Battery Systems
for
X-38 Crew Return Vehicle (CRV)
and
Deorbit Propulsion Stage (DPS)

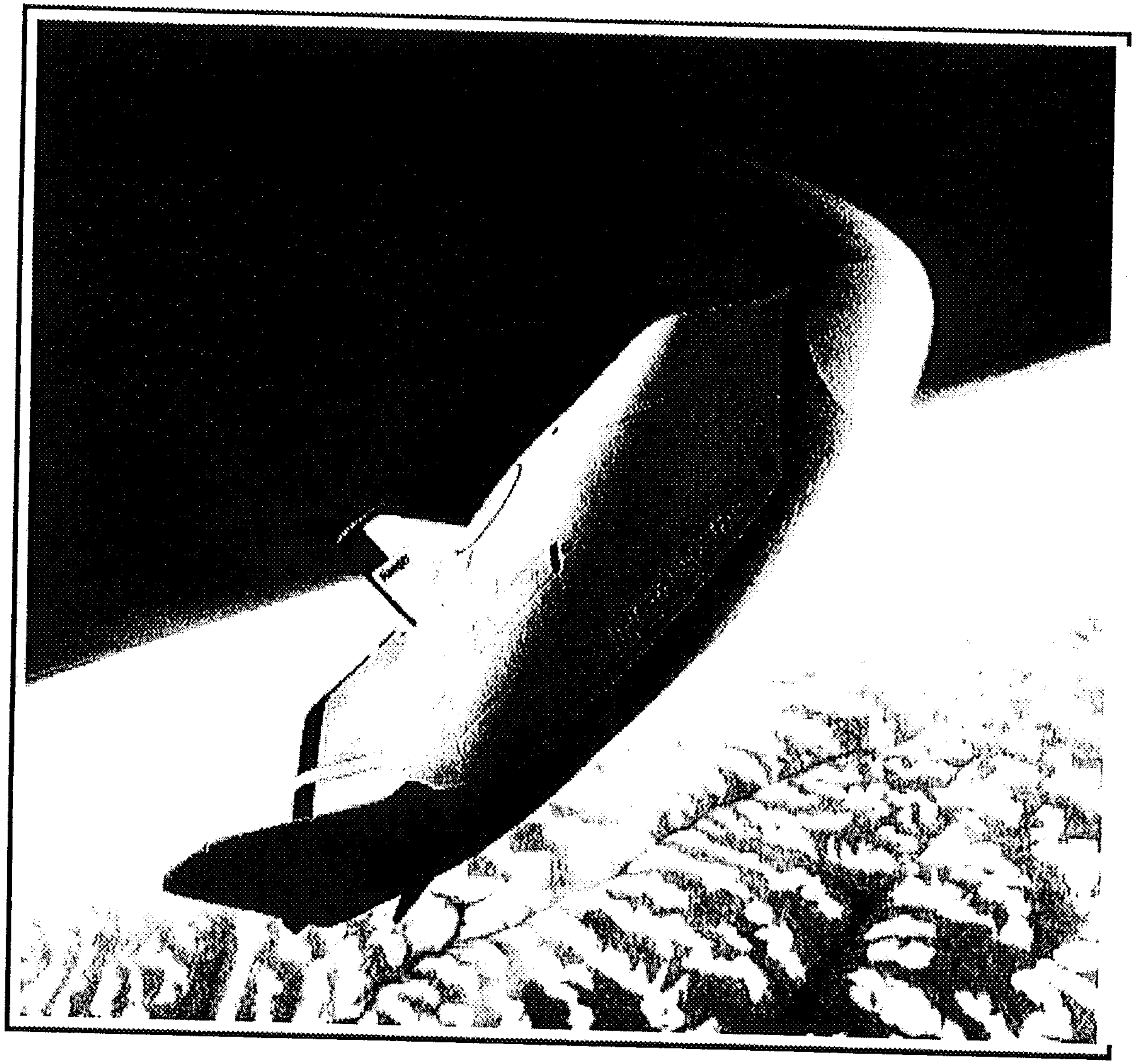
NASA Aerospace Battery Workshop 1997

Outline

- Introduction
- Objectives/Approach
- Requirements/Groundrules
  - Common
  - 28V
  - 270V
- Design Trades/Solutions/Redundancy Plan/Margins
  - 28V DPS
  - 28V CRV
  - 270V CRV
- Envelope/Size/Mass
- Interfaces
- Deviations from OPS CRV

