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Preliminary Performance of Lithium-ion Cell Designs for Ares I Upper Stage Applications

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Abstract

NASA's Ares I Crew Launch Vehicle (CLV) baselined lithium-ion technology for the Upper Stage (US). Under this effort, the NASA Glenn Research Center investigated three different aerospace lithium-ion cell suppliers to assess the performance of the various lithium-ion cell designs under acceptance and characterization testing. This paper describes the overall testing approaches associated with lithium-ion cells, their ampere-hour capacity as a function of temperature and discharge rates, as well as their performance limitations for use on the Ares I US vehicle.

Introduction

The purpose of this document is to describe the acceptance and characterization testing of the Lithium-ion (Li-ion) battery cell candidates for the Ares I Crew Launch Vehicle (CLV) Upper Stage (US) Electrical Power System (EPS) Battery Unit (BU). The lithium-ion battery designed for the Ares I Upper Stage must operate in a harsh thermal environment and still provide the necessary ampere-hour capacity while delivering its discharge energy within the power quality guidelines outlined in the CxP-70050 document for 28 volts DC (VDC) power systems. The cells were evaluated to provide information to develop battery procurement specifications and to ensure the functional and safety margins were met for the human-rating guidelines. These tests were conducted at the NASA Glenn Research Center (GRC) in the Space Power Research Laboratory.

Preliminary Cell Designs

Three cell options under consideration for the Upper Stage Electrical Power System (US-EPS) were evaluated at the NASA Glenn Research Center. Three different state-of-the-art cell designs that had previous aerospace heritage, ABSL's 18650HR; Lithion's NCP12-2; and Saft's VL4V, were assessed. These cells are different in construction details and chemistry, have different form factors, and possess a range of energy and discharge power capabilities. The nominal cell capacities were 1.1, 4, and 12 ampere-hours (Ah), respectively. The two smaller cell designs were cylindrical while the 12 Ah cell was a prismatic configuration. Photographs of the representative cells from each vendor are shown in Figure 1. Table 1 contains a summary of the cell designs tested.[1]

[1]Additional details for all three lithium-ion designs are available at: Lithion NCP12-2: http://www.yardney.com/Lithion/Documents/Cell%20specs/NCP12-2newV2.pdf
Saft VLV: http://www.saftbatteries.com/Produit_Large_VLV_cell_range_301_64/Default.aspx
ABSL 18650HR Cell Datasheet: http://www.abslspaceproducts.com/technical

ABSL 18650HR | Saft VL4V cell | Lithion NCP12-2 cell

Figure 1.—Li-ion cells evaluated for CLV US.

TABLE 1.—CELL CHARACTERISTICS

Vendor	Cell model	Nameplate capacity, Ah	Geometry	Dimensions, mm	Mass, kg	Maximum continuous discharge current, A	Discharge operating temperature, °C
Lithion	NCP12-2	12	Prismatic	111 × 71 × 25.2 (H × W × T)	0.422	120	–40 to 60
Saft	VL4V	4	Cylindrical	35.2 × 175.4 (D × H)	0.320	500	–30 to 60
ABSL	18650HR	1.1	Cylindrical	18 × 65 (D × H)	0.0405	11	–20 to 60

Physical Inspection

The purpose of the incoming inspection is to verify that the batteries do not have any initial defects upon delivery. The initial inspection consists of four steps: physical inspection, case polarity, weight measurement, and dimension measurement.

Upon receiving the battery cell for testing the following data were recorded:

- Date of Manufacture
- Cell Lot Number
- Manufacturer Part Number
- Date Received In-house
- Cell Lot Number
- Cell Serial Number

The lithium-ion cell case polarity (case positive, case negative, case neutral) was determined by performing electrical measurements with a digital multimeter to ensure the cells were consistent in design. Cells were weighed using a precision balance to assess manufacturing variability and obtain an accurate technical performance metric on specific energy and energy density. The test cells dimensions were measured (length, height, and width) for prismatic cells; (diameter and length) for cylindrical cells using a precision caliper.

TABLE 2.—ABSL BATTERY CELL PHYSICAL AND ELECTRICAL INSPECTION

MANUFACTURER: ABSL PART #/LOT #: 18650HR
DATE OF MANUFACTURE: DATE RECEIVED IN-HOUSE: 12 JUNE 2007

Serial number	Weight, g	Dimensions, cm			Voltage, V			Resistance, Ohms	
	Bare cell	Diameter	Height	Height w/ terminals	+ to --	-- to case	+ to case	-- to case	+ to case
NA18KAAI048	41.15	1.799	6.49	6.49	3.12	0.0	3.12	N/A	>1MΩ
NA18KAAJ044	41.15	1.803	6.50	6.50	3.10	0.0	3.10	N/A	>1MΩ
NA18KAAJ052	41.20	1.800	6.49	6.49	3.10	0.0	3.10	N/A	>1MΩ
NA18KAAJ053	41.12	1.804	6.49	6.49	3.10	0.0	3.10	N/A	>1MΩ
NA18KAAJ111	41.10	1.800	6.49	6.49	3.11	0.0	3.11	N/A	>1MΩ
NA18KAAJ120	41.14	1.797	6.49	6.49	3.11	0.0	3.11	N/A	>1MΩ
NA18KAAJ125	41.07	1.802	6.49	6.49	3.11	0.0	3.11	N/A	>1MΩ
NA18KAAL092	41.08	1.800	6.50	6.50	3.11	0.0	3.11	N/A	>1MΩ
NA18KAAL111	41.19	1.800	6.49	6.49	3.11	0.0	3.11	N/A	>1MΩ
NA18KAAT040	40.71	1.798	6.49	6.49	3.02	0.0	3.02	N/A	>1MΩ
Average	41.09	1.800	6.49	6.49	3.10	0.0	3.10	N/A	>1MΩ

