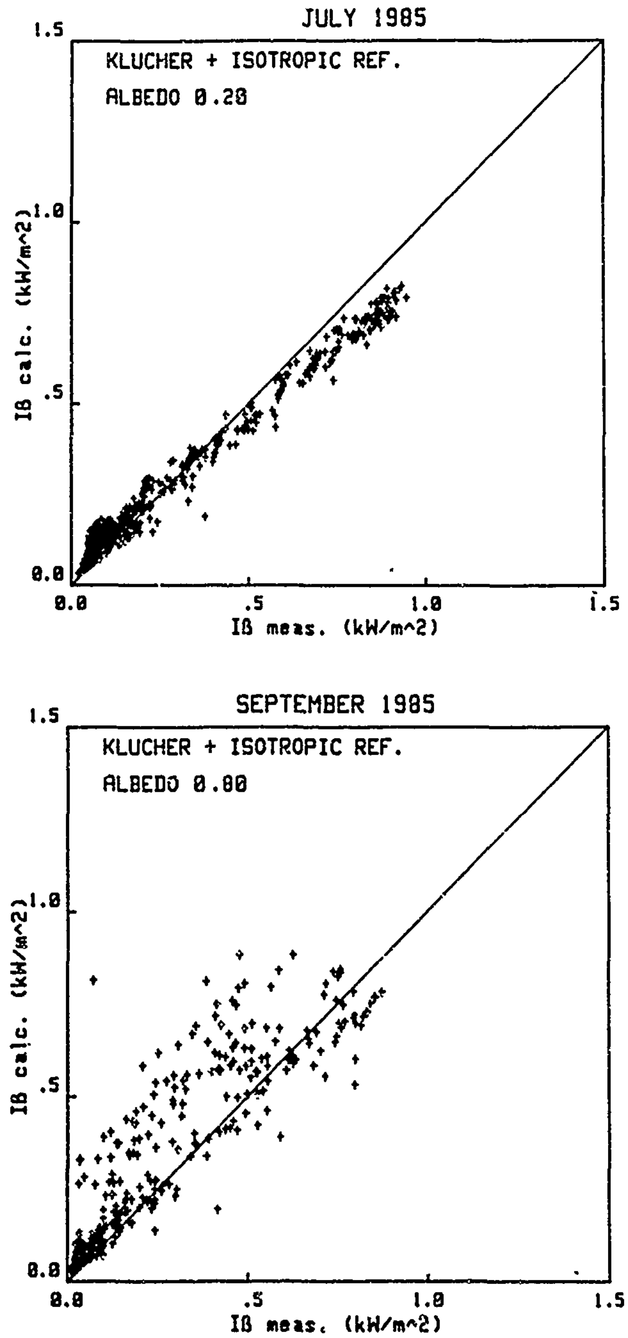



FIGURE 17 COMPARISON BETWEEN MEASURED AND CALCULATED RADIATION