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NiH₂ CAPACITY FADE DURING EARLY CYCLING

**JOHNSON CONTROLS BATTERY GROUP, INC.
NICKEL HYDROGEN BATTERY DIVISION**

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GENERAL CAPACITY LOSS OBSERVATIONS

Terrestrial batteries:

- stored in warehouse for over 18 months
- no capacity loss
- electrodes contain cadmium additive
- electrodes contain no cobalt additive
- discharged to 1.0 volt/cell at C/2 rate prior to storage
- open circuit storage at room temperature

Initial aerospace batteries:

- stored in warehouse for over 18 months
- no capacity loss
- electrodes contain cobalt/cadmium additive
- discharged to 1.0 volt/cell at C/2 rate prior to storage
- voltage above 1.0 volt/cell at end of stand
- open circuit storage at room temperature

Recent aerospace batteries:

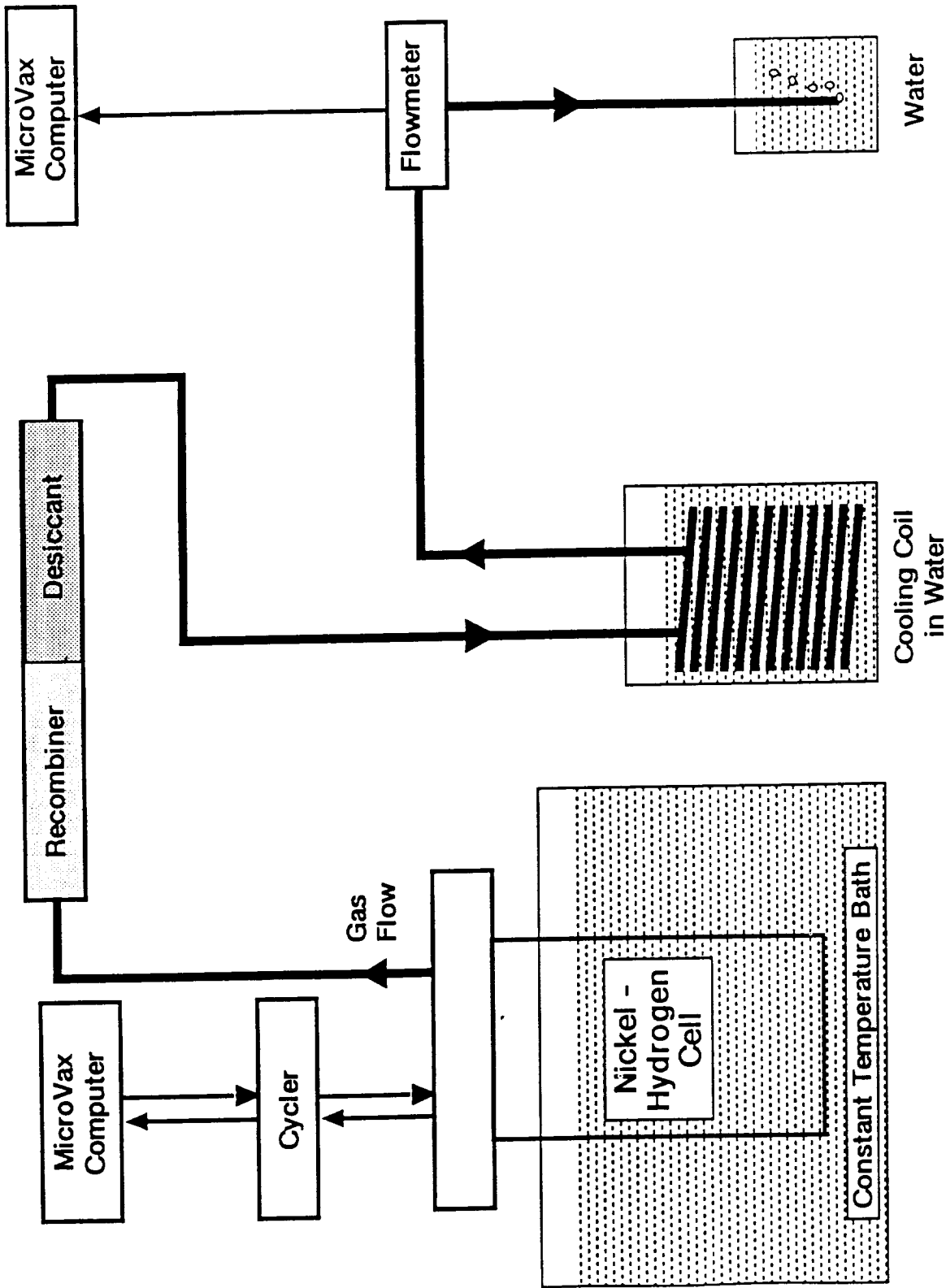
- capacity loss of over 25% seen in 3-8 week storage periods
- electrodes contain all cobalt additive
- shorted to 0 volts prior to storage
- charged stand methods not effective for recovery
- standard LEO or stepped LEO cycling was effective for recovery
- LEO cycling allowed recovery in 30-40 cycles

