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Simplified Aid for Extra-Vehicular Activity Rescue (SAFER) Battery Assessment

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Acknowledgments

The NESC assessment team wishes to thank the JSC Energy Systems Test Area (ESTA) team (Mr. Oscar Huerta, Mr. Adan Garza, Mr. Tony Parish, Mr. Pete Sanchez, Mr. Pablo Salazar, and Mr. Dereck Lenoir) for their technical leadership, attention to detail, timeliness, and execution throughout the duration of the SAFER Battery Assessment.

The NESC assessment team also thanks Dr. Judith (Judy) Jeevarajan, Underwriters Laboratory, for her expert technical guidance early in the planning phase; Dr. Boyd C. Carter, The Aerospace Corporation, for his statistical analysis of the test cell acceptance test data; Ms. Amalia Aviles, The Boeing Company, for her detailed engineering support of the SAFER battery build and test activities; and Mr. James Russell, The Boeing Company, for providing samples of FiberFrax® Durafelt™ material.

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NASA Engineering and Safety Center Technical Assessment Report

Simplified Aid for Extra-Vehicular Activity Rescue (SAFER) Battery Assessment

March 30, 2017

Report Approval and Revision History

NOTE: This document was approved at the March 30, 2017, NRB. This document was submitted to the NESC Director on February 13, 2018, for configuration control.

Approved:	*Original Signature on File*	2/14/18
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Christopher J. Iannello, NASA Technical Fellow for Electrical Power	03/30/2017

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Technical Assessment Report

1.0 Notification and Authorization

Mr. J. Leggett, International Space Station (ISS) Chief Engineer, requested the NASA Engineering and Safety Center (NESC) conduct an assessment of the ISS Simplified Aid for Extra-Vehicular Activity Rescue (SAFER) Battery against post Boeing Company model 787-8 Dreamliner commercial aircraft lithium (Li) battery failures lessons learned. Specifically, this task was focused on assessing the severity of a cell-to-cell propagating thermal runaway (TR) event in the SAFER non-rechargeable Li battery power system.

An out-of-board initial summary for SAFER Battery Assessment was approved on July 24, 2014, by the NESC Review Board (NRB).

The key stakeholders for this assessment are the NESC, the Johnson Space Center (JSC) Power and Propulsion Division, the ISS Program, and the ISS Extra-Vehicular Activity (EVA) Office.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 2/15/18

Dr. Christopher J. Iannello	Date

Significant Contributors:

Dr. Thomas P. Barrera	Date	Ms. Concha Reid	Date
Dr. Dan Doughty	Date	Ms. Penni Dalton	Date
Mr. Sam Stuart	Date		

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
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Ms. Penni Dalton	Technical Co-Lead, Battery Specialist	GRC
Dr. Dan Doughty	Battery Specialist	Battery Safety Consulting, Inc.
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Ms. Pam Sparks	Project Coordinator	LaRC/AMA

3.1 Acknowledgements

The NESC assessment team wishes to thank the JSC Energy Systems Test Area (ESTA) team (Mr. Oscar Huerta, Mr. Adan Garza, Mr. Tony Parish, Mr. Pete Sanchez, Mr. Pablo Salazar, and Mr. Dereck Lenoir) for their technical leadership, attention to detail, timeliness, and execution throughout the duration of the SAFER Battery Assessment.

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4.0 Executive Summary

In 2013, the Boeing Company model 787-8 Dreamliner commercial aircraft experienced three catastrophic lithium (Li) battery failures [1−3]. The cause of each failure resulted in a single-cell thermal runaway (TR) condition, which propagated to adjacent battery cells. Two of the failures involved rechargeable lithium-ion (Li-Ion) batteries, and the third event involved a non-rechargeable lithium-manganese dioxide (Li-MnO_2) battery. In response to these Li battery failures, the NASA Engineering and Safety Center (NESC) approved a technical assessment of the International Space Station Simplified Aid for Extra-Vehicular Activity Rescue (SAFER) Li non-rechargeable battery. This assessment was conducted to evaluate the SAFER Li non-rechargeable battery safety design features against Boeing 787 Dreamliner Li battery failure lessons learned [4]. Specifically, this investigation focused on assessing the severity of a SAFER battery TR hazard conditions.

To meet the assessment objectives, external short and single-cell TR testing was performed under relevant worst-case environments utilizing flight hardware configurations. The investigation was completed by a team of NASA and industry battery subject matter experts. Test management, engineering, and technician expertise was provided by the Johnson Space Center Propulsion and Power Division, and Energy Systems Test Area organizations.

Observations and findings were developed based on test results and analysis obtained from this assessment. Observations and findings were used to formulate NESC recommendations consistent with NASA and industry Li battery requirements standards, guidelines, and lessons learned.

The entire list of findings, observations and recommendations can be found in Section 8 of this report. Key findings, observations and recommendations are summarized below.

The SAFER battery design propagated single-cell TR to neighboring cells throughout all cells on the same side of the centrally located circuit board as the trigger cell such that under ambient conditions, a single-cell TR in the 4S bundle side results in cell-to-cell TR propagation to all 12 cells in that bundle (i.e., Tests #1, #2, and #3) and a single-cell TR in the 10S bundle side results in cell-to-cell TR propagation to all 30 cells in that bundle (Test #4). The NESC team concluded that SAFER battery capacity gauge board cavity provides sufficient spacing of approximately 3.5 inches between the 4S-cell and 10S-cell bundles to prevent propagation of TR to the opposite side of battery pack. The NESC team recommends the Extra-Vehicular Activity (EVA) Program Office move to redesign this battery using the latest lessons learned in other EVA battery redesigns at its earliest convenience.

In addition to the test-result-based findings, the team reviewed SAFER battery documentation. In the SAFER battery hazard report the NESC team found no explicit mention of single-cell TR and propagation. The team recommends the report be revised to include this hazard explicitly. Also, the team found SAFER flight battery build procedures do not include a process step for cell matching and selection and recommends this be included.

In addition, the NESC team acknowledges the variability in trigger methods even for small cell for factors and recommends the technical community undertake a study to develop a standard test method for initiating TR.

And finally, the NESC team recommends the EVA Program assess the impact of the test result (i.e. partial single-cell TR propagation) to the operation of the SAFER pack and the EVA crew member as that work is considered out of scope for this assessment.

5.0 Assessment Plan

5.1 Background

In January 2013, two separate Li-Ion rechargeable battery failures occurred on The Boeing Company 787-8 (B-787) Dreamliner commercial passenger aircraft. The first (i.e., Japan Airlines B-787; JA829J) and second (i.e., All Nippon Airways B-787; JA804A) battery failures originated in the aircraft auxiliary power unit and main Li-Ion batteries, respectively. The subsequent root cause investigations concluded that both B-787 Li-Ion battery incidents were initiated by single-cell TR events, which propagated to adjacent battery cells [1,2]. The severity of the resulting propagating cell-to-cell TR events was catastrophic to the B-787 battery function and operation.

In July 2013, a third Li battery failure occurred on an unoccupied B-787-8 Dreamliner aircraft (i.e., Ethiopian Airlines B-787; Stand 326) while parked on the ground at London-Heathrow airport [3]. The incident was caused by a non-rechargeable Li-MnO_2 battery, which served as the primary power source for the aircraft Emergency Locator Transmitter (ELT) radio location device. The resulting incident investigation concluded the failure of the ELT non-rechargeable Li-MnO_2 battery, "…*most likely resulted from an external short-circuit, in combination with the early depletion of a single cell, leading to thermal runaway which propagated to adjacent cells*" [3].

Commercial off-the-shelf (COTS) non-rechargeable Li-MnO_2 cells are commonly used in various aeronautics, military, and consumer electronics applications. Specifically, it was noted the B-787 ELT battery (UltraLife™ U10013) and ISS SAFER battery (Duracell® Ultra® CR123) utilize similar Li-MnO_2 battery technologies. Table 5.0-1 compares selected characteristics of these Li-MnO_2 cell technologies.

Table 5.0-1. Selected ISS SAFER (Duracell® Ultra® CR123) and B-787 ELT (Ultralife™ U10013) Li-MnO_2 Battery Cell Characteristics.

Cell Characteristic	Duracell® Ultra® CR123	Ultralife™ U10013
Electrical		
Chemistry	Cathode: MnO_2 Anode: Li	Cathode: MnO_2 Anode: Li
Li Content (g)	0.55	3.4
Nominal Operating Voltage (V)	3.00	3.00
Capacity (ampere hour (Ah))	1.50 [1]	11.1 [2]
Thermal		
Nominal Operating Range (°C)	−20 to +75	−40 to +72
Mechanical		
Weight (g)	17	115
Geometry	Cylindrical	Cylindrical
Common Name (Size)	2/3A	D
Safety		
Internal Positive Temperature Coefficient (PTC) Device	Yes	No
External Vent	Yes	Yes

Notes:
1. C/30 discharge at room temperature to 1.55 V.
2. 250 mAh discharge to 2.0 V at 23 °C.

5.2 Objectives

As a result of these aeronautics industry Li battery failure incidents, the NESC initiated safety assessments of the various ISS Extravehicular Mobility Unit (EMU) Li battery power sources. Specifically, the NESC was requested to assess the SAFER battery. The assessment included tasks which characterized the safety of the SAFER battery design against the B-787 Dreamliner Li battery failure standards and lessons learned [4].

The assessment objectives were:

1. Extend the existing SAFER Li battery test database by performing updated safety tests representative of industry experience with similar Li battery power systems.
2. Conduct credible worst-case SAFER Li battery safety tests designed to quantify the severity of a TR condition that may result in cell-to-cell propagation.
3. Develop technical recommendations based on the test results.

5.3 Test Approach

The test approach was to conduct characterization testing broadly defined as any testing whose objectives are to further quantify certain performance or safety characteristics. Characterization testing was not conducted for the purposes of flight article qualification or certification. Figure 5.3-1 shows the general test sequence flow diagram. Initial single cell-level characterization (Phase I) included a tailored cell acceptance test program per ISS requirements [5]. Phase II testing was conducted at the bundle level of cell integration. Test battery bundles were configured in either a 4-cell (i.e., 4 cells connected electrically in series, 4S) or 10-cell (i.e., 10 cells connected electrically in series, or 10S) architecture with, or without, PTC devices and/or Schottky diodes. Finally, Phase III testing was conducted at the SAFER battery-level (i.e., three 14-cell bundles electrically connected in parallel). Battery-level test article configuration and test environments were developed based on ISS SAFER flight configurations and environments.

5.3.1 External Short Testing

The objective of this test series was to evaluate if an external short condition would create a TR hazard in the SAFER battery. Specifically, the ability of the external PTC device to protect the SAFER battery, under selected external short conditions was evaluated. Due to the availability of similar Duracell® Ultra® CR123 single-cell external short test data, testing at the single-cell external short testing was not performed. However, 4S- and 10S-cell bundle testing in various electrical and mechanical configurations was conducted.

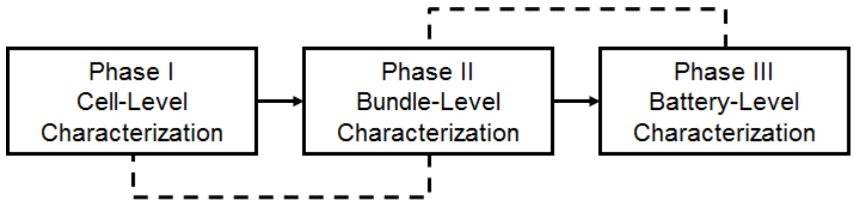
5.3.2 Single-Cell Heater Trigger TR Testing

The objective of this testing was to characterize the COTS Duracell® Ultra® CR123 SAFER battery cell under various heater trigger test conditions. This testing enabled optimization of heater power, location, and type for the development of test procedures in support of the subsequent SAFER battery TR test phase.

5.3.3 Battery TR Testing

The objective of this testing was to quantify severity and evaluate the extent of cell-to-cell propagation of TR failure in a single cell. The test approach was to conduct a series of single-cell heater trigger tests to determine the voltage, current, and temperature characteristics of a single-cell TR event. Trial test runs were conducted to optimize the thermocouple placement, heater location (i.e., side or bottom), and heater power. The results of the single-cell heater trigger tests were used to support the subsequent SAFER battery TR test phase.

Test management, engineering, administration, and support personnel, and general safety operations, test facilities, and other resources were supplied by the JSC ESTA.



Note: Dotted lines represent test opportunities to repeat certain tests if required.

Figure 5.3-1. Generalized Test Flow Diagram for SAFER Battery Characterization Testing

5.4 Assessment Plan

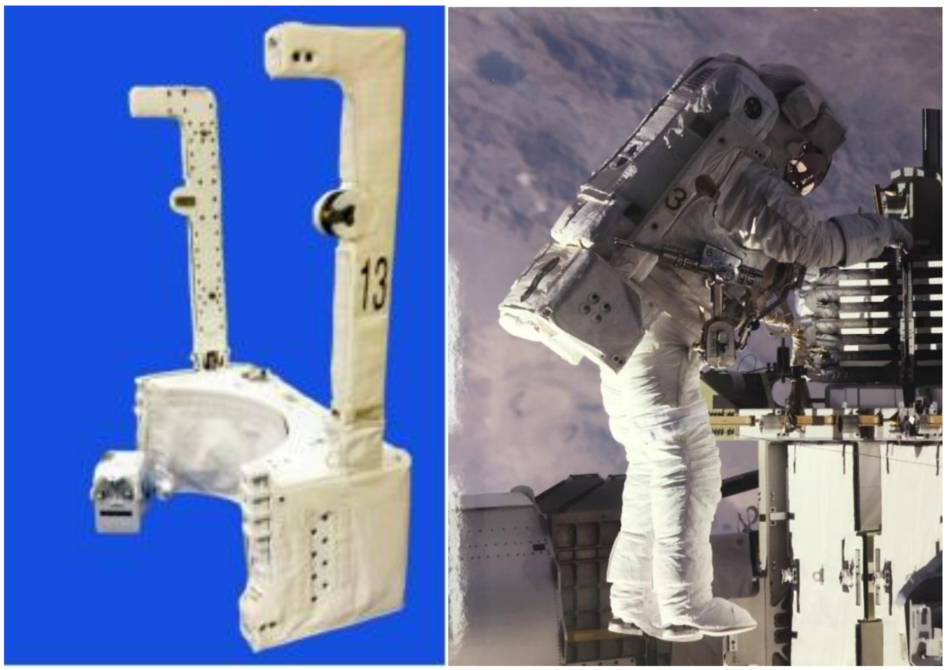
Key elements of the assessment plan and approach were:

1. *NESC Assessment Team*: Organized an assessment team chosen from the NESC Electrical Power Technical Discipline Team (TDT). Team members had no direct technical, cost, or schedule responsibility for the SAFER battery product under review.
2. *Integrated Concurrent Engineering and Technical Assessment*: Implemented a concurrent engineering approach for all aspects of the project. As such, the NESC assessment team was fully integrated with JSC ESTA personnel. In addition, the team worked concurrently with the SAFER subject matter experts in the ISS EVA and Safety & Mission Assurance Offices.
3. *Heritage SAFER Battery Data*: Utilized existing data and analysis archived in support of the heritage SAFER battery program. These data included, but were not limited to: product specifications, interface control documents, test plans and procedures, drawings, raw data, engineering reports, analysis, and other supporting engineering information.
4. *Test Plans, Procedures, and Data Management*: General test requirements were developed and documented in test plans, which were updated as required. Test procedures were developed from test plans for implementation throughout each test phase. Test data including time series data, images, and videos were archived on the NASA Safety Center Knowledge Now (NSCKN) data management tool under the SAFER battery Community of Practice (CoP).
5. *Test As You Fly Philosophy*: Employed engineering ground test articles, which were the best possible form, fit, and function of flight ISS SAFER cell and battery products. Utilized flight test specifications and procedures as required. Flight-like environments were analyzed and integrated into the test procedures and facilities.
6. *Industry Lessons Learned*: Incorporated industry lessons learned and knowledge gained from NASA Li-Ion cell and battery heater TR trigger testing activities [6−9]. A special emphasis on heater trigger testing protocols was emphasized.

6.0 System Description and Technical Risk Considerations

6.1 SAFER System Description

First flown in 1994 on Space Transportation System (STS)-64, the ISS SAFER is a self-contained, 24-jet free flyer that provides adequate propellant and control capability to allow an EVA crewmember separated from the ISS to perform a self-rescue back to the station (Figure 6.1-1). The integrated SAFER is worn when a United State of America (USA) astronaut conducts an EVA.



a) ***b)***

Figure 6.1-1. a) ISS SAFER System Unit and b) USA Astronaut on EVA with SAFER Attached to EMU

The SAFER consists of main unit, tower latches, hinges, avionics unit, and three hardware modules: propulsion, hand controller module (HCM), and intra-vehicular activity (IVA) replaceable battery pack [10]. The SAFER fits around the EMU primary life support system (PLSS) without limiting suit mobility (Figure 6.1-2). Control is provided through crewmember inputs from a single HCM. The HCM is stowed in a cavity on the right side of the SAFER propulsion module when not in use, and activated when needed. To deploy the HCM, the crewmember pulls up on a deployment handle mounted on the front, right side of the propulsion module. The crewmember then grabs the HCM from the tray, holds the module in his left hand, and turns on the power switch. This switch fires a pyrotechnic device that pressurizes the propulsion system. The HCM can then be used to perform self-rescue.

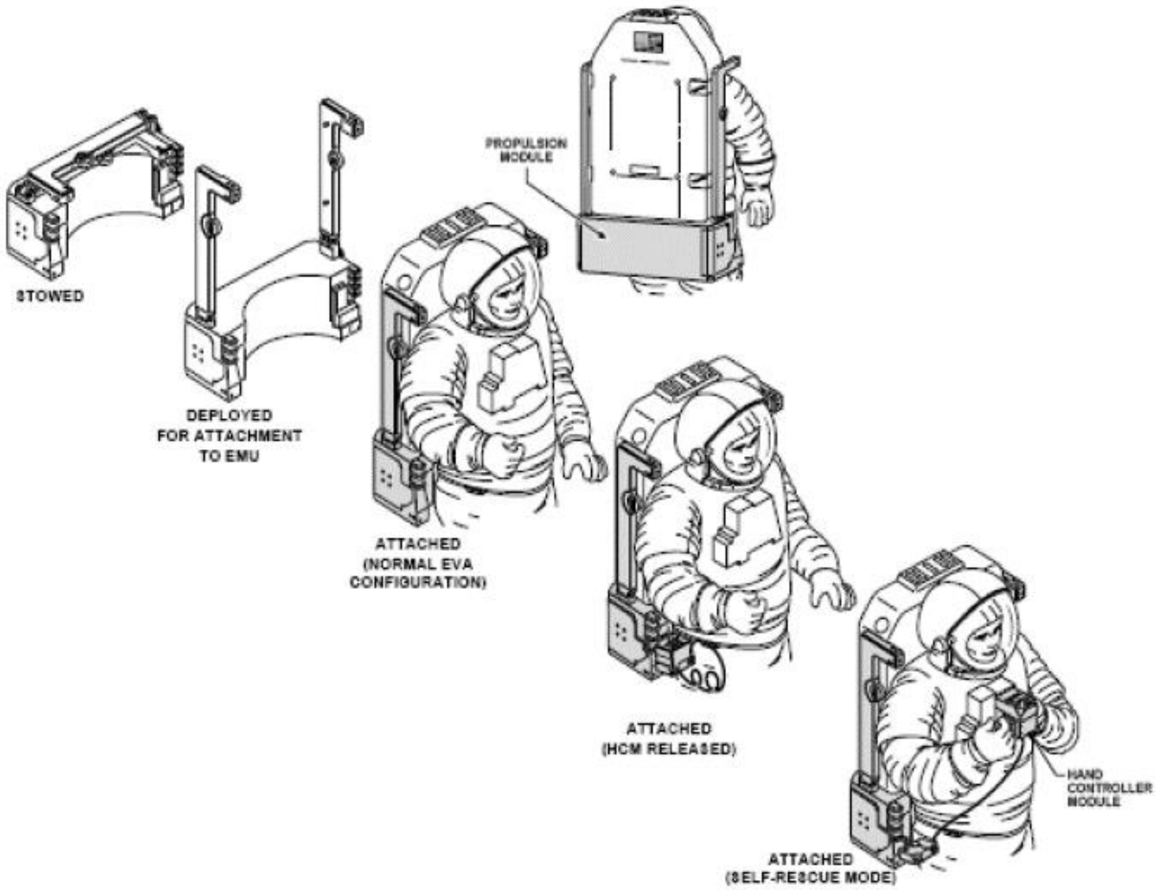


Figure 6.1-2. ISS SAFER System Overview

The SAFER battery assembly is launched unattached and soft stowed in foam with the SAFER (Figure 6.1-3). The battery assembly is installed on-orbit to the main unit, underneath the propulsion module, with eight captive fasteners. The assembly is designed to be replaceable during ground or on-orbit IVA servicing. The assembly connects to a SAFER with one cable/electrical. Once on-orbit, the assembly is stored in an ISS pressurized area.

Note: SAFER battery assemblies may be stored in the ISS airlock or other pressurized locations.

Figure 6.1-3. On-orbit SAFER Battery Assemblies in their Stowage Bags

6.2 SAFER – Battery Description

The SAFER receives primary electrical power from the battery assembly. The assembly is composed of a gauge board, an electrical cable, and 42 non-rechargeable Li cells. These cells are the COTS Duracell® Ultra® CR123 Li-MnO_2 design used in various commercial high-power electronic devices. Table 6.2-1 summarizes the general mechanical, electrical, thermal, and safety characteristics of the Duracell® Ultra® CR123 cell design [11,12].

The batteries provide capacity for the avionics subsystem to perform 52 1-minute on-orbit IVA checks, and one EVA self-rescue of 13-minute (minimum) duration, within an operating voltage range of 19 to 42 V. To meet these SAFER system voltage and capacity mission requirements, the battery cells are electrically connected into a series-parallel (s-p) battery topology. First, the SAFER battery contains individual 4- and 10-cell “bundles” with their cells connected electrically in series (Figure 6.2-1). Cells are connected by nickel tabs spot-welded to the cell terminals. Each cell bundle contains a SRP-200F resettable PTC thermal fuse and a dedicated Schottky diode. Individual 4S- and 10S-cell bundles are connected electrically in series to form a 14-cell series string [13]. Finally, three 14-cell series strings are electrically connected in parallel to form a 14s-3p battery architecture.

Table 6.2-1. Selected Design, Electrical, and Safety Performance Characteristics of the Duracell® Ultra® CR123 Cell Design

Cell Characteristic	Duracell® Ultra® CR123
Electrical	
Chemistry	Cathode: MnO_2 Anode: Li
Li Content (g)	0.55
Nominal Operating Voltage (V)	3.00
Nominal Internal Impedance (ohm @1kHz)	0.25
Capacity (C/30 mAh discharge at room temperature to 1.55 V)	1500
Thermal	
Nominal Operating Range (°C)	−20 to +75
Mechanical	
Terminal Design	Flat, Recessed Negative Terminal, Nickel Plated Steel
Dimension (height × depth, mm)	34.5 × 17.0 (with terminal)
Average Weight (g)	17
Safety	
Internal PTC Device	Yes
External Vent	Yes

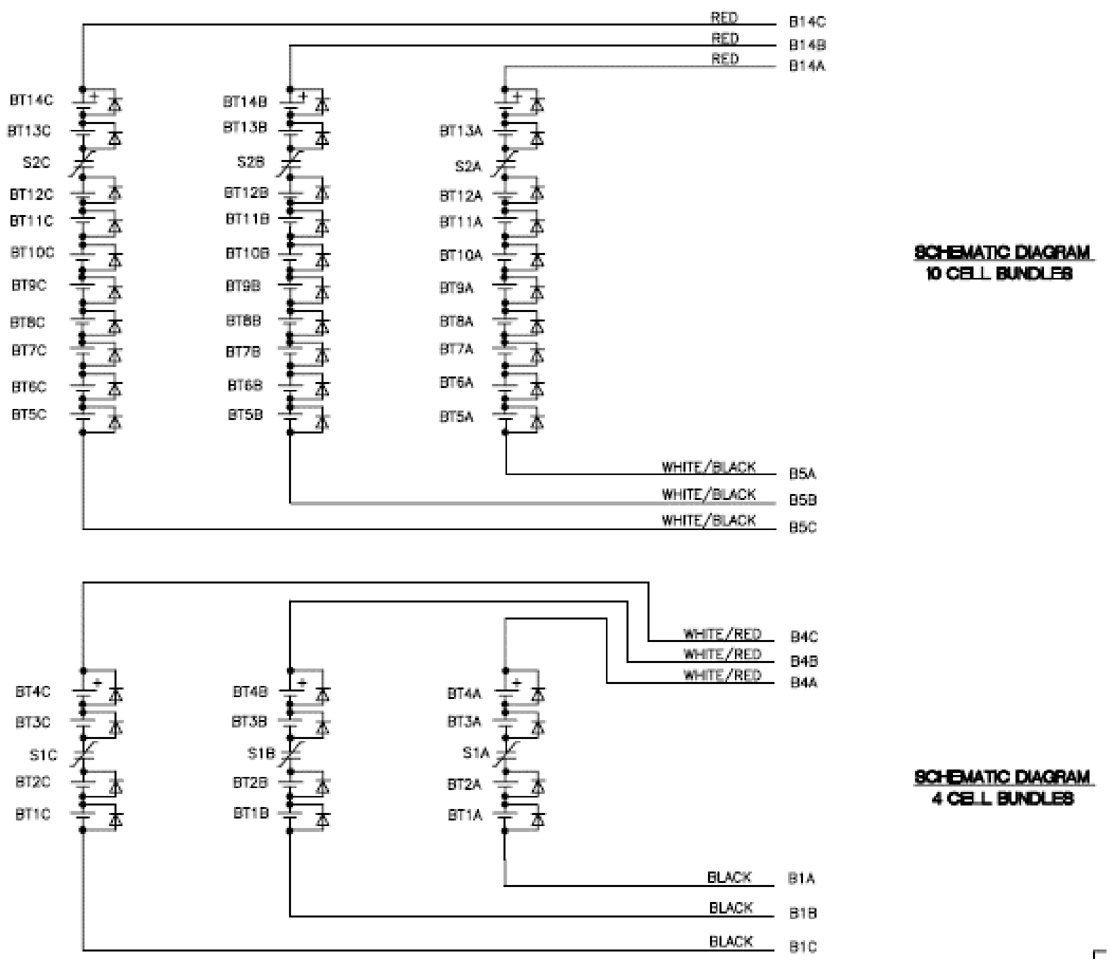


Figure 6.2-1. Electrical Schematic of 4- and 10-cell Bundles [13]

Battery cell bundles and gauge board are packaged in an aluminum metal case lined with foam. The aluminum metal case consists of a 6061-T6 cover and a 7075-T7351 lower housing. The cover and housing are coated with white A276 Chemglaze® paint. Stainless steel fasteners and inserts are used to assemble and close the case. The cell bundles are cushioned in the case with polyimide foam faced with Kapton® tape. A Vespel® SP-1 circuit board cover and a cellulose acetate butyrate insert are used to secure the gauge board in the case.

The battery gauge board is a printed wiring board assembly based on a Microchip Technology Inc. MTA11200B chip. The MTA chip with integrated circuit (IC) calculates battery voltage, temperature, and remaining battery capacity. The battery capacity gauge IC is continuously powered to measure battery capacity during storage, and when connected to the SAFER. An integrated harness cable assembly utilizes an RS232 communication link to communicate with the SAFER avionics subsystem.

The SAFER battery assembly is an orbital replacement unit (ORU) with a 3.5-year service life. Selected electrical, thermal, and mechanical characteristics of the SAFER battery are provided in Table 6.2-2. Figures 6.2-2 and 6.2-3 show the SAFER battery assembly components and a flight assembly, respectively.

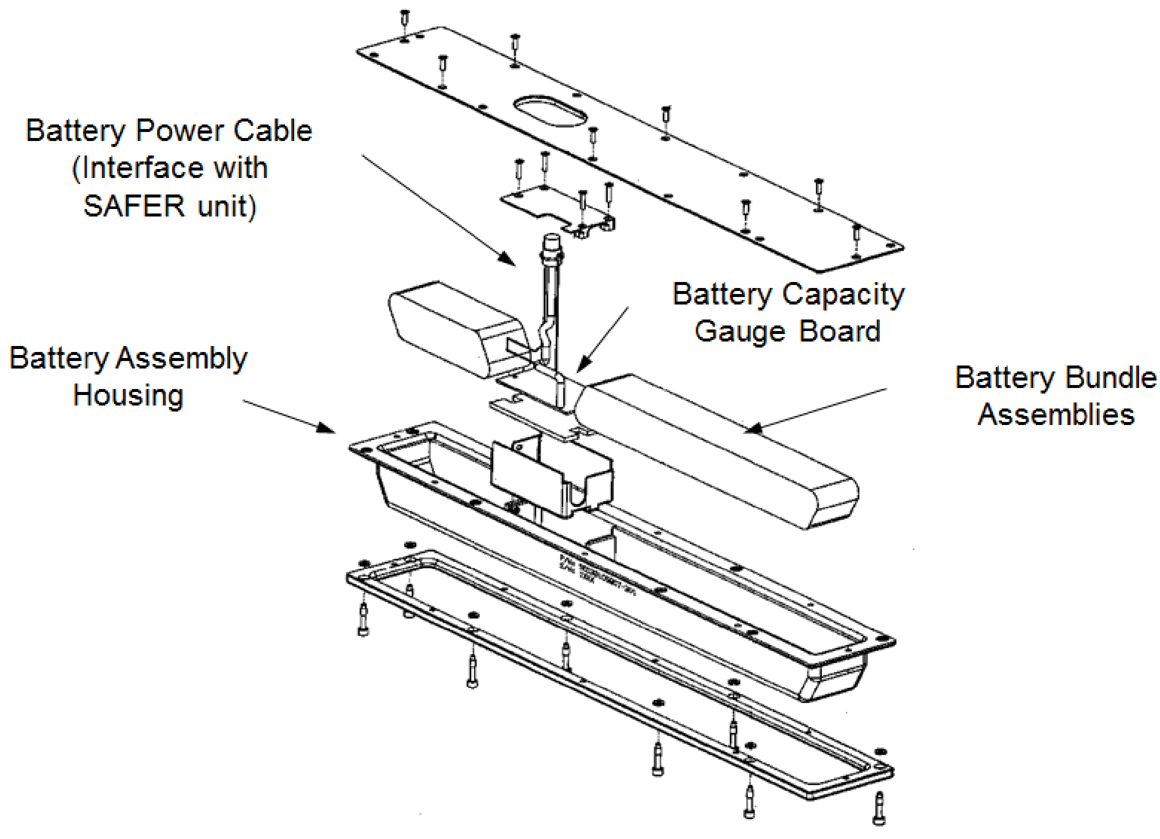


Figure 6.2-2. SAFER Battery Assembly Components

Figure 6.2-3. SAFER Flight Assembly

Table 6.2-2. Selected Electrical, Thermal, and Mechanical Characteristics of the SAFER Battery (p/n SED33105907-31).

SAFER Battery Characteristic	Description
Electrical	
Cell	Duracell® Ultra® CR123
Cell Type	Non-rechargeable Li
Cell Chemistry	Li-MnO_2
Nominal Operating Voltage (V)	40
Operating Voltage Range (V)	36 ± 8
Nominal Capacity (Ah)	3.75
Useful Life (years)	3.5 ORU
Thermal	
Nominal Operating Range (°C)	−20 to +75
Mechanical	
Dimension (length × width × height, cm)	50.50 × 7.62 × 4.98
Weight (kg)	1.99

6.3 Technical Risk Considerations

Non-rechargeable and rechargeable cell TR is generally defined as a phenomenon which occurs when the battery cell rate of heat generation exceeds the rate of heat rejection, causing a rise in the cell temperature. As the cell temperature increases, the rates of reaction for exothermic chemical processes in the liquid and gas phases increases at a rapid rate. The cell internal pressure will simultaneously increase with temperature and other material decomposition processes. The next most common events include venting, electrolyte leakage, ignition of gas-phase flammable gases, smoke, fire, and/or ejecta. Specifically, for the Duracell® Ultra® CR123 heritage flight non-rechargeable cell design, thermal degradation resulting in TR, may produce hazardous fumes of Li and manganese, hydrofluoric acid, Li oxides, carbon, sulfur, and other toxic products [14]. Depending on the cell geometry and other TR characteristics, the cell contents (*e.g.*, electrodes and windings) may be ejected in an uncontrollable and catastrophic manner.