TABLE 3.—SAFT BATTERY CELL PHYSICAL AND ELECTRICAL INSPECTION

MANUFACTURER: SAFT PART #/LOT # NUMBER: VL4V
DATE OF MANUFACTURE: RECEIVED IN-HOUSE: 21 MARCH 2007

Serial number	Weight, g	Dimensions, cm			Voltage, V			Resistance, Ohms	
	Bare cell	Diameter	Height	Height w/ terminals	+ to --	-- to case	+ to case	-- to case	+ to case
605-120	320.3	3.3	15.2	17.6	3.57	0.0	3.57	1.3	>1MΩ
605-190	324.0	3.4	15.3	17.7	3.57	0.0	3.56	0.2	>1MΩ
606-28	323.8	3.4	15.3	17.5	3.58	0.0	3.58	1.1	>1MΩ
606-64	319.6	3.4	15.4	17.8	3.57	0.0	3.57	0.9	>1MΩ
606-69	318.1	3.6	15.4	17.6	3.58	0.0	3.58	0.1	>1MΩ
606-85	320.0	3.4	15.3	17.7	3.58	0.0	3.58	0.2	>1MΩ
606-324	324.2	3.3	15.4	17.8	3.57	0.0	3.57	0.6	>1MΩ
606-332	322.3	3.4	15.4	17.8	3.57	0.0	3.57	0.1	>1MΩ
606-338	320.1	3.3	15.4	17.7	3.58	0.0	3.58	2.1	>1MΩ
641-35	328.2	3.4	15.4	17.6	3.58	0.0	3.58	0.1	>1MΩ
641-37	327.4	3.4	15.4	17.7	3.58	0.0	3.58	0.6	>1MΩ
641-43	327.0	3.5	15.2	17.4	3.57	0.0	3.57	0.4	>1MΩ
641-67	327.8	3.4	15.3	17.8	3.58	0.0	3.58	0.4	>1MΩ
641-89	328.3	3.4	15.3	17.5	3.58	0.0	3.58	0.1	>1MΩ
641-114	328.3	3.4	15.4	17.8	3.58	0.0	3.58	0.2	>1MΩ
Average	324.0	3.4	15.3	17.7	3.58	0.0	3.58	0.6	>1MΩ

TABLE 4.—LITHION BATTERY CELL PHYSICAL AND ELECTRICAL INSPECTION

MANUFACTURER: LITHION PART #/LOT # NUMBER: NCP12-2
DATE OF MANUFACTURE: 09/2007 RECEIVED IN-HOUSE: 19 SEPT. 2007

Serial number	Weight, g	Dimensions, cm				Voltage, V			Resistance, Ohms	
	Bare cell	Length	Width	Height	Height w/ terminals	+ to --	-- to case	+ to case	-- to case	+ to case
12-2-1671	448.6	7.17	2.45	10.20	11.36	3.35	2.69	0.66	>1MΩ	8.3
12-2-1672	448.4	7.17	2.46	10.23	11.31	3.54	2.78	0.75	>1MΩ	10.4
12-2-1673	448.4	7.15	2.46	10.17	11.37	3.53	2.76	0.76	>1MΩ	10.8
12-2-1674	448.1	7.17	2.46	10.18	11.34	3.45	2.76	0.68	>1MΩ	8.8
12-2-1675	448.7	7.17	2.48	10.18	11.35	3.46	2.72	0.74	>1MΩ	10.3
12-2-1676	448.4	7.16	2.44	10.19	11.37	3.46	2.72	0.73	>1MΩ	10.3
12-2-1678	444.8	7.15	2.52	10.18	11.29	3.51	2.78	0.72	>1MΩ	9.8
12-2-1679	449.2	7.16	2.46	10.18	11.29	3.54	2.88	0.65	>1MΩ	8.2
12-2-1680	447.4	7.18	2.47	10.14	11.39	3.53	2.76	0.76	>1MΩ	11.0
12-2-1681	446.3	7.16	2.44	10.21	11.36	3.50	2.76	0.71	>1MΩ	9.8
12-2-1682	448.4	7.16	2.45	10.18	11.33	3.52	2.87	0.64	>1MΩ	7.9
12-2-1683	448.1	7.15	2.52	10.18	11.32	3.52	2.78	0.73	>1MΩ	9.9
12-2-1684	445.7	7.15	2.44	10.18	11.38	3.40	2.80	0.59	>1MΩ	6.8
12-2-1685	448.0	7.15	2.32	10.20	11.32	3.50	2.75	0.76	>1MΩ	10.7
12-2-1690	449.1	7.17	2.46	10.15	11.31	3.53	2.76	0.76	>1MΩ	10.9
Average	447.8	7.16	2.45	10.18	11.34	3.49	2.77	0.71	>1MΩ	9.6

Cell Performance Tests

The battery cell evaluation consisted of the cell acceptance testing previously described along with performance testing over a range of temperatures. The cells were tested to ascertain their ability to deliver the required energy and power levels for future Constellation missions.

Stabilization

The purpose of stabilization testing was to exercise the cells for a few cycles and establish stable electrical performance under benign conditions. This stabilization procedure was performed on each cell prior to other testing. Stabilization consisted of three cycles with a constant current charge at C/8 and 20 °C to 4.100 V/cell then a taper charge to C/50 followed by a discharge at C/5 and 20 °C to 3.000 V. The cell ampere-hour capacity, voltage, and temperature were measured.

Capacity and Voltage Characterization

The purpose of the characterization testing was to determine the cell's ampere-hour capacity and to characterize voltage performance at several discharge rates and temperatures. Three cells were selected at random from the cell lot for characterization testing. The test procedure consisted of charging at 20 °C at a constant current of C/2 to 4.100 V/cell followed by charging at constant voltage until a C/50 current was reached. Discharges were performed at temperatures of 0, 20, and 60 °C, and rates of C/10, C/2, C, 2C, 4C, 8C, or to the maximum recommended temperatures and rates the cell vendor specified. A single charge/discharge cycle was completed at each test condition. The cell ampere-hour capacity, voltage, and temperature were measured.

