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# Development and Flight of a 250-A-h Lithium Thionyl Chloride Battery

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**A program to develop and fly a lightweight lithium thionyl chloride battery on the Titan IV Centaur upper stage was conducted. A high-rate battery cell was developed and tested to the environments and load profiles required. While the cell design was maturing, the cells were integrated into a battery housing. The battery assembly was subjected to a series of mechanical and thermal tests to qualify the structure for flight. During the development, design revisions were needed in the cell bus bars, locating rods and insulating washers, bus bar to electrode welds, and battery structure mounting flanges to withstand vibration levels. Stress corrosion in electrode tabs was found to cause intergranular cracking that could lead to safety-related problems. An isolated electrode led to a cell explosion during discharge. Proper orientation of substrate grain structure eliminated the problem. A total of 13 batteries completed a test matrix resulting in qualification for use on the Centaur upper stage. An initial procurement of five batteries was completed in 1995 culminating in the successful flight of two batteries on May 14, 1995. The batteries' installed weight was 84 lb (38 kg) less than the silver–zinc batteries that they replaced.**

## Introduction

IN 1986, several military satellite programs, concerned with a growing launch system performance deficit, sought ways to increase the satellite weight delivered to final orbit. The high-rate lithium thionyl chloride primary battery, at that time in the research and development demonstration stage, was identified as a candidate to replace the silver–zinc batteries being used.

Lithium thionyl chloride batteries showed the potential for at least 50% improvement in specific energy over silver–zinc batteries. The lithium battery developed in this program exhibited a nameplate specific energy of 180 W-h/kg compared to the 120 W-h/kg of the silver–zinc batteries that they replaced.

In addition to reduced weight, the long storage life of the lithium battery compared to the silver–zinc battery was attractive from an operational viewpoint. Once activated, the silver–zinc battery has a storage life of about 60 days, whereas the lithium battery, activated at manufacture, can be stored significantly longer at ambient conditions. Another advantage of the lithium battery is minimal launch base processing since the battery is activated and sealed at the factory. Silver–zinc batteries require activation and conditioning at the launch base.

Prime contracts were awarded for the development and qualification of a battery to replace the 250-A-h primary silver–zinc battery utilized on the Titan IV Centaur upper stage. The requirements/goals for this challenging development effort are shown in Table 1. This article describes the successful program to develop, qualify, and build batteries for flight.

In this article, details of the flight development program are provided with attention focused on challenges faced during the cell and battery development. When available, references are provided for further information regarding certain aspects of the cell and battery development. Specific results of cell characterization and battery qualification tests have been previously published.[1,2]

## Program Overview

Based on previous cell designs, a scaled-up cell capable of meeting the Titan IV Centaur requirements (Table 1) was developed. The Centaur cell is a cylinder with flat-plate construction held in place by compression and locating rods through the electrodes. Figure 1 is a representation of the basic cell design. Each cell has a glass-to-metal seal that comprises the positive terminal and two nickel feedthroughs for the negative terminals. A safety burst disk on each cell precludes catastrophic failure.

The final battery configuration contains two tiers and is shown in Fig. 2. The structure consists of a monolithic aluminum machined housing with two layers of machined cavities for the cells; the top layer contains five cells and the bottom layer contains four cells. The battery structure incorporates integral mounting feet.

Documentation and configuration control were an important part of this program. Since the ultimate purpose of the effort was to develop a flight-qualified battery, this control system was in place prior to the critical design review and was maintained through the conclusion of qualification testing.

Safety was of paramount importance in the cell and battery designs. The safety program included detailed procedures for handling the cell and battery and extensive safety testing at the cell and battery level. Results indicated that, with proper procedures in place, the lithium thionyl chloride high-rate battery could be integrated into an operational environment.

