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APPLICATION, SIZING, TESTING AND PERFORMANCE OF THE PHOTOVOLTAIC BATTERY SUBSYSTEM AT NATURAL BRIDGES NATIONAL MONUMENT, UTAH

November 1981

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Prepared for
THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE-AC02-76ET-20279

Additional copies available from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $6.50
Microfiche $3.00

DOE/ET/20279-153

Distribution Category UC 63a-e

DOE/ET/20279--153

DE82 007040

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ABSTRACT

An MIT Lincoln Laboratory Request for Proposals for the battery subsystem for the 100-kW peak photovoltaic power system for Natural Bridges National Monument (NBNM) was released on 24 May 1978. Two years later, on 7 June 1980, the system was dedicated.

During those two years, the battery subsystem was designed, modified, tested, installed, retested and again modified. The subsystem includes 224 lead-acid (with calcium alloy) cells, hydrogen recombiners, an air-lift pump system and electrolyte level indicators. Problems and solutions related to these subsystem components are discussed. Further details concerning the battery selection, design, tests and performance throughout the battery's life are also included.

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1.0 NATURAL BRIDGES NATIONAL MONUMENT

A 100-kW peak photovoltaic (PV) system was installed at Natural Bridges National Monument (NBNM) in Utah during the winter and spring of 1980. It is a stand-alone system, as shown in Fig. 1, containing a 100-kW peak PV array, a 750-kWh storage battery subsystem, a 50-kVA inverter, a 5-kVA uninterruptible power supply (UPS) inverter and a 40-kW diesel generator. The diesel generator provides backup power to supplement or replace the array/battery energy output to the load and to supply energy for periodic battery equalization via a battery charger. The batteries are cycled daily by charge from the PV array and discharge to the site load through the main inverter.

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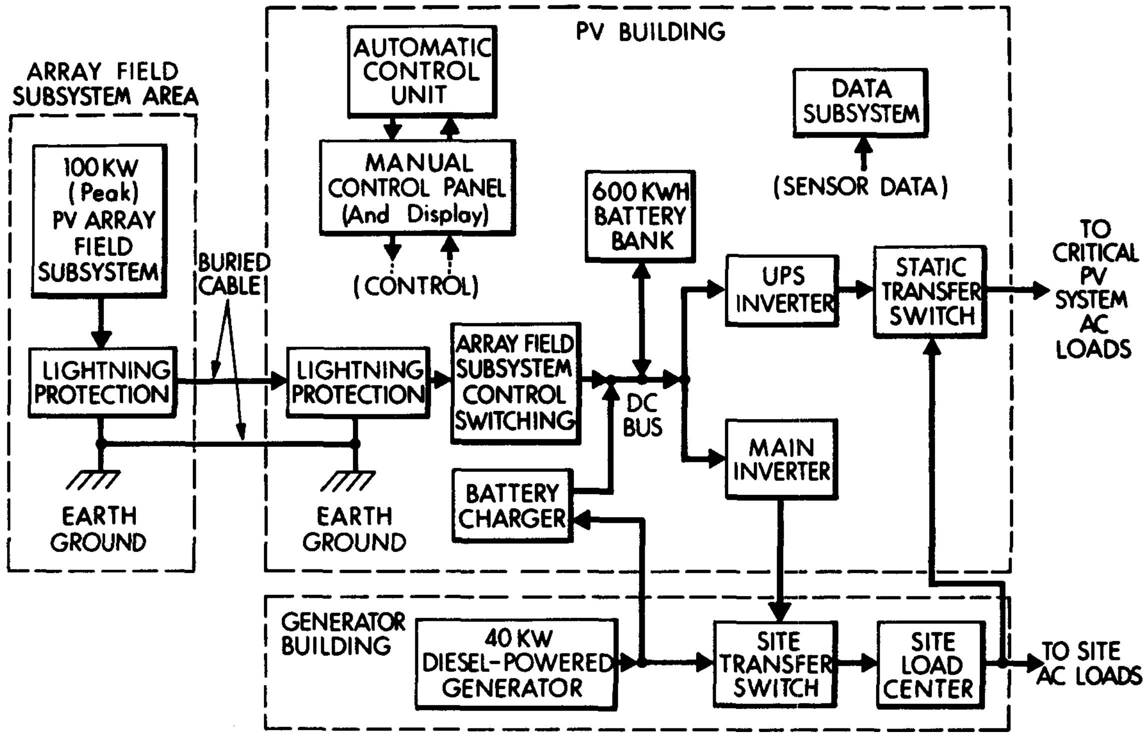

Fig. 1. NBNM PV power system block diagram.

NBNM is located in the southeast corner of Utah, almost 40 miles west of Blanding, Utah, and about 80 miles northwest of the point where the four states of Utah, Arizona, New Mexico and Colorado meet. It is administered by the National Park Service (NPS) and was selected by the Department of Energy (DOE) to be the site of the PV power system. (1) The major factors which make this site an ideal location for a PV system are its remoteness, its electrical independence (the electricity was previously supplied by two diesel generators), a diversified year-round range of electrical demand and energy consumption, and its abundant insolation at 6500 feet for 300 days annually.

The NBNM site loads consist of a visitor center, three residences, three small apartments, two trailers for the temporary staff and a maintenance building. Minor loads are a generator building, fee station, well house, and new PV building which houses the batteries, power conditioning, control, and data units. The most recent measurements and estimates show that the average daily load with conservation measures will be less than 10 kW or 240 kWh (see Table I). There is no distinct daily profile. The average consumption before the PV installation was 12 kW in the summer and 17 kW in the winter. (The high winter load was due to the excess of electric heaters which have since been removed.) The peak power demand had been as high as 27 kW before the PV installation. As will be shown, these loads represent a very light discharge rate for the deep-discharge designed batteries.

TABLE I

NBNM SITE LOADS

Load Sites	Summer Loads Before PV	(kW/24 hrs) After PV	Winter Loads Before PV	(kW/24 hrs) After PV
Visitor Center	7.0	4.0	7.5	3.0
Residences	2.5	2.0	3.5	2.0
Maintenance Building	2.0	1.5	5.5	2.5
Generator Building	0.5	0	0.5	0.5
PV Building	0	0.5	0	1.0
TOTAL	12.0	8.0	17.0	9.0

2.0 SIZING

The NBNM battery subsystem design considerations and selection procedures have been used as a design example in the Handbook for Battery Energy Storage in Photovoltaic Power Systems by Bechtel National, Inc. (2) They are also described here in greater detail along with the manufacturer's charge and discharge curves.

2.1 Energy Storage Requirements

The early studies of site loads were made by spot-checking power consumption, examining power ratings, and devising design models and system simulations. It was determined at that time that the maximum battery discharge power rate would be less than 40 kW and that the daily average energy removed from the battery would be 450 kWh, with a maximum of 600 kWh.

Battery voltage requirements were generally established by power level and were specifically constrained by present industrial standards and operating voltage ranges (voltage window) for available inverter equipment. Based on these considerations, it was determined that the allowable battery voltage range (from discharge cut-off to equalization) would be 210 to 280 volts.

It was also decided that the minimum acceptable life would be five years with the battery subsystem capable of delivering 600 kWh of useable capacity at end of life. The operating temperature range was specified as 35°F to 95°F with the possibility of experiencing a non-operating temperature as low as -11°F if the heating system should fail and the site become non-operational.

2.2 Battery Selection

Only one battery manufacturer responded with a proposal, C & D Batteries Division. The battery size and makeup was then determined through negotiations with C & D. The battery requirement was large enough to warrant some custom design, and C & D proposed a design based upon its industrial-type deep-discharge battery for propelling electric industrial lift trucks. The number of plates per cell, the modular organization into steel trays and the cell top layout were customized to NBNM requirements.

Due to the restrictive operating voltage window, a relatively low final charging voltage was necessary to allow adequate depth of discharge. This top voltage was established at 2.50 volts/cell with the provision that air-lift pumps (see Section 2.3.4) be employed to provide mixing of the electrolyte. Normally, electrolyte mixing is accomplished by the gassing accompanying higher charge voltages; however, due to a relatively tall cell height in addition to the lower voltage, this normal method would not have provided sufficient mixing.

The voltage window established the number of series-connected battery cells required: 280 volts divided by 2.50 volts per cell determined that 112 cells were required. The final cell discharge voltage was determined by dividing the final discharge voltage of 210 volts by 112 cells, providing a relatively high level of 1.875 volts per cell.

To have 600 kWh available at end-of-life with an expected deterioration to 80% of rated capacity (end-of-life for a lead-acid battery is generally defined as the point where the capacity drops to 80% of the rated capacity), an initial, or rated, battery capacity of 750 kWh was indicated. The maximum discharge rate may be approximated by dividing 750 kWh by 40 kW (maximum battery discharge rate), which is the 18.75 hour rate.

"Fan curves" defining storage capacity per positive plate were used to determine the exact effect of the final discharge voltage limit and to establish cell size. Fan curves for specific plate designs are available from many manufacturers. These curves present the capacity in ampere-hours that can be removed from a plate as a function of discharge current (in amperes) at various discharge rates (in hours) to various final discharge voltages. The fan curve used for this design is presented in Fig. 2.

The required cell was manufactured with a standard plate design characterized by the curves presented in Fig. 2, and the number of plates was set in accordance with storage requirements. The standard plate design provides a rated capacity of 160 Ah at a 6-hour rate to a final discharge voltage of 1.70 volts/cell. Figure 2 also indicates that, for this system, the installed capacity (i.e., the available plate capacity when discharged at the system specified rate of 18.75 hours to 1.875 volts/cell) is also 160 Ah. Therefore, the relatively high final discharge voltage limit is ameliorated by the relatively low discharge rate.

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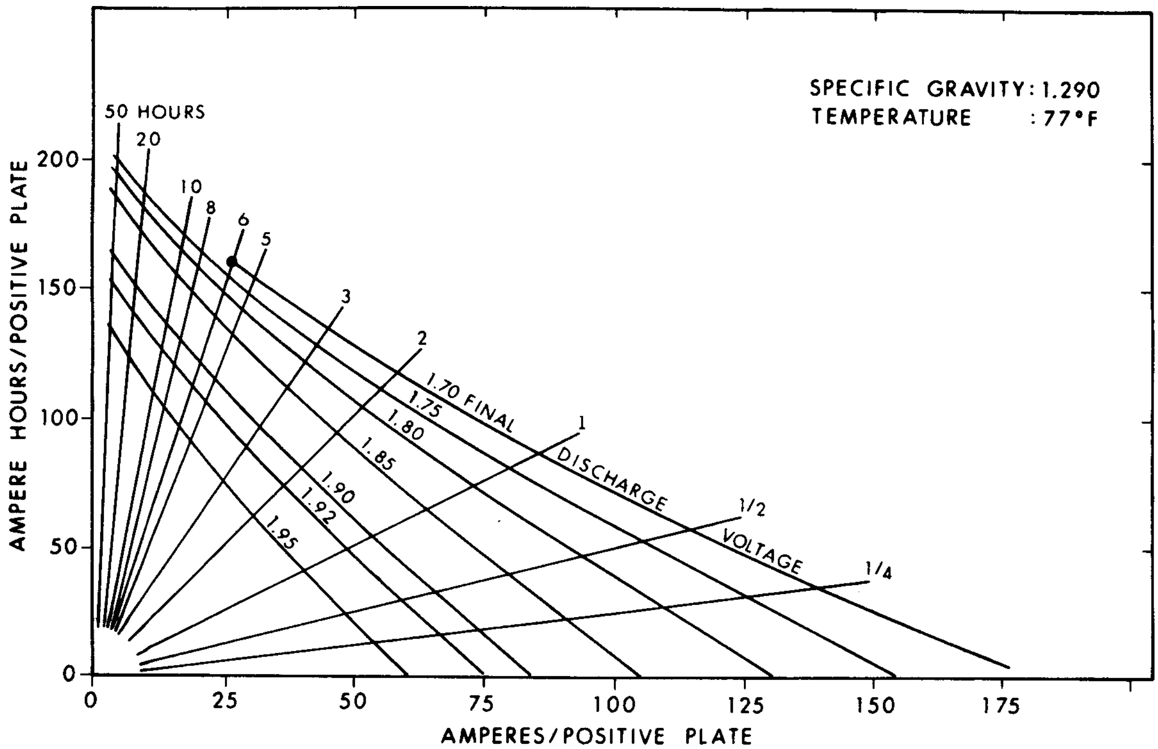

Fig. 2. NBNM battery fan curves from C & D Batteries Division.