Top Level CRV Requirements

- Provide for the safe return of ISS crew of zero to 6 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



CRV Advantages over Soyuz

- Returns a crew of six with wider size tolerances
- Has 700 nmi of cross range
  - Lifting body aerodynamics
  - Electromechanical Actuators for flight surface control
  - 2 flaps, 2 rudders
- Soft, precise land landing at many more sites
  - Gliding parafoil
  - Electric motors power winches to control the chute
- 3 year on-orbit life
- Potentially refurbishable

Unique Approach to X-38 Program

- 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

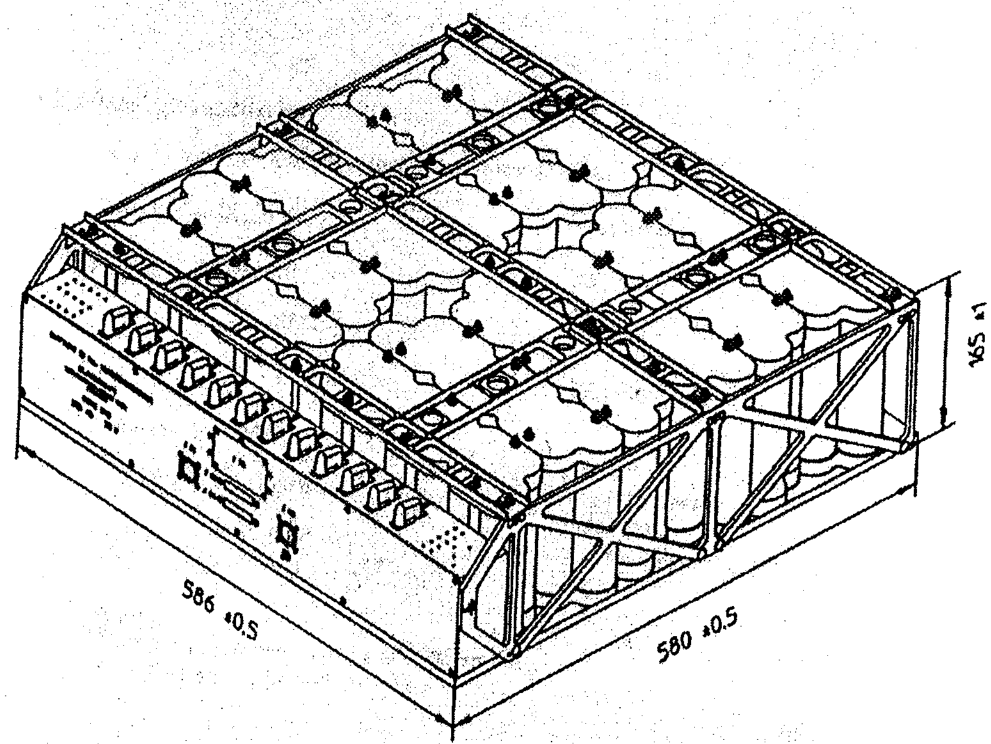
Battery Objectives and Approach

- Provide safe battery designs for lowest volume and cost, and within schedule
- Take advantage of less complex reqts for V201 vs OPS CRV to simplify design and reduce cost
- Use only existing commercial cell designs as building blocks for larger battery
- Derive battery designs from the ASTRO-SPAS design which is the largest lithium battery design with Shuttle flight experience
- Place maximum amount of battery energy on DPS
- DPS battery is non rechargeable
- CRV batteries are rechargeable

Eric Darcy/281-483-9055

FRIWO SILBERKRAFT

Technical Data of Space qualified Lithium-SO_2 Batteries



Requirements and Groundrules

- Common to all batteries
  - 1 failure tolerant for mission success and to a critical hazard
  - 2 failure tolerant to a catastrophic hazard
  - Compliant to "Manned Space Vehicle Battery Safety Handbook" JSC-20793
  - 9 year useful life (5 for storage, 1 in transit, 3 on-orbit)
  - Capacity gauge circuit to track %Ah remaining with 1% resolution
  - Gauge draws < 50 microA (<2 Ah over 4 years) from the battery
  - Refurbishable by replacing battery strings
  - Capable after vibration to 14 grms

Requirements and Groundrules (cont.)

- 28 V High Energy Density Battery (Wh/L)
  - 28.9 kWh over a continuous 9 hour period for Crew Return Vehicle
    - Avionics 2.2 kW for 9 hours
    - ECLSS 0.9 kW for 9 hours
    - RCS 1.0 kW for 1 hour
  - 7.0 kWh over a continuous 7 hour period for Propulsion Module
- 270 V High Power Density Battery (W/L)
  - 4 kWh over a 25 minute period for EMAs, then Winches
    - EMAs peak at 100 kW (400A) for 80ms every 2s for 15 minutes
    - Baseline load is 8.91 kW (33A) for 15 minutes
    - Winch peak is 50 kW (200A) for 5s at end of 10 minutes
    - Baseline load is 4.05 kW (15A) for 10 minutes

DPS Battery Requirements

- Performance
  - 29.4 kWh at 28 +5V, -4V at 7 hour rate after
  - 3 years on-orbit while at 0 to 30C (14 days for V201)
  - Minimum capacity = 1050 Ah
  - Average Power = 4.2 kW
  - Peak Power = 5.5 kW for <1 minute
  - Vacuum exposure for 3 years (14 days for V201)
  - Non-operating exposure range -31C to 72C
  - Use high energy density commercial lithium primary cell design
  - Compliant with NASA RP 1353 "Primary Battery Design and Safety Guidelines Handbook"
- Operation
  - Expired batteries replaced on ground, if CRV/PM returned via Shuttle
  - A rechargeable 28V battery on CRV is used for monthly check-outs

Li Cell Charaterization Approach

- Released an SOW to determine feasibility of candidate cell designs
- Schedule (finish by Dec 97) and cost (<$25K) restraints
- Response from vendors;
  - Friwo-Silberkraft; test both SO_2 and MnO_2 for $24.9K
  - WGL: only willing to sell their BCX DD-cells, Crane did testing, $24.6K
  - YTP: test $SOCl_2$ DD-cell in two phases $22.4K and $22.3K
  - Eagle Picher: wanted too much ($62K) with using existing cells
  - Centaur: no formal bid yet
  - Ultralife: can not support schedule
  - Bluestar, PCI, and BEI: no bid or no response

Eric Darcy/281-483-9055

SOW for Li Cell Characterization for Manned Spacecraft

- Purpose - Determine performance and safety of a candidate building block cell
- Design - Consider only existing cell designs with very minor modifications
- Manufacture - Build enough (26 minimum) cells to support verification tests
- Performance tests
  - Cell capacity at 3 rates and 2 temperatures
  - Cell Vibration of BOL and EOL cells (14.1 grms at 0.16 g^2/Hz)
  - Acceptance tests (leakage, weight, dimensions, OCV, CCV, X-ray)
- Safety tests
  - Cell voltage reversal at 3 rates and 2 temperatures
  - Cell short circuit at 2 rates and max temperature
  - Cell charging with and without diode protection
  - High temperature exposure and heat-to-vent
- Cell Pressure Analysis to determine pressure vs temperature at all states of charge
- Deliverables - Test report with complete cell drawings to establish configuration control

Lithium Cell Design Trades

Company	Chemistry	Cell	Mass, lbs	Volume, cu.in.	Remarks
Friwo-Silberkraft	SO2	G62	643.10	16,618.15	Proven battery design, highest volume
Friwo-Silberkraft	MnO2	M25	629.80	11,870.08	Same batt design, Li-MnO2 cell
Wilson Greatbatch	BCX II	DD	435.09	8,869.92	Vendor will only do cell work
Yardney	SOCl2	IRDD-3H	525.20	10,050.67	High temp DD cell, experienced vendor