Battery Cell Test Program

Capacity testing was used to determine the ampere-hour capacity, the useful ampere-hour capacity and the discharge voltage curve of a cell. The ampere-hour capacity is a measurement of the coulombs delivered by the battery cell between 100 percent state-of-charge (SOC) (constant current C/2 charge to 4.1 V, followed by constant voltage charge to C/50 taper current) and 3.00 V at the various discharge rates). The useful ampere-hour capacity is defined as the capacity between 100 percent SOC and 3.375 V. This cell level requirement is derived from Volume I of CxP-70050 Power Quality Specification which requires the BU must supply a steady state voltage within the range from 27 to 36 VDC for load currents from 0 A to the rated current specified. The 3.375 V cutoff assumes an eight-cell battery. Increasing the number of cells to nine will allow operation to a lower voltage at the end of discharge but would pose a similar issue at the high end of range allowed by the Power Quality Specification.

Capacity Testing Procedure

During electrical testing, the voltage, current, temperature, time, and cycle number were recorded by commercial Arbin BT2000 battery cell test units. The BT2000 performed the function of programmable power supply during charge operations, acted as a programmable load during discharge operations, and performed all of the data acquisition functions during testing. These units were operated using the MitsPro software through a local personal computer. This software was programmed to control the desired cell charge and discharge current or power profiles, monitor the cells for unsafe operating conditions, and collect the desired test data. Voltage and current measurements were accurate to 0.1 percent of full scale range. The cell was connected to the battery test equipment with the appropriately sized wires and connectors as depicted in Figure 2. A fuse was installed on the positive current carrying leads between the cell and the power supply to protect the cell against excessive currents during charge or discharge.

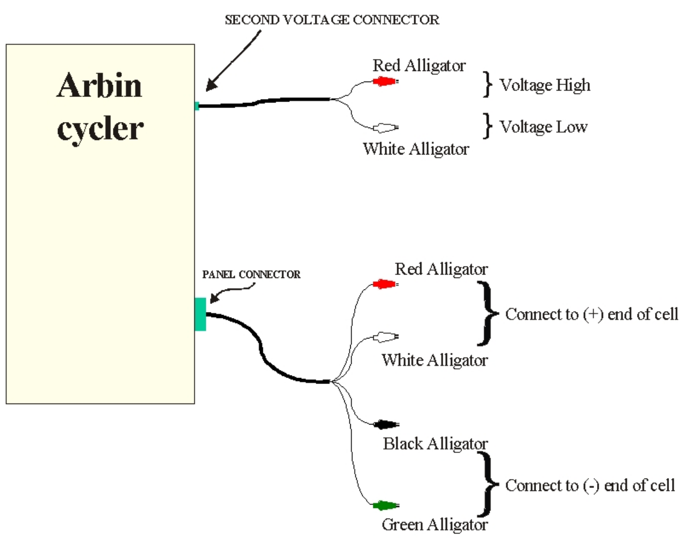

Figure 2.—Typical electrical connection schematic.

The lithium-ion battery cells were tested in environmental chambers with a gaseous nitrogen purge. This test set-up provided controlled temperatures for the testing, an inert atmosphere to prevent water condensation build-up on the cells, and an additional level of safety to reduce propagation of fire in the event of a cell failure. During testing, cells were soaked for at least 12 hr before the initiation of a test to allow the internal temperature of the cell to equilibrate at the test temperature. After reaching 100 percent SOC at 20 °C, the cells were immediately placed on open circuit and allowed to soak for at least 12 hr at the specified discharge temperature test condition before commencing the discharge.

A typical set of cell discharge voltage curves is shown in Figure 3. The horizontal red line indicates the minimum discharge voltage of 3.375 V. The curves show the discharge voltage at different discharge rates. For the data presented in Figure 3, the discharge capacity measured to 3.000 V at the C/2 rate was approximately 12.3 Ah, whereas the useful discharge capacity measured to 3.375 V is approximately 9.1 Ah. Approximately 25 percent of the stored ampere-hour capacity would not be available for the mission due to the minimum voltage requirement. Another example with an even more drastic difference was at the 4C rate. The capacity to 3.0 V is approximately 11.5 Ah; however the useful capacity is nearly 0 Ah since the entire discharge curve is below the minimum 3.375 V threshold.