The phenomena of non-rechargeable Li battery TR hazards were first documented in the 1970s and 80s with the increase of commercial and aerospace industry needs for high gravimetric and volumetric energy density energy storage systems. The causes of non-rechargeable Li battery thermal abuse events have been documented to include those identified in the SAFER battery hazard report [15]. In this work, however it was found that the SAFER battery hazard report had not identified TR propagation as a hazardous condition.

Thermal analysis and testing to determine Li battery TR risk is currently required for all NASA manned space programs [16]. In some cases, these requirements include verifying that a single-cell TR event will not cause a TR battery-level cell-to-cell propagation condition. Determining the risk of Li battery TR propagation may be assessed by considering the likelihood and consequences of the TR event, where:

$$Risk \propto [Likelihood \times Consequences].$$

Traditionally, the likelihood of occurrence of a TR event has been mitigated by implementing cell-level design safety features such as vents and PTC devices. To further mitigate the likelihood of a TR event, improvements in cell manufacturing quality processes and implementation of perceptive cell screening acceptance test methods (such as self-discharge and soft-short test protocols) have been employed. Non-destructive cell screening methods such as X-ray and computerized tomography-scanning are also commonly used to reduce the risk of TR events resulting from energetic internal cell faults.

The severity of a TR event is highest when a single-cell TR event cascades to adjacent cells or battery components resulting in an uncontrollable catastrophic hazard. This type of propagating TR event is likely to result in catastrophic battery failure with the possibility of collateral system-level impacts.

7.0 Data Analysis

7.1 Cell Procurement

Test cell procurement was completed by the JSC Propulsion and Power Division. In support of the forecasted scope of testing, approximately 894 COTS button-top Duracell® Ultra® CR123 Li/MnO_2 non-rechargeable cells were procured [17]. This bulk cell procurement was intended to exceed the total cell need, plus spares, for the planned testing. The Duracell® Ultra® CR123 Product Safety Data Sheet is shown in Appendix A.

7.1.1 Cell Lot Acceptance Testing

All cells were pre-acceptance tested (i.e. screened) prior to full acceptance testing. Cell-level acceptance testing characterized the baseline Duracell® Ultra® CR123 cell performance. The pre-acceptance and full-acceptance testing scope was tailored from the ISS flight SAFER battery acceptance procedure and lot certification test plan [5]. Tailoring rationale was based on establishing a minimum set of critical pre-screening and acceptance tests required to meet the assessment test objectives. Table 7.1-1 lists the cell pre-acceptance and full-acceptance testing performed. Open circuit voltage (OCV), alternating current (AC) impedance, and closed circuit voltage (CCV) testing was performed at ambient temperature and pressure conditions [5]. Cell identification and physical characteristics were recorded per flight procedures [18]. Cell abnormalities observed during visual inspection were documented with digital photography or other methods. Cells which pass acceptance testing were candidates for further testing and analysis.

Raw data collected from cell acceptance testing is shown in Appendix B. Visual inspection indicated that approximately 97 cells or 10.9% were found to have various physical defects (e.g., positive side indentations or external damage to the cell sleeves). Cell defect images were reviewed to determine if any cell warranted rejection.

CCV testing was performed to measure the amount of voltage drop under constant-current load conditions. The CCV performance test is considered superior to an OCV measurement for the purposes of determining cell beginning-of-life performance. Results from a representative CCV test is shown in Figure 7.1-1. Each cell was discharged at 0.500 ± 0.005A for 10 seconds using a four-wire measuring circuit. A 30-second OCV period proceeded each CCV load test.

Table 7.1-1. Pre-acceptance and Full-Acceptance Tests Conducted on Duracell® Ultra® CR123 Cells

Test	Description	Pass/Fail
Visual Inspection	Perform a visual inspection on the test articles and record any observations of electrolyte leakage, corrosion, bulges, dents, shrink-wrap sleeve integrity, and/or deformations.	Damage which is deemed more than superficial from a mechanical or electrical insulating standpoint
Length (mm)	Measure and record the length, to 0.1 mm, of each test cell.	avg.± 3σ
Diameter (mm)	Measure and record the length, to 0.1 mm, of each test cell.	avg. ± 3σ
Mass (g)	Measure and record the mass, to 0.01 g, of each test cell.	avg. ± 3σ
OCV (V)	Measure and record OCV of each cell at room temperature.	3.200 ± 0.050
AC Impedance (ohm)	Measure and record AC impedance at 1 kHz and room temperature.	avg. + 3σ
CCV (V)	Load test each cell at 0.500 ± 0.005A (ampere) constant current, and then measure cell voltage at the end of a 10-second discharge period.	2.890 (minimum)

Note: Pass/fail criteria are for SAFER flight cells.

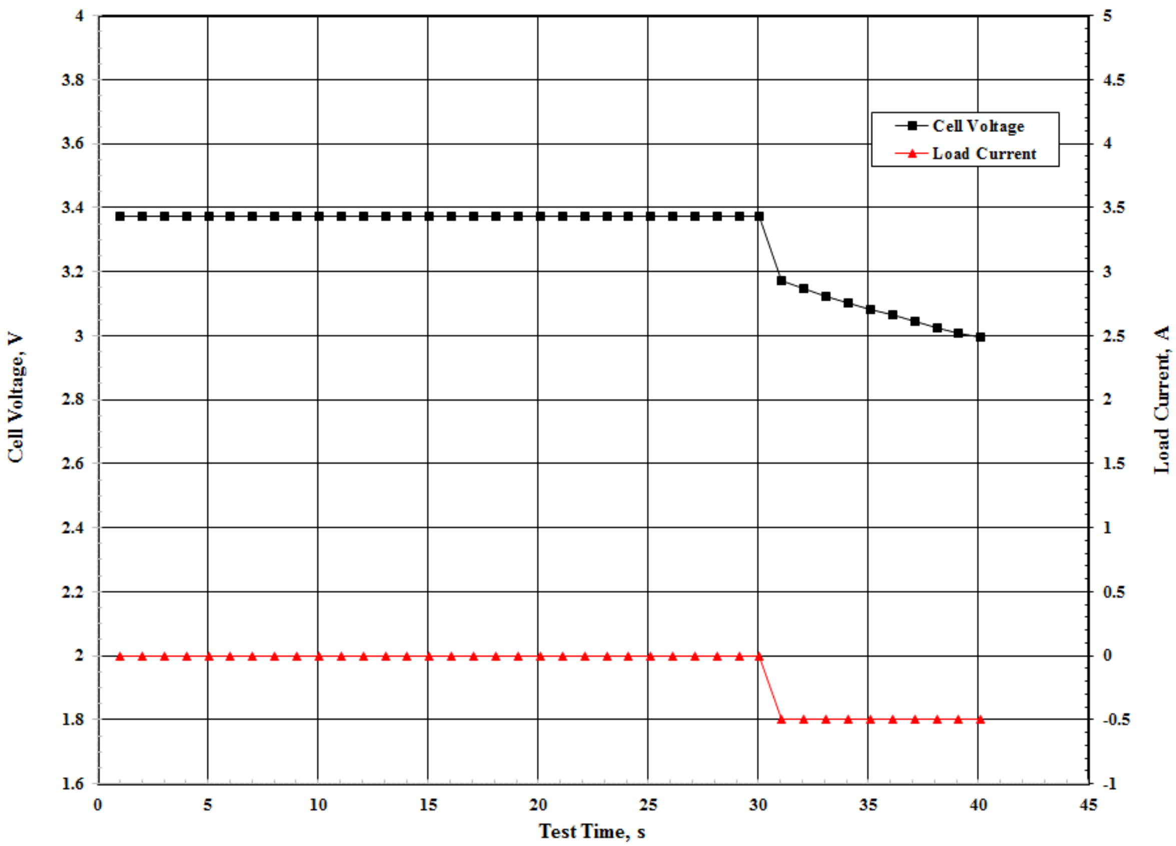


Figure 7.1-1. CCV Test for Cell ID# 13 at Ambient Temperature (21 °C) Conditions

7.1.2 Cell Selection Statistical Analysis

The cell acceptance test data were analyzed using a non-parametric Method of Fourths [19] statistical analysis with the results summarized in Table 7.1-2. These data were used to screen cells prior to testing. In addition, these data were used to select cells for 4S and 10S bundle manufacturing in support of external short and SAFER battery-level testing.

The Stem and Leaf plot for the test cell weights is shown in Figure 7.1-2. The median cell mass is 16.34 g, with the lower fourth (F_L) of 16.29 g, and the upper fourth (F_U) of 16.40 g (Table 7.1-2). Although the Method of Fourths identified 10 cells as outside values, possibly from a different distribution, a review of the Stem and Leaf plot reveals the cells appear to be from the same, almost normal, distribution. Therefore, no test cells were rejected due to mass.

Table 7.1-2. Test Cell Acceptance Test Data Summary

Test	F_L	Median	F_U
Mass (g)	16.29	16.34	16.40
Diameter (mm)	16.40	16.43	16.46
Length (mm)	34.14	34.18	34.23
OCV (V)	3.244	3.249	3.251
CCV (V)	2.867	2.875	2.881
AC Impedance (ohms)	0.288	0.303	0.314

The Stem and Leaf plots for the cell diameters and lengths are shown in Figures 7.1-3 and 7.1-4, respectively. The Method of Fourths identified 10 cells with outside values for diameter and 17 cells that had outside values for length (Appendix C). No test cells were rejected for length or diameter.

Stem and Leaf plot of the test cell AC impedance data is shown in Figure 7.1-5. Differences in the cell tab electrical contact resistance may have impacted the AC impedance test results. A large percentage of the outside values are cells with serial number 100 or lower. Approximately 31 test cells corresponding to AC impedance values greater than 0.354 ohms (i.e., high outside values) were not used in this assessment (Appendix C).

The Stem and Leaf plot for OCV at ambient temperature is skewed (Figure 7.1-6). There are 2 outside values that are low, and 18 that are high. Test cells whose OCV values found to have outside values were rejected and not used in this assessment (Appendix C).

The Stem and Leaf plot for the CCV test results is shown in Figure 7.1-7. Variations in electrical contact with the test cell temperature differences in time of measurement may have influenced the CCV test results. Test cells whose CCV values found to have outside values were rejected and not used in this assessment.

As indicated, test cell CCV acceptance test data was used as the primary means to select cells for 4S- and 10S-cell bundle manufacturing. OCV and AC impedance acceptance test data was used as a secondary criterion for test cell selection. Using the flight cell OCV pass/fail criteria (i.e., 3.20 $\pm$ 0.050 V), 663 of the 894 test cell population cells passed (i.e., 65% pass). However, using the flight cell CCV pass/fail criteria (i.e., 2.890 V minimum), 42 of the 894 test cell population passed (i.e., 4.7% passed). The technical risk to accepting cells which were outside of the flight cell specification range was determined to be low relative to the assessment objectives.

```
16.0    79
16.1    0122
* * * Outside Values * * *
16.1    33
16.1    55555555
16.1    66666667777
16.1    8888888999999999
16.2    00000000001111111111111
16.2    2222222222222222333333333333
16.2    44444444444444444444444444555555555555555555
16.2    666666666666666666666666677777777777777777777777
16.2 H  8888888888888888888888889999999999999999999999999999999
16.3    000000000000000000000000000000000000000111111111111111111111111111111111111111111111
16.3    22222222222222222222222222222222233333333333333333333333333333333333333333333333
16.3 M  44444444444444444444444444444444444444444445555555555555555555555555555555555555555
16.3    66666666666666666666666666666666777777777777777777777777777777777777
16.3    88888888888888888888888888888888888889999999999999999999999999999999999
16.4 H  000000000000000000000000000111111111111111111111
16.4    2222222222222222222222222222223333333333333333333333
16.4    44444444444444444444444455555555555
16.4    666666666666666666666666777777777
16.4    88888888888888899999999
16.5    0000000011111111
16.5    22223333
16.5    44555
16.5    66666
* * * Outside Values * * *
16.5    799
16.7    7
```

Figure 7.1-2. Stem and Leaf Plot of Mass (g) Measurements for Duracell® Ultra® CR123 Test Cells

```
16.13    0
16.14    00
16.16    0
16.23    0
16.26    0
16.27    0
* * * Outside Values * * *
16.34    0
16.35    00000
16.36    0000000000
16.37    000000000000000000000000000
16.38    000000000000000000000000000000000000000000000000000000000000000000
16.39    000000000000000000000000000000000000000000000000000000000000000000000000000000
16.40 H  00000000000000000000000000000000000000000000000000000000000000000000000000000000
16.41    00000000000000000000000000000000000000000000000000000000000000000
16.42    000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
16.43 M  00000000000000000000000000000000000000000000000000000000000000000000000000000
16.44    000000000000000000000000000000000000000000000000000000000000000000000000
16.45    0000000000000000000000000000000000000000000000000000000000000
16.46 H  00000000000000000000000000000000000000000000000000000000
16.47    00000000000000000000000000000000000000000000000000000
16.48    00000000000000000000000000000000000000000000000000
16.49    0000000000000000000000000000000000000000000000
16.50    0000000000000000000000000000
16.51    0000000000000
16.52    0
16.53    00
16.54    000
* * * Outside Values * * *
16.58    0
16.59    0
16.67    0
```

Figure 7.1-3. Stem and Leaf Plot of Diameter (mm) Measurements for Duracell® Ultra® CR123 Test Cells

```
34.0     0
* * * Outside Values * * *
34.0     11
34.0     22
34.0     4445555555
34.0     666666667777777777
34.0     88888888888888899999999999999999999
34.1     0000000000000000000000000000000000011111111111111111111111111111
34.1     22222222222222222222222222222222222223333333333333333333333333333333333333333333333333333333
34.1 H 44444444444444444444444444444444444444444444444445555555555555555555555555555555555555555555555555555555555555
34.1     6666666666666666666666666666666666666666666666777777777777777777777777777777777777777777777777777777
34.1 M 88888888888888888888888888888888888888888888889999999999999999999999999999999999999999999999999999
34.2     0000000000000000000000000000000000000000011111111111111111111111111111111111111111
34.2 H 2222222222222222222222222222222222222222233333333333333333333333333333333333333333333
34.2     44444444444444444444444444555555555555555555555555555555555
34.2     666666666666666666666666677777777777777777
34.2     88888888888888888888888888889999999999999999999999
34.3     0000000111111
34.3     222333333
34.3     4444455
34.3     6666
* * * Outside Values * * *
34.3     778889999
34.4     0122347
```

Figure 7.1-4. Stem and Leaf Plot of Length (mm) Measurements for Duracell® Ultra® CR123 Test Cells

```
0.25     0133333
0.25     5688
0.26     0111122444
0.26     56666777788888999999999
0.27     0000011111111222222333333333344444444
0.27     55555666666777777888888888888889999999999
0.28     000000001111111112222222222222333333333333333344444444
0.28 H 555555555555555556666666666666666677777777777778888888888888888999999999
0.29     0000000000000111111111111111222222233333333333333333344444444444444444444
0.29     55555555555555555555556666666666667777777777777777777788888888888888899999999999
0.30 M 0000000000001111111111111111222222222222222333333333333333333333333334444444444444444444444
0.30     555555555555555555555666666666666777777777777777778888888888888888888888889999999999999999
0.31 H 0000000000000111111111111111111111111111122222222222222223333333333333333333333333333344444444444
0.31     555555555555555555666666666666677777777777777778888889999999999
0.32     00000000000011111111112222222222222333333333444444
0.32     5555556666778888889999
0.33     0001111112233334444
0.33     5555556667888888999
0.34     001234
0.34     56666778899
* * * Outside Values * * *
0.35     44555
0.36     0244679
0.37     0123
0.38     459
0.39     69
0.40     36
0.41     4
0.43     8
0.44     01
0.47     11
0.49     6
0.54     5
```

Figure 7.1-5. Stem and Leaf Plot of AC Impedance (ohms) Measurements at 1 kHz and Ambient Temperature for Duracell® Ultra® CR123 Test Cells

```
3.144   9
3.213   8
* * * Outside Values * * *
3.234   9
3.235
3.236
3.237   4457778
3.238   112345668
3.239   0001366666666669999999
3.240   0000000222222222222233334455555556666667778888888889999
3.241   01122233444555555577888889999
3.242   01111111111112244444444444455557777777777777777888888888
3.243   0000001111112333344444444555677777778888
3.244 H 001112333344555666789999999999999
3.245   0022222222222222222222333333555555555555555666668888888889999
3.246   0001111122223334455556677777889999
3.247   000011111112222223333444444444555555555577777777777778888
3.248 M 000000000000000111111133333333333334444444666666666666666666777777777888899999
3.249   00000001111111122222333333333334444555555555555566666666666666666777777788888888899999999999999999999999
3.250   000000000111111222222222222222222223333333333333333355555555555555555555555555555555556668888888888888888899999999
3.251 H 11111111111111112222222222222444455555555556777777777788888899999
3.252   001111222333444444444444444555556667777777777777777888888999
3.253   00001111113333334446666666666667999
3.254   02355566678889999
3.255   12355668888
3.256   1144577777
3.257   001113667777
3.258   00034679
3.259   29
3.260   46
* * * Outside Values * * *
3.350   09
3.353   12
3.354   47
3.356   9
3.358   4
3.371   9
3.372   7
3.374   67
3.375   8
3.377   048
3.378   4
3.380   5
```

Figure 7.1-6. Stem and Leaf Plot of OCV (V) Measurements at Ambient Temperature for Duracell® Ultra® CR123 Test Cells

```
2.77   4
2.79   8
2.80   6
2.81   5777
2.82   0134669
2.83   22456788
2.84   0133
* * * Outside Values * * *
2.84   77
2.84   8888999999
2.85   001
2.85   222233333
2.85   4444444555555555
2.85   6666677777777
2.85   8888999999999999999
2.86   0000000000000011111111111111
2.86   22222222222233333333333
2.86   4444444444444444444444444444455555555555555555555555
2.86 H 666666666666666666666777777777777777777777777
2.86   8888888888888888888888889999999999999999999999
2.87   000000000000000000000000001111111111111111111
2.87   2222222222222222222222222222222222222222222233333333333333333333333333
2.87 M 44444444444444444444444444444444444444444444444445555555555555555555555555555555555555555555
2.87   666666666666666666666666666666667777777777777777777777777777777777777777
2.87   8888888888888888888888888888888888888999999999999999999999999999999999999
2.88 H 00000000000000000000000000000011111111111111111111111111111111111
2.88   2222222222222222222222222222222222222222223333333333333333333
2.88   44444444444444444444444444444555555555555555555555
2.88   666666666666666666666777777777777777777777777
2.88   8888889999
2.89   0000000111
2.89   22223333
2.89   44
2.89   6
2.89
2.90   0
* * * Outside Values * * *
2.91   6
2.92   8
2.93   225
2.94   0
2.95   4
2.96   7
2.97   447
2.98   459
2.99   013
```

Figure 7.1-7. Stem and Leaf Plot of CCV Test Measurements at Ambient Temperature for Duracell® Ultra® CR123 Test Cells

7.1.3 Cell Matching

Cells selected for testing were matched using the Stem and Leaf plot statistical analysis results. Although cell matching for the purposes of manufacturing SAFER flight batteries is not specified, industry best practices dictate that cell matching reduces cell-to-cell variability within a string of electrical connected cells [20].

7.1.4 Summary and Findings

The Duracell® Ultra® CR123 cells were procured and screened using a tailored SAFER flight cell acceptance test procedure. The test results were analyzed to screen the cell population in support of cell selection and matching for 4S- and 10S-cell bundle manufacturing. Statistical analysis was used to identify outliers from the test cell population. (See Section 8.1, F-1 through F-3).

7.2 External Short Test

7.2.1 Objectives

The objective of this testing was to evaluate the TR safety risk caused by an external short to the SAFER battery. Specifically, the ability of the external PTC device to protect the SAFER battery, under selected external short conditions, was evaluated.

7.2.2 Background

Lessons learned from the B-787 ELT Li battery incident root cause and corrective action (RCCA) investigation were incorporated into the approach for the subject testing [3]. The RCCA investigation concluded the inability of the ELT non-rechargeable Li-MnO_2 battery PTC device to reliably protect the system from a high-impedance external short was a causal factor. This determination was in part due to a PTC thermal fuse trip analysis under various environmental operating conditions.

The SAFER batteries are individually protected from external shorts by Schottky bypass diodes and external PTC devices (Figures 7.2-1 and 7.2-2 [21]). The Schottky bypass diodes (1N5819) protect each cell by providing a “bypass” function for shunting discharge current around a weak or failed open cell. These blocking diodes are supplied by Vishay General Semiconductor (Sheldon, CT).

The PTC (SRP-200F) devices are designed to function as resettable thermal fuses, which will trip and inhibit the current flow as a function of temperature (Appendix D). Furthermore, each individual cell has an internal PTC device located under the positive terminal cap. Under elevated temperature conditions, the internal cell PTC thermal fuse will trip, and block current flow through the bundle cell string. Elevated temperature may be caused by high voltage or current from an abuse condition.

The effect of temperature on the hold and trip currents for the SRP-200F PTC device is shown in Figure 7.2-3 [22,23]. The rated hold and trip currents are specified in still air at 20 °C. However, as a thermally activated fuse, any change in temperature will affect PTC device performance. SAFER battery operating conditions in Region A will trip the SRP-200F PTC thermal fuse, causing a decrease in bundle-level current flow. Operating conditions corresponding to Region B will cause the PTC device to trip or remain in a low-resistance state. Under these operating conditions, the PTC device may, or may not, adequately protect the bundle from current flow.

Finally, Region C operating conditions will cause the PTC device to remain in a low-resistance state, or hold condition, whereby the battery bundle electrical circuit will operate nominally. These data were used to select the external short load values for the 4S- and 10S-cell bundle-level external short tests conducted in this assessment.

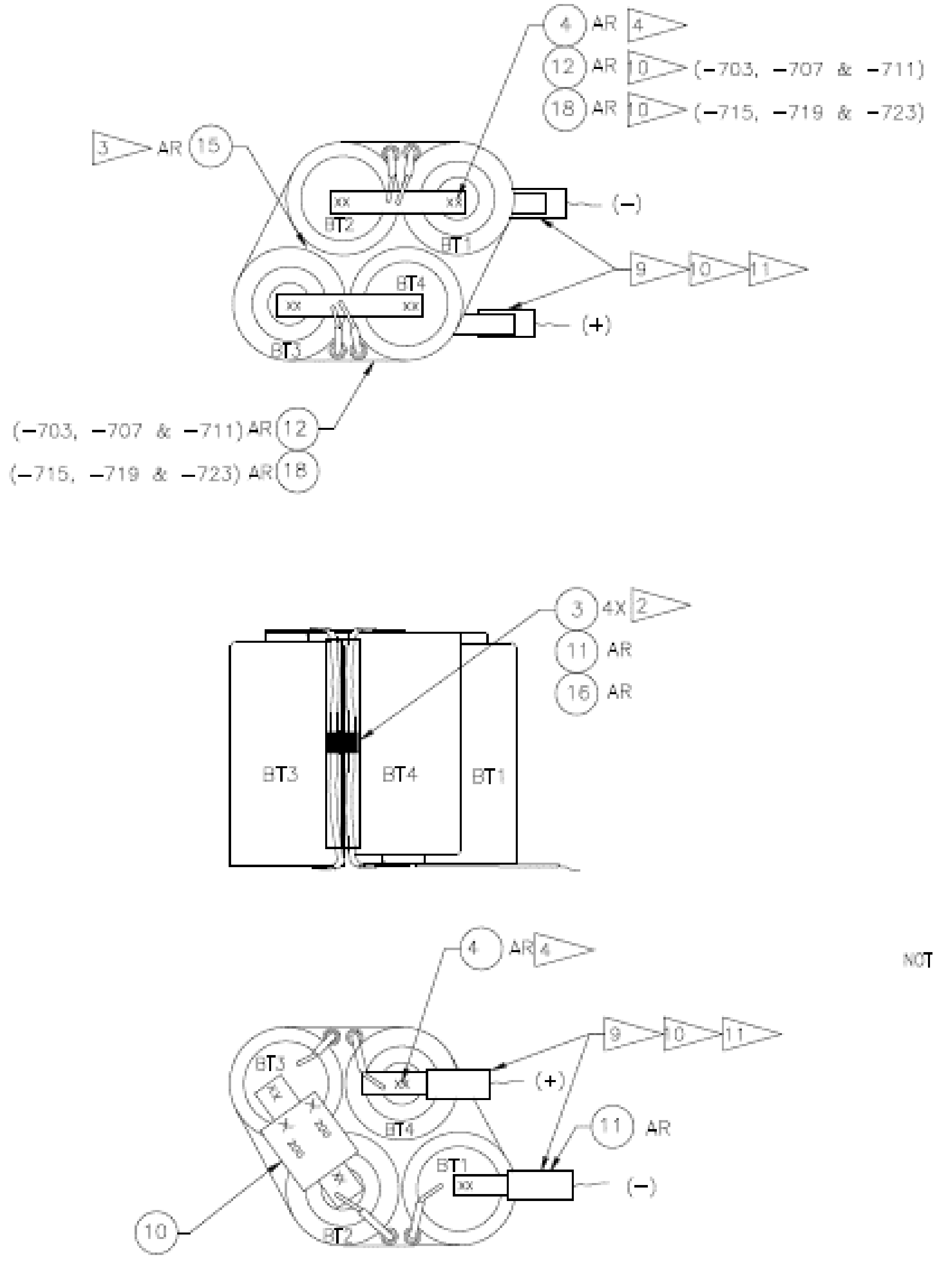


Figure 7.2-1. Schematic Drawing of SAFER Battery 4S-cell Bundle
External SRP-200F PTC thermal fuse is located between cells BT2 and BT3 [21]

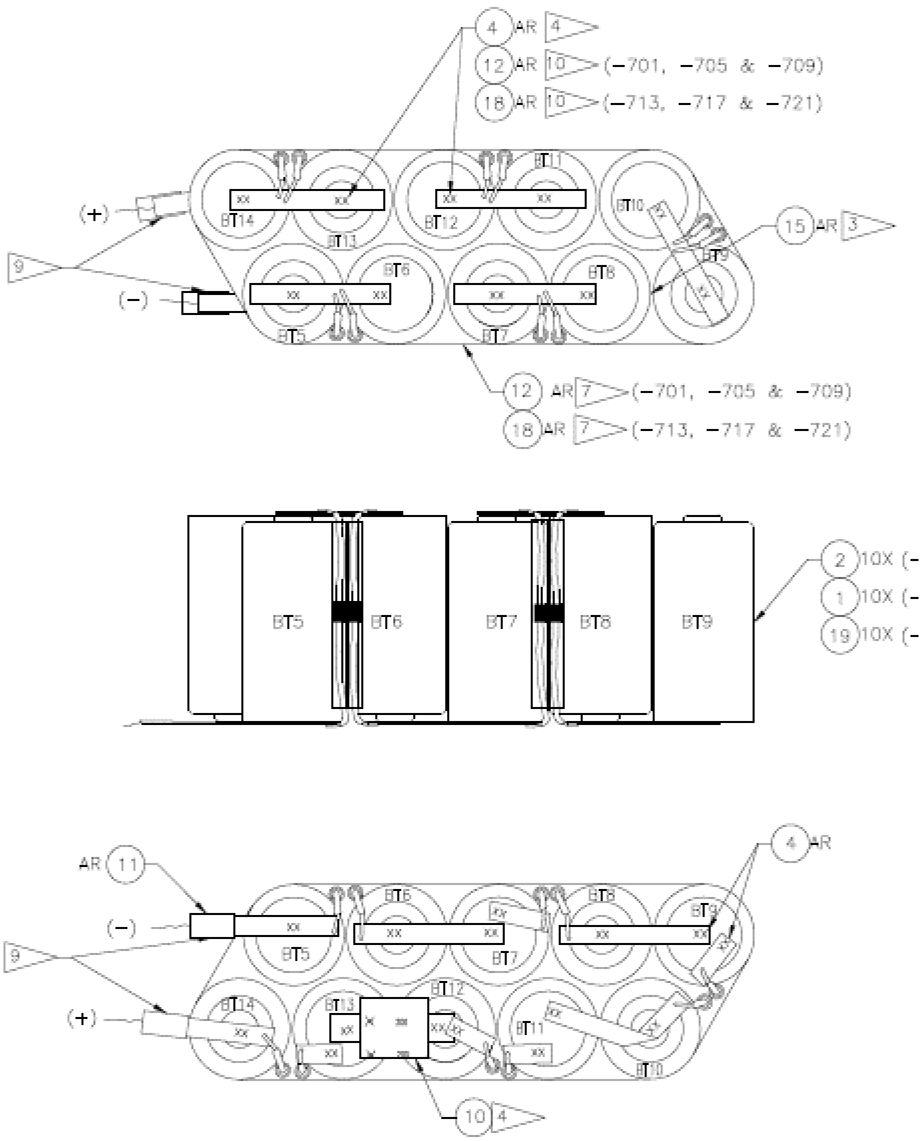


Figure 7.2-2. Schematic Drawing of SAFER Battery 10S-cell Bundle
External SRP-200F PTC thermal fuse is located between cells BT12 and BT13 [21]

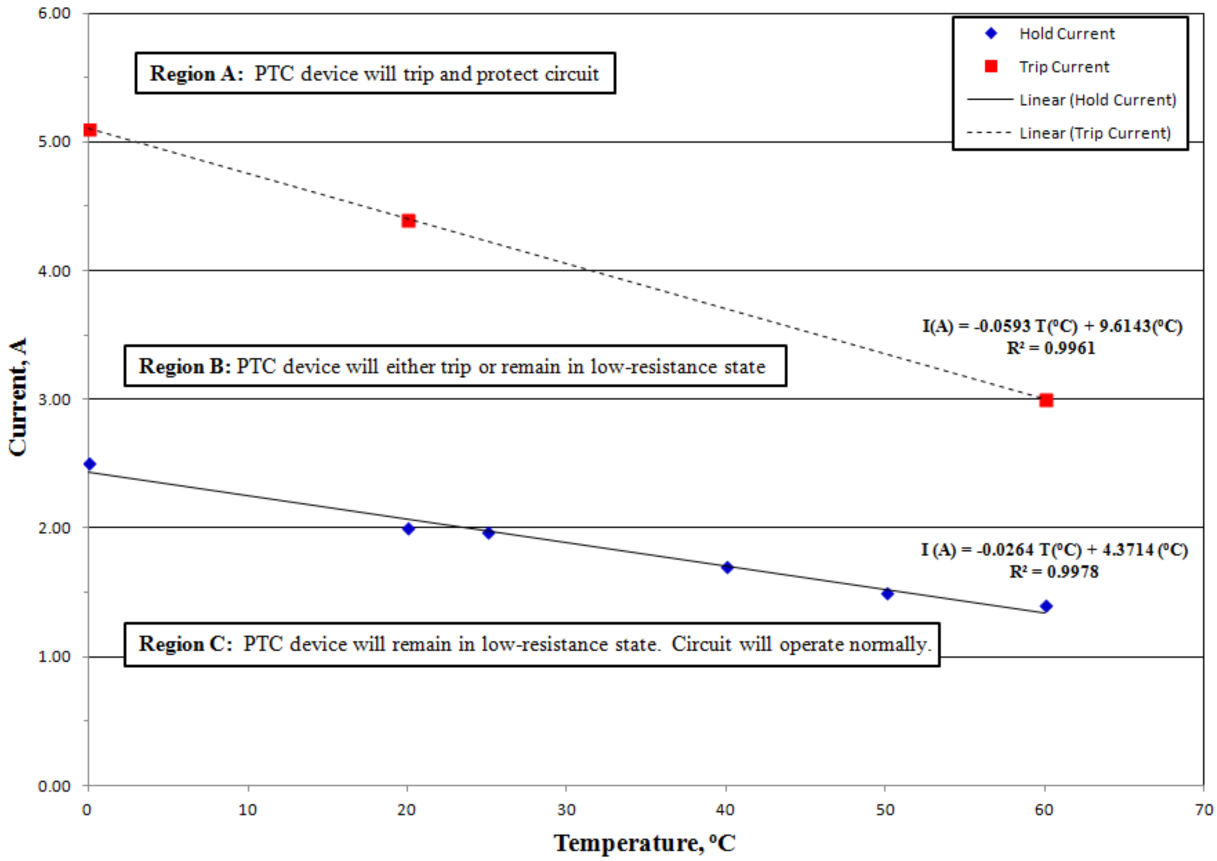


Figure 7.2-3. Effect of Temperature on Hold and Trip Currents for the SAFER Battery SRP-200F PTC Thermal Fuse [22,23]

7.2.3 Test Plan

A test plan was developed and managed throughout the assessment (Appendix E). Test plan updates were provided to the JSC ESTA organization to support test procedure, test facility, and allocation of other test resources [24]. Test readiness reviews (TRRs) and delta-TRRs were conducted to support technical changes (*e.g.*, test matrix or test article configuration changes) to the assessment baseline. A test hazard analysis was conducted to assess and mitigate any safety hazards involved with the SAFER battery test program [25]. Hazard controls were implemented to mitigate any safety risk to personnel, test articles, or facilities.

