



NiH₂ Cycle Life Study

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Abstract

Cycle life studies have been performed at Eagle Picher Technologies (EPT), on HST Mantech design cells with various pedigrees of slurry and dry sinter processed electrodes, to evaluate peak load voltage performance during generic load profile testing. These tests provide information for determining voltage and capacity fade (degradation) mechanisms, and their impact on nickel hydrogen cell cycle life. Comparison of peak load voltage fade, as a function of State of Charge and cycle life, with capacity data from HST indicates that the cycle life limiting mechanism is due to impedance growth, and formation of a second discharge plateau. With a second plateau on discharge, capacity from the cell is still available, but at an unacceptable low voltage of 0.8 V per cell (17.6 V battery). Data shows that cell impedance increases with cycle number and depth of discharge, as expected.



Mantech Cell Cycle Test History

- Mantech Cells on Duty Cycle Test at 41 °F at Various Load Levels Since 1996
 - Generic LEO Load Profile with Peak Load Test for Minimum Voltage Test
 - Concern With Spacecraft is Low Bus Voltage Trip into Safe-Mode
 - Reconditioning Scheduled Annually During Cycling
 - Also Perform Reconditioning to Maintain Voltages Above Minimum Requirement
 - 19 - 22 Cells in Series Configuration
- Lot 1 Slurry Process Cells Added 3/96 - Completed 35.2K Cycles
- Lot 2, 3 Slurry Process Cells Added 9/97 - Completed 26.7K Cycles
- HST Dry Sinter Cells (3) added 9/97
 - Previously Cycled 6 Years at MSFC (~33K Cycles) - Unknown Storage History
 - Removed From Test 10/00 (16K + ~33K Cycles) - Cold Storage @ EPT
- Lot 5 Slurry Process Cells Added 10/98 - Completed 21.0K Cycles
- Lot 6 Slurry Process Cells Added 10/00 - Completed 10.5K Cycles

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Mantech cells have been on EPT Test Bed since 1996 to evaluate the minimum bus voltage to be experienced by operational load profiles.

Cells containing manufacturing Lots from several slurry and dry sinter process electrodes evaluated

HST Dry Sinter (S/N 200, 204, & 285)

1988 On-Orbit Build

Lot 3 (S/N 101) slurry cell, similar to HST Lot 10/11



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Eagle Picher Cell Life Test Load Profiles

Test	Ave. Dischg.	Ave. Dischg.	Ave. Batt. Load	Max. DOD	Peak Load	Battery	Profile	Comments
Profile	Amps	Minutes	Ahout/rev	AH	Amps	Max V	Dates	
ML1	12.8	52.3	11.2	28.8	15.2	33.1	3/14/96 -	Lot 1 Cells (3/96)
ML2	12.8	52.3	11.2	33.0	25.0	33.1	- 4/26/97	
HL1	16.2	49.3	13.3	32.4	32.4	33.1/33.6	4/26/97 - 8/18/97	
HL7	14.8	49.3	12.2	25.1	31.2	33.6	8/18/97 - 9/13/97	
HL8	14.2	49.3	11.7	22.0	31.2	33.6	9/13/97 - 1/28/98	Lot 2, 3, HST Cells Added (9/97)
UHL	11.7	47.3	9.2	40.8	27.3	33.2	1/28/98 - 5/23/98	
HL8	14.2	49.3	11.7	22.0	31.2	33.2	5/23/98 - 10/9/98	Lot 5 Cells Added (10/98)
HL10M	15.0	49.3	12.4	30.0	32.3	33.2/33.6	10/9/98 - 8/9/99	
HL12M	13.9	49.3	11.4	25.7	29.4	32.8/33.0	8/9/99 - 6/22/01	HST Cells Removed Lot 6 Added (10/00)
HL14R	10.8	47.4	8.6	14.1	30.0	32.8	6/22/01 - 3/21/02	
HL15R	10.8	47.4	8.6	17.1	30.0	32.8/33.0	3/21/02 -	

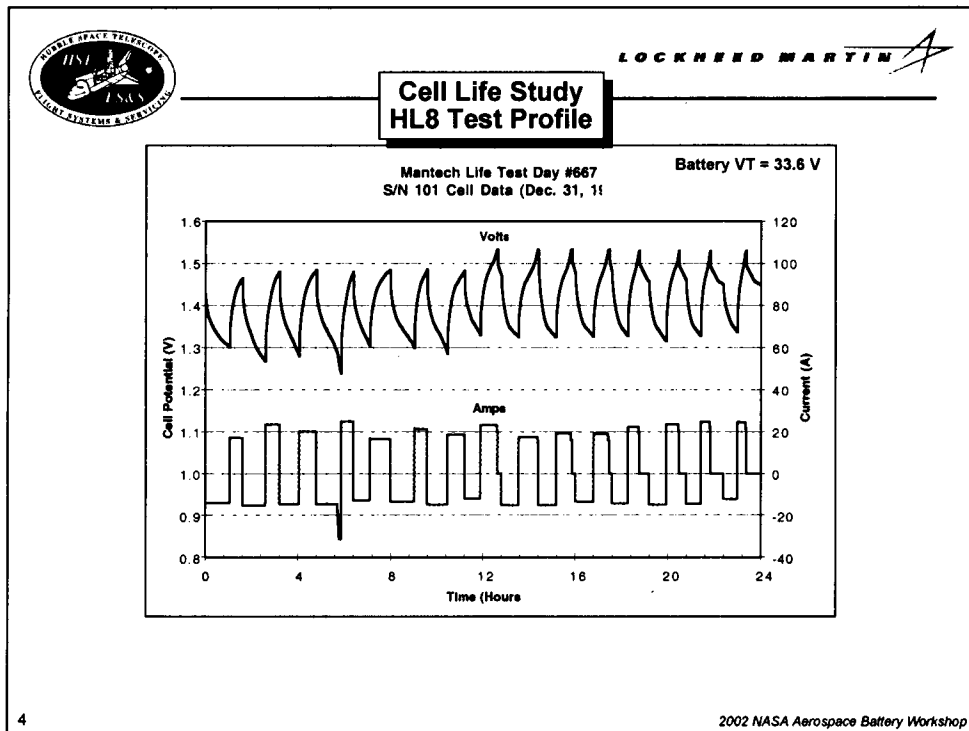
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Various Test Load Profiles have been used to evaluate differences in Cell Lots

