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Development and characterization of a high capacity lithium/thionyl chloride battery

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Abstract

A 30 V lithium/thionyl chloride battery with 320 Ah capacity capable of operating at currents of 14 to 75 A has been developed and tested over a temperature range from 15 to 71 °C. The 81 lb battery consists of nine series connected cylindrical cells in a three-by-three arrangement within an aluminum case. The cells are of a parallel disc electrode design with a total active surface area of 10 200 cm^2. Cells and batteries have each been tested for safety, performance and to a space environment. The battery has clearly performed in excess of the specification requirements. The cell design is very adaptable to many battery design requirements.

Keywords: Lithium/thionyl chloride cells; Thionyl chloride; Safety; Space applications

1. Introduction

In 1987 a program was initiated at GTE, sponsored by the department of the Air Force and under the contract direction of Jet Propulsion Laboratories (JPL), to design, build and test a primary 150 Ah lithium/thionyl chloride battery to serve as the main battery on the Centaur-G launch vehicle.

Yardney purchased GTE's Lithium Battery Operations in 1988 and in February 1989 the direction of the program was modified from a 150 Ah battery to a 250 Ah battery.

A parallel electrode design was chosen based on GTE's successful 10 000 Ah MESP battery development and production program.

The initial development was on a low rate 150 Ah cylindrical cell. The final electrochemical parameters were developed on a fractional 25 Ah cell stack using the same diameter as the 250 Ah cell. The advantage of this approach is that all electrical performance testing can be done at one tenth scale of the 250 Ah cell. Another advantage is that by adding one pair of electrodes to the stack increases the total surface area by 88 cm^2 and the stack height by 0.165 cm, which allows tailoring of the load voltage with minimal change to the overall cell dimensions. This design concept provides the flexibility to vary the capacity, discharge current or operating voltage of the cell with minor modifications to the cell hardware.

The Centaur battery consists of nine series connected cells in a three-by-three arrangement. The horizontal operating position of the cells in the battery required substantial thermal and orientation testing.

2. Cell design

The cell stack consists of 132 pairs of electrode discs laser welded to their corresponding busbar. The total electrode surface area is 10 200 cm^2. The orientation of the electrodes is perpendicular to the central axis of the cylindrical cell case. The cell dimensions for the 250 Ah cell are 8.1 cm in diameter by 28.7 cm high as shown in Fig. 1. The cell weight is 3 kg or 6.6 lb. Anode and cathode busbars are offset 180° from each other to compensate for nonuniform *IR* losses along the electrodes and to achieve uniform active material utilization during discharge. The busbars are connected through a stress loop to their corresponding glass-to-metal feedthrough in the cell over. The cell case is floating. For additional safety the cell is designed to be lithium-limited based on the proposed discharge profile. The carbon electrodes are made from a blended mixture of Chevron Shawinigan Black and Cabot Black

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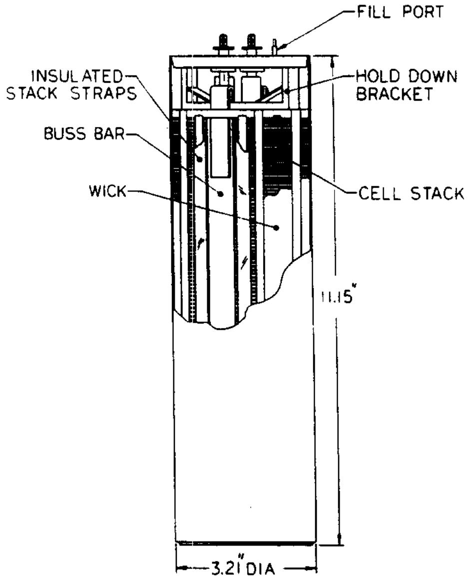

Fig. 1. 320 Ah Centaur cell.

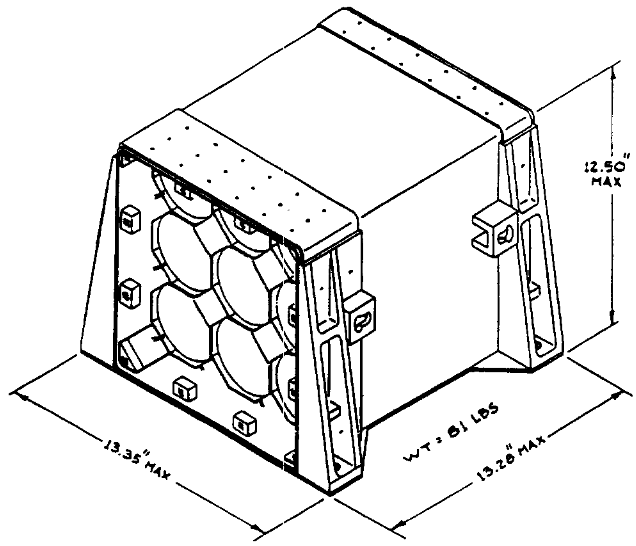

Fig. 2. Centaur battery.

