# Battery/Ultracapacitor Evaluation

for

X-38 Crew Return Vehicle (CRV)

by
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1998 NASA Aerospace Battery Workshop

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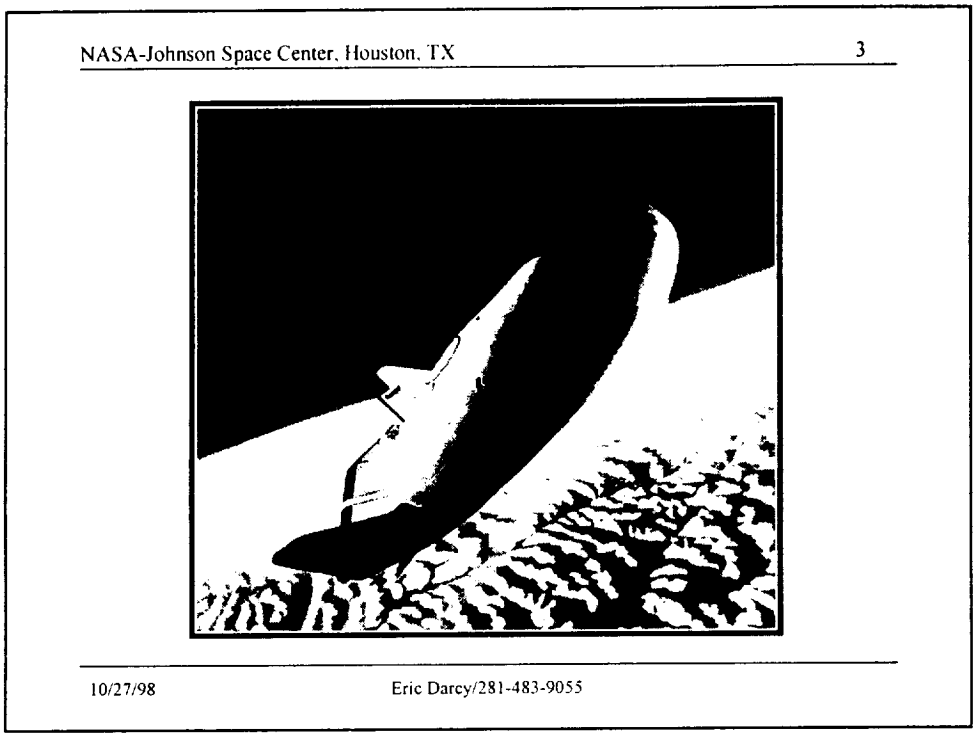



# •Top Level CRV Requirements

•Provide for the safe return of ISS crew of zero to 7 in case

- –emergency return of ill or injured crew person
- –ISS can not maintain critical systems, pressure, attitude, or is contaminated
- –Shuttle is not available to return crew

•Crew return without pressure suits

•On-orbit lifetime of 3 years

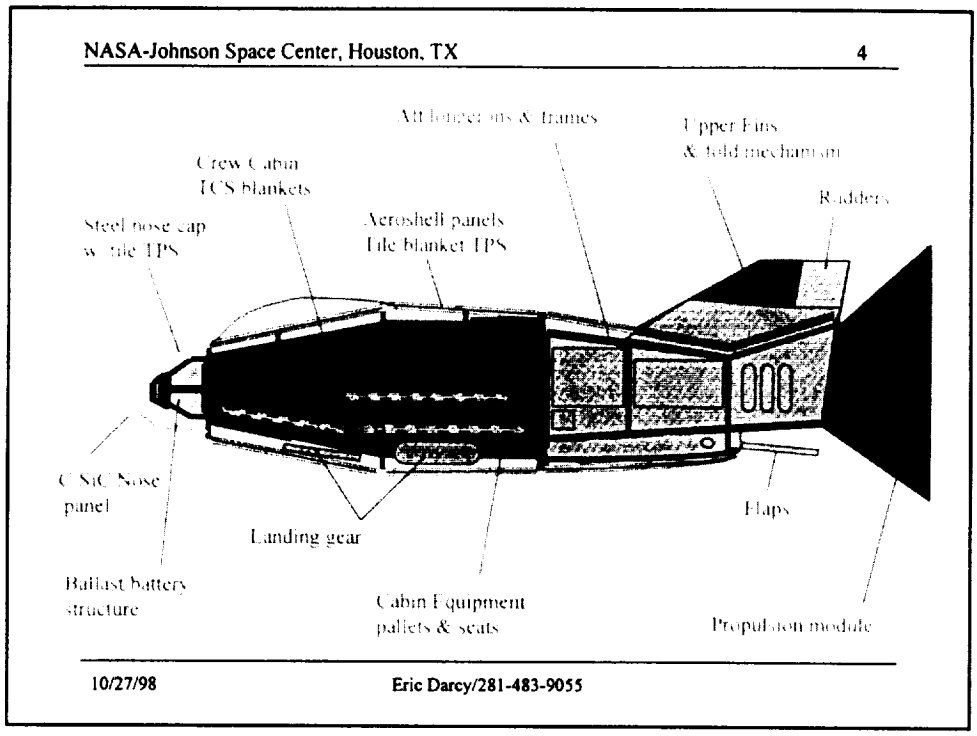
•700 nautical miles of cross range

•Land lander

•Separation time from ISS < 3 minutes

•Planned return mission time is 3 hours maximum

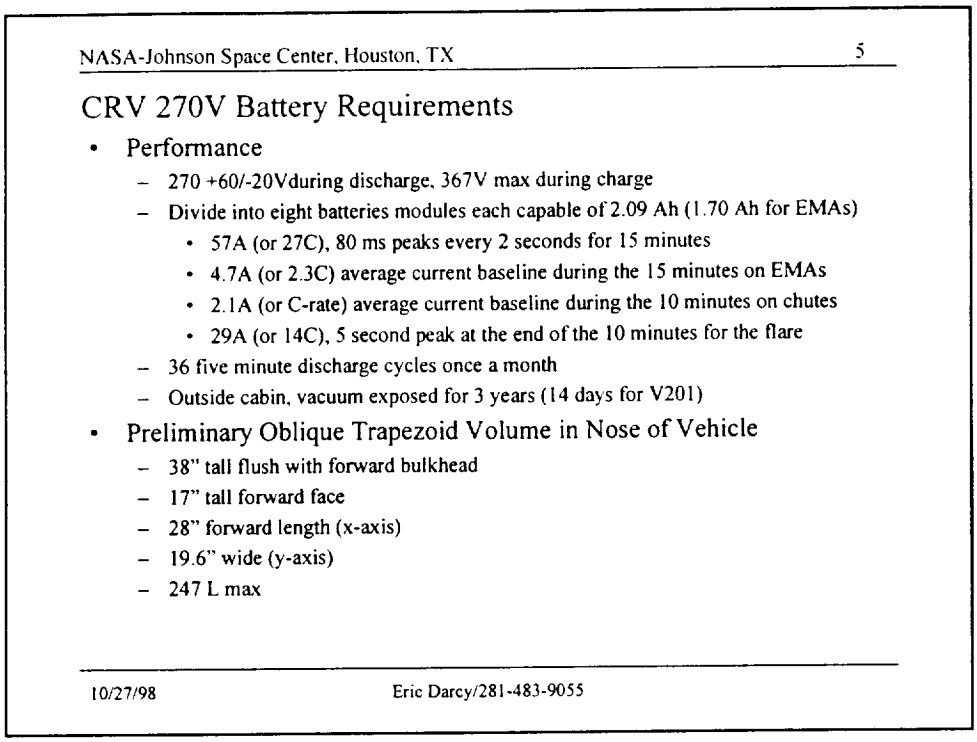
•Contigency return mission time is 9 hour maximum