Subsequent testing of the Centaur lithium thionyl chloride battery demonstrated compliance with the requirements for

**Table 1 Requirements for lithium battery development program**

| |
|---|
| Dimensions = 10.8 × 13.3 × 13.4 in. (27.4 × 33.8 × 34 cm) |
| Weight = 85 lb (39 kg) |
| Life = 6 yr at −18°C, 120 days on-pad |
| Load voltage = 26–32 V |
| Voltage delay = less than 10 ms |
| Nameplate capacity = 250 A-h |

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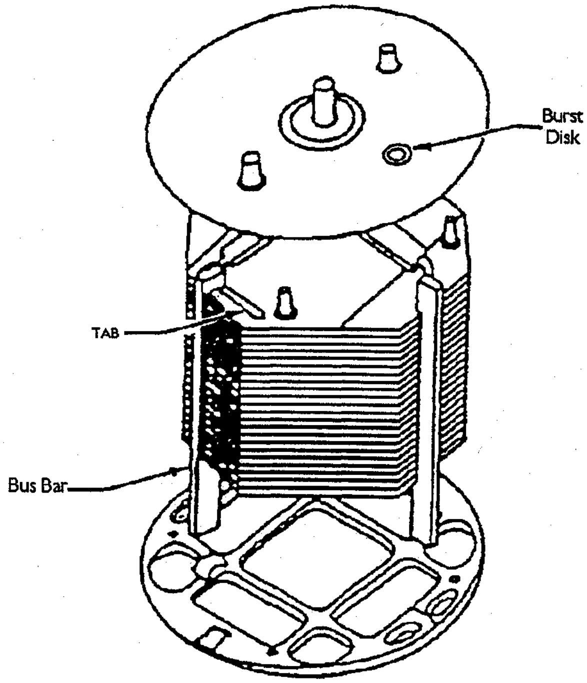


Fig. 1 Sketch of the lithium thionyl chloride cell design. The cell dimensions are 5.23 in. (13.3 cm) in diameter by 4.81 in. (12.22 cm) long with terminals and 3.88 in. (9.87 cm) long without terminals. The container is type 304 L stainless steel. The anodes are lithium foil pressed onto both sides of a chemically etched nickel 200 substrate. The cathodes are carbon-pasted onto both sides of a chemically etched nickel 200 substrate. The electrical connections are tungsten-inert-gas (TIG) welded to nickel bus bars. The separator is composed of a layer of nonwoven glass and a layer of glass tissue to ensure anode and cathode separation. The electrolyte is a $LiAlCl_4-SOCl_2$ solution with additives to improve the voltage delay characteristics.

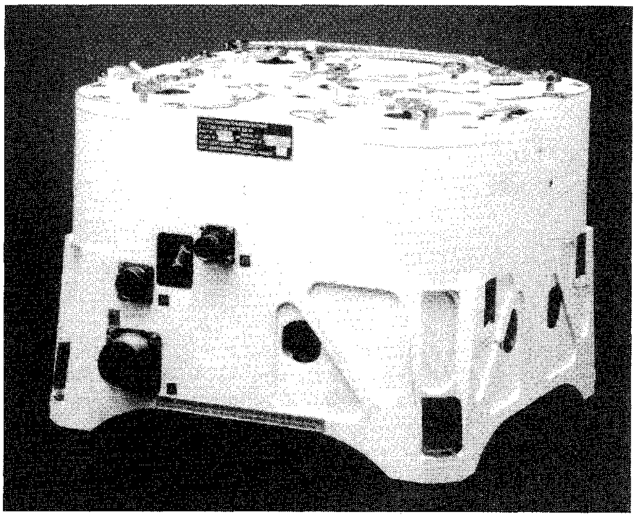

Fig. 2 Photograph of the 250-A-h lithium thionyl chloride battery. The overall dimensions are 10.205 in. (25.92 cm) high by 13.118 in. (33.22 cm) long by 13.118 in. (33.22 cm) wide. The weight is 86 lb (mass of 39.1 kg). The external surfaces are painted with white thermal control paint and a single temperature transducer is mounted at the calculated warmest point. Integral redundant heater circuits are fitted around the battery structure to maintain the temperature at 40°C.

the Centaur application. As a result of the successful qualification of the battery, a flight application was identified and flight batteries were built, tested, delivered, and successfully flown.

## Cell Development

Several significant technical challenges were encountered and solved during cell development. These challenges included survival of transmitted vibration levels, electrode tab intergranular cracking, attaining voltage performance, meeting storage requirements, and selection of burst disks.