Four and ten-cell bundle testing, Tables 7.2-1 and 7.2-2, respectively, was conducted to characterize their safety performance under specified external test conditions. External load and PTC device installation were chosen as the test variables. PTC thermal fuse location was consistent with the flight SAFER battery 4S- and 10S-cell bundle configurations (Figure 7.2-1 and 7.2-2). External load resistance values were chosen based on Figure 7.2-3 and previous SAFER battery test results [26]. All test bundles were configured in a flight-like configuration with Schottky bypass diodes. All bundle test articles were equipped with thermocouples, with a tolerance of ±2 °C, positioned to sufficiently measure temperature gradients (Figure 7.2-4). Images of representative 4S- and 10S-cell bundle test configurations are shown in Figures 7.2-5 and 7.2-6, respectively.

Table 7.2-1. External Short Test Matrix for the 4S-cell Bundle Safety Tests PTC device region corresponds to Figure 7.2-1.

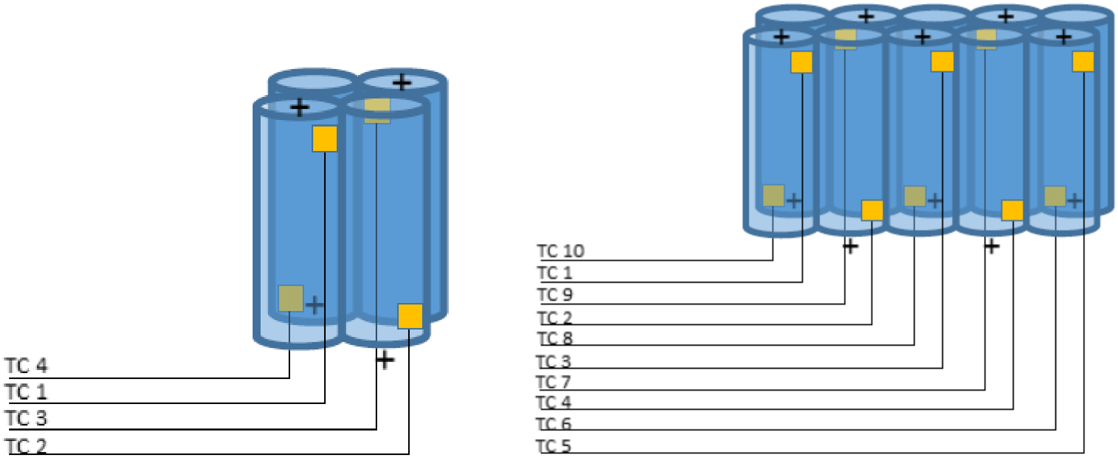
Test No.	**Electrical Configuration**	**External Load (ohm)**	**Schottky By-Pass Diodes**	**PTC Device Region**	**PTC Device Installed**
1	4S	10	Yes	C	No
2	4S	10	Yes	C	Yes
3	4S	3.5	Yes	B	No
4	4S	3.5	Yes	B	Yes
5	4S	1.0	Yes	A	No
6	4S	1.0	Yes	A	Yes
7	4S	0.10	Yes	A	No
8	4S	0.10	Yes	A	Yes
9	4S	0.05	Yes	A	No
10	4S	0.05	Yes	A	Yes

Note: All testing was conducted at ambient temperature and pressure.

Table 7.2-2. External Short Test Matrix for the 10S-cell Bundle Safety Tests PTC device region corresponds to Figure 7.2-2.

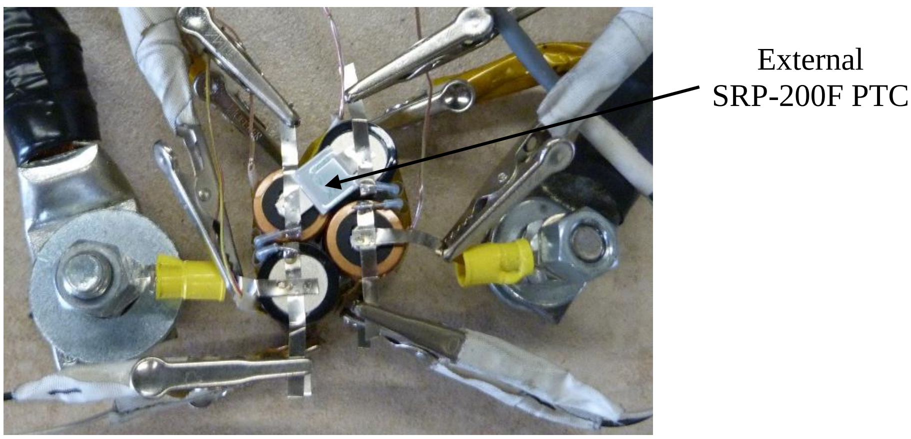
Test No.	**Electrical Configuration**	**External Load (ohm)**	**Schottky By-Pass Diodes**	**PTC Device Region**	**PTC Device Installed**
1	10S	25	Yes	C	No
2	10S	25	Yes	C	Yes
3	10S	9	Yes	B	No
4	10S	9	Yes	B	Yes
5	10S	1.0	Yes	A	No
6	10S	1.0	Yes	A	Yes
7	10S	0.5	Yes	A	No
8	10S	0.5	Yes	A	Yes
9	10S	3	Yes	A	No
10	10S	3	Yes	A	No

Note: All testing was conducted at ambient temperature and pressure.

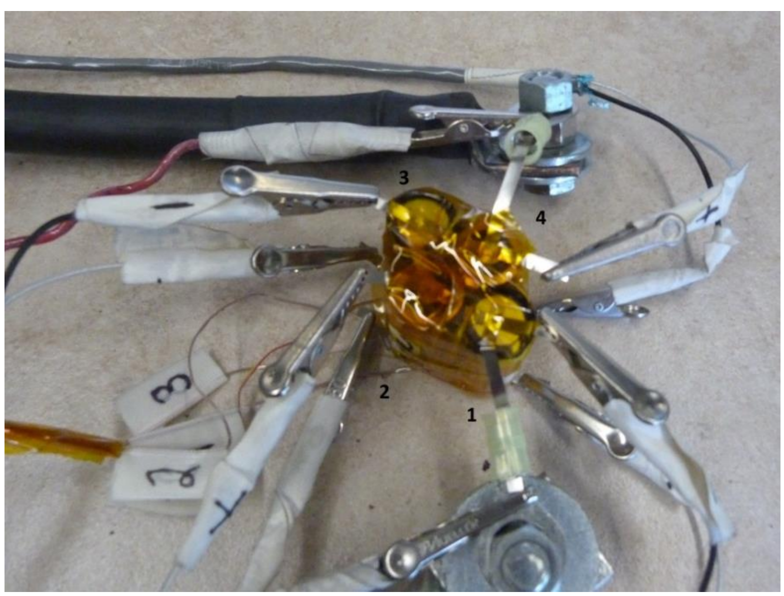


a) 4S-cell bundle. ***b) 10S-cell bundle.***

Figure 7.2-4. Thermocouple Placement for SAFER Battery Bundle External Short Testing



a) Top-view of 4S-cell bundle test article (external PTC device installed).



b) Top-view of packaged 4S-cell bundle test article (external PTC device installed).

Figure 7.2-5. External Short Test Configuration of a Representative 4S-cell Bundle Test Article

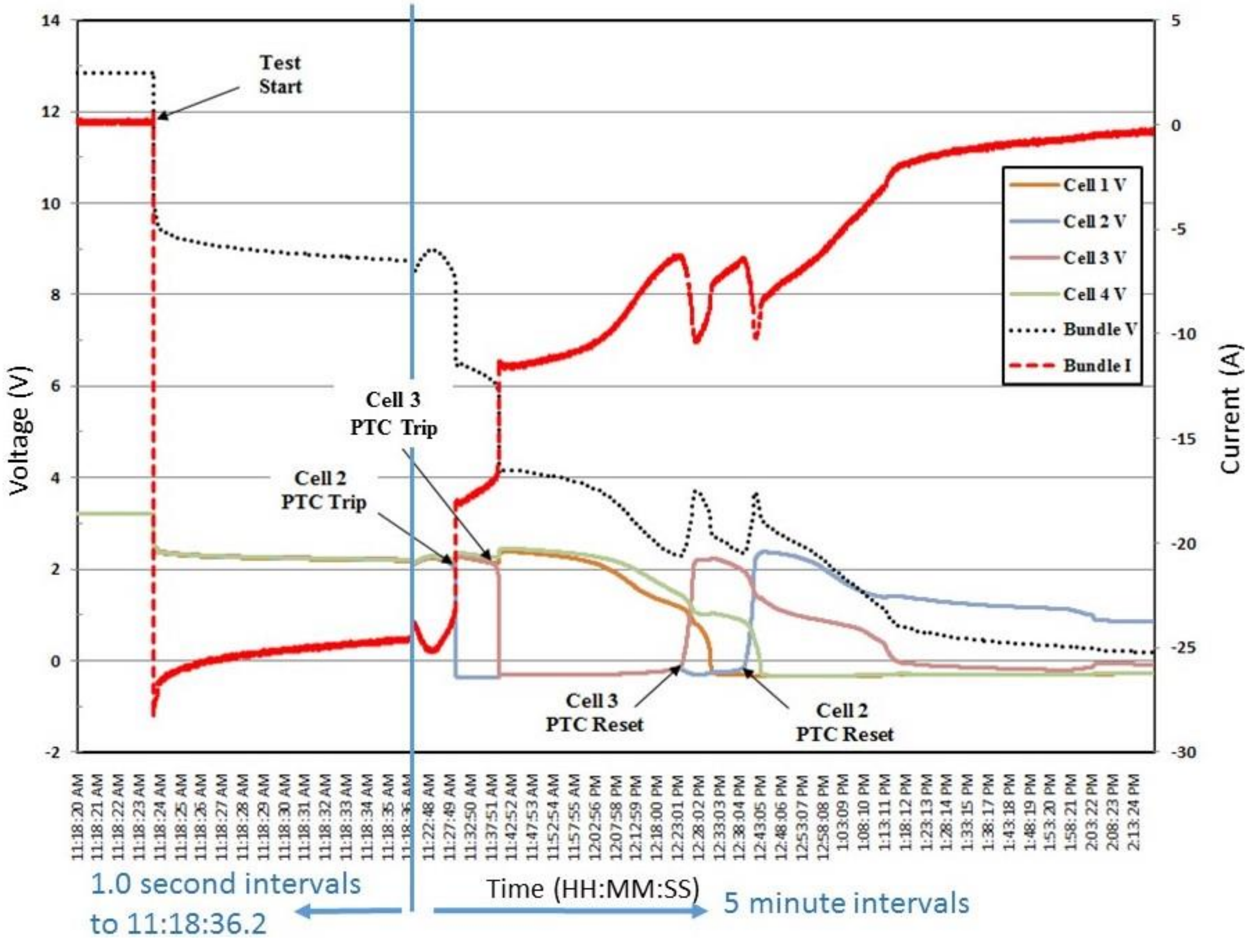
Figure 7.2-6. External Short Testing 10S-cell Bundle Test Configuration

7.2.4 Results and Discussion

The SAFER battery (P/N SED33105907) has been safety certified and qualified per ISS requirements [27]. As part of the certification, JSC ESTA conducted SAFER battery testing in support of an updated SAFER battery hazard report [27,28]. This testing included external short testing (i.e., no external SRP-200F PTC device; Schottky diodes installed; 3.5-ohm resistive load) of a SAFER battery 14S (one 4S bundle electrically connected in series with a 10S bundle) bundle. The results indicated that some cells exhibited venting and electrolyte leakage. Maximum measured cell temperatures during this test were 123 °C, which is below the 180 °C Li melting point. As such, there was no evidence of cell TR was observed [15].

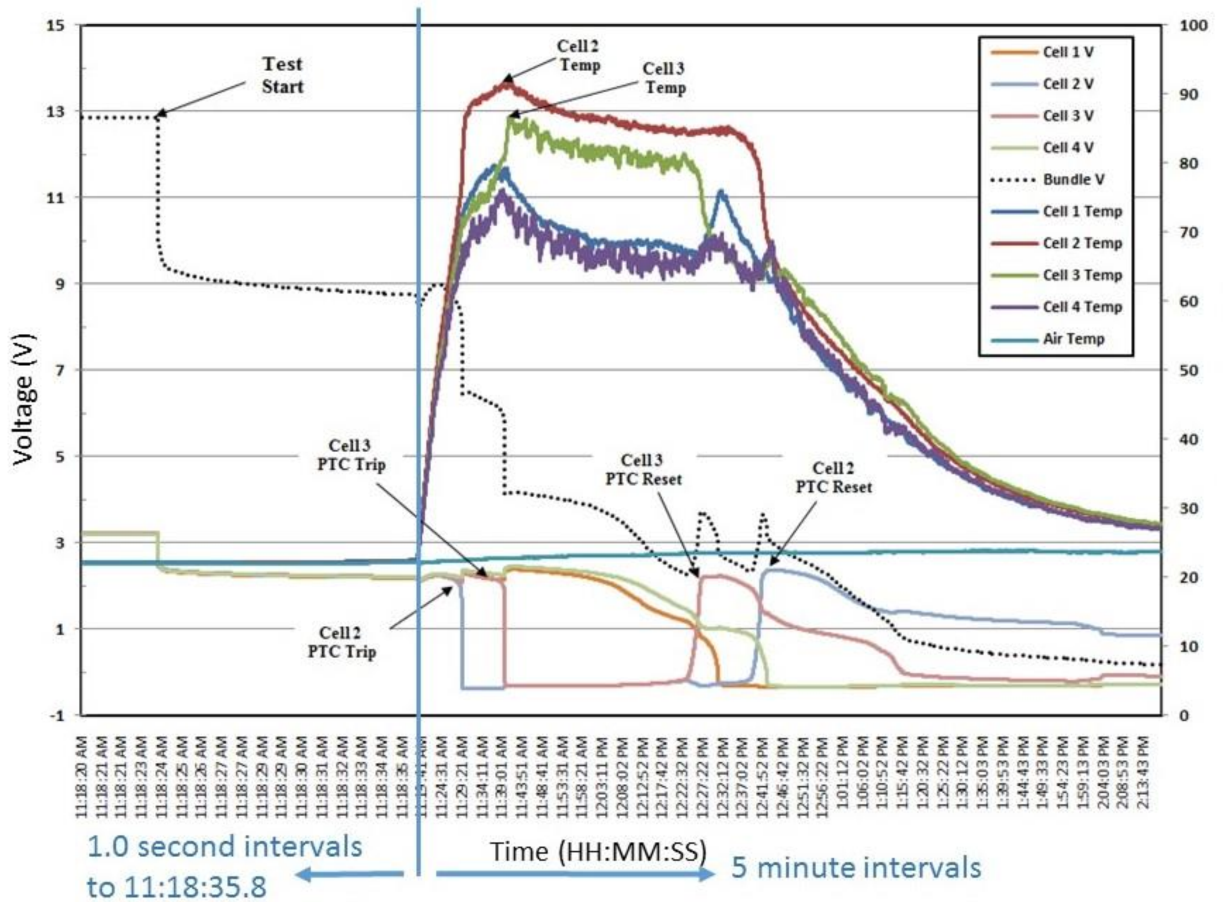
7.2.4.1 4S-Cell Bundle External Short Testing

A results summary for the 4S-cell bundle external short testing are shown in Table 7.2-3. Ten 4S-cell bundle external short tests were conducted. Peak temperatures were highest for test articles with no installed external PTC device. Test 12 (i.e., 3.5-ohm, no PTC device) had the highest peak temperatures, while Test 19 (i.e., 0.05-ohm, PTC device) had the lowest peak temperatures. External short test results for Test #12 are shown in Figures 7.2-7 and 7.2-8 and specific PTC trip and rest function is shown in Table 7.2-4. The internal Cell #2 (cell ID#344) PTC thermal fuse trips instantaneously at approximately 80.2^{o}C, followed by Cell #3 internal PTC thermal fuse instantaneously tripping at approximately 81.1^{o}C. The subsequent decrease in bundle load current aids in mitigating the internal temperatures of Cells #1 and #4. As a result, the internal cell PTC thermal fuses for these cells did not trip. Cell voltage PTC re-set signatures were observed to gradually transition from a tripped state to a re-set completion state over a 5-6 min. time period. Cell #3 PTC device re-set temperature range was 79.7^{o}C (re-set initiation) to 73.3^{o}C (re-set complete), followed by Cell #2 internal PTC device re-setting between 82.7^{o}C (re-set initiation) to 66.9^{o}C (re-set complete). The minor variation between the PTC trip and re-set initiation temperatures is most likely due to an expected hysteresis in trip/re-set performance, which is common in commercial PTC devices. Due to the tripping of the Cell #2 and Cell #3 internal PTC thermal fuses, the 4S-cell bundle was not at risk of over-discharge or other adverse abuse condition. Cell #2 reached a peak of 91.7 °C, which is significantly less than the expected TR temperature of approximately 175−180 °C for the SAFER battery cell design. Post-test inspections indicated no evidence of cell venting or electrolyte leakage (Figure 7.2-9).



Note: External resistive load = 3.5 ohm; no external PTC device. Ambient temperature and pressure.

Figure 7.2-7. Voltage-current Characteristics for SAFER Battery 4S-cell Bundle External Short Test #12



Note: External resistive load = 3.5 ohm; no external PTC device. Ambient temperature and pressure.

Figure 7.2-8. Voltage-temperature Characteristics for SAFER Battery 4S-cell Bundle External Short Test #12

Table 7.2-3. Summary of Results From the 4S-cell Bundle External Short Testing

Test Date (Test No)	Test Decription (Cell ID)	Cell ID	Peak Temp (°C)	Peak Current (A)	Peak Voltage (V)	Pre-OCV (V)	Post-OCV (V)	Pre AC Imp (Ω)	Post AC Imp (Ω)
11-Mar-15	**10Ω, 1.1A, No PTC**	**1-4S**		1.13	11.89	12.78	7.08	1.00	OC
(10)	Cell 170	**Cell 1**	41.59			NR	1.64	NR	OC
	Cell 297	**Cell 2**	42.08			NR	1.74	NR	OC
	Cell 299	**Cell 3**	42.28			NR	1.94	NR	OC
	Cell 300	**Cell 4**	39.29			NR	1.73	NR	OC
12-Mar-15	**10Ω, 1.1A, PTC**	**2-4S**		1.31	12.88	12.86	5.12	1.05	OC
(11)	Cell 303	**Cell 1**	41.12			3.21	1.32	0.25	OC
	Cell 304	**Cell 2**	45.86			3.21	1.28	0.24	OC
	Cell 305	**Cell 3**	43.95			3.21	1.22	0.25	OC
	Cell 320	**Cell 4**	42.51			3.21	1.32	0.24	OC
23-Mar-15	**3.5Ω, 3.1A, No PTC**	**5-4S**		28.33	12.88	12.85	3.25	0.98	OC
(12)	Cell 337	**Cell 1**	79.72			3.21	0.72	0.23	OC
	Cell 344	**Cell 2**	**91.72**			3.22	1.34	0.24	2.87
	Cell 347	**Cell 3**	86.80			3.22	0.61	0.24	OC
	Cell 500	**Cell 4**	76.14			3.21	0.61	0.24	OC
25-Mar-15	**3.5Ω, 3.1A, PTC**	**4-4S**		28.18	12.91	12.86	11.46	1.10	1.20
(13)	Cell 330	**Cell 1**	63.75			3.22	2.87	0.26	0.28
	Cell 333	**Cell 2**	69.27			3.22	2.86	0.25	0.28
	Cell 336	**Cell 3**	67.20			3.21	2.87	0.25	0.27
	Cell 470	**Cell 4**	64.35			3.21	2.86	0.28	0.30
30-Mar-15	**1Ω, 11.0A, No PTC**	**3-4S**		7.19	12.96	12.86	4.41	1.05	OC
(14)	Cell 307	**Cell 1**	84.42			3.21	1.42	0.26	OC
	Cell 314	**Cell 2**	**89.71**			3.21	1.25	0.26	OC
	Cell 329	**Cell 3**	78.42			3.22	0.79	0.26	OC
	Cell 420	**Cell 4**	81.43			3.22	0.97	0.27	OC
31-Mar-15	**1Ω, 11.0A, PTC**	**8-4S**		7.00	12.97	12.84	11.80	1.02	0.92
(15)	Cell 368	**Cell 1**	38.38			3.21	2.96	0.25	0.21
	Cell 369	**Cell 2**	42.49			3.22	2.97	0.25	0.21
	Cell 370	**Cell 3**	45.92			3.21	2.97	0.25	0.21
	Cell 549	**Cell 4**	40.33			3.20	2.97	0.22	0.20
1-Apr-15	**0.1Ω, 110.0A, No PTC**	**9-4S**		14.56	13.04	12.85	4.47	0.96	OC
(16)	Cell 374	**Cell 1**	68.65			3.22	1.15	0.25	OC
	Cell 378	**Cell 2**	78.81			3.22	1.35	0.24	0.41
	Cell 382	**Cell 3**	75.77			3.22	1.14	0.25	OC
	Cell 864	**Cell 4**	76.55			3.21	0.86	0.22	OC
1-Apr-15	**0.1Ω, 110.0A, PTC**	**10-4S**		13.70	12.45	12.85	12.05	1.02	0.94
(17)	Cell 384	**Cell 1**	35.83			3.22	3.01	0.26	0.22
	Cell 392	**Cell 2**	42.04			3.22	3.02	0.26	0.23
	Cell 669	**Cell 3**	45.07			3.20	3.01	0.24	0.22
	Cell 871	**Cell 4**	37.92			3.21	3.01	0.22	0.20
6-Apr-15	**0.05Ω, 220.0A, No PTC**	**11-4S**		14.82	13.09	12.93	4.66	0.96	OC
(18)	Cell 077	**Cell 1**	75.09			3.23	1.09	0.24	OC
	Cell 083	**Cell 2**	81.94			3.23	1.41	0.25	OC
	Cell 199	**Cell 3**	71.46			3.23	1.02	0.25	OC
	Cell 203	**Cell 4**	79.38			3.23	1.15	0.24	OC
16-Apr-15	**0.05Ω, 220.0A, PTC**	**12-4S**		14.08	12.41	12.88	12.01	0.96	0.95
(19)	Cell 711	**Cell 1**	34.33			3.22	3.00	0.24	0.23
	Cell 855	**Cell 2**	38.95			3.22	3.00	0.23	0.22
	Cell 868	**Cell 3**	40.67			3.22	3.00	0.24	0.22
	Cell 870	**Cell 4**	36.03			3.22	3.00	0.23	0.21

Note: No evidence of cell-level TR was observed. NR - Not recorded, and OC - Open Circuit.

Table 7.2-4. Summary of PTC Function Test 12

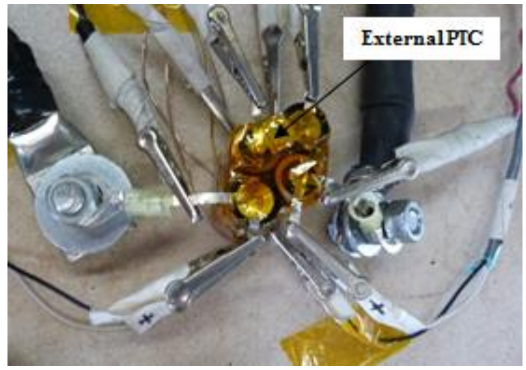
Cell PTC Trip	Trip/Re-Set Signature	Cell 2	Cell 3
Test Time (HH:MM:SS)	*Instantaneous*	11:29:30	11:39:44
Temp (°C)		80.2	81.1
Cell PTC Re-Set			
Test Time (HH:MM:SS)	*Gradual Transition*	12:38:54 to 12:44:12	12:22:13 to 12:27:32
Temp (°C)		82.7 to 66.9	79.7 to 73.3

a) Pre-test images.

b) Post-test images.

Figure 7.2-9. External Short Test Configuration Pre- and Post-test Images of Test #12
Note: No evidence of cell venting, electrolyte leakage, ignition of gas-phase flammable gases, smoke, and/or fire, or TR was observed.

Test #13 was conducted to investigate the effectiveness of the installed SRP-200F external PTC device on a 4S-cell bundle during an external short. Test conditions for Tests #12 and #13 were identical, except the Test #13 4S-cell bundle had an external SRP-200F PTC thermal fuse installed (Figure 7.2-10). External short test results for Test #13 are shown in Figures 7.2-11 and 7.2-12. Cell #2 (cell ID #333) reached a peak temperature of 69.3 °C, which was less than Cell #2 (cell ID #344) from Test #12. The external PTC device tripped at approximately 65 °C and 23A. Subsequent to the external PTC thermal fuse trip event, the 4S-cell bundle temperature decreases with no evidence of any internal cell fuse trip events. The external PTC device was observed to function as expected for Tests #11, #15 (Figures 7.2-13 and 7.2-14), #17, and #19.



a) Test #12 – No PTC device. *b) Test #13 – PTC device installed.*

Figure 7.2-10. External Short Test Configuration Pre-test Images of Test #12 and #13 4S-cell Bundle Test Articles

Note: Test #12 and #13 utilized an external resistive load = 3.5 ohm.

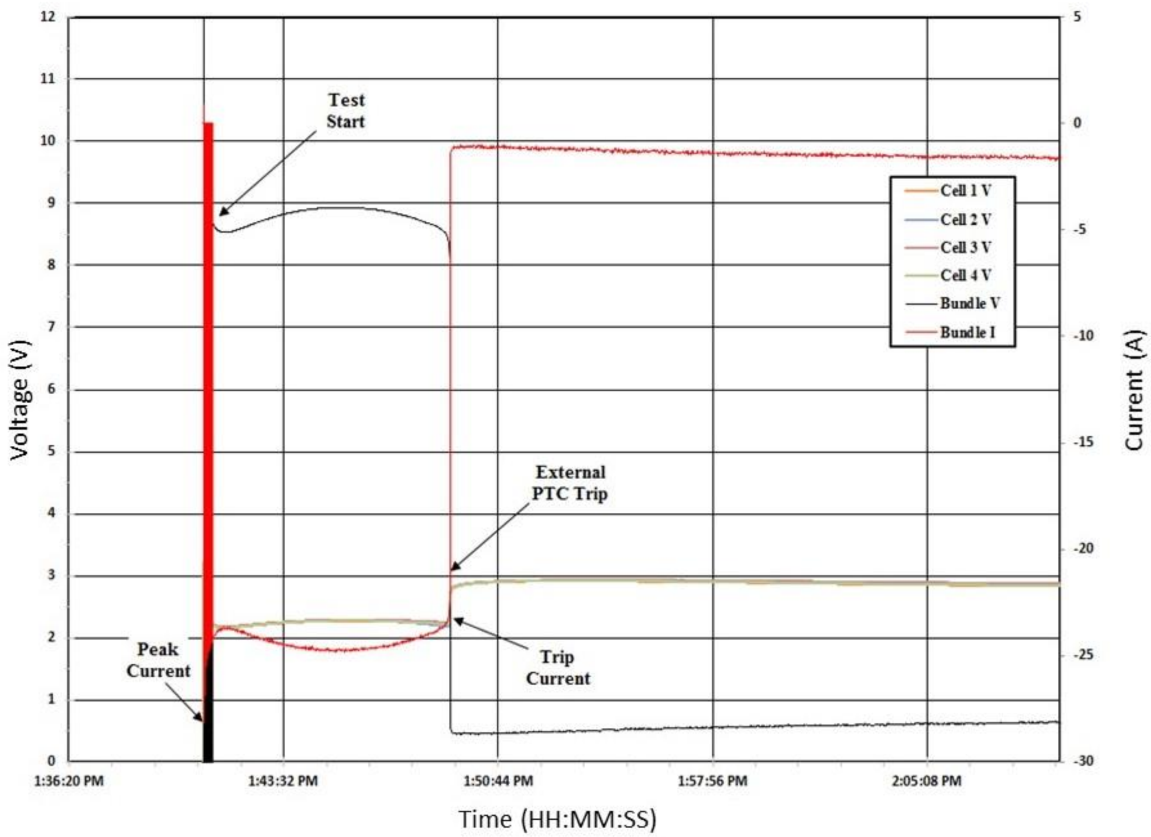
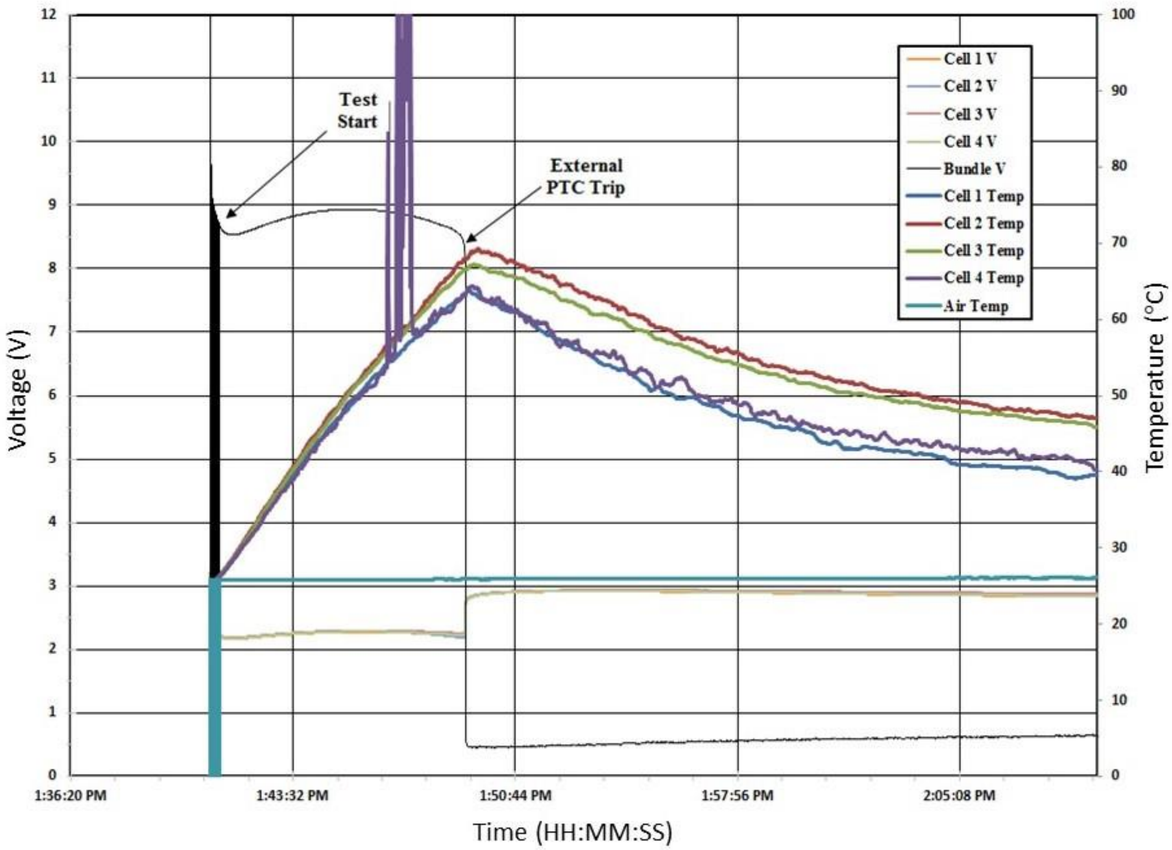


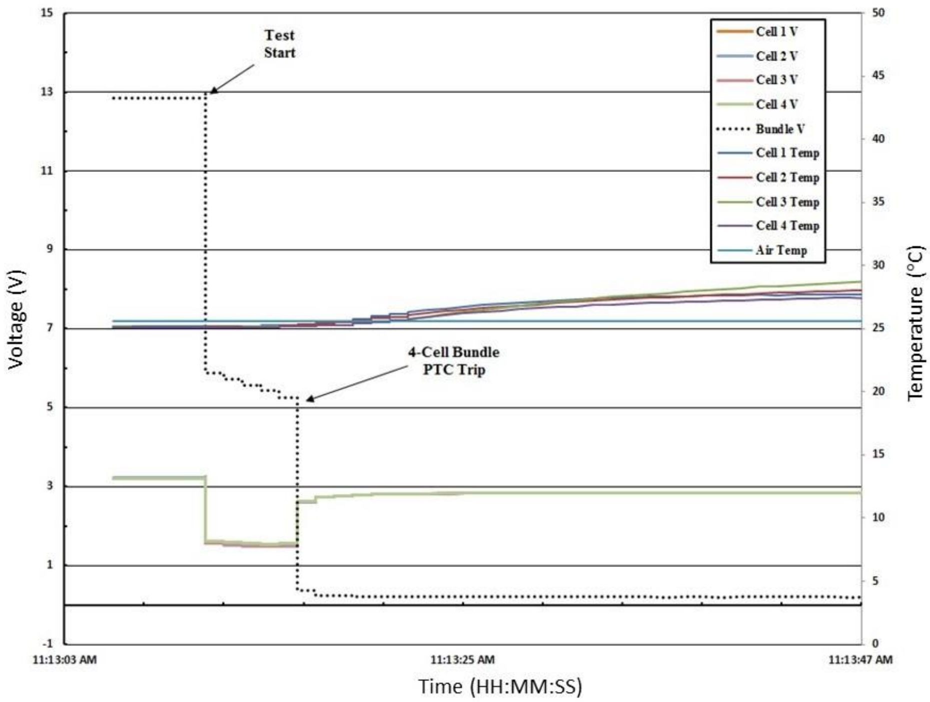
Figure 7.2-11. Voltage-current Characteristics for SAFER Battery 4S-cell Bundle External Short Test #13

External resistive load = 3.5 ohm; PTC device installed. All testing was conducted at ambient temperature and pressure.