# •Mission design

## –V-201 mission objectives

- •Demonstrate launch on STS
- •Demonstrate on-orbit activation and checkout
- •Demonstrate RMS deployment
- •Access on-orbit handling qualities
- •Assess system performance
- •Demonstrate de-orbit burn
- •Demonstrate de-orbit module separation and entry attitude maneuvers
- •Assess entry and hypersonic flight performance
- •Assess atmospheric flight performance
- •Demonstrate parachute operations
- •Assess landing accuracy
- •Demonstrate landing performance
- •Demonstrate system shutdown




•Unique Program Approach for X-38

•Design, Build, and Test in small increments for rapid feedback

–Pallet Drops (parachute weight tests)

–Dog House Drop (parachute drop test with a vehicle-like shape)

–V-131 (X-24 aero shape with fixed surfaces dropped from a B52)

–V-132 (same shape with EMA controlled surfaces)

–V-133 (20% bigger, again B52 dropped)

–V-201 (Shuttle launched, 5/00, unmanned return test)

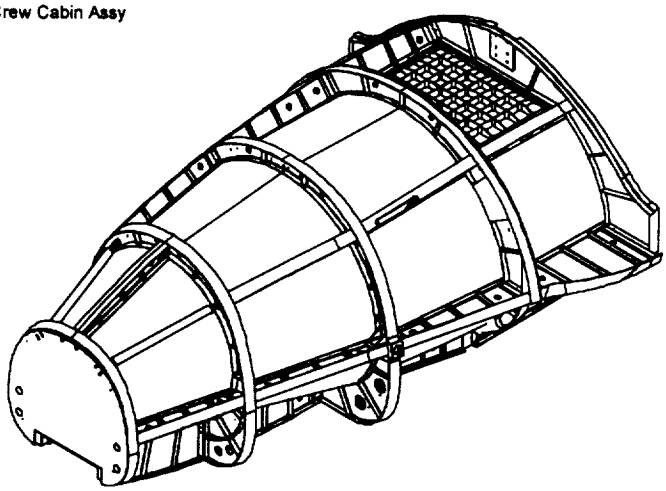
–V-202 (Ariane launched, 3/02, unmanned return test)

•No prime contractor (except for Deorbit Propulsion Stage) thru V-202

•Later, a prime contractor will build operational CRVs for ISS

## Battery Envelope (preliminary)

X-38 Vehicle 201
Crew Cabin Assy



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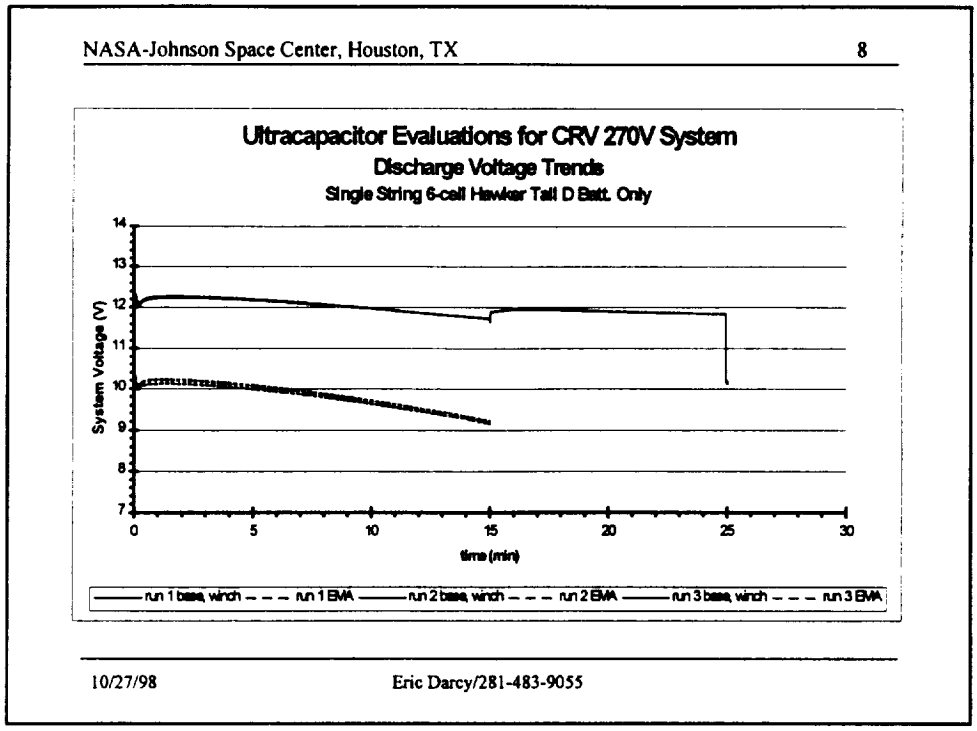
## Early Battery Point Design and Test Results

- All testing performed by Symmetry Resources, Inc., in Arab, AL
- In early 1997, first pursued Hawker Cyclon Tall D-cell as baseline cell
- Resulting Point Design with Hawker Tall D-cell
  - 1P - 160S battery module
  - 67.5 kg/module
  - 540 kg/total battery
  - 340mm x 760mm x 112mm, (28.94 L/module)
  - 231.5 L/total battery
- Observations
  - Cell internal resistance = 7.9 mohms
  - Need lower impedance cell design and higher power density

