N93-20504

CHARGE RETENTION TEST EXPERIENCES
ON HUBBLE SPACE TELESCOPE
NICKEL-HYDROGEN BATTERY CELLS

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CHART 1

The Hubble Space Telescope (HST) Nickel-Hydrogen Battery Module was designed by Lockheed Missile & Space Co (LMSC) and manufactured by Eagle-Picher Ind. (EPI) for the Marshall Space Flight Center (MSFC) as an Orbital Replacement Unit (ORU) for the Nickel-Cadmium batteries originally selected for this Low Earth Orbit Mission. The Hubble Space Telescope was successfully launched on 24 Apr 90 and is presently being operated in orbit by the Goddard Space Flight Center (GSFC) in Greenbelt, MD with the science mission being managed by the Space Telescope Science Institute in Baltimore, MD.

Nickel-Hydrogen Battery Cell Chemistry

- Provides a lighter design with longer life potential than Nickel-Cadmium
- Has a higher rate of self discharge during open circuit stand than that of Nickel-Cadmium

Provisions were not provided for this higher rate of self-discharge because Nickel-Cadmium batteries were originally slated for the HST launch and deployment mission.

Concern: Nickel-Hydrogen Charge Retention limitations could have caused capacity disparities if all contingencies had been used during launch and deployment of the HST.

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CHART 2

The Nickel Hydrogen Battery cell provides a higher specific energy (w-hr/lb.) over the Nickel-Cadmium cell design. The negative electrode utilizes the relatively stable performance characteristics of the Hydrogen electrode of the Oxygen-Hydrogen fuel cell instead of the less stable characteristics of the Cadmium electrode. The Cadmium electrode tends to shed active material during life which causes a slow deterioration and loss of capacity due to shorting from dendrite growth. This makes the Nickel-Hydrogen cell a more robust design for space missions.

One major drawback to the Nickel-Hydrogen cell design is its inherent self discharge characteristics. As much as 10% of the capacity can be lost in a 24 hour period if the cell is allowed to to stand open circuit at room temperature.

Since Nickel-Cadmium batteries were originally slated for the HST launch and deployment mission, provisions were not provided for the higher Nickel-Hydrogen self-discharge characteristics by way of an improved of trickle charging interface. Nickel-Hydrogen trickle-charging charge inefficiencies generate more heat, and a heat rejection system could not be developed to accommodate this characteristic in time for the HST launch.

There was a concern that insufficient capacity would remain in the Nickel-Hydrogen battery system at 77°F while the HST/shuttle remained on the launch pad through several launch scrubs. Also, there was always the possibility of a delay in deployment once the shuttle was in orbit. The battery system is required to supply the electrical power to the HST following umbilical disconnect from the shuttle until the solar array system can be deployed.

Lockheed NEED FOR CHARACTERIZATION

With the increased amount of capacity that the HST Nickel-Hydrogen battery system had and reviewing other test results from charge retention tests, it appeared that adequate capacity would be available for deployment with all contingencies included.

Given that capacity was such a critical matter, testing for a very accurate prediction of the charge retention performance characteristics was needed.

During this testing, the sensitivity to capacity fade due to open circuit/ fully discharged stands at room temperature was revealed.

The purpose of this presentation is to summarize capacity fade characterization of this cell design and to show the methods used to regain this capacity.

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CHART 3

The HST battery system utilizes six batteries (sized primarily for autonomous safe modes) with 65 to 95 amp-hr capacity per battery, depending on how the system is charged. Most of the published charge retention data for Nickel-Hydrogen cells exists for up to 72 hours and extrapolation of this data provides a well behaved decay curve. It was determined that about 42 Amp-hr per battery (including 15% contingency) was needed after 168 hours of open circuit stand.

This being a critical parameter for successful deployment, a high fidelity test data base was required for this particular cell design.

The Extended Charge Retention Test (ECRT) was contrived and conducted from August 89 through March 90. More details of this test will be given later.

During the ECRT, sensitivity to capacity fade was discovered during room temperature, open circuit, fully discharged stand periods.

An overview of this phenomena and the methods used to recover this capacity is the intent of this presentation.