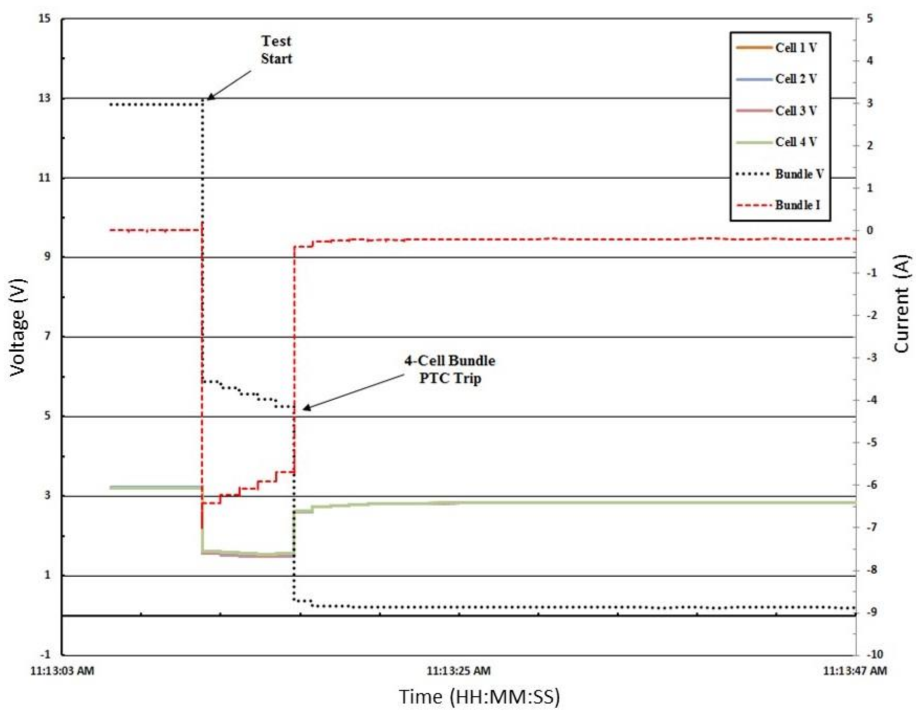
Note: External resistive load = 3.5 ohm; PTC device installed. All testing was conducted at ambient temperature and pressure.

Figure 7.2-12. Voltage-temperature Characteristics for SAFER Battery 4S-cell Bundle External Short Test #13



Note: External resistive load = 1.0 ohm; PTC device installed. All testing was conducted at ambient temperature and pressure.

Figure 7.2-13. Voltage-temperature Characteristics for SAFER Battery 4S-cell Bundle External Short Test #15

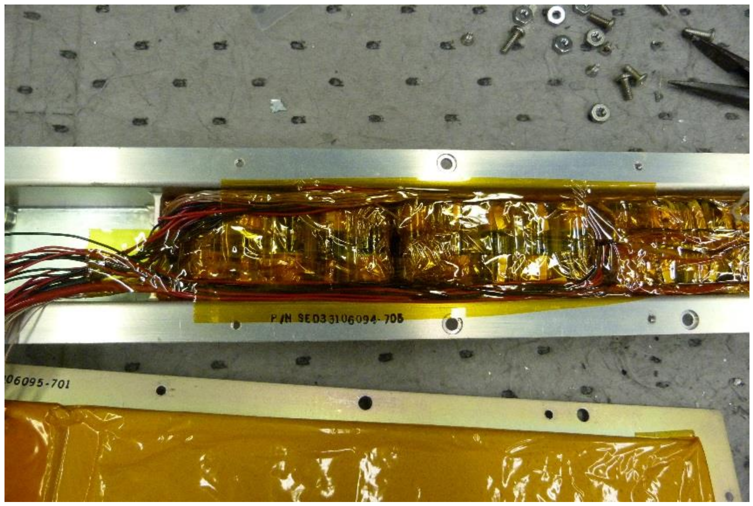


Note: External resistive load = 1.0 ohm; PTC device installed. All testing was conducted at ambient temperature and pressure.

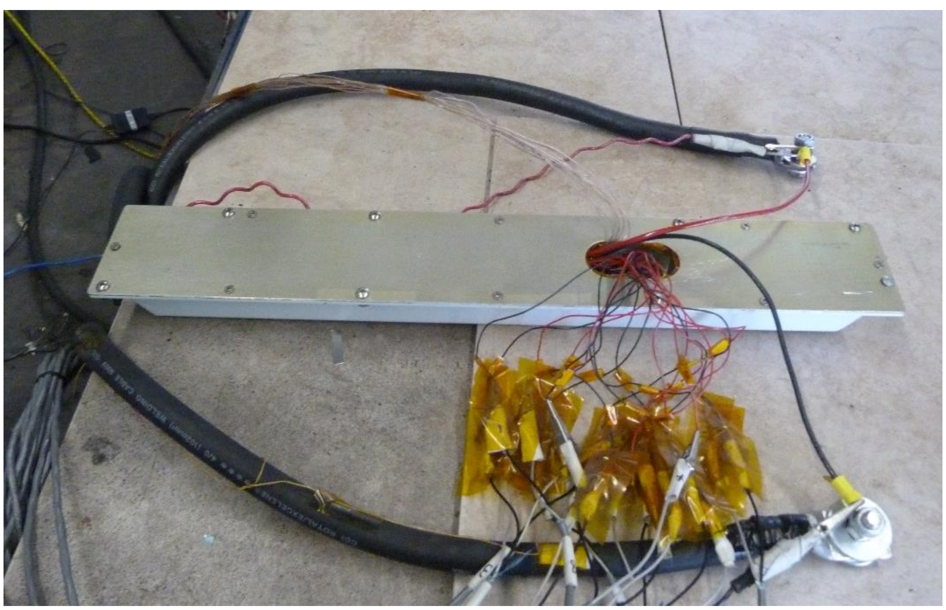
Figure 7.2-14. Voltage-current Characteristics for SAFER Battery 4S-cell Bundle External Short Test #15

7.2.4.2 10S-Cell Bundle External Short Testing

A results summary for the 10S-cell bundle external short testing are shown in Table 7.2-5. Supplementary Test #2 utilized a 10S-cell bundle, with no external PTC device and cell Schottky diodes, configured into a SAFER battery housing (Figure 7.2-15). This test configuration was similar to a previous work completed by the JSC ESTA team [28]. The 3.0-ohm external load value was chosen based on an estimate of the maximum possible power output of the 10S bundle.



a) 10S bundle test article packaged with adjacent 10S bundles. Adjacent 10S bundles served only as thermal mass simulators.



b) Completed 10S bundle with SAFER battery housing electrical and mechanical configuration.

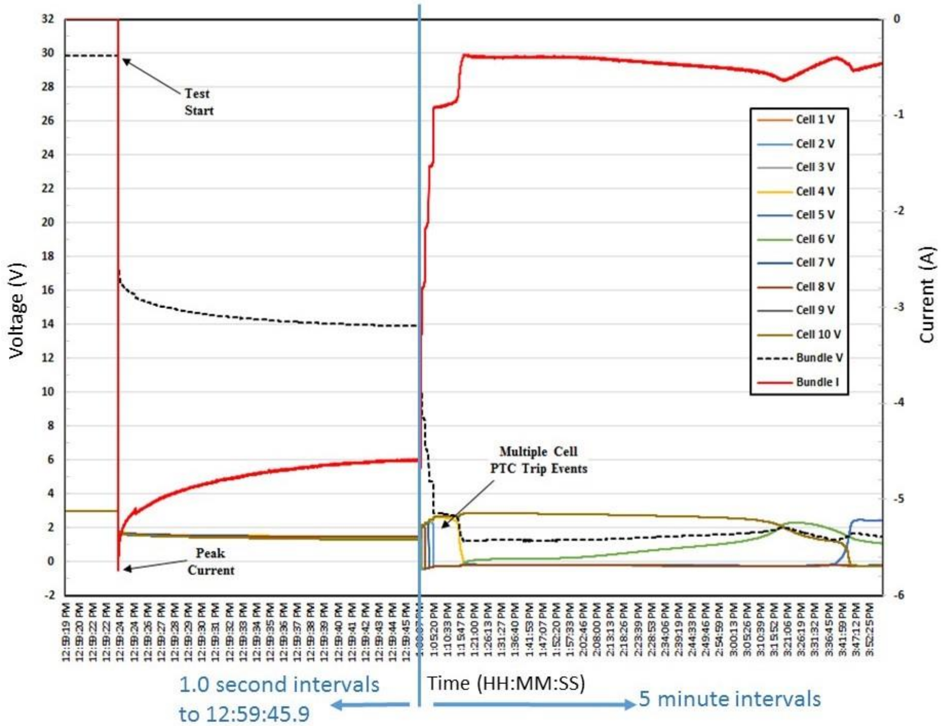
Figure 7.2-15. External Short Test Configuration Pre-test Images of Supplementary Test #2

Table 7.2-5. Summary of Results From the 10S-cell Bundle External Short Testing

Test Date (Test No)	Test Decription (Cell ID)	Cell ID	Peak Temp (°C)	Peak Current (A)	Peak Voltage (V)	Pre-OCV (V)	Post-OCV (V)	Pre AC Imp (Ω)	Post AC Imp (Ω)
7-Apr-15	25Ω, 1.1A, No PTC	1-10S		2.05	31.98	32.19	15.54	2.47	OC
(20)	Cell 034	Cell 1	64.83			3.22	1.50	0.25	OC
	Cell 041	Cell 2	70.83			3.22	1.38	0.26	OC
	Cell 045	Cell 3	83.35			3.22	2.03	0.25	1.11
	Cell 047	Cell 4	82.11			3.22	1.65	0.25	OC
	Cell 051	Cell 5	75.35			3.22	1.47	0.25	OC
	Cell 052	Cell 6	75.50			3.22	1.54	0.26	OC
	Cell 054	Cell 7	79.75			3.22	1.55	0.24	OC
	Cell 058	Cell 8	76.50			3.22	1.56	0.26	OC
	Cell 061	Cell 9	67.50			3.21	1.45	0.25	OC
	Cell 064	Cell 10	57.74			3.22	1.47	0.23	OC
8-Apr-15	25Ω, 1.1A, PTC	2-10S		2.00	30.60	30.55	12.87	2.23	OC
(21)	Cell 073	Cell 1	70.02			3.06	1.58	0.23	OC
	Cell 075	Cell 2	72.54			2.99	1.48	0.21	OC
	Cell 091	Cell 3	73.99			3.00	2.12	0.21	0.57
	Cell 093	Cell 4	83.82			3.00	1.68	0.21	OC
	Cell 095	Cell 5	75.63			3.00	1.43	0.21	OC
	Cell 098	Cell 6	80.42			3.00	1.54	0.20	OC
	Cell 101	Cell 7	73.98			3.01	0.07	0.21	OC
	Cell 121	Cell 8	76.18			3.01	1.33	0.20	OC
	Cell 132	Cell 9	67.23			3.01	0.05	0.20	OC
	Cell 134	Cell 10	63.69			3.06	1.57	0.22	OC
Test #22	9.0Ω, 3.1A, No PTC	Postponed							
Test #23	9.0Ω, 3.1A, PTC	Postponed							
9-Apr-15	1.0Ω, 3.1A, No PTC	5-10S		11.62	32.00	31.96	15.70	2.44	OC
(24)	Cell 001	Cell 1	86.18			3.07	0.96	0.22	OC
	Cell 190	Cell 2	80.95			3.22	1.50	0.26	2.54
	Cell 194	Cell 3	87.59			3.21	2.40	0.25	0.26
	Cell 195	Cell 4	88.95			3.21	2.27	0.24	0.30
	Cell 196	Cell 5	79.86			NR	1.54	NR	2.22
	Cell 197	Cell 6	62.32			3.21	1.22	0.25	OC
	Cell 198	Cell 7	84.15			3.21	2.73	0.25	0.27
	Cell 201	Cell 8	90.94			3.21	1.30	0.25	OC
	Cell 205	Cell 9	82.70			3.21	1.06	0.25	2.93
	Cell 209	Cell 10	71.50			3.21	1.03	0.25	OC
Test #25	1.0Ω, 27.5A, PTC	Postponed							
Test #26	0.50Ω, 55A, No PTC	Postponed							
Test #27	0.50Ω, 55A, PTC	Postponed							
14-Apr-15	3.0Ω, No PTC; Open-Air	3-10S		4.45	31.31	32.10	12.73	2.44	OC
	Cell 127	Cell 1	78.73			3.21	1.03	0.26	OC
	Cell 137	Cell 2	84.51			3.21	1.18	0.25	OC
	Cell 139	Cell 3	78.94			3.21	2.18	0.25	0.29
	Cell 143	Cell 4	84.64			3.22	1.43	0.24	2.68
Suppl. Test #1	Cell 151	Cell 5	79.47			3.21	0.87	0.24	OC
	Cell 154	Cell 6	88.01			3.21	1.26	0.25	OC
	Cell 156	Cell 7	87.45			3.21	1.54	0.24	OC
	Cell 157	Cell 8	69.71			3.21	1.14	0.24	OC
	Cell 161	Cell 9	81.18			3.21	1.12	0.25	OC
	Cell 163	Cell 10	73.99			3.21	1.04	0.24	OC
20-Apr-15	3.0Ω, No PTC; Housing	7-10S		5.73	29.89	31.76	16.91	2.50	OC
	Cell 035	Cell 1	96.60			3.18	2.52	0.37	0.56
	Cell 247	Cell 2	99.52			3.17	1.40	0.38	OC
	Cell 248	Cell 3	100.81			3.17	1.68	0.37	0.68
	Cell 250	Cell 4	96.75			3.17	1.39	0.38	OC
Suppl. Test #2	Cell 253	Cell 5	90.45			3.17	1.84	0.38	OC
	Cell 255	Cell 6	86.08			3.17	1.90	0.39	OC
	Cell 257	Cell 7	96.00			3.17	1.82	0.38	OC
	Cell 258	Cell 8	96.47			3.17	1.73	0.39	OC
	Cell 259	Cell 9	93.85			3.20	2.19	0.39	OC
	Cell 265	Cell 10	86.71			3.20	1.58	0.39	OC

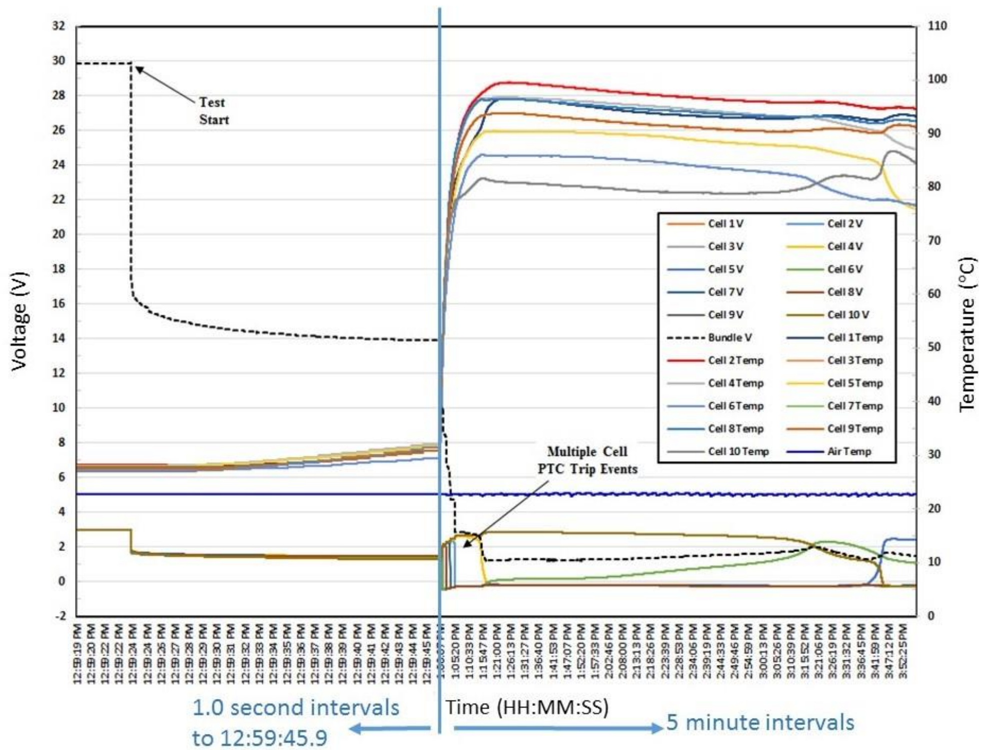
Note: No evidence of cell-level TR was observed. NR- Not recorded, and OC - Open circuit.

External short test results for Supplementary Test #2 are shown in Figures 7.2-16 and 7.2-17. After the external short was applied, the results indicated that except for Cell #10, all the individual cell internal PTC thermal fuses tripped between 30 and 90 °C. Cell #8 (cell ID#201) reached a peak of 90.9 °C, which is similar to the peak temperature of Cell #2 (ID#344) measured in the 4S-cell bundle Test #12. The internal cell PTC device for Cell #10 (ID #209) did not trip, which corresponded to the lowest peak temperature (71.5 °C) in the 10S-cell bundle string. Post-test visual inspections of the 10S-cell test article confirmed that there was no evidence of cell venting or electrolyte leakage (Figure 7.2-18). These data are similar to the SAFER battery 14S string external short test results [28].



Note: External resistive load = 3.0 ohm; no PTC device installed. All testing conducted at ambient temperature and pressure.

Figure 7.2-16. Voltage-current Characteristics for SAFER Battery 10S-cell Bundle External Short Supplementary Test #2



Note: External resistive load = 3.0 ohm; no PTC device installed. All testing conducted at ambient temperature and pressure.

Figure 7.2-17. Voltage-temperature Characteristics for SAFER 10S-cell Bundle External Short Supplementary Test #2

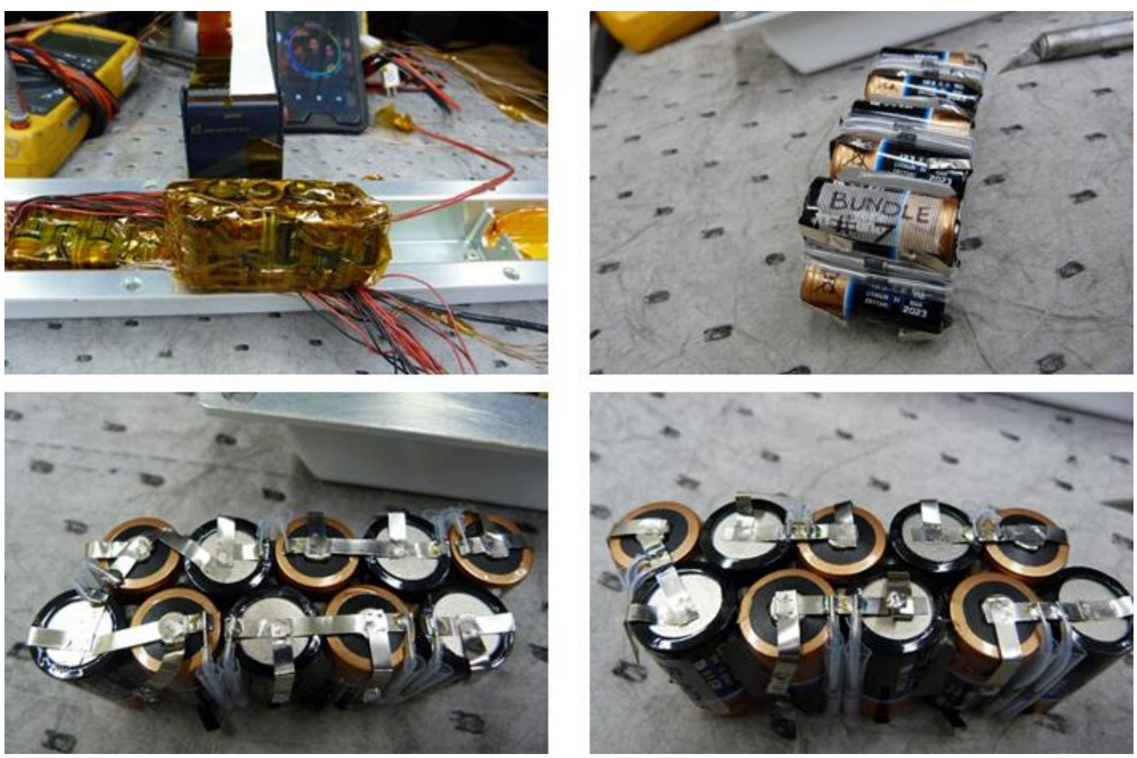


Figure 7.2-18. External Short Test Configuration Post-test Images of Supplementary Test #2 No evidence of cell venting or TR.

7.2.5 Summary and Findings

SAFER battery testing was performed to evaluate the safety risk of TR caused by an external short to the SAFER battery. Specifically, the ability of the external PTC device to protect the SAFER battery, under selected external short conditions was evaluated. (See Section 8.2, O-1 through O-4.)

7.3 Single-Cell Trigger-Cell TR Testing

7.3.1 Objectives

The objective of this testing was to characterize the COTS Duracell® Ultra® CR123 SAFER battery cell under various heater trigger test conditions. This testing enabled optimization of heater power, location, and type for the development of test procedures in support of the subsequent SAFER battery TR test phase.

7.3.2 Test Methodology

Prior to performing TR testing at the battery level, single cells were tested with different heater powers to optimize the wattage that would initiate a TR event. Trigger-cell TR tests were conducted by placing a heater on the cell housing. Trials were conducted with the heater on the cell side or on the bottom to determine its worst-case location. Various heater powers were used to experimentally determine the most effective heater input required to initiate TR. Optimizing the heater power was necessary to reduce the possibility of predisposing the surrounding cells to enter TR via heating when bundle/battery-level testing was performed.

As the cells were under test, at the moment TR occurred, the cell heater was manually deactivated so as to not continue to provide an additional source of heat input into the cell.

Single-cell trigger-cell tests were conducted at ambient and a worst-case temperature of 49 °C. The 49 °C ‘hot-case’ test condition was derived from the 38 °C maximum hot case thermal environment the battery could be exposed to during the mission, plus an 11 °C thermal analysis uncertainty margin [29,30]. Test articles were subjected to the test temperature for at least 1 hour prior to commencing the tests, and were actively maintained at the test temperature ±3 °C to the point in time when the cell heaters were activated.

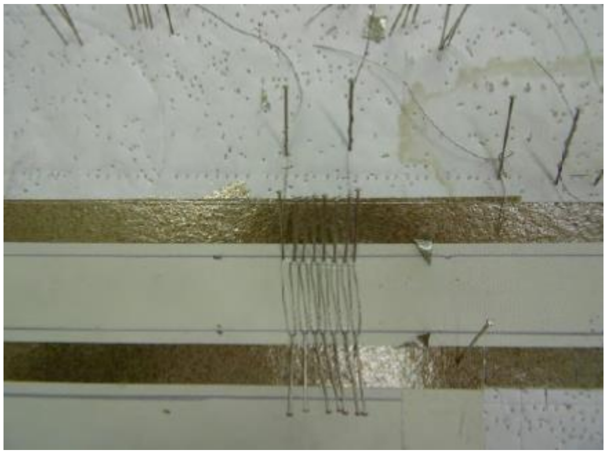
A summary of the test conditions and results are shown in Table 7.3-1. Test articles were randomly chosen from cells successfully screened to the cell acceptance test (Section 7.1), which was based on the ISS Lot Acceptance Test criteria [5]. Two cells were tested at each set of conditions to replicate results. In some cases, the heater power and location was adapted based on results from prior tests. These modifications were to add tests that could provide additional data as required, or to eliminate tests that were deemed no longer necessary.

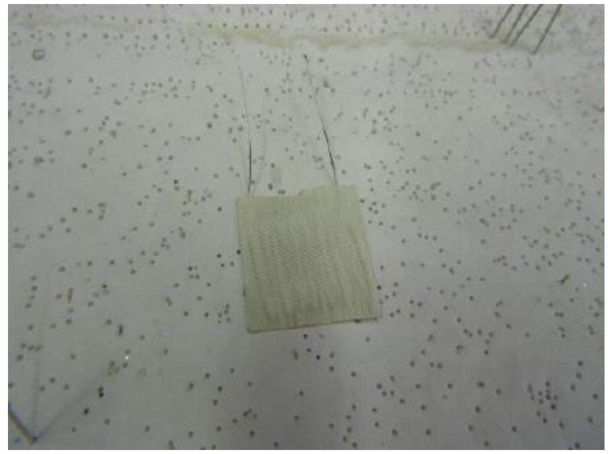
Table 7.3-1. Test Conditions and Results for Single-Cell Trigger-Cell Tests

Trial Run	Cell ID	Heater Power (W)	Heater Location	Cell Temp (°C)	Time to TR (min)	Cell Jacket Temp at Start of TR (°C)	Max Cell Jacket Temp (°C)	Max Positive Terminal Probe Temp (°C)	Comments
1	53	15	Bottom	Ambient	-	-	~ 161	N/A	No thermal runaway after 44 min
1	70	15	Bottom	Ambient	~ 22	~ 199	~ 575	N/A	
2	44	15	Side	Ambient	~ 11	~ 180	~ 733	N/A	
2	50	15	Side	Ambient	~ 9	~ 158	~ 518	N/A	
3	119	10	Bottom	Ambient	-	-	~ 120	-	No thermal runaway after 1 hr
3	123	10	Bottom	Ambient	-	-	~ 119	-	No thermal runaway after 1 hr
4	129	10	Side	Ambient	-	-	~ 143	-	No thermal runaway after 1 hr
4	133	10	Side	Ambient	-	-	~ 162	-	No thermal runaway after 1 hr
5	142	20	Bottom	Ambient	~ 8.5	~175	~ 621	~632	
5	167	20	Bottom	Ambient	~ 8.3	~172	~ 645	~882	
6	169	20	Side	Ambient	~ 5.7	~209	~ 734	~409	
6	175	20	Side	Ambient	~ 6.5	~204	~ 684	~532	
7	406	25	Bottom	Ambient	~ 7	~155	~ 661	~ 275	
7	419	25	Bottom	Ambient	~ 6.3	~ 177	~649	~ 1158	Heater power unstable
8	208	25	Side	Ambient	~ 4.7	~ 182	~ 582	~ 340	
8	402	25	Side	Ambient	~ 5	~ 176	~ 608	~ 437	
12	216	15	Side	49	~ 9:31	~ 250	~ 746	~ 690	False start @ < 00:00; Heater not connected
12	246	15	Side	49	~ 7:19	~ 198	~ 569	~ 430	Clamp TC faulty
16	252	20	Side	49	~ 5:23	~ 178	~ 735	~562	
16	308	20	Side	49	~ 6:10	~ 178	~ 585	~ 652	
18	312	25	Side	49	~ 4:16	~ 170	~ 577	~ 502	
18	318	25	Side	49	~ 3:51	~ 228	~ 717	~ 552	False start @ < 00:00; Heater not connected
22a	251	35	Side	Ambient	~ 2:26	~ 186	~ 700	N/A	
22a	522	35	Side	Ambient	~ 2:45	~ 173	N/A	N/A	Heater appears to have shorted
23a	579	40	Side	Ambient	~ 2:22	~ 216	N/A	N/A	Lost jacket temp after ~ 230°C
23a	839	40	Side	Ambient	~ 1:54	~ 170	~ 730	N/A	Heater appears to have shorted
S12	17	35	Side	Ambient	~ 2:18	~ 134.8	~ 851	N/A	Spare cell; Ceramic heater (6.526 Ω DMM, 6.8 Ω data); TC on cell jacket
S13	135	35	Side	Ambient	~ 2:14	~ 170.2	~ 694	N/A	Spare cell; Ceramic heater (6.417 Ω DMM, 6.5 Ω data); TC on cell jacket
S14	25	35	Side	Ambient	~ 3:10	~ 155	~ 668	N/A	Spare cell; Ceramic heater (12.47 Ω DMM, 7.2 Ω data); TC on cell can; Op Error
S15	78	35	Side	Ambient	~ 2:48	~ 146.9	~ 599	N/A	Spare cell; Ceramic heater (7.49 Ω DMM, 7.2 Ω data); TC on cell can
22b	128	35	Side	Ambient	~ 2: 47	~ 348	~ 492	N/A	Ceramic heater (6.56 Ω DMM, 6.4 Ω data); TC on cell can; Cell can TC too close to heater
22b	315	35	Side	Ambient	~ 2:06	~ 169	~ 1280	N/A	Ceramic heater (6.713 Ω DMM, 6.6 Ω data); TC on cell can
23b	381	40	Side	Ambient	~ 2:07	~ 130	~ 622	N/A	Ceramic heater (6.88 Ω DMM, 6.8 Ω data); TC on cell can
23b	706	40	Side	Ambient	~ 2:07	~ 175	~ 827	N/A	Ceramic heater (9.89 Ω DMM, 7.0 Ω data); TC on cell can
22c	26	35	Side	Ambient	~ 2:27	~ 173	~ 655	~ 375	Ceramic heater (7.1 Ω DMM, 6.9 Ω data); TC on cell can
22c	266	35	Side	Ambient	~ 2:18	~ 125	~ 551	~ 619	Ceramic heater (6.8 Ω DMM, 6.9 Ω data); TC on cell can
23c	486	40	Side	Ambient	~ 2:00	~ 163	~ 700	~ 216	Ceramic heater (6.9 Ω DMM, 6.9 Ω data); TC on cell can
23c	740	40	Side	Ambient	~1:40	~ 110	~ 213	~ 605	Ceramic heater (7.2 Ω DMM, 7.0 Ω data); TC on cell can; Cell OCV 3.02 V (low); Heater Current = ~ 5A startup then ~ 2.3A

7.3.3 Single-Cell Trigger-Cell Test Set-up

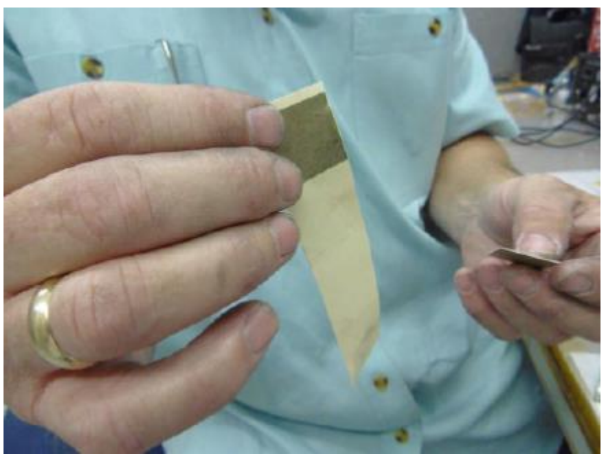
Two different types of heaters (i.e., patch and ceramic) were used for the testing. Initially, a patch heater was used, which functioned reliably for heater powers below 35 W. The patch heater consists of nichrome wire looped in a serpentine pattern (Figure 7.3-1a), which was positioned in between two pieces of thermosettable glass cloth tape (Figure 7.3-1b). A sheet of mica was affixed to the heater top and the assembly was further wrapped in glass cloth tape (Figure 7.3-2a). Insulated copper wires were soldered onto the heater wire ends and wrapped in glass tape to complete the heater assembly (Figure 7.3-2b) [31]. The patch heater design was successfully used in the SAFER battery TR Tests #1 and #2.





a) *b)*

Figure 7.3-1. Part a) Loops of nichrome wire on glass tape during heater assembly. Part b) Nichrome wire sandwiched between glass tape

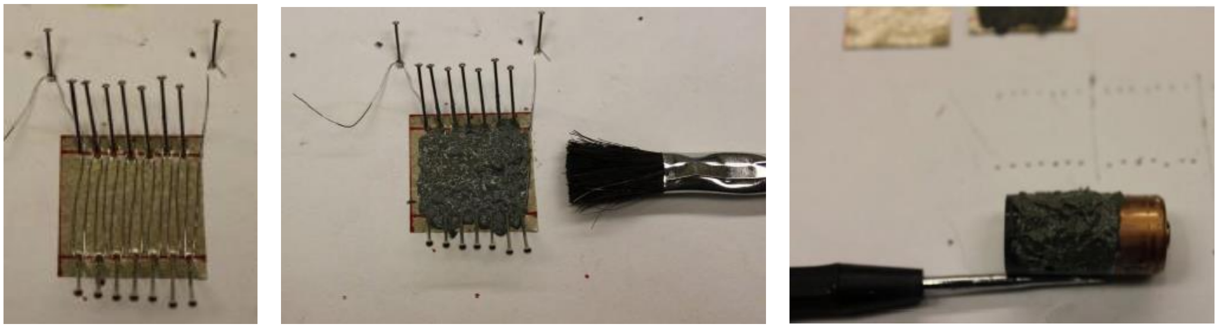


a) *b)*

Figure 7.3-2. Part a) Mica on heater top to be wrapped in glass tape. Part b) Completed patch heater.