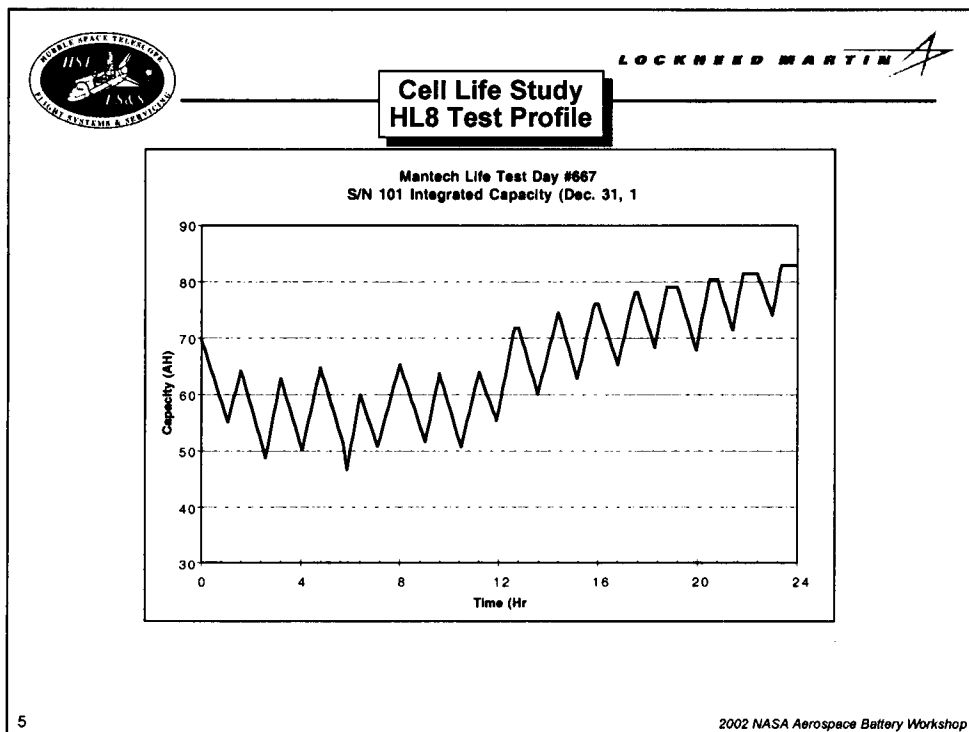
HL8 and HL10 Profiles similar to HST in DOD. Operational scenarios examined using other profiles.

Next group of slides show voltage and current for profile, followed by slide showing the DOD - Intent is to show these very fast to give flavor of testing. Each set of slides is solar day just prior to a reconditioning event, usually performed at 6 month intervals. State of Charge is usually lower after 6 months of cell cycling.

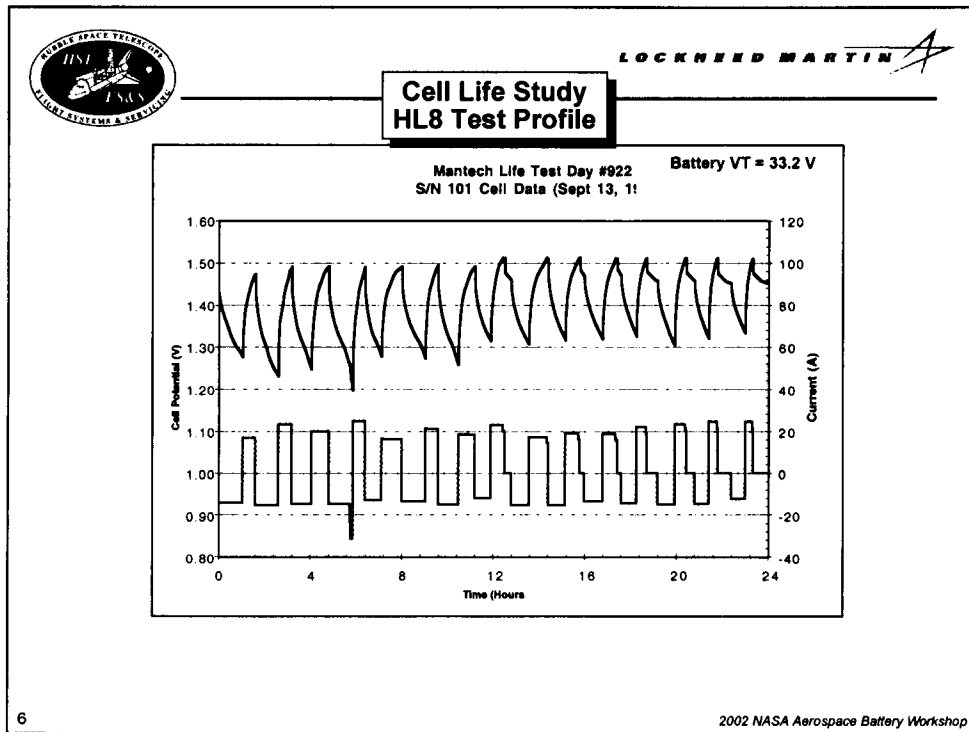


Typical LEO cycle for Lot 3 slurry cell S/N 101, having 15 revolutions per day where early Revs have less sun, and thus less battery charging, and last Revs have much sun, and thus charge current is turned off. Maximum battery voltage was 33.6 V for this period of testing, which results in a higher state of charge.

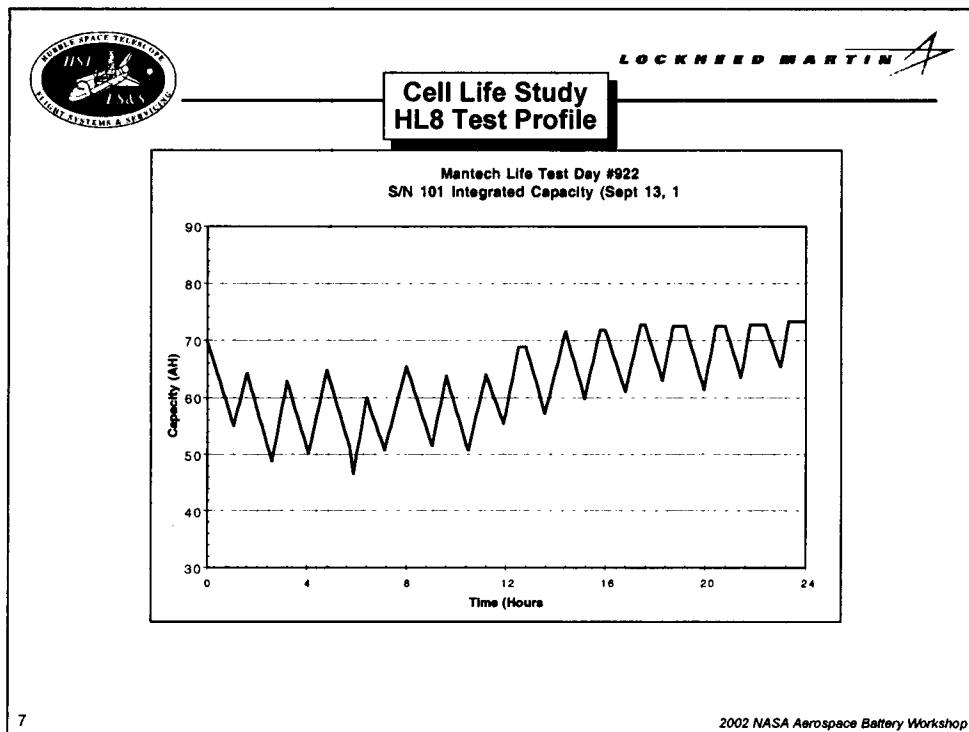
Profile has peak load of 31.2 Amp on 4th discharge revolution which is lowest state of charge during the solar day. Using dV/dI on the peak load the Impedance is determined and will be reported upon later in this Paper



For the same solar day as the previous slide, this slide details the battery capacity based upon integrated ampere hours. No strain gauge data was available at this point in testing. The cell capacity ranges between 85 and 47 Ah, with an initial capacity for the solar day assumed at 70 Ah, and 100 % charge efficiency.