CHARGE EFFICIENCY TEST PROGRAM

Experiments were designed to measure the charge efficiency of the nickel electrode as a function of rate and temperature. The test matrix was varied to incorporate both cobalt, cadmium and combinations of the two nickel electrode additives. Electrolyte concentration was eliminated as a variable and was held constant at 31% KOH. Three groups of four (4) cells were tested sequentially. Lithium hydroxide was added to the electrolyte in the second set of test cells.

CELL ADDITIVE COMPOSITIONS

| <u>Cell #</u> | <u>Bath Additive Composition</u> | <u>Electrode Additive Composition¹</u> |
|---------------|--------------------------------------|---|
| X004 | 0% Co/10% Cd | 0.1% Co/5.6% Cd |
| X007 | 10% Co/0% Cd | 10.6% Co/0.1% Cd |
| X010 | 3.3% Co/6.7% Cd | 4.1% Co/3.3% Cd |
| X013 | 6.7% Co/3.3% Cd | 7.1% Co/1.8% Cd |



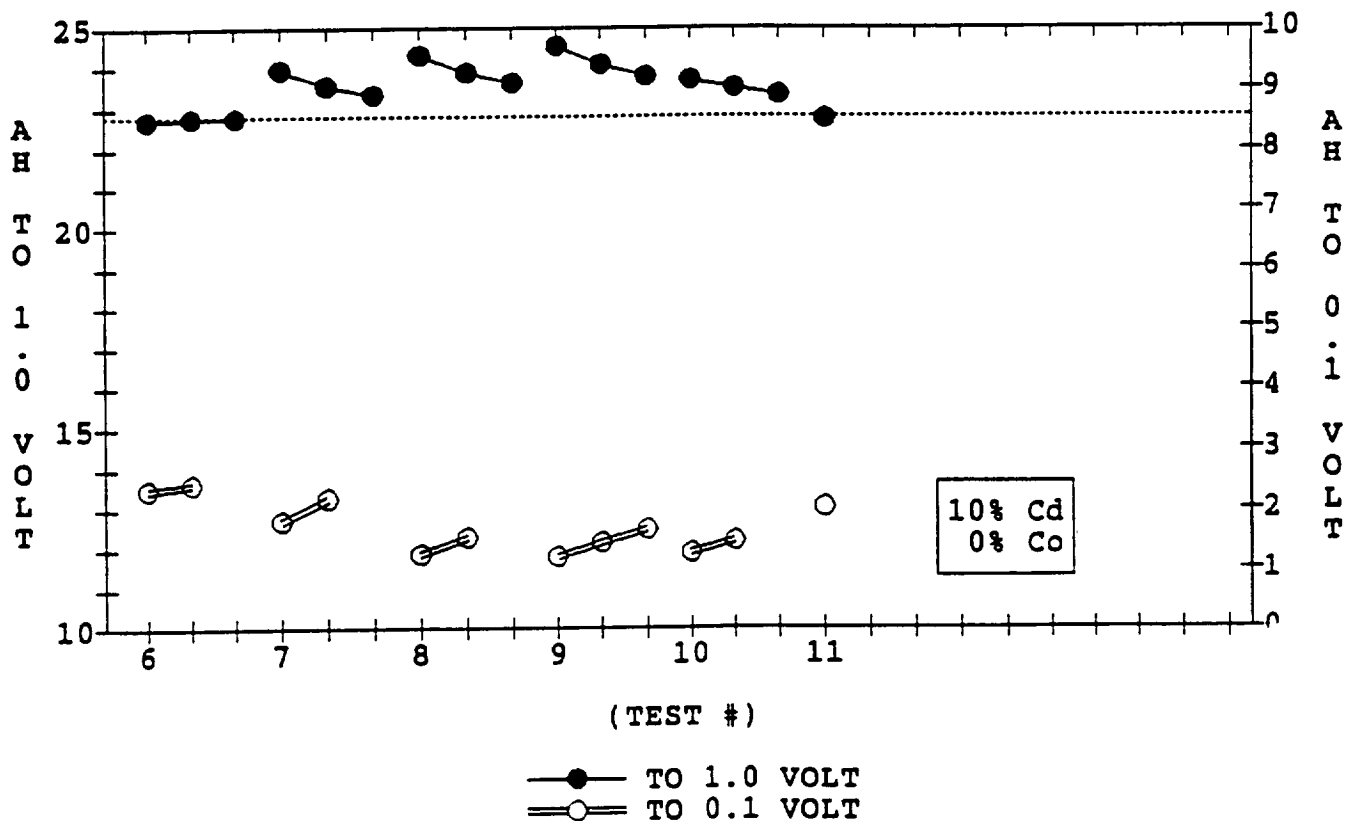
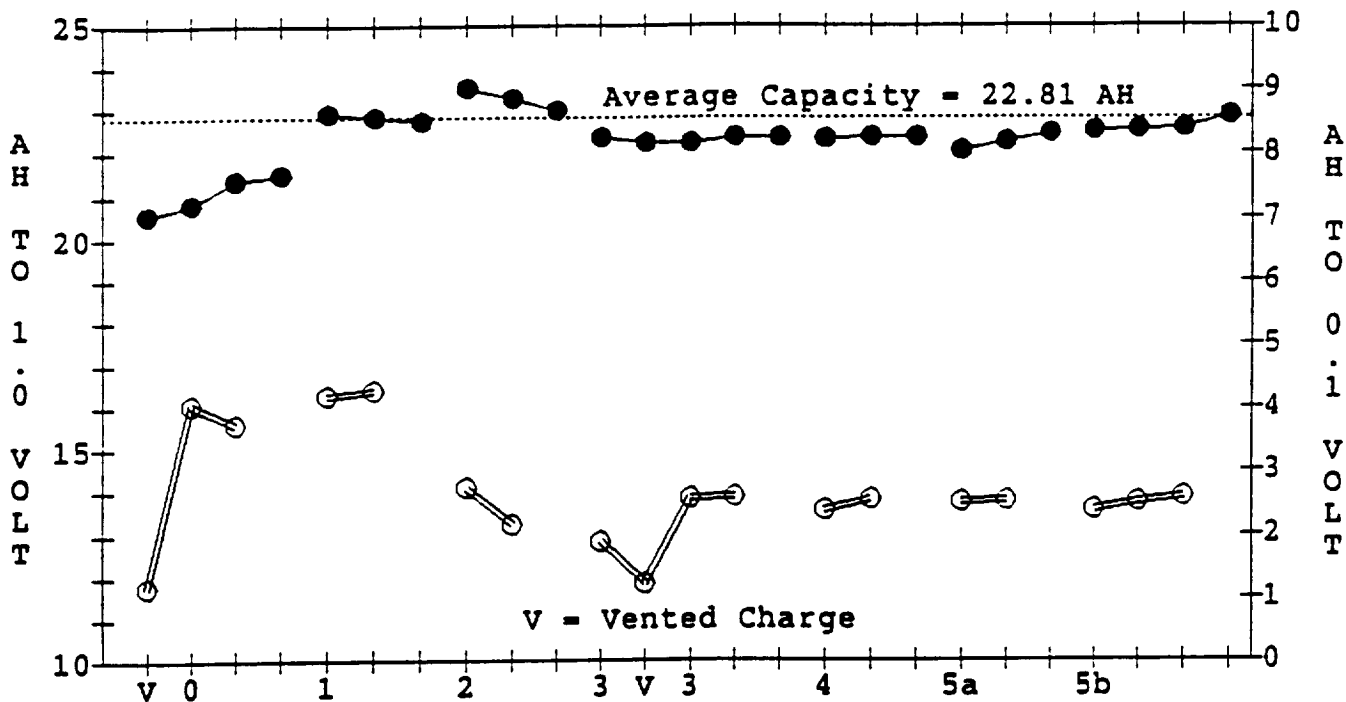
Experimental Set-Up to Measure Charging Efficiency

TESTING SEQUENCE

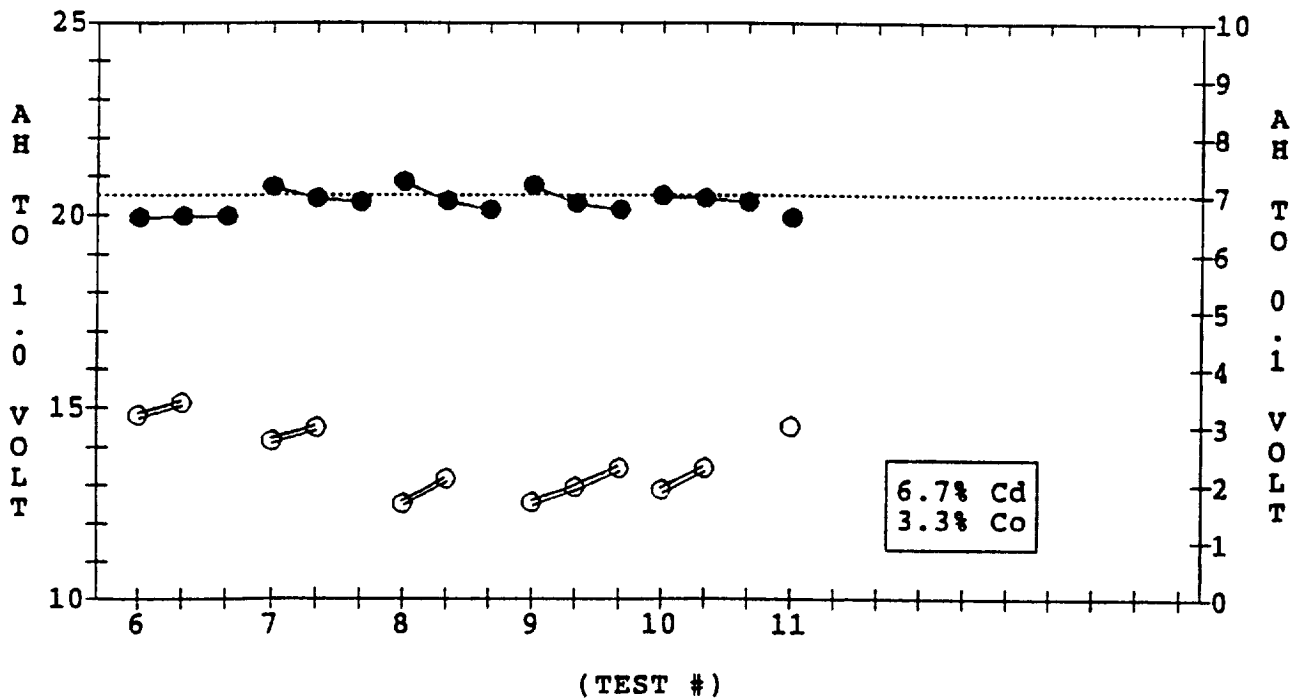
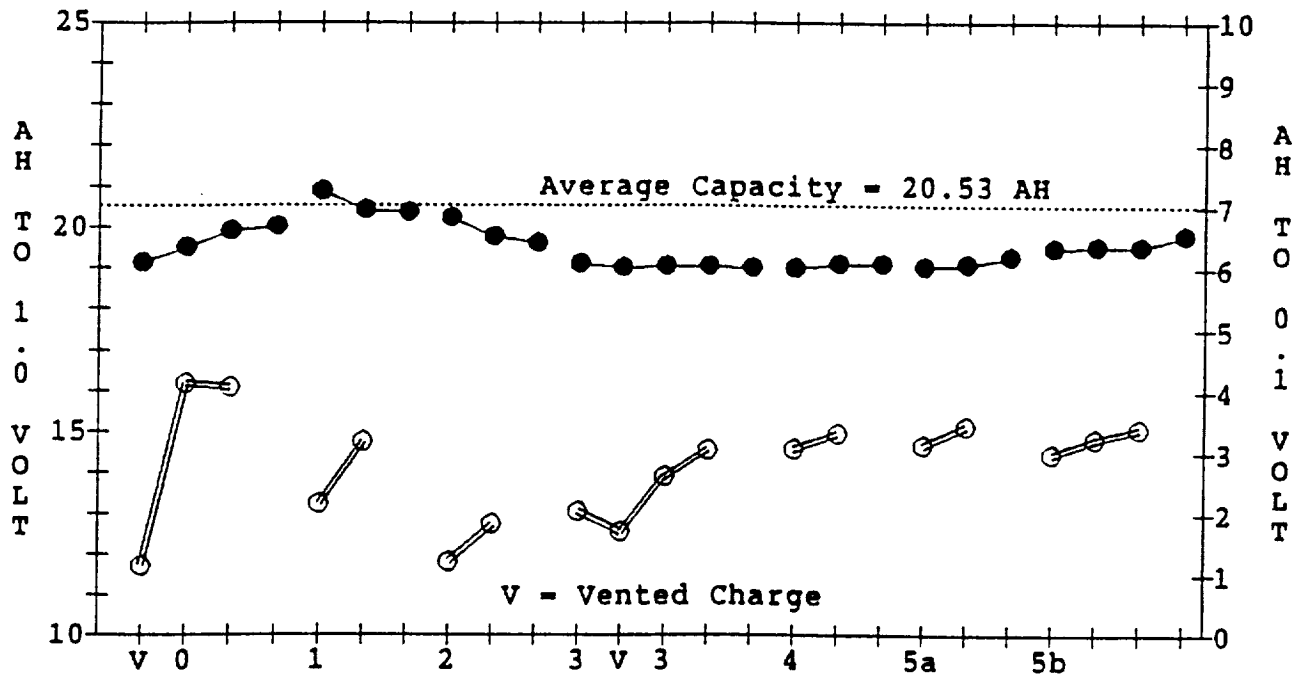
After assembly, each cell completed a routine condition/ activation cycle regime followed by a two (2) week LEO cycle period designed to stabilize performance.

Prior to testing and after each efficiency test the cells were characterized by three charge/discharge cycles at 10° C to determine how the prior test had affected capacity and also to bring the cells to a reproducible state of charge before the next efficiency test. The first two cycles consisted of a C/10 charge for 16 hours followed by a 10A (~C/2) discharge to 1.0 volt and a 4.78 A discharge to 0.1 volt. On the third discharge the cells were only discharged to 1.0 volt and allowed to remain on open circuit.

DISCHARGE CAPACITY OF TEST CELL X004 DURING CHARACTERIZATION. T = 10 DEGREES C.

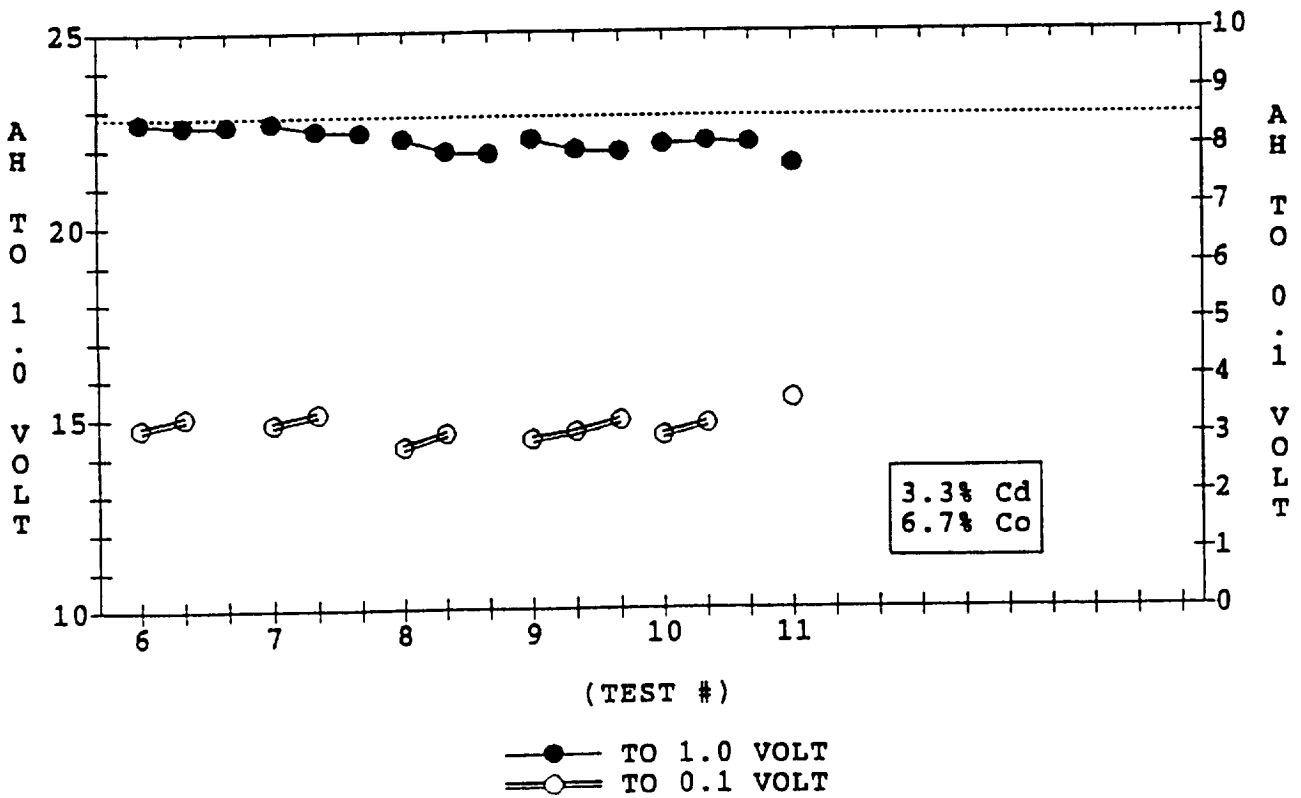
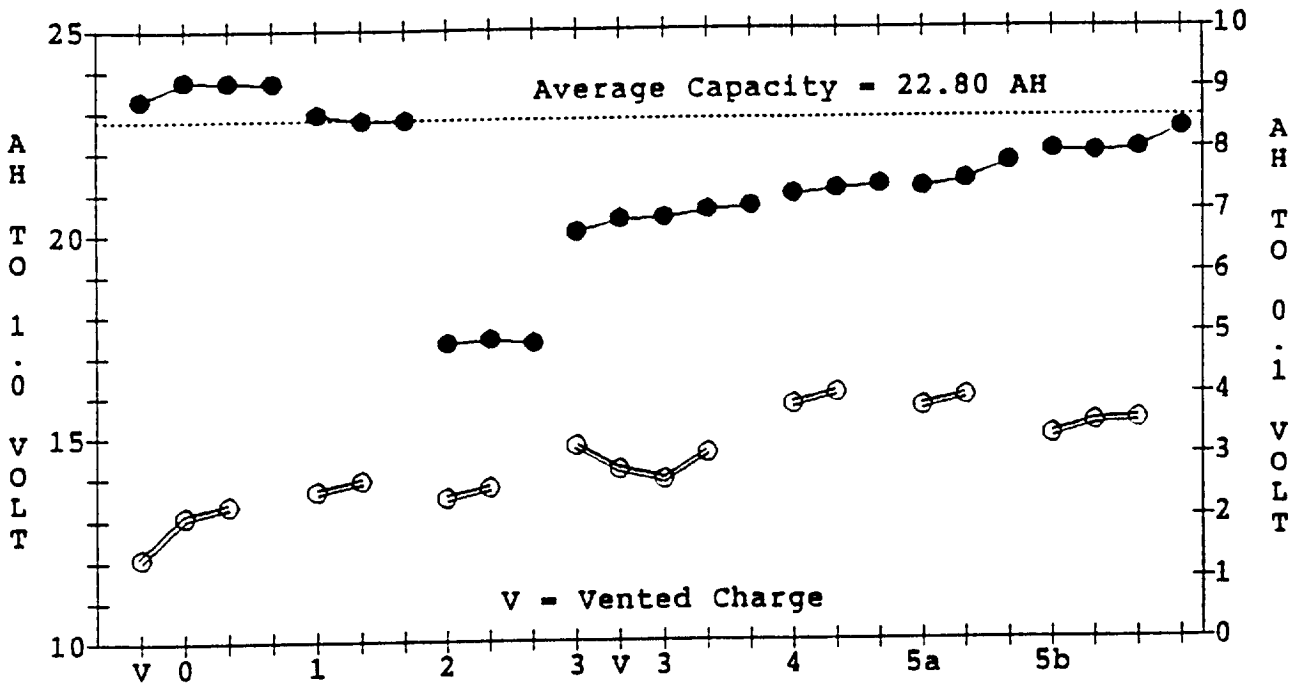


DISCHARGE CAPACITY OF TEST CELL X013 DURING CHARACTERIZATION. T = 10 DEGREES C.