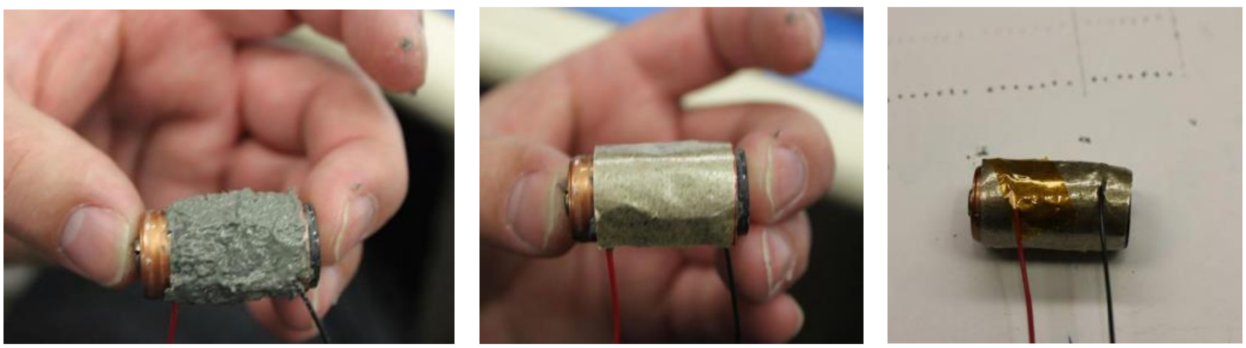
When it became necessary to use higher power to more rapidly initiate a TR event, the patch heater was no longer adequate to provide stable current at high power. Based on previous JSC ESTA test experience, a ceramic heater design was identified for use at power levels above 35 W. The ceramic heater design was successfully used in the SAFER battery TR Tests #3 and #4.

The ceramic heater consists of nichrome wire looped in a serpentine pattern (Figure 7.3-3a) on a sheet of mica paper. A high-temperature alumina ceramic-based adhesive and sealant putty was then applied onto the nichrome wire (Figure 7.3-3b), and allowed to dry for 12 hours. Insulated copper wires were twisted around the heater wires. Additional putty was applied to the cell in an area equivalent to the heater size and allowed to dry (Figure 7.3-3c). The heater was positioned on the putty covered cell with the wires facing outwards. Putty was applied to fill cracks and other discontinuities and allowed to dry (Figure 7.3-4a). The heater was then covered with additional mica paper (Figure 7.3-4b). Finally, mica tape was used to cover the entire cell/heater arrangement and secured with Kapton® tape (Figure 7.3-4c). The ceramic heater fabrication cycle required several days for each test article.



a) b) c)

Figure 7.3-3. Part a) Loops of nichrome. Part b) Nichrome wire covered with sealant putty. Part c) Cell covered with sealant putty and mica paper.



a) b) c)

Figure 7.3-4. Part a) Putty applied to cell. Part b) Mica paper covering heater. Part c) Mica tape covering cell, secured by Kapton® tape.

Figure 7.3-5 shows a comparison of patch and ceramic heater operating at 35 W. The start time for all heaters is normalized to time "zero." Cells ID# 251 and 522, which used the patch heater, the heater power began increasing about midway during the run. Cell ID# 522 heater shorted at some point during the run as the data indicated a lack of control with exponentially increasing power toward the end of the run. Cell ID# 026, 128, 266, and 315 ceramic heaters performed more consistently.

For the test set-up, the cell was fastened to an aluminum block using a hose clamp. The aluminum block was anchored to a table. Low thermal conductivity felt with high temperature stability (i.e., FiberFrax® Durafelt™) was used to thermally insulate the cell from the block and the clamp. A patch heater was installed either on the cell side (i.e., between the cell and block), or on the cell bottom. A thermocouple was installed on the cell side, located between the cell and clamp. This thermocouple location was on the opposite cell side from the heater in cases where heaters were not on the cell bottom. Thermocouples were attached to the aluminum block and the clamp and were suspended in the air. In later tests, an additional thermocouple was placed near the positive cell terminal to measure the ejected cell content temperature during a TR event.

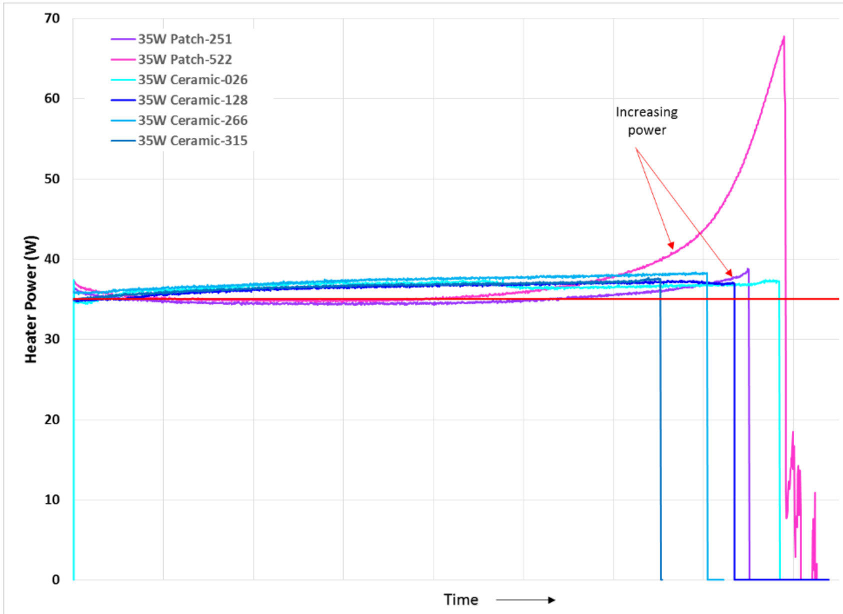


Figure 7.3-5. Comparison of Patch and Ceramic Heater Performance at 35 W

Figure 7.3-6 shows a diagram of the test set-up with heater and thermocouple locations. In Figure 7.3-7, these features are annotated on a cell image within the test set-up.

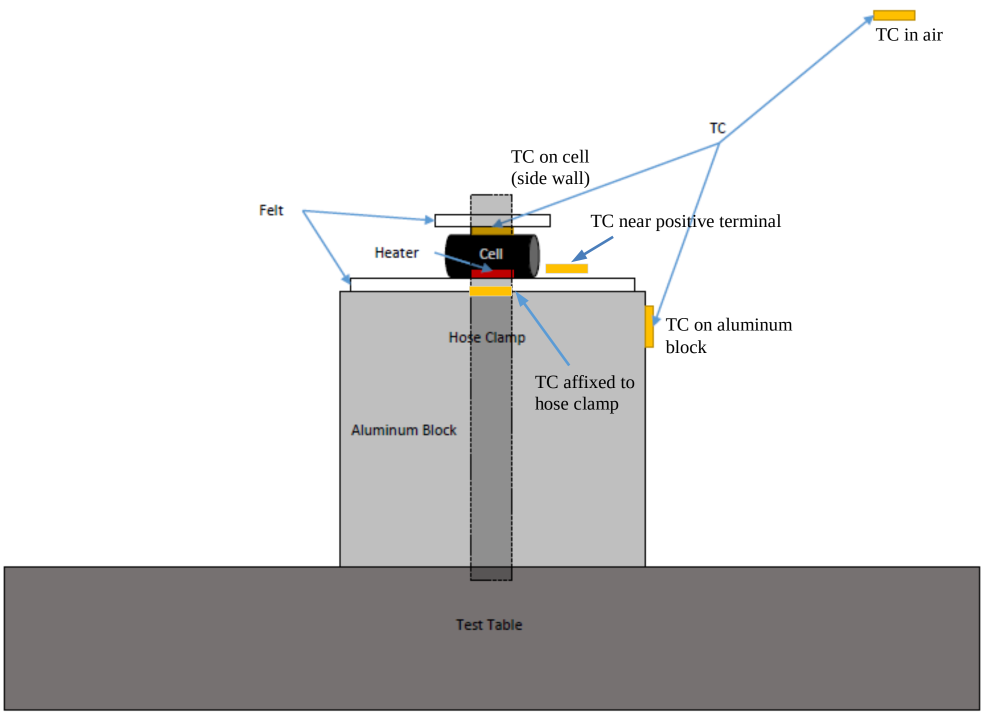


Figure 7.3-6. Diagram of Test Set-up, Heater, and Thermocouple Locations

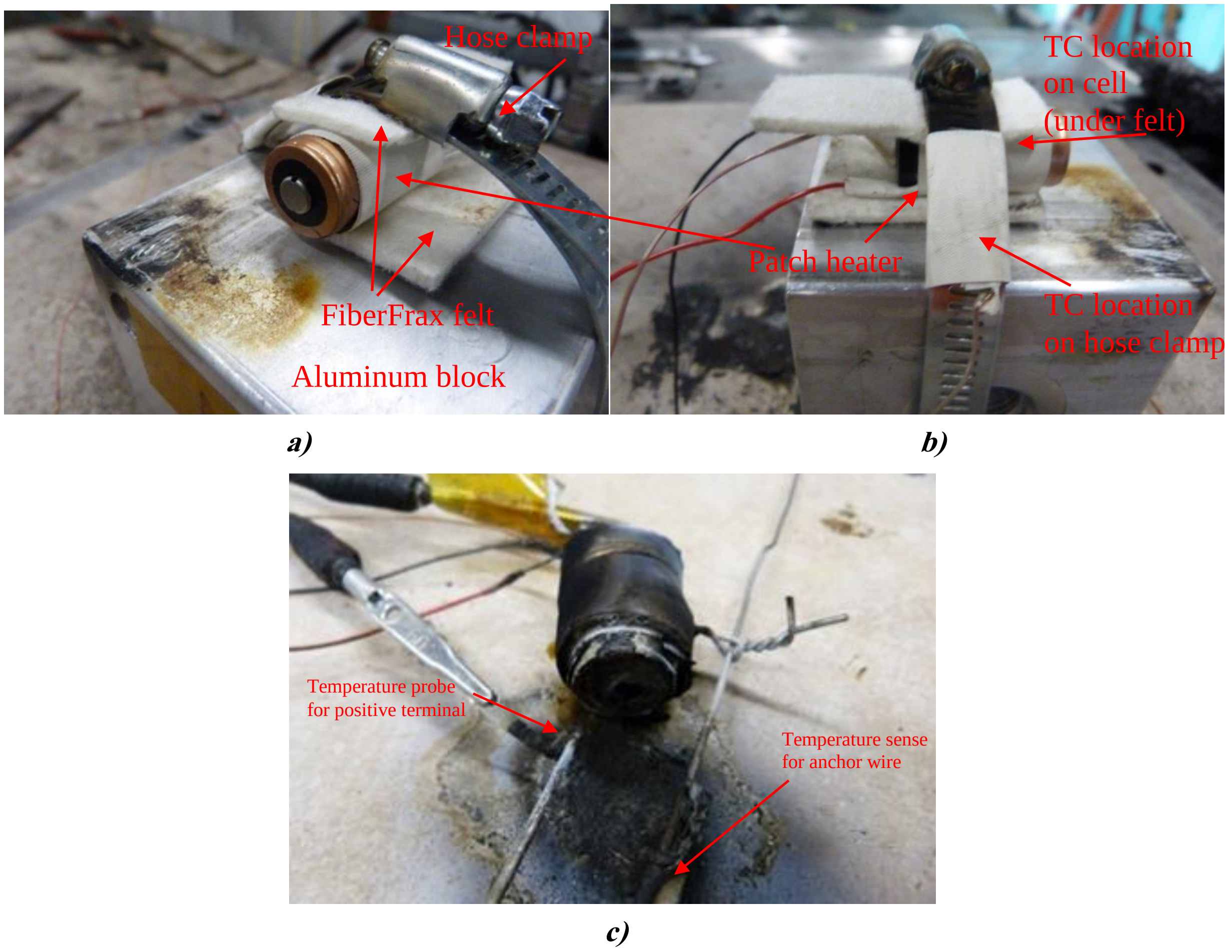


Figure 7.3-7. Test Set-up, Heater, and Thermocouple Locations

For tests in which the plan called for the cell to be at 49 °C, the cells were: outfitted with a heater, thermocouples, clamp, and insulating felt and placed in a 49 °C thermal chamber for 15 hours minimum. The cells were then transferred to an open-air test area where they were placed on a hotplate set to 49 °C. Insulating felt and a plastic bin were placed over the cell to maintain temperature while the cell was electrically connected. The total transfer time from the thermal chamber to the test cell was under 5 minutes.

For installation ease and test engineer safety, an anchor wire was used in lieu of the aluminum block and hose clamp to secure the cell in the test area for the bulk of the hot test cases, and for ambient tests that were chronologically run after the hot cases. Figure 7.3-8 shows an insulated cell at 49 °C being readied for testing.

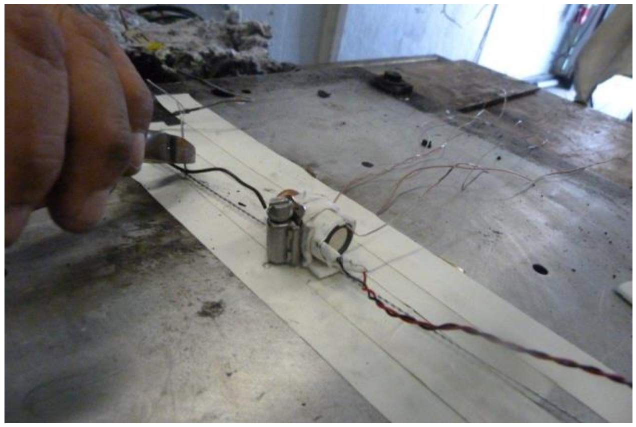


Figure 7.3-8. Cell on a 49 °C Hotplate Being Prepared for Testing

Table 7.3-2 shows the key thermal events for the major cell constituent materials in the Duracell® Ultra® CR123. These data can lend insight into the temperatures at which individual cell components began to breakdown.

Table 7.3-2. Key Thermal Events for Major Cell Constituent Materials

Temperature (°C)	Event
85	Boiling point of 1,2 dimethoxyethane
135	Melting point of polypropylene
180	Melting point of Li
236	Melting point of lithium perchlorate
242	Boiling point of propylene carbonate
243	Boiling point of ethylene carbonate
300	Decomposition of carbon black
423	Melting point of lithium trifluoromethane sulfonate
535	Decomposition of manganese dioxide

7.3.4 Single-Cell Heater Trigger-Cell Test Results

The general sequence of events associated with a typical single-cell heater trigger test is shown in Figure 7.3-9. The corresponding trigger-cell temperature response during test is shown in Figure 7.3-10. Time shown in video are not synchronized with data acquisition time stamp. These data and images are for Cell ID#044, which had a patch heater with a 15-W power level attached to its side. Cell temperature corresponds to the cell jacket temperature.

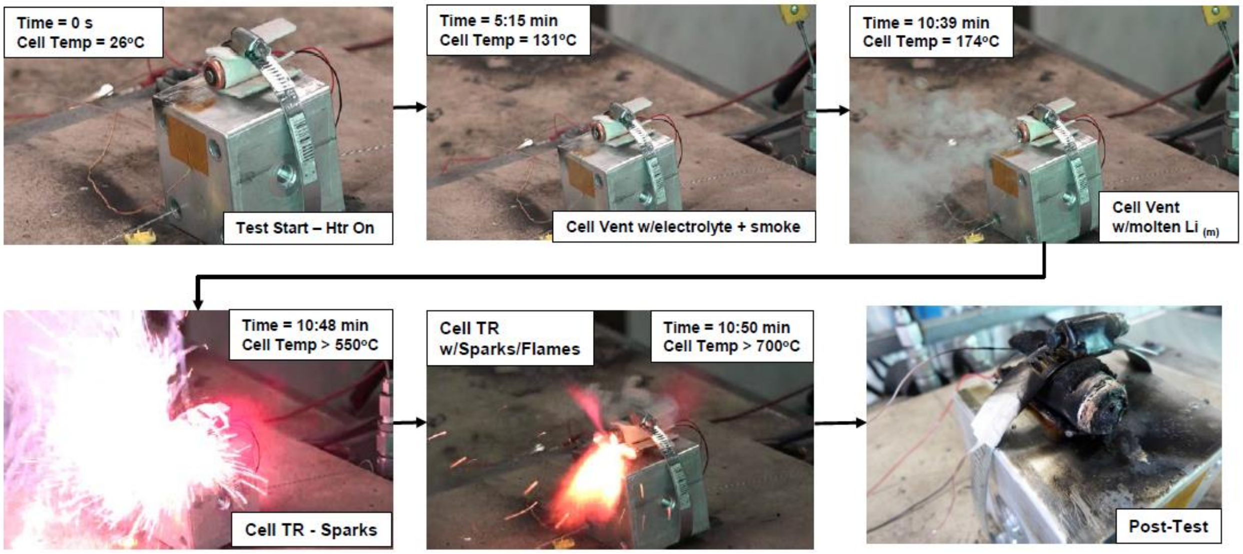


Figure 7.3-9. Representative cell Response to Trigger-cell Testing Leading to TR Event (Cell ID#044)

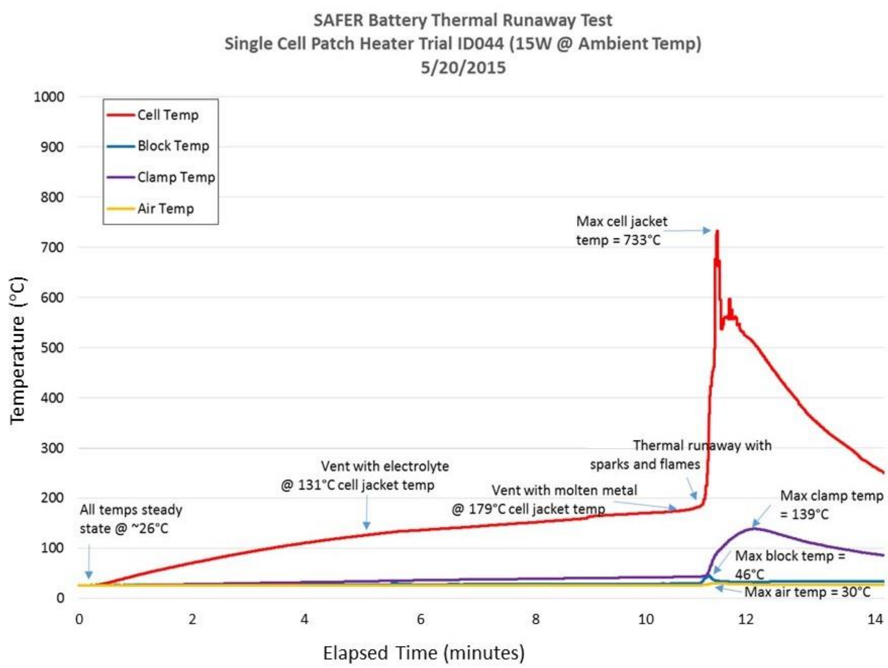


Figure 7.3-10. Temperature Response in Trigger Cell at Ambient Temperature with 15-W Heater

The cell temperature was 26 °C at the test start. At 5:25 minutes after the heater was turned on, the cell vented with electrolyte and smoke. The measured cell temperature at this point was 131 °C. Note the cell core temperature could be at least 10 °C hotter than the jacket temperature at the thermocouple location [32]. At 10:65 minutes and 174 °C, the cell ejected molten Li. The TR event occurred at 10:48 minutes and >550 °C. Immediately following the TR event , ejecta was accompanied by flames, and the cell temperature had risen to over 700 °C. Flames were visible for approximately 1 minute after the TR event. The cell case remained intact with no internal components being ejected.

Based on experience from prior NESC Li cell TR studies [33], the assessment team deduced the time to achieve TR in this case was too long and would likely cause adjacent cell heating prior to a trigger-cell TR event in a bundle level test. Hence, the target time for a single cell to achieve TR was established at between 2 and 3 minutes. The single-cell trials were continued at varying power levels to attempt to achieve TR within the target time. Heater powers of 20 and 30 W were initially chosen for battery level tests. Based on those test results (see Section 7.4), a 35-W heater was used.

Data for several representative tests are given in Figures 7.3-11 through 7.3-15.

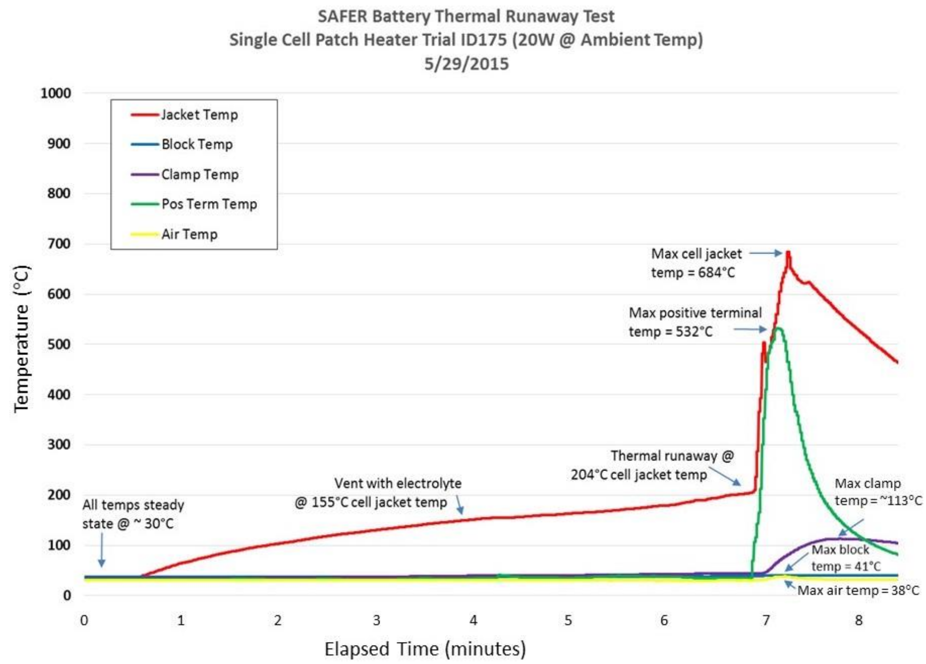


Figure 7.3-11. Temperature Response in Trigger Cell at Ambient Temperature with 20-W Heater

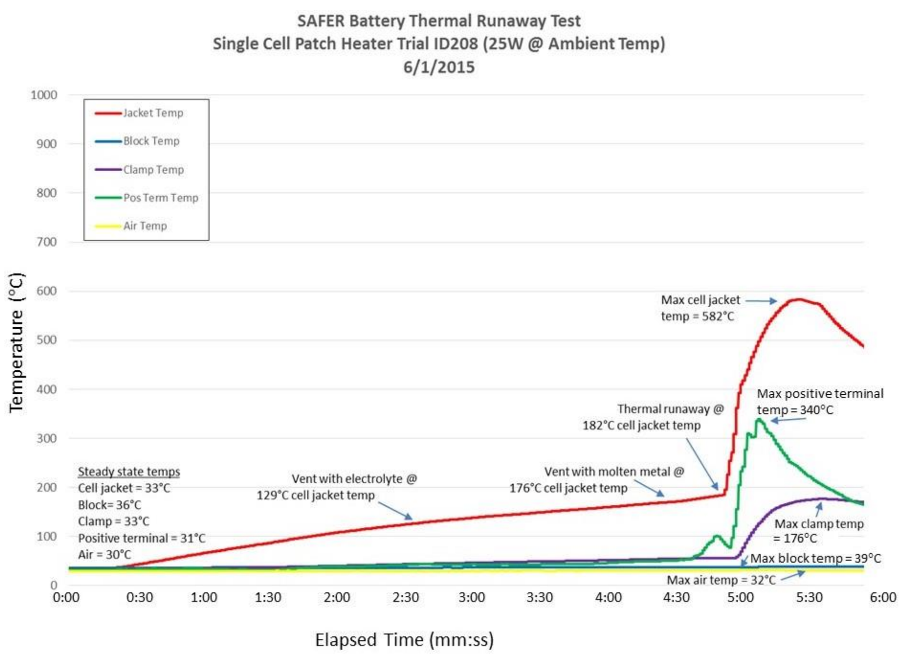


Figure 7.3-12. Temperature Response in Trigger Cell at Ambient Temperature with 25-W Heater

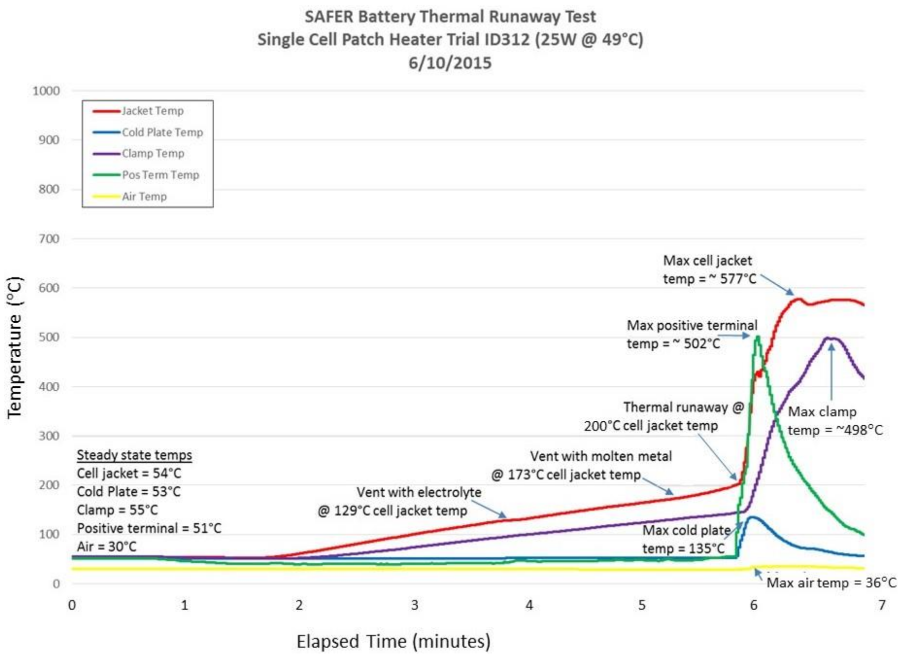


Figure 7.3-13. Temperature Response in Trigger Cell at 49 °C with 25-W Heater

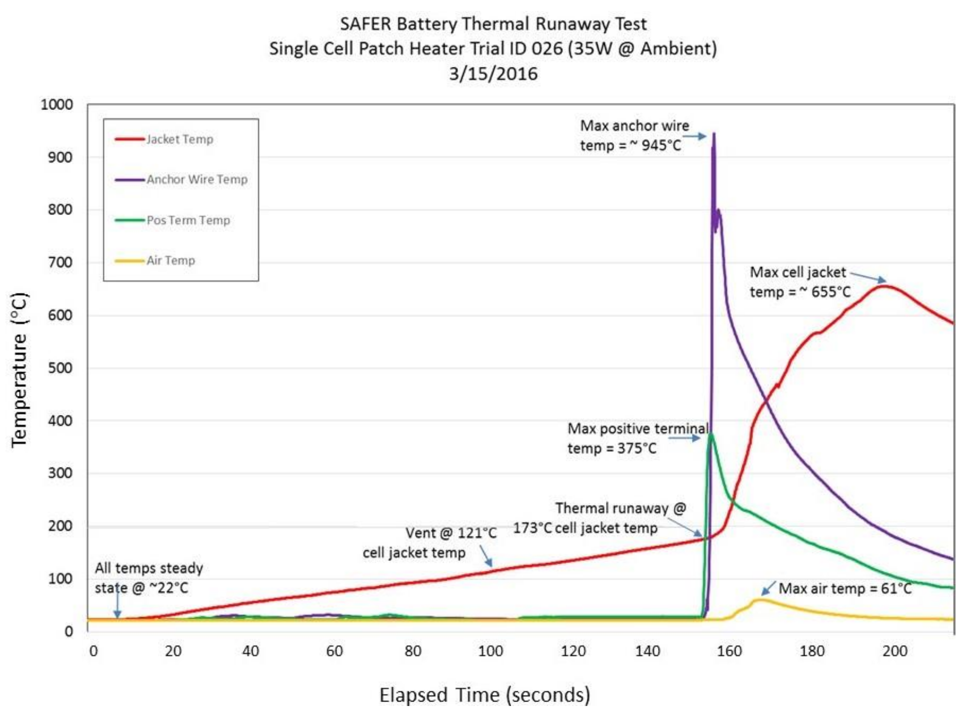


Figure 7.3-14. Temperature Response in Trigger Cell at Ambient Temperature with 35-W Heater

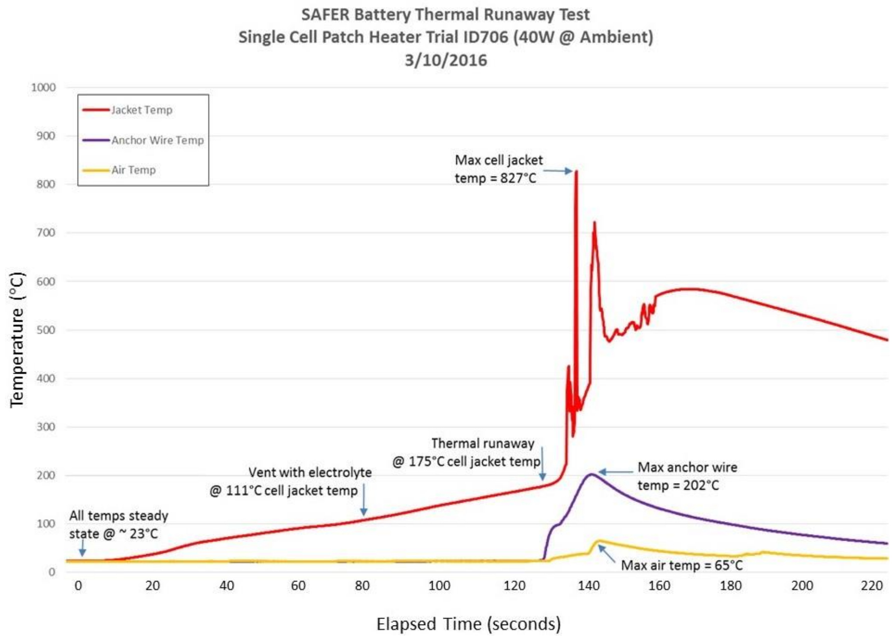


Figure 7.3-15. Temperature Response in Trigger Cell at Ambient Temperature with 40-W Heater

The effect of heater power and location and cell starting temperature (i.e., ambient versus 49 °C) on TR temperature for the single cell heater trigger tests is shown in Figure 7.3-16. The results indicate the TR temperature was not affected by cell starting temperature variations. The effect of heater power on the maximum cell jacket temperature and time to TR is shown in Figure 7.3-17. These results indicate that as heater power is decreased, the time to TR increases. In addition, the maximum cell jacket temperature does not vary significantly with heater power.