The total number of positive plates required was determined by dividing the total required capacity of 750 kWh by the capacity per positive plate. Assuming an average of 1.93 volts/cell during discharge, the total capacity per positive plate became 160 Ah x 1.93 volts/cell x 112 cells, or 34.58 kWh/plate. Dividing 750 kWh by 34.58 kWh/plate equals 22 positive plates.

Cell construction is such that:

Total plates/cell = 1 + 2(Total positive plates/cell).

Solving this equation results in the requirement for a 45-plate cell, which is larger than commercially available versions of the cell design selected for this application. Therefore, two 23-plate cells (11 positive plates/cell) in parallel were selected and they provide a rated capacity of 761 kWh (22 plates x 34.58 kWh/plate). This results in an average daily depth of discharge of 59% [450 kWh (from section 2.1) divided by 761 kWh] and a maximum daily depth of discharge of 79% (600 kWh divided by 761 kWh). Under these conditions, C & D estimated a 6-year battery life.

2.3 Battery Cell Description

In summary, each lead-calcium cell includes a total of 23 plates, 11 positive and 12 negative plates. The 11 positive plates each have a capacity of 160 Ah providing a total cell capacity of 1760 Ah at the manufacturer's 6-hour rate to a final discharge voltage of 1.70 volts per cell. With a rated battery energy capacity of 761 kWh (obtained by multiplying the average discharge voltage by the ampere-hour capacity: 1.93 v/c x 1760 Ah x 224 cells), the useable energy capacity is 80% of 761 kWh or approximately 600 kWh. The expected operating range of battery discharge rates is shown in Fig. 3.

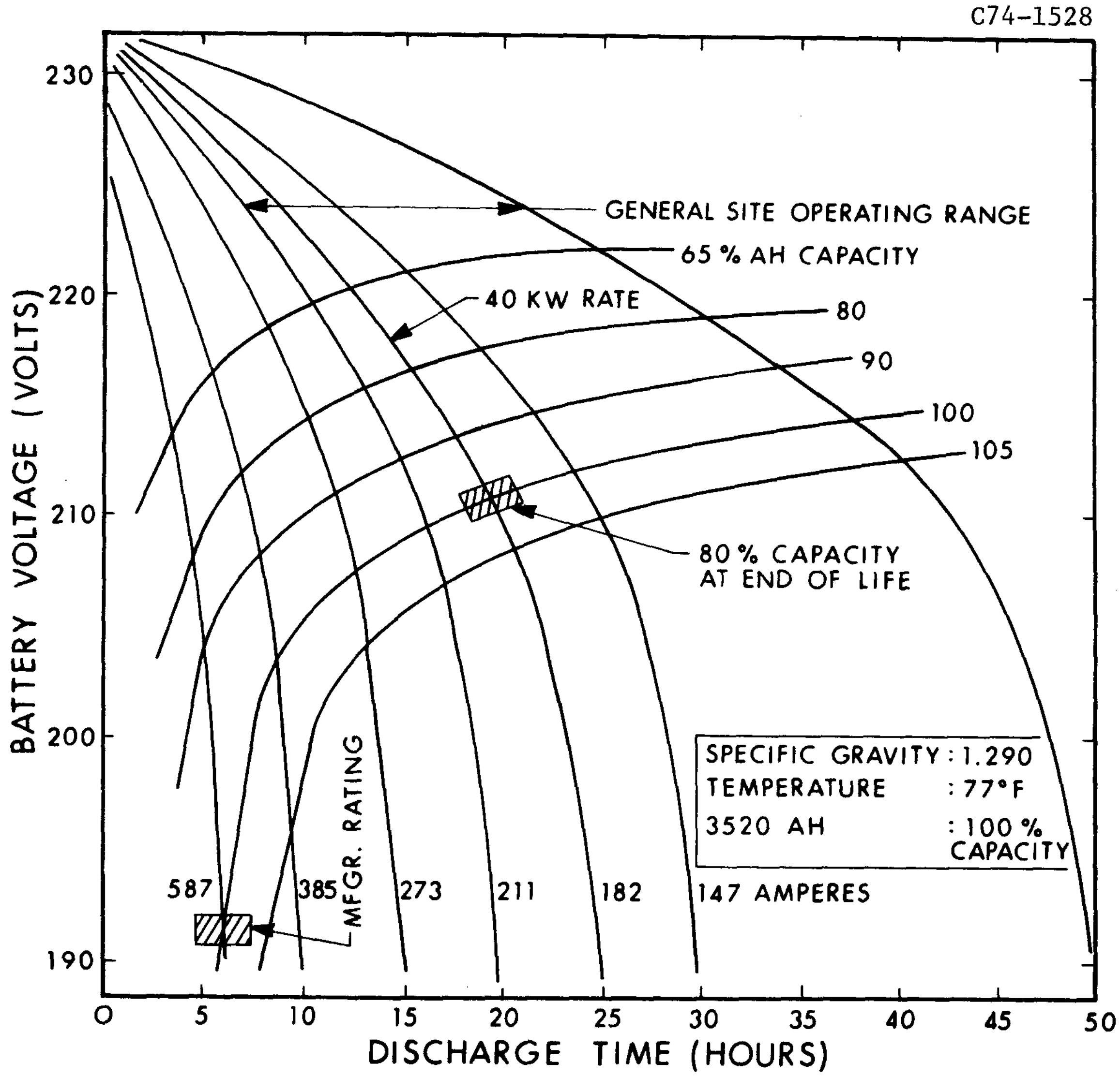

Fig. 3. Manufacturer's beginning-of-life discharge curves.

An alternate hybrid cell design, using lead-antimony positive plates and lead-calcium negative plates, was also considered. Although it was expected to yield 6% more output at any discharge rate, the increased gassing, power loss and water consumption made it an unacceptable choice. Refer to Section 2.3.2.

2.3.1 Antimony vs. Calcium

Pure lead is too soft and weak to fabricate grids for deep-discharge applications and tests are being made with various kinds of additives. (3) Antimony is the most common element employed as an alloying agent with lead as it increases the tensile strength of the grid and casting ability of pure lead. Antimony, however, migrates from the positive grid to the negative plate during charge, causing an increased self-discharge rate and a lower hydrogen over-voltage of the sponge lead. During charge conditions, the lower hydrogen over-voltage causes the cell to gas at a lower potential, hence a higher charge current is required to offset these side reactions and keep the negative plates charged. The higher charge current hastens the corrosion of the positive grid, which releases antimony at a faster rate, accentuating the grid degradation, water loss, and hydrogen gas production.

Calcium hardens and increases the tensile strength of lead, but does not affect the negative plate since calcium is electro-negative to lead (where antimony is electro-positive) and is not deposited on the negative plate. (4) The small amount of calcium which is released as the positive grid corrodes, falls harmlessly to the bottom of the cell. Therefore, the current required to hold a given voltage on charge (or float) in the lead-calcium cell remains constant throughout its life, with minimal water loss and hydrogen production.

2.3.2 Hydrogen Production

The battery room must be ventilated to keep the percentage of hydrogen in air to less than 4% by volume--the point at which explosion can occur. The method of calculating the amount of ventilation required is presented here.

The lead-calcium cell recommended for use at NBNM had a specified rating for a maximum gassing current of 7 amperes at 125°F and 2.50 volts/cell. For the two parallel 112 cell strings, minimum required ventilation is obtained by:

$$Q = \frac{0.027}{C} \times I \times n \qquad \text{(Ref. 5)}$$

where: Q = required ventilation rate in cfm

C = maximum allowable hydrogen concentration in percentage

I = charging current through cells

n = number of total cells in battery.

If a 2% maximum hydrogen concentration is allowed, the amount of air circulation necessary to keep the atmosphere clear of hydrogen is:

$$Q = \frac{0.027}{2} \times 7 \times 224 = 21.2 \text{ cfm.}$$

This required ventilation of 21.2 is relatively low and comparable to a total natural air change within the 10 by 50 by 9-foot room provided for the battery storage facility in:

$$\frac{4500 \text{ ft}^3}{21.2 \text{ cfm} \times 60 \text{ min/hr}} = 3.5 \text{ hours.}$$

This battery room was designed to allow for a total air change in 3.5 hours through two large exhaust fans, one single and one double door, door louvers, and four windows.

The power consumption associated with the hydrogen production during equalization is:

280 volts x 14 amperes = 3.9 kW.

If equalization takes 15 hours, the energy involved is 58.5 kWh, which is a small portion of the total site energy consumption and therefore of no great concern.

For the alternate hybrid battery, gassing was expected to be three to four times as much as the calcium battery initially, and up to 30 or 40 times as much at end-of-life. This corresponds to a high minimum ventilation requirement of 21.2 x 40 = 848 cfm and a significant power consumption of 3.9 x 40 = 156 kW. (This would be impossible to provide by using on-site equipment.) In addition to these unfavorable figures, the self discharge for the hybrid cell at 77°F was indicated as 10% per month initially and as much as 10 to 15% per week at end-of-life. For the calcium cell, a constant 10 to 12% per year was indicated. The hybrid construction was therefore rejected and the calcium cell accepted.

2.3.3 Hydrogen Recombiners

Certain accessories were added to the lead-calcium cells to assure full operation to the expected end-of-life. Figure 4 is a photograph of the finished battery module which is made up of two rows of four series cells. These cells are not paralleled within the module so that the modules may be connected together to form two long strings. Refer to Section 4.1.

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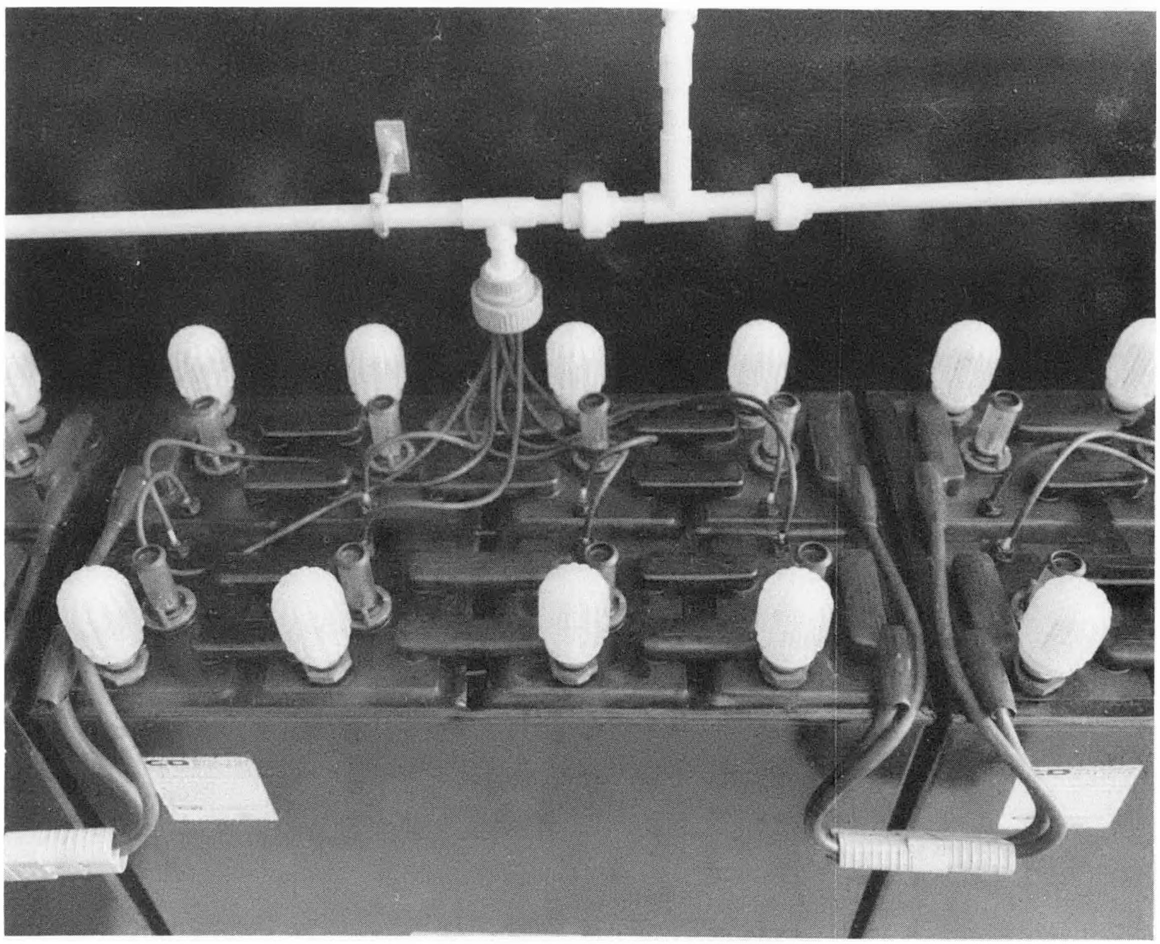

Fig. 4. NBNM battery module.