Li/MnO_2 cell has some advantages

- less hazardous than BCX or $SOCl_2$ options
- NCR may not be required for internal short hazard
- only chemistry w/o voltage delay issue
- acceptable volume

Design Solutions/Redundancy Plan/Margins

- 28V DPS Battery Point Design
  - Using reference Cell: Li/MnO_2 32Ah cell (P/N M25) from Friwo-Silberkraft, Germany
  - Battery String = 12 cells in series
  - Battery Module = 12 strings in parallel
  - Flight Battery Set = 4 Battery Modules
  - Voltage: Open Circuit = 38V, Closed Circuit = 24-33V
  - Capacity starting at 0C = 1536 Ah vs 1050Ah required
  - Redundancy Plan: 3 modules needed, 4 flown
  - Margin after one module fails: 9.7%
  - Capacity gauge circuit in each module
  - Battery mounting plate for each module

Envelope/Size/Mass

Battery module Size	w/ Battery Mounting Plate
– 586.5 mm wide	620 mm wide
– 580.5 mm deep	620 mm deep
– 166 mm tall	206 mm tall
– 72 kg	79 kg

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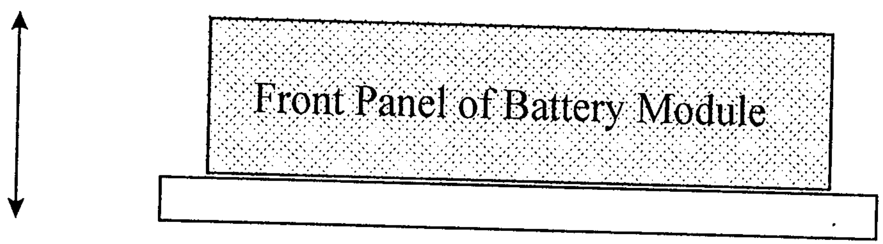
206 mm

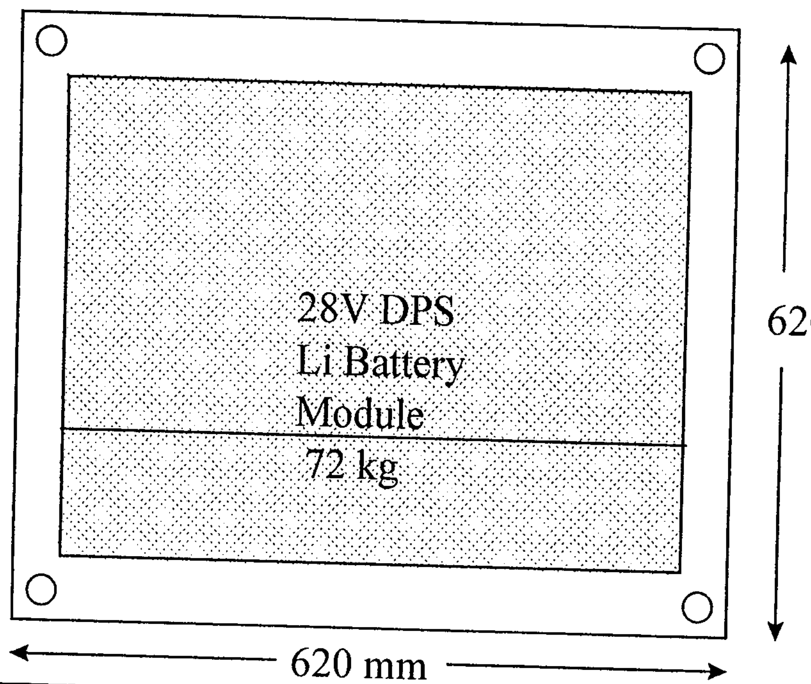


Mounting plate t=40 mm

Plate Weight = 7 kg

DPS will require 4 battery modules like below

Total weight = 79 kg



Interfaces

- Structural
  - BMP to be designed by DPS contractor
  - Built by battery vendor
- Electrical
  - Power - Pair of 8 AWG stud post connectors for +, -
  - Data from Capacity Gauge (8 wires, RS-422)
    - CHG: need +5V for wake-up from avionics, switched off during sleep mode
    - TXD: output battery data to avionics every 1.7s
    - CTS, RXD: inputs for GSE only to calibrate, modify, inspect parameters
    - data output: 16 byte packet (%Ah remaining, voltage, current, temperature)
    - Serial output data format: 9600 baud, 8-bit, no-parity, 1stop bit
    - Each of the 4 lines has a dedicated return line
- Thermal
  - Starting battery temp: 0 to 30C
  - Non operating exposure: -31C to 72C
  - Generates an average 840W of heat during discharge

CRV 28V Battery Requirements

- Performance
  - 7.2 kWh at 28 + 5V,- 4V
  - Average power = 3.6 kW
  - Peak power = 7.2 kW for seconds?
  - Minimum Capacity = 258Ah at 2 hr rate after 36 cycles
  - Self-discharge <1% per day
  - Stowed in cabin, capable of vacuum exposure non-operating
  - Temperature range at start of operation = 10C to 45C
  - Non-operating temperature = -40C to 55C
- On-Orbit Operation
  - 1 hour discharge every month over 3 years (over 1 year for V201)
  - Recharge in 4 hrs from 4.2 kW max at 120V or 28V (28V only for V201)
  - Unavailability time < 5 hours/month including 1 hour check-out (99.3%)
  - Top-off continuously from 40 W max at 120V or 28V (28V only for V201)

NiMH Cell Design Trades

28V MV Battery Cell Design	258 Ah Capacity, Ah	# of cells	mass, lbs	volume, cu.in.
Sanyo NiMH HS-35S	37.00	184.00	493.05	78,217.30
Sanyo NiMH HS-50S	53.00	138.00	531.30	86,940.00
Sanyo NiMH HR-4/3FAU	3.50	2,208.00	411.71	75,288.38
Toshiba NiMH TH-3500	3.40	2,208.00	355.40	67,154.11

Smaller NiMH cells are used in point design because

- more Wh/L and less memory effect than any NiCd
- more quickly available and less costly than large prismatic NiMH cells
- proven on EMU Helmet Lights on STS-82 and STS-86

NiMH Cell Charaterization Approach

- Awarded a SOW to determine abuse tolerance of best 2 candidate cells
  - Toshiba TH-3500 3.398 Ah at C/2 over 100 cycles
  - Sanyo HR-4/3FAU 3.503 Ah at C/2 over 100 cycles
- Above cell designs have demonstrated highest Wh/L in our testing
- Schedule (finish by Jan 97) and cost <$15K

NiMH Cell Abuse Tolerance Testing On-going

- Purpose - Determine safety of a candidate building block cell
- Design - Consider only existing cell designs with very minor modifications
- Manufacture - Build enough (43 minimum) cells to support verification tests
- Performance tests
  - Cell capacity at C/2 with 2C pulses at RT
  - Cell Vibration
  - Acceptance tests (leakage, weight, dimensions, OCV, CCV)
- Safety tests
  - 100% Cell voltage reversal on 3 cells
  - Cell short circuit with 23 cells in series
  - Cell overcharging tolerance
  - High temperature exposure and heat-to-vent

Design Solutions/Redundancy Plan/Margins

- 28V CRV Battery Point Design
  - Reference Cell: NiMH 3.4Ah cell (P/N TH-3500) from Toshiba, Japan
  - Battery String = 23 cells in series
  - Battery Module = 12 strings in parallel
  - Flight Battery Set = 8 Battery Modules
  - Voltage: Open Circuit = 31V, Closed Circuit = 24-31V
  - Capacity starting at 10C = 316 Ah vs 258Ah required
  - Redundancy Plan: 7 modules needed, 8 flown
  - Margin after one module fails: 7.4%
  - Capacity gauge circuit in each module
  - Charger circuit in each module accepting 28V input
  - Battery mounting plate for each module

Envelope/Size/Mass

Battery module Size	w/ Battery Mounting Plate
– 465 mm wide	505 mm wide
– 284 mm deep	325 mm deep
– 79 mm tall	109 mm tall
– 20.5 kg	26 kg

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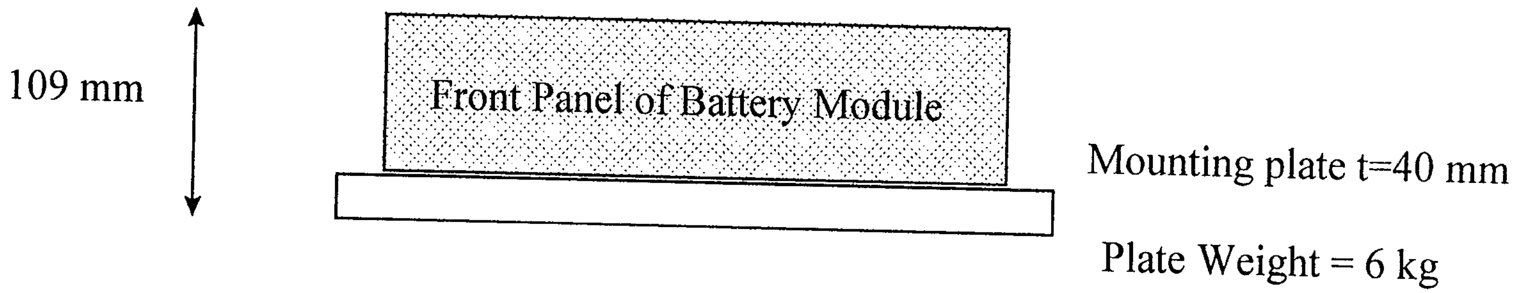
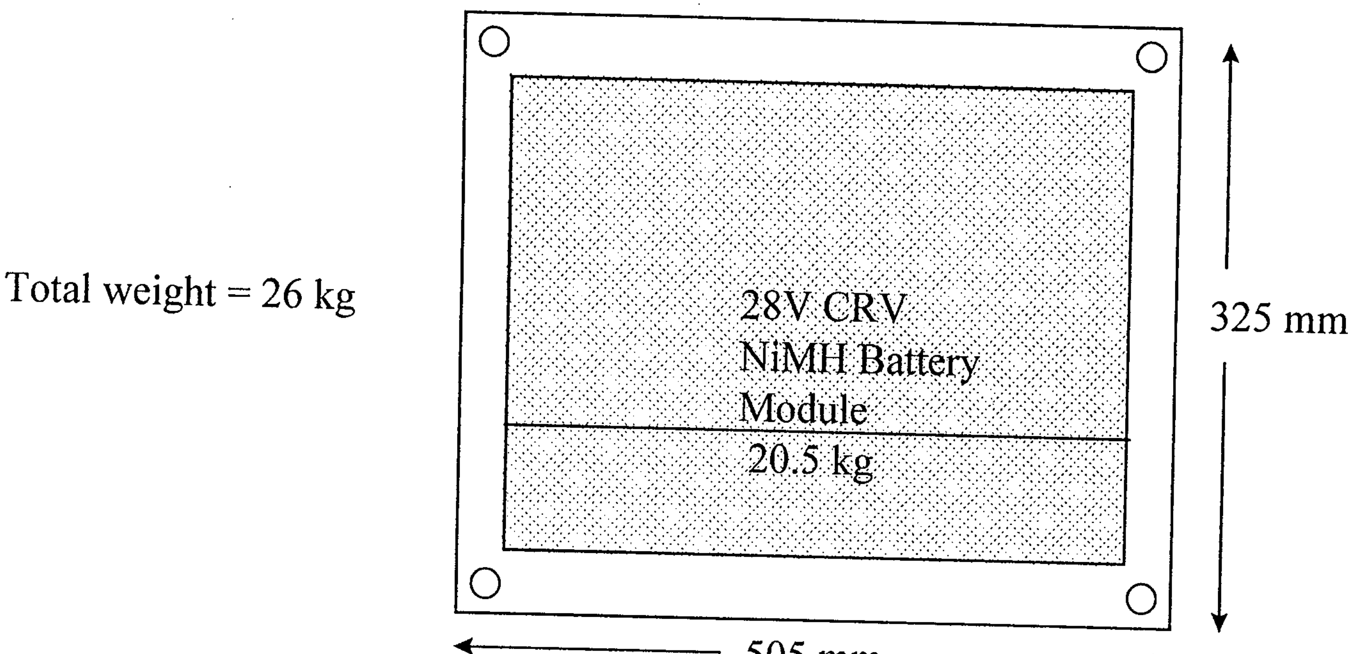