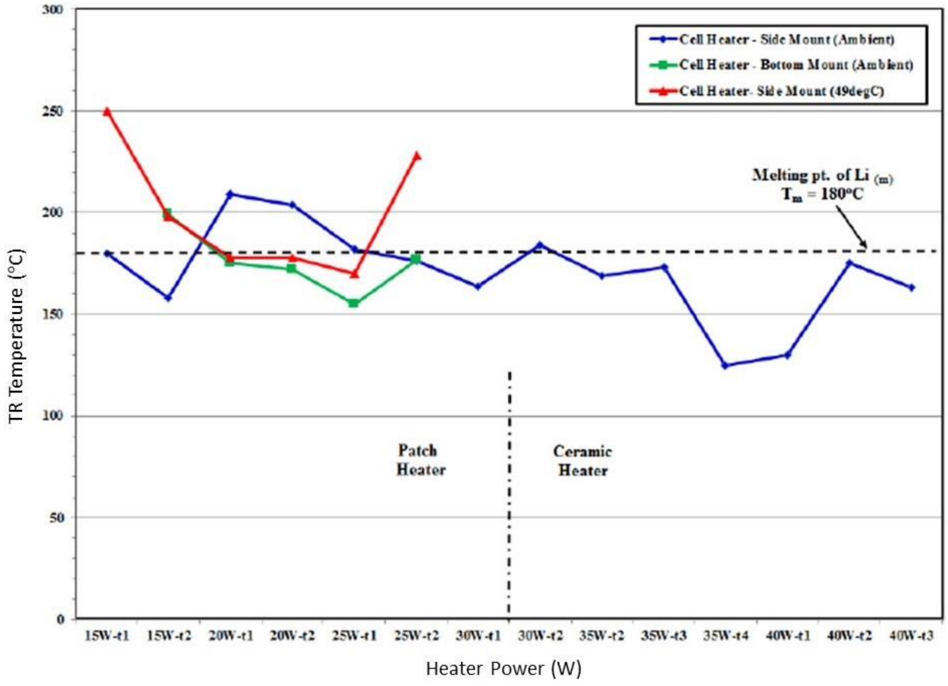


Figure 7.3-16. Effect of Heater Power, Heater Location, and Starting Temperature on TR Temperature for the Single Cell Heater Trigger Tests

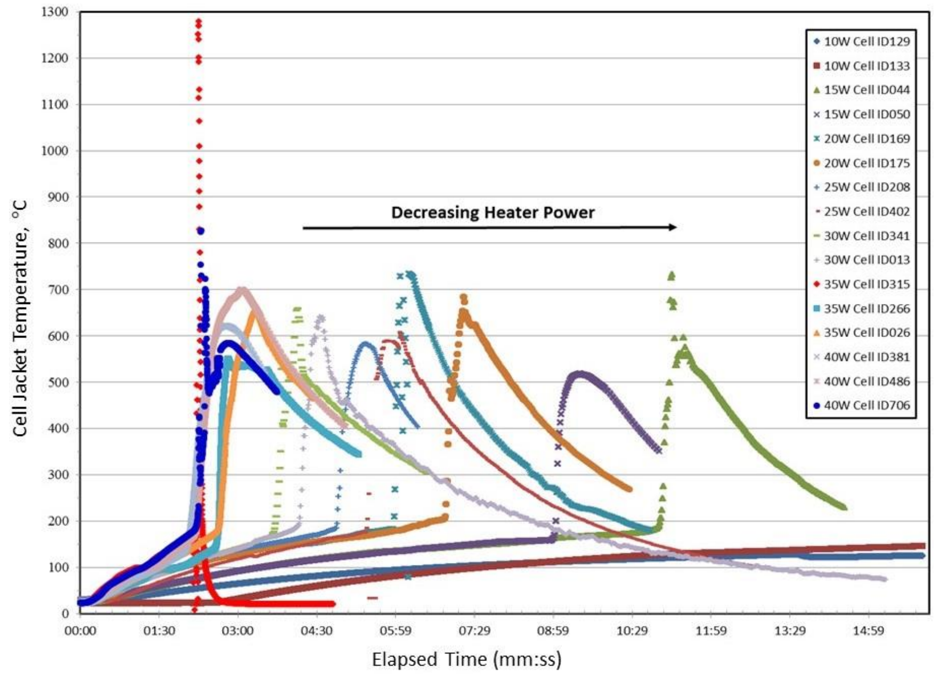


Figure 7.3-17. Effect of Heater Power on the Maximum Cell Jacket Temperature and Time to TR

7.3.5 Summary and Findings

Single cell heater trigger-cell testing was conducted on SAFER battery cells to determine the optimal heater power setting and heater location to initiate TR. Ultimately, 35 W was determined to be the ideal heater power to initiate a TR event within the SAFER battery design. (See Section 8.1, F-4 through F-6.)

7.4 Battery TR Testing

7.4.1 Objectives

The objective of this testing was to quantify severity and evaluate the extent of cell-to-cell TR propagation from a single-cell TR event. The approach was to:

- Conduct worst-case testing with flight-like SAFER battery test article and interfaces.
- Conduct tests at ambient temperature and pressure.
- Utilize results from single-cell heater trigger testing.
- Avoid over-test (false-positive case) condition(s).

7.4.2 Experimental

Trigger-cell location within the SAFER battery was analyzed by considering the SAFER battery cell packaging design and previous lessons learned from NESC-sponsored EMU Li-Ion battery testing [33]. Based on the results of this analysis, five candidate trigger-cell locations were identified to best support worst-case battery-level TR testing (Figure 7.4-1).

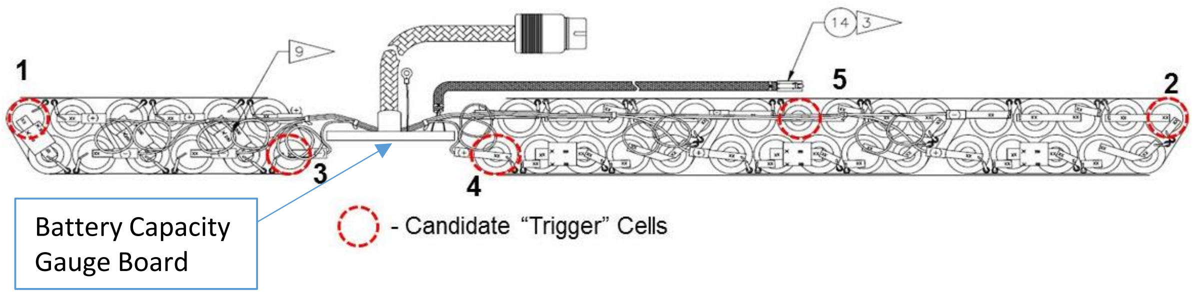


Figure 7.4-1. Trigger-cell Locations for Battery-level Over-temperature Testing

Selection of trigger-cell locations which represented the worst-case for thermal heat transfer within the battery design was based on the following rationale:

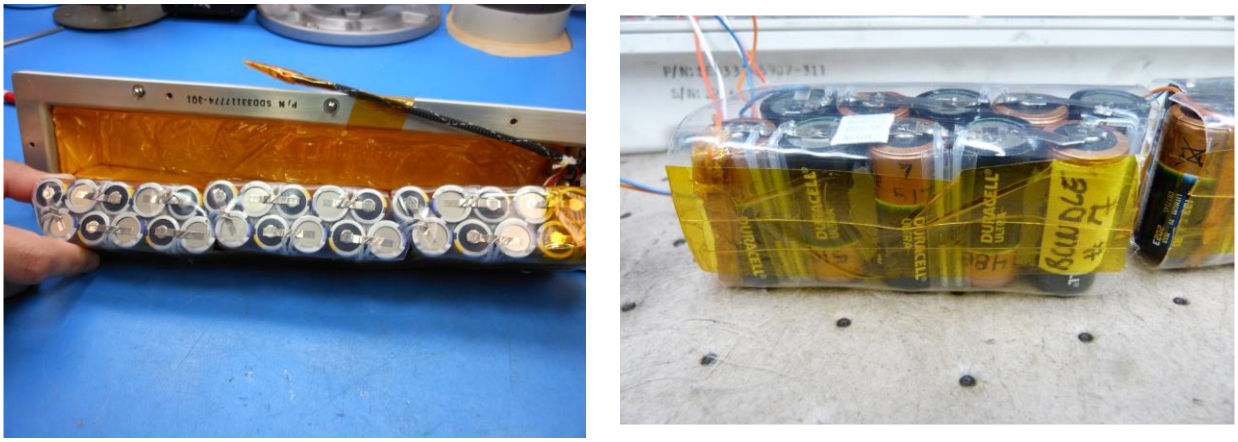
1. Trigger cells are placed in both 4S and 10S sides of battery
2. Trigger cell(s) with fewest adjacent cells (i.e., Positions #1, #2, #3, and #4).
   - From previous NASA studies, it was determined that trigger-cell locations with fewer adjacent cell(s) reduce likelihood of thermal biasing (over-test) test condition [34].
3. Positions #3 and #4 are nearest to gauge board.
4. Trigger-cell Position #5 location is closest to SAFER flight heritage temperature sensor location

Based on these analyses, trigger cells were located in Position #1 for Battery TR Tests #1, #2 and #3. The trigger cell was located in Position #2 for Battery TR Test #4. The battery pack volume containing the gauge board and wiring is 8.97 cm long × 6.35 cm wide × 4.97 cm deep, with a 0.23-cm wall thickness. Therefore, the spacing between the 4S and 10S bundles is 8.97 cm, which is critical in analyzing bundle-to-bundle propagation.

The second decision regarding the test configuration was the trigger-cell heating method to produce TR conditions. This topic is discussed in Section 7.3. The heater levels chosen were: 20 W for Test #1, 30 W for Test #2, and 35 W for Tests #3 and #4.

To best simulate the relevant SAFER battery flight unit configuration and environment, battery-level heater trigger testing with a SAFER unit mass simulator was conducted. The test articles were assembled in a 'flight-like' configuration.

Figures 7.4-2 and 7.4-3 show cell assembly and bundling, the SAFER flight unit battery pack assembly on the left, and the test articles on the right. Every effort was made to simulate the flight hardware configuration. However, as indicated the environment was ambient temperature and pressure.



a) Flight configuration. ***b) Flight-like configuration.***

Figure 7.4-2. Cell Assembly and Bundling in Flight Unit (left) and Test Unit (right)

a) Flight configuration. ***b) Flight-like configuration.***

Figure 7.4-3. Assembly of Battery Packs, Flight Unit (left) and Test Unit (right)

During Tests #1 and #2 post-test battery cell effluent combustion and ejecta were observed. It was assessed the combustion contributed to a non-flight-like situation that constituted an over-test. Therefore, it was determined that an interface plate was necessary to avoid post-test combustion. A flight-like SAFER mass simulator interface was designed and added to the battery pack for Tests #3 and #4 that restricted the access of ambient air (i.e., oxygen source) to the test article. Keeping in mind the SAFER battery is also stowed in the pressurized volume and hence testing at worst case in air was performed. Figure 7.4-4 shows the flight-like SAFER mass simulator interface compared to the SAFER flight interface.

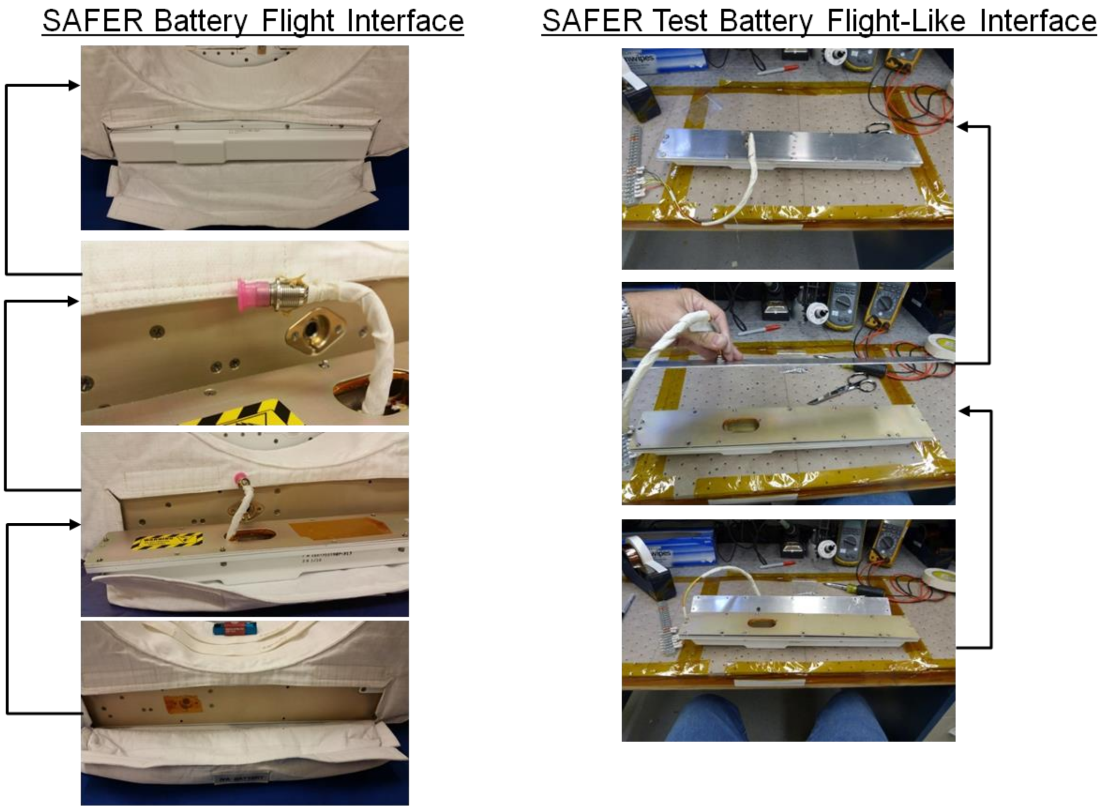


Figure 7.4-4. SAFER Flight Unit (left), and Test Unit (right), with the Mass Simulator Interface

Table 7.4-1 shows the test type and condition for the battery-level trigger-cell over-temperature testing. For each test run, the trigger cell was heated to initiate TR while the battery was contained within its housing in the flight configuration. The heater power, trigger-cell locations, and test temperature selection are indicated.

Table 7.4-1. 14S-3P Battery-level TR Trigger-cell Over-temperature Characterization Test Matrix

Test #	Trigger-cell Location	Heater Power (W)*	Heater Location*	Temperature*	Interface Plate	Estimated Test Duration (hour)	No. of Test Articles	Status
1	1	20	Side	Ambient	No	1	1	Completed 6/18/15
2	1	30	Side	Ambient	No	1	1	Completed 7/1/15
3	1	35	Side	Ambient	Yes	1	1	Completed 4/27/16
4	2	35	Side	Ambient	Yes	1	1	Completed 5/25/16

* Recommendations based on the results of the single-cell over-temperature trigger heater testing.

Originally, eight tests were planned. However, after conducting the first four tests of which Tests #3 and #4 were of greatest value, the assessment objectives were met and testing was terminated.

Unless otherwise specified, temperature sensors were placed in the same locations on the cells and within the battery as they are placed for external short-circuit testing. In addition to recording heater voltage and current, the temperature of the environment in close proximity to the test article was monitored and recorded. Video monitoring was recorded for all trigger-cell over-temperature testing.

7.4.3 Discussion of Results

Four SAFER battery-level TR tests were performed between June 2015 and May 2016. These tests will be summarized in the order performed.

Test #1 – 20-W heater on cell in Position #1

Figure 7.4-5 shows trigger-cell and thermocouple locations for Test #1, which utilized a patch heater on the designated trigger cell.

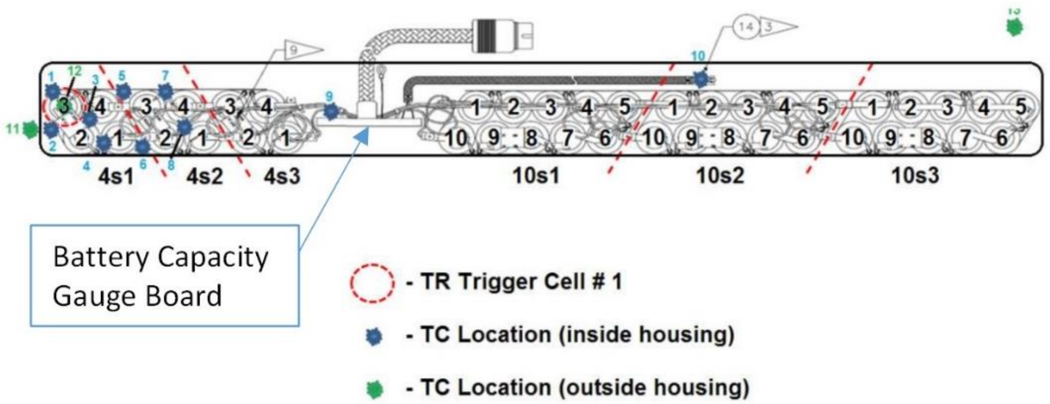


Figure 7.4-5. Test #1 Trigger-cell and Thermocouple Locations

Cells were bundled and the battery pack was assembled in a flight-like configuration. Assembly images are shown in Figure 7.4-6. Note there was a relatively large opening over the gauge board that served as feed-through for the voltage sense lines and thermocouple outputs.

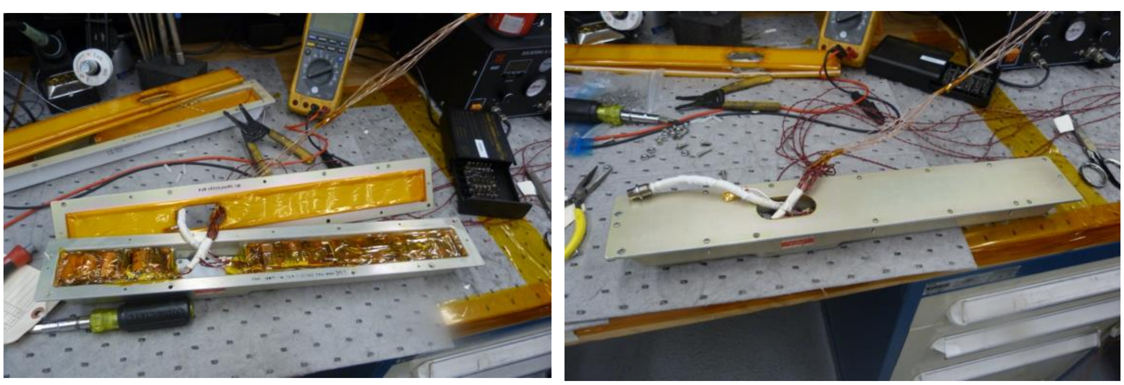


Figure 7.4-6. Test #1 Assembly

Trigger-cell temperature and voltage readings for Test #1 are shown in Figure 7.4-7. The heater power was applied at about 2 minutes, and trigger-cell TR occurred at about 13 minutes, at which time the heater power was turned off. Trigger-cell maximum temperature was approximately 850 °C. Voltage drop of the 4S1 bundle occurs at about 7 minutes, indicating the cell had vented. Voltage drop of the 10S bundle side occurs at approximately 13 minutes, indicating that an external shorting path had occurred, leading to electrical discharge of the 10S bundle side cells.

Thermocouple temperature data from Test #1 is given in Figure 7.4-8. Note that, except for the "free air" and housing temperatures, the maximum temperatures for most thermocouples was in excess of 800 °C. There is some noise in the thermocouple measurements, which causes spikes in temperature values in excess of 1000 °C. However, it is very unlikely the actual temperatures reached this high level.

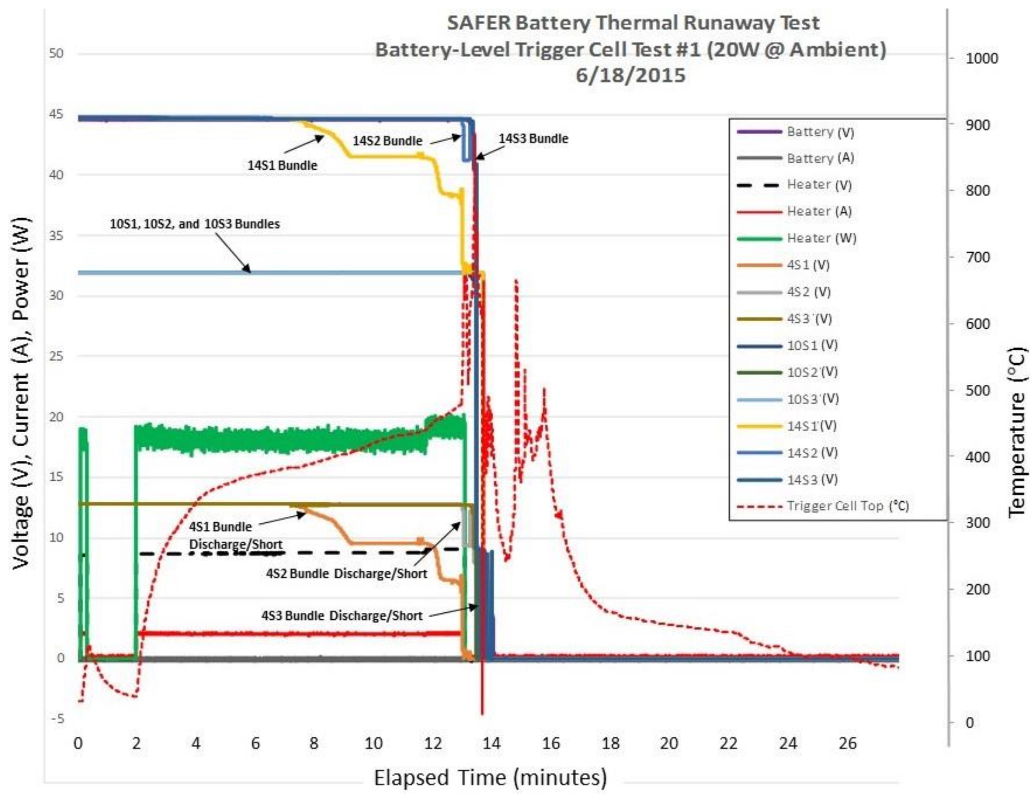


Figure 7.4-7. Trigger-cell Temperature and Voltage Readings for Test #1 (Voltage (V), Current(Amps), Power (W) on the left, and Temp (C) on right

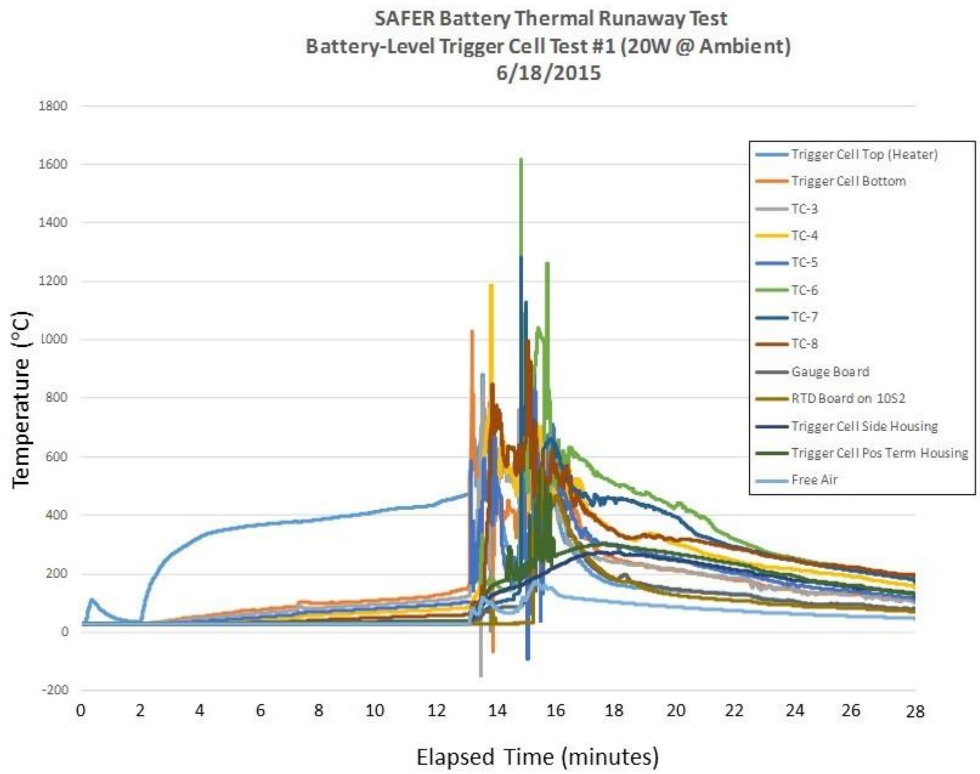


Figure 7.4-8. Thermocouple temperature plots for Test 1.

Test video shows the TR propagation from the trigger cell to the battery pack with substantial fire from the feed-through opening above the gauge board connector. Vented electrolyte vapors (e.g., 1,2-dimethoxy ethane and ethylene carbonate) are flammable, which contributed to the fire intensity. The fire burned almost continuously until the last 4S bundle side cell TR occurred.

The post-test images and destructive physical analysis (DPA) (Appendix F) show that complete cell-to-cell propagation occurred in the 4S bundle side, and all 12 cells were consumed. Most cells on 4S bundle side had can breach. However, images show (Figure 7.4-9) that all cells on the 10S bundle side were only slightly damaged, and did not enter TR.

Figure 7.4-9. Test #1 Post-test Images of Exemplar Cells from 4S Bundle Side (left) and from 10S Bundle Side (right)

The gauge board was melted and burned during the test. However, the space occupied by the gauge board and associated wiring was sufficient to provide thermal isolation to protect the 10S bundle side. Additionally, due to circulating current paths created in the 4S bundle side failure, external short-circuit condition was likely seen by 10S bundle side cells. The DPA notes in Appendix F show the 10S bundle side voltages of approximately 5V, which is approximately 2.5 V/cell down from a nominal 3-V/cell for a fresh cell. Therefore, the cell electrical discharge made them less susceptible to TR.

The following is a Test #1 summary of major events:

1. Position #1 trigger cell experienced TR with venting, smoke, and fire, which was not contained in the battery pack.
2. TR propagated to all 12 4S bundle side cells.
3. Battery case temperatures exceeded 800 °C.
4. Capacity gauge board was destroyed during TR event.
5. No 10S bundle side cells experienced TR. Possible contributors are:
    a. Physical separation of the 10S bundle side from the 4S bundle side.
        i. The capacity gauge board cavity spacing restricts heat transfer to 10S bundle side.
    b. The 4S bundle side cell TR created an electrical short circuit path that depleted the 10S bundle side cell charge.
6. Test #1 was considered invalid due to the time required to initiate trigger-cell TR (approximately 9 minutes), and the resulting fire magnitude and duration.

Test #2 – 30-W heater on cell in Position #1

Figure 7.4-10 shows trigger-cell and thermocouple locations for Test #2, which utilized a patch heater on the designated trigger cell.

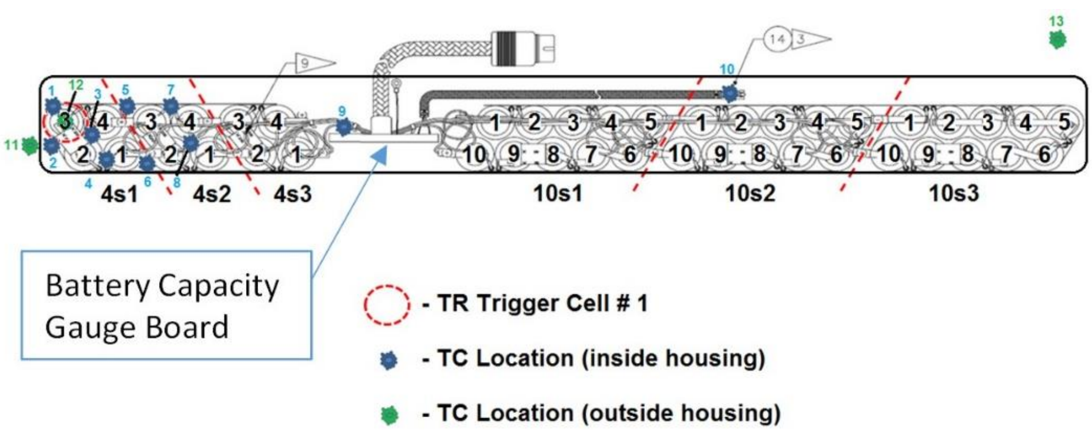


Figure 7.4-10. Trigger-cell and Thermocouple Locations for Test #2.

Assembly images are shown in Figure 7.4-11. Note the battery pack assembly and the opening for voltage sense lines and thermocouple feed-through above the gauge board connector were similar to Test #1.

Trigger-cell temperature and voltage readings for Test #2 are shown in Figure 7.4-12. The heater power was applied, and trigger-cell TR occurred at about 4 minutes, at which time the heater power was turned off.

The higher wattage heater (i.e., 30 W versus 25 W in Test #1) caused the trigger-cell TR at a shorter time. Trigger-cell maximum temperature was approximately 400 °C. The 4S1 bundle voltage drop occurred at about 4 minutes, indicating the trigger cell had vented. The 14S1 bundle voltage drops at this time, but the 10S1-cell voltage remains constant until about 10 minutes elapsed time.

Figure 7.4-11. Test #2 Assembly

4S2 bundle voltage drop occurred at approximately 6.5 minutes, indicating that TR effects. The 14S2 voltage drops proportionally at this time, but the 10S2-cell voltage remains constant until about 10 minutes.