The insertion of hydrogen catalytic recombination devices into each cell was recommended in place of a complex hydrogen exhaust system to recombine the hydrogen and oxygen given off near end-of-charge. The recombiner then allows the resulting water vapor to condense and flow back into the cell, thus minimizing the amount of hydrogen escape and water loss. Appendix A shows the efficiency curve of the hydrogen recombiner supplied by its manufacturer, Hoppecke. [NB The hydrogen recombiners cannot be used with any lead-antimony cell because the antimony hydride (stibine gas) given off slowly poisons the catalyst of the recombiner and decreases its effectiveness and reliability.] At an efficiency of 80%, this recombiner reduces ventilation requirements to: 20% x 21.2 cfm = 4.2 cfm, which would permit safe operation with little or no forced ventilation. This simplifies battery installation and reduces unnecessary heat loss through ventilation in cold weather. The selected recombiners have a 15-ampere rating.

2.3.4 Air-Lift Pumps

Another feature of the NBNM battery subsystem is the use of air-lift pumps to agitate the electrolyte at the end-of-charge. This addition was necessary in order to prevent electrolyte stratification. Because of the limited top charging voltage of 2.50 V per cell, there is insufficient gassing at the end-of-charge to mix the electrolyte completely. Continued operation of the batteries in stratified electrolyte causes nonuniformity of depth-of-discharge over the plate surface. The electrolyte density (specific gravity) which surrounds the bottom of the plates becomes very high and the active material in that portion of the plates discharge to a greater depth than the active material at the top of the plates where the electrolyte density is lower. This results in softening of the positive active material and subsequent loss of capacity at the bottom of the plates. Appendix B shows the side view of a lead-calcium cell with a hydrogen recombiner, an air-lift pump and an electrolyte level indicator.

Electrolyte agitation is accomplished by forcing air through tubes inserted into each cell, such that the air is bubbled through the electrolyte from the bottom of the cell, thus mixing the electrolyte to prevent stratification. A low pressure air supply of 5 psig is used to supply 0.03 scfm to each cell through a plastic distribution manifold. Orifices inserted into each cell line insure equal air distribution. The air is stored in a 120-gallon tank which is capable of supplying a constant air flow to the cells for one cycle lasting approximately 15 to 20 minutes. This air-lift system is automatically cycled three times every afternoon when the array power output begins to drop, for a total of 45 to 60 minutes. (Air pumped into the cells is normally vented through the recombiners.) The three cycles are spaced two hours apart at 12:00, 2:00 and 4:00 p.m.

2.3.5 Level Indicators

The third cell accessory (Appendix B) visually indicates to an observer the level of the cell electrolyte. This is done by means of a styrofoam float which follows the electrolyte surface and is connected to a plastic tube topped by a marker. The marker indicates whether or not the cell needs water. Water is added, if necessary, only at the end of a full charge when the electrolyte level is at its highest. After the termination of the charge, the level drops slightly as entrapped gas is vented from the cell. The level indicator then displays the correct high-level condition. A pressure relief cap is located on the top of each indicator to prevent dangerous buildup of pressure within a cell due to the air-lift operation. Although air is normally vented through the recombiner and non-airtight seals around the three accessories, the relief cap is a necessary extra precaution.

2.3.6 Manufacturer's Curves

C & D has provided a set of charge and discharge curves (Appendix C) from which to determine the battery's operating characteristics. Discharge curves are given for the 8-hour to 50-hour rates (constant current discharges), and the charging curves are given for a constant current/constant voltage-type charge from various states of discharge. Further tests were made on the battery to develop and expand the charge/discharge curves at various constant current rates; these tests are described in Section 3.2.

3.0 TESTING

Several tests were run on the battery subsystem both at the factory and at MIT Lincoln Laboratory. The standard acceptance test was run at C & D Batteries

Division. At Lincoln Laboratory, tests were run under expected PV array charging and NBNM load discharging conditions. Tests were also performed on the hydrogen recombiners, level indicators and air-lift pump system at MIT Lincoln Laboratory, where all of the battery modules were set up as a system.

3.1 Acceptance Tests

3.1.1 Battery Cells

The standard C & D battery acceptance test was performed on 14 August 1979 at the C & D plant in Conshohoken, Pennsylvania. (From the time that the C & D proposal had been accepted to the battery cell acceptance test, eleven months had elapsed.) The test consisted of a full-capacity discharge at the manufacturer's rating, i.e., the 6-hour rate (constant 293 A/cell) to 1.70 V/cell. The cells were to reach an 85% capacity, which means that by the time 1496 Ah/cell (0.85 x 1760 Ah) had been removed, the cell voltage should not have dropped below 1.70 volts. NB During the first 6 to 8% of a battery's life, the battery chemistry gradually approaches its peak-capacity condition. It takes approximately 10 to 20 cycles before the battery can give 100% of its rated capacity. This is part of the formation process of the battery plates.

Open-circuit voltage, cell specific gravity and cell temperature were taken on a pilot cell before the test began. (The cells had previously been equalized.) Sixty randomly selected cells were connected in series and each cell's voltage was taken approximately every hour. Appendix D gives the temperature correction factor and test data. Towards the end of the discharge, the readings were taken at the calculated times corresponding to 80%, 85% and 90% capacity. For example: at a starting temperature of 83°F, it would require 6.13 hours at 293 amperes to discharge the cell 100%. This gives an equivalent total capacity of 6.13 hr. x 293 amperes = 1797 Ah. Therefore, it would take 80% x 1797 Ah divided by 293 amperes or 4.90 hours to reach an 80% depth-of-discharge at the 293-A rate. With a starting time of 0850, the finish time is 4 hours 54 minutes later or 1344.

It was shown that each cell had reached 85% capacity and, in fact, all but one of the 60 cells had reached 90% capacity. It would have been desirable to trace that one lower cell throughout its life; unfortunately, C & D does not serialize its cells until they are built into modules, hence the present position of this one lower cell is unknown.

The lead-calcium cells were then accepted to be placed into the battery modules.

3.1.2 Battery Accessories

The acceptance tests on the special devices on the tops of each cell were made in December 1979 at MIT Lincoln Laboratory. Many problems were found with all three devices, the hydrogen recombiner, the air-lift system and the level indicator. (6) The main problem was in the integration of the three units, each of which had operated satisfactorily individually but not in combination. Modifications had been made to the original designs which in turn resulted in new problems. After the tests at MIT Lincoln Laboratory, further redesign and modifications were made by C & D in conjunction with MIT Lincoln Laboratory at the NBNM site in 1980.

When the batteries arrived at Lincoln Laboratory in October 1979, testing began immediately to confirm and augment the charge/discharge curves received from C & D. The completed air-lift system arrived later and was installed and connected to all 224 cells for initial testing. C & D had only been able to test the air-lift with eight cells (one module) because of space limitations at their plant.

One restrictor (orifice) was used to supply a given air flow to each group of eight cells. It was found that the hydrogen recombiners caused back pressures to build within the cells, affecting electrolyte levels. This resulted in electrolyte being forced or pumped through the level indicators, causing electrolyte to be sprayed over the battery module.

Some of the causes of the cell back-pressure differences (other than the hydrogen recombiner) included air-lift pump tubes which were cracked or broken just below the cell cover. It was found that the tubes were both defective and had been improperly inserted. All air-lift pump tubes were therefore replaced by tubes from a different batch. In addition to the air-lift problem, the electrolyte level indicators were prone to sticking because of liquid surface-tension effects and stray particles from the styrofoam float. The resultant blockages caused high internal battery pressures which in turn caused electrolyte to be sprayed over the battery module. C & D Batteries Division went to work to solve both the level indicator and the orifice problems. Solutions were implemented during the summer of 1980 (see Section 5.1).

Yet another problem with the air-lift operation was electrolyte seepage from the air-lift pump tube's seal at the cell top. During the bubbling process, a jet of electrolyte is sprayed onto the under side of the cell top cover at the entry point of the air-lift pump. Since the cell is slightly pressurized because of the recombiner back pressure, leaks in the seal allow electrolyte to seep onto the cell top and form puddles. This problem was found to be caused by defective cover machining which prevented proper gasket seals. The sharp edges caused by the poor machining were rounded off at Lincoln Laboratory, but final tests had to wait until the orifice and back-pressure problems were implemented.

It was believed that many of the problems with the battery accessories could be solved by adding individual orifices to each air-lift pump line so that each cell would be assured of receiving an equal amount of air flow, thus eliminating the need for the single orifice supplying eight cells. (NOTE: The U.S. Navy keeps their submarine batteries from stratifying by having separate air-flow restrictors for each cell.) In fact, individual orifices were finally used at NBNM.

Tests were made on the air-lift system in February 1980 after shipment to the NBNM to confirm the suspected inadequacy of the design of one restrictor for eight cells. (7) (The air-lift system tests were part of a series of tests to check out the installation before final PV system turn on.) The cells were discharged to 30% state-of-charge (SOC) and then recharged to 90% SOC. Specific gravity readings were taken on all 224 cells, the air-lift system was turned on so that each cell was bubbled for 20 minutes, and all gravity readings were retaken.

During discharge, the electrolyte density slowly decreases while the plates are converted to lead sulfate. With the rising of the less dense electrolyte, mixing occurs. During recharge, the electrolyte is converted to a higher specific gravity and sinks to the bottom of the cell. There it remains until an equalization can mix all of the electrolyte or a forced mixing is induced. Therefore, by the time 90% SOC was reached on the recharge test, a significant difference in the specific gravity readings was expected. If there was little or no difference, then it could be assumed that the cell was not getting enough air.

Test results showed that over 25% of the cells showed no significant change in specific gravity readings. This, added to the tests made at MIT Lincoln Laboratory, showed that the fault lay in the design of the air-lift system. C & D agreed to modify the system and to supply new orifices for each cell's air-lift pump.

The electrolyte level indicators were also further redesigned by C & D. The main problem was that during any occurrence of pressure buildup inside the cell case, the electrolyte could be drawn up the tube and sprayed over the battery module, causing corrosion and a possible shock hazard. C & D agreed to redesign the level indicators, thus eliminating the air seal provided by the lower tube surrounding the float and the electrolyte level, and to install a pressure relief device (which would open at about 1 psi) on the top of each level indicator. Earlier tests made by C & D suggested that the lowest bursting pressure of these cells would be approximately 10 psi at the points where the cell top and sides are sealed together. Therefore, a one-psi relief valve would provide a generous safety margin in the event of any pressure buildup.

Further modifications were made as follows:

1. Thicker acid-resistant gaskets were added to the openings in the cell tops to stop leaks and seepages.
2. Covers were spot-faced again to correct defective cover machining.
3. Air-lift system leaks were sealed.

3.2 In-House Testing

From October to December 1979, before the batteries were shipped to NBNM, many tests were made to confirm and augment the charge/discharge curves received from C & D. (8) The purposes of the tests were as follows:

- To determine a family of charge and discharge curves at various constant currents.
- To determine the specific gravity vs. SOC at various rates of charge and discharge and on open circuit.
- To determine cell voltage variations during charge, discharge and on open circuit.
- To verify recombiner operation on each cell.
- To assemble and test the air-lift system.
- To determine and correct any negative effects resulting from the combined operation of the air-lift system, recombiners and electrolyte level indicators.
- To determine the constant power discharge and charge curves at the rate at which the batteries were to be tested at the NBNM site.
- To perform and record sets of tests made at various SOCs which would simulate the effects caused by the solar array during partially cloudy and partially sunny days.
- To gather any data from the tests which would be useful for the NBNM computer simulation of the site operation.