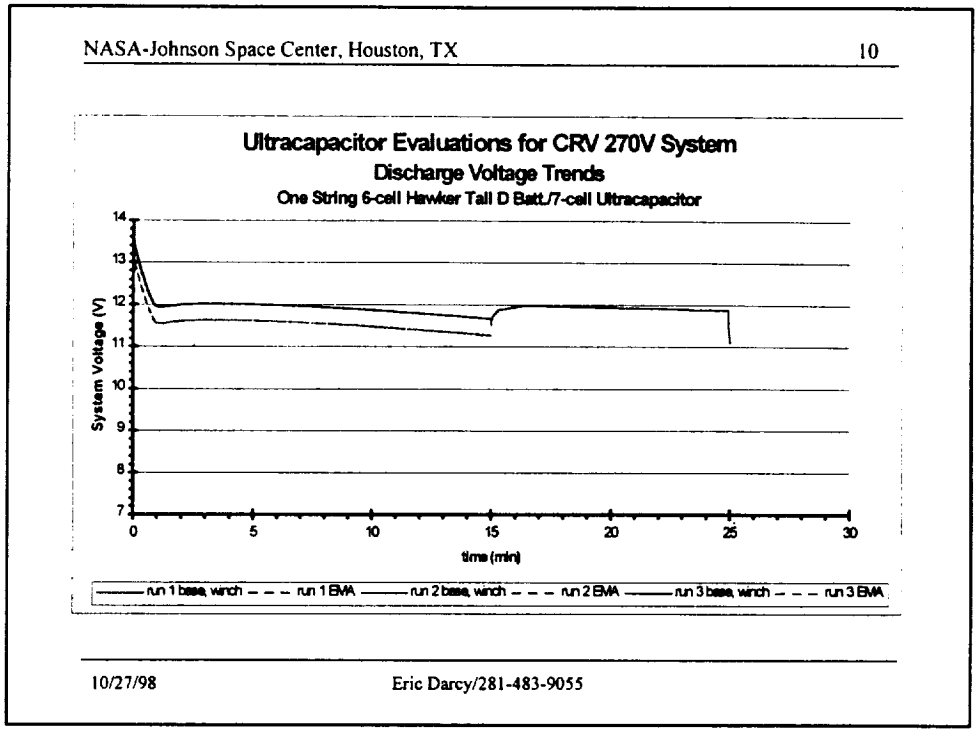



Test Conditions and Results

- Discharge at 25 deg C
- Minimum EMA voltage = 9.2V/6 cells (= 246V for 160S)
- Mininum Winch voltage = 10.2V/6 cells (= 272V for 160S)
- Maximum voltage sag = 2.4V/6 cells (= 64V for 160S) during last EMA pulse

## Ultracapacitor Bank

- Capacitor bank of 7 capacitor in series
- Capacitor bank rated at 142 Farads using unit cell rated at
  - 1000 Farad, 2645 J
  - 390 g ⟶ 1.88 Wh/kg
  - 160mm x 75mm x 24mm ⟶ 2.55 Wh/L
  - ESR = 1.85 mohm
  - above values based on 2.3V float voltage
  - specific power = 4210 W/kg, power density = 5701 W/L
  - above values based on surge voltage = 2.7V
- Bank and cell are commercially available from Maxwell Technology
  - bank P/N PCM14014X
  - capacitor P/N PC2623

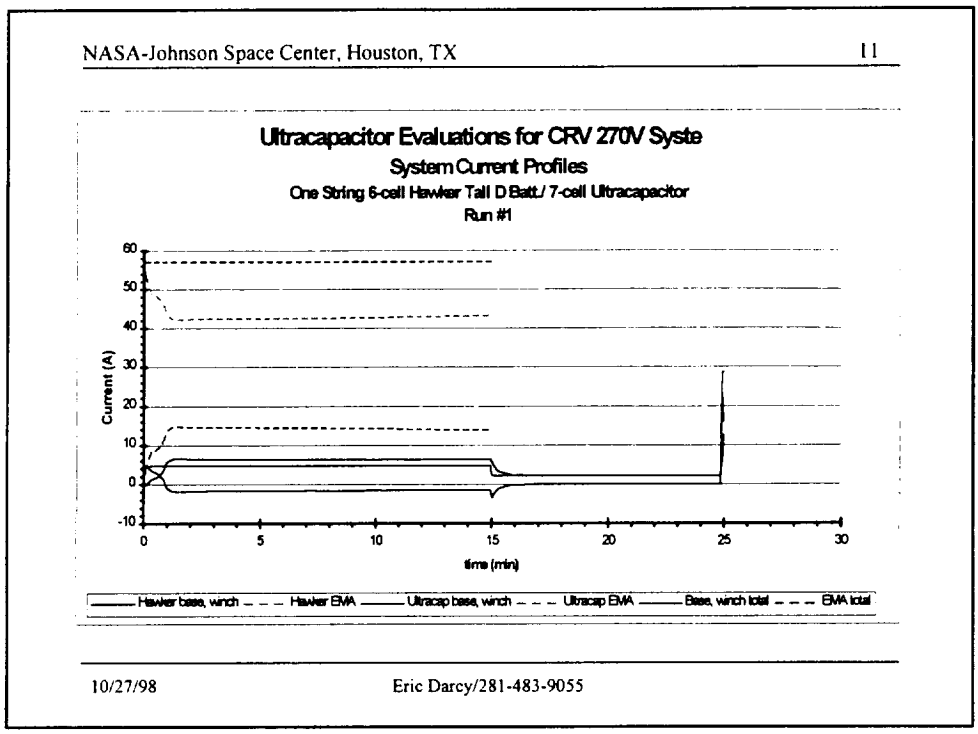



Test Method

- 1 Battery string and 1 capacitor bank were charged independently
- Hawker battery string was charged to 14.7 with a 6 amp limit for 16 hours
- Capacitor bank charged to a voltage = OCV of battery string (13.02V)
- Cells in capacitor bank were monitored and equalized for proper balancing
- Immediately after, battery and cap bank were paralleled and discharge began
- Original power profile was run (57A peak)
- Battery and total currents were measured throughout run

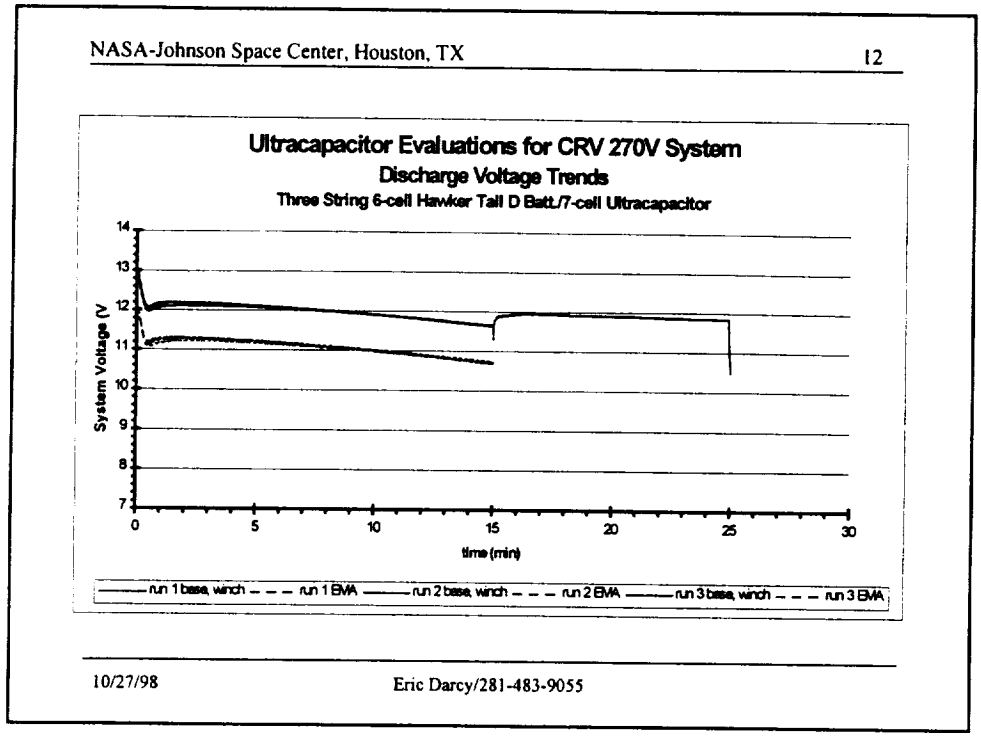
Results,

- Minimum EMA voltage = 11.3V (1.88 V/LA cell)
- Minimum Winch voltage = 11.1V (1.85 V/LA cell)