Pearls carbon. Anode and cathode substrates are made from electroformed and electroetched Nickel-200, respectively. The electrolyte is 1.5 M lithium tetrachloroaluminate in thionyl chloride. Each cell is equipped with a BS & B RFB pressure vent set at 300 psi.

3. Battery design

The Centaur battery consists of nine series connected cells as shown in Fig. 2 assembled into an aluminum-battery case with attached mounting feet. Each cell is potted in its own aluminum octagonal cylinder, all electrically insulated from each other and the aluminum battery case. The nine octagonal cylinders are all welded together on their tangent sides and are also welded to the aluminum case where they are tangent. The front of the battery box has a reinforcing doubler welded around the outside for additional support in the area where the intercell wiring and battery connectors are located.

The intercell connectors consist of 8 AWG silver coated copper conductors per MIL-W-813/11 crimped and soldered on each end to silver plated copper terminals. The terminals are connected to the terminal post of the glass-to-metal seal by means of a split lock washer and a hexnut both silver plated. Each intercell connection has a stress relief loop. The total overall battery weight is 81 lb.

The battery design has performed in excess of the specification requirements by satisfying all electrical performance and dynamic test requirements. The battery also satisfied all performance requirements during simulated worst case hot (WCH), worst case cold (WCC) and space environmental testing.

4. Cell evaluation

The cell is designed to meet the Centaur-specification by providing discharge capabilities at 42 A continuously with pulses up to 75 and 60 A discharge for 30 min near the end of life. The entire profile requires a minimum capacity of 250 Ah. The cell has a fresh capacity of 320 Ah and a gravimetric energy density of 164 Wh/lb (361 Wh/kg) and a volumetric energy density of 11.92 Wh/in^3 (0.73 Wh/cm^3).

5. Electrolyte molarity

Four different concentrations of electrolyte salts in thionyl chloride were evaluated for electrical and thermal performance at 15 °C. The cells were discharged in a vertical position and the results are shown in Table 1.

The electrical performance for each of the four cells is similar but the operating temperature of the cell with 1.5 M electrolyte salts was significantly lower thus making it the electrolyte of choice for the battery design. Figs. 3 and 4 illustrate the current and voltage behavior of the cell with 1.5 M electrolyte during discharge at the Centaur discharge profile.

6. Isothermal test

Part of the qualification test program was to study cell performance at four different temperatures (40, 80, 120 and 160 °F) in an isothermal bath. The cells were discharged at constant current (14, 42 and 60 A)

Table 1
Cell testing [a]

Cell S/N	Molarity	EOD (Ah)	EOD (Wh)	Wh at 250 Ah	Average voltage			T_{max} (°C)
					at 42A	at 60A	after 60A	
73	1.5	318	1042	828	3.33	3.20	3.21	39
74	1.8	323	1059	840	3.35	3.22	3.18	46
75	1.2	320	1050	829	3.32	3.23	3.24	45
78	1.0	323	1056	825	3.33	3.22	3.24	45

[a] All cells tested at 15 °C in highly convective chamber.

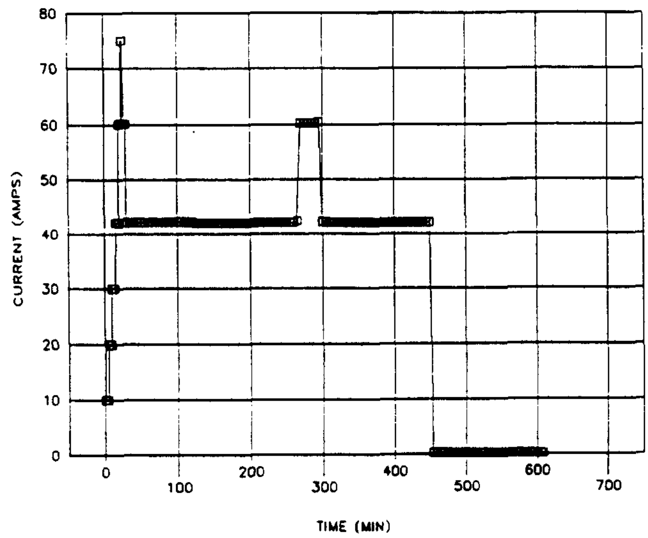

Fig. 3. Centaur cell current profile; vertical discharge at 15 °C.