4S3 bundle voltage drop occurred at approximately 8 minutes, indicating that TR effects. The 14S3 voltage drops proportionally at this time, but the 10S3-cell voltage remains until about 12 minutes.

These voltage measurements are indicators of 4S bundle TR propagation. The cell-to-cell TR propagation was slower in Test #2 than Test #1. This indicates the more rapid trigger-cell heating allowed less heating of adjacent cells, which did not predispose the adjacent cells to early TR.

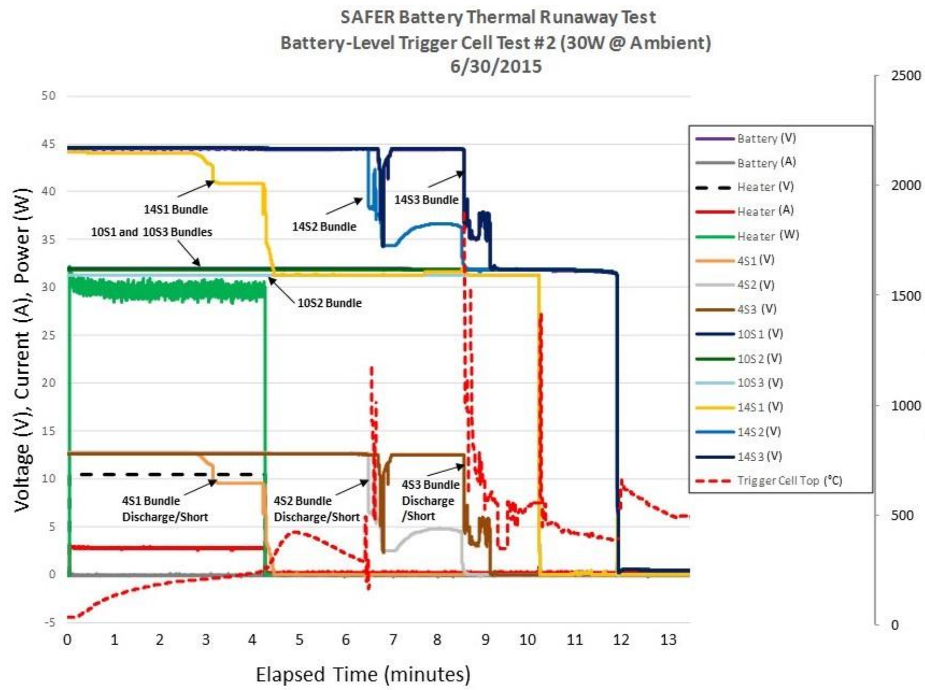


Figure 7.4-12. Test #2 Trigger-cell Temperature and Voltage Readings

Thermocouple temperatures are shown in Figure 7.4-13. Note that cell TR propagation occurred over an 11-minute interval, from approximately minute 4 to approximately minute 15 elapsed time.

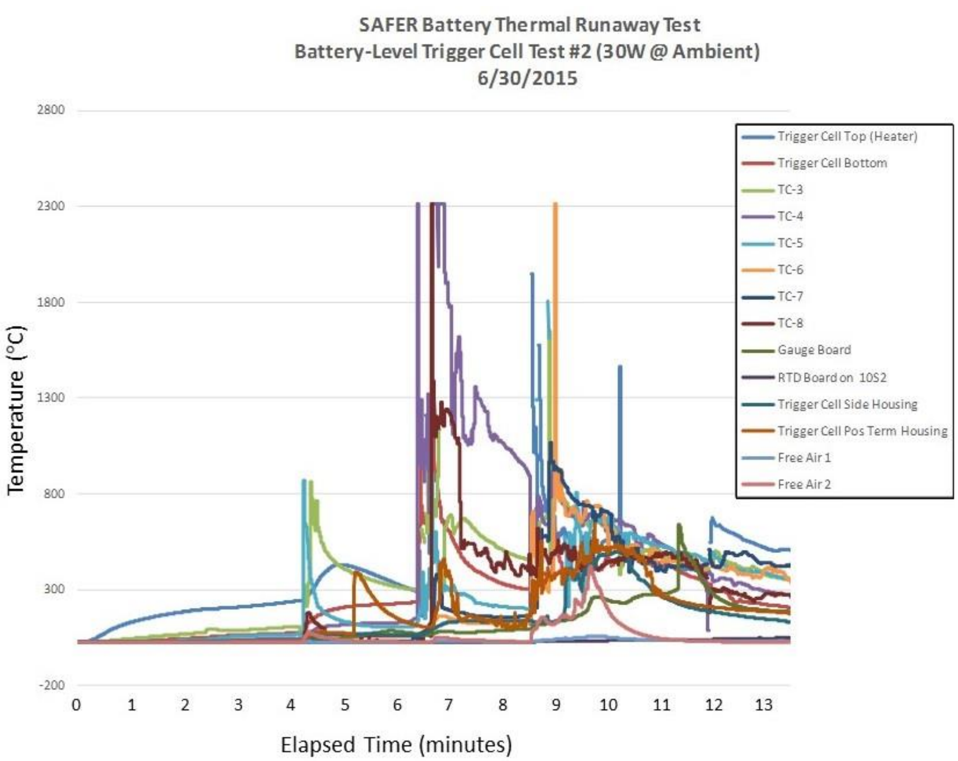
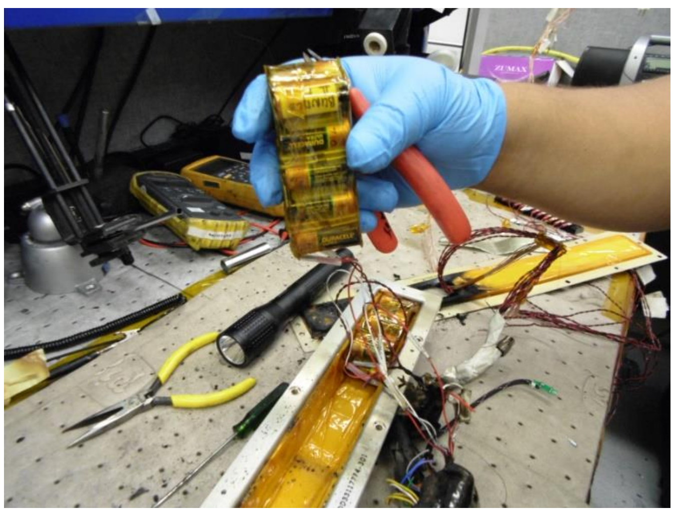


Figure 7.4-13. Test #2 Thermocouple Temperature Plots

The post-test images and DPA show that cell-to-cell TR propagation occurred in the 4S bundle side, and all 12 cells were consumed. As in Test #1, the open feed-through allowed cell vapors and ejecta to escape the battery pack, which caused a sustained fire. The fire intensified after TR propagation to the adjacent cells and burned almost continuously until the last 4S bundle side cell TR occurred. The gauge board was melted and burned during the test.

Most 4S bundle side cells had a can breach (Appendix F). However, images show the 10S bundle cells (Figure 7.4-14) were only slightly damaged, and did not enter TR.

a) Close up of 4S bundle cavity and demarcation line between 4S bundle and 10S bundle.



b) Removal of 10S bundle.

Figure 7.4-14. Test #2 Post-test Images

The 10S bundle side voltage (Appendix F) was higher than in Test #1. Voltages for the 10S1, 10S2, and 10S3 bundles were 12.6, 8.7, and 8.3 V, respectively. These cells are highly discharged, which made them less susceptible to TR.

The following is a Test #2 summary of major events:

1. Position #1 trigger cell experienced TR with venting, smoke, and fire, which was not contained in the battery pack.

2. TR propagated to all 12 4S bundle side cells.
    a. The heater duration was slightly over 4 minutes.
    b. Propagation from cell-to-cell was slower, since the trigger-cell heater wattage was higher.
3. Battery case temperatures exceeded 800 °C.
4. Capacity gauge board was destroyed during TR event.
5. No 10S bundle side cells experienced TR. Possible contributors are:
    a. Physical separation of the 10S bundle side from the 4S bundle side.
        i. The capacity gauge board cavity spacing restricts heat transfer to 10S bundle side.
    b. The 4S bundle side cell TR created an electrical short circuit path that depleted the 10S bundle side cell charge.
6. Test #2 was considered invalid due to resulting fire magnitude and duration.

Test #3 – 35-W heater on cell in Position #1

Figure 7.4-15 shows trigger-cell and thermocouple locations for Test #3, which utilized a ceramic heater on the designated trigger cell.

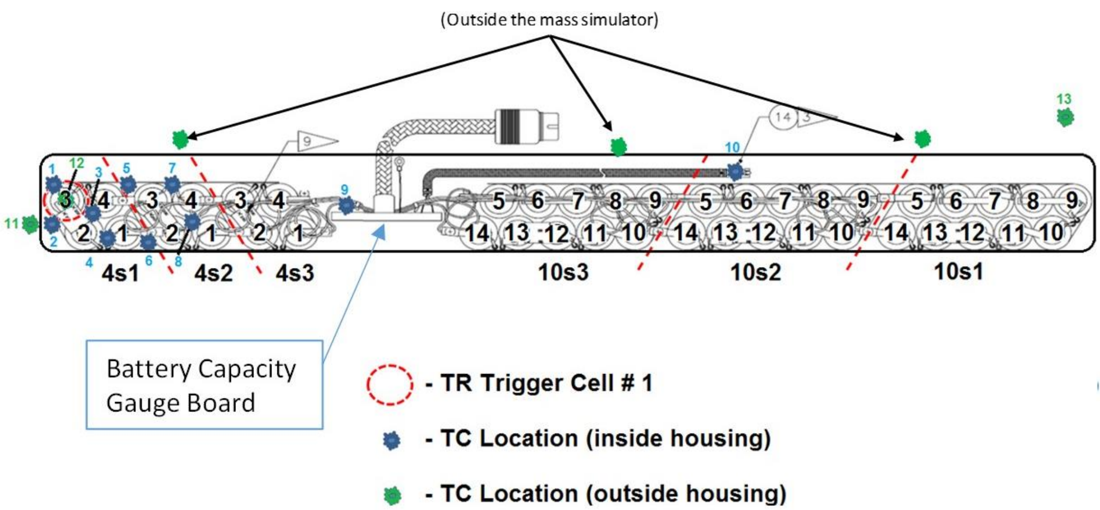


Figure 7.4-15. Test #3 Trigger-cell and Thermocouple Locations

Cells were bundled and the battery pack was assembled in a flight-like configuration. Assembly images are shown in Figure 7.4-16. Note the SAFER mass simulator interface was installed on the battery pack that served as feed-through for the voltage sense lines and thermocouple outputs.

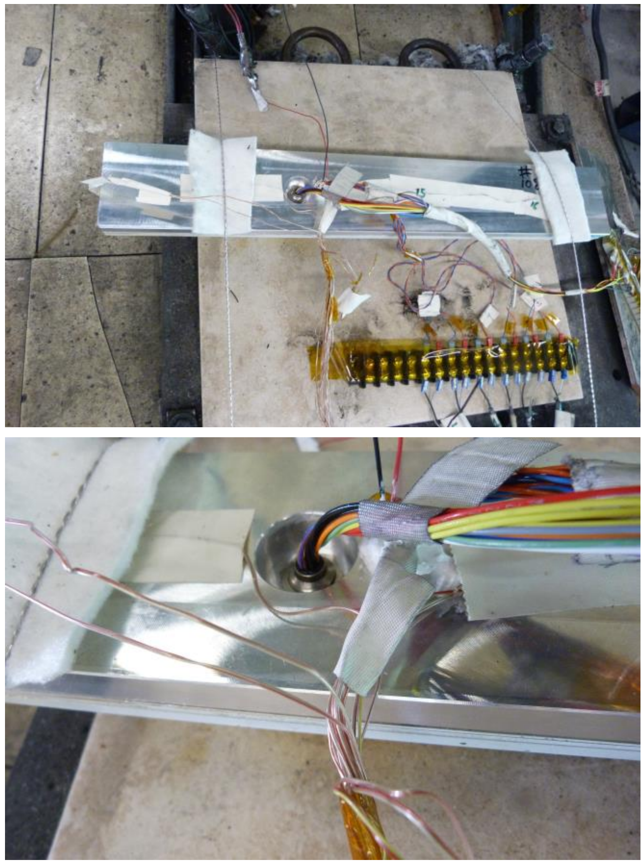


Figure 7.4-16. Test #3 Assembly

Trigger-cell temperature and voltage readings for Test #3 are shown in Figure 7.4-17. The heater power was applied at the start of the timer, and full TR of the trigger cell occurred at about 3 minutes, at which time the heater power was turned off.

The higher-wattage heater (i.e., 35 W compared to 25 W in Test #1) caused the trigger-cell TR at significantly shorter time. This may be due to the change in patch heater design (i.e., ceramic versus patch) and applied wattage. The trigger-cell maximum temperature was over 700 °C. The 4S1 bundle side voltage decrease occurred at slightly under 2 minutes in elapsed time, indicating the trigger cell had vented. TR occurred at 3 minutes, at which time heater power declined significantly. Heater power was turned off at 4 minutes (see Figure 7.4-17). The 4S1 bundle side voltage drops to zero at approximately 3 minutes. The 14S1 string voltage drops proportionally at this time, but the 10S1 bundle side voltage fluctuated for the next 80 seconds. The 10S1 bundle side voltage remained steady until about 5.8 minutes, when it dropped to zero volts.

The 4S2 bundle side voltage drop occurred at approximately 4 minutes, indicating that TR had affected those cells. The 4S2 bundle side voltage reaches zero volts at approximately 4.5 minutes. The 14S2 string voltage dropped proportionally at this time. The 10S2 bundle side voltage remained steady until about 5.5 minutes, when is dropped to zero volts.

The 4S3 bundle side voltage drop occurred at approximately 4.5 minutes, indicating that TR had affected those cells. Interestingly, one cell in the 4S3 bundle survived and provided nearly 3 V until approximately 5.2 minutes. The 14S3 string voltage dropped proportionally at this time.

The 10S bundle side voltage remained until about 5.8 minutes, at which time it dropped to zero volts.

These voltage measurements are indicators of TR propagation through the battery pack 4S bundle. The propagation from cell-to-cell was slower in Test #3 than Test #1. This indicates the more rapid trigger-cell heating caused less heating of adjacent cells, and did not predispose the adjacent cells to early TR.

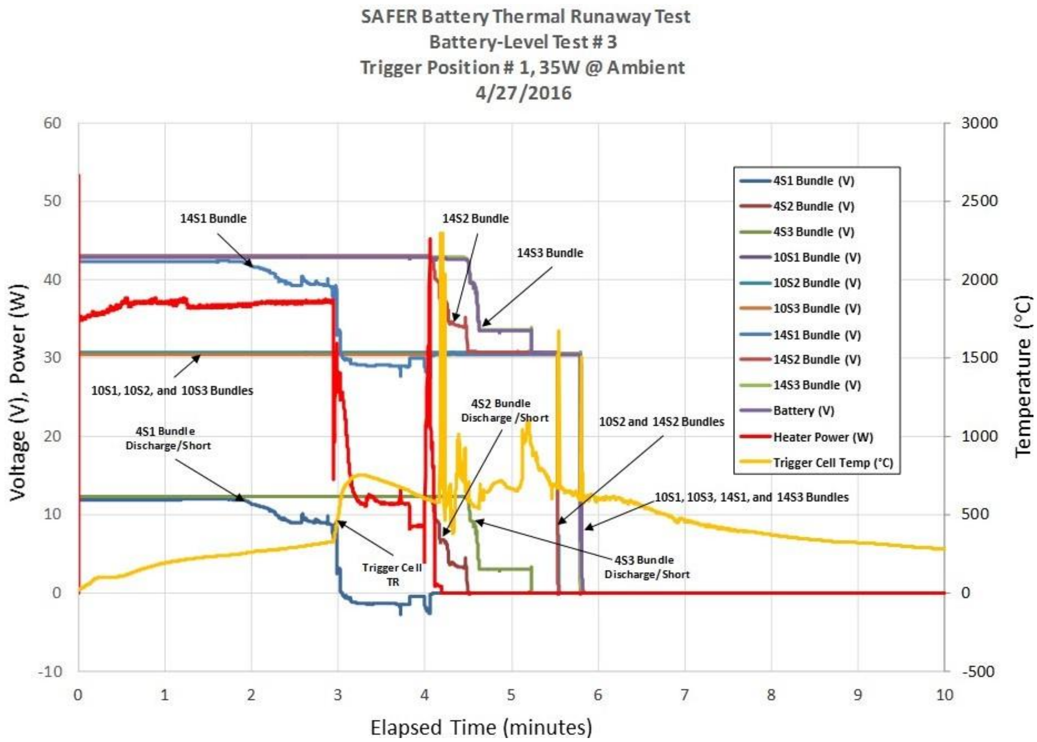


Figure 7.4-17. Test #3 Trigger-cell Temperature and Voltage Readings

Thermocouple temperatures and heater power are shown in Figure 7.4-18. Trigger-cell TR occurred at approximately 3 minutes, at which time the heater power was reduced. It appears there may have been some shorting of the power leads, as the power fluctuated between 3 minutes and slightly over 4 minutes, when the heater power was turned off. Additional heater power detail is shown in Figure 7.4-19.

Note the 4S bundle side TR propagation occurred over a shorter time interval (i.e., approximately 3 minutes).

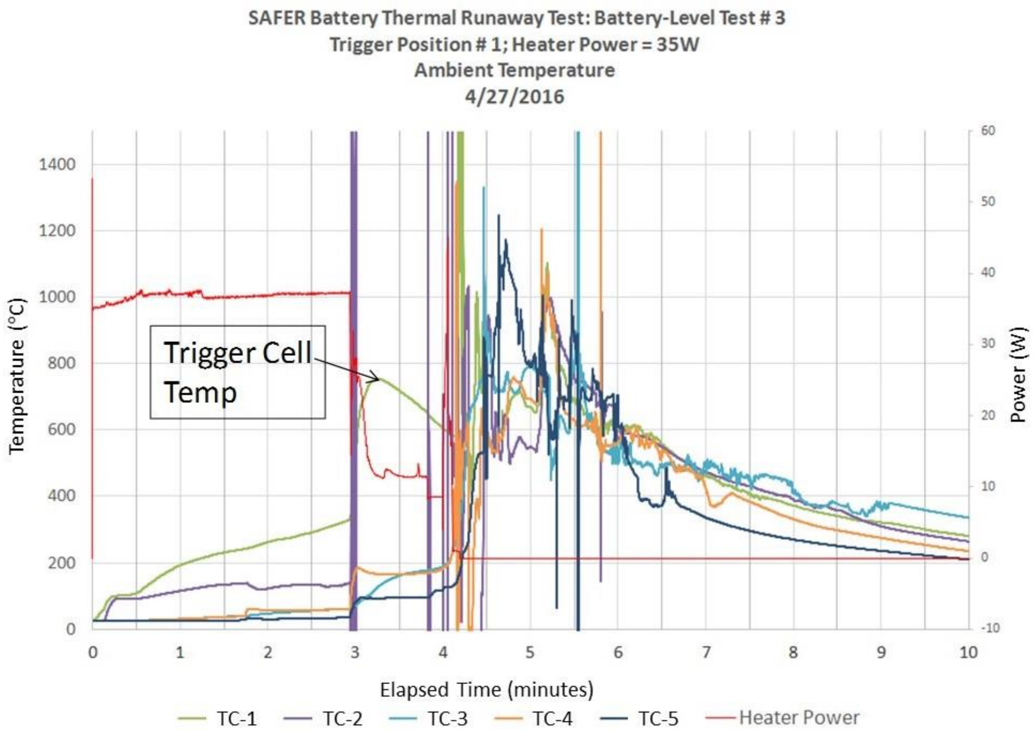
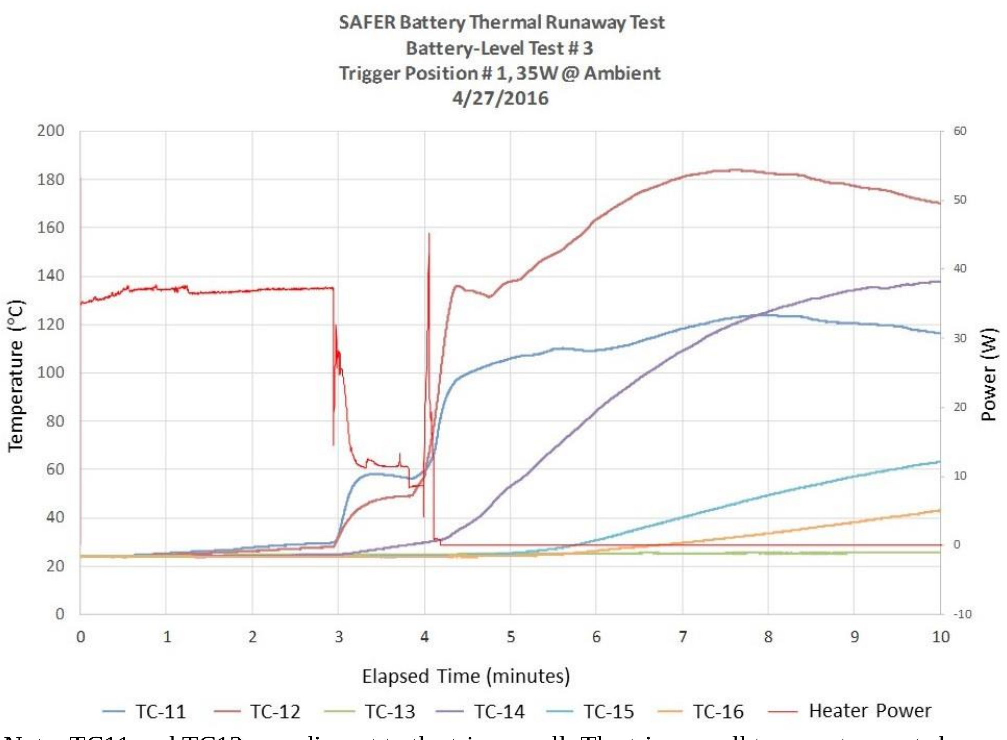


Figure 7.4-18. Test #3 Thermocouple Temperatures and Heater Power



Note: TC11 and TC12 are adjacent to the trigger cell. The trigger-cell temperature not shown.

Figure 7.4-19. Detail of Heater Power, with Thermocouple Temperatures

The post-test images in Figure 7.4-20 and DPA notes show that cell-to-cell TR propagation occurred in the 4S bundle side, and all 12 cells were consumed. TR did not occur in any cells in the 10S bundle side. However, unlike Tests #1 and #2, there was no sustained fire since the external feed-through was sealed, and cell vapors and ejecta could not easily escape the battery pack. Small flames intermittently were seen, but the 'secondary fire' was negligible. The gauge board was melted and burned during the test.

Most 4S bundle side cells had can breaches (Appendix F). However, images show that all 10S bundle side cells were slightly damaged, and did not enter TR.

a) 4S bundle side. ***b) 10S bundle side.***

Figure 7.4-20. Test #3 Post-test Images

10S bundle side voltages (Appendix F) were significantly higher than in Tests #1 or #2. 10A, 10B, and 10C bundle side voltages were 30.2, 27.2 and 27.1 V, respectively. These cells were at a high state of charge, with 10A bundle at near full charge. This was unexpected since the 10S bundle side voltage readings during the test were measured at zero volts after 5.8 minutes. The 10S bundle side voltage drop shown in Figure 7.4-17 could be caused by open-circuit electrical failure during the TR propagation.

The following is a Test #3 summary of major events:

1. Position #1 trigger cell in Position 1 experiences TR with venting, smoke, and fire, which were largely contained in the battery pack.
    a. The reduced amount of fire compared to Test #1 & #2 was likely due to the addition of flight-like SAFER unit mass simulator.
    b. No sustained fire was observed since the feed-through was sealed, and cell vapors and ejecta could not easily escape the battery pack.
2. TR propagated to all 12 4S bundle side cells.
    a. The heater power application duration was slightly over 4 minutes.
    b. TR propagation from cell-to-cell occurred over a period of approximately 3 minutes.
3. Battery case temperatures exceeded 800 °C.
4. Capacity gauge board was destroyed during TR event.
5. No 10S bundle side cells experienced TR. Possible contributors were:
    a. Physical separation of the 10S bundle side from the 4S bundle side.
        i. Capacity gauge board cavity spacing restricts heat transfer to 10S bundle side.
6. This test was considered acceptable.

Test #4 – 35-W heater on cell in Position #2

Figure 7.4-21 shows trigger-cell and thermocouple locations for Test #4, which utilized a ceramic heater on the designated trigger cell.

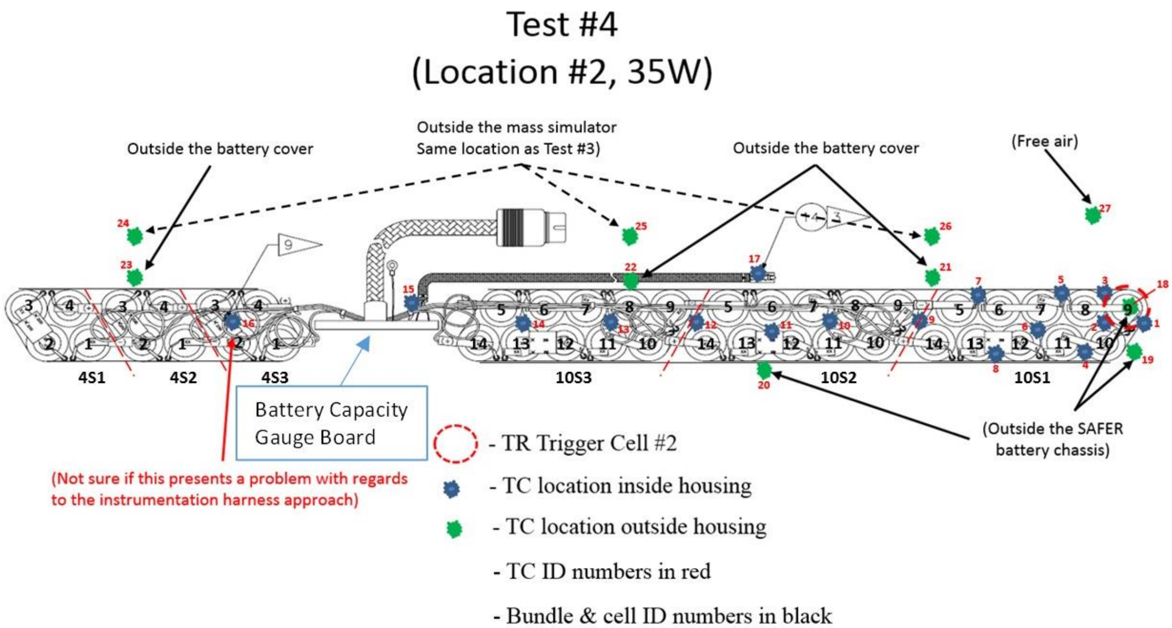
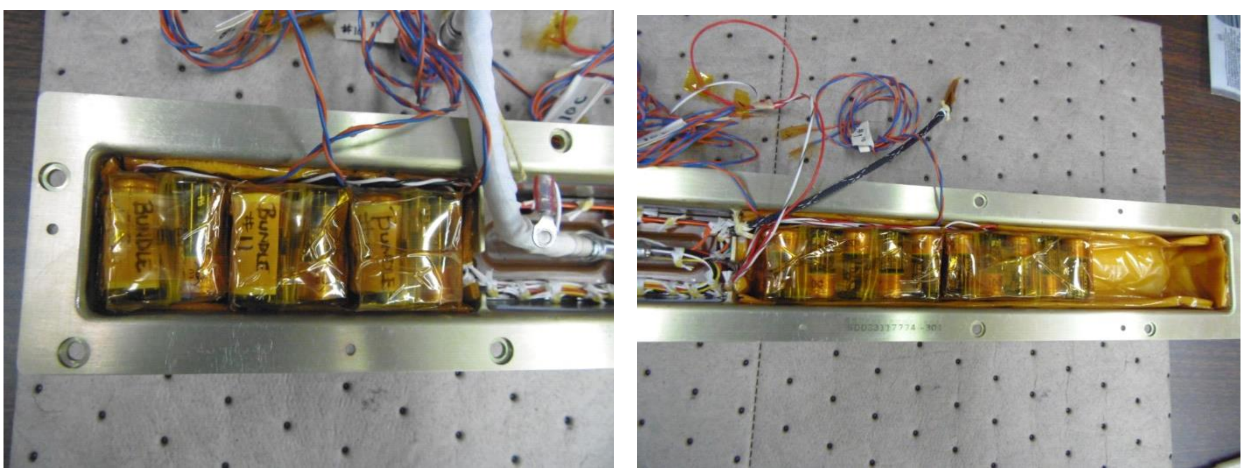


Figure 7.4-21. Test #4 trigger-cell and Thermocouple Locations

Cells were bundled and the battery pack was assembled in a flight-like configuration. Assembly images are shown in Figure 7.4-22. Note that a SAFER mass simulator interface was installed on the battery pack that served as feed-through for the voltage sense lines and thermocouple outputs. The feed-through assembly is essentially the same as seen in Test #3 (Figure 7.4-16).



a) 4S bundle side. ***b) 10S bundle side.***

Figure 7.4-22. Test #4 Assembly

Trigger-cell temperature and voltage readings for Test #4 are shown in Figure 7.4-23. 10C bundle side voltage decreased at about 2.5 minutes, indicating trigger cell venting. The 10C bundle voltage dropped to zero volts at slightly over 4 minutes, at which time the heater power was turned off.

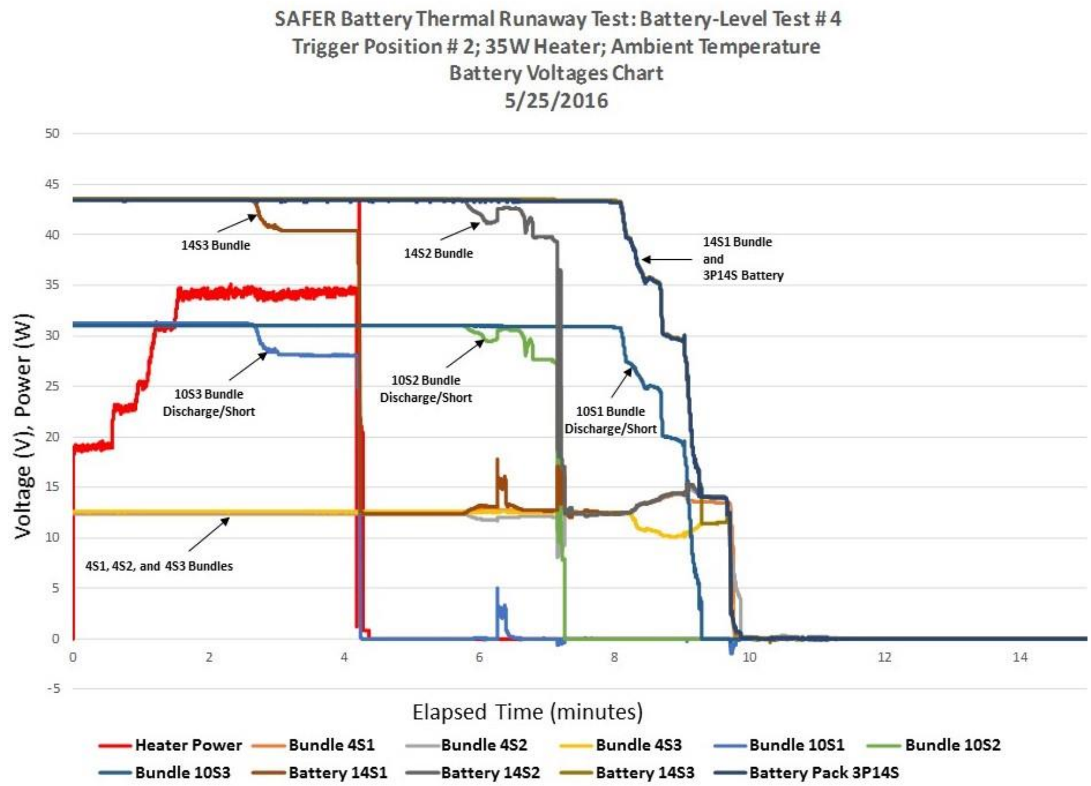


Figure 7.4-23. Test #4 Heater Power and Voltage Readings

The 10B bundle side voltage showed instability at about 6 minutes, indicating TR had progressed to that bundle. The voltage of this bundle dropped to zero volts at slightly over 7 minutes elapsed time. The 10C bundle side voltage showed instability at about 8.5 minutes, indicating TR had progressed to that bundle. The voltage of this bundle dropped to zero volts at slightly less than 10 minutes elapsed time. These voltage measurements are indicators of TR propagation through the 10S bundle side of the battery pack.