## Results

- Capacitor current is 95% (54A) of total at first
- Capacitor current levels to 75% (43A) after 1 minute
- Battery is charging capacitor at 2A during EMA off peaks
- Capacitor bank absorbs most of Winch pulse at first
- Capacitor bank current fades about 10A at end of 5s Winch pulse

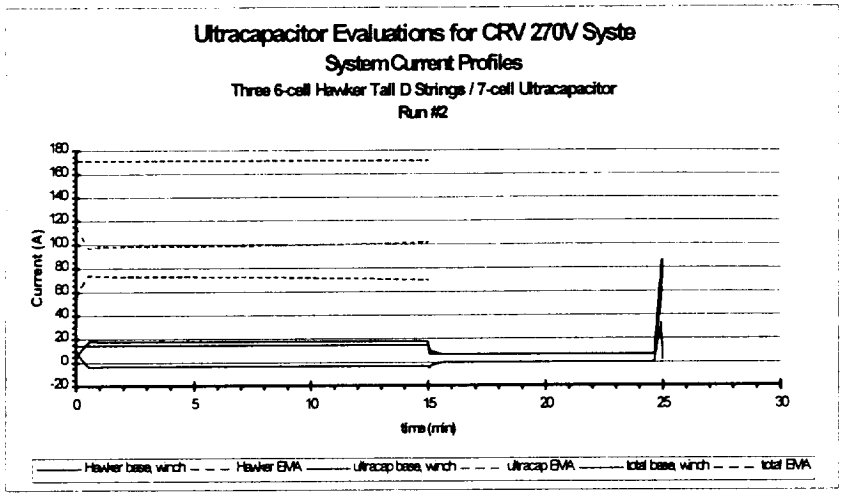



Test Method

- 3 Battery strings and 1 capacitor bank were charged independently
- Hawker battery strings were charged to 14.7 with a 6 amp limit for 16 hours
- Capacitor bank charged to a voltage = OCV of battery string (13.02V)
- Cells in capacitor bank were monitored and equalized for proper balancing
- Immediately after, batteries and cap bank were paralleled and discharge began
- 3X original power profile was run (171A peak)
- Total battery and total hybrid currents were measured throughout run

Results

- Minimum EMA voltage = 10.7V (1.78 V/LA cell)
- Minimum Winch voltage = 10.5V (1.75 V/LA cell)






## Results

- Capacitor current is 70% (120A) of total at first
- Capacitor current levels to 58% (100A) after 1 minute
- Battery is charging capacitor at 5A during EMA off peaks
- Capacitor bank absorbs only 40% (35A) of Winch pulse at first
- Capacitor bank current fades about 2A at end of 5s Winch pulse

## Summary

- Results indicate
  - Battery/capacitor hybrid does load share as expected
  - At triple currents, one bank of capacitors in parallel with three batt strings
    - increases load voltage by 16% during last EMA pulse
    - increases load voltage by only 3% during 5 second winch pulse
  - 4x currents would result in capacitor bank sharing < 50% of peaks
  - 7 cap in parallel with 6 batteries results in caps charged to 1.91V/cap
  - Need better voltage matching to more fully charge caps
- Hybrid Point Design
  - starting at 2.7V/cap, 330V bank consists of 122 in series
  - 122S bank weighs 47.9 kg and consumes 35.2 L
  - 22% more volume than 1P-160S battery of Hawker Tall D-cells

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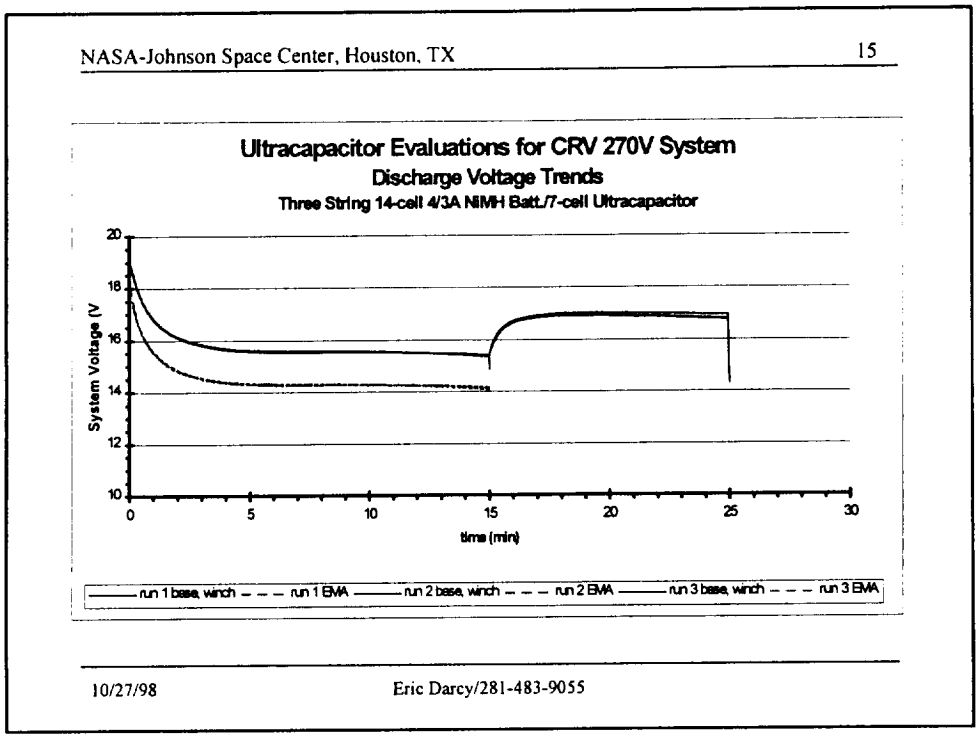
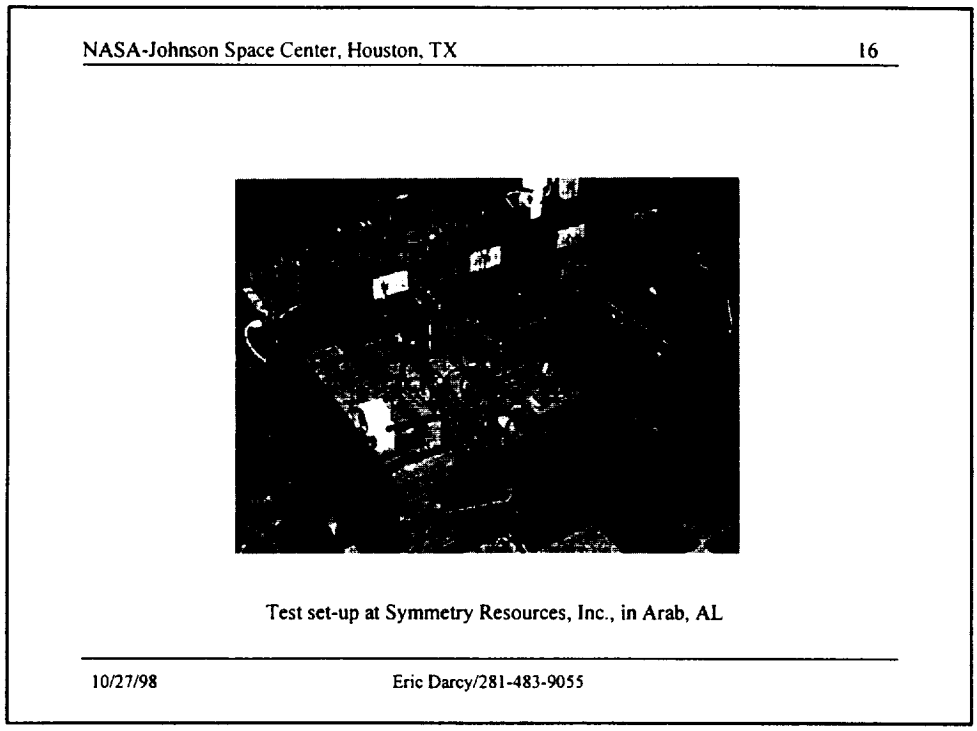



Test Method

- 3 Battery strings and 1 capacitor bank were charged independently
- 14S strings of Sanyo 4/3A NiMH cells charged to 0.35A for 16 hours
- Capacitor bank charged to a voltage = OCV of battery strings (19.2V)
- Cells in capacitor bank were monitored and equalized for proper balancing
- Immediately after, batteries and cap bank were paralleled and discharge began
- 3X original power profile was run (171A peak)
- Total battery and total hybrid currents were measured throughout run

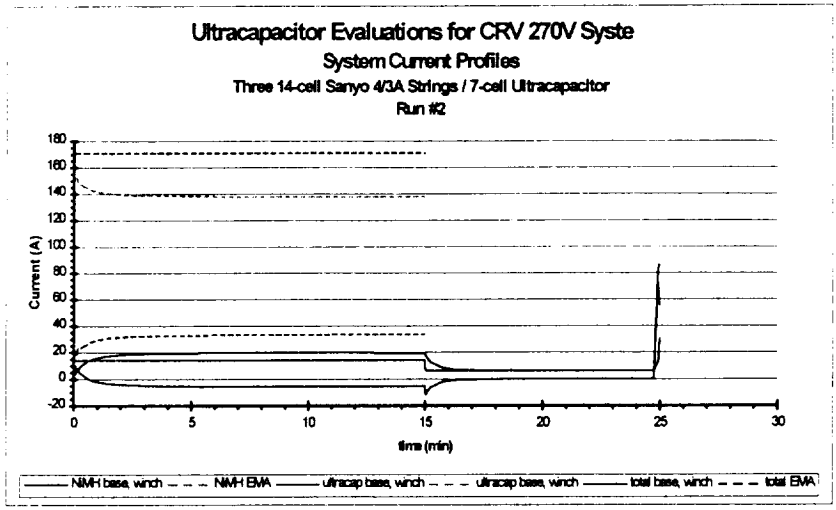
Results

- Minimum EMA voltage = 14.1V (1.01 V/NiMH cell)
- Minimum Winch voltage = 14.4V (1.03 V/NiMH cell)




Test set-up at Symmetry Resources, Inc., in Arab, AL

- Ultracapacitor bank is in background
- NiMH battery is in foreground






## Results

- Capacitor current is 90% (154A) of total at first
- Capacitor current levels to 81% (138A) after 3 minutes
- Battery is charging capacitor at ~6.7A during EMA off peaks
- Capacitor bank absorbs only 84% (73A) of Winch pulse at first
- Capacitor bank current fades about 18A at end of 5s Winch pulse

## Summary of NiMH/Capacitor Hybrid

- Test results indicate
  - Capacitors charged to 2.75V/ea when paralleled with 14-cell NiMH
  - Load voltage during EMA pulses barely > 1V/MH cell
  - Majority (> 80%) of pulse current absorbed by capacitor bank
  - non-peak EMA current provide entirely by MH cell
  - Better load voltage balance between EMA and Winch pulses
  - non-peak current reaches is ~7A/cell, which is too high for this cell
- Conclusions
  - Ultracapacitors can be paired with batteries with complimentary results
  - Impedance balance between battery & capacitor bank is crucial to results
  - Power density (W/L) of present ultracapacitor technology is not high enough for CRV in a straight parallel w/ batteries hybrid configuration

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## Modified CRV 270V Battery Requirements

- Performance
  - 270 +30/-65Vduring discharge, 345Vmax during charge
  - Divide into eight batteries modules each capable of 2.65 Ah (2.06 Ah for EMAs)
    - 81A (or 31C), 60 ms peaks every 2 seconds for 15 minutes
    - 6A (or 2.3C) average current baseline during the 15 minutes on EMAs
    - 3A (1.1C) average current baseline during the 10 minutes on chutes
    - 33A (or 12C), 10 second peak at the end of the 10 minutes for the flare
  - 36 five minute discharge cycles once a month
  - **Bus voltage < 300V during 40 kW regenerative charging (40.5A for 60 ms)**
  - Outside cabin, vacuum exposed for 3 years (14 days for V201)
  - 247 liters available in nose in an oblique trapezoid shape

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## High Power Cell Design Trades

| Cell Design | Cell Size | Cell 1C Cap. (Ah) | Batt Module configuration | Max OCV (V) | Final EMA Volt (V) | Final Winch Volt (V) | Estimated Battery Module Mass (kg) | Estimated Battery Module Volume (L) |
|---|---|---|---|---|---|---|---|---|
| Hawker lead acid | D | 1.90 | 2P-125S | 274 | 211 | 229 | 62.30 | 31.46 |
| Bolder lead acid | 9/5C | 1.00 | 3P-115S | 252 | 215 | 204 | 43.47 | 19.92 |
| Energizer Ni-MH | subC | 2.00 | 3P-210S | 286 | 213 | 241 | 46.75 | 20.52 |
| Sanyo NiCd | D | 4.00 | 1P-218S | 301 | 209 | 243 | 45.78 | 23.75 |
| Energizer NiCd | subC | 1.70 | 3P-200S | 274 | 220 | 235 | 45.36 | 19.44 |

Assumptions used
- Effective internal resistance (Re) of cells based on delta V:delta I performance under test
- Re was measured at 10% increments during 1C discharges with 10C, 80 ms pulses
- Cell interconnect resistance of 0.5 mohms used for each cell
- Total cell mass (volume) x 1.5 (x2.0) = estimated battery module mass (volume)

Conclusions
- NiCd Cs cell yields module with lowest volume, Bolder lead acid close second.
- 8 Hawker lead acid D-cell battery modules exceeds available volume (247L)

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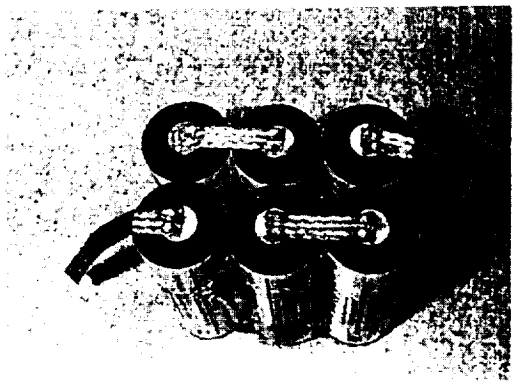
Test Method

- Cells were charged per the manufacturer's recommendation
- Allowed to rest at OCV for > 1.5 hours
- Discharged at C-rate with 10C, 80 ms pulses every 5.987 minutes at 25 degC
- Data allows Re to be calculated at 10% SOC increments from 90 to 10%
- Re = deltaV/delta I

## Bolder Technology Lead Acid Cell

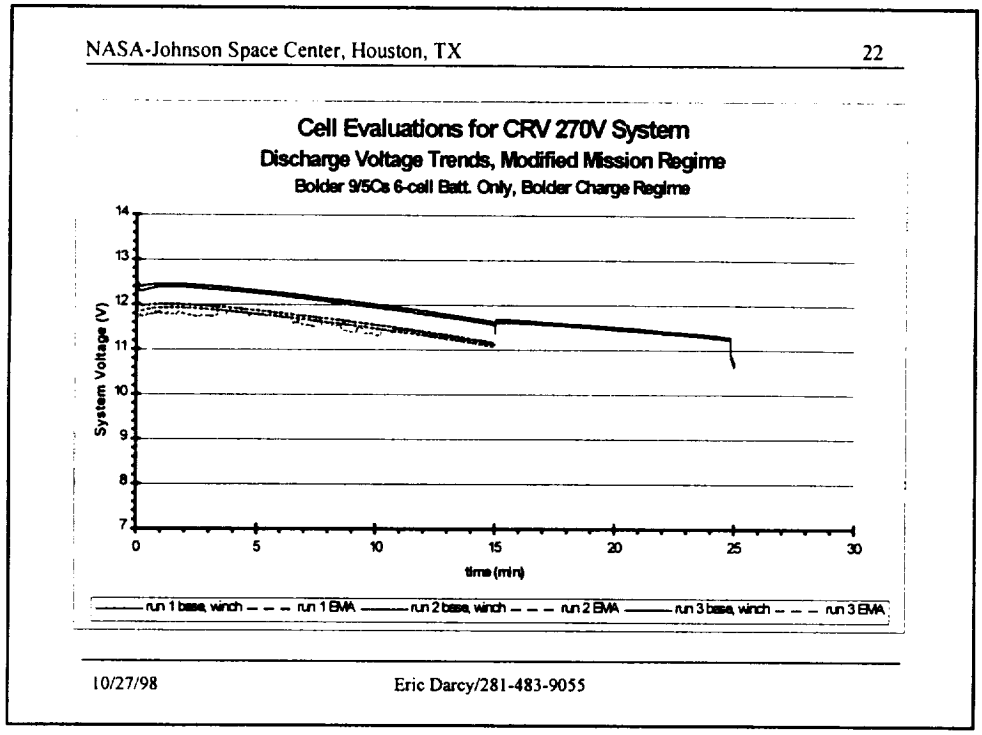
- Thin metal film cell contruction yields very high power
  - 9/5C sized cell delivering 1.0 Ah
  - cell is 90g, 22.9 mm diameter x 70.1 mm tall
  - cell impedance < 2 mohm, similar to 1000F capacitor





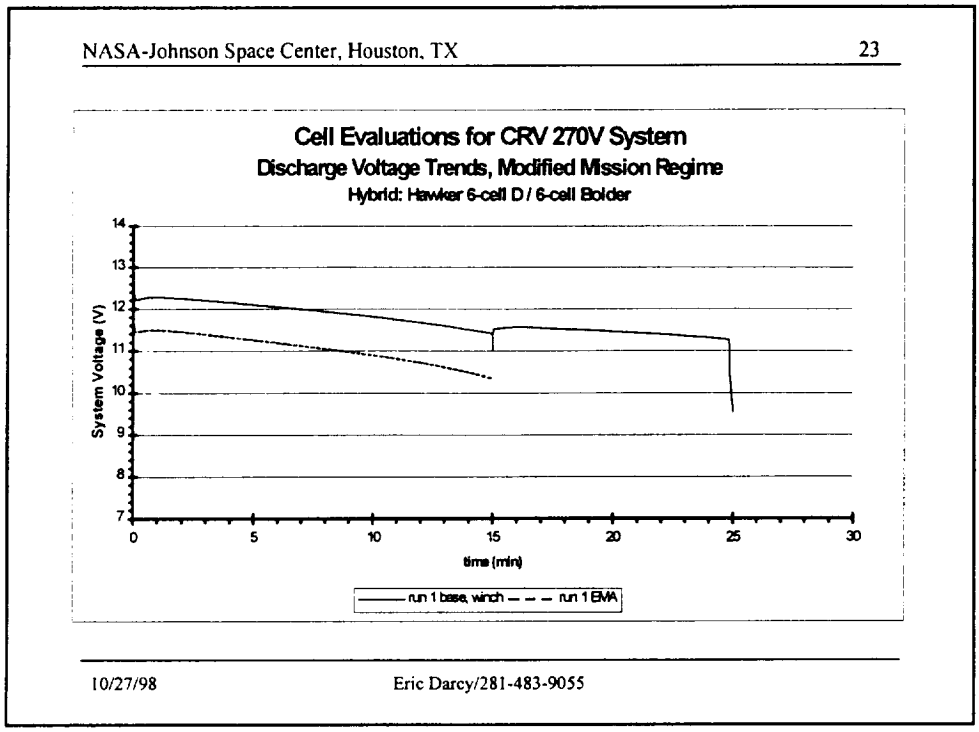
# Impedances are very similar

- Bolder 9/5C LA cell (1F)
- Maxwell capacitor (1000F)




Test Conditions and Results

- Charging followed Bolder's recommended "Current Regulated Taper Charge"
- Discharge at 25 deg C at 1/3 current levels of the new profile (27A peak)
- Minimum EMA voltage = 11.1V/6 cells (= 212V for 115S)
- Mininum Winch voltage = 10.7V/6 cells (= 204V for 115S)
- Maximum voltage sag = 0.9V/6 cells (= 17V for 115S) during winch pulse

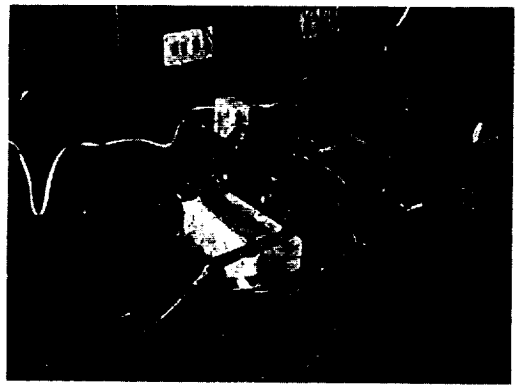



Test Method

- 1 Bolder 6S and 1 Hawker 6S strings were charged independently
- Immediately after, battery strings were paralleled and discharge began
- new power profile was run (81A peak)
- Total Hawker and total hybrid currents were measured throughout run

Results

- Minimum EMA voltage = 10.4V (1.73 V/LA cell)
- Minimum Winch voltage = 9.65V (1.61 V/LA cell)

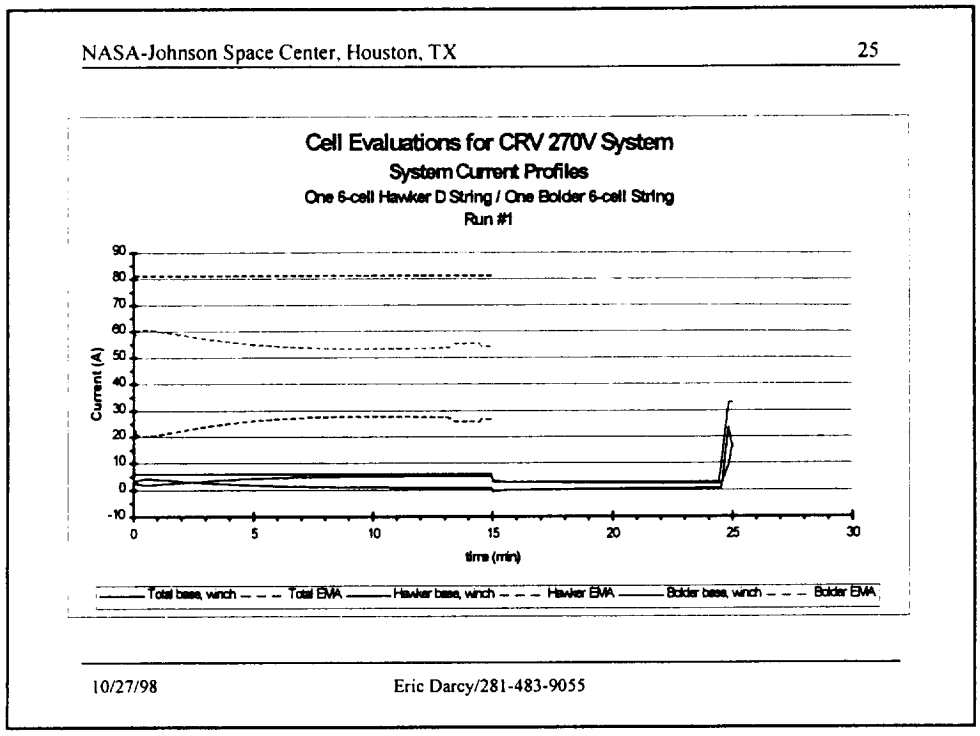


Test set-up at Symmetry Resources, Inc., in Arab, AL



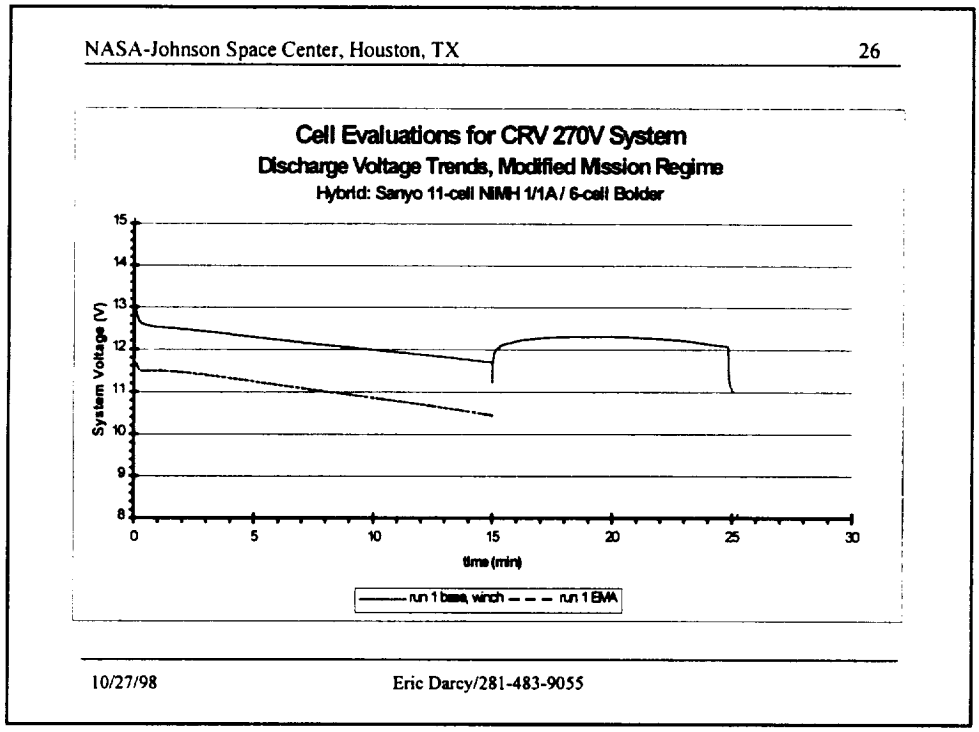
Test set-up at Symmetry Resources, Inc., in Arab, AL

- Bolder LA battery is in background
- Hawker LA D-cell battery is in foreground




## Results

- Bolder current is 75% (61A) of total at first
- Bolder current levels to 66% (53A) after 8 minutes
- Bolder base currents starts at 4A tapers to 1A during EMA phase
- Bolder absorbs only 70% (23A) of Winch pulse at first
- Bolder current fades about 7A at end of 10s Winch pulse
- Bolder does too high a share of EMA base load, little left for winch
- A slightly higher ratio of Hawker to Bolder cells may work better