INTENSITIES - KLUCHER'S MODEL

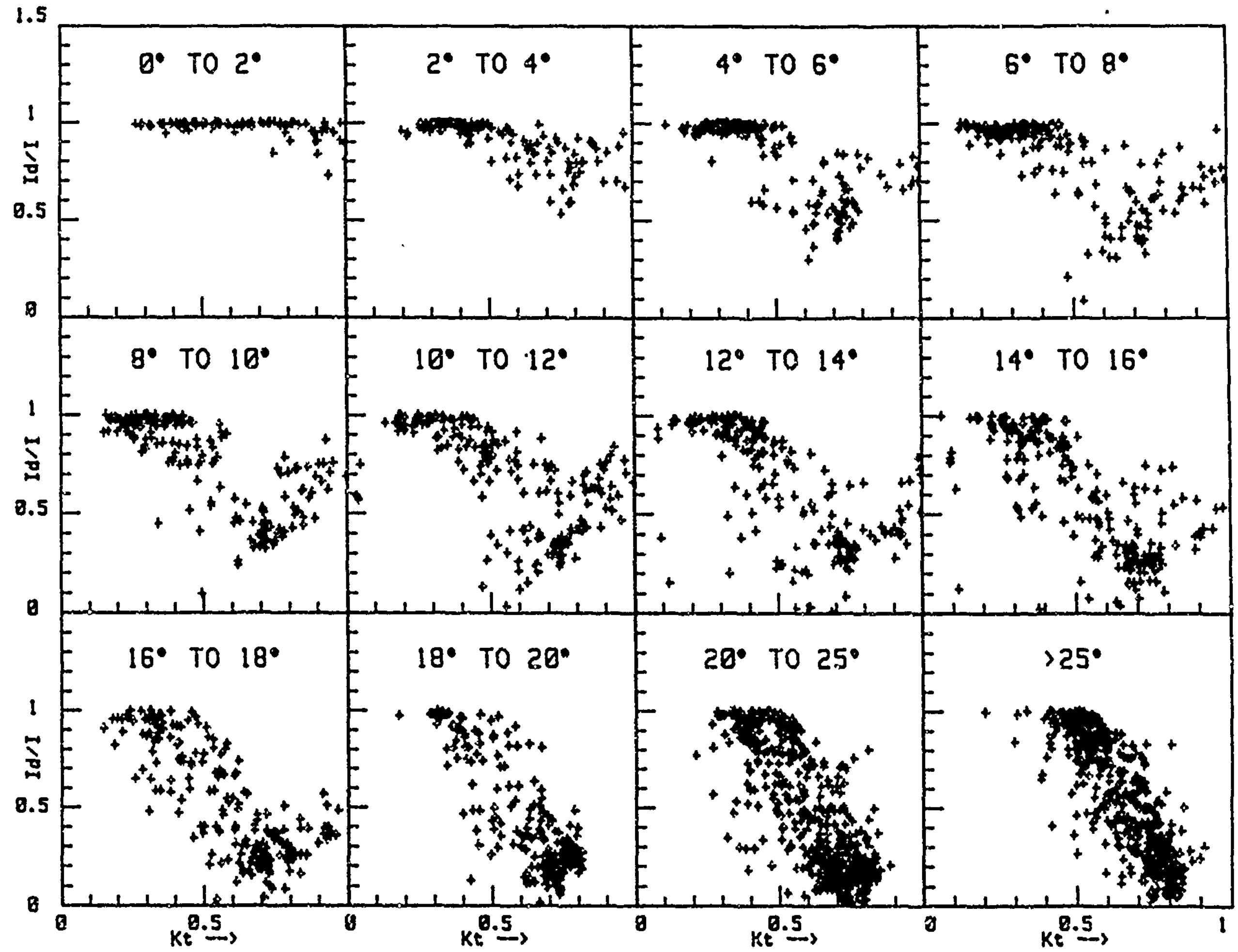
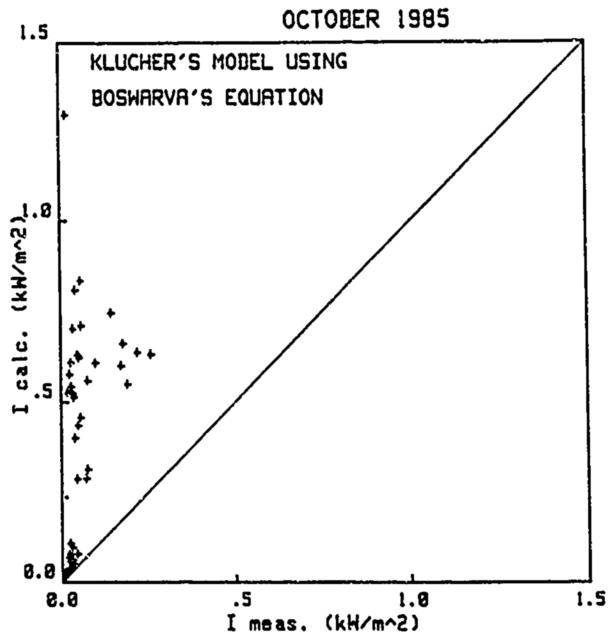