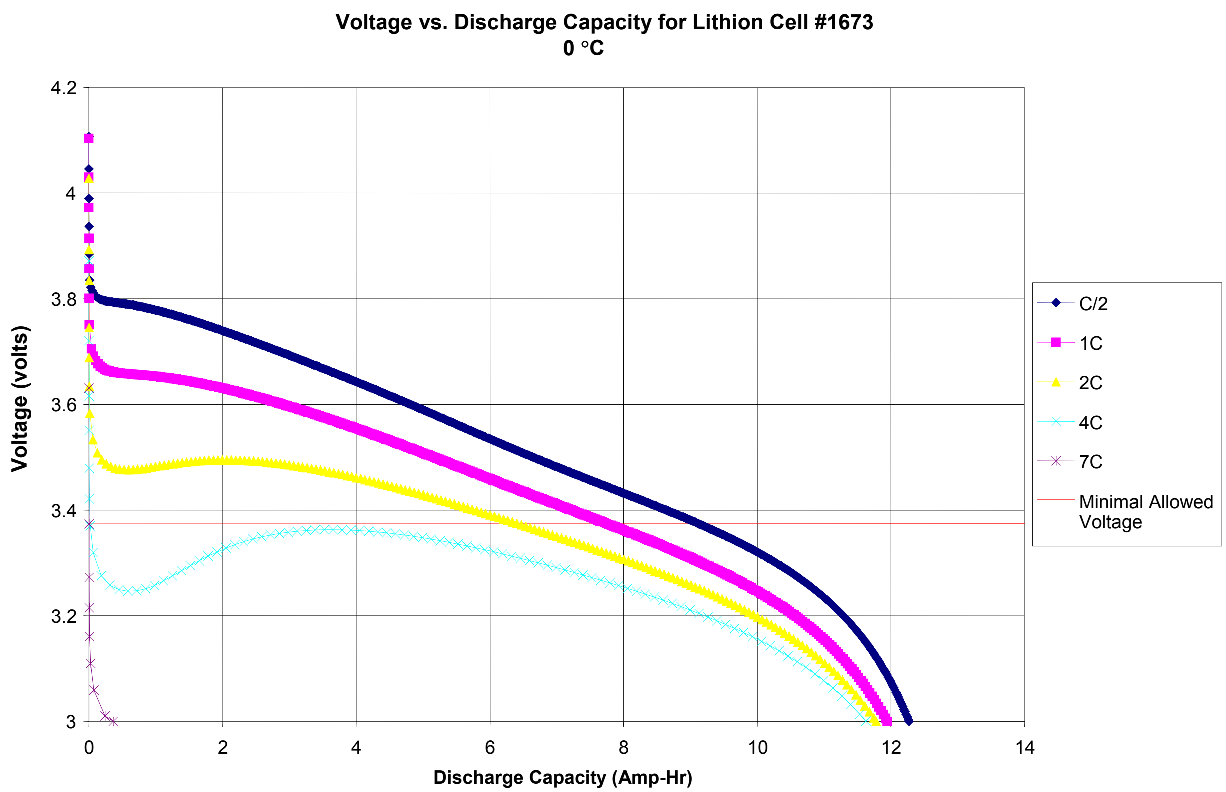

Figure 3.—Typical Lithion cell discharge voltage curve.

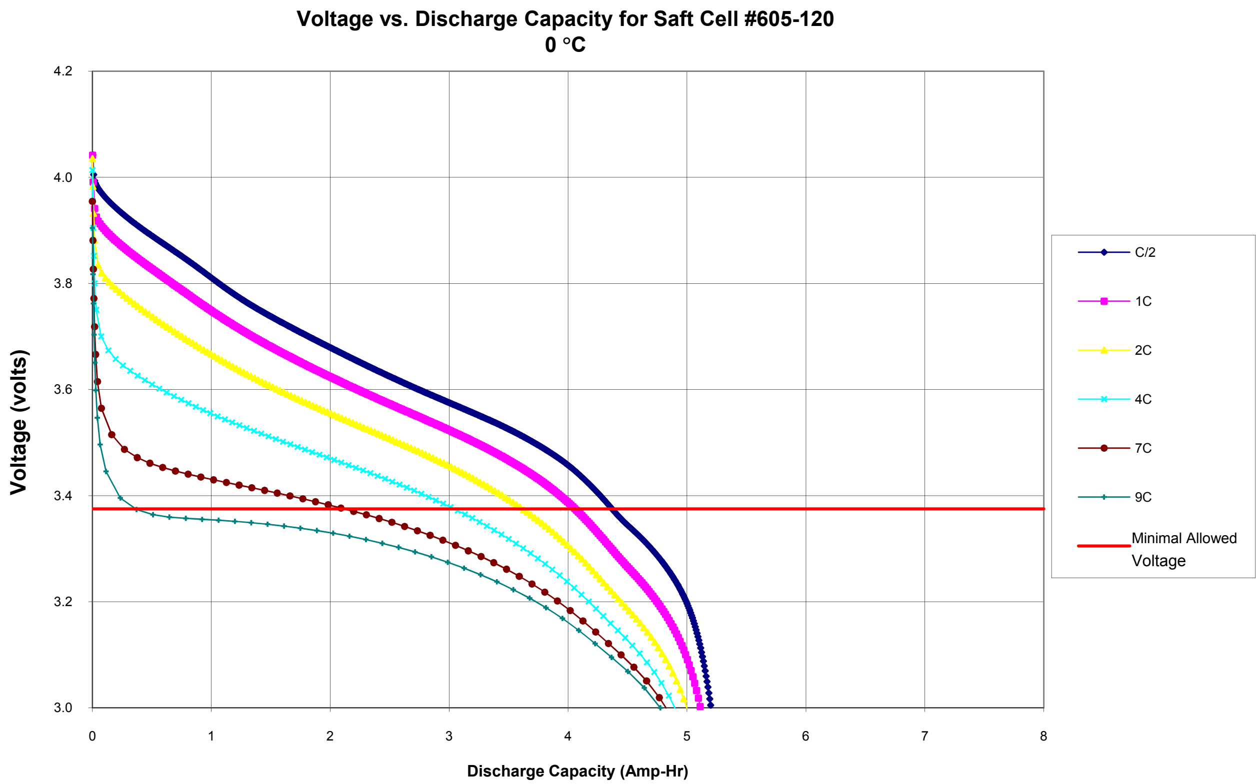

Figure 4.—Typical Saft cell discharge voltage curve.