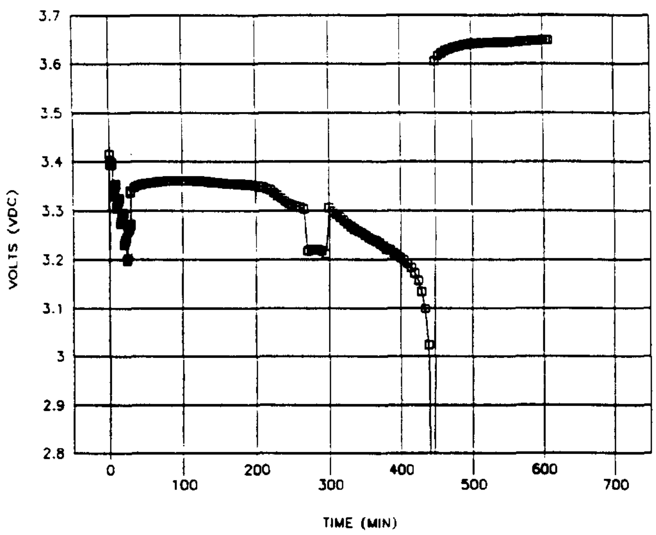

Fig. 4. Centaur cell voltage profile; vertical discharge at 15 °C.

in a horizontal position. Most of the discharges were terminated at the required capacity of 250 Ah as these cells would be subjected to further environmental or safety testing. All cells delivered the required capacity of 250 Ah and stayed well above 3 V during the entire discharge as shown in Table 2.

Table 2
Isothermal discharge tests

Temperature (°F)	Current (A)	Average voltage (V)	Capacity (Ah)
40	14	3.342	251.4
	42	3.230	255.4
	60	3.139	284.4
80	14	3.449	250.3
	42	3.306	255.7
	60	3.232	312.5
120	14	3.53	252.2
	42'	3.404	290.4
	60	3.353	251.8
160	14	3.536	294
	42	3.428	281.2
	60	3.377	251.3

Table 3
Centaur discharge profile

Time (min)	Current (A)
turn on	10
5	10 to 20
10	20 to 30
15	30 to 42
20	42 to 60
24	60 to 75
267	42 to 60

7. Battery performance

During the battery qualification program, battery performance was studied under the conditions of the Centaur discharge profile in a simulated space environment, see Table 3.

8. Battery discharge at room temperature

The discharge was performed at an ambient temperature of 15.5 °C, the open-circuit voltage (OCV) of the battery prior to discharge was 33.11 V with the individual cells ranging from 3.678 to 3.680 V.

The initial battery voltage dropped to 18 V at turn on with the 10 A load and recovered to 30 V in less than 1 s. The test was shut down overnight after 3 h of discharge. The capacity removed from the battery during this time was 124.489 Ah. After 14 h on OCV the Centaur discharge profile was continued and the battery yielded a capacity of 329.26 Ah to the 28.8 V cutoff. The discharge profile shown in Fig. 5 indicates when the battery was restarted, the voltage was 29.5 V instead of 30.7 V when the test was interrupted. This was primarily due to the loss of the self-heating advantage of continuous discharge. The maximum temperature achieved during discharge on the battery was 47.9 °C. The test was completed without problems.

9. Worst case hot battery test

The objective of this test is to safely demonstrate battery performance in vacuum chamber environment that simulates the space condition of Payload Battery worst case hot (WCH). During the test the battery will be discharged according to the Centaur high rate profile. In this test all nine cells within the battery are monitored for voltage and temperature readings.

The battery is stabilized within the test chamber at 90 °F (32.2 °C). (This simulates the Payload Battery prelaunch temperature of 90 °F.) The chamber pressure is reduced to 10^{-5} mmHg. The battery is being discharged using the high rate current profile in Table 4 to 250 Ah.

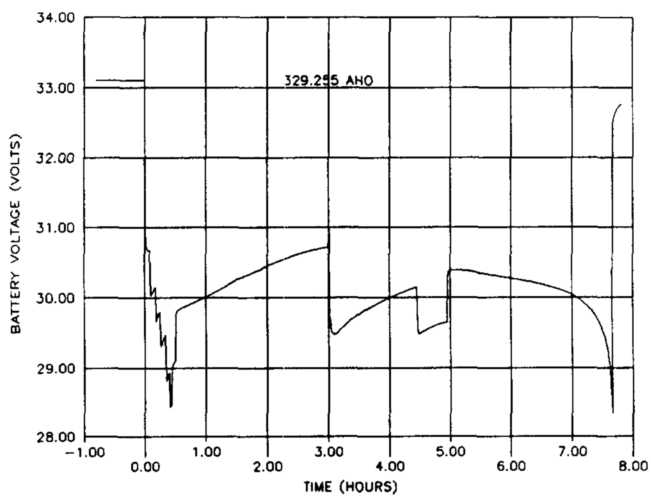

Fig. 5. Centaur battery capacity discharge.