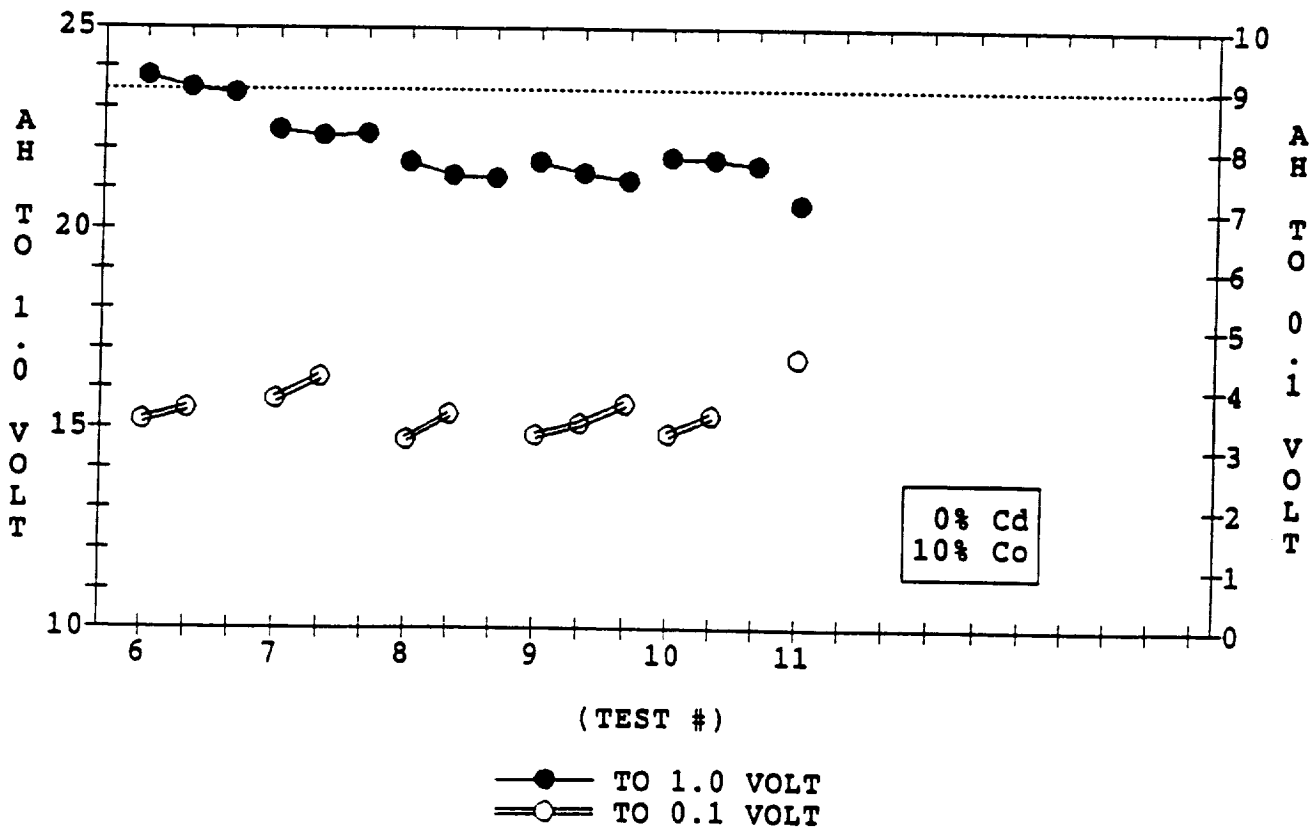
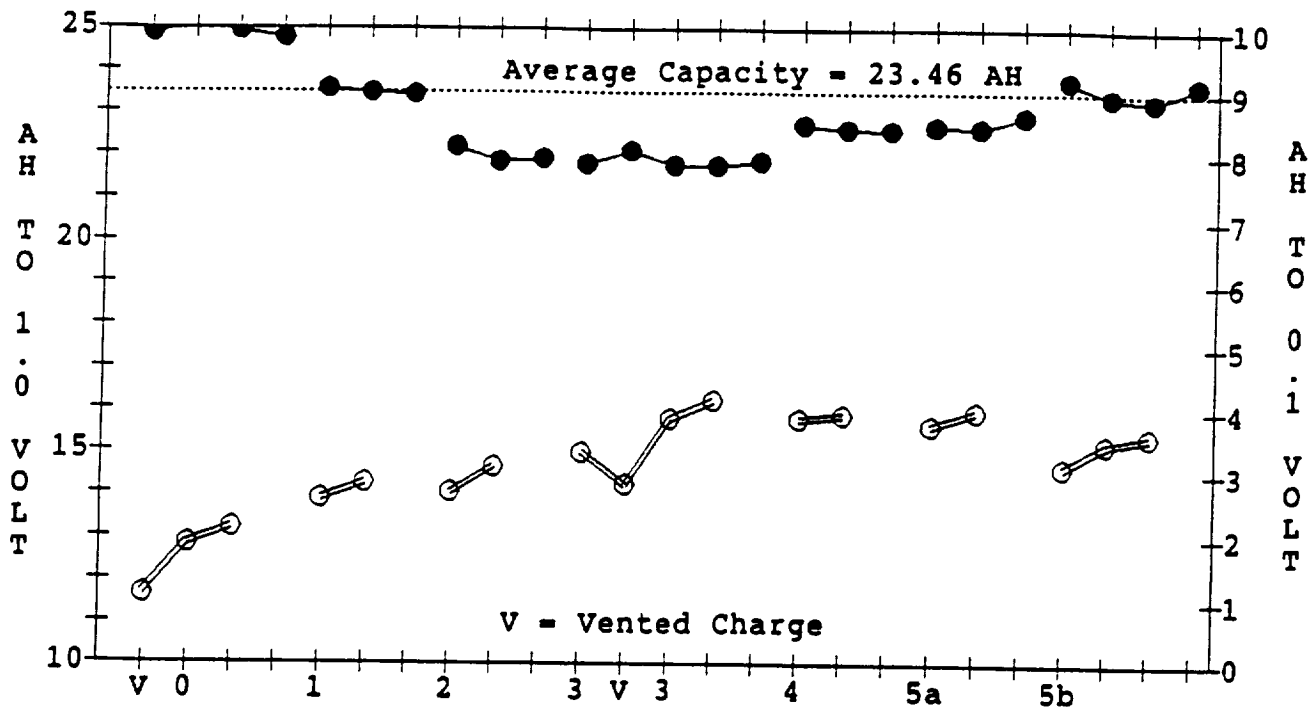