CRV will require 8 battery modules like below



Interfaces

- Structural
  - BMP to be designed by JSC
  - Built by battery vendor
- Electrical
  - Power - Pair of 12 AWG stud post connectors for +, -
  - Data from Capacity Gauge (8 wires, RS-422)
    - CHG: need +5V for wake-up from avionics, switched off during sleep mode
    - TXD: output battery data to avionics every 1.7s
    - CTS, RXD: inputs for GSE only to calibrate, modify, inspect parameters
    - data output: 16 byte packet (%Ah remaining, voltage, current, temperature)
    - Serial output data format: 9600 baud, 8-bit, no-parity, 1stop bit
    - Each of the 4 lines has a dedicated return line
- Thermal
  - Starting battery temp: 10 to 40C
  - Non operating exposure: -31C to 55C
  - Average heat generation during discharge = 180W, during charge = 720W

CRV 270V Battery Requirements

- Performance
  - 270 +60/-20Vduring discharge, 360-367V during charge
  - Average power = 1.651 kW, Peak Power = 100 kW during 80 ms
  - Minimum Capacity = 14.68 Ah after
  - 36 five minute discharge cycles once a month
  - Self-Dischage < 0.2% per day
  - Outside cabin, vacuum exposed for 3 years (14 days for V201)
  - Commercial lead acid cells
- On-orbit Operations
  - 5 minute discharge every month over 3 years (over 1 year for V201)
  - Recharge in 4 hrs from 4 kW max at 120V (GSE charging only for V201)
  - Unavailability time < 5 hours/month, including check-out (= 99.3%)
  - Top-off continuously from 20 W max at 120V (GSE charging only for V201)
  - GSE charging on pad no earlier than T-10 days

Eric Darcy/281-483-9055

High Power Cell Design Trades

Cell Design	1C Cap. (A-h)	Total # cells	Battery mass (#)	Battery volume (cu.in.)
Hawker Cyclon D	1.90	1920	1052.6	14744.5
Hawker Cyclon Tall D	3.70	1280	1073.1	14852.7
Hawker Cyclon X	3.90	1280	1427.1	19800.7
EPS NiCd Cs EPP-1750CS	1.65	3690	613.7	7296.7
EPS Ni-MH Cs EMP-2200CS	2.00	3690	602.4	7335.0
Sanyo NiCd D N-4000DRL	4.00	2214	1022.9	14719.1
Sanyo NiCd Cs N-1700SCR	1.70	3936	654.6	8581.7
Bolder 9/5 Cs	1.20	2880	727.4	10147.9

Hawker Cyclon Tall D cells used in point design because
- Vacuum exposure tolerance of Cyclon cell has been demonstrated by test
- Crimp seals of NiCd and NiMH cells are untested at vacuum
- NiCd, NiMH require too many cells in series

Cyclon Tall D-cell Performance and Abuse Tests

- Purpose - Determine performance and safety of a candidate building block cell
- Performance tests
  - Capacity cycling - 36 cycles with CRV peak profile while at 10, 25, and 40C
  - 12V battery capacity cycling
    - Discharge - crude CRV profile
    - Charge - CV with 1A current limit
  - Cell Vibration
  - Acceptance tests (leakage, weight, dimensions, OCV, CCV)
    - 2 months exposure to 80C w/ and w/o vacuum
    - < 0.2% mass loss in both cases
- Safety tests
  - 100% voltage reversal on 12 V battery - benign vent
  - Short circuit with 15 cells in series at 90A - no vent
  - 12V battery overcharging tolerance - benign vent
  - High temperature exposure and heat-to-vent - benign