FIGURE 18 RELATIONSHIP BETWEEN D/H AND KT AS A FUNCTION OF SOLAR ELEVATION



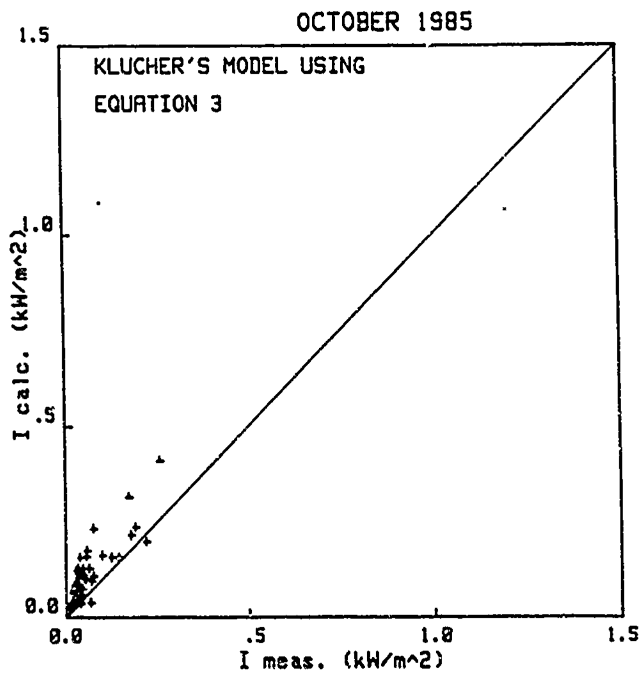




FIGURE 19 COMPARISON BETWEEN MEASURED AND CALCULATED RADIATION INTENSITIES

diffuse to global radiation (D/H) and atmospheric transmitivity Kt defined as the ratio of global to extra-terrestrial radiation (H/Ho). This relationship is independent of solar elevation; however, analysis of the experimental data collected at Alert on the 80° inclined and horizontal surfaces shows a strong dependenace at low solar elevations (Fig 18). Using this data it has been possible to derive a new empirical relationship sky condition (D/H) and atmospheric transmitivity (Kt) that provides much improved agreement, between calculated and observed irradiance on sloped surfaces at low solar elevations. This is illustrated in Fig 19 which shows a comparison between modelled and observed data for October 1985.

The discussion in this section is intended only as a summary of work in the area of radiation modelling. Details can be found in recent publications (14 & 15). The importance of this work is that good understanding of methods to estimate radiation on inclined surfaces in the Arctic has been obtained. Importance deficiencies in existing models have been identified and improvements made. The development of an improved radiation model should allow the sizing of photovoltaic/battery systems to meet various Canadian Forces requirements in the Arctic with a greater degree of confidence.

## 4.0.0 CONCLUSIONS AND RECOMMENDATIONS FOR SYSTEM SELECTION

The results presented in this report have demonstrated that it is possible to use a photovoltaic/battery system for powering the remote sites of the High Arctic Data Communication System during the summer months. The following specific technical points have been addressed.

### 4.1.0 Selection and Sizing of the Photovoltaic Array

Based on the results of these studies, it is recommended that a 400 watt (peak) photovoltaic array be used at the HADCS sites. This array is conservatively sized and should meet the power requirements under the worst weather conditions anticipated at any of the sites. Panels selected for installation at these sites should be capable of meeting the rigorous specifications defined by Canadian Coast Guard Specification MA2055. Amongst other things, this specifications requires an operating temperature range of -60° to +40°C and that the panels and mountings be designed to withstand wind loadings of up to 175 km/h from any direction. In the tests carried out under this program the photovoltaic arrays performed well without any apparent degradation. 400 watt arrays mounted at Mt Grant and Blacktop Mt. have shown no adverse effects as a result of environmental extremes during the period of installation.

In order to meet the voltage cut-off requirement of 12.8V, it was considered necessary to operate the PV/battery system as a nominal 14V (7 lead-acid cells in series) rather than at 12V which is the normal rating for PV panels. In the present studies it was determined that no problems were encountered with operating the system at this higher voltage. It should be noted that the panels selected for these test consisted of 40 series connected cells. In recent years there has been a trend to reduce the number of cells to 36. In the selection of PV panels care should be taken to ensure that the voltage at maximum power point is in the 17.5 - 18.0 V range.

### 4.2.0 Selection and Sizing of the Lead-Acid Storage Batteries

The batteries selected for installation in the experimental PV/battery system were based on Exide DH-5 and DD-5 cells. These cells, which were chosen because of the extensive experience of the Canadian Coast Guard, utilise a pure lead grid and have a 1.300 specific gravity electrolyte Laboratory and field measurements have shown that these cells accept charge efficiently even at the low temperatures (-40°C) encountered during the early spring at the HADCS sites.

The ability of lead-acid cells to accept charge at low temperatures was a major concern at the start of this project. It was a pleasant surprise therefore to discover that these cells accepted charge efficiently at -40°. No other cell types have been tested during the course of this work. It is possible that the use of pure lead as grid material explains the good charge acceptance. It is well known that the addition of almost any alloying element to lead lowers the overvoltage for hydrogen evolution making recharge less efficient especially, at low temperature. For this reason it is recommended that other cells using antimony or calcium as an alloying element not be substituted unless the low temperature charge acceptance is confirmed by laboratory testing.

Based on the experimental results carried out it is recommended that a 14V, 2000 Ah lead-acid battery be used for energy storage. With this battery capacity and a 400 watt PV array the system should be capable of meeting the power requirements at the HADCS sites for six to seven months during the summer reliably even during years of bad weather.

### 4.3.0 Performance of SAFT 608Z Zinc-Air Cells

The results of discharge of a zinc-air battery indicate that, while there is a capacity loss of as much as 25% over the four year period, there are no major problems in extending the discharge period of these cells from two to four years. The reduction in capacity may require the addition of an extra battery box to the existing system. In view of the current excess capacity and the fact that the solar power system can probably be used for seven rather than six months, it seems probable that the existing zinc-air (potash) battery will be adequate.

