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OPERATIONAL RESULTS OF RUSSIAN-BUILT PHOTOVOLTAIC ALTERNATIVE ENERGY POWERED LIGHTHOUSES IN EXTREME CLIMATES

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ABSTRACT

This paper summarizes operational histories of three Russian-designed photovoltaic (PV) lighthouses in Norway and Russia. All lighthouses were monitored to evaluate overall system and Nickel Cadmium (NiCad) battery bank performance to determine battery capacity, charging trends, temperature, and reliability. The practical use of PV in this unusual mode, months of battery charging followed by months of battery discharging, is documented and assessed. This paper presents operational data obtained from 2004 through 2007.

1. INTRODUCTION

A cooperative effort between the United States Department of Energy (DOE)/National Nuclear Security Administration's (NNSA) Global Threat Reduction Initiative (GTRI) and the Russian Federation Navy is being implemented to recover radioisotopic thermoelectric generators (RTGs) and, where necessary, replace them with alternative energy systems to power approximately 400 lighthouses. This unusual application of renewable energy (PV and wind) allows the disposal of highly radioactive sources from remote, unsecured locations where RTGs are in use.

Initially, two Russian-built photovoltaic systems (Saturn Company of Krasnodar) were installed in Honningsvag, Norway and at Cape Shavor in the Murmansk region of Russia. Figure 1 shows the PV, controller, batteries, and lighthouse unit installed in Honningsvag, Norway. Sandia National Laboratories and the Southwest Technology Development Institute developed a data acquisition system (DAS) for recording operational data of the Honningsvag installation. The Norwegian Kystverket Lighthouse Commission implemented the DAS and collected the data. Kurchatov Institute in Moscow was contracted to develop and implement a similar system for the Cape Shavor lighthouse and for other pilot installations that followed. A third system, also instrumented by Kurchatov Institute, Karbas, Russia, includes a small wind electric system in addition the PV system.

Fig. 1: PV Lighthouse, Honningsvag, Norway.

2. PV LIGHTHOUSE SYSTEMS

2.1 Overall System Descriptions

The PV lighthouse systems consist of five 40 peak Watt (Wp) PV modules providing 200 Wp total. A charge controller manages charging and discharging of the 950 Ampere-hour (Ah) nickel cadmium (NiCad) battery bank operated at 12 volts. The PV system schematic, shown in Figure 2, is designed to power a 10-watt light emitting diode (LED) signal beacon produced by the Nav-Dals company of St. Peterburg, Russia. The LED is operated at a 50 percent duty cycle throughout the Arctic winter dark period.

2.2 Monitoring Approach

The Norwegian Kystverket Lighthouse Commission implemented a data acquistion system (DAS) and collected the data. Sandia National Laboratories and the NMSU Institute for Energy & Environment developed a data acquisition system (DAS) for recording operational data of the Honningsvag installation. Kurchatov Institute in Moscow developed and implemented a similar, but low power DAS for the Cape Shavor lighthouse and for other pilot installations.

The DAS is designed to measure load voltages and currents, power consumption current and voltage, battery current,voltage, and temperature. The DAS was design to operate in conjunction using only minimal power from the lighthouse power supply.

The datalogger operates in two modes: routine mode and radio communication mode. In the routine mode, the logger measures data every 10 seconds and record on the internal flash memory for 15 minute averages. Voltage and current parameters are monitored to detect dynamic charging and discharging currents and voltages between the controller and the batteries. The DASs are outfitted with BlueTooth radio enabled communication. All of the data recorded by a DAS is collected and processed on a regular basis. Data is recorded and plotted by Julian Day; the Julian calendar runs from 1 to 365 with day one being January 1. Graphs in this paper are provided in the calendar year time scale as month/day/year.