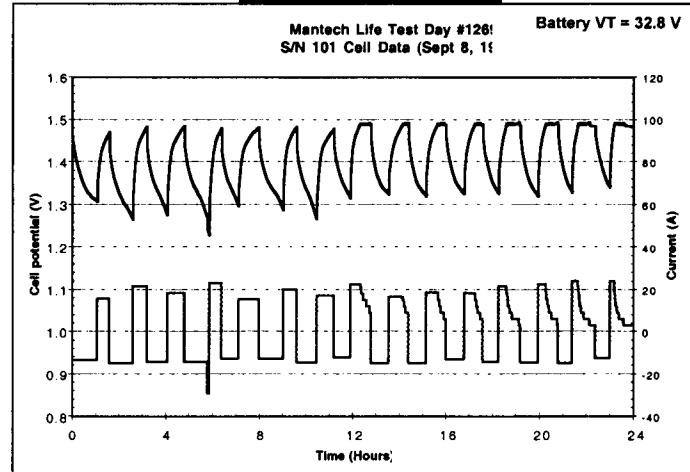
Another HL8 solar day, but with maximum battery voltage set at 33.2 V.
Results in lower state of charge at end of solar day.



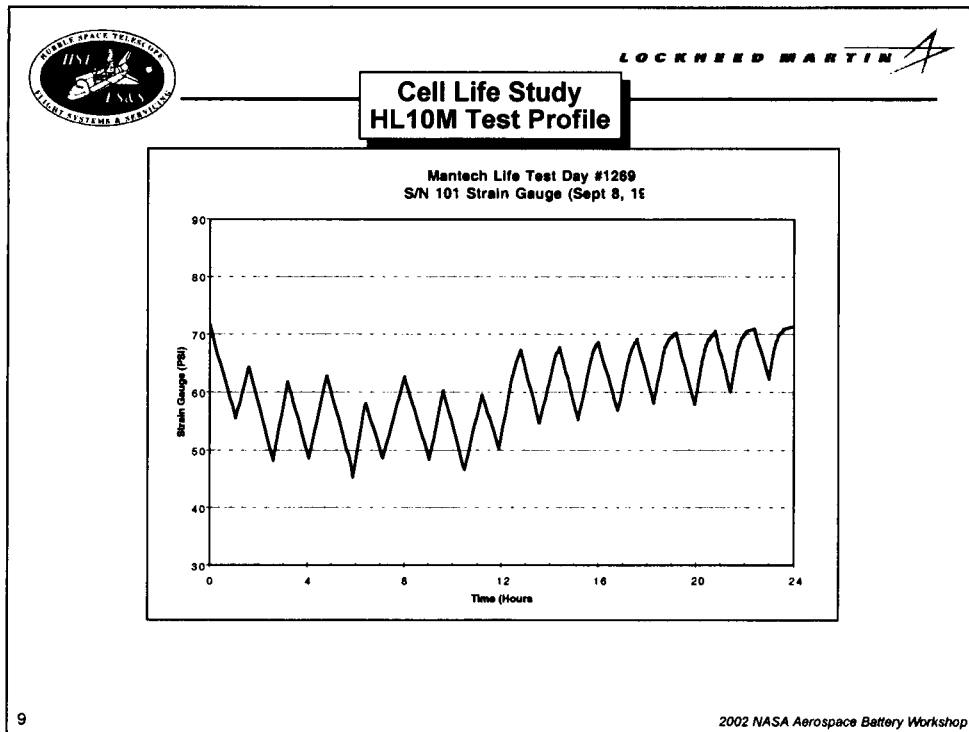
HL8 profile, but to lower maximum battery voltage - results in cell capacity ranging from 74 to 46 Ah, with an initial solar day capacity of 70 Ah assumed. SOC is lower at end of solar day



Cell Life Study HL10M Test Profile



HL10M profile has maximum battery voltage of 32.8 V, and exhibits taper charge control. Peak load is 32.3 Amps

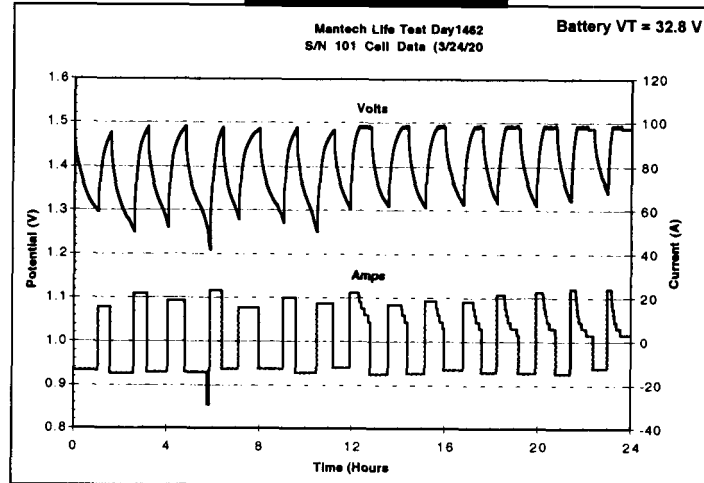


Strain Gauge data for S/N 101 was added to data acquisition. Cell capacity ranges from 72 to 46 Ah



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Cell Life Study HL12M Test Profile



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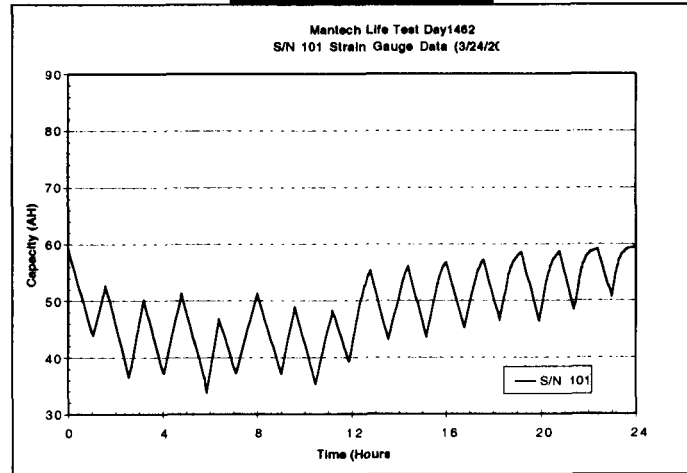
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HL12M test profile has higher loads than HL10M



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Cell Life Study HL12M Test Profile



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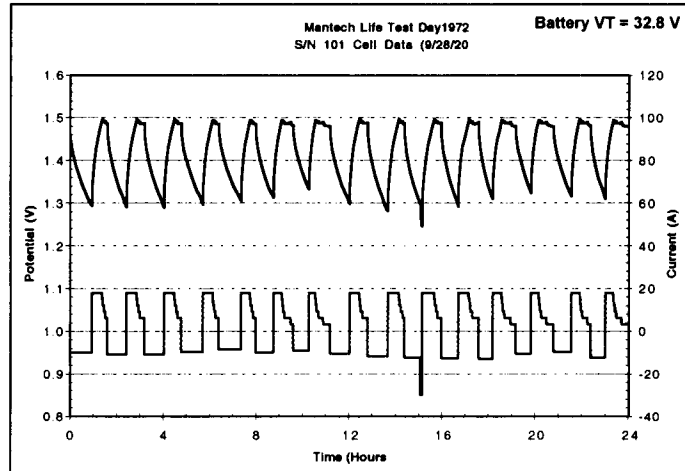
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HL12M cell capacity ranges from 58 to 35 Ah resulting in much lower states of charge for cell after 6 months of cycling.