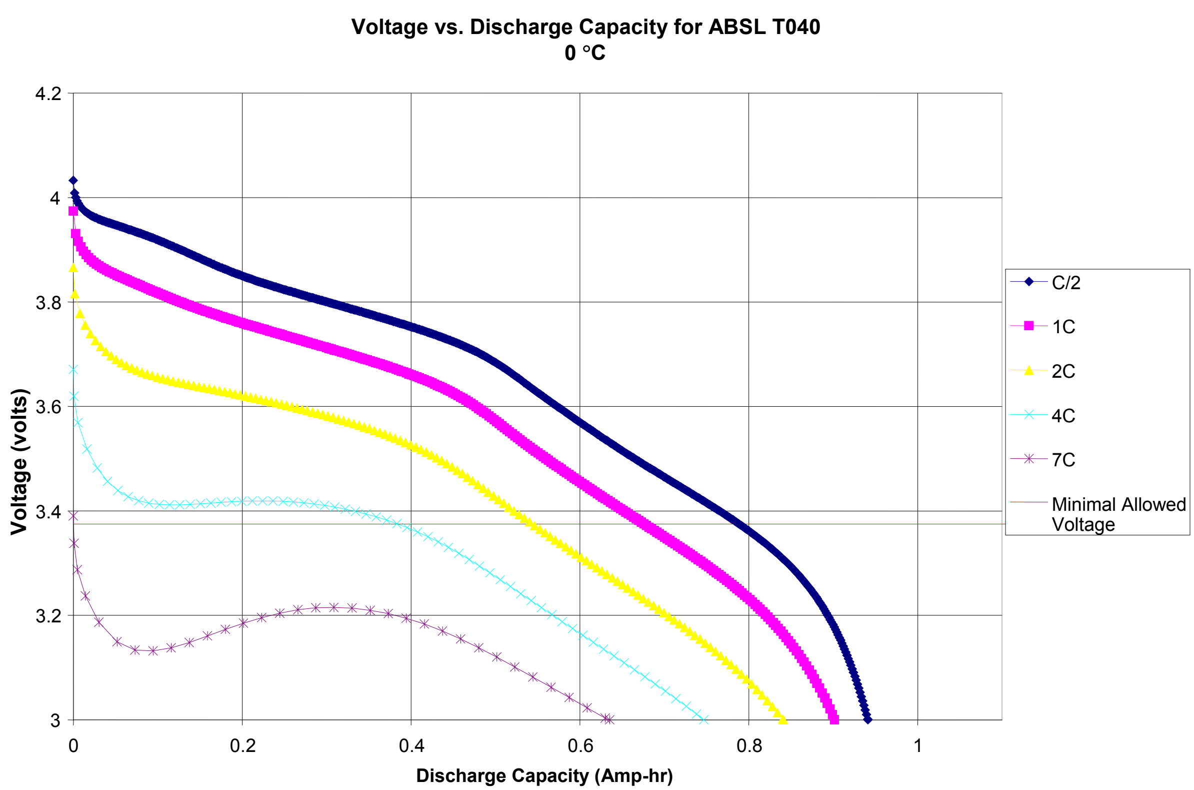

Figure 5.—Typical ABSL cell discharge voltage curve.

Useful Amp-hour Capacity Results

The useful capacity test results are summarized in Table 5. The rows of Table 5 are grouped according to cell type subdivided by temperature range. Each column in the table indicates a different discharge rate. The results include the average value and standard deviation of the tests that were obtained for the specified condition. The number of individual tests for the condition was also listed. Figures 3, 4, and 5 illustrate the same information previously described.

TABLE 5.—USEFUL CAPACITY MEASUREMENT RESULTS

	Tem (°C	Discharge Rate (A-									
		0.5 C	**1 C**	**2 C**	**3 C**	**4 C**	**5 C**	**7 C**	**8 C**	**9 C**	**10 C**
Saft	**0**	4.38	4.06	3.59	-	2.97	-	1.98	-	0.51	-
4.4 A-hr	STDEV	+/- 0.12	+/- 0.15	+/- 0.17		+/- 0.22		+/- 0.39		+/- 0.44	
	# Tests	12	12	12		12		12		8	
	2	5.66	5.55	5.38	5.51	4.81	5.33	-	5.13	-	-
	STDEV	+/- 0.27	+/- 0.30	+/- 0.28	+/- 0.07	+/- 0.00	+/- 0.10		+/- 0.18		
	# Tests	6	7	7	4	3	4		4		
	6	5.04	5.00	4.95	-	4.80	-	4.68	-	4.57	-
	STDEV	+/- 0.08	+/- 0.09	+/- 0.09		+/- 0.10		+/- 0.12		+/- 0.09	
	# Tests	12	9	12		12		7		12	
Lithion	**0**	9.04	7.69	6.36	-	0.01	-	0.00	-	-	-
12 A-hr	STDEV	+/- 0.04	+/- 0.04	+/- 0.04		+/- 0.00		+/- 0.00			
	# Tests	3	6	6		6		4			
	2	12.13	11.80	11.00	-	9.53	-	-	-	-	-
	STDEV	+/- 0.55	+/- 0.50	+/- 0.46		+/- 0.61					
	# Tests	12	18	18		18					
	4	12.60	12.47	11.86	-	10.77	-	-	-	-	-
	STDEV	+/- 0.21	+/- 0.07	+/- 0.04		+/- 0.08					
	# Tests	14	15	3		3					
	6	11.54	11.64	10.80	-	9.03	-	8.13	-	-	-
	STDEV	+/- 0.02	+/- 0.12	+/- 0.18		+/- 0.27		+/- 0.33			
	# Tests	2	4	6		6		4			
ABSL	**0**	0.79	0.67	0.53	-	0.33	-	0.00	-	-	-
1.08 A-hr	STDEV	+/- 0.00	+/- 0.00	+/- 0.01		+/- 0.03		+/- 0.00			
	# Tests	8	12	12		12		0			
	2	1.02	0.99	0.90	-	-	0.67	-	0.41	-	0.19
	STDEV	+/- 0.00	+/- 0.00	+/- 0.01			+/- 0.00		+/- 0.01		+/- 0.14
	# Tests	2	2	2			2		2		2
	6	0.96	0.93	0.89	-	0.77	-	0.64	-	-	0.47
	STDEV	+/- 0.01	+/- 0.01	+/- 0.00		+/- 0.01		+/- 0.01			+/- 0.03
	# Tests	12	12	12		4		8			4

Figure 6 addresses the Saft VL4V 4 Ahr cylindrical cell. The capacity at 20 °C and a C-rate discharge was 5.55 Ahr. The discharge capacity was relatively flat at 20 °C from the C-rate to the 8C discharge rate test condition. The minimum capacity was attained at the 8C discharge rate with a value of 5.13 Ahr. At 60 °C, the capacity at the C-rate was 5.00 Ahr, a reduction of 10 percent in capacity. There was a linear reduction in capacity with increasing discharge rate. At the 9C discharge rate, the average measured capacity was 4.57 Ahr. This equates to an 8.6 percent reduction in capacity compared to the C-rate at 60 °C and a 17.7 percent reduction compared to the 20 °C, C-rate condition. At 0 °C, the capacity at the C-rate was 4.06 Ahr, a reduction of 27 percent from the standard 20 °C, C-rate capacity. The 0 °C capacity characterization exhibited a marked decrease in capacity with the higher discharge rates. At the 9C-rate, the capacity was 0.51 Ahr which equates to 87.5 percent reduction in capacity compared to the 0 °C C-rate capacity and a 91 percent reduction from the 20 °C C-rate capacity.