### 4.4.0 Voltage Regulation

A voltage regulator is used to charge the the lead acid battery bank at the recommended charge voltage (2.4V/cell at 20°C). This regulator must be temperature compensated so that the charging voltage is increased as the temperature drops. The shunt regulators used in these studies incorporated a "fail-safe" design.

In this design failure of the control electronics resulted in the battery being connected directly to the solar panels. This design is inherently much more reliable than a series regulator which, on failure, disconnects the battery from the solar panel and quickly results in complete discharge of the battery bank.

Experience with the 400 watt system at Alert has shown that direct connection of the solar array to the lead-acid battery does not cause problems. Very little water loss occurred during a year of operation in this mode. In addition, there is evidence that the higher charging voltage presents the electrolyte stratification that observed when the recommended charging voltages were utilised. The long term implications of higher charging voltages on battery life are not understood at the present time.

### 4.5.0 Interfacing the Photovoltaic System to the Existing (Zinc-Air) Battery

The most critical problem encountered in developing a photovoltaic/battery system to supplement the primary battery system at the HADCS sites has been interfacing the two systems without compromising reliability. This problem has been addressed by Diversitel Communication Inc under contract. A prototype microprocessor based system was installed on Blacktop Mt in June 1987. Suggestions have been made by Diversitel Communications recently (9) to further simplify the design so that the clock/calendar and microprocessor could be eliminated. The proposed strategy has been evaluated using the data collected at Alert and it is considered to be sound.

## 5.0.0 RECOMMENDATION FOR FURTHER STUDIES

The present studies have demonstrated the feasibility of using a photovoltaic/battery system to supplement the existing air depolarised battery for 6 or 7 months of the years. It is anticipated that this will reduce the frequency of battery replacement from once per year to once every two years. Substantial cost savings will be achieved by this modification to the HADCS system.

Additional savings could be achieved if a suitable source of power could be found for the winter months. The following system appear to offer some promise and should be investigated.

### 5.1.0 Liquid Fueled Thermoelectric Generator/PV Hybrid

Global Thermoelectric Power System Ltd have made considerable progress with the development of a thermo-electric generator that will operate reliably on a liquid fuel such as JP4. When combined with a photovoltaic/battery system, such a system would only require about 500 kg (180 gallons) of fuel per year. Long term reliability remains a concern; however, this system hold considerable promise if these questions can be resolved by further development.

### 5.2.0 Stand-Alone Photovoltaic/Battery System

It should be possible to provide the power to the HADCS sites using a stand-alone PV system if the size of the photovoltaic battery and lead-acid storage battery were increased. To operate the site during the winter months, the battery must be capable of delivering approximately 8640Ah. In practice a considerably larger battery capacity would be needed to prevent freezing of the batteries at low temperatures. At-40°C, for example, the electrolyte starts to freeze when the battery is only 30% discharged. Using this as a maximum allowable depth of discharge, then the total battery capacity that needs to be installed would be 28,800Ah which would weigh about 11,500kg or almost six times as much as the existing zinc-air (air depolarised) battery. In practice, because some freezing of the electrolyte does not result in battery damage or loss of performance, it is probably acceptable to allow the batteries to drop to a 50% state-of-charge. This would allow the installed capacity to be reduced to 17,280Ah which would weigh about 6,800kg.

Further reduction of the size of the lead-acid battery could be achieved if they were housed in a heated shelter. For example, if the batteries were allowed to drop to a 20% state of charge then the installed capacity could be reduced to 10,800Ah which would weigh only 4200kg or only twice as much as the existing battery. Options for heating the shelter would include a liquid fuel (JP4 or naphtha) heater or possibly the use of a solar/thermal storage system.

Installation of a stand-alone photovoltaic system could eliminate the need for battery replacement with the possible exception of installation of a back-up system as required.

## 5.3.0 Photovoltaic/Wind Hybrid System

In many locations in Canada, it is common that wind and solar energy availability complement each other. That is during winter when solar radiation levels are low, winds are often high. Based on the available wind and solar data for Alert and Eureka, this does not appear to be the case for northern Ellesmere Island where, in fact, winds are generally low during the winter as well. It appears unlikely that a photovoltaic/ wind hybrid system is a viable source of power for the HADCS sites. It is recommended, however, that wind availability at the HADCS sites be assessed to see if this conclusion is valid at the higher elevations. This data is currently being collected at the sites and should be readily available.

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The High Arctic Data Communications System (HADCS) was established to provide reliable communication between CFS Alert and Ottawa. The use of air depolarized cells as a power supply for HADCS is costly in terms of maintenance and battery replacement.

This study evaluates the use of a Photovoltaic/Battery System for HADCS. Installation and monitoring of this alternative system occurred, and the results of this evaluation are presented.

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