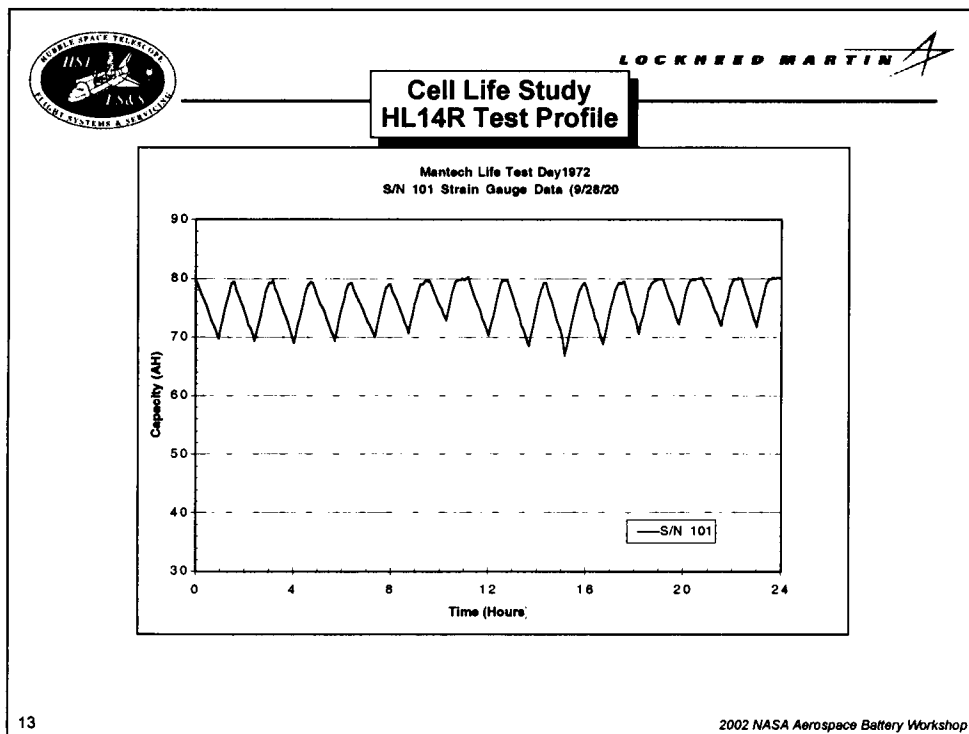


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Cell Life Study HL14R Test Profile



HL14M Profile is more benign from previous profiles. Maximum load is shifted to Rev # 10.

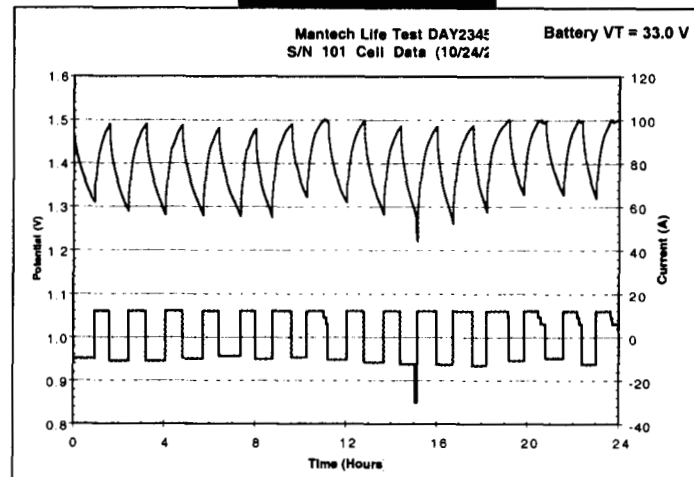


HL14M Profile results in higher states of charge on battery. Charts later will show high recharge ratios and high dissipation rates.



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Cell Life Study HL15R Test Profile



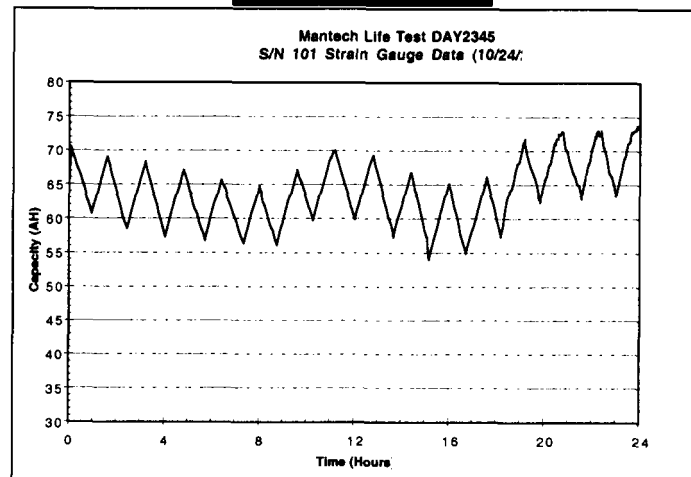
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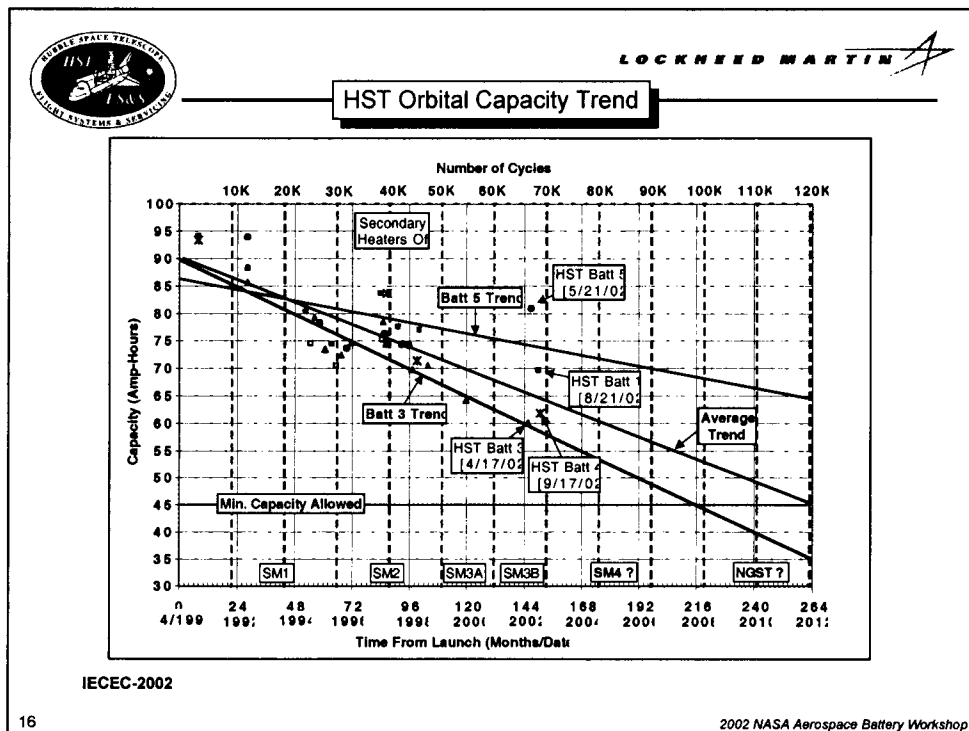
HL15R Profile is similar to HL14R except that charge current is reduced from 18 to 11 amps. This has several added benefits which will be discussed later.



Cell Life Study HL15R Test Profile

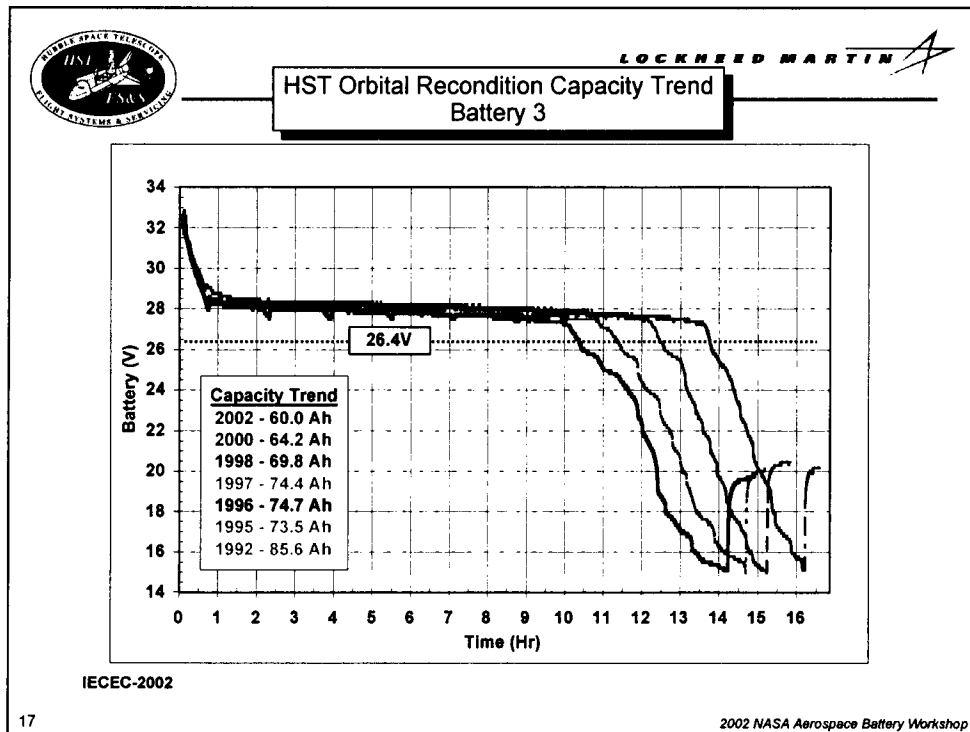


HL15R Profile details capacity ranging from 73 to 54 Ah.



Slide details the on-orbit reconditioning capacities for the six HST batteries. Worst case is Battery # 3 which will intercept the minimum battery capacity requirement of 45 Ah/Battery in 2008. More reconditioning capacity data is required to confirm trending after SM3B replacement of Charge Control Unit.

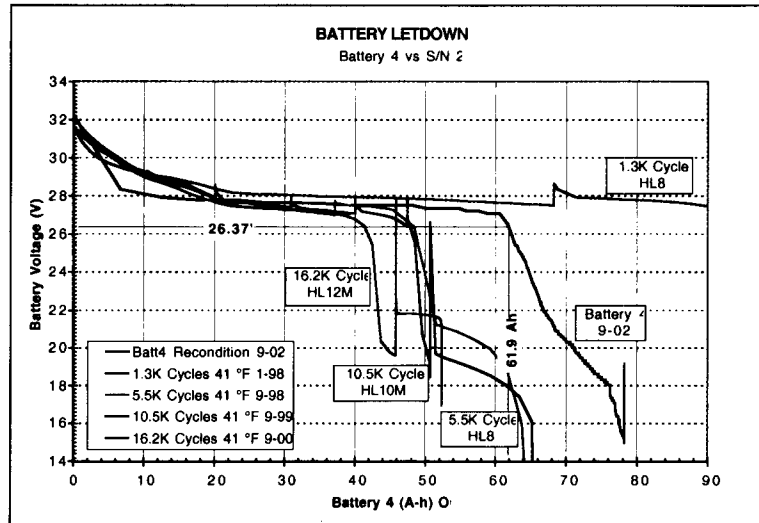
This is update of slide shown at IECEC-2002.



Shown at IECEC-2002, this slide details the on-orbit reconditioning capacity measurements for Battery # 3 which shows the gradual loss of capacity. Note also the inflections in the discharge curves below 26 V which imply cell drop-out which will be discussed later.



HST Recondition Capacity Comparison Battery 4 Orbital vs S/N 204 Ground



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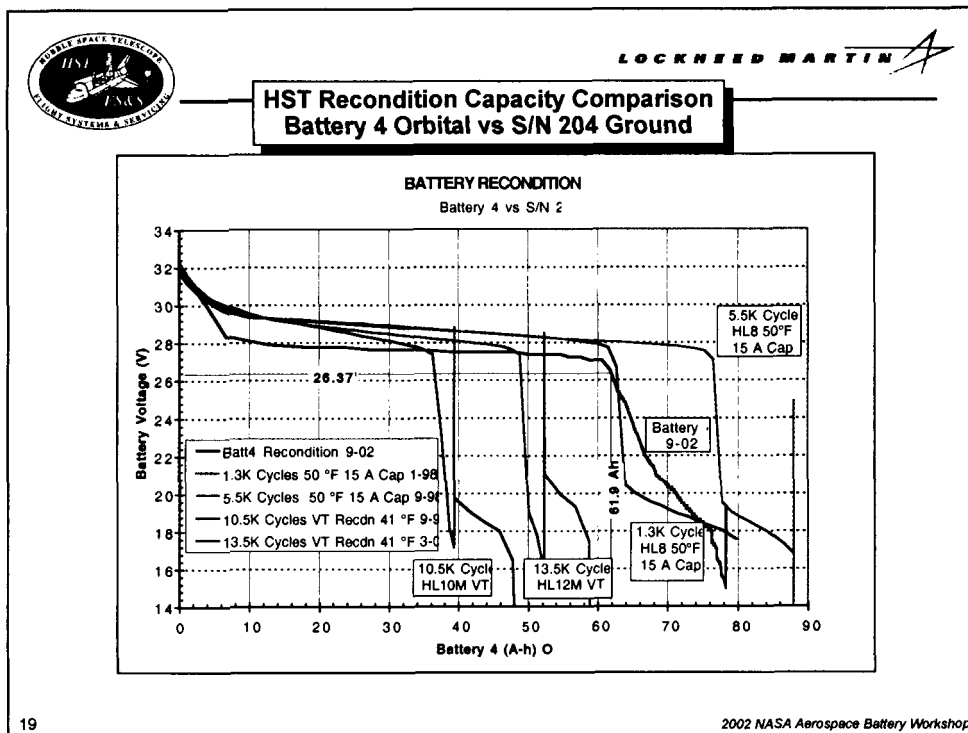
This chart compares the HST orbital Battery #4 reconditioning performed in September, with the EPT Cycle Life Test Bed which included S/N 204, HST dry sinter cell. S/N 204 had been cycled at MSFC for ~33K cycles, and then put on the EPT test. The letdown discharge is shown on this slide. The next slide will show the subsequent reconditioning cycle