It was established by the tests that the battery subsystem should operate as predicted by C & D, with the inclusion of a few modifications to the air-lift system and the electrolyte level indicators as discussed in the previous section.

The battery tests started with the measurement of a family of charge and discharge curves. C & D had supplied a plausible family of discharge curves which could easily be double-checked. However, little data were available on the charging curves, hence a repeatable baseline charge curve was required. The type of tests made were two full discharges at a very slow rate, the 50-hour rate (this is approximately the slowest rate expected to be used at the site); two full discharges at a very fast rate, the 10-hour rate (this was thought to be the fastest rate to be seen at the site); and four full charges at the C/13 rate (or 15-hour rate). With these four charges, a baseline charge curve was found and further curves could be plotted around this base curve for the computer model (Fig. 5). Numerous measurements were also made of cell specific gravity and cell voltage, along with checks on the operation of the hydrogen recombiners and the electrolyte level indicators. Equalizing curves were also recorded.

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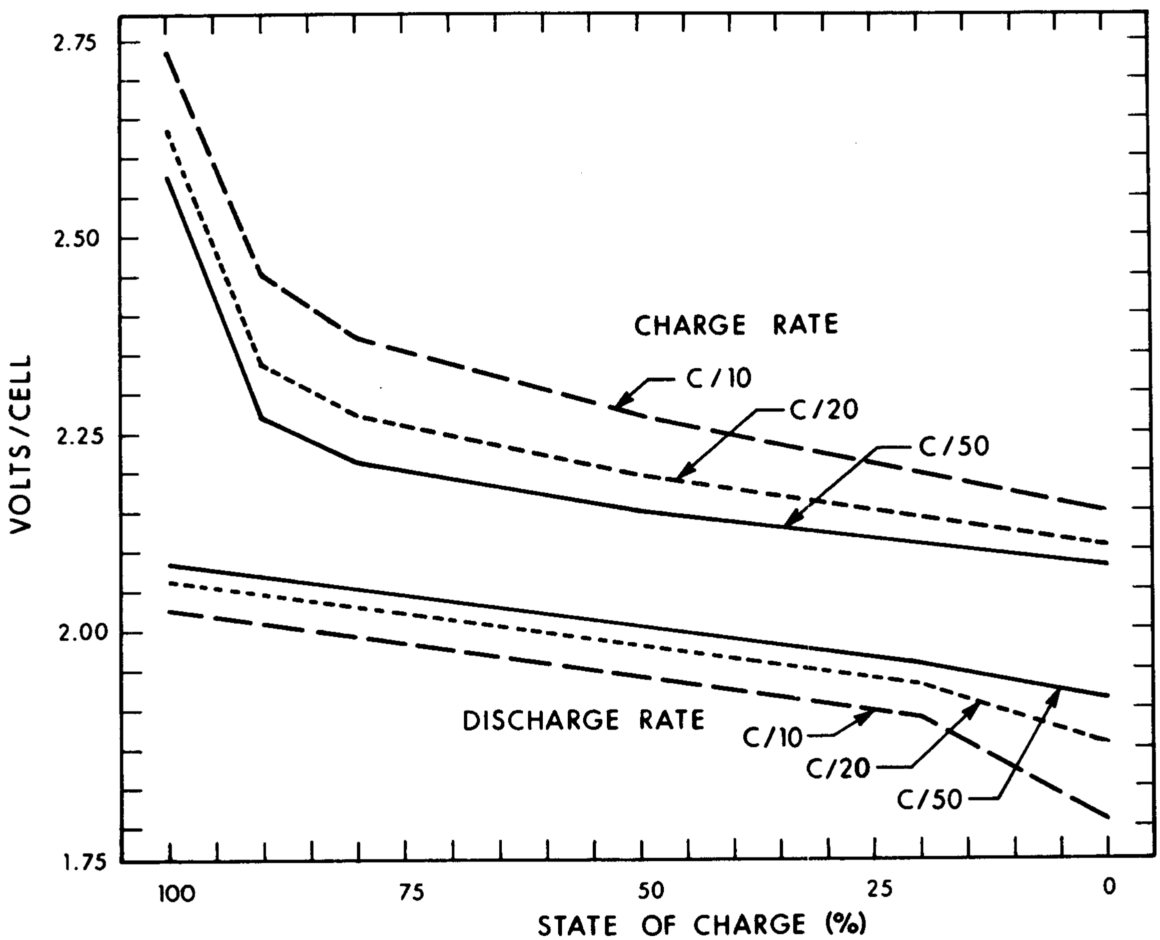

Fig. 5. Simulated NBNM battery characteristics.

The two battery strings were placed in parallel and two full discharges and charges were made at approximately the 40-kW rate in order to determine the characteristic curves of the periodic test runs that will be made at NBNM.

These test runs, called capacity performance tests, can be used to keep track of battery degradation and to warn when new battery cells will be needed. The experimental curves are given in Fig. 6. The theory behind this performance test is to establish a standard curve at a specified rate with a specified final voltage and time (similar to the manufacturer's rating in the acceptance test). If the battery reaches the specified final voltage before the specified time, then the battery's capacity has dropped and end-of-life is near. In this application, it was decided to choose constant power discharge and charge rates as this would be the easiest to set up at NBNM. The 42-kW rate was chosen as a suitable rate for both charge and discharge.

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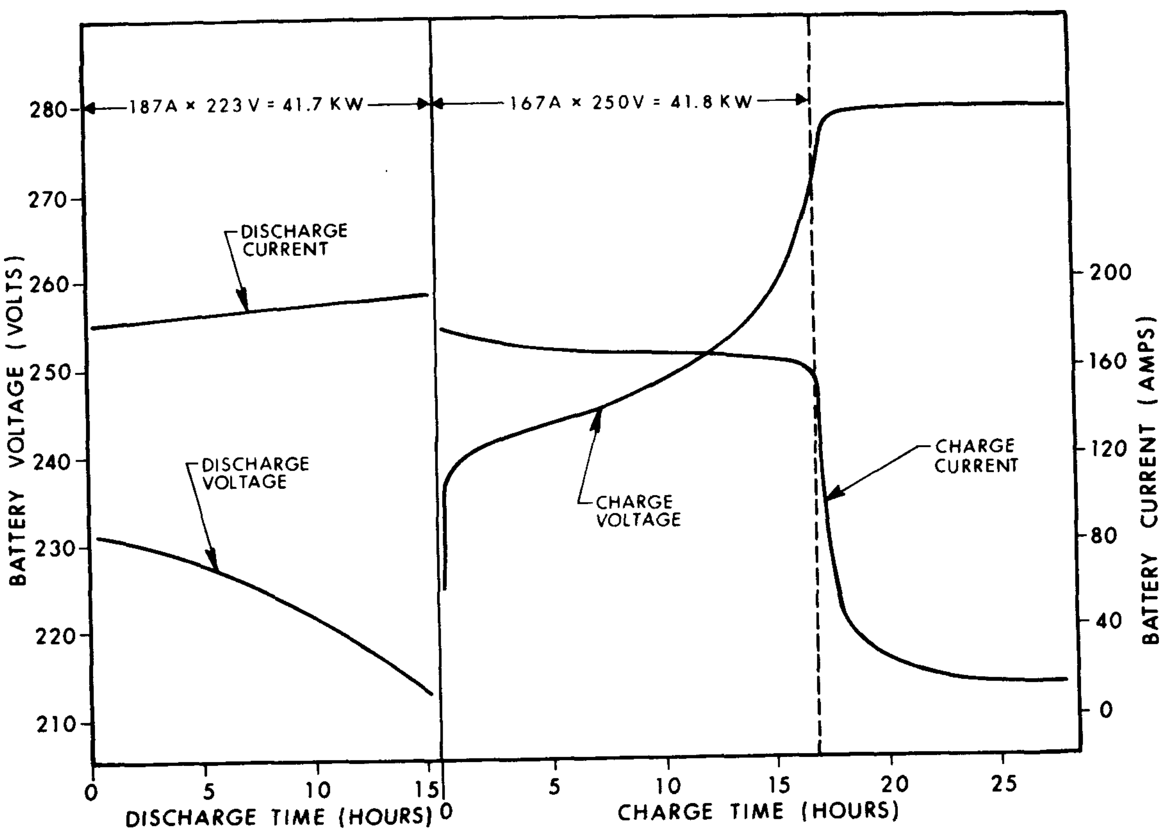

Fig. 6. Battery capacity performance test curves.

The final series of tests performed on the batteries attempted to simulate transient changes in battery voltage and current on charge and discharge which occur when the sun repeatedly disappears and reappears from behind clouds. The first set of tests were performed during discharge, at 90%, 50% and 25% states of charge. The discharge was to represent a cloudy day, and the sudden rise of voltage at given intervals was to represent the sun appearing from behind the clouds: a partially sunny day. The second set of tests were performed during charge, at 25%, 45% and 72% states of charge, representing a partially cloudy day with the sun disappearing behind clouds at given intervals throughout the day.

The data were analyzed with respect to battery internal resistance measurements. It was determined that data had to be taken under controlled laboratory conditions in order to obtain a repeatability by which an accurate analysis could be made.

4.0 INSTALLATION AND OPERATION

4.1 Battery Room Design

A PV building was built at NBNM to house the PV controller, the inverter, the batteries, and the battery chargers. The battery room was so constructed that the batteries were sealed from the rest of the building to prevent the interchange of hydrogen between rooms and to prevent damage to the other rooms in the event of an explosion. (Many redundant safety precautions were built into the room because of the lack of applicable codes and historic data on battery rooms in a public environment.)

The battery room has internal dimensions of 10 by 50 feet with a 9-foot ceiling. There are two exits, at either ends of the room, opening to the outside. The two walls separating the battery room from the rest of the building (north and west walls) are constructed of eight-inch reinforced concrete. The 50-foot south wall is made up of four blow-out sections and contains four small, high double windows which also serve as explosion apertures. The fourth wall has a large double door and two explosion-proof exhaust fans.

A thermal analysis was made on the PV building and the heating and ventilation systems were set up so that excess heat dissipated in the inverter room could be distributed to the rest of the building in the winter or diverted outside in the summer. The permissible operating temperature range is large because human occupancy is not common. Thermostats are attached to fans which circulate air between rooms or from the outside, depending upon temperature differentials. Heaters and swamp coolers are available for use during periods of extreme temperatures or for personal comfort when work assignments require extended time in the building. However, due to the heat liberated from the equipment, heater operation should be infrequent.

The battery room layout is such that there is no need for battery racks. Twenty-eight battery modules are set end to end along the north and south walls, 14 on each side (see Fig. 7), such that there are two series strings of 112 cells. The ends of the battery strings are paralleled and connected to the PV system via a fused disconnect switch shown in Fig. 8 (unit 211). At the halfway point within the strings, a battery isolation switch (unit 212) has been installed to isolate the battery subsystem into two 112-volt (nominal) sections when it is disconnected from the PV system for maintenance or repairs. These two safety switches are located just outside the doors to the battery room and are in addition to the remote disconnect switch (unit 213). A spare module is kept in a nearby building and given a boost charge periodically. Refer to Section 4.3 for safety features included in the battery room.

4.2 Monitor and Control

Battery control is accomplished both by manually operated (safety) switches and by the microprocessor controller. The system has been designed such that if the microprocessor fails or loses power for any reason, the batteries will automatically be protected from overcharge or overdischarge, and the charge and discharge modes, manually.

4.2.1 Manual Control

The operator can control battery operation manually by turning on the diesel generator to charge the battery or by turning off the generator and

Fig. 7. PV building battery room.

connecting loads for discharge. The batteries also can be totally disconnected from the system via a remote control, three-pole circuit breaker (unit 213 in Fig. 8) which isolates the batteries from the load and the array. Two other switches further isolate the batteries: a fused disconnect switch (unit 211) and a safety isolation switch (unit 212), which were discussed in the previous section. Both are large knife switches located just outside the doors of the battery room.

4.2.2 Microprocessor Control

Under normal circumstances, the microprocessor handles the operation, control and monitoring of the PV system. For the battery subsystem, the microprocessor keeps track of battery SOC, voltage, current and temperature.