Air Force "Pineapple Slice" Cell Design with the following:

- 48 Dry Sintered Nickel Positive Electrodes
  - Aqueous Impregnation
- 48 Platinum Negative Electrodes
- Zirconium oxide Cloth Separators and Gas Screens
- Activated with 27% KOH electrolyte
- Wall wick (Zirconium oxide)
- Hydrogen Precharge (15 psia)

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CHART 4

The HST cell design features related to this discussion are as follows:

The AF pineapple slice electrode shape is used and a plastic core is employed with all the electrode leads running through the plastic core. The positives are dry sintered nickel impregnated by an aqueous process. The negatives are fuel cell grade platinum Hydrogen gas electrodes. The separator material between the positive and negative electrodes is Zirconium oxide cloth. Gas screens are provided between the negative electrodes while the positives are positioned in a "back to back" configuration. Activation of the cell is performed using 27% KOH electrolyte. Inventory of electrolyte is maintained in the cell stack by way of a wall wick on the inside of the pressure vessel. Cells are sealed with one atmosphere (zero gage) of Hydrogen, thus giving a slight negative precharge or a positive limited cell.

Cell Design

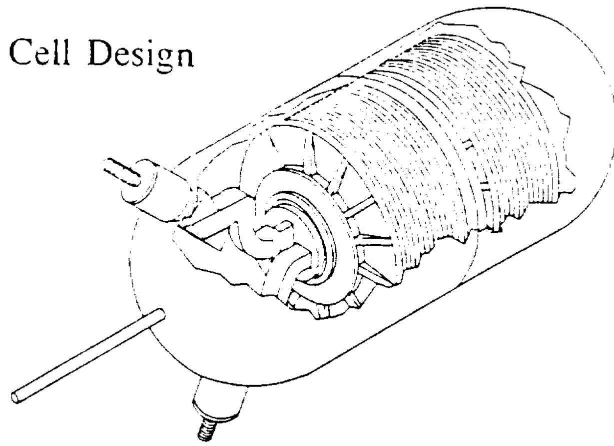

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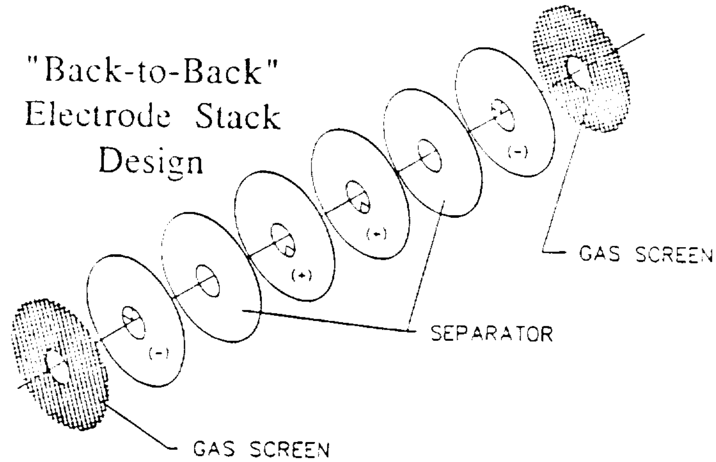
CHART 5

The HST Ni-H2 cell is designated by Eagle-Picher as the "RNH-90-3" cell design. This design features terminals exiting one end of the pressure vessel for ease in battery wiring which also allows for a low battery profile. The terminals are insulated from the pressure vessel by nylon seals. The pressure vessel is made from 0.040" Inconel 718 parent material which provides the high burst pressure margin required for astronaut handling in space.



The exploded view of the electrode stack shows how the electrodes are separated relative to each other. "Back to Back" means that every two positives are adjacent to each other. It can be seen here why this electrode is described as a "pineapple slice". The pointed tabs protruding inward from the electrode bodies are used for attaching corresponding electrode leads.