Table 4
Worst case hot load profile

Time (h)	Time (min)	Δ Time (min)	Current (A)	Capacity (Ah)	Cumulative capacity (Ah)
0.000	0		2.75	0	0
0.875	52.5	52.5	2.75	2.41	2.41
2.000	120	67.5	22	13.92	16.33
2.500	150	30.0	16.5	9.63	25.95
3.000	180	30.0	39.88	14.10	40.05
3.500	210	30.0	42.63	20.63	60.68
3.500	210	0.0	49.5	0	60.68
6.000	360	150.0	49.5	123.75	184.43
6.000	360	0.0	51.19	0	184.43
6.500	390	30.0	51.19	25.58	210.00
6.500	390	0.0	42	0	210.00
7.583	455	65.0	42	45.50	255.52

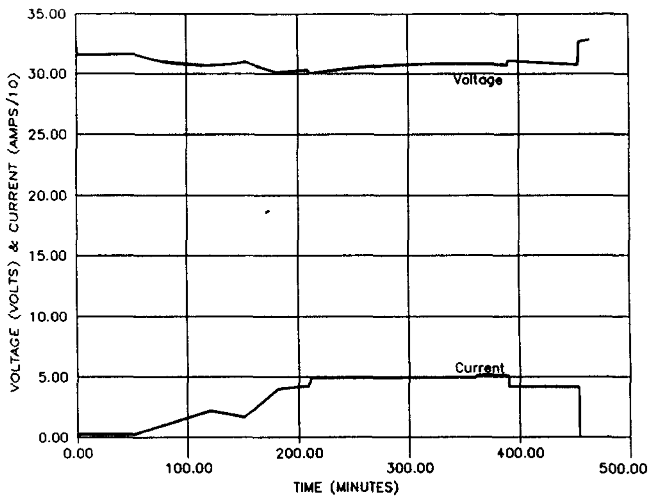

Fig. 6. Worst case hot Payload battery, capacity discharge.

In the actual test the battery was discharged to a capacity of 254.8 Ah and reached a maximum temperature of 99.0 °C which was recorded after 400 min into discharge after the 52 A pulse. The battery dropped to 15.84 V upon application of the 20 s 22 A voltage delay test which was performed ahead of the current profile test. The voltage recovered to 28 V after 0.555 s and 29 V after 2.368 s.

The voltage and current profiles during capacity discharge of the WCH battery are shown in Fig. 6. The highest internal temperature during discharge was 99 °C. The temperature performance is shown in Fig. 7. The discharge was completed without problems.

10. Worst case cold battery test

The objective of this test is to demonstrate that the battery will operate with no anomalies in a vacuum that simulates the space environment of the Payload

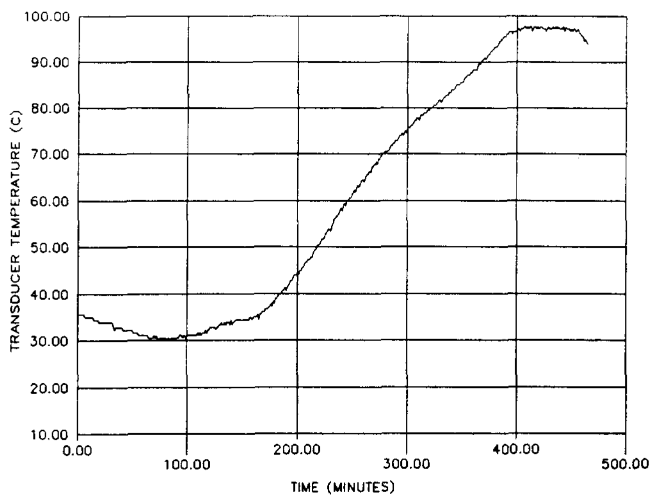

Fig. 7. Worst case hot Payload battery, temperature profile during capacity discharge.