1.3K Cycles HL8 profile resulted in pumped up cell

5.5K Cycles HL8 profile capacity is 46 Ah to 26.4 V

10.5K Cycles HL10M = 45 Ah Capacity

16.2K Cycles HL12M = 42 Ah Capacity



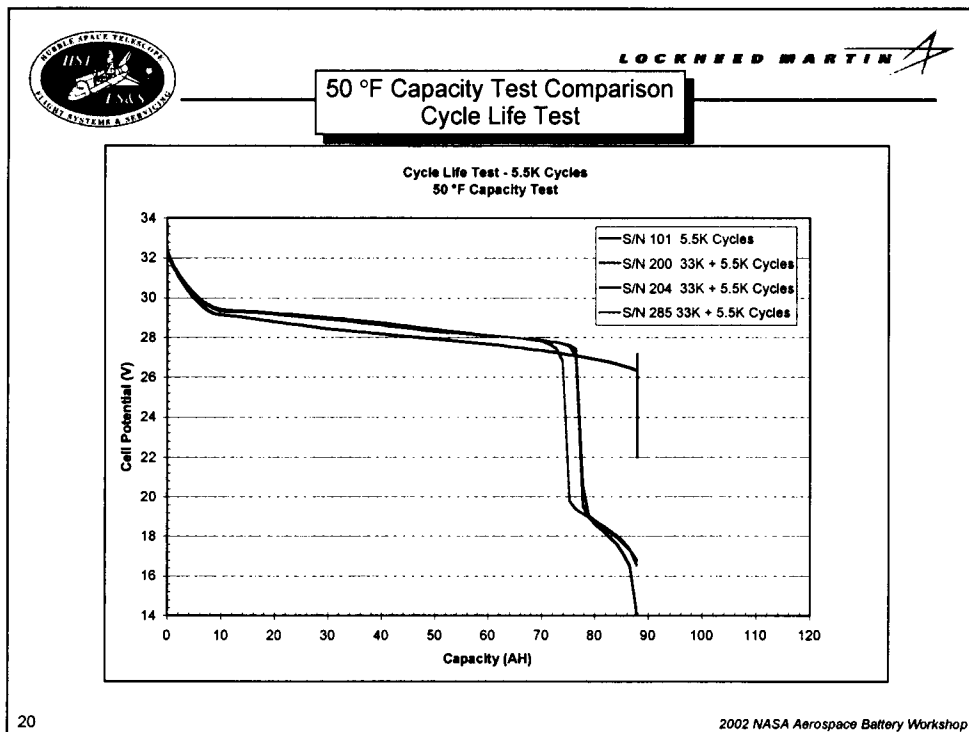
This slide shows the HST Battery 4 conditioning cycle as compared to S/N 204 on the EPT test bed. Reported are reconditioning cycles performed at two charge conditions (Full charge, and VT controlled charge).

1.3K Cycles HL8 50°F Capacity Check (of pumped up cell)

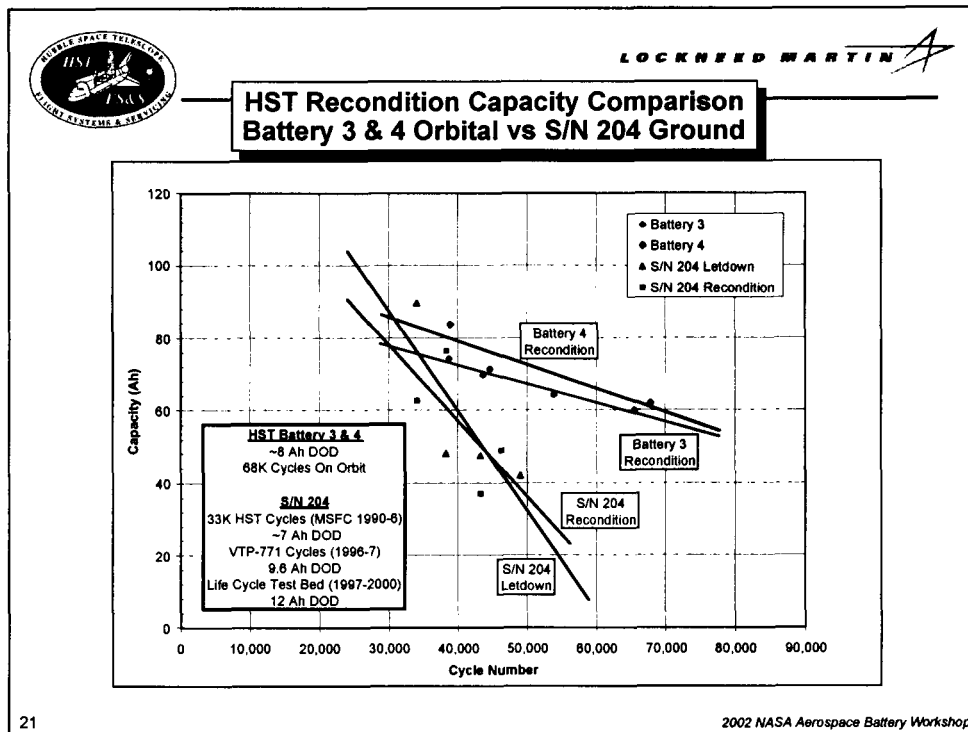
5.5K Cycles HL8 50°F Capacity Check

10.5K Cycles HL10M Reconditioning cycle with VT control

13.5K Cycles HL12M Reconditioning cycle with VT control



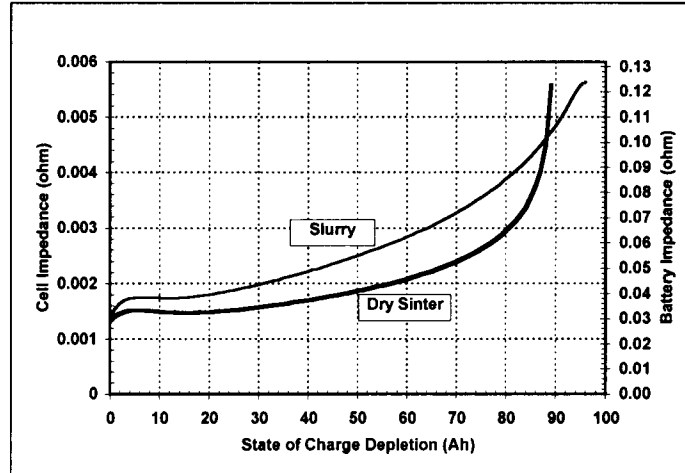
Discharge cycle during 50 F capacity test performed at 5.5K cycles on S/N 101 (slurry) and S/N 200, 204, & 285 (dry sinter) cells. Note dry sinter cells having 33 K cycles at MSFC and 5.5K cycles on EPT test have higher discharge plateau, but lower discharge capacity than slurry cell with only 5.5K cycles of cycling