Eric Darcy/281-483-9055

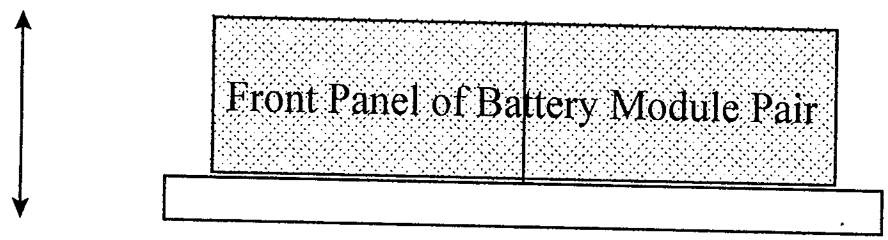
Design Solutions/Redundancy Plan/Margins

- 270V CRV Battery Point Design
  - Reference Cell: Lead acid 2.5 Ah cell (P/N Cyclon Tall D) from Hawker Energy Products, MO
  - Battery String = 32 cells in series
  - Battery Module = 5 strings in series
  - Flight Battery Set = 8 Battery Modules
  - Voltage: Open Circuit = 342V, Closed Circuit = 250-320V
  - Capacity starting at 0C = 20 Ah vs 14.68Ah required
  - Redundancy Plan: 7 modules needed, 8 flown
  - Margin after one module fails: 19.2%
  - Capacity gauge circuit in each module
  - Charger circuit in each module accepting 120V input
  - One battery mounting plate for two modules side by side

Envelope/Size/Mass

2 battery module size	w/ Battery Mounting Plate
680 mm wide	750 mm wide
760 mm deep	830 mm deep
122 mm tall	172 mm tall
122 kg	135 kg

172 mm

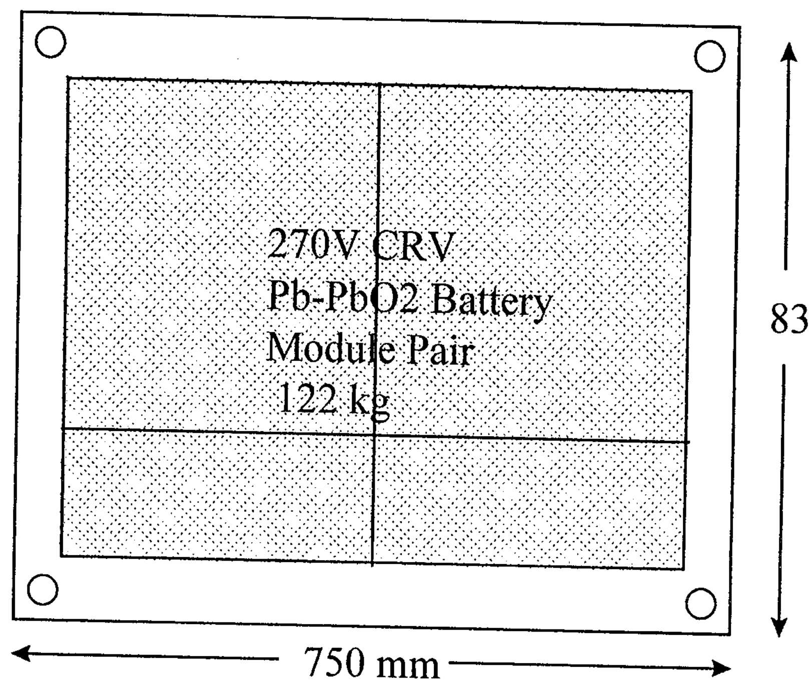


Mounting plate t=50 mm

Plate Weight = 13 kg

CRV will require 8 battery modules like below

Total weight = 135 kg



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    - data output: 16 byte packet (%Ah remaining, voltage, current, temperature)
    - Serial output data format: 9600 baud, 8-bit, no-parity, 1stop bit
    - Each of the 4 lines has a dedicated return line
- Thermal
  - Starting battery temp: 10 to 50C
  - Non operating exposure: -31C to 60C

Deviations from OPS CRV

- Friwo proposes M25 lithium cell design vs M62
  - unproven shutdown separator = possible NCR for internal short
  - M25 is current production line
- waive NHB5300.4 guidelines for solder, PWB, etc, use high quality commercial standard
- Life requirements reduced
- MIL-W-22759 wire inspection by RIFT lab waived except on 270V system
- Clean room requirements waived

Eric Darcy/281-483-9055