Table 5
Worst case cold discharge profile

Δ Time (min)	Current (A)	Capacity (Ah)	Cumulative capacity (Ah)
60	1.19	1.190	1.190
150	Ramping to 16.86	22.563	23.753
90	16.86	25.290	49.043
20	42.50	14.167	63.209
40	49.50	29.667	92.876
30	51.19	25.595	118.471
470	16.86	132.070	250.541

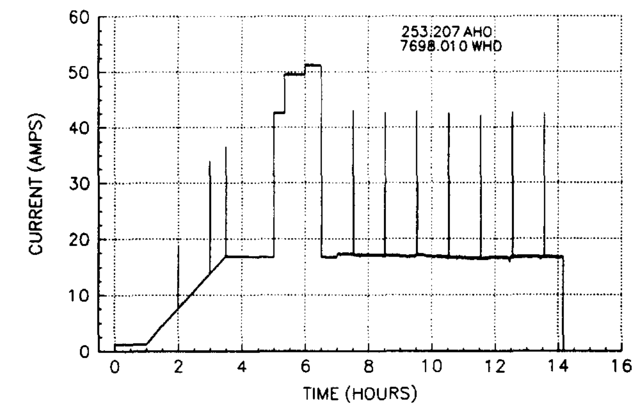

Fig. 8. Worst case cold Payload battery, battery current profile during capacity discharge.

Battery worst case cold (WCC). The battery will be subjected to the Centaur minimum current profile as shown in Table 5.

The battery will approximate Payload Battery WCC prelaunch, by allowing to stabilize in vacuum at 60 °F (15.6 °C). After stabilization the battery will be discharged at the Centaur minimum current profile to

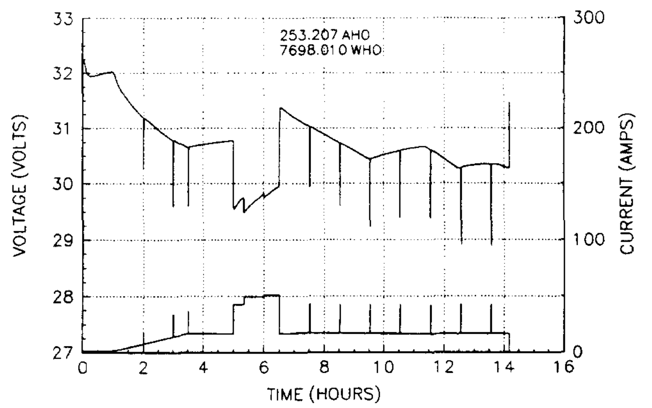

Fig. 9. Worst case cold Payload battery, voltage and current profile during capacity discharge.

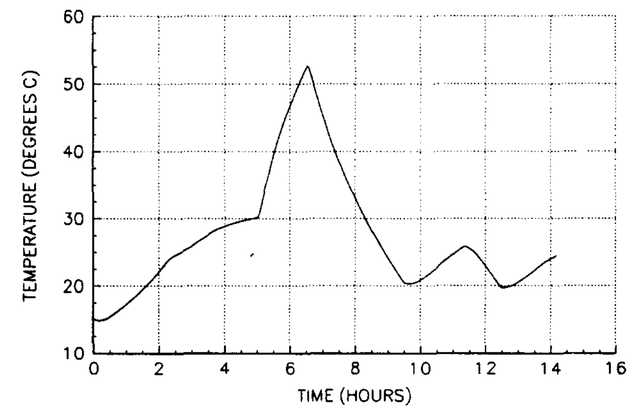

Fig. 10. Worst case cold Payload battery, maximum temperature profile during capacity discharge.

255 Ah. In addition to the continuous current load superimposed current pulses will be incorporated into the load profile. All current pulses are 30 s in duration and range from 18.5 to 42.5 A at different time intervals until 250 Ah are achieved from the battery.

The battery met all the requirements of the WCC test while delivering a capacity of 253.21 Ah following the current profile in Fig. 8. The discharge voltage is shown in Fig. 9. The worst case internal battery temperature behavior is illustrated in Fig. 10. The maximum was 53 °C. WCC test was performed without problems.

11. Summary

Yardney Technical Products has successfully built and tested a versatile intermediate rate cell that exceeded the basic specification requirements for the Centaur battery. The cell is capable of discharge rates to 75 A with an operating temperature range from 15 to 71 °C. The gravimetric energy density is 164 Wh/lb (361 Wh/kg) and volumetric energy density is 11.92

Wh/in^3 (0.73 Wh/cm^3). The cell has passed environmental shock and vibration as well as thermal testing required for space applications. The cell design is very adaptable to many battery design requirements.

The battery has clearly performed in excess of the specification requirements. The battery satisfies all voltage and current and capacity requirements. The battery also completed dynamic testing with vibration loading to 26g's r.m.s. and shock loading to 200g's of 3000 Hz. The battery has satisfied all performance requirements during simulated WCH, WCC and space environmental testing.

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