This slide compares the reconditioning trending for HST orbital batteries 3 & 4 versus ground conditioning of S/N 204 at higher DODs.
Dry sinter S/N 204 cycle history is given



Battery Model Impedance Prediction



IECEC-2002

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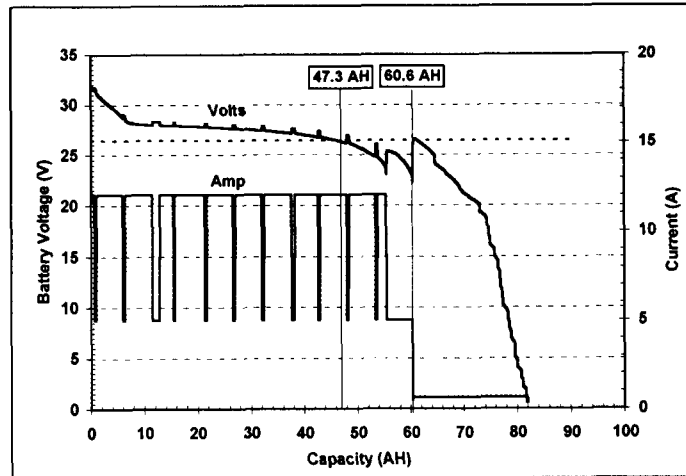
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From IECEC-2002, this slide shows the interaction between state of charge depletion (DOD) and battery impedance. Higher DODs result in higher impedance. This data is from HST 1996 Mini-Verification Study comparing slurry with dry sinter.

As the cell walks down in state of charge during cycling, the operational hysteresis shifts towards the right, with the battery impedance increasing

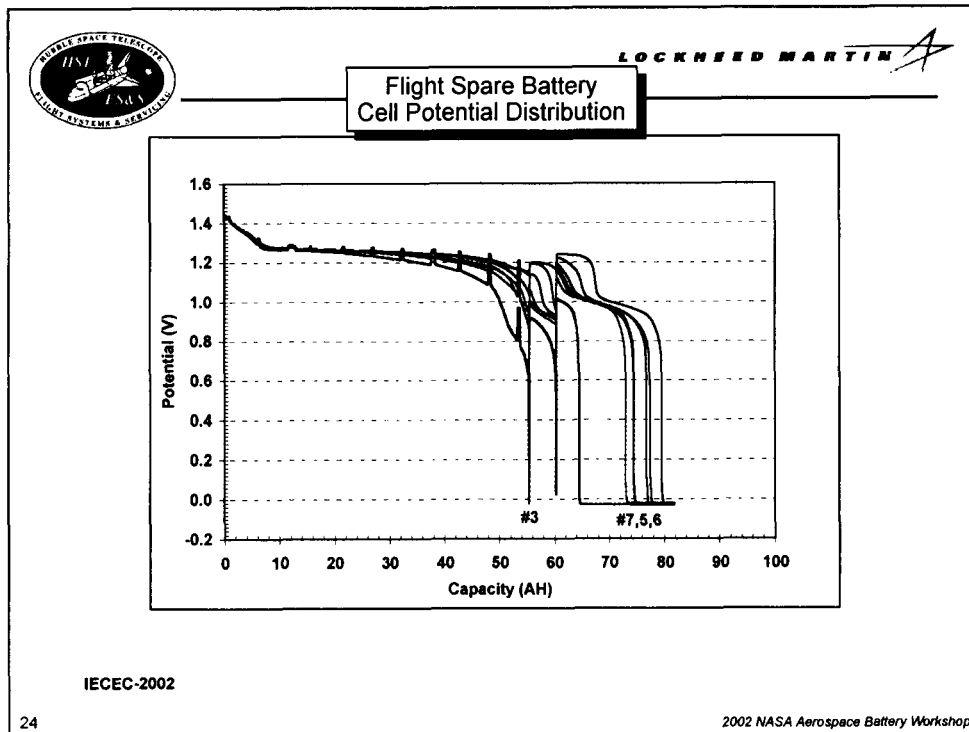


Flight Spare Battery Pulse Discharge

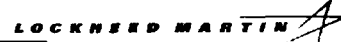


IECEC-2002

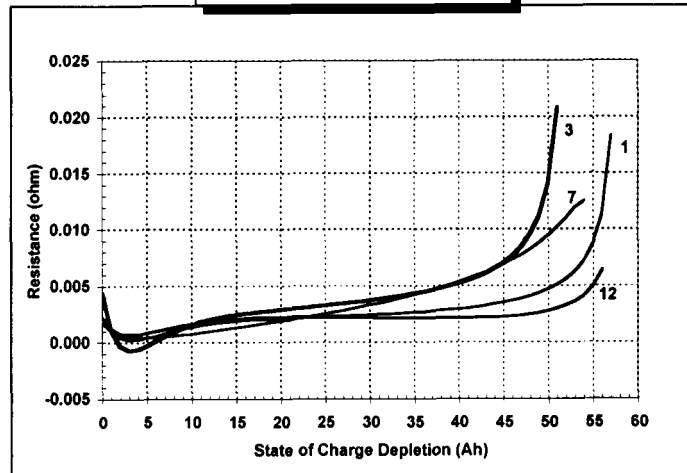
Special test performed upon HST Flight Spare Battery at MSFC. Note inflections in the battery voltage below 25 V. Battery current pulsed was pulsed in order to model cell impedance.



Individual cell potentials for special HST Flight Spare Battery test. Note drop out and second plateau of cells.