● TO 1.0 VOLT
○ TO 0.1 VOLT

DISCHARGE CAPACITY OF TEST CELL X010 DURING CHARACTERIZATION. T = 10 DEGREES C.



DISCHARGE CAPACITY OF TEST CELL X007 DURING CHARACTERIZATION. T = 10 DEGREES C.



DEFINITION OF CAPACITY FADE TEST

Three capacity check cycles run at 10°C and 23°C before initiating test.

Stand at room temperature, open-circuit, 50 psig hydrogen.

Prior to the first stand cells were discharged at C/2 rate to 1.0 volt/cell

First stand was 48 days duration (open circuit voltages were steady in the 1.2-1.3 volt range for all cells except X004 throughout the stand).

Cell X004 started stand at 1.3 volts but dropped suddenly to 0 volts after 27 days. Cell behaved normally in capacity cycling following the stand.

Prior to the second stand cells were discharged at C/2 rate to 0.5 volt/cell then shorted across a 1-ohm resistor for 16 hours.

Second stand was 40 days duration (all cell voltages were steady at 0 volts throughout).

Cell X007 did not recover from the second stand. Voltage behavior on subsequent charge attempts suggests that cell is shorted.

CAPACITY FADE TEST RESULTS

| | 0% Co/10% Cd | 10% Co/0% Cd | 3.3% Co/6.7% Cd | 6.7% Co/3.3% Cd |
|--|------------------|------------------|------------------|------------------|
| Cell: | X004 | X007 | X010 | X013 |
| | <u>10°C 23°C</u> | <u>10°C 23°C</u> | <u>10°C 23°C</u> | <u>10°C 23°C</u> |
| Theoretical Ah Capacity ¹ : | 23.9 | 23.8 | 24.0 | 23.9 |
| Initial Test | | | | |
| Ah capacity to 0.5 volt: | 24.0 23.4 | 23.9 20.7 | 24.3 21.8 | 21.9 19.7 |
| Utilization: | 100% 98% | 100% 87% | 101% 91% | 91% 82% |
| Following First Stand ² | | | | |
| Ah capacity to 0.5 volt: | 25.5 25.4 | 26.4 22.1 | 27.4 23.0 | 25.7 22.4 |
| Utilization: | 107% 106% | 111% 93% | 114% 96% | 108% 94% |
| % change from previous test: | +6% +9% | +10% +7% | +13% +6% | +17% +14% |
| Following Second Stand ³ | | | | |
| Ah to 0.5 volt: | 25.8 24.6 | --- --- | 25.5 21.3 | 24.5 21.1 |
| Utilization: | 108% 103% | --- --- | 106% 89% | 103% 88% |
| % change from previous test: | +1% -3% | --- --- | -7% -7% | -5% -6% |
| % change from initial test: | +4% +5% | --- --- | +5% -2% | +12% +7% |

¹Based on weight gain from total active material.
²248-day stand following C/2 discharge to 1.0 volt cut-off.
³340-day stand following shorting cells to 0 volts.