Assembly Configuration

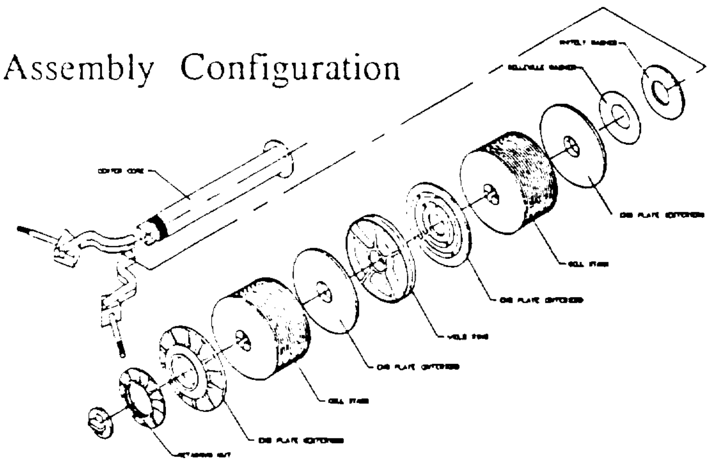


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CHART 7

This is an exploded view of all the cell internal components. Two cell electrode stacks are separated by a weld ring which provides a backing plate for the pressure vessel girth weld where the two halves of the vessel are fused.

Extended Charge Retention Test (ECRT)

- 48 residual cells, 24 from each Flight lot, were placed into cell testing fixtures.
- All cells were cycled six times to the 50°F acceptance capacity test sequence
- One additional capacity test conducted at 50°F served as a baseline
- All cells were then charged up and left open circuit
- The temperature was raised to 68°F in the testing fixture
- Two cells (one from each lot) were discharged following 4, 12 and 24 hour stand periods, and then every day, up to 21 days

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CHART 8

The Extended Charge Retention Test (ECRT) was conducted on 48 cells from the two flight cell lots. These cells had passed acceptance testing and were residual from battery cell matching. The cells were placed in the testing fixture and kept isothermal in aluminum blocks during the entire test period.

All cells were conditioned by performing 50°F acceptance test capacity cycles until sufficiently conditioned. A capacity cycles is madeup of 24 hours of charge consisting of 9.3 amps for 10 hours followed by 4.0 amps for 14 hours (160 %), one hour open circuit followed by 15 amp discharge to 0.9 Vdc per cell. Cells were shorted down with 0.2Ω resistor to 0.1 Vdc/cell.

The cells were then charged at 50°F, open circuited for four hours while the temperature stabilized at 68°F, and then discharged at 15 amps for a "baseline capacity" measurement.

Again, the cells were charged at 50°F, and open circuited at 68°F for varying lengths of time. The first pair (one from each lot) was discharged (15 amps) after 4 hours of open circuit, the second pair was discharged following 12 hours, the third following 24 hours, then the remaining pairs were discharged every day up to 21 days (504 hours).

The capacities obtained following the open circuit stands were divided by the respective "baseline" capacities to obtain a high fidelity percent capacity retained versus open circuit time plot.

Extended Charge Retention Test (ECRT)

The previous sequence of tests was repeated twice at the following temperatures:

Second series of charge open circuit stands:

Charge temperature: 32°F
Open circuit temp. 77°F

Third series of charge open circuit stands:

Charge temperature: 32°F
Open circuit temp. 32°F

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CHART 9

The original testing sequence was repeated for two more temperature conditions. The second condition had the charge up performed at 32°F with the open circuit temperature held at 77°F. The third condition also had the charge up performed at 32°F, but this time the open circuit temperature was held at 32°F.

These three open circuit conditions were all considered potential scenarios which could occur in the shuttle payload bay while awaiting launch, and each proved invaluable for on pad processing scenario trades.

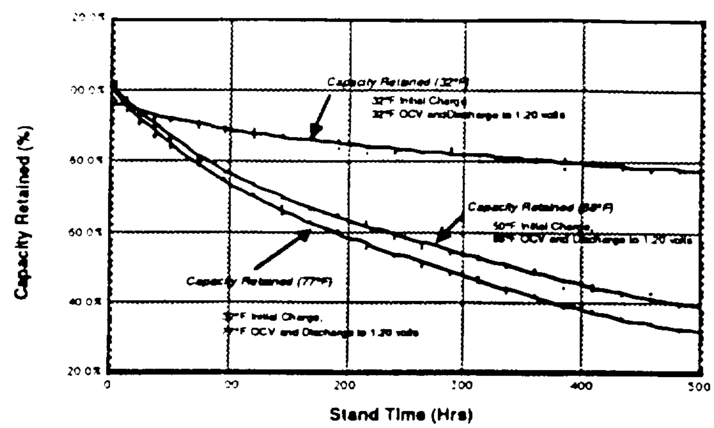

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CHART 10

The final results of the Extended Charge Retention Tests (ECRT) performed to support the launch of the HST showed good correlation with temperature and open circuit stand time.