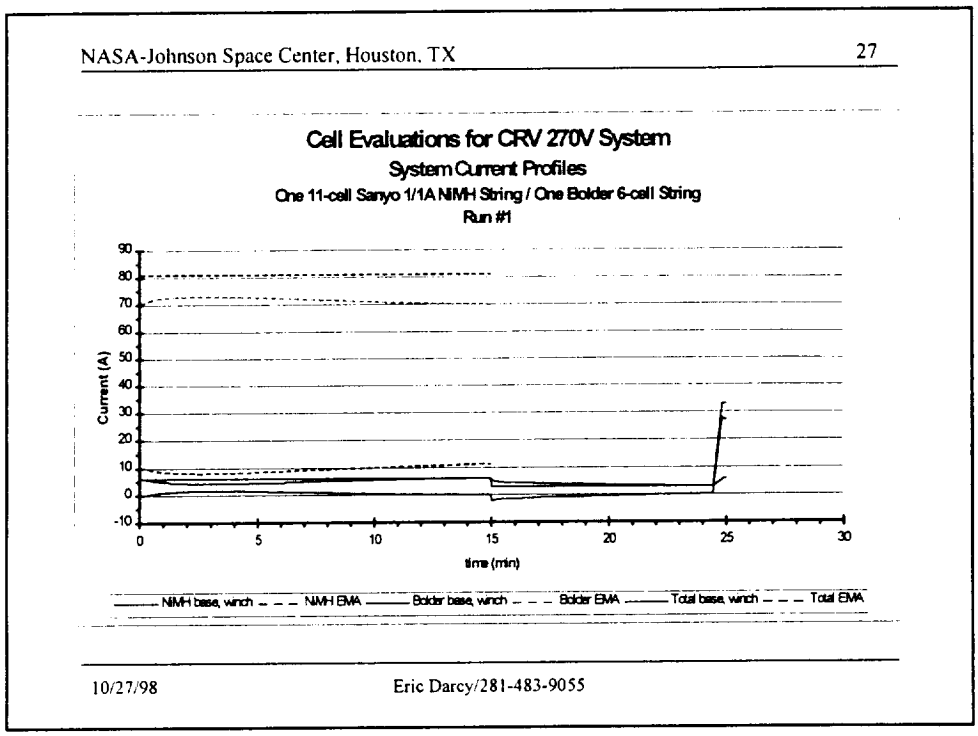



Test Method

- 1 Bolder 6S and 1 Sanyo 11S strings of "A"cells were charged independently
- Immediately after, battery strings were paralleled and discharge began
- new power profile was run (81A peak)
- Total Sanyo and total hybrid currents were measured throughout run

Results

- Minimum EMA voltage = 10.45V (0.95 V/NiMH cell)
- Minimum Winch voltage = 11.06V (1.01 V/NiMH cell)




## Results

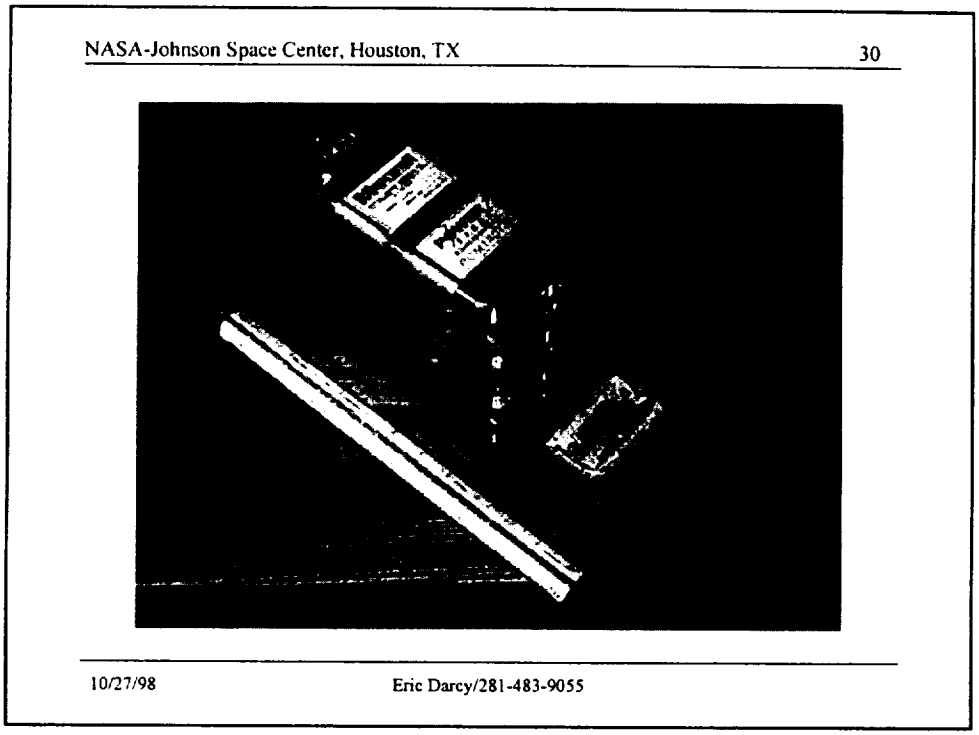
- Bolder current is 88% (71A) of total at first
- Bolder current peaks to 90% (73A) after 2 minutes
- Bolder current ends EMA phase at 86% (70A)
- Bolder base currents starts at 0A, peaks at 2A, and ends at 0A during EMA phase
- Bolder absorbs only 85% (28A) of Winch pulse at first
- Bolder current fades only 1A at end of 10s Winch pulse
- A-size NiMH cells are pushed hard during base loads (6A max)
- Using a NiMH more capable of 2C rates would boost EMA voltage

## Observations and Point Design Comparisons

- Observations
  - Bolder only system requires 3 strings and has very little energy margin
  - Parallel 6 Bolder cells with 6 Hawker D-cells
    - 130 cells of each in series
    - 48.8 kg, 23.9 L vs Bolder only system 43.5 kg, 19.9 L
    - A slightly higher ratio of Bolder:Hawker cells may improve peak sharing
  - Parallel 6 Bolder cells with 11 Sanyo NiMH A-cells
    - higher capacity NiMH cell improves winch pulse voltage
    - Cell string ratio = 125 Bolder: 225 Sanyo
    - Hybrid module is 23.1 kg, 12.1 L
    - **47% mass reduction, 39% volume reduction**
    - Using a NiMH cell more capable of 2C rates will boost EMA voltages

## Issues with lead acid and conclusions

- Regenerative braking result in voltages above 300V with lead acid
  - Hawker D reached 2.356V when charged at 10A for 60 ms at 98% SOC
  - Bolder 9/5C reached 2.924V when charged at 36.5A for 60ms at 98% SOC
  - Bolder 9/5C reached 2.925V when charged at 36.5A for 60ms at 90% SOC
- 300V maximum is required to prevent corona discharge hazard
  - Energizer subC NiCd reached 1.451V, charged at 20A for 60ms at 98% SOC
- Conclusions for X-38
  - Ultracapacitors are too voluminous when paralleled w/ batts w/o regulation
  - Bolder cell has higher useful power density (W/L) than Ultracaps over entire mission profile
  - 300V Max voltage reqt rules out any lead-acid system
  - NiCd subC only system is baselined




Volume comparison

- Bolder 6-cell battery
- 7S Ultracapacitor Bank