Engineering development cells were built to verify the ability to withstand the random vibration launch environment, which was $13.7G_{\rm rms}$, applied to the battery; the cells experienced transmitted vibration levels as high as $22.3G_{\rm rms}$. The initial cell design underwent revisions to meet this environment. Stress relief loops were added to electrodes tabs, Tefzel® locating rods were introduced and strengthened, and insulating washers were inserted between electrodes to stiffen the electrode stack. Current collector busbars were also modified to eliminate sharp corners and doublers were added to high-stress areas. Detailed welding schedules were developed to ensure the integrity of the busbar-to-electrode tab welds. The resulting cell design survived the required vibration environment of $22.3G_{\rm rms}$.

At the same time, intergranular cracks were found in anode tabs. After extensive work it was determined that environmentally assisted stress corrosion was responsible for the cracking.[3] The intergranular cracking had safety implications and was therefore crucial to solve. It was discovered that electrically isolated lithium in the cell environment was subject to stripping and plating because of lithium ion concentration gradients formed during discharge.[4] If a lithium anode became electrically isolated from the stack because of intergranular cracking of the tab connection, resulting lithium plating could form an internal short circuit. The only unintentional cell incident that occurred during this development was attributed to this phenomenon. The cell exploded during discharge. The mechanism was confirmed by intentionally clipping the anode tabs of several electrodes in a test cell. The test cell was then discharged identically to the earlier cell. The test cell exploded at approximately the same voltage and discharge capacity.

As a result of analysis and testing, it was determined that the intergranular cracking phenomenon could be precluded by redesigning the anode substrate with respect to the orientation of the grain structure in the substrate material, which was determined by the rolling direction of the material. Metallographic examination of the cracked tabs indicated that cracking occurred only in anode substrates whose tabs had grain alignment perpendicular to the length of the tab; no cracking was found in tabs whose grain alignment was longitudinal with respect to the length of the tab. Once this redesign was accomplished, no further intergranular cracking was observed and no other safety incidents occurred.

For one particular mission, a stringent voltage requirement of 29.2 V at up to 60 A existed. Since the battery design had been constrained to nine series-connected cells, the 29.2 V at high rates was difficult to meet. Electrode surface area was maximized and internal cell resistance was minimized while maintaining the integrity of the cell. Even with these design solutions implemented, it was found that the high-voltage requirement could only be met at 40°C. This temperature also provided for maximum capacity, as indicated in Fig. 3. The baseline operating temperature was therefore 40°C and the majority of cell and battery tests were carried out at this temperature.

The storage requirements at low temperatures (less than 5°C) have been demonstrated for up to one year. Storage times at −18°C with little or no performance degradation for up to six years are anticipated. Storage at ambient temperature has been demonstrated for up to eight months, and it is anticipated that storage at ambient temperature for one year with little or no degradation should be possible. However, meeting the requirement for storage at higher temperatures has not been demonstrated. Although cells can be exposed for one month to 32°C, longer exposure at this temperature results in increased voltage

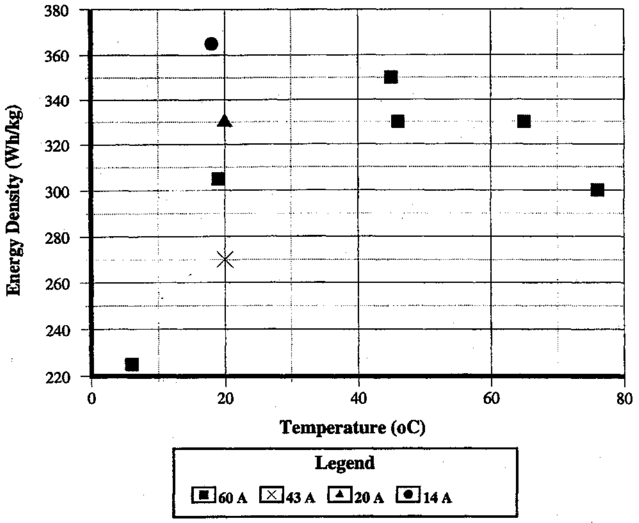


**Fig. 3 Specific energy (or energy density) as a function of temperature and current.**

delay and decreased capacity. This characteristic requires well-controlled storage conditions. Further work will define the storage envelope in terms of temperature and time.

A burst disk vent value of 13 bars was initially selected to meet the cell thermal and safety requirements. However, cell-level thermal tests were performed under anticipated worst-case hot temperatures, which resulted in premature vent operation. It became apparent that the pressure-temperature relationship of the electrolyte solution under these conditions was not well understood. After extensive thermal modeling and testing to characterize the pressure-temperature relationship, a burst disk with a vent value of 23 bars and an additionally reinforced cell cover were selected. The higher vent value permitted safe operation under all defined requirements.

Throughout the development, a total of 39 engineering cells was tested to validate design improvements. To characterize the cell design, 102 cells were built and organized into a test matrix to measure performance and safety under various mechanical, thermal, storage, and time parameters. Results from these tests have been previously published.[1]

## Battery Development

Challenges faced in the battery development included structural integrity to survive vibration and shock, thermal design and modeling, and voltage performance. Much of the battery design work was carried out at the same time that the cell design was undergoing refinement, particularly with respect to the structural and thermal aspects of the cell and battery design, where the designs are interdependent.

Initially, the battery structure consisted of an aluminum housing with nine machined cavities to which mounting legs were attached. The entire assembly was rigidized with a baseplate to which the mounting legs and housing were bolted. This structure failed initial vibration tests.

Subsequently, the battery was redesigned with the aid of extensive finite element modeling.[5] The resulting monolithic aluminum battery structure (Fig. 2) survived both the mechanical environments and minimized the transmitted environments to the cells. The monolithic structure contributed to increasing the specification battery weight above the initial requirement to 86 lb (39 kg). However, the robust structure met all requirements for vibration and shock.

The thermal design of the battery took into account the thermal environment of the launch vehicle and the significant heat generated by lithium thionyl chloride cells during discharge. Complicating the thermal design was the fact that a single battery was developed to meet a variety of applications; each application had a different discharge profile and thermal environment associated with the profile. The thermal design had to maintain a minimum temperature above 10°C to meet the minimum voltage and capacity requirements, while limiting the temperature to below the safe operating temperature of 100°C with respect to the cell burst disk.

Once the thermal environment for the battery was thoroughly defined, the heat generation characteristics of the cells were determined and the thermal characteristics of the battery were modeled. Results from basic research on the heat-generation characteristics of lithium thionyl chloride cells were combined with results from the Centaur cell characterization tests to determine their heat generation.[6] Detailed thermal models were then developed and validated by thermal vacuum testing carried out as part of the battery qualification program.

Thermal vacuum testing representing all applications was carried out under worst-case hot and cold conditions.[7] Test results indicated that the battery met requirements over the range of anticipated thermal environments.

During the battery development, three development engineering test (DET) batteries were constructed and tested. One DET battery was subjected to discharge only. A second DET battery was subjected to vibration and shock; the cells in this battery underwent destructive physical analysis (DPA) with no anomalies found. The final DET battery was subjected to thermal testing.

## Battery Qualification

To demonstrate design requirements for use on Centaur, a total of 13 qualification batteries were built to released and controlled drawings and subjected to a matrix of tests. The qualification matrix included electrical, mechanical, thermal, and safety tests. A detailed discussion of qualification test results may be found in Ref. 2.

Eleven of the 13 batteries were discharged under varying regimes. These data are summarized in Table 2. All batteries met the generic voltage criteria of 26 V minimum. Batteries exposed to elevated temperatures required several hundred milliseconds more than the specified 0.01 s to reach 26 V.

Six battery tests were conducted under thermal vacuum conditions to demonstrate various combinations of worst-case hot or cold mission profiles. The thermal model was validated utilizing data from the worst-case hot and cold mission tests.

To validate the battery mechanical integrity, six batteries were subjected to vibration and shock testing while under load. Five of the six batteries were subjected to DPA following the test. Inspection revealed that some locating rods were bent and in several cells of one battery, some cathode tabs showed cracks in the bent region of the rods. The cracks extended only partially across the tabs, and no tabs were completely severed. Extensive analysis indicated that the cracks were caused by fatigue and had no impact on battery performance. Further-

**Table 2 Battery qualification test results**

| Battery number | Average current, A | Average temperature, °C | Total capacity, A-h |
|---|---|---|---|
| 1 | 42.5 | 60 | 323.8 |
| 2 | 44.4 | 62 | 314.4 |
| 3 | 44.9 | 59 | 306.7 |
| 4 | 13.6 | 6 | 280.5 |
| 5 | 30.0 | 38 | 302.3 |
| 6 | 44.6 | 60 | 308.9 |
| 7 | 42.9 | 36 | 248.1[a] |
| 8 | | Not discharged | |
| 9 | 40.0 | 49 | 314.6 |
| 10 | | Not discharged | |
| 11 | 38.0 | 39 | 287.8 |
| 12 | 42.5 | 70 | 251.1[b] |
| 13 | 15.7 | 25 | 324.0 |

[a]Battery 7 exposed to high-temperature storage conditions.
[b]Battery 12 had more capacity to 26 V, but was not discharged beyond the capacity required for the thermal test.

more, the qualification environments were at least 6 dB higher than flight levels and qualification environment durations were several times longer than flight-level durations, indicating a significant margin in the battery design; in fact, analysis indicated that damage would be three orders of magnitude less at flight levels and durations than at qualification levels and durations. All batteries met the qualification requirements; the battery that exhibited the cracked tabs in several cells provided in excess of 300-A-h capacity.

Operational life and storage testing of two batteries were performed to validate the expected handling of batteries through actual use. Battery test data indicated a minimum on-pad life capability of 120 days. Further testing is expected to expand the on-pad capability to beyond 120 days.

The battery design failed to pass electromagnetic interference (EMI) testing. Test results indicated that the thermostatically controlled heater circuit was the source of the EMI exceedance. Since the heater circuit is not used in flight, a plan was developed to disable the thermostats and control the heater circuit external to the battery from a ground power source.

Battery safety was validated by testing seven batteries under abuse conditions required by range safety. Three batteries, two with 13-bar and one with 23-bar burst disks, were subjected to overtemperature testing; two batteries were reversal tested, and one battery was subjected to a 1-m drop and another to explosive atmosphere/heater operation test. Normal venting of cells was observed in the overtemperature and reversal testing. In the 1-m drop the battery sustained visual external physical damage only. Furthermore, the battery was unaffected by the explosive atmosphere test. Short circuit and reversal tests were performed only at the cell level and were considered acceptable to satisfy range safety.

The battery qualification testing indicates that the lithium thionyl chloride battery meets all generic Centaur requirements except EMI. Further details of the qualification testing are presented in Ref. 2.

## Flight Battery Manufacturing

The initial flight build of five batteries and associated test cells was carried out in six months. Most hardware and materials were available from a previous program. A manufacturing readiness review was held shortly after program go-ahead to verify configuration, facilities, and schedule.

Lessons learned during development were carried into manufacturing with all cells in a battery from a single production lot, anode substrates aligned to minimize stress corrosion effects, welding of electrode leads carefully controlled and documented, and storage of cells and batteries at low temperature.

An apparent anomaly in a cell voltage during the cell filling operation for one of the flight batteries was noted during the hardware acceptance review. The open circuit voltage of each cell is monitored during cell filling (cells are filled with electrolyte prior to cell insertion into the battery housing). Normally, the voltage continuously increases during this operation; in this cell, though, the voltage indicated a transient drop during filling. Even with this drop, however, the voltage met requirements for this operation.

The apparent anomaly triggered an investigation, which led to an extensive review of cell fill data and to a series of tests. Results of this investigation revealed that the cell filling had been momentarily interrupted; laboratory tests showed that reinitiation of filling results in a temporary voltage drop associated with a rapid passivation of the cell can, which is connected to the lithium electrode in this design.[8] With these results, it was concluded that such voltage transients are normal phenomena and the cell was deemed acceptable for flight.

The batteries were shipped by military air transport directly to the launch site. The batteries were shipped in insulated containers designed to meet the requirements of the Department of Transportation.[9] The batteries were cooled to $-18°C$ prior to shipping and were placed in cold storage upon arrival at the launch site.

## Flight

Two flight batteries were installed in the normal launch flow. The transient voltage response of the batteries was monitored during processing to ensure that voltage requirements would be met at transfer from ground to airborne power. Additionally, two coupon cells were processed in parallel with the flight batteries; these cells were subjected to identical temperatures, discharges, and timelines as the flight batteries to provide confidence in the batteries' performance.

On May 14, 1995, the Titan IV/Centaur successfully delivered a satellite to orbit with the 250-A-h lithium thionyl chloride batteries providing power for the Centaur upper stage.

## Conclusions

The Centaur lithium thionyl chloride battery has completed a program path from development through flight. An alternative to the silver–zinc launch vehicle battery has been demonstrated on the Centaur upper stage with a weight savings of 42 lb (19 kg) per battery.

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