The data can be used for predicting capacity retained for a launch scenario where trickle charge is not provided on the pad (assuming battery installation can be made on the pad).

LMSC developed a capacity prediction model with the following assumptions:

- First order kinetics with respect to hydrogen gas density
- Arrhenius model behavior

$$C(t) = C(t_o) \exp[-k(t-t_o)]$$

The following rate constant (k) relationship with respect to temperature was obtained by analysis of self-discharge characteristics of similar Nickel-Hydrogen cell designs:

$$k = 354.9 \exp(-3510 / T)$$

where:

k is in units of reciprocal hours

T is the temperature in degree Kelvin

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CHART 11

In the early planning stages for the Nickel-Hydrogen batteries for the HST, a self discharge capacity math model was developed which would generated capacity as a function of temperature and time.

Assumptions were:

First order kinetics with respect to hydrogen gas density

Arrhenius equation behavior

Fitting open circuit capacity data from similar Nickel-Hydrogen cell designs, this relationship of the first order rate constant was arrived at.

PREDICTION AT 68°F

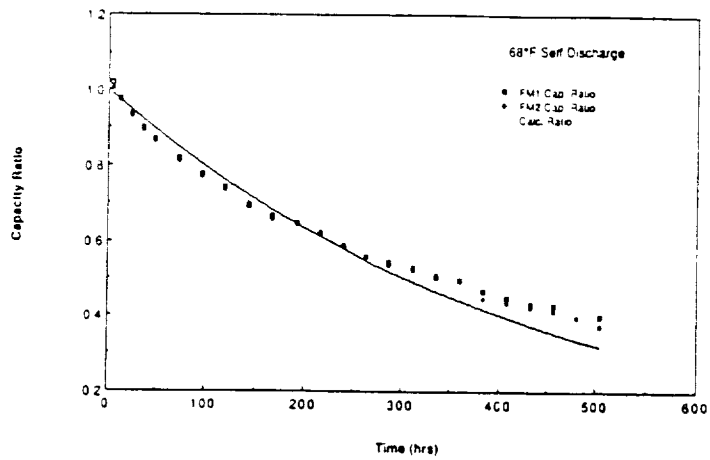

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CHART 12

This is the actual capacity of the two lots of flight cells along with the Arrhenius prediction curve at 68°F.

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PREDICTION AT 77°F

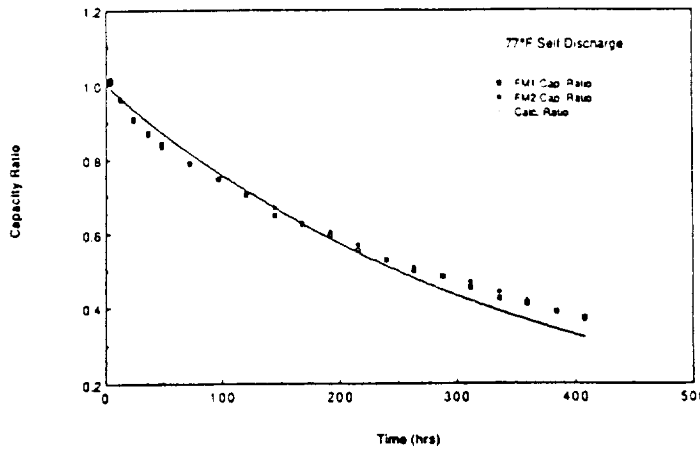

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CHART 13

This is the actual capacity of the two lots of flight cells along with the Arrhenius prediction curve at 77°F.