Plot of heater power and thermocouple temperatures is shown in Figure 7.4-24. Because of the large number of thermocouples, the plot is difficult to comprehend. Figure 7.4-25 is provided as a simplified view of the heater power and external thermocouple temperature data.

The first TR occurred at slightly over 4 minutes elapsed time. The last TR occurred at slightly under 12 minutes elapsed time. This longer interval (i.e., approximately 8 minutes) reflects the large number of cells (i.e., 30) that entered TR.

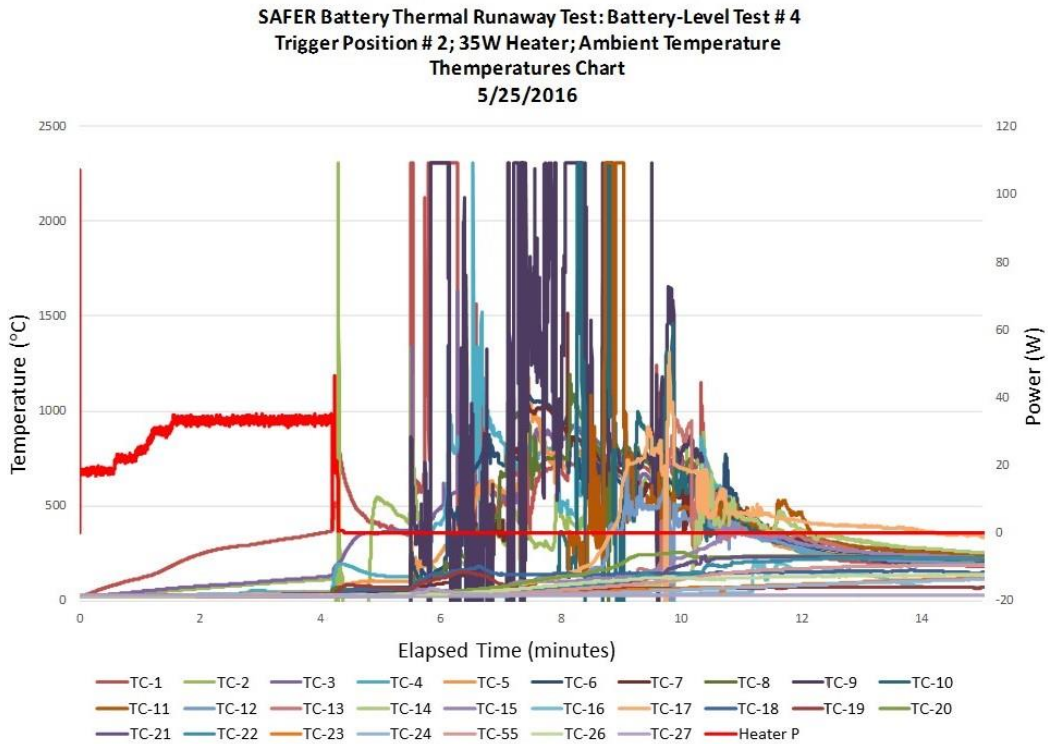


Figure 7.4-24. Test #4 Thermocouple Temperature Plots

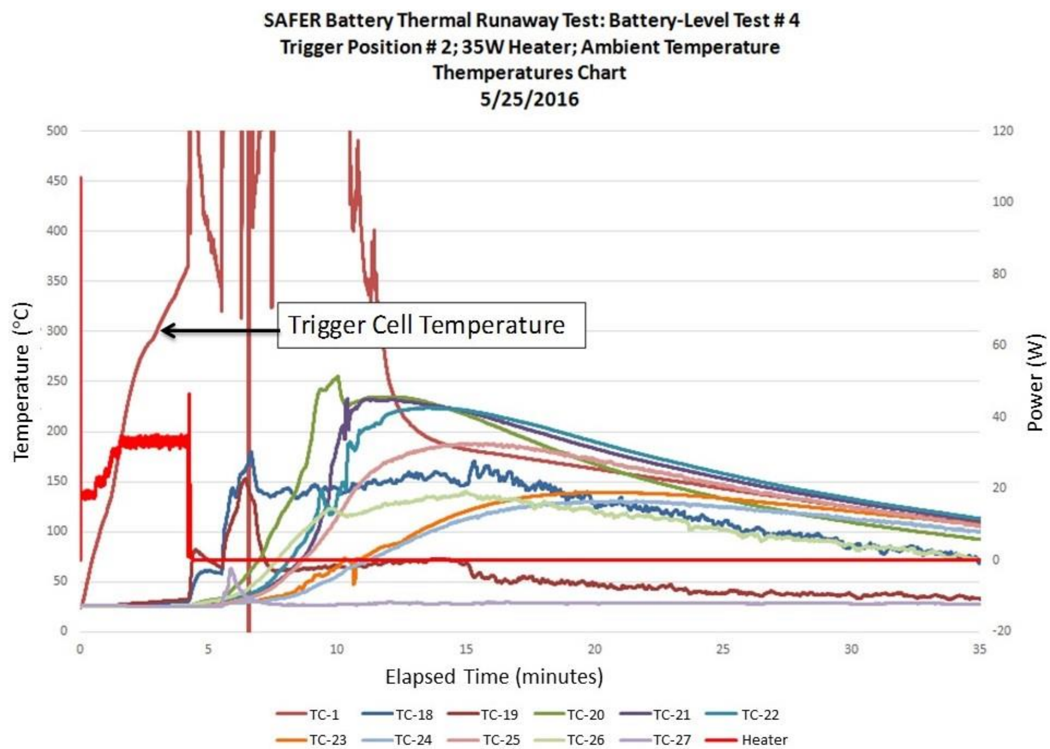


Figure 7.4-25. Test #4 External Thermocouple Temperature Plots

The data in Figure 7.4-25 show:

- Thermocouples (TCs) 18 and 19 are near the trigger cell and respond when it enters TR at approximately 6 minutes.

- TCs 20, 21, and 22 are on the battery case exterior surface reach the highest temperatures of approximately 220 to 255 °C.
- All other TCs on the 10-cell side of battery pack had peak temperatures at no greater than approximately 180 °C.
- TCs 23 and 24 on the 4-cell side of battery pack had peak temperatures of approximately 130 to 140 °C.
- TC 27 (i.e., air measurement) responded to an external fire at about 6 minutes and then returned to ambient temperature readings.

The battery pack case temperature profile was monitored using an infrared (IR) camera. Figure 7.4-26 shows screen shots of the IR camera output at various test times.

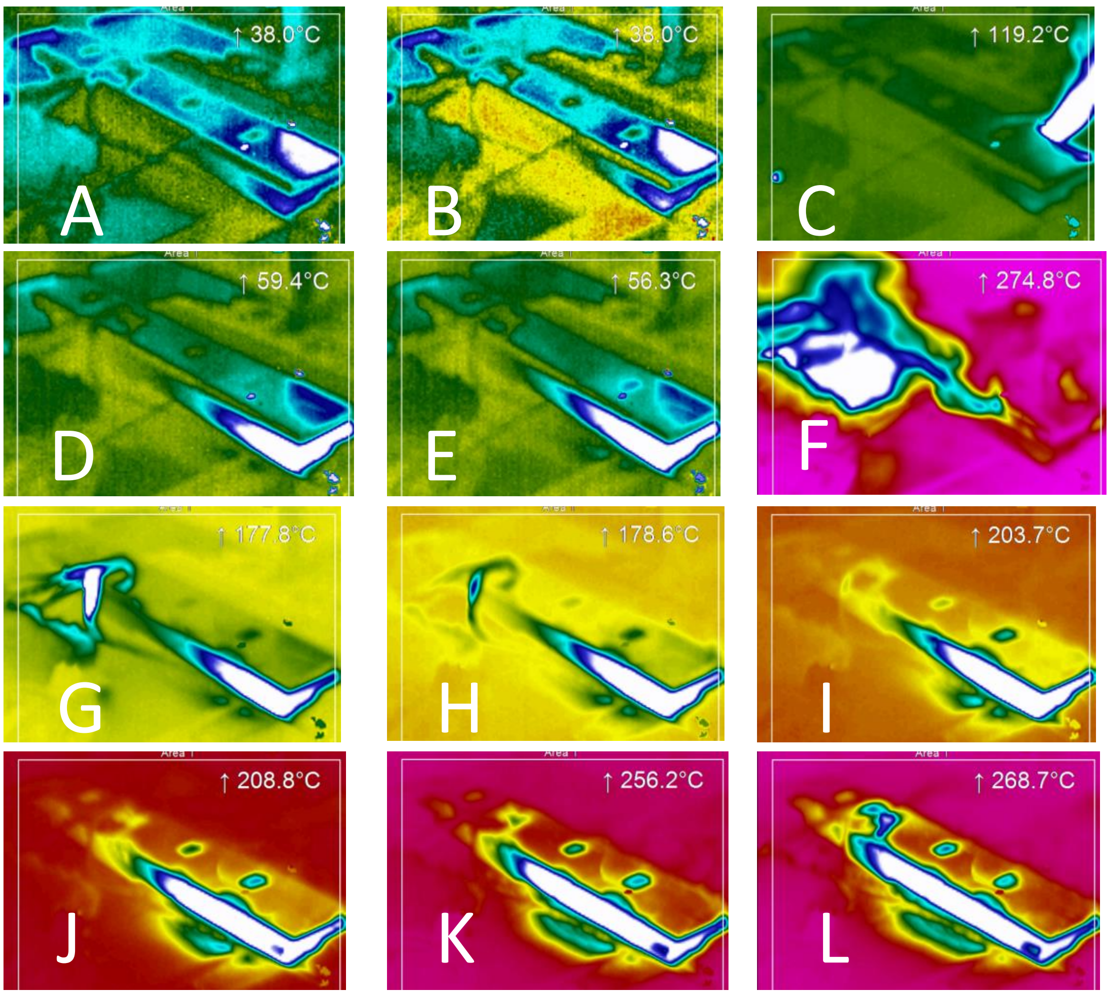


Figure 7.4-26. Test 4 IR Images at Various Times during SAFER Battery-level TR

The Table 7.4-2 gives the time and temperature data for the inset images in Figure 7.4-26. Note the IR temperature readout records the highest temperature sensed in the IR image frame. Temperatures in C and F images are higher than temperatures in subsequent images because the IR camera was recording the flame temperature.

These data show the progressive battery pack case external surface heating during 10S bundle side TR propagation. Note there is an induction period of about 1 minute before the case temperature exceeds 170 °C. This is in general agreement with the thermocouple temperatures displayed in Figure 7.4-25. The maximum IR temperature data was 268.7 °C. This is also in general agreement with the thermocouple data, which had the highest temperatures of approximately 220 to 255 °C.

Table 7.4-2. Time and Temperature Data for the Figure 7.4-26 Inset Images

Image in Figure 7.5-26	IR Image Title	Time (mm:ss)	Elapsed Time (mm:ss)	Temperature (°C)
A	Heater On	04:03.0	00:00.0	38.0
B	Pre TR Onset	04:16.8	00:13.8	38.0
C	Post TR Onset	04:17.8	00:14.9	119.2
D	Heater Off	04:29.5	00:26.5	59.4
E	Pre Propagation	05:19.4	01:16.4	56.3
F	Post Propagation #1	05:20.4	01:17.5	274.8
G	Post Propagation #2	05:47.0	01:44.1	177.8
H	Post Propagation #3	06:22.3	02:19.4	178.6
I	Post Propagation #4	07:23.3	03:20.3	203.7
J	Post Propagation #5	08:23.0	04:20.0	208.8
K	Post Propagation #6	09:22.9	05:20.0	256.2
L	Post Propagation #7	10:22.8	06:19.8	268.7

The post-test images and DPA show that cell-to-cell propagation occurred in the 10S bundle side, with all 30 cells being consumed. TR did not occur in any cells in the 4S bundle side. Unlike Tests #1 and #2, there was no sustained fire since the feed-through was sealed, and cell vapors and ejecta could not easily escape the battery pack. Small flames were intermittently observed, but the 'secondary fire' was negligible. The gauge board was melted and burned during the test.

Most 10S bundle side cells had can breaches (Appendix F). However, the images show all the 4S bundle side cells were only slightly damaged, and did not enter TR. See Figure 7.4-27.

Figure 7.4-27. Test #4 Post-test Image of Open Battery Pack

Voltage of the 4S bundle side (Appendix F) show that external shorting occurred, reducing state of charge. Voltages for Bundles 4S1 , 4S2 and 4S3 were 3.2, 1.2, and 5.7 V, respectively. Initial voltages were 12.3 to 12.6 V. These cells are highly discharged, which makes them less susceptible to TR.

The following is a Test #4 summary of major events:

1. Position #2 trigger experienced TR with venting, smoke and fire, but they were largely contained in the battery pack.
    a. The reduced amount of fire as compared to Tests #1 and #2 was likely due to addition of flight-like SAFER unit mass simulator.
    b. No sustained fire was observed since the feed-through was sealed, and cell vapors and ejecta could not easily escape the battery pack.
2. TR propagated to all 30 10S bundle side cells.
    a. The heater duration was slightly over 4 minutes.
        i. The longer heater time could be due to the different trigger-cell location compared to Tests #1, #2, and #3.
    b. Propagation from cell-to-cell occurred over a period of approximately 8 minutes.
        i. Many more cells were involved in TR, compared to 4S bundle side.
3. Battery case temperatures exceeded 800 °C.
4. Capacity gauge board was destroyed during TR event.
5. No 4S bundle side cells experienced TR. Possible contributors were:
    a. Physical separation of the 10S bundle side from the 4S bundle side.
        i. Capacity gauge board cavity spacing restricts heat transfer to 4S bundle side.
    b. The 10S bundle side cell TR created an electrical short circuit path that depleted the 4S bundle side cell charge.
6. This test was considered acceptable.

7.4.4 Summary and Findings

See Section 8.1, F-7 through F-10.

8.0 Findings, Observations, and NESC Recommendations

8.1 Findings

The following findings were identified:

F-1. The SAFER battery hazard report does not identify single-cell TR propagation as a hazard.

F-2. Flight-similar OCV and CCV cell acceptance testing resulted in a significant number of out-of-specification test cells.

F-3. SAFER flight battery build procedures do not include a process step for cell matching and selection.

F-4. Results from the single-cell heater trigger varied with heater power level and type (i.e., patch versus ceramic).

- At constant heater power levels, cell TR onset temperature and maximum cell temperatures varied.
- At increasing heater power levels, cell TR onset time decreases.

F-5. Cell TR onset temperature and maximum cell temperature were independent of 49 °C hot-case test conditions and heater location.

F-6. Parametric single-cell heater trigger TR testing was successful in determining worst-case heater power to induce cell-level catastrophic TR condition.

- Single-cell heater trigger testing at 10 W did not result in a catastrophic TR condition.
- Single-cell heater trigger testing between 15 and 40 W resulted in catastrophic TR conditions.
- 35 W is maximum heater power that Duracell® Ultra® CR123 cell can endure without cell rupture.

F-7. Under ambient conditions, a single-cell TR in the 4S bundle side results in cell-to-cell TR propagation to all 12 cells in that bundle (i.e., Tests #1, #2, and #3).

F-8. Under ambient conditions, a single-cell TR in the 10S bundle side results in cell-to-cell TR propagation to all 30 cells in that bundle (Test #4).

F-9. SAFER battery capacity gauge board cavity provides sufficient spacing of approximately 3.5 inches between the 4S-cell and 10S-cell bundles to prevent propagation of TR to the opposite side of battery pack.

F-10. Ambient oxygen sources (such as air) increases severity of SAFER battery TR consequences.

8.2 Observations

O-1. Results from the 4S- and 10S-cell bundle external short tests indicate that the external bundle PTC thermal fuse operated nominally under the test conditions employed.

O-2. Results from the 4S- and 10S-cell bundle external short tests were consistent with previous JSC ESTA SAFER battery external short test results.

O-3. External short testing of 4S- and 10S-cell SAFER battery bundles without an external PTC device did not result in a TR condition.

- Cell-level PTC thermal fuses provided adequate TR fault protection.

O-4. External short testing of 4S- and 10S-cell SAFER battery bundles with external and cell-level PTC devices did not result in a TR condition.

O-5. Time to cell TR onset temperature decreases with increasing heater power.

O-6. Cell TR onset and maximum cell TR temperatures were independent of heater location (bottom versus side).

O-7. Cell TR onset temperatures occurred near the melting point (180°C) of lithium metal.

8.3 NESC Recommendations

The following NESC recommendations were identified and directed towards the ISS EVA Program Office, JSC Propulsion and Power Division, and the NESC Electrical Power TDT:

ISS EVA Program Office

R-1. Develop a SAFER battery design which mitigates the hazardous effects of cell-to-cell TR propagation which may result in venting, electrolyte leakage, ignition of gas-phase flammable gases, fire, smoke, and/or ejecta. ***(F-7 through F-10).***

R-2. Conduct worst-case systems engineering analysis to quantify the effects of SAFER battery TR on the SAFER unit function and operation. ***(F-7 through F-10).***

R-3. Update the SAFER flight battery hazards report to include TR propagation as a hazard condition. ***(F-1).***

NESC Electrical Power TDT

R-4. (a.) Develop acceptable test methods to induce TR that most reliably simulates Li cell and battery level causes for TR hazards. (b.) Encourage the adoption of these new test methods into an Agency standard to support current and future NASA Li battery applications. ***(F-4 through F-6).***

JSC Propulsion and Power Division

R-5. Conduct a detailed SAFER battery procurement and acceptance test process and procedures review. The review should include, but not be limited to, an evaluation of the CCV test screening methodology, procedure, and pass/fail criteria. ***(F-2).***

R-6. Include cell matching as part of selecting flight cells for SAFER flight battery manufacturing. ***(F-3).***

9.0 Alternate Viewpoint

There were no alternate viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

10.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

11.0 Lessons Learned

No applicable lessons learned were identified for entry into the NASA Lessons Learned Information System (LLIS) as a result of this assessment.

12.0 Recommendations for NASA Standards and Specifications

As per R-4, it is recommended that the NESC Electrical Power TDT use the results from this study to develop acceptable test methods to induce TR that most reliably simulates Li cell and battery level causes for TR hazards. These new test methods should be adopted into a subsequent revision JSC20793 Crewed Space Vehicle Battery Safety Requirements to support current and future NASA Li battery applications.

13.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Lessons Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure.
Observation	A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization’s operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example,

the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions.

14.0 Acronyms and Nomenclature List

A	Ampere
AC	Alternating Current
Ah	ampere hour
CCV	Closed Circuit Voltage
CoP	Community of Practice
COTS	Commercial Off-The-Shelf
DPA	Destructive Physical Analysis
ELT	Emergency Transmitter Locator
EMU	Extra-vehicular Mobility Unit
ESTA	Energy Systems Test Area
EVA	Extra-vehicular Activity
F_L	Lower Fourth
F_U	Upper Fourth
g	Grams
HCM	Hand Controller Module
Hz	Hertz
IC	Integrated Circuit
IR	Infrared
ISS	International Space Station
IVA	Intra-vehicular Activity
JSC	Johnson Space Center
k	Kilo
Li	Lithium
Li-Ion	Lithium Ion
Li-MnO_2	Lithium-Manganese Dioxide
LLB	Long Life Battery
LREBA	Li-Ion Rechargeable EVA Battery Assembly
mAh	milliamp hour
mm	millimeter
MTA	Microchip Technology Inc.
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering Safety Center
NRB	NESC Review Board
NSCKN	NASA Safety Center Knowledge Now
OCV	Open Circuit Voltage
Ω	Ohms
ORU	Orbital Replacement Unit
PTC	Positive Temperature Coefficient
RCCA	Root Cause and Corrective action
s-p	series-parallel
SAFER	Simplified Aid For Extra-Vehicular Activity Rescue
STS	Space Transportation System

TC	Thermocouple
TDT	Technical Discipline Team
TR	Thermal Runaway
TRR	Test Readiness Review
USA	United States of America
V	Voltage

15.0 References

1. National Transportation Safety Board (NTSB): *Aircraft Incident Report: Auxiliary Power Unit Battery Fire Japan Airlines Boeing 787-8, JA829J Boston, Massachusetts January 7, 2013*. NTSB/AIR-14/01, PB2014-108867, Notation 8604, November 21, 2014.
2. Japan Transport Safety Board (JTSB): *Aircraft Serious Incident Investigation Report: Emergency Evacuation Using Slides All Nippon Airways Co., LTD. BOEING 787-8, JA804A Takamatsu Airport at 08:49 JST, January 16, 2013*. AI2014-4, September 15, 2014.
3. Department for Transport Air Accidents Investigation Branch: *Report on the serious incident to Boeing B787-8, ET-AOP London Heathrow Airport 12 July 2013*. Aircraft Accident Report 2/2015, Department for Transport Air Accidents Investigation Branch, Farnborough House, UK, 8/19/2015.
4. Iannello, C.: *Assessment of International Space Station (ISS)/Extravehicular Activity (EVA) Lithium-ion Battery Thermal Runaway (TR) Severity Reduction Measures*. NASA Engineering Safety Center, NESC Request #TI-14-00942, February 28, 2014.
5. Randall, D.: *Specification for Acceptance and Lot Certification Testing of 2/3A Lithium-Manganese Dioxide Cells for the Batteries of the Simplified Aid for EVA Rescue (SAFER)*. NASA/JSC, Engineering Directorate Propulsion and Power Division, SAFER-BAT-001, Rev J., NASA-Johnson Space Center, Houston, TX, March 2012.
6. Darcy, E.: "Thermal Runaway Severity Reduction Assessment & Implementation: On LREBA." NAS*A Aerospace Battery Workshop*, Huntsville, Al, November 18−20, 2014.
7. Darcy, E.: "Thermal Runaway Severity Reduction Assessment & Implementation: On Li-ion Batteries." *Space Power Workshop*, Aerospace Corporation, Manhattan Beach, CA, May 12−14, 2015.
8. Shack, P.; Iannello, C.; Rickman, S.; and Button, R.: "NASA Perspective and Modeling of Thermal Runaway Propagation Mitigation in Aerospace Batteries." *NASA Aerospace Battery Workshop*, Huntsville, AL, November 18−20, 2014.
9. Jeevarajan, J.; Lopez, C.; and Orievkwu, J.: "Can Cell-to-Cell Thermal Runaway Propagation in Li-ion Modules Be Prevented?" *NASA Aerospace Battery Workshop*, Huntsville, AL, November 18−20, 2014.
10. NASA/JSC, Engineering Directorate, Software, Robotics, and Simulation Division: *Risk Assessment Executive Summary Report (RAESR) for the International Space Station (ISS) Simplified Aid for EVA Rescue (SAFER)*. JSC 37467, December 2015.
11. Duracell® Ultra® CR123 Specification Datasheet (www.duracell.com).

12. Duracell® Declaration of Conformity (www.duracell.com), 12/31/2013.

13. Cell Bundle Assembly Schematic, SID33109327, Rev. D, 4/15/1998.

14. Proctor and Gamble: Duracell® Lithium Manganese Dioxide Batteries and Cells, Product Safety Data Sheet, March 28, 2013.

15. NASA Phase III Hazard Report: *ISS SAFER LiMnO2 Battery exposes Crew and/or Equipment to Toxic/Corrosive Materials, Fire, or Explosion*. ISS_SAFER-002, 2/7/2014.

16. Jeevarajan, J.; and Darcy, E. C.: *Crewed Space Vehicle Battery Safety Requirements*. National Aeronautics and Space Administration, Johnson Space Center, Houston, TX, JSC 20793, Rev. C, January, 2014.

17. Battery Junction Internet website, www.batteryjunction.com.

18. NASA/JSC ESTA: *Operating Checklist*. ESTA-OC-ALL-01557, December 10, 2010.

19. Carter, B. J.: *Identification of Outside Values in Cell/Battery Capacity Data*. TOR-2008(8555)-3, The Aerospace Corporation, 15 May 2008.

20. NASA/JSC Engineering Directorate Propulsion and Power Division: "A*ssembly/Refurbishment Procedures for the IVA Battery Assembly of the U.S.A. Simplified Aid for EVA Rescue (SAFER*)." SAFER-BAT-003, Rev. F, December, 2013.

21. SAFER Cell Bundle Assembly Drawing, NASA/Johnson Space Center, Houston, TX, SED33109326, Code ID 21356, Rev. K.

22. Tyco Electronics RayChem Circuit Protection: *PolySwitch PTC Device*. SRP200, SCD 241790, Rev. G, July 25, 2002.

23. Tyco Electronics RayChem Circuit Protection: "PolySwitch Resettable Devices – Strap Battery Devices." p. 201.

24. NASA/JSC ESTA: *Test Plan: NASA ISS Simplified Aid for EVA Rescue (ISAFER) Battery Thermal Runaway Test NESC Battery Test Program*. NASA/JSC, Propulsion and Power Division, Houston, TX, ESTA-TP-7B247, 2/29/15.

25. NASA/JSC ESTA: *Test Plan: NASA ISS Simplified Aid for EVA Rescue (ISAFER) Battery Thermal Runaway Test NESC Battery Test Program*. NASA/JSC, Propulsion and Power Division, Houston, TX, ESTA-HA-7B247, 2/19/15.

26. Symmetry Resources, Inc.: *SAFER Cell Acceptance and Lot Certification: Duracell® Ultra® CR123. SRI Job #24F*. June 29, 2012.

27. Government Certification Approval Request, G6193, SED33105907-313, Intravehicular Activity Battery Assembly, 5/5/2014.

28. NASA/JSC: *Short Circuit Safety Testing for SAFER Battery*. ESTA-DP-7B219-1A, June 28, 2014.

29. NASA/JSC: *ISS SAFER System Thermal Analysis Summary*. Internal NASA Johnson Space Center/JACOBS Memorandum JETS-JE33-13-TAED-DOC-0004, June 3, 2013.

30. Welch, John W.: *Comparison of Recent Satellite Flight Temperatures with Thermal Model Predictions*. SAE Technical Paper 2006-01-2278, 2006.

31. NASA/JSC: *SAFER Patch Heater Design Comparisons*. NASA JSC Internal document, March 17, 2016.

32. Internal discussions with Daniel Doughty, August 2016.

33. Rickman, S.; Button, R.; Darcy, E.; and Graika, J.: *Assessment of International Space Station (ISS)/Extravehicular Activity (EVA) Lithium-ion Battery Thermal Runaway (TR) Severity Reduction Measures*. Final Report, NESC-RP-14-00942, (in works) 2017.

34. Wilke, S.; Schweitzer, B.; Khateeb, S.; and Al-Hallaj, S.: "Preventing thermal runaway propagation in lithium ion battery packs using a phase change composite material: An experimental study." *J. of Power Sources*, 340, 51-59, 2017.

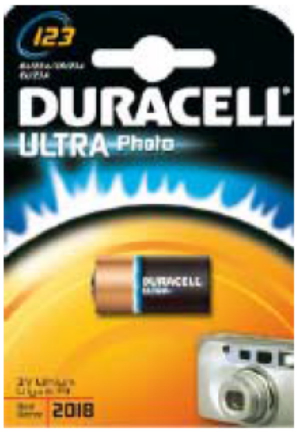
Appendix A. P&G Product Safety Data Sheet

P&G

Product Safety Data Sheet (PSDS)

SECTION 1: IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

Product Name: DURACELL LITHIUM MANGANESE DIOXIDE BATTERIES AND CELLS



Representative Product Image/ Packaging

Identity: Lithium Batteries and Cells (HPL)
Description: Consumer Product

Size/Designation	Voltage	IEC Designation	Lithium Content (g) per Cell/Battery
CR-V3	3	CR-V3	1.4g (Battery)
123, 123A, 2/3A, PL123	3	CR17345	0.55g (Cell)
223/223A	6	CR-P2	1.1g (Battery)
245	6	2CR5	1.1g (Battery)
CR2	3	CR17355	0.3g (Cell)
28L	6	2CR13252	.12g (Battery)
1/3N	3	CR1108	0.06g (Cell)
DL1604	9		0.9g (Battery)

Product Use: Energy Source
PSDS Date of Preparation: March 28, 2013 (replaces November 29, 2012); Reaffirmed/Updated April 11, 2014
Company Identification:

EUROPEAN OFFICE
Procter& Gamble International Operations SA
47 route de Saint-Georges,
1213 Petit-Lancy, 1, Geneva,
Telephone: +41-58-004-6111

US Office
P&G - Duracell
Berkshire Corporate Park
Bethel, CT 06801 USA
Telephone: 203-796-4000

SECTION 2: HAZARDS IDENTIFICATION

These products are classified as Articles under REACH and are not subject to the requirements for Information in the Supply Chain (Safety Data Sheets and Labels). While batteries may release hazardous substances if damaged, this is not an intended release as defined under REACH. Batteries are not classified as hazardous under the CLP.

The following information is provided to assist in the safe use of our products.

CAUTION: Battery can explode or leak if heated, disassembled, shorted, recharged, exposed to fire or high temperature or inserted incorrectly. Keep in original package until ready to use. Do not carry batteries loose in your pocket or purse. Keep batteries away from children. If swallowed, consult a physician at once. Under certain misuse conditions and by abusively opening the battery, exposed lithium can react with water or moisture in the air causing potential thermal burns or fire.

SECTION 3: COMPOSITION/INFORMATION ON INGREDIENTS

Chemical Name	CAS Number	EINECS Number	Amount
1,2-Dimethoxyethane*	110-71-4	203-794-9	5-10 %
Carbon Black	1333-86-4	215-609-9	0-5%
Ethylene Carbonate	96-49-1	202-510-0	0-5%
Graphite	7782-42-5	231-955-3	0-5%
Lithium	7439-93-2	231-102-5	1-5 %
Lithium Perchlorate	7791-03-9	232-237-2	<1.5 %
Lithium Trifluoromethane Sulfonate	33454-82-9	251-528-5	0.5%
Manganese Dioxide	1313-13-9	215-202-6	15-45 %
Propylene Carbonate	108-32-7	203-572-1	1-10 %

*SVHC Substance per Candidate List Updated June 18, 2012

SECTION 4: FIRST AID MEASURES

General Advice: The chemicals and metals in this product are contained in a sealed can. Exposure to the contents will not occur unless the battery leaks, is exposed to high temperatures or is mechanically, physically, or electrically abused.

Eye Contact: If battery is leaking and material contacts the eye, flush thoroughly with copious amounts of running water for 30 minutes. Seek immediate medical advice.

Skin Contact: If battery is leaking and material contacts the skin, remove any contaminated clothing and flush exposed skin with copious amounts of running water for at least 15 minutes. If irritation, injury or pain persists, seek medical advice.

Inhaled: If battery is leaking, contents may be irritating to respiratory passages. Move to fresh air. If irritation persists, seek medical advice.

Swallowed: If battery is swallowed seek immediate medical advice. Batteries lodged in the esophagus should be removed immediately since leakage, caustic burns and perforation can occur as soon as two hours after ingestion. If mouth area irritation or burning has occurred, rinse the mouth and surrounding area with tepid water for at least 15 minutes. Do not give ipecac.

Note to Physician: Published reports recommend removal from the esophagus be done endoscopically (under direct visualization). Batteries beyond the esophagus need not be retrieved unless there are signs of injury to the GI tract or a large diameter battery fails to pass the pylorus. If asymptomatic, follow-up x-rays are necessary only to confirm the passage of larger batteries. Confirmation by stool inspection is preferable under most circumstances. Potential leakage of less than 50 milligrams of dimethoxyethane and propylene carbonate. Dimethoxyethane rapidly evaporates. Do not give ipecac.

SECTION 5: FIