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INVESTIGATION OF STACKED ARRAY LITHIUM POLYMER CELLS PERFORMANCE IN HIGH-G ENVIRONMENTS

Richard Granitzki
Alfred Rotundo
Kyle Schaarschmidt

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14. ABSTRACT

The utilization of commercial lithium cell battery technology in high acceleration military environments to meet high power demands of telemetry and precision munitions electronics systems places these batteries in environments they were not designed to endure. This paper investigates the performance of individual lithium polymer cells under high acceleration environments to observe effects associated with location and placement of the cells on top of one another within munitions.

15. SUBJECT TERMS

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INTRODUCTION

The utilization of commercial lithium cell battery technology in high acceleration military environments to meet high power demands of telemetry and precision munitions electronics systems places these batteries in environments they were not designed to endure. Stacking multiple lithium-polymer (Li-Po) cells on top of each other requires each lower cell to support the mass of adjacent cells as well as possible mechanical structure load path transfers, all during high acceleration gun launched environments. Burke, Irwin, et al. (ref. 1) reported single cell voltage drops back in 1997 associated with high acceleration environments that lithium-ion batteries were subjected to and were able to adjust battery chemistries in order to demonstrate success. The batteries being studied in this report are Hyperion G3 CX 25C 240mAh single cell batteries. These cells have been previously tested in high acceleration environments successfully (ref. 2). While the use of Li-Po cells in stacked arrays is very common in munitions development projects, the investigation into whether an observable voltage drop is present in individual cells that are stacked on top of each other has not been reported on.

BATTERY TEST VEHICLE

Test Vehicle Analysis

The test vehicle being used to monitor the battery performances fits within a M483 155-mm Cargo Projectile. Within the test vehicle, five electronics cups are mated to each other. The model of the test vehicle and electronics cups is shown in figure 1, and a description of the cup's function is described in table 1.

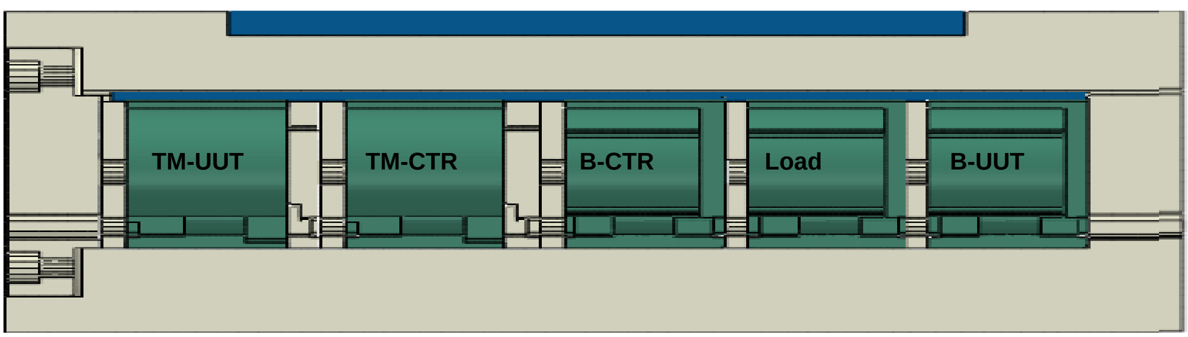


Figure 1
Battery test vehicle configuration

Table 1
Electronics cup function description

Electronics cup	Purpose/use
TM –UUT (telemetry unit under test)	To provide a wiring pass through to enable setting of the onboard recorder (OBR) contained in TM-CTR from the top of the test vehicle
TM- CTR (control telemetry unit)	The OBR used to record internal surface mount high-g triaxial acceleration and battery voltages
B-CTR	Controlled battery power for TM-CTR and load
Load	To provide a constant 324-mA discharge circuit for each individual battery under test
B-UUT	Batteries (unit) under test

A model of the battery test vehicle within the M483 Cargo Projectile shown with meshes can be seen in figure 2.

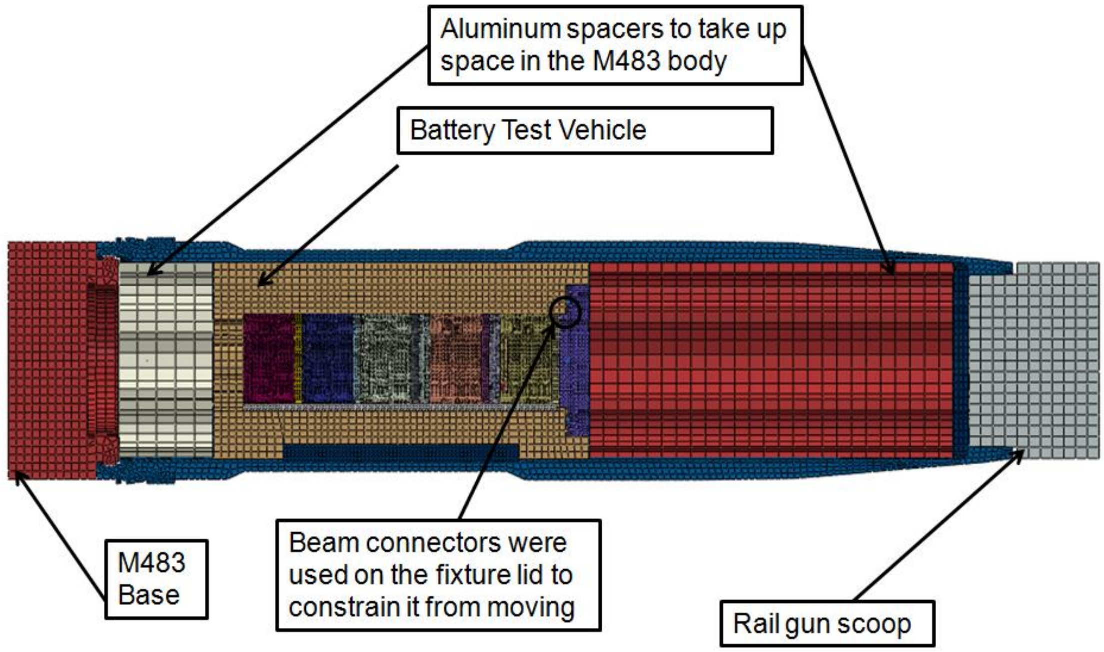


Figure 2
M483 Cargo Projectile with battery test vehicle

The simulation was run with a U.S. Modular Artillery Charge System (MACS) Zone 5 (fig. 3) permissible individual maximum pressure (PIMP) +10% (fig. 4) base pressure curve applied to the base of the projectile with a spin rate of 1,700 rad/sec applied to the outside surface of the back of the projectile with smooth step amplitude. Firing a projectile at PIMP +10% refers to 110% of the PIMP in the weapon system per International Test Operating Procedure 4-2-504 (ref. 3).

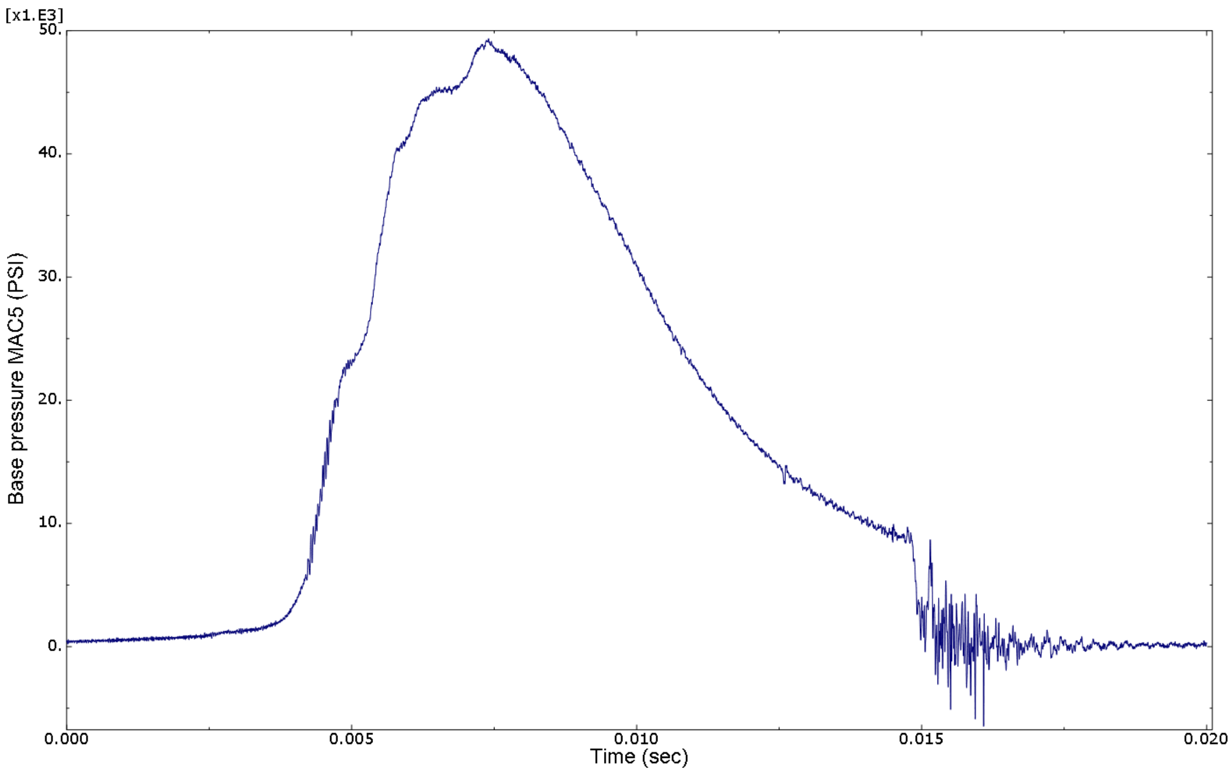


Figure 3
MACS 5 pressure curve

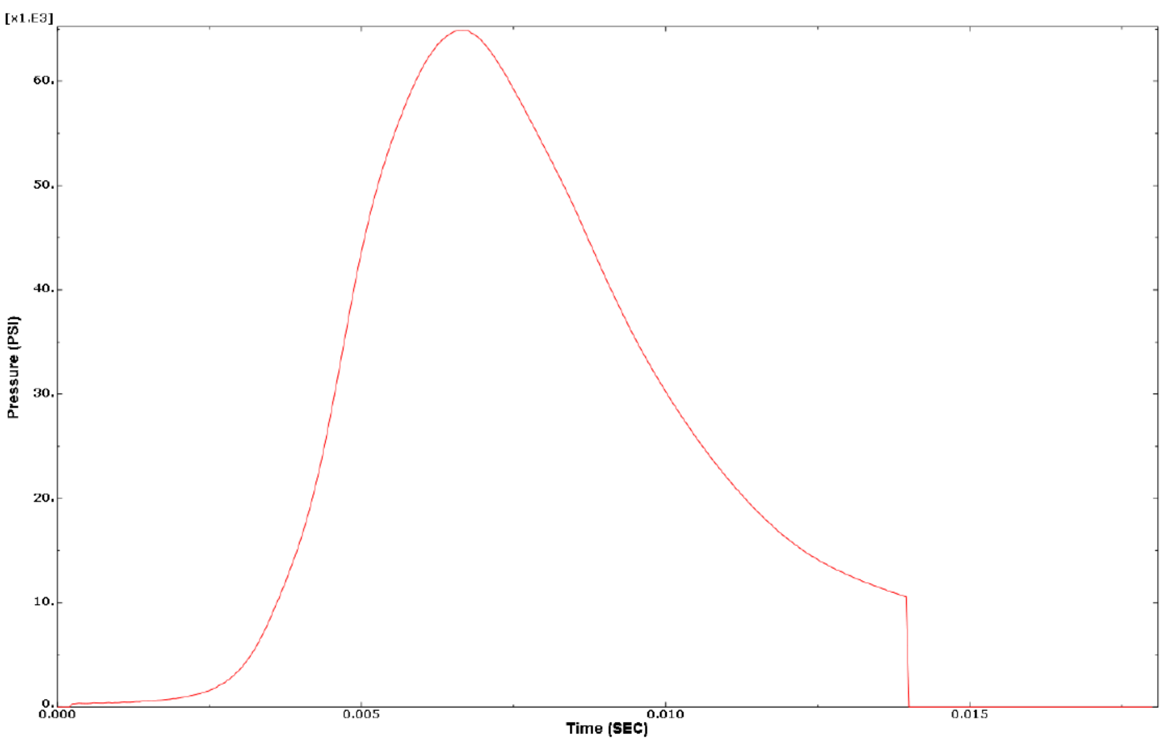


Figure 4
PIMP+10 pressure curve

A finite element analysis (FEA) equivalent plastic strain of the integrated projectile for the MACS 5 base pressure was conducted with the results shown in figure 5.

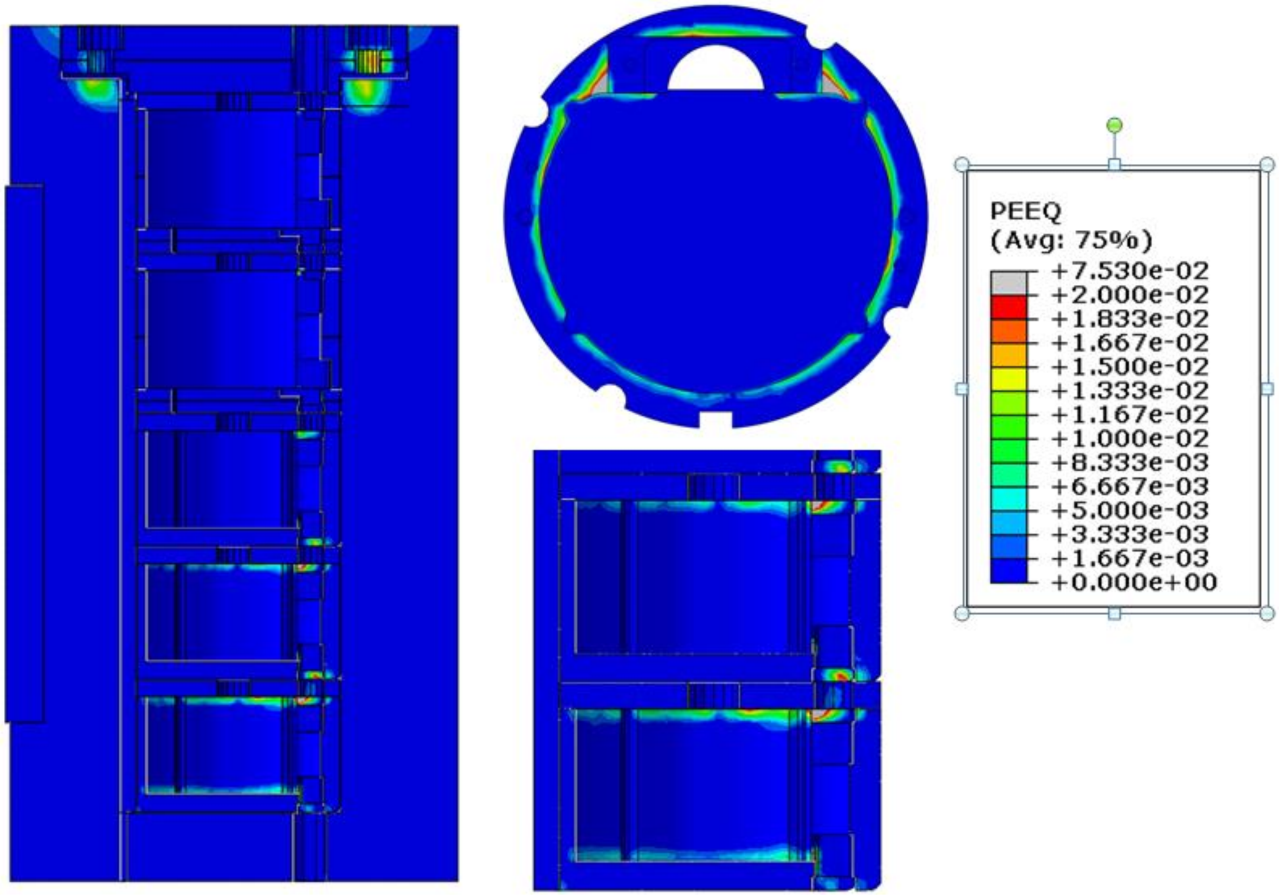


Figure 5
MACS 5 FEA equivalent plastic strain (PEEQ)

About 1.3% plastic strain is present on the top corner of the bottom cup (battery - unit under test), which may cause enough deformation to prevent reuse. After each test firing, the bottom cup is recommended to be inspected before being considered for reuse. The same analysis was then run with a PIMP + 10% base pressure and is shown in figure 6.

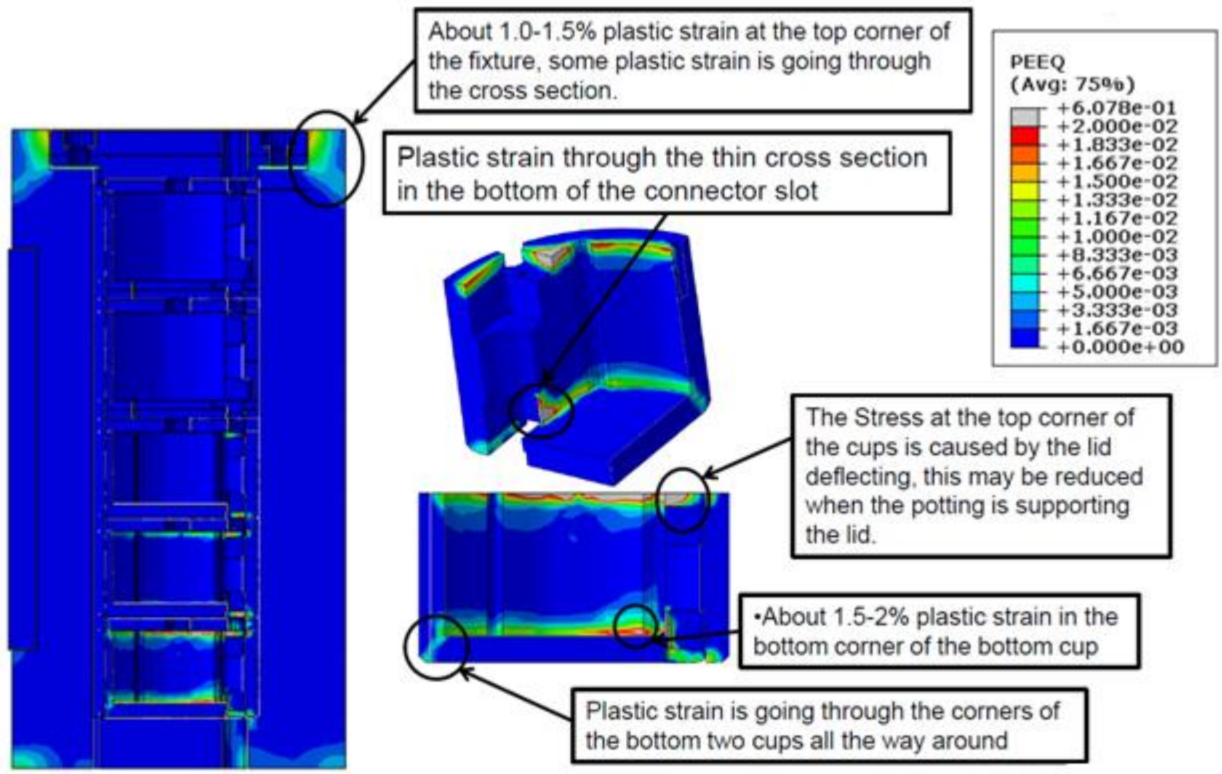


Figure 6
PIMP+10% PEEQ

Greater plastic strain is evident on the bottom cup. As noted in the figure, potting as well as electronics components are not modeled. The integration of these components may reduce some of the stresses by nature of load path transfer, and to achieve a conservative design, these materials were not modeled.

Next, material yields were computed using von Mises yield criterion. Figures 7 and 8 illustrate the analysis results for both MACS 5 and PIMP +10% 65,000 to 70,000-psi stresses identified at the top and bottom corners of the bottom cup.

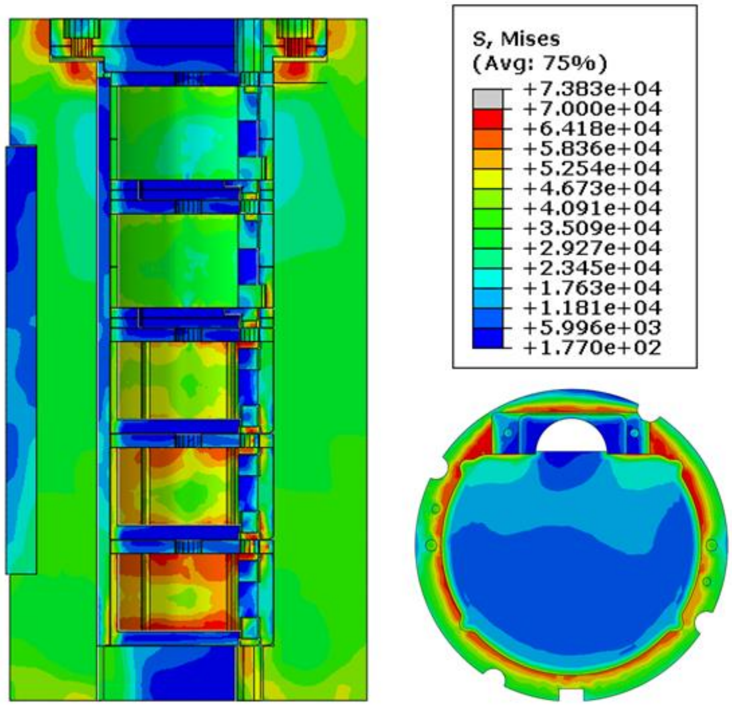


Figure 7
MACS 5 von Mises yield analysis

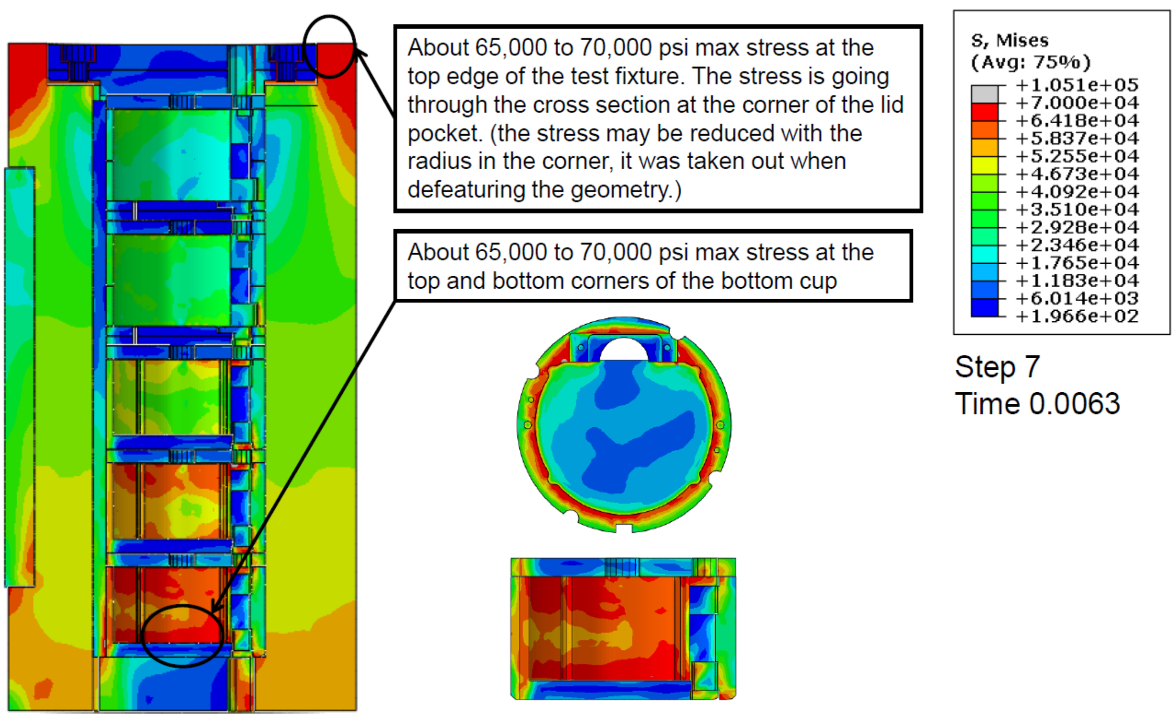


Figure 8
PIMP+10 von Mises yield analysis

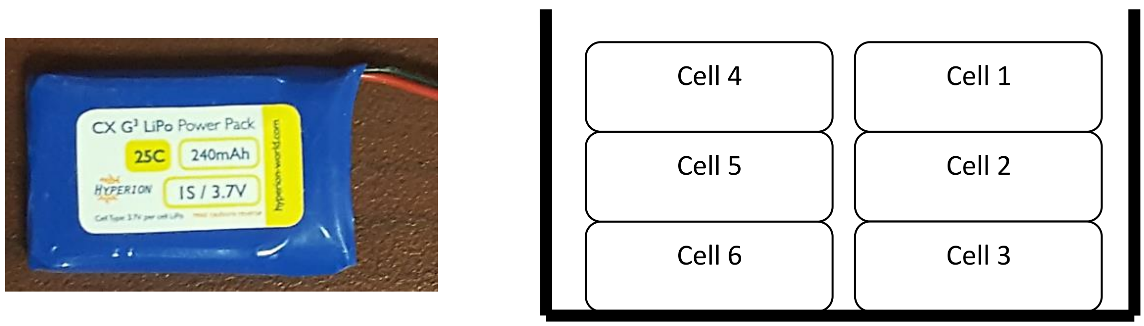
For the MACS 5 analysis, the bottom cup further indicates the stresses seen at the bottom cup may cause material yield. During the PIMP+10% analysis, the bottom cup has low plastic strain through the thickest wall sections.

Based on the analysis, the following recommendations are made:

- Although low plastic strain exists at the top corners of the test vehicle, this may be reduced by using a stiffer shim that will also decrease the changes of getting the fixture stuck in the carrier after testing.
- The bottom cup should not be reused if shot at PIMP +10%.

Test Vehicle Hardware

For this investigation, six cells will be placed in the bottom cup (battery - unit under test) of the test vehicle with each cell being independently loaded and monitored. At this location, the cup will undergo the most predicted stress as evidenced in the analysis presented. The orientation for the cells is shown in figure 9.



(a)
Battery under test cell

(b)
Integrated cell numbering

Figure 9
Orientation of the cells in the bottom cup of the test vehicle

Test Vehicle Instrumentation

The instrumentation used to monitor the individual battery cell voltage levels during the testing event was the ARRT-170 ferroelectric random-access memory-based OBR (FOBR) telemeter. The FOBR is a 14 channel, 500-kHz sampling recorder that is triggered by an inertial switch after an arming delay period and available with three high-g accelerometers. After the 15-min arming delay period, a regulated 324-mA load was applied to each battery under test.

LIVE-FIRE TESTING

Live-fire testing was be conducted using the Soft Catch (SCat) Gun at MACS 5 from the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ. The SCat Gun provides a relevant environment to conduct recoverable, low-cost, and expedient testing to evaluate component's, subsystem's, and systems' survivability during live-fire reliability tests. Prior to subjecting the batteries to an operational environment, new cells were charged with a 200-mA charging current. Their resulting voltage levels are shown in table 2.

Table 2
Battery pretest voltages

Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
4.41V	4.42V	4.36V	4.36V	4.41V	4.37V

The battery test vehicle was the fired in the SCat Gun, test number 913, at MACS 5 propellant and no spin. The resulting axial and radial measurements taken from a surface mount triaxial Endevco M73 accelerometer are shown in figure 10 with each battery cell's measured voltage overlaid. The battery voltages in the graph had a 100-point moving average filter applied to the voltage measurements. Starting measured voltages differed than that of the noted pretest voltages. The trickle charging feature of the battery charger post-charging was one potential reason for the difference in measurement for the batteries, which had a higher starting voltage than that of table 2.

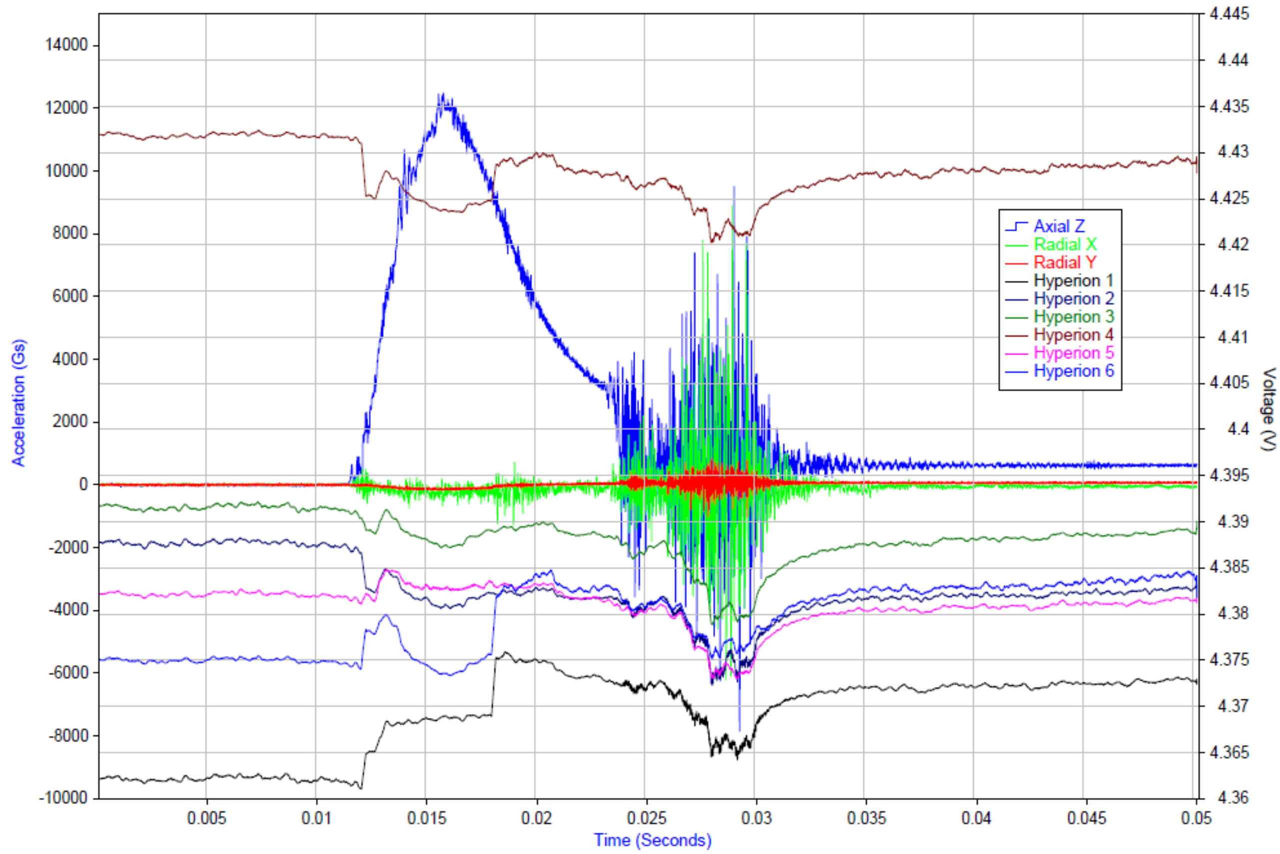


Figure 10
SCat Gun test 913 MACS 5 acceleration curve with individual battery voltages under 324-mA discharge

The test vehicle experienced a peak acceleration of 12,490 G's. Table 3 lists the acceleration phase durations that were experienced by the test vehicle.

Table 3
Acceleration phase durations

Acceleration phase	Duration (ms)
In-bore acceleration	~12
Setback	~4
Deceleration	~8
Set forward	~2
SCat transition tube	~6

During setback, battery voltage measurements recorded a drop in voltage as the test vehicle reached its peak acceleration. At approximately 12 ms into recording during setback, a voltage increase was measured for a couple milliseconds before continuing to drop as it reached peak acceleration. Following peak acceleration, as the test vehicle decelerated, voltage measurements rebounded slightly. Extracted measurements are shown in table 4.

Table 4
In-bore acceleration battery voltage measurements

Battery no.	Prelaunch voltage (V)	Setback (peak acceleration) voltage (V)	Change in voltage (mV)	Preset forward voltage (V)	In-bore acceleration voltage change (mV)
1	4.362	4.368	+ 6	4.373	+ 11
2	4.387	4.382	- 6	4.382	- 5
3	4.392	4.387	- 5	4.388	- 4
4	4.432	4.424	- 8	4.428	- 4
5	4.382	4.383	+ 1	4.381	- 1
6	4.375	4.373	- 2	4.383	+ 8

Illustrated previously in figure 10, measurements of three batteries (nos. 1, 5, and 6) recorded a voltage increase during setback, which differed from the expected trend of battery nos. 2, 3, and 4.

The set forward acceleration phase recorded much lower battery voltage changes (table 5) than what was noted for the in-bore acceleration voltage change due to the shorter duration of the phase. As the test vehicle enters the transition tube section of the SCat Gun, a long duration voltage drop is experienced, and the measured values (table 6) are greater in magnitude than that of the shorter duration set forward phase.

Table 5
Set forward acceleration battery voltage measurements

Battery no.	Prelaunch voltage (V)	Preset forward voltage (V)	Peak set forward voltage (V)	Set forward change in voltage (mV)	Change in voltage from prelaunch (mV)
1	4.362	4.373	4.371	- 2	+ 9
2	4.387	4.382	4.379	- 3	- 8
3	4.392	4.388	4.386	- 2	- 6
4	4.432	4.428	4.426	- 2	- 6
5	4.382	4.381	4.380	- 1	- 2
6	4.375	4.383	4.380	- 3	+ 5

Table 6
SCat transition tube battery voltage measurements

Battery no.	Peak set forward voltage (V)	SCat transition tube voltage (V)	SCat transition tube change in voltage from peak set forward voltage (mV)
1	4.371	4.365	- 6
2	4.379	4.372	- 6
3	4.386	4.379	- 7
4	4.426	4.420	- 6
5	4.380	4.373	- 7
6	4.380	4.375	- 5

The overall gun launched testing event battery measurements undergoing a 324-mA load is shown in table 7.

Table 7
Pre and post-gun launched battery voltage measurements

Battery no.	Prelaunch voltage (V)	Post-launch voltage settling (V)	Total event change (mV)
1	4.362	4.372	+ 10
2	4.387	4.383	- 4
3	4.392	4.389	- 3
4	4.432	4.429	- 3
5	4.382	4.381	- 1
6	4.375	4.383	+ 8

CONCLUSIONS

A battery voltage anomaly was observed during this testing event on battery nos.1, 5, and 6 where these batteries experienced an increase in voltage when the expected result was a decrease in voltage like that of battery nos. 2, 3, and 4. The signal conditioning and constant current load circuits were done in two printed circuit boards (PCB) stacked on top of each other with battery nos. 1, 2, and 3 on one board and 4, 5, and 6 on another. Battery nos. 1, 2, 4, and 5 were mounted on the top side of the PCBs in the direction of flight with battery nos. 3 and 6 on the underside of the PCBs. This configuration did not match the two groups of battery observations reducing the likelihood of instrument induced measurement errors.

More testing is recommended in order to obtain a larger sample size to further support the expected battery trend as well as conducting the test at the nominal cell voltage of 3.7VDC. In regard to the performance of each battery placed in a three cell stack, no conclusive trends were able to be observed to offer any gun hardening insight. Cells at the top of the stack were outliers in terms of voltage measurement. This doesn’t yield anything meaningful as all of the starting prelaunch battery voltages were different resulting from the manner in which the cells took their initial charge and responded to the constant current load being applied. The measurements for the center and bottom located cells also yielded no voltage trends that would indicate cell crushing or damage from the mass of other cells under inertial loading.

In general, designers of power systems for gun launched munitions should ensure that enough voltage potential exists to account for inertial loading voltage drops. In this test, an 8-mV drop in voltage in a 12,490-G gun launched environment was observed after applying a 100-point moving average filter to the recorded battery voltages, which was not large enough to cause regulator brown out in this design.

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