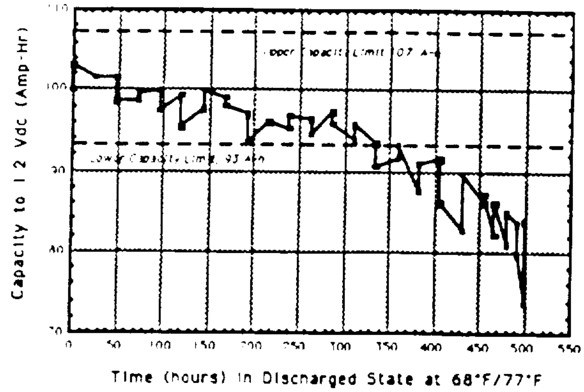

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CHART 14

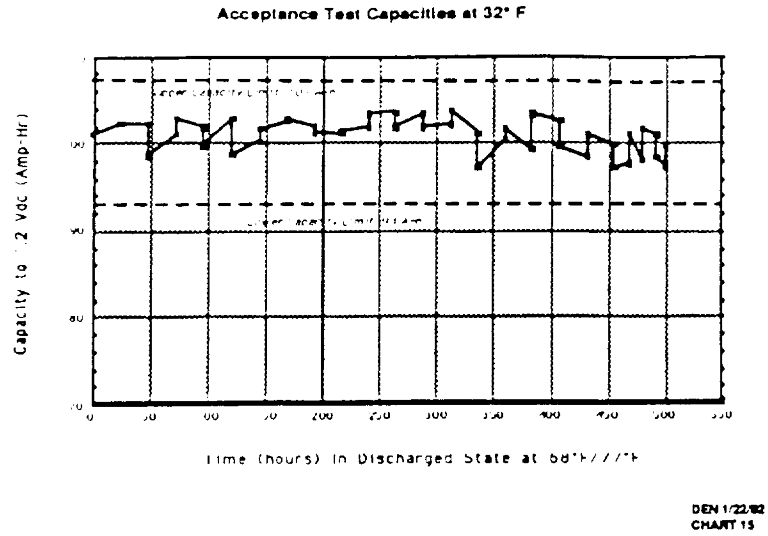
The baseline capacity of the cells remaining in the discharged open circuit condition experienced a larger fade in capacity than cells stored in the charged open circuit condition.

This graph depicts this capacity fade phenomena with discharged open circuit storage time.

Before presenting the next graph, let me explain the construction and the data used in this graph first.

This is a plot of the baseline capacity of the cells just prior to the last (32°F/32°F) condition of the Extended Charge Retention Tests. The abscissa is the time a particular pair of cells spent in the discharged open circuit condition. All cells were discharged in the same sequence of charged open circuit time. Cells discharged first (4 hours after charge up) spent 500 hours discharged open circuit at 68°F and then at 77°F. These cells showed the most pronounced capacity fade. Cells left charged open circuit for longer times showed proportionally less capacity fade.

A very distinct fade in capacities can seen here as discharged open circuit time increases.



This plot has the same abscissa as the previous plot representing relative lengths of time that a particular cell pair spent discharged open circuit condition. The ordinate represents the acceptance test capacities of particular cell pair. As stated before, all cells were acceptance tested and considered nominal performing cells. Note the low (93 A-h) and high (107 A-h) acceptance test capacity limits shown on this and the previous graph for relative capacity performance criteria.

Cell capacity performance can be correlated with time in the discharged open circuit state.

Following are efforts made to recover this faded capacity.

Following the 32°F charge / 32° open circuit ECRT sequence, cycling was performed to attempt capacity recovery of the deficient cells.

- A full 32°F capacity test cycle with 24 hr charge; 10 hrs at 9.3 amps followed by 4.0 amps for 14 hrs (160%), one hour open circuit, 15 amp discharge to 0.9 Vdc/cell, short down with 0.2 Ω to 0.1 Vdc/cell
- A 32°F, 24 hr charge; 10 hrs at 9.3 amps followed by 4.0 amps for 14 hrs (160%)
- 20 cycles
  - 15 amp discharge for 2 hours
  - 9.3 amp charge for 4 hours (124% charge return)

A 32°F capacity test with the following results (next graph)

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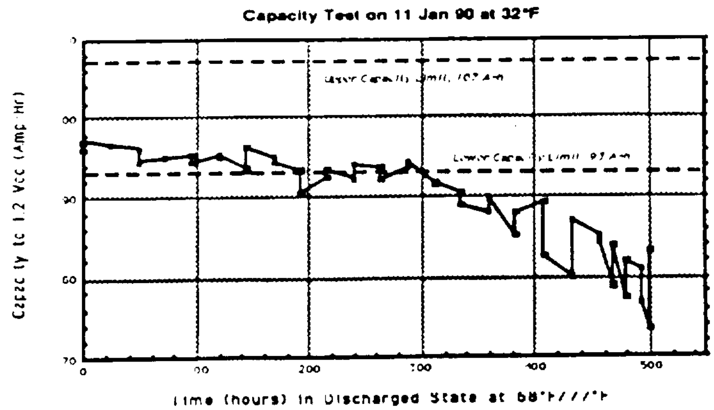
CHART 16

Another 32°F capacity cycle was performed and then the cells were recharged to full state of charge at 32°F and placed on 6 hour, 30% DoD cycles with a 1.24 recharge ratio.