Flight Spare Battery Cell Impedance Distribution



IECEC-2002

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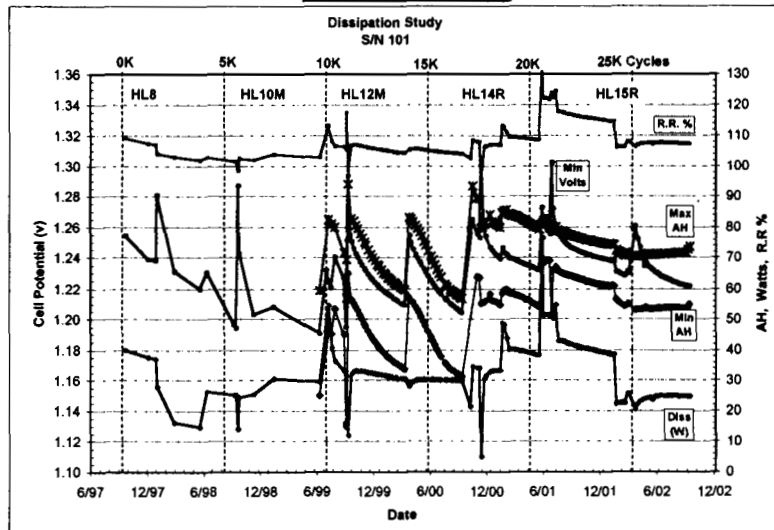
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Impedance data extracted from special HST Flight Spare Battery test. The worst case cells (#3 & 7), an average cell (#1), and the best cell (#12) are shown.



Cell Life Study 9/1/97 - 11/1/02

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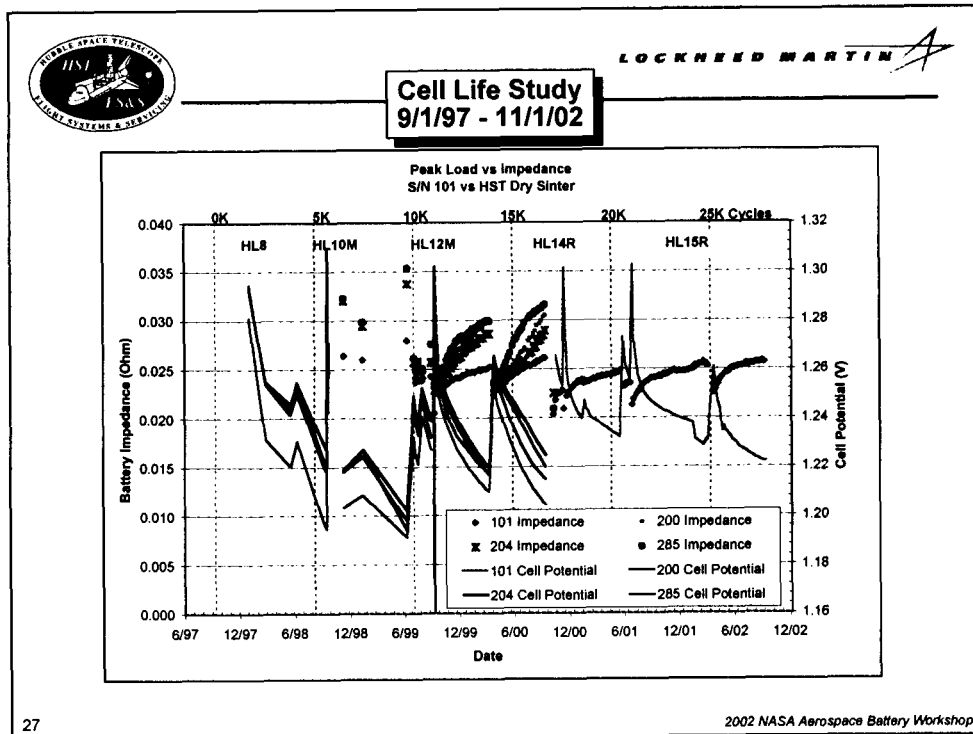


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From the EPT Cycle Life Test bed, this slide shows the cycle life test history for S/N 101 Lot 3 slurry cell, which started in 9/97 and is continuing. The top trace (red) shows the recharge ratio. The purple trace is the maximum Ah capacity during the solar day, while the blue trace is the minimum Ah capacity (strain gauge data). The dark blue trace, starting on 9/97, is the minimum cell potential during the solar day corresponding to the peak load. The black trace is the cell heat dissipation.

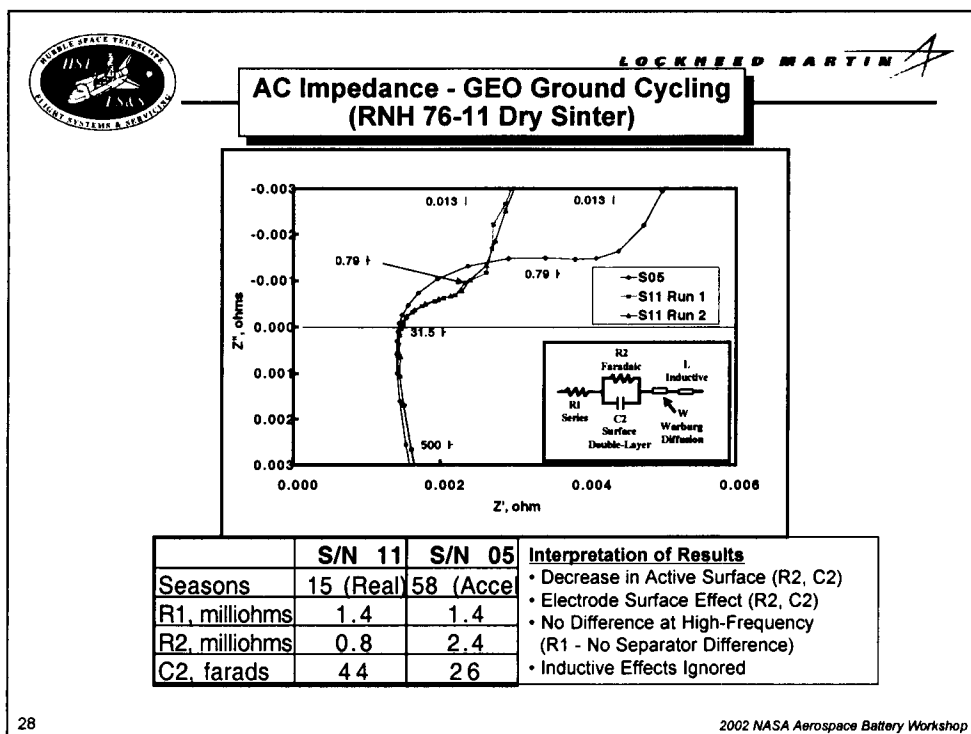
Note peak load voltage and min/max Ah capacities decrease after each reconditioning for all load profiles, except for HLM15R, where everything is stable, except peak load voltage continues to decrease after reconditioning.



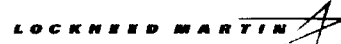
This chart repeats the minimum load voltage for S/N 101 Lot 3 slurry data from the EPT Test bed, as well as the three HST dry sinter cells tested (S/N 200, 204, and 285). The slide also details the cell impedance at the peak load based upon a dV/dI calculation.

Impedance of HST dry sinter cells is higher than Lot 3 slurry cell - shows cycle aging

The cell impedance walks up, while the peak load voltage walks down between cell reconditioning cycles, even for profile HLM15R.



AC Impedance study of dry sinter cells exposed to real and accelerated GEO cycling. The accelerated cell shows higher impedance (R2), and reduced active electrode surface area (C2) as aging effects. No sign of separator dry out was observed in the high frequency impedance (R1)



REFERENCES

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