Figure 7 focuses on the Lithion NCP12-2 prismatic lithium-ion cell. The capacity at 20 °C and a C-rate discharge was 11.8 Ahr. The discharge capacity indicates a moderate correlation with increasing discharge rate up to the 4C-rate. The cell design is not capable of supporting high rate discharge except at elevated temperatures. At 20 °C and the 4C-rate, the measured capacity was 9.53 Ahr, a reduction of 19.3 percent from the standard 20 °C C-rate capacity. At the 60 °C thermal environment, the capacity at the C-rate was 11.64 Ahr, a reduction of only 1.40 percent in capacity. At 60 °C and the 4C discharge rate, the capacity was 9.03 Ahr which is a 23.5 percent reduction when compared to the standard 20 °C C-rate capacity. The 0 °C capacity characterization for the C-rate was 7.69 Ahr or 35 percent of the standard 20 °C C-rate capacity. The 0 °C capacity for the 4C-rate was almost nonexistent at 0.01 Ahr.

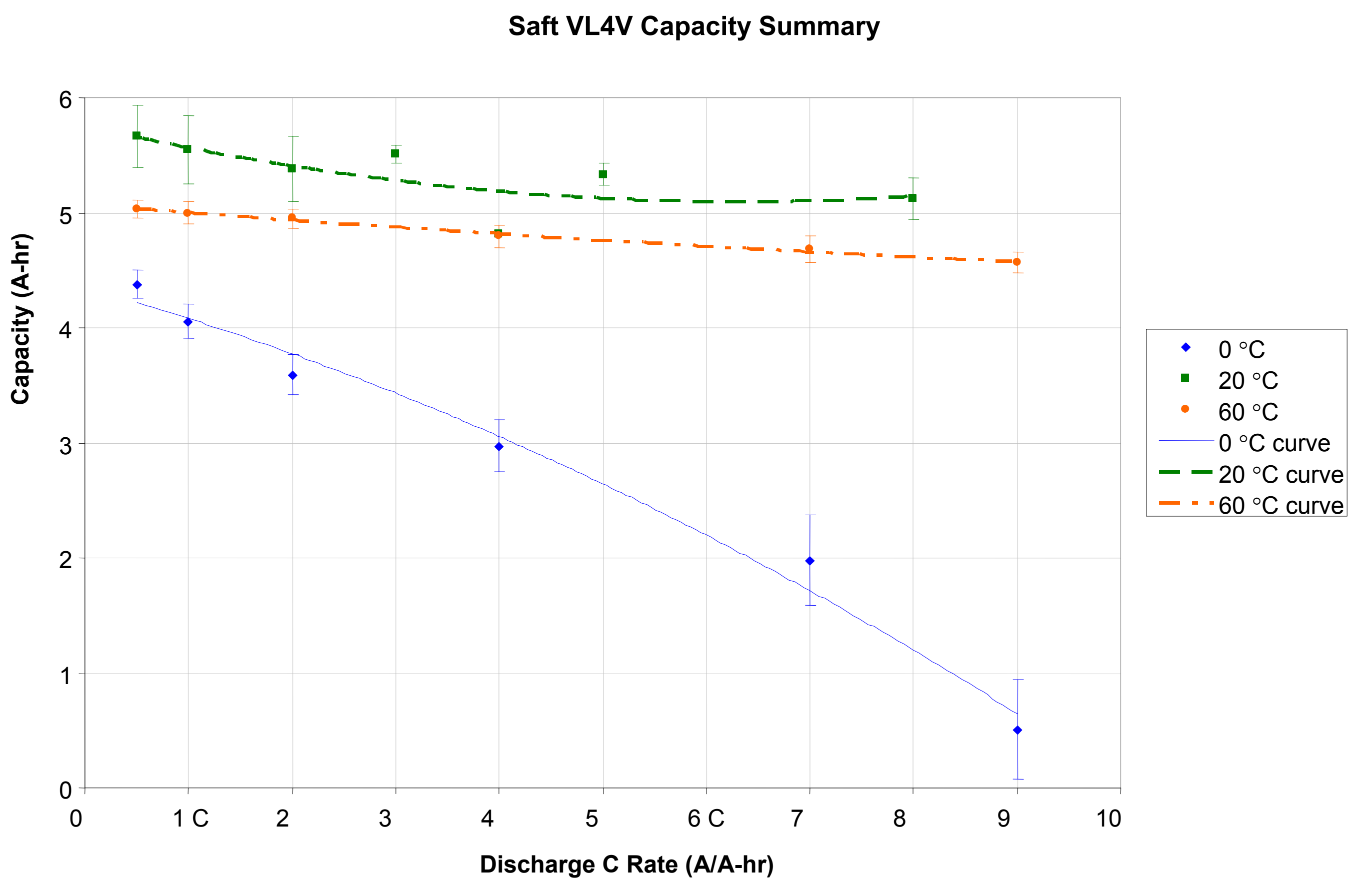

Figure 6.—Saft VL4V capacity.