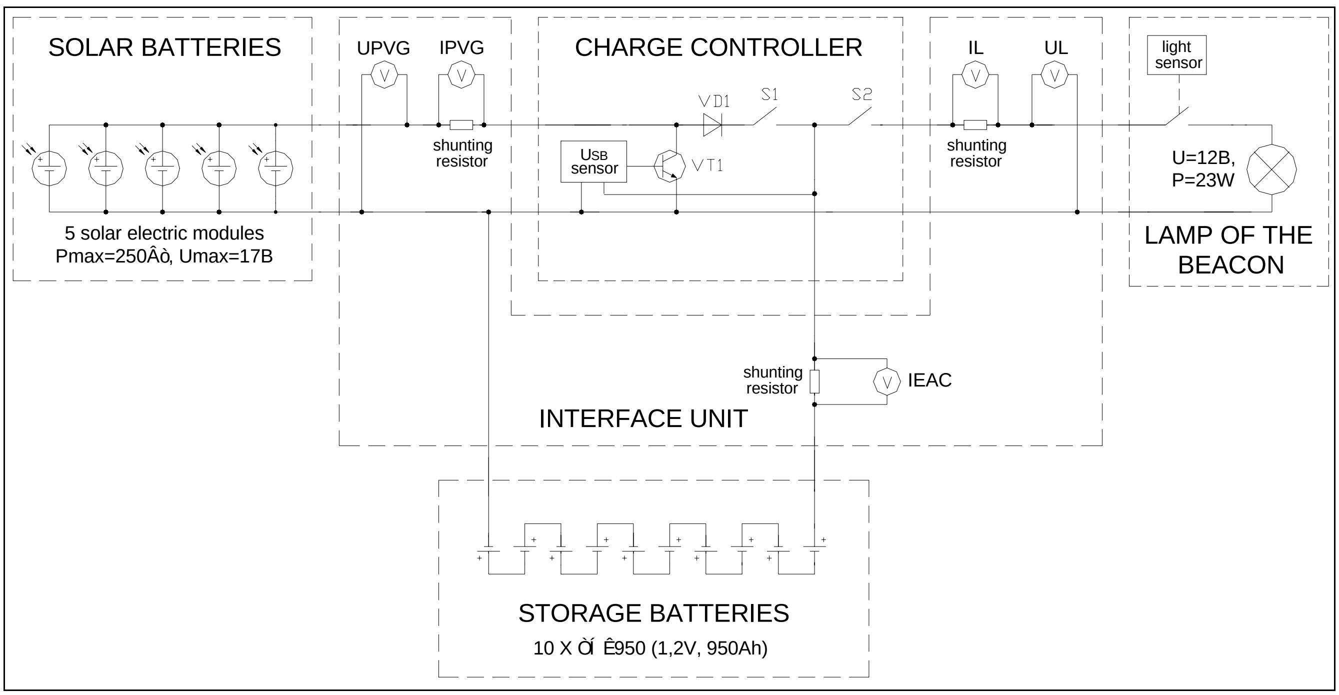

Fig 2: Schematic layout of PV lighthouse systems.

3. MONITORING RESULTS AND DISCUSSION

3.1 Cape Shavor, Russia

The Cape Shavor system in Russia, shown in Figure 3, was installed in 2003/4. The Cape Shavor data logger began recording data in June, 2004. Figures 4 and 5 present NiCad battery voltage and currents, respectively, from June 5 through September 13, 2004. As Figure 4 indicates, the battery bank was fully recharged and the charge controller maintained it in float charge condition throughout the summer. The charge controller maintains a peak charge voltage of 16.7 volts at 5° C and below, and gradually decreases peak charge voltage to 16.2 volts at 20° C. In Figure 5, positive current represents batteries discharging, while negative current represents battery charging. During the very sunny summer period, the battery bank is found to be operating in trickle charge mode. The system functioned well and the battery bank was maintained at full state of charge during the summer period (1).

Fig.3 : Saturn PV lighthouse system at Cape Shavor, Murmansk, Russia.

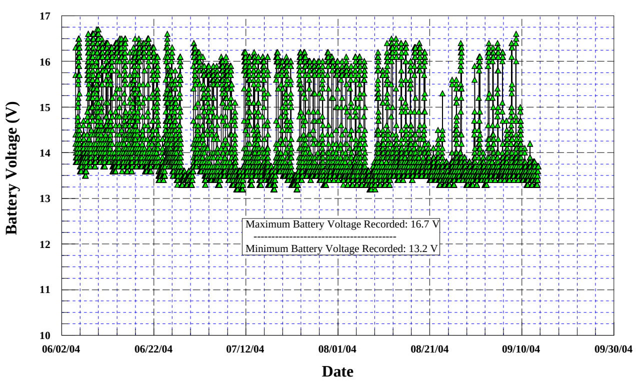

Fig. 4: Summertime Cape Shavor NiCad battery voltage from June 5-Sept 13, 2004.

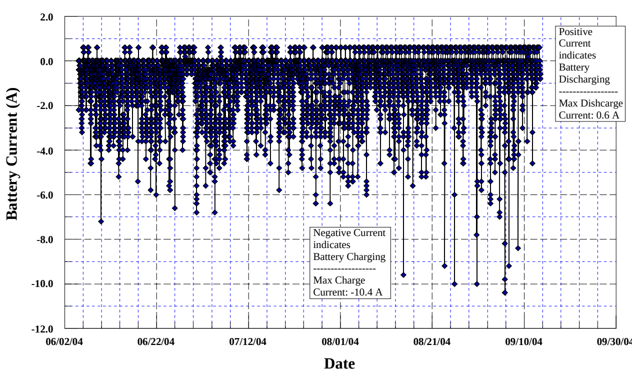

Fig. 5: Summertime Cape Shavor NiCad battery current from June 5-Sept 13, 2004.

Figure 6 presents the average battery voltage for the next period of fall operation: August 27 through December 6, 2004. The battery is initially fully charged, but by autumnal equinox, with daylight periods growing ever shorter, the net battery current was in continuous discharge. From this point to the end of the recording period, the average battery voltage dropped slowly. Minimum battery voltage of 12.2 was recorded on November 24. From that date until the end of the recording period, battery voltage remained between 12.2 – 12.3 V under condition of near-constant discharge (1).

Figure 7 shows the average current from the battery during the same fall period. The batteries were fully charged and the negative values represent trickle charging of the batteries until the autumnal equinox. From that point until the end of the recording period, the decreasing periods of sunlight were not sufficient to offset the near-constant discharge of the batteries powering the LED load (1).

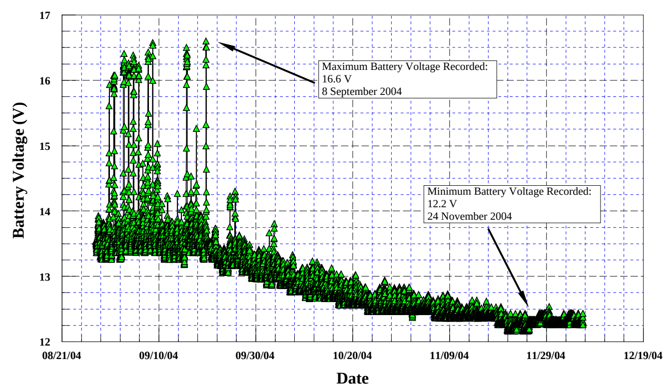

Fig. 6: Fall Cape Shavor NiCad battery voltage from August 27 – December 6, 2004.

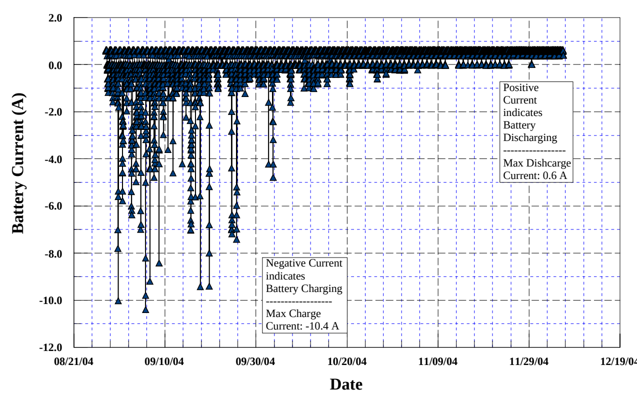

Fig. 7: Fall Cape Shavor NiCad battery current from August 27 – December 6, 2004.

Finally, Figure8 represents the cumulative battery current during the fall period. The batteries were experiencing net charge conditions (net negative current) until about September 21. From that point on, the batteries were discharging (current readings became positive). From September 21 until December 6, the batteries discharged approximately 746 Ah to meet the lighthouse load (1).

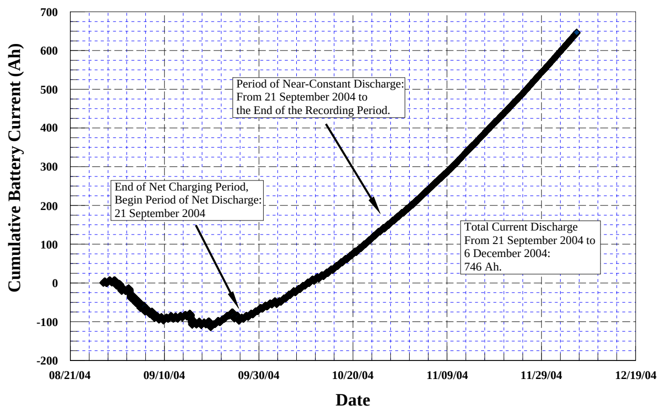

Fig. 8: Cape Shavor NiCad cumulative battery current from Aug 27 – Dec 6, 2004 showing near constant discharge after the fall equinox.

3.2 Honningsvag, Norway

The photovoltaic system installed in the summer of 2003 in Honningsvag, Norway (Figure 1) is identical to the system installed in Cape Shavor. The system consists of five PV 40 Wp modules capable of producing 200 Wp total. A charge controller is used for charging the 12 Volt, 950 Ah NiCad battery bank. The system is designed to operate a 10 Watt Navi-Dals LED beacon at a 50 percent duty cycle throughout the polar night. The DAS was operated from January 27 through June 5, 2004. This allowed collection of data during the period of lowest battery voltage from maximum winter discharge to full summer recharge of the batteries. Figure 9 shows the battery voltage during this period (1).

The lowest battery voltage was recorded on February 3 at 12.37 Volts. The first sunny day lasted approximately five hours on February 6 and represents the start of battery recharge. Prior to this date, there were only days with three to four hours of partial sunlight. The battery continually charged until it was fully recharged on March 28 as indicated by a voltage spike (PV array open circuit voltage) produced due to the battery's inability to accept any additional charging current (1).

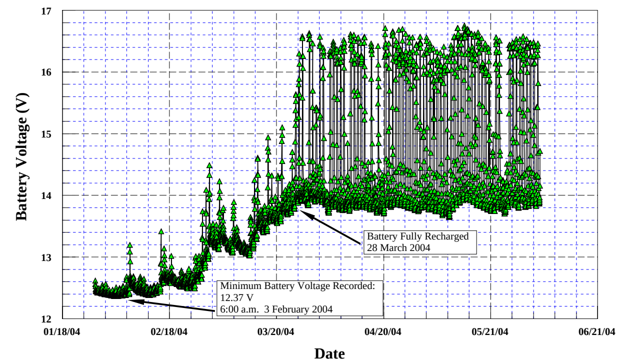

Fig. 9: Honningsvag NiCad battery bank voltage from Jan 27 – June 5, 2004.

Figure 10 shows the cumulative battery current for the Honningsvag PV lighthouse system. The battery experienced a net discharge until mid-February as evidenced by the positive current in the graph. After mid-February the battery was continuously charged until March 28 when it was fully charged, as evidenced by the negative current readings and the rise in battery voltage as illustrated in Figure 10. The battery continued to trickle charge after March 28. The net battery charge recorded was 612 Ah of charge. Given a 950 Ah capacity battery bank accepting 612 Ah of recharge, it is estimated that the total depth of discharge over the winter was approximately 65 percent of the total battery capacity (1). This is acceptable usage for a NiCad battery bank and should not damage the battery bank (1).

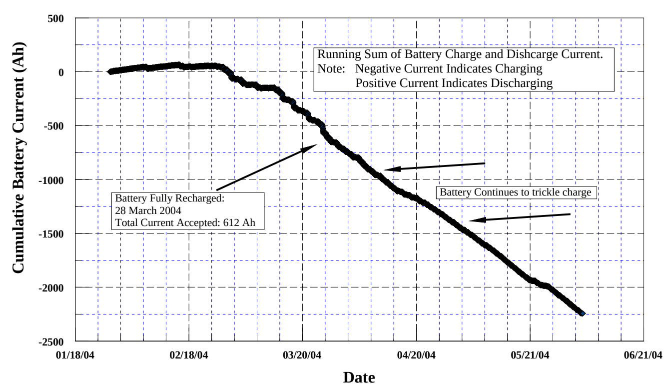

Fig. 10: Honningsvag NiCad cumulative battery charging current demonstrating growing charging current as the spring progresses.

3.3 Karbas, Russia

In addition to the two systems discussed previously, eight additional systems were installed at operating lighthouses by the Norwegians and in cooperation with the Murmansk regional government. One of these sites, Karbas, is a hybrid system which also incorporates a small wind generator to supplement the PV array. The battery voltage recorded at Karbas system is shown in Figure 11. The charging profile is different for this system than for the two other PV systems with no regular daily cycle. As shown, the minimum voltage recorded in this summer data was 12.7 V. Figure 12 shows that even in calm wind periods from July to August 2005, the average battery voltage was trickle charged by the PV system and maintained above 12.8 V.

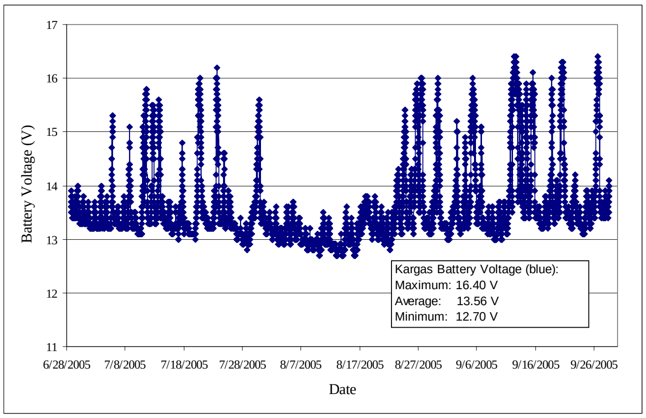

Fig 11: Karbas summertime NiCad battery voltages.

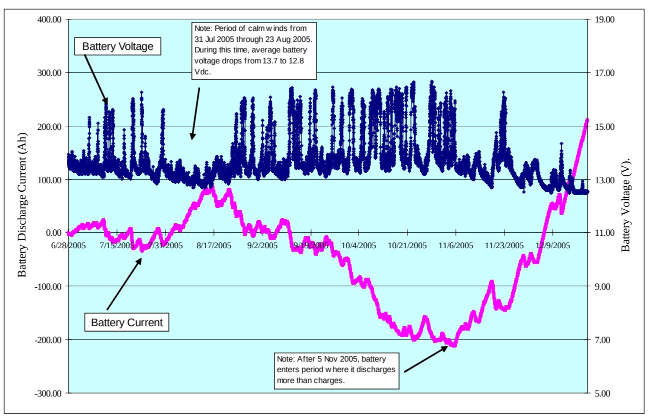

Fig 12: Karbas hybrid system NiCad summer/fall battery current and voltage.

3.4 Overall Battery Performance Comparison

In general, the PV lighthouse designs have proved sufficient to operate the LED beacon load throughout the winter. The key for an all solar system is to have a sufficiently sized battery bank that can last the weeks of the polar night. The minimum battery voltage recorded was 12.37 volts at the Honningsvag installation and the batteries recharged from early February through the end of March. Thereafter they were maintained at float charge thoughout the summer. At the end of the dark period, the Honningsvag battery accepted 612 Ah of current, indicating that the maximum depth of discharge for that battery was approximately 65 percent during the winter with a 35 percent state of charge remaining.

There were only some minor system mechanical issues with the installations. The front ordinary glass of the PV panels sometimes cracked from the extreme thermal cycling. There was also some rust buildup on the lighthouse. The supplier response has been to incorporate tempered glass toreplace to the ordianary in panels. Stainless steel hardware will be used to replace the ordinary steel hardware of the original design.

Table 1 summarizes overall NiCad battery performance data for the Russian Cape Shavor system from 2005-07. The negative values on the Table 1 indicate charging amp-hours while positive values represent discharging. During the first years of operation the NiCad batteries performed well and maintained capacity. After several years of operation the NiCad battery bank showed some reduced capacity. Voltage and currents recorded at Shavor from winter periods showed that the battery bank voltage minimum gradually dropped over the years. Excessive battery discharge was observed in the winter of 2005-2006 and consequently the system went offline for a short period. Figure 13 shows the voltage and current recorded for December through June during which the battery voltage recorded was as low as 10V in 2005 and 5.7V in 2006. Despite undergoing excessive discharge, it does show that the battery bank voltage recuperated during the spring of 2006 after suffering three battery bank over-discharge events. Battery capacity decreases with age, depth-of-discharge, and operating temperature. It is likely that the excessive discharged experienced last winter, has reduced some capacity of the battery in 2006

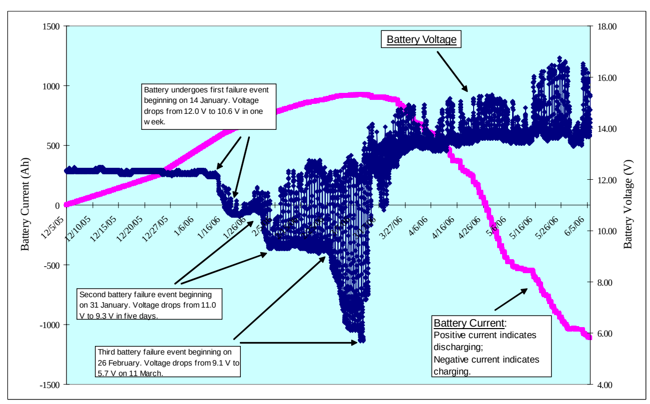

Fig 13: Cape Shavor Nickel Cadmium battery current and voltage: Dec 5, 2005 to June 6 2006.

TABLE 1: SHAVOR BATTERY PERFORMANCE

Date	Net Batt Ah Charge	Avg Batt Volts	Max Batt Volts	Min Batt Volts	Avg Batt Temp °C	Monthly % Batt Discharge
2005						
Jan-June	N/A	N/A	N/A	N/A	N/A	N/A
July	-532	14.1	16.6	13.2	16.1	0 %
Aug	-295	13.8	16.5	13.1	15.1	0 %
Sept	-43	13.6	16.7	13.0	9.2	0 %
Oct	278	12.7	13.4	12.4	4.4	29.3 %
Nov	387	12.4	12.8	12.3	0.0	40.8 %
Dec	370	12.2	12.4	12.1	-6.0	39.0 %
2006						
Jan	360	11.4	12.3	10.2	-6.8	38 %
Feb	167	9.9	12.7	10.1	-9.6	18 %
Mar	-23	11.4	14.9	5.7	-5.5	0 %
Apr	-903	13.7	15.3	13.1	3.9	0 %
May	-814	14.1	16.7	13.3	7.8	0 %
June -Oct	N/A	N/A	N/A	N/A	N/A	N/A
Nov	367	12.4	12.7	12.3	-6.0	39 %
Dec	442	12.4	12.5	12.3	-3.1	46.5 %
2007						
Jan	380	11.2	12.3	9.4	-7.5	40 %
Feb	185	9.7	12.3	9.2	14.5	19.5 %
Mar	-168	12.0	14.5	8.8	0.0	0 %
Feb	-596	14.0	15.0	13.0	2.5	0 %
Mar	-826	13.9	16.3	13.5	6.4	0 %
Apr	-415	14.1	16.5	13.4	9.3	0 %

TABLE 2: KARBAS BATTERY PERFORMANCE

Date	Net Batt Ah Charge	Avg Batt Volts	Max Batt Volts	Min Batt Volts	Avg Batt Temp °C	Monthly % Batt Discharge
2005						
June	-0.4	13.5	14.0	13.3	11.5	0 %
July	18.7	13.5	16.2	12.8	16.2	0 %
Aug	-30.8	13.3	16.0	12.7	14.9	4 %
Sept	60.8	13.8	16.4	12.8	16.2	0 %
Oct	153.8	14.5	16.6	13.2	4.9	0 %
Nov	-143.1	13.6	16.3	12.5	0.7	15 %
Dec	340.1	12.7	14.3	12.3	05.7	36 %
2006						
Jan	-41.85	13.2	14.3	12.5	-5.9	5 %
Feb	8.7	13.6	14.5	13.6	1.4	0 %
Mar	-102.9	13.7	16.4	13.0	-5.9	11 %
Apr	-55.8	13.6	15.1	13.1	2.8	6 %
May	-55.8	13.9	16.6	13.0	6.9	6 %
June	-44.6	13.7	16.4	12.8	13.2	5 %
July	13.4	13.9	16.5	13.1	13.4	0 %
Aug	-179.5	13.1	14.0	12.7	13.2	19 %
Sept	40.8	13.6	16.8	12.9	7.4	5 %
Oct	-216	13.7	16.7	12.6	0.8	23 %
Nov	-203	12.8	13.8	12.3	-5.2	22 %
Dec	-428	12.6	13.5	12.3	-2.6	45 %

Table 2 summarizes NiCad battery performance for the Karbas hybrid system site. This site has sufficient wind resource to maintain battery voltage even during the dark winter period. Minimum recorded battery voltage was only 12.3 Volts all winter. The highest discharge month recorded was in December 2006 at 45% discharge, but this deficit was readily recharged by the wind turbine and battery bank voltage never significantly dropped as compared to the all solar systems.

4. CONCLUSIONS

The PV LED lighthouses have met the LED load in the extreme Arctic environment. They key to success for these systems is sufficiently sizing the battery bank large enough to last the many weeks of the long polar night, so supplementing power generation with wind energy. Comparison of these systems reveals valuable performance characteristics of both PV and NiCad batteries in Arctic conditions. The durability of NiCad batteries in cold climate is clearly demonstrated by their continous operation in discharge mode during months of darkness and sub-freezing temperatures.

There have only been some small mechanical deficiencies noted from using ordinary plate glass that cracked due to thermal cycling, and rust on metal hardware. Tempered glass and stainless steel hardware correct these issues.

NiCad batteries were appropriately selected for the extreme cold and have proved to operate reliably in a winter climate in which they experienced operating temperature as low as -14°C or (2.7°C annual average). All lighthouses performed well during the sunny months (March to November) sufficiently charging and maintaining battery voltage in excess of 12.2 Volts (average). During the winter periods of polar night darkness (November through early February), NiCad batteries experienced voltage drop to as low as 8.8 Volts. Even with the low voltage drop, the batteries maintained sufficient capacity to keep the LED beacon load powered throughout the winter until PV current charging resumed in February. The NiCad batteries would recover their full capacity during the summer periods. Despite the deep discharging cycle behavior and the abuse during freezing condition, results show that after four years of operation there has been minimal storage capacity decrease in the batteries and the PV LED lighthouse systems continue to perform reliably. Similarly, hybrid systems that added a small wind turbine to the PV system, as in the case of Karbas, helped maintained fully charged battery bank voltages during the dark winter months.

This project demonstrates that alternative energy systems can be used effectively to power remote lighthouses and beacons even in extreme Arctic conditions, and thus replaced RTG powered lighthouse beacons. The unique and robust characteristics of these PV systems enable the removal of highly radioactive materials from the delicate Arctic environment.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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