PERFORMANCE OF HIGH VOLTAGE MODULES UNDER ABUSE CONDITIONS

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ABSTRACT

The Electric Auxiliary Power Unit (EAPU) or the Advanced Hydraulic Power System (AHPS) is a Shuttle Upgrade program. Of the two battery design approaches that were considered in support of this program, the current paper concentrates on the testing performed on the small-cell approach. Testing performed at both ComDev Space, Canada and at NASA-JSC is described in this paper. Testing included those under mission profile conditions and off-nominal abusive conditions.

INTRODUCTION

In the past six years, a few COTS (Commercial-off-the-shelf) li-ion batteries have been used for Shuttle and Station applications[1-3]. These are typically batteries with low voltage and capacities, with 10.8 V and 4.0 Ah being the maximum. The AHPS program requires a 360 V, 120 Ah battery to power the hydraulic system for critical actuators for the Shuttle during ascent and descent and for functional checks while the Shuttle is in-orbit. The auxiliary power units are critical for the safe operation of the Shuttle, and at least two of the three units must be operational to safely complete a mission. The AHPS, an upgrade to the existing hydrazine APU system, consists of the battery system, an electro-hydraulic drive unit with an electric motor, a high voltage power distribution and control unit and a cooling system.

Two alternate approaches were studied for the 230-360 V battery. One involved the use of high capacity li-ion cells (large cell approach) in a single string to provide the required power. The second option used 18650 li-ion cells (small cell approach) in a series/parallel combination for the same purpose. In the past few years papers[4-6] have been presented at various conferences describing this battery development activity. This paper will focus on the testing carried out on the small cell program.

The small cell battery consists of an 82S 90P combination of cells to give a 270 +90/-40 V battery that will provide a total of 28 kWh through the entire mission profile. The battery will be in two half-battery modules in series with each half-battery module having a 41S 90P configuration (Figure 1) to provide half the total battery voltage. The modules include the cells, short circuit protection, structure, thermal control, heaters, dead-face switch, and instrumentation. The design can provide for replacement of the battery after every mission or for a six-mission three-year life.

The testing was performed on an engineering unit submodule battery (EUSB) that consisted of a 41S 5P configuration and representing 1/36th of the flight battery (Figure 2). The cells used in this module are Sony 18650 (hard carbon), 1.5 Ah, li-ion cells. The power profile is a 99 minute profile with a 130 kW, 3 second pulse, at 91 minutes into the power profile. This is split between a 36 minute ascent portion and a 63 minute descent portion.

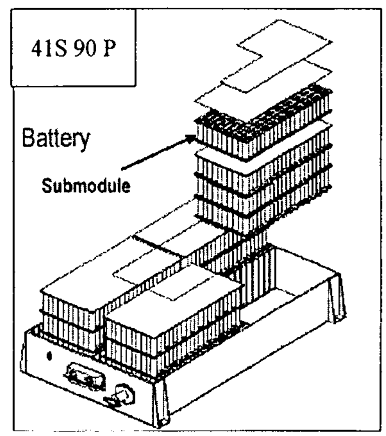

Figure 1. Schematic of an AHPS battery half-module.

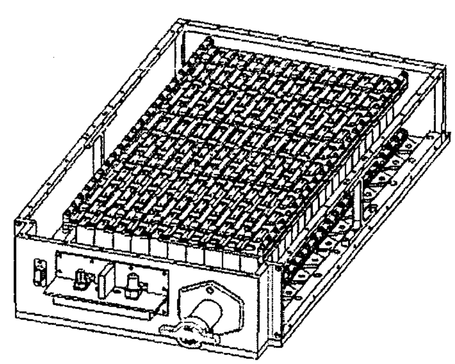

Figure 2. The Engineering Unit Submodule Battery (EUSB) with a 41S 5P configuration.

TESTS, RESULTS AND DISCUSSION

The EUSBs were all provided from a contract with ComDev Space in Cambridge, ON. The tests described in this paper were either performed at Com Dev or at NASA-JSC and, in some instances, in both locations.

Mission Profile Tests for Cycle Life:

The purpose of these tests was to subject the EUS to a number of mission cycles to evaluate capacity degradation and resistance growth as a function of cycles and temperature. The EUSBs were tested using the 3-APU and 2-APU (Figure 3) power profiles, the latter using design sizing case with one of the three APUs failed. The temperatures ranged from 20 °F to 150 °F. Except at high temperature, the module design meets the performance requirements as shown in Figure 4, with the voltage during the 3 second pulse staying above 115 V per half-battery module (230 V for the full battery). The EUSBs met the 6-mission 30 cycle test requirement.

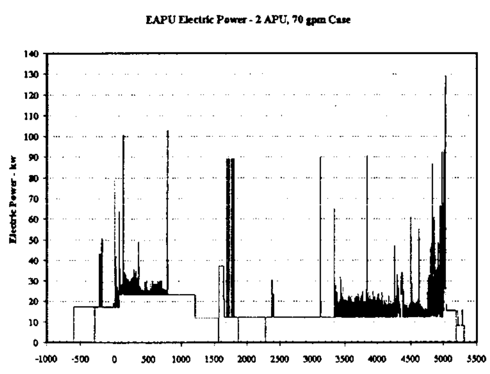

Figure 3. Typical Mission Power Profile for a 2-APU Case.

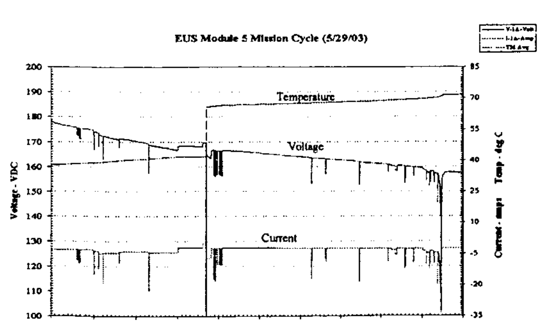

Figure 4. Performance of 41S 5P EUSB under a typical mission cycle.

Hot and Cold Short Mission Tests:

Testing under the mission temperature extremes indicated that the cold temperature mission will be met by the size of the battery used but the hot mission will not. Short and long mission profiles were used for the testing, and the maximum temperature tested was 150 °F during the on-orbit and descent profile portions of the test. The short hot mission had a 14.5 hour hot temperature soak time between ascent and descent portions of the discharge profile and the long hot mission had a 14.4 day soak time. Under both conditions, the PTCs in the cells were a limitation as they tripped just before or during the 3 second pulse (Figure 5) after being exposed to the hot temperature extremes during the mission phase.

This indicated that more parallel strings will be required if the Sony 18650 cells are used in the battery design. The PTC characteristics vary with manufacturer, and cells with more robust PTCs do exist in the commercial market.

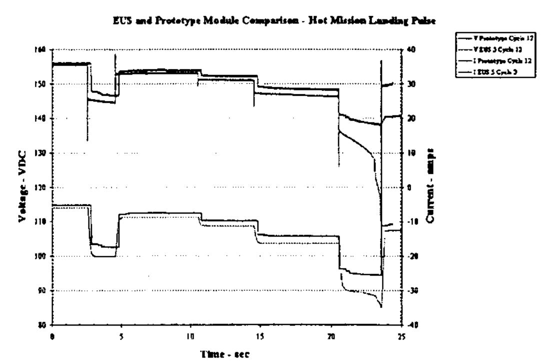

Figure 5. Voltage and Current Profiles During a Hot Mission Profile.

Hard Short:

The purpose of this test was to verify the safe shutdown when the EUSB when subjected to an external electrical short. This test was performed at ambient conditions. The EUS battery design includes diodes across groups of 6 cells. In the initial part of the AHPS test program, the voltage limitation of the PTCs in the Sony cells was discovered (Figure 6). The diodes are needed to allow acceptable cell shutdown when subjected to an external circuit via a PTC inside each cell. The diodes prevent reverse voltages that are produced when the PTC trips under short circuit conditions. Using the diode scheme, the short circuit test was performed successfully on a 41S 5P module. The module with the diodes tolerated a hard short circuit condition and provided nominal functional performance after it was recharged after the short circuit test.

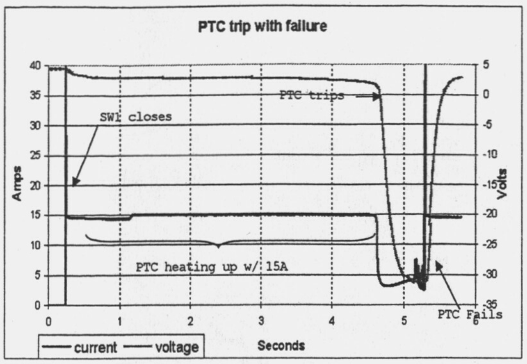

Figure 6. PTC Failure in a Series String with Voltage Greater than 30 V.

Smart Short:
A smart short circuit test was performed on the 82 S 5P module at ComDev Space and the module displayed tolerance to it. The value of the smart short was equivalent to a load of 500 mohms on a single cell and a total of 8.2 ohms for an 82S 5P battery module. The PTCs tripped in a cascading manner, but the module was functional after the test. A second smart short test was performed at NASA-JSC on a single module with a load of 1 ohm. The PTCs tripped in a cascading manner during the smart short as shown in Figure 7. The cells recovered in voltage after the short is removed. Post-capacity check cycling indicated that the battery would accept only 0.56 Ah of charge, and the subsequent discharge was unsuccessful. Post-test inspection of cell voltages in the module showed that some of the cells could have been overcharged, resulting in their CIDs being activated.

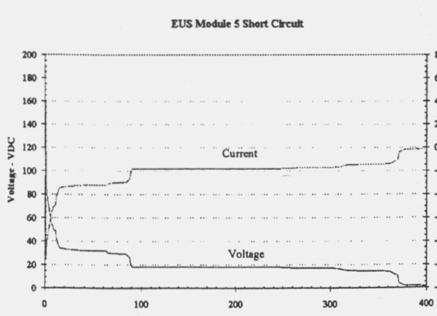

Figure 7. Smart Short Test Displaying the Cascading Trip of Cell PTC Devices.

Collateral Damage Test:
The purpose of this test was to evaluate if catastrophic failure of one cell will propagate and damage adjacent cells. This test was performed at ambient conditions. The test was performed after removing diode protection for one module in two places. It had been shown earlier that the absence of diodes for every six cells in the 41S string causes the PTC to fail short and ignite. The short circuit protection for one string of the EUSB was disabled by cutting the wire to the diode in two places. For this test, two EUSBs were electrically connected in parallel and a hard short applied. The top cover and safety covers were removed from each making the cells and diode boards visible. The modules were placed top-to-top as shown in Figure 8 to simulate cell to cell orientation in a full size battery that has multiple layers or trays of cells. No collateral damage was observed although there was a rise in temperature and visual damage of the cells in the vicinity of the removed diodes. The current and voltage characteristics of the module with the diodes removed are given in Figure 9.

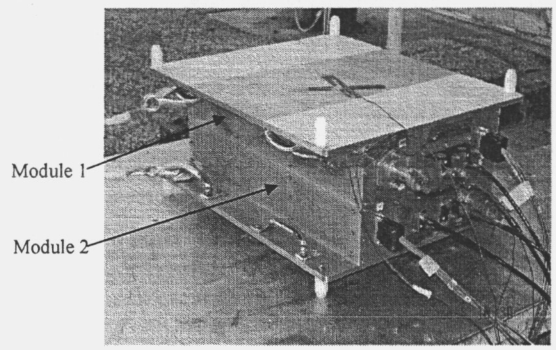

Figure 8. Collateral Damage Test With Two EUSBs in Parallel and With the Cells Facing Each Other.

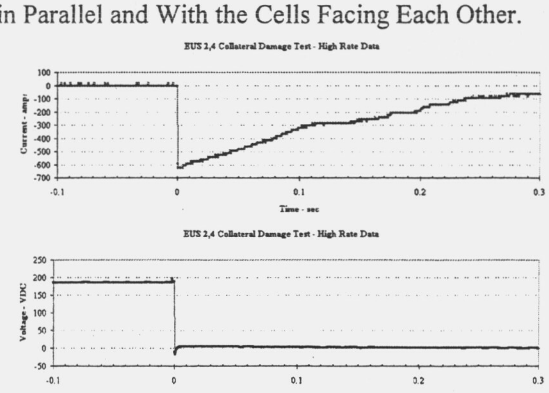

Figure 9. Current and Voltage characteristics recorded during the Collateral Damage Test.

Overcharge:
The EUSB was subjected to a normal charge using a C/5 current to 4.4 V/cell. The EUSB was then overcharged using the same current to a limit of 5.5V / cell. It was observed that there was a steady module voltage and temperature increase until a plateau was reached at about 4.8 V / cell. The plateau was

observed for approximately one hour and then the voltage suddenly increased to 5.0 V in less than five minutes, the module reached 248 °F (120 °C) and then a thermal runaway occurred almost instantaneously thereafter (Figure 10).

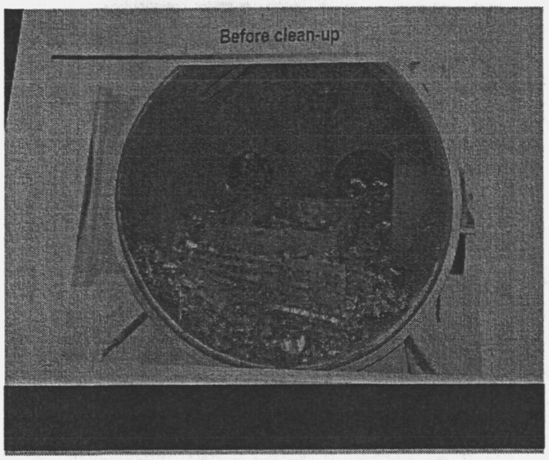

Figure 10. Results of An Overcharge Test on a Fully Charged EUSB.

In single cells, the Current Interrupt Device (CID) offers protection when the voltage goes above 5.0 V. The decomposition of electrolyte above 5.0 V along with the presence of gassing agents causes an increase in pressure inside the cell that in turn activates the CID. The CID is a non-resettable protective device that is present inside the 18650 li-ion cells and it prevents the cells from going into a thermal runaway under an overcharge condition. It was determined from the overcharge test conducted on the EUSB that the CID does not offer protection when a large number of cells are present in a series/parallel combination.

CONCLUSIONS

The testing on the small-cell design EUSBs showed that the small-cell design is a very feasible approach. Under the smart short conditions, the EUSB demonstrated safe shutdown. However, performance degradation incurred due to the overheating of the EUSB made it unusable for post-operation. The EUSB demonstrated a safe shutdown when subjected to failure of the short circuit protection diodes combined with an external short circuit, and no collateral damage to adjacent cell tray was observed. However, damage to the battery did result in making it unusable for follow-on operation. The current study also indicated that the CID cannot be relied upon for overcharge protection in a module as it does for single cells.

ACKNOWLEDGMENTS

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REFERENCES

1. J. A. Jeevarajan, J. S. Cook, J. Collins, F. J. Davies and B. J. Bragg, *Proceedings of the 203rd Meeting of the Electrochemical Society*, Paris, France, April **2003**.

2. J. A. Jeevarajan, F. J. Davies, B. J. Bragg and S. M. Lazaroff, *Proceedings of the 39th Power Sources Conference*, June **2000**.

3. J. A. Jeevarajan and B. J. Bragg, Proceedings of *The 1999 NASA Aerospace Battery Workshop*, Huntsville, AL, November **1999**.

4. J. A. Jeevarajan, E. C. Darcy, F. J. Davies and P. Cowles, *Proceedings of the 203rd Meeting of the Electrochemical Society*, Paris, France, April **2003**.

5. P. R. Cowles, E. C. Darcy, F. J. Davies and J. A. Jeevarajan, *Proceedings of the 2002 NASA Aerospace Battery Workshop*, Huntsville, AL, November **2002**.

6. J. A. Jeevarajan, W. Zhang and B. W. Irlbeck, *Proceedings of 40th Power Sources Symposium*, Cherry Hill, NJ, June **2002**.