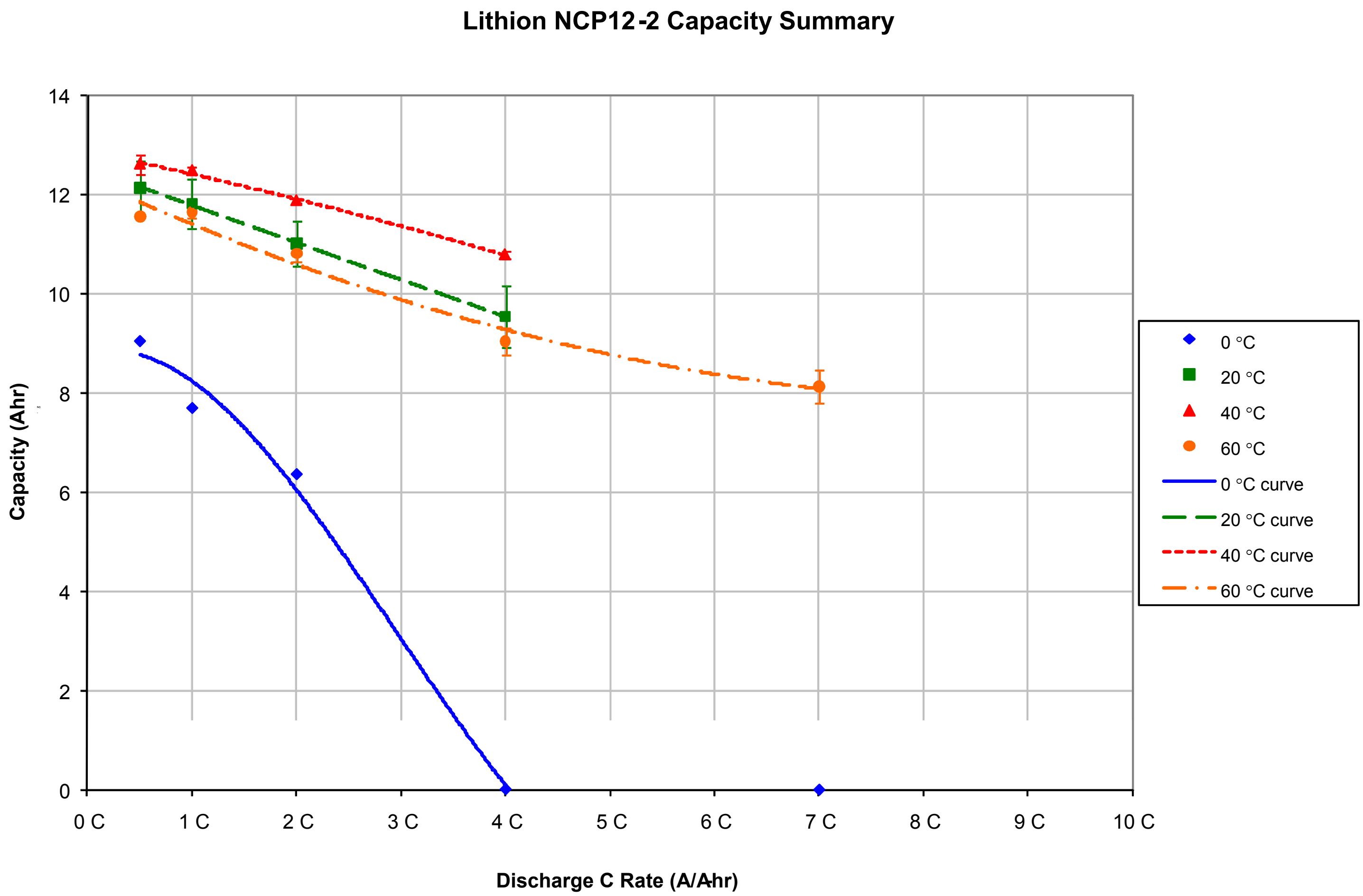

Figure 7.—Lithion NCP12-2 capacity.

Figure 8 captures the ABSL 18650HR 1.1 Ahr cylindrical cell. The capacity at 20 °C and a C-rate discharge was 0.99 Ahr. At the 10C-rate the capacity of 0.19 Ahr showed an 81 percent reduction in capacity from the standard 20 °C, C-rate capacity. At 60 °C and the C-rate, the measured capacity was 0.93 Ahr, a 6.1 percent capacity reduction. At 60 °C and the 10C-rate, the capacity was 0.47 Ahr which was 50 percent less than the C-rate capacity at 60 °C and 53 percent less than the standard 20 °C C-rate capacity. The 0 °C and a C-rate discharge was 0.67 Ahr. This is a 33 percent reduction in capacity from the standard capacity at 20 °C. At the 4C-rate the capacity was 0.33 Ahr or a 50 percent reduction in capacity from the 0 °C and C-rate capacity.

Some general trends are clear across all of the results. The first is that the effective capacity is reduced as the discharge rate increases. The Saft VL4V was the least sensitive to this effect, while the ABSL cell 18650HR is the most sensitive. The second general observation is that the effective capacity drops significantly at low temperature. Elevated temperatures had an effect on the cells, but they were less sensitive to it. The Saft VL4V had a reduced capacity at 60 °C. The Lithion NCP12-2 had an increased capacity at 40 °C and a slightly reduced capacity at 60 °C. The ABSL 18650HR transitioned from a slightly reduced to an increased capacity as the discharge rate increased at 60 °C.

Based upon the C-rate discharge at 20 to 25 °C, the Saft VL4V cell had a capacity of 5.55±0.3 Ahr and the Saft datasheet indicated a nominal 4.4 Ahr capacity. Therefore, the actual capacity of the Saft VL4V cell is considerably greater than the vendor's specified capacity. Lithion's NCP12-2 cell exhibited 11.8±0.5 Ahr versus the vendor's datasheet of 12.1 Ahr which is within experimental error. The ABSL 18650HR had a capacity of 0.99±0.00 Ahr while the ABSL datasheet indicated a capacity of 1.1 Ahr or a 10 percent reduction in useable capacity. These lithium-ion cell designs are appropriate for aerospace