It was hypothesized that cycling to lower depths of discharge than the cell was used in service with a high recharge ratio would restore capacity performance.

A subsequent 32°F capacity test showed that this did not occur (next graph)



The overall capacities were less after cycling at lower depths of discharge followed by 1.24 recharge ratio.

Following the 11 Jan 90 Capacity Test, the following sequence of conditioning was performed:

Two low rate overcharge cycles:

- **A 32°F charge up (9.3 amp for 10 hrs)**
- **32°F low rate overcharge (4.0 amp for 72 hrs) (410%)**
- **15 amp discharge to 0.9 Vdc / cell, 0.2 Ω short down to 0.010 Vdc / cell**

One warm charged open circuit stand:

- **A 32°F charge up (9.3 amp for 10 hrs)**
- **32°F low rate overcharge (4.0 amp for 14 hrs) (160%)**
- **77°F charged open circuit stand for 168 hrs**
- **15 amp discharge to 0.9 Vdc / cell, 0.2 Ω short down to 0.010 Vdc / cell**

A 32°F capacity test with the following results (next graph)

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CHART 18

Subjecting the cells to extended low rate (C/23 or 4.0 amp) overcharge for extended periods did not improve capacity performance.

The cells were then charged up to full state of charge (32°F is a very efficient charge temperature) and allowed to stand open circuit, in the charged state at 77°F.

A 32°F capacity test with the following results was performed (next graph)

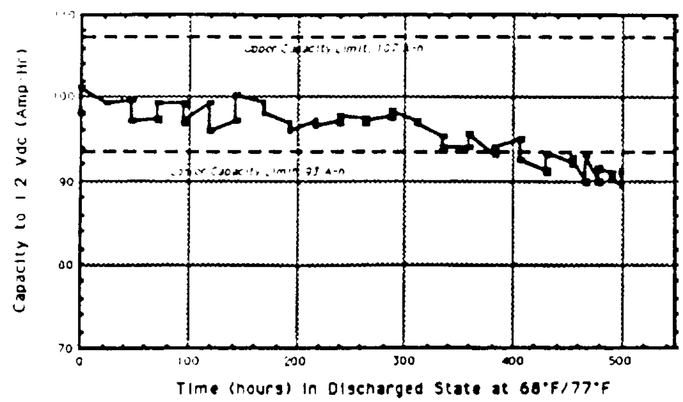

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CHART 19

An improvement in capacity of cells which had previously spent more time in the discharged open circuit condition was observed.

Following the 5 Feb 90 Capacity Test, the following sequence of conditioning was performed:

One warm charged open circuit stand:

- **A 32°F charge up (9.3 amp for 10 hrs)**
- **32°F low rate overcharge (4.0 amp for 14 hrs) (160%)**
- **77°F charged open circuit stand for 118 hrs**
- **15 amp discharge to 0.9 Vdc / cell, 0.2 Ω short down to 0.10 Vdc / cell**

A 32°F capacity test

A 32°F resistor drain

- **A 32°F charge up (9.3 amp for 10 hrs)**
- **32°F low rate overcharge (4.0 amp for 14 hrs) (160%)**
- **After one hour open circuit, 1.0 Ω short down to 1.0 Vdc / cell**
- **0.2 Ω short down to 0.10 Vdc / cell**

A 32°F capacity test with the following results (next graph)

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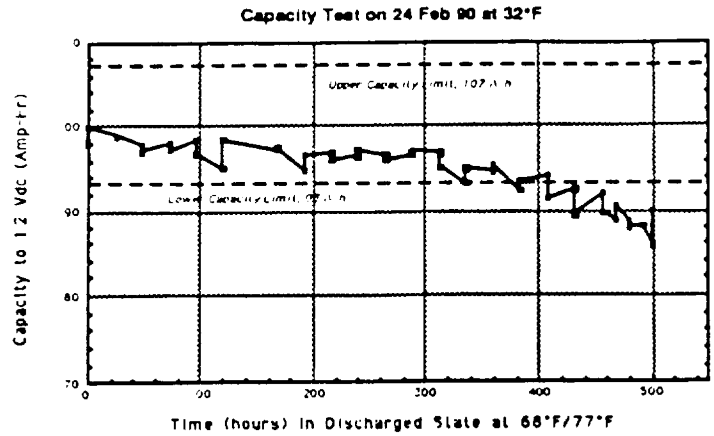
CHART 29

Again, the cells were charged up and allowed to stand charged open circuited, this time for 118 hours instead of 168 hours.