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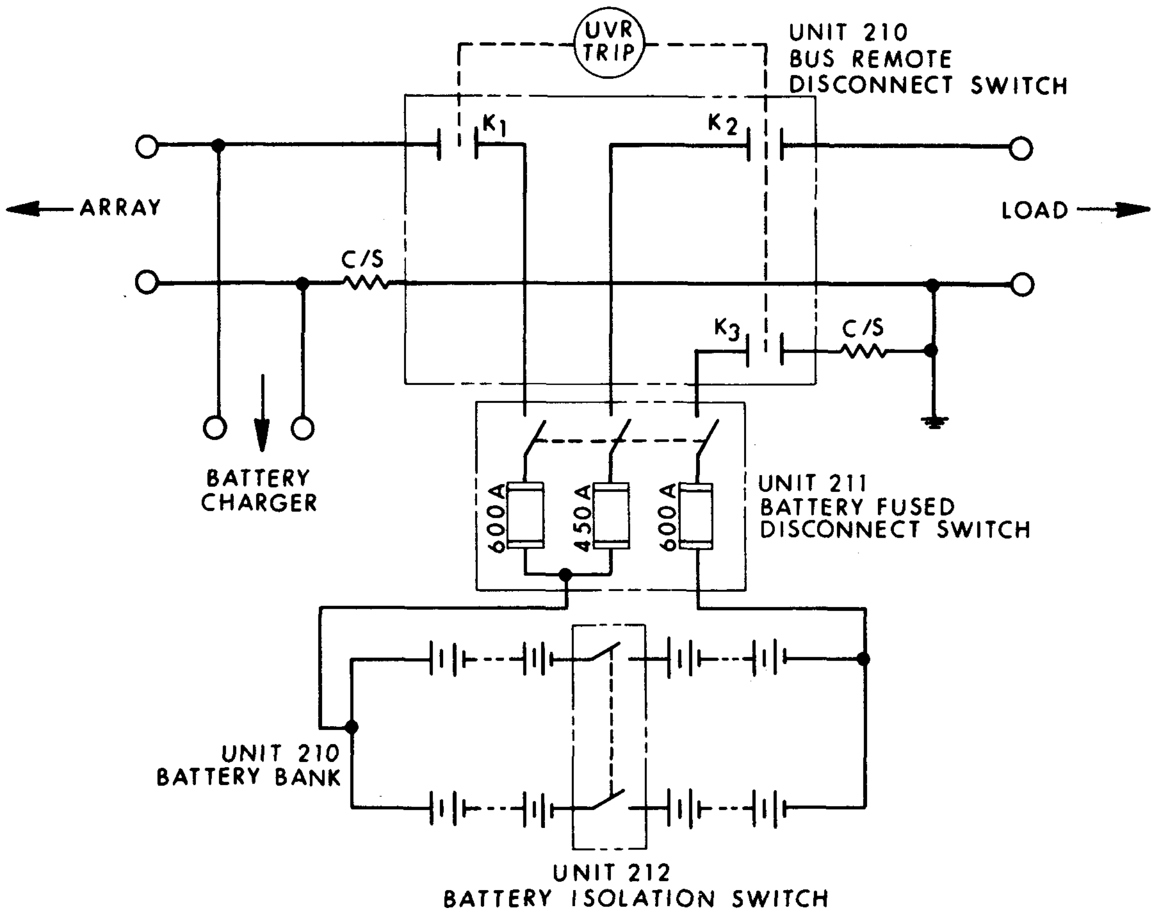

Fig. 8. Battery electrical layout and fusing.

The battery SOC is basically calculated by monitoring and recording the total number of ampere-hours removed from and returned to the battery. Inaccuracies in the meter's output are due to the fact that more ampere-hours must be returned to the battery than were removed, because of the extra current used during gassing. A weighting factor has been incorporated into the charge; however, for an improved SOC follower, the weighting factor would have to be used only during the gassing part of the charge. For example, during partially cloudy days when the bus voltage hovers below the gassing potential, the SOC meter would be crediting a larger portion of charging time with a higher SOC gain than in reality. This problem, however, was beyond the scope of the project at the time, so the weighting factor is used as an efficiency factor which can be adjusted to take into account any changes due to battery operation and life.

In order to prevent battery overcharge, a voltage limit of 280 volts is held constant by the shedding of array strings. If discharge commences and the voltage drops below a fixed level, say 277 volts, the array strings are automatically reconnected to return the voltage to 280. At a constant battery voltage of 280, the charging current will eventually decay, indicating a nearly full-charged battery (approximately 97%). The SOC meter at this point can be recalibrated by resetting it to 100%. If the SOC meter reaches 100% at this time, it will remain at 100%, giving the battery's actual capacity time to catch up as further charge is delivered.

A 20% SOC is the lowest allowable. At this point, the backup diesel generator is automatically brought on-line until the battery is charged to 80% SOC. The diesel generator may also come on-line if the battery voltage reaches a predetermined end value. This is an either/or generator turn-on signal. An emergency backup has been incorporated such that if the microprocessor controller fails, the site load will be disconnected automatically from the battery so that it will not be overdischarged. This backup is a voltage-only cutout which disconnects the main and the UPS inverter from the battery; it is adjustable and set about two volts lower than the end voltage that initiates diesel turn-on (see Table II).

4.2.3 Temperature Correction

The cell temperature should be taken into account for battery end voltage and backup voltage cutout. Depending upon the electrolyte temperature, these end voltages are adjusted by MIT Lincoln Laboratory personnel in order to keep the diesel from cutting in too early or too late. For example, a rise/fall of cell temperature of 3°F from a 77°F reference will roughly give a 1% apparent increase/decrease of the nominal ampere-hour capacity (to a fixed end voltage). Table II shows what the diesel turn-on voltage and the main inverter cut-out voltage should be a function of cell temperature. (Calculations were based upon Table I of IEEE STD 450-1975, "Capacity Correction Factors for Temperatures at Variances to Standard 25°C at 1-Hour Through 8-Hour Rate Discharges.")

TABLE II

BATTERY VOLTAGE AS A FUNCTION OF CELL TEMPERATURE

Temperature Range (°F)	Diesel Turn-on Voltage (V)	Main Inverter Current Voltage (V)
92° and above	218	216
84° - 91°	217	215
74° - 83°	216	214
65° - 73°	215	213
58° - 64°	214	212
51° - 57°	213	211
below 50°		

Note: This table assumes a minimum discharge rate of 90 A to reach the full Ah rating of the battery. Voltage drops across battery leads and connectors are not included.

4.3 Safety

As mentioned previously, many superfluous safety precautions were built into the battery room because of the paucity of safety codes and historic data on battery rooms in a public environment. The eight-inch concrete wall, the blow-out windows and wall panels, and the two large exhaust fans are all redundant when considering the fact that the batteries will produce very little gas with the hydrogen recombiners in place (see Section 2.3). The existence of numerous air leaks through the windows and door frames (cracks around the doors are at least an eighth of an inch wide) will also eliminate the possibility of any significant or dangerous buildup of hydrogen outside the battery cell cases. Two hydrogen gas sensors are located on the ceiling of the battery room and will turn on the fans if gas at 1% by volume is detected. If the fans fail to dissipate the hydrogen gas and the concentration increases to as little as 2% by volume, an alarm will sound.

Safety apparatus has also been installed in case of acid burns from the battery's electrolyte. Two eyewash stations are located at either end of the room, along with a shower with emergency pull chain. Two drains are located in the floor to drain off water from the shower or to dispose of any electrolyte spills. The drains connect with the sewage lines, thus any electrolyte spills must be washed down with copious amounts of water and baking soda.

Two fire extinguishers are located at either end of the battery room, and smoke detectors fixed to the ceiling will sound an alarm in the event of a fire. Fire is an important consideration in a battery room. It is most dangerous in the form of a lighted cigarette because of its inconspicuousness. Cigarettes can easily be waved over a battery cell where hydrogen production occurs. If any of the battery accessories are removed when inspecting a cell, hydrogen is released and can be ignited by the heat of a lighted cigarette.

Authorized personnel entering and working in the battery room have various protective equipment with which to work and safety procedures to follow. Protective equipment includes:

- Face shield
- Acid-resistant gloves
- Acid-resistant aprons and coats
- Shoe covers
- Eyewash facilities and shower
- Bicarbonate of soda or equivalent for neutralizing and cleaning up any electrolyte spillage
- Insulated tools and rubber mat for working around or on the battery
- Insulated, non-metallic flashlight.

Refer to Reference 9 for further safety information.

5.0 PERFORMANCE

5.1 Installation

The NBNM battery subsystem was installed in the battery room of the PV building at NBNM in January 1980 and the initial site testing began in February. As discussed in section 3.1.2, the concentration was aimed at the air-lift system operation. The batteries were discharged to 30% SOC and then recharged, running the air-lift pumps periodically. The conclusions established were that each air-lift pump tube would need a separate orifice, that the level indicators would need modifications to accommodate a pressure relief cap, and that the air leaks would need plugging.

After initial installation tests, plans were made for modifications and inspection by C & D and for final acceptance tests. This was arranged for the week of 22 July 1980. C & D not only planned to complete the air-lift system modifications, but also to mix a phosphoric acid additive into the battery electrolyte which would slightly lower the battery capacity but improve cycle life. The original estimation of an average daily depth of discharge of 60% had been reduced to 25% after closer study of the site load and the introduction of a few conservative measures. With this reduced load and the addition of a certain amount of phosphoric acid (too little could have a negative effect on life), battery life could be almost doubled, i.e., to ten years.

Before the final acceptance tests, the NBNM PV system was dedicated on 7 June 1980 and placed into operation. Data collection was started and a sample of the battery data is shown in Fig. 9. It is a typical sunny day--as the battery (bus) voltage reaches the upper limit of 280 V [see Fig. 9(a)] the PV array strings begin to shed, dropping the array and battery current (1:00 am). During the nighttime hours, the battery current is negative, representing the site load (approximately 60 amps). Figure 9(b) shows the battery voltage and SOC versus time. When the battery current is positive, the SOC is increasing or steady at 99%; when negative, the voltage drops and the SOC starts to decrease. Figure 9(c) is interesting with its display of the battery voltage and current versus SOC. This plot is most useful when the battery current is relatively constant, for then it can provide a voltage discharge curve with respect to SOC. By piecing together the constant current sections from other days, a family of curves can be obtained.

5.2 Final Acceptance Tests

Upon arrival on 22 July 1980, all of the cells were found to be sufficiently equalized and after air-lift operation there was no significant change in specific gravity. The phosphoric acid additive was then added to the cells and the

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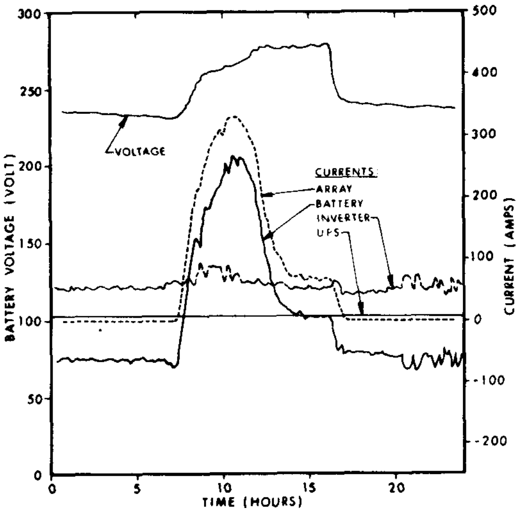

FIG. 9(a): VOLTAGE AND CURRENT VS. TIME

C74-1534

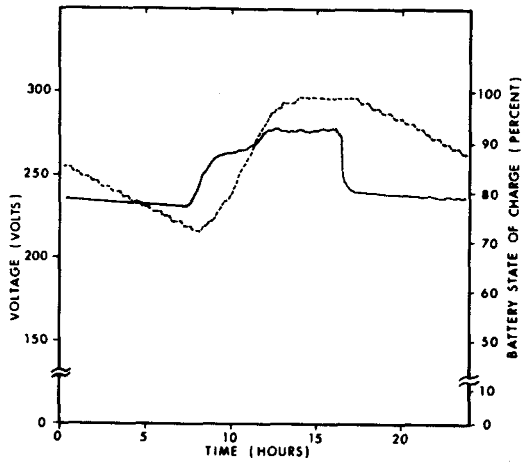

FIG. 9(b): VOLTAGE AND SOC VS. TIME

C74-1535

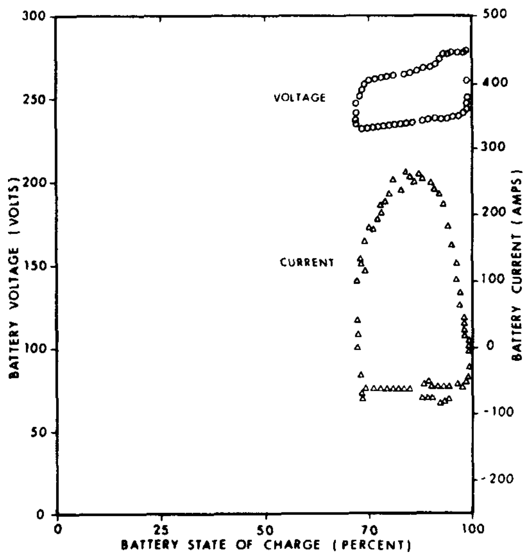

FIG. 9(c): BATTERY VOLTAGE AND CURRENT VS. SOC

Fig. 9. NBNM battery data sample.

electrolyte levels were brought up to their correct high-level positions. The level indicators were modified and individual orifices were added to each air-lift pump line.