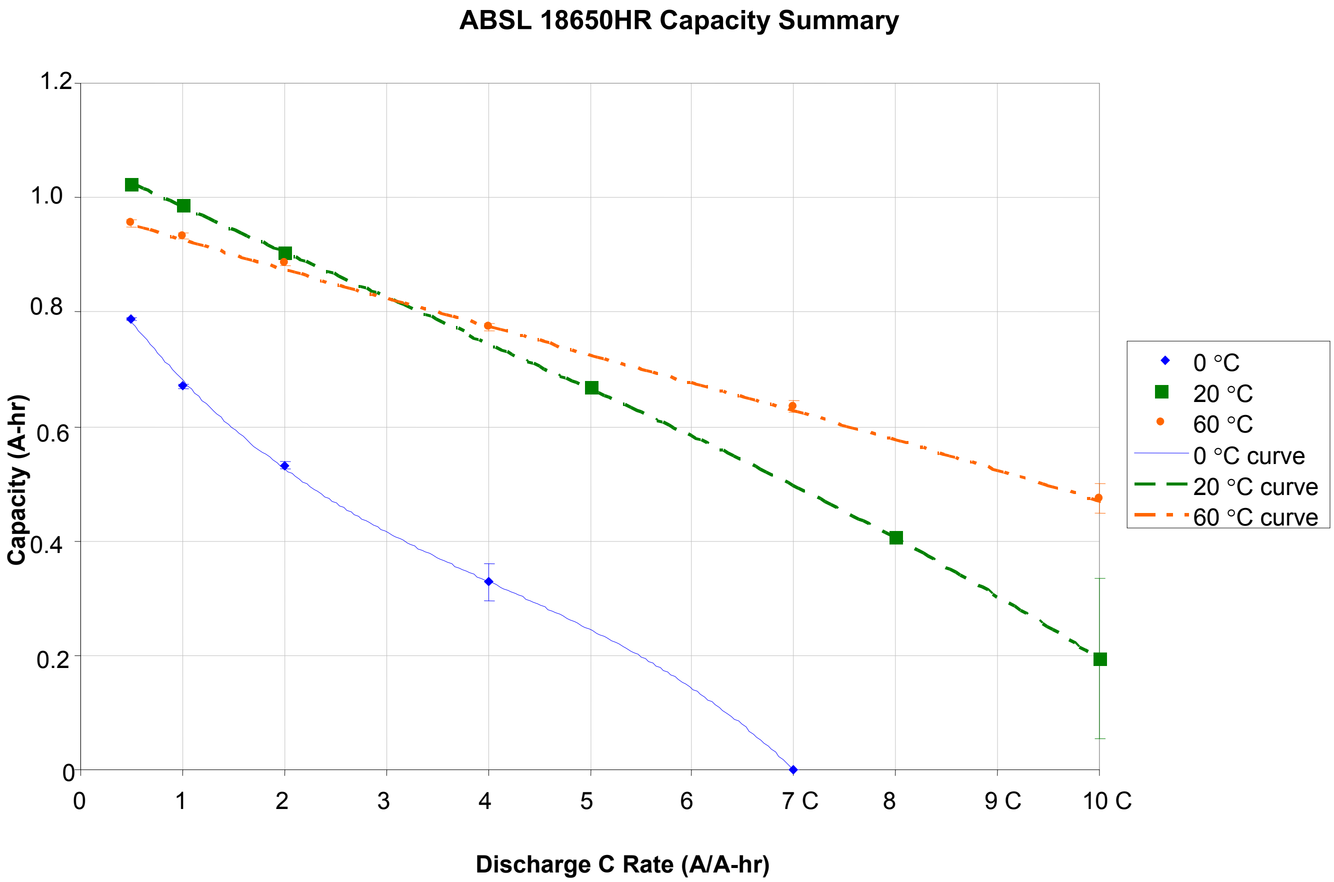

Figure 8.—ABSL 18650HR capacity.

applications, however the 0 °C temperature requirement for Ares I has a severe impact on the useful delivered capacity of the lithium-ion battery cell above the 3.375 voltage limit. The Saft VL4V cell was limited to the 4C discharge rate and delivered only 2.97$\pm$0.22 Ahr. This was a 53 percent reduction in useable capacity from the C-rate discharge at 20 °C conditions. The Lithion NCP12-2 was limited to the 2C discharge rate and delivered only 6.36$\pm$0.04 Ahr for a 54 percent reduction in capacity from the C-rate discharge at 20 °C conditions. The ABSL 18650HR cell was limited to the 2C discharge rate and delivered only 0.53$\pm$0.01 Ahr. Again this translates to a 53 percent reduction in useable capacity from the C-rate discharge at 20 °C conditions.

Conclusions

The three state-of-the-art lithium-ion cell designs evaluated exhibit satisfactory performance results for future Constellation missions. Specific cell designs need to be evaluated for missions on a more detailed basis to capture the intricacies of the mission and battery performance. The Saft VL4V showed the least sensitivity to discharge rate at temperatures above 20 °C. The Lithion NCP12-2 cell design had a strong dependence on temperature and discharge rate performance. Discharge rates were limited to the 4C for the 20 and 40 °C temperatures. Only at the 60 °C temperature was the cell capable of discharging at the 7C-rate. At the 0 °C temperature, the capacity significantly falls off with discharge rate with almost no capacity at the 4C rate. The ABSL 18650HR cell showed capacity performance somewhere between the Saft and Lithion cell designs. High discharge rates of up to 10C were achieved with a 60 to 80 percent reduction in delivered capacity.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The purpose of this document is to describe the acceptance and characterization testing of the Lithium-ion (Li-ion) battery cell candidates for the Ares I Crew Launch Vehicle (CLV) Upper Stage (US) Electrical Power System (EPS) Battery Unit (BU). The lithium-ion battery designed for the Ares I Upper Stage must operate in a harsh thermal environment and still provide the necessary ampere-hour capacity while delivering its discharge energy within the power quality guidelines outlined in the CxP-70050 document for 28 volts DC (VDC) power systems. The cells were evaluated to provide information to develop battery procurement specifications and to ensure the functional and safety margins were met for the human-rating guidelines. These tests were conducted at the NASA Glenn Research Center (GRC) in the Space Power Research Laboratory.

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