Since there was a desire to accelerated this self discharge, allowing for recovery to come quicker, the self discharge was "coaxed along" by adding a low rate, constant resistance discharge. The one ohm resister gives approximately a 1.25 amp discharge, which was thought to be a "half way medium" between the standard 15 amp discharge and the slow, charged open circuited self discharge rate.

A 32°F capacity test with the following results was performed (next graph)



A comparison to this cell capacity profile compared to the profile of 5 Feb 90, it appears that the results are going in the wrong direction.

Apparently the <u>charged</u> open circuited shelf discharging stands is what is needed to allow capacity recovery.

MORE WARM CHARGED OPEN CIRCUIT

Following the 24 Feb 90 Capacity Test, the following sequence of conditioning was performed:

One warm charged open circuit stand:

- A 32°F charge up (9.3 amp for 10 hrs)
- 32°F low rate overcharge (4.0 amp for 14 hrs) (160%)
- 77°F charged open circuit stand for 21 days
- 15 amp discharge to 0.9 Vdc / cell
- 0.2 Ω short down to 0.10 Vdc / cell

A 32°F capacity test

A 32°F capacity test with the following results (next graph)

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CHART 22

Again, the cell set was fully charged , but this time allowed to stand at room temperature in a charged open circuit state for a full 21 days.

Two 32°F capacity tests were run, the second gave more favorable results as appear on the following graph.

Capacity Test on 24 Mar 90 at 32 °F

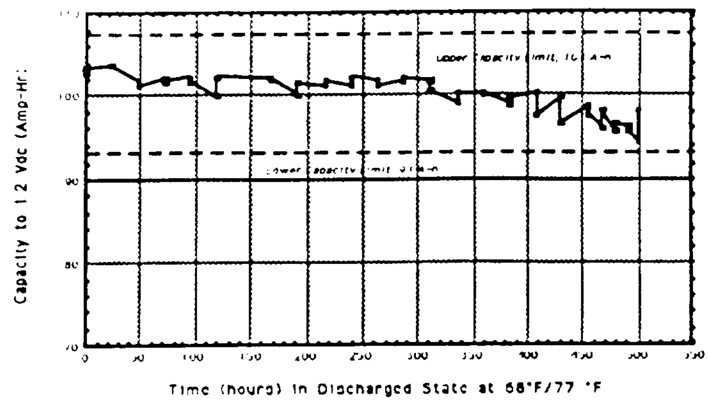

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CHART 23

All cells are now within the specified capacity requirement band for the 32°F ATP capacity test.

Cells which spent the most time in the discharged open circuited condition at room temperature continue to show some disparity compared to their acceptance test 32°F capacity performance.

Based on these results, it was concluded that charged open circuit storage at warm temperatures is the preferred storage mode for periods up to 21 days.

The 32°F capacity performance of all cells was restored to within the specification requirements

A slight disparity in capacity in the cells exists which were stored in the discharged open circuit condition for longer periods.

Charged open circuit stand at warm temperature appears to restore capacity lost due to warm, discharged open circuit stands for nickel-hydrogen cells having sight hydrogen precharge.

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CHART 24

The 32°F capacity performance of all cells was restored to within the specification requirements, but there still existed a slight disparity in capacity for the cells which were in a discharged open circuit condition for the longer time spans.

It is a well known fact that battery cell performance is a strong function of prior test/storage history, and it is difficult to say exactly which conditioning effort made the strongest contribution to the capacity recovery however, charged open circuit stand appears to restore capacity lost due to warm, discharged open circuit stands of nickel-hydrogen cells having sight hydrogen precharge.

One explanation of this recovery response is that warm charged open circuit stand allows the nickel electrode to discharge at its own rate (self-discharge) facilitating re-incorporation of active material during subsequent low temperature recharge.

This information is presented to the technical community to further understand the operations of battery cell chemistry under specific operating conditions.

Nickel-Cadmium Technologies Session