In order to test the new air-lift system and to mix fully the additive with the electrolyte, a discharge to 47% SOC was made. During the recharge, the air-lift pumps were run for two 20-minute periods and this was found sufficient to mix the electrolyte. The air-lift system operated satisfactorily with its modifications. The back-pressure problem was eliminated with the level indicator modifications and there were no fountains of electrolyte over the modules.

One small accident did occur when the electrolyte levels were brought up to their high level positions. Not all of the cells were filled at the same time because a long trip into town had to be made to collect more sulfuric acid and pure water. Approximately half of the cells were filled before they were fully charged (after the air-lift system tests) and the high-level positions had to be estimated. Unfortunately, some of the levels were misjudged, creating an overfilled and subsequently "flushed" cell. The next day, after the battery had been put back on charge overnight to equalize, it was found that some of the cells had overflowed. This incident emphasized the importance of topping up cells only after an equalizing charge.

The path of the electrolyte during the overflow had been through the stone catalyst in the recombiner and out its vent hole. If allowed to stand, the cells could have become contaminated by the poisoned electrolyte dripping back into the cell. (The palladium in the stone catalyst is poisonous to the lead-acid battery.) Fortunately, the cells were on charge and electrolyte was being forced out of the cell, not in. Electrolyte samples were tested as a precaution and found to be free from contamination. At this point, the battery subsystem was finally complete and accepted.

5.3 Operation Problems

Two major problems have occurred since the final acceptance tests in July, the first just weeks later on 13 August 1980. The National Park Service informed Lincoln Laboratory that approximately one-third of the cells were leaking electrolyte over the modules and onto the floor. The leaks appeared to be at the rubber gasket beneath the cap securing the air-lift pump tube on the cell top and were noticed especially during the air-lift pump operation.

Many discussions with C & D resulted in the conclusion that the gaskets used were BUNA-N material which does crack in time when in contact with sulfuric acid. It was agreed to replace them with Neoprene or equivalent o-rings. A second cause of the leaks was due to the poor cell cover machining as discussed in section 3.1.2. C & D agreed to design a field tool to re-machine any faulty cell top surface.

The second major problem was identified after examination of a series of cell gravity and voltage measurements taken after each equalization (every two to three weeks). It was eventually confirmed late in September 1980 that two cells, from the same module, had slowly dropping voltages and gravities. NBNM was visited by Lincoln Laboratory personnel early in October and it was found that the cells were receiving the correct amount of air from the air-lift system (the electrolyte was being mixed) and that the problem with the two cells was probably related to their internal chemistry.

Table III shows the gradual degradation of the two cells' voltages and gravities as compared with the other cells in that module. It was clear that C & D would have to analyze these cells and C & D arranged to visit the site in November to correct the electrolyte leakage problem and to exchange the bad module with the spare.

The trip to NBNM was made, all of the gaskets were replaced with o-rings, and the faulty cell tops were remachined. The recombiners and level indicators were also checked. There had been a growing problem with the level indicators of frequent breakage upon removal for specific gravity measurements. Many hairline cracks were found, resulting in a need for replacements and spares. It was discovered that the level indicators tended to stick to the rubber washers and when added force was applied, they tended to crack and break. Silicone grease had been used to alleviate this problem, but evidently the frequent applications were time consuming and therefore expensive. It was decided to remove the recombiners instead when specific gravity readings were made since

TABLE III(a)

Specific Gravities of Module 26 (S/N 9C00610)

Date	1*	2	3	4	5	6*	7	8
7/26/80	1274	1285	1279	1280	1285	1283	1283	1278
8/02/80	1270	1285	1280	1280	1285	1270	1280	1275
8/29/80	1246	1280	1278	1285	1288	1250	1278	1277
9/12/80	1244	1288	1282	1284	1288	1243	1284	1275
9/26/80	1236	1300	1293	1295	1298	1251	1295	1285
10/10/80	1250	1299	1290	1287	1298	1248	1295	1284
10/23/80	1238	1290	1283	1289	1294	1232	1290	1285

TABLE III(b)

Cell Voltages of Module 26 (S/N 9C00610)

Date	1*	2	3	4	5	6*	7	8
7/26/80	2.45	2.45	2.46	2.46	2.51	2.49	2.50	2.51
8/02/80	2.40	2.45	2.46	2.46	2.51	2.40	2.50	2.51
8/29/80	2.32	2.46	2.47	2.45	2.51	2.33	2.50	2.52
9/12/80	2.34	2.45	2.46	2.44	2.51	2.35	2.50	2.52
9/26/80	2.25	2.44	2.45	2.43	2.49	2.24	2.48	2.50
10/10/80	2.25	2.45	2.45	2.44	2.50	2.27	2.50	2.52
10/23/80	2.28	2.43	2.45	2.42	2.52	2.28	2.48	2.53

*Degrading cells

the recombiners are of sturdier construction. This arrangement, however, is only a compromise; the adaptor between the cell top and recombiner has threads and is not a simple twist lock. These threads were not meant for constant use and future problems should be expected. Also, not all of these adaptors were properly sealed with glue--only those with obvious leaks had been glued.

At C & D, analysis of the two bad cells began with a slow charge for several days. The gravities and voltages came up to the correct level but within a few days the same two cells had dropped again. The cells were then removed from the module for full analysis but nothing obvious was found. It is believed, however, that there was a small internal short circuit at the bottom of the cells or a pinhole in the separators which caused a slow discharge. The cells were rebuilt with new separators, boost-charged, and shipped back to NBNM as the spare module.

Soon after the removal of the module with the two bad cells, it was noted that the specific gravity of one cell in the replacement module was not being brought up to its correct level after equalizing charges. Its voltage, however, was acceptable. The air-lift pump in that cell was examined and no problem was found. C & D was notified and is being kept up-to-date on any deterioration in this cell.

Regular maintenance checks continue with special attention paid to any leaking cells, bad recombiners and electrolyte levels. By unscrewing the recombiners to take specific gravity measurements, the threads and hence the seals will gradually degrade, resulting in possible leaks around the recombiners' adaptors. The recombiners themselves are easily dented when warm and should be checked for internal damage.

The electrolyte levels only have to be checked two or three times each year. It was expected that when the levels dropped from the upper to the lower rings on the level indicators, approximately 60 to 70 gallons of distilled or deionized water would be needed to refill all 224 cells. Since the preferred upper level was lowered to 1/2-3/4 of the distance between the rings, the expected water addition is now approximately 30 gallons. The first addition of water to the cells since the July 1980 final acceptance tests took place seven months later, in March, and the total battery took 27 gallons of water, as expected.

Future tests and analyses will be made on the battery subsystem to:

- reduce maintenance requirements
- determine the most efficient method of recording cell data without risking unnoticed cell deterioration
- keep track of battery degradation due to age.

Maintenance of the battery subsystem consists of automatic equalizations but manual data taking afterwards (twice a month), automatic air-lift pump operation, water additions (two or three times a year), and periodic inspections of level indicators, recombiners, air-lift pumps, cell terminals and connections, and the spare battery (boost charge). After battery equalizations, the PV system is shut down for safety reasons so that the battery may be off-line during the specific gravity measurements. During this time, the site is run on the diesel generator for 3-4 hours. It takes 2-3 hours for the voltage and gravity measurements to be made by two people working together. Consideration is being given to reducing the data-taking after equalizations to once a month, and/or to taking data from a sample of cells on a rotating basis so that all of the cells would be read at least once or twice a year. With a probable ten-year life, this unique battery subsystem at NBNM can accumulate much data relevant to future battery-equipped PV energy systems.

6.0 REFERENCES

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APPENDIX A
THE HYDROGEN CATALYTIC RECOMBINER

A-1 shows the efficiency curve of the hydrogen recombiner as supplied by the manufacturer, Hoppecke of Germany. Fifteen amperes corresponds to approximately an 85% recombiner operating efficiency. Peak operating efficiency was designed to occur at the cell finishing rate of 7 A at 2.50 volts per cell where the batteries would be at full charge.

The recombiner side view in A-2 gives details of the inner workings of the recombiner. The hydrogen and oxygen gasses rise up through the opening in the thermoplastic sleeve and are absorbed by the absorber material. The catalyst rod in the center of the absorber material (not marked) recombines the hydrogen and oxygen, producing water vapor and heat. The vapor then condenses on the thermoplastic casing and is directed back down through the openings in the thermoplastic sleeve and returned to the electrolyte.

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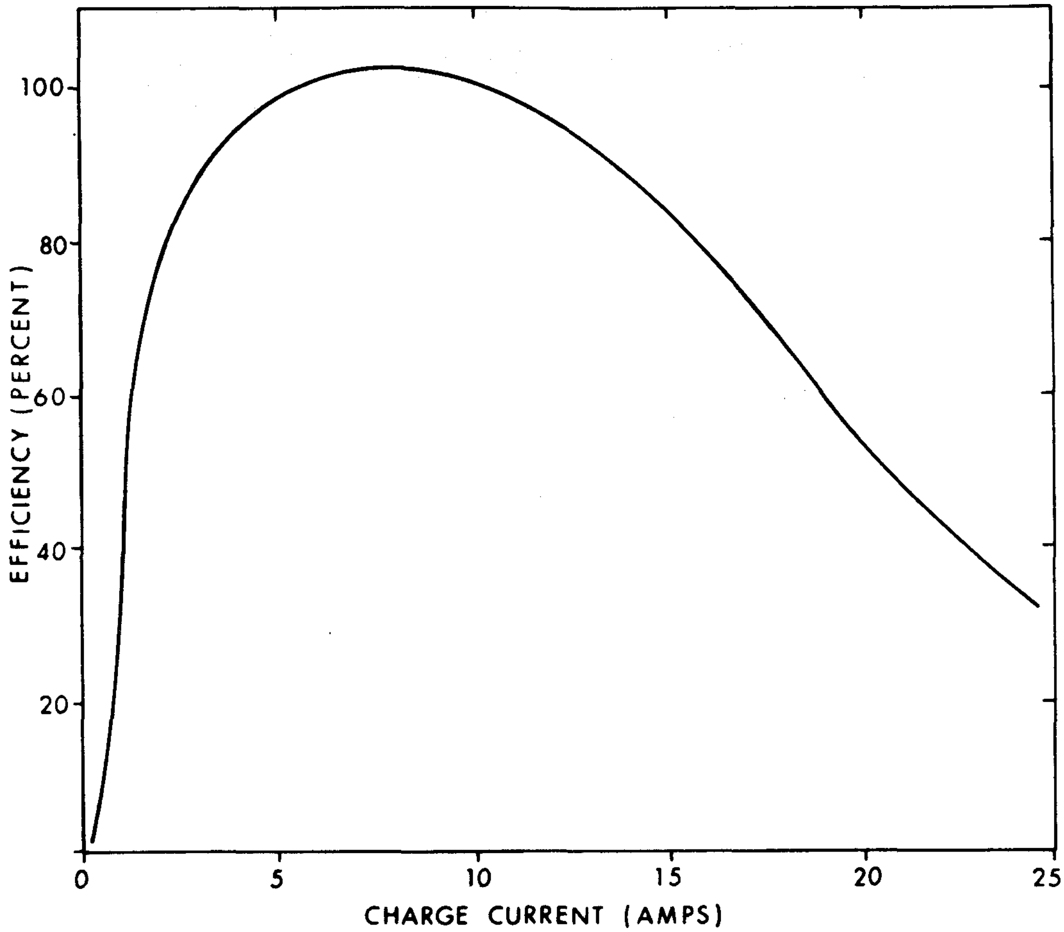
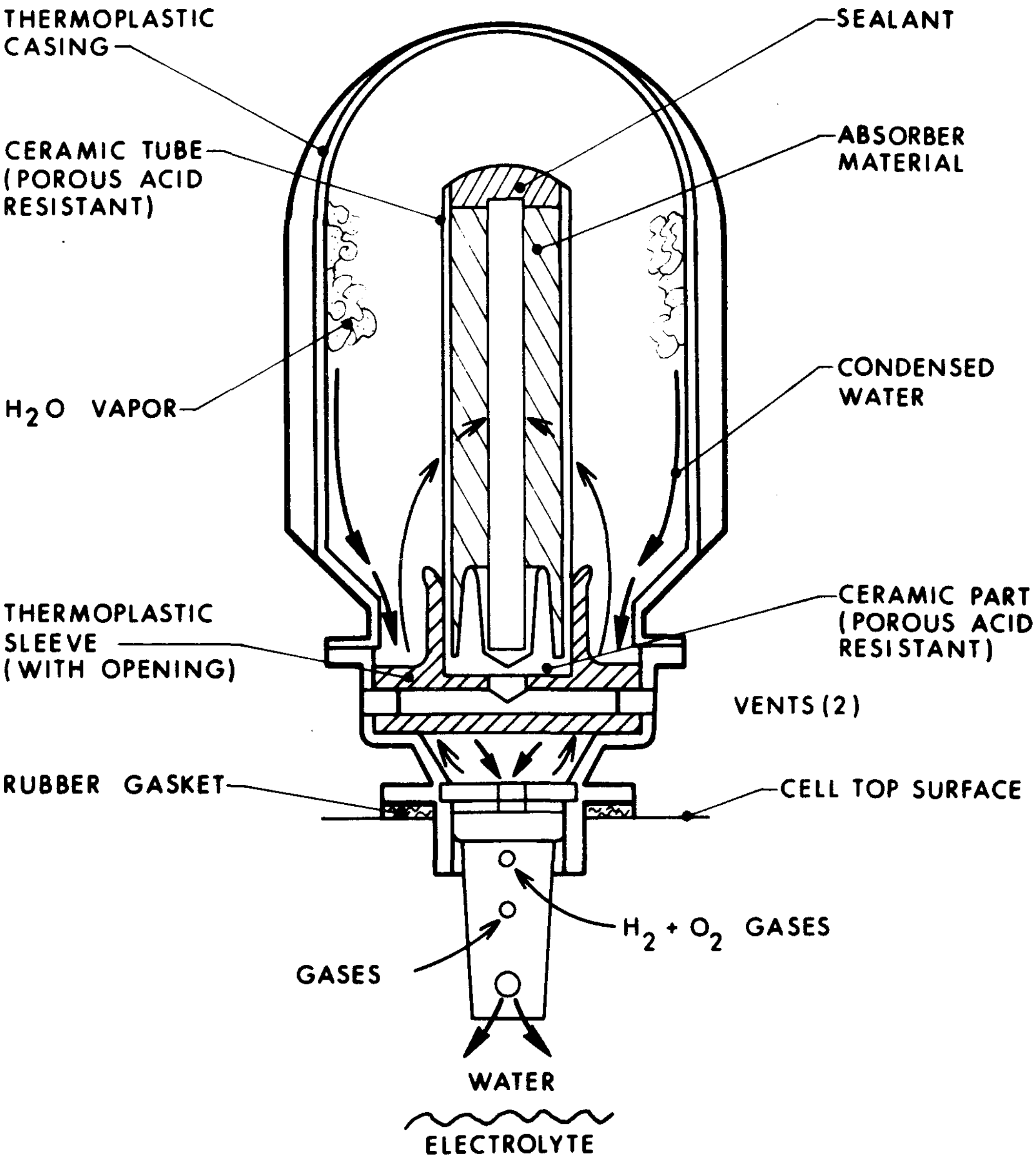


15-AMP AQUAGEN HYDROGEN-OXYGEN RECOMBINATION EFFICIENCY

APPENDIX A-1

C74-1537



15-A AQUAGEN HYDROGEN-OXYGEN RECOMBINER

APPENDIX A-2

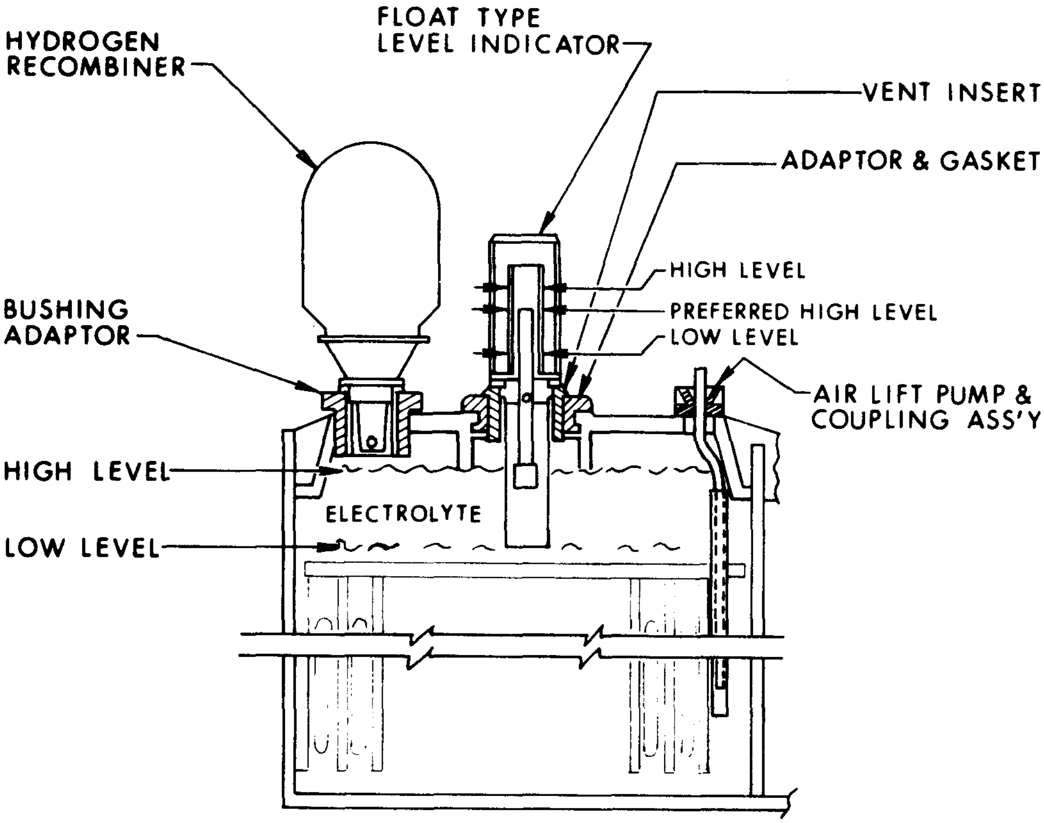
APPENDIX B

NBNM BATTERY CELL SIDE VIEW

This side view is of one cell which is part of an eight-cell module. Note especially the cell accessories:

- Hydrogen recombiner
- Electrolyte level indicator
- Air-lift pump tube.

C74-1537



NBNM BATTERY CELL SIDE VIEW

APPENDIX B

APPENDIX C
BATTERY MANUFACTURER'S CHARGE AND DISCHARGE CURVES FOR THE NBNM BATTERY

C & D Batteries Division has provided a set of discharge (C-1) and recharge (C-2) curves. Both sets are for the QP-160-23 battery at a standard temperature of 77°F and a specific gravity of 1.290 g/cc. The discharge curves are specified in units of total amperes per two strings. The time taken to reach the PV system end voltage of 210 V (1.875 V/cell) is also noted for each curve. The charge curves are based on a constant current charge to 2.425 per cell at which time the voltage remained constant until the current tapered to a low value (approximately 15 amperes per two strings). No start time is given for the charge curves.

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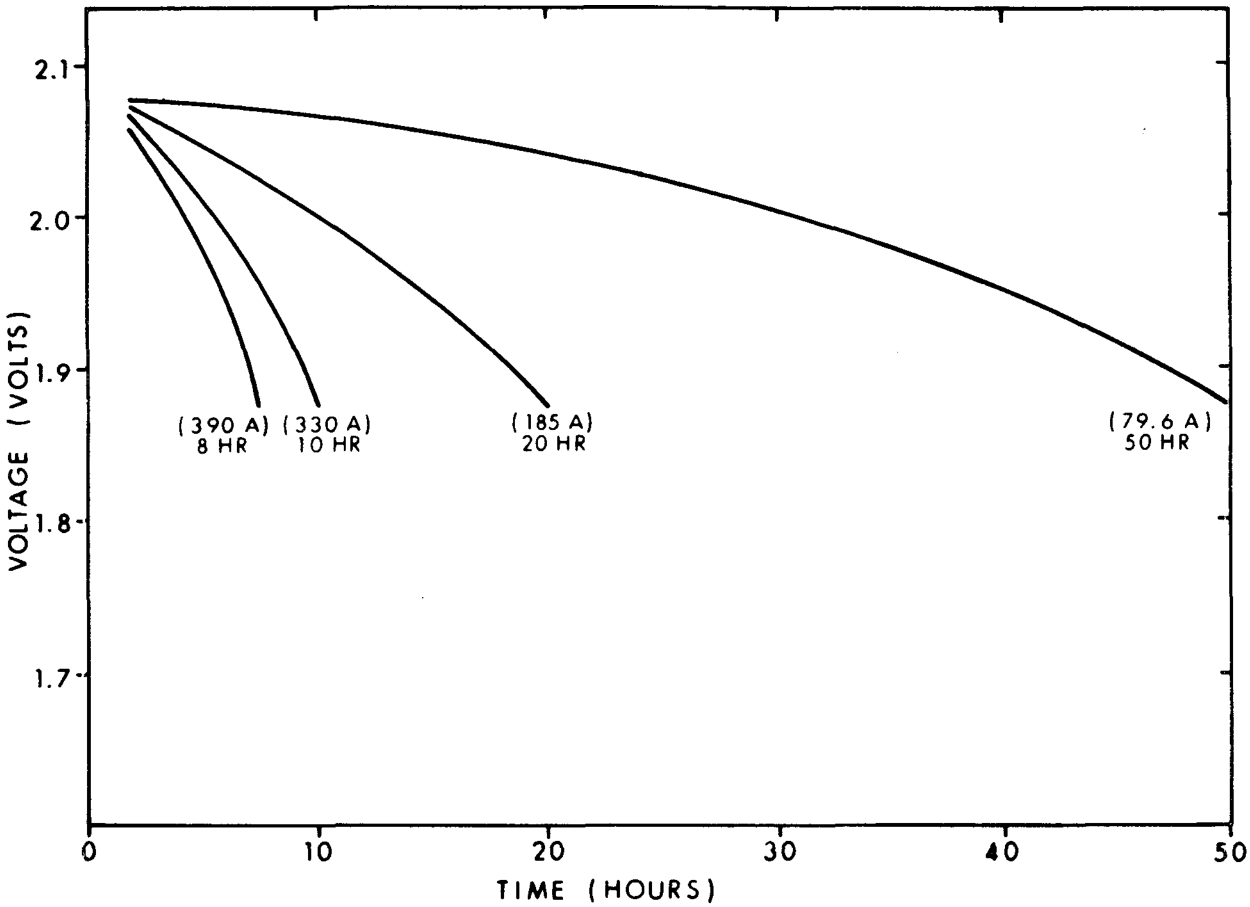
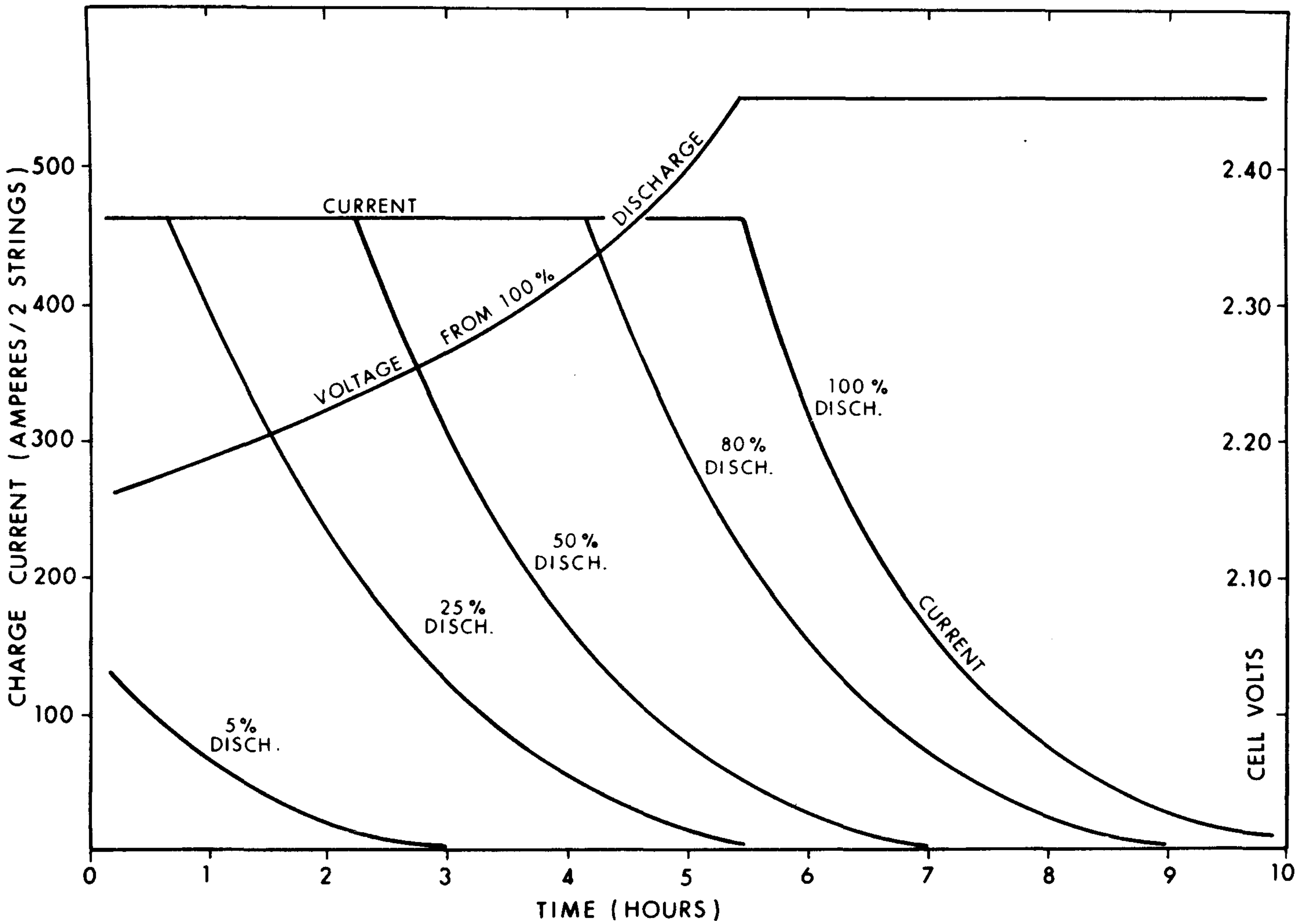


CELL VOLTAGE VS. TIME
AT VARIOUS RATES OF DISCHARGE

APPENDIX C-1



CALCULATED RECHARGE CURRENT VS. TIME BASED ON ASSUMED SOLAR ARRAY OUTPUT AND 750 KWH AS 100% BATTERY CAPACITY

APPENDIX C-2

APPENDIX D

ACCEPTANCE TEST FOR THE NBNM BATTERY CELLS

C & D Batteries uses a temperature correction table as shown in D-1. At the time of the NBNM battery acceptance test, the cell temperature (measured in a pilot cell) was 83°F. Therefore, instead of taking 5.40 hours to do a 90% discharge (at the standard temperature of 77°F), it would take 5.53 hours.

D-2 is a copy of the data taken of a representative 60 cells being prepared for the NBNM battery modules. It can be seen that all but one of the cells (no. 30 on page 2) showed at least a 90% capacity defined at the 6-hour rate to 1.70 V.

CAPACITY DISCHARGE TEMPERATURE CORRECTION

TABLE FOR SIX (6) HOUR FACTORY DISCHARGES.

TEMP AT START OF DISCHARGE °F	TIME REQUIRED FOR 90% CAPACITY		TIME REQUIRED FOR 100% CAPACITY		TEMP. AT START OF DISCHARGE °F	TIME REQUIRED FOR 90% CAPACITY		TIME REQUIRED FOR 100% CAPACITY	
	HRS.	MIN.	HRS.	MIN.		HRS.	MIN.	HRS.	MIN
60	4	58	5	31	81	5	29	6	6
61	5	0	5	33	82	5	30	6	7
62	5	1	5	35	83	5	31	6	8
63	5	2	5	36	84	5	32	6	9
64	5	4	5	38	85	5	34	6	11
65	5	6	5	40	86	5	35	6	12
66	5	8	5	42	87	5	37	6	14
67	5	10	5	44	88	5	37	6	15
68	5	11	5	45	89	5	38	6	16
69	5	12	5	47	90	5	39	6	17
70	5	14	5	49	91	5	40	6	18
71	5	16	5	51	92	5	41	6	19
72	5	18	5	53	93	5	42	6	20
73	5	20	5	55	94	5	43	6	21
74	5	21	5	57	95	5	44	6	22
75	5	22	5	58	96	5	45	6	23
76	5	23	5	59	97	5	46	6	24
77	5	24	6	0	98	5	47	6	25
78	5	26	6	2	99	5	48	6	26
79	5	27	6	3	100	5	49	6	27
80	5	28	6	4	DO NOT START DISC. ABOVE 100°F				

Paul L. Rinaldi

Paul L. Rinaldi
Q.C. Supervisor
Conshohocken, Pa.
2-28-75

APPENDIX D-1

INDUSTRIAL CELLS CAPACITY DISCHARGE (6HR. RATE)

C&D BATTERIES an Eltra company

TYPE CELL Q160-23 W.O. NO. 10126

TEST DATE 8-14-79 TEST RATE 293 AMPS START TIME 0850

TEST CORR. DISC. HOURS — MIN. — FOR — % CAPACITY

SEQUENCE	HOUR NO.			1	2	3	4	80%	85%	90%		
	TIME			0950	1050	1130	1230	1344	1403	1421		
	O.C. VOLT	T.C. SP. GR.	TEMP.	VOLT	VOLT	VOLT	VOLT	VOLT	VOLT	VOLT		
1	2.16	1.292	83	1.99	1.96	1.95	1.91	1.86	1.81	1.77		
2				1.99	1.96	1.95	1.91	1.85	1.79	1.74		
3				2.00	1.97	1.96	1.92	1.88	1.84	1.80		
4				2.00	1.98	1.96	1.90	1.87	1.83	1.81		
5				1.98	1.96	1.94	1.90	1.84	1.78	1.72		
6				1.99	1.96	1.94	1.93	1.84	1.77	1.70		
7				2.01	1.99	1.97	1.91	1.89	1.86	1.83		
8				1.99	1.96	1.95	1.93	1.85	1.80	1.77		
9				2.00	1.98	1.97	1.94	1.88	1.83	1.82		
10				2.02	1.98	1.97	1.93	1.89	1.85	1.83		
11				2.02	1.99	1.97	1.90	1.89	1.85	1.83		
12				1.99	1.96	1.94	1.90	1.85	1.80	1.81		
13				2.02	1.99	1.98	1.91	1.89	1.82	1.79		
14				1.99	1.97	1.95	1.91	1.86	1.82	1.80		
15				1.99	1.98	1.95	1.92	1.86	1.82	1.79		
16				2.00	1.98	1.97	1.93	1.88	1.83	1.82		
17				2.01	1.98	1.97	1.94	1.89	1.84	1.82		
18				2.02	1.99	1.98	1.94	1.89	1.86	1.84		
19				2.01	1.98	1.97	1.91	1.88	1.83	1.81		
20				2.00	1.97	1.96	1.92	1.89	1.82	1.79		
21				1.99	1.96	1.94	1.90	1.84	1.79	1.74		
22				2.01	1.99	1.97	1.93	1.89	1.85	1.83		
23				2.00	1.97	1.96	1.92	1.87	1.82	1.79		
24				1.99	1.96	1.94	1.90	1.84	1.79	1.76		
25				2.02	1.99	1.98	1.94	1.88	1.86	1.84		
26				2.02	1.99	1.98	1.94	1.90	1.87	1.84		
27				2.01	1.98	1.97	1.93	1.88	1.85	1.82		
28				2.00	1.98	1.96	1.94	1.88	1.84	1.81		
29				1.99	1.96	1.95	1.91	1.85	1.80	1.76		
30				2.01	1.98	1.97	1.93	1.88	1.84	1.81		

Q.C. INSPECTORS SIGN [signature]

C&D QC1 8-14-79

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APPENDIX D-2

INDUSTRIAL CELLS CAPACITY DISCHARGE (6HR. RATE)

C&D BATTERIES an Eltra company

TYPE CELL Q 160-23 W.O. No. 10126

TEST DATE 8-14-79 TEST RATE 293 AMPS START TIME 0850

TEST. CORR. DISC. HOURS — MIN. — FOR — % CAPACITY

SEQUENCE	HOUR NO.			1	2	3	4	80%	85%	90%		
	TIME			0950	1050	1130	1230	1344	1403	1421		
	O.C. VOLT	T.C. Sp. GR.	TEMP.	VOLT	VOLT	VOLT	VOLT	VOLT	VOLT	VOLT		
1				2.00	1.98	1.97	1.94	1.90	1.86	1.83		
2				2.02	1.98	1.97	1.94	1.90	1.86	1.82		
3				2.00	1.98	1.96	1.92	1.88	1.83	1.81		
4				2.01	1.98	1.97	1.93	1.88	1.84	1.82		
5				2.00	1.99	1.97	1.94	1.89	1.86	1.84		
6				2.01	1.98	1.97	1.93	1.88	1.85	1.83		
7				2.01	1.98	1.97	1.93	1.88	1.83	1.80		
8				2.02	1.99	1.98	1.94	1.89	1.86	1.81		
9				2.01	1.98	1.97	1.93	1.88	1.84	1.81		
10				2.01	1.98	1.96	1.93	1.87	1.84	1.81		
11				2.00	1.97	1.95	1.92	1.91	1.86	1.80		
12				1.99	1.98	1.97	1.91	1.87	1.85	1.79		
13				2.01	1.98	1.97	1.93	1.89	1.85	1.73		
14				2.01	1.99	1.95	1.93	1.89	1.84	1.83		
15				2.01	1.98	1.97	1.91	1.87	1.85	1.80		
16				2.01	1.97	1.96	1.93	1.86	1.82	1.80		
17				2.00	1.98	1.97	1.92	1.85	1.82	1.80		
18				2.01	1.97	1.95	1.93	1.86	1.78	1.76		
19				2.00	1.97	1.95	1.91	1.86	1.82	1.79		
20				1.99	1.96	1.95	1.90	1.87	1.84	1.75		
21				1.99	1.97	1.95	1.90	1.89	1.86	1.76		
22				2.00	1.98	1.96	1.91	1.87	1.83	1.76		
23				2.00	1.98	1.97	1.93	1.84	1.78	1.76		
24				2.02	1.97	1.96	1.94	1.87	1.83	1.81		
25				2.00	1.96	1.95	1.92	1.84	1.80	1.79		
26				1.99	1.98	1.96	1.90	1.88	1.84	1.71		
27				2.01	1.96	1.95	1.92	1.83	1.84	1.80		
28				1.99	1.98	1.97	1.90	1.87	1.83	1.74		
29				2.01	1.98	1.97	1.93	1.89	1.84	1.76		
30				1.99	1.95	1.94	1.89	1.85	1.75	1.61		

Q.C. INSPECTORS SIGN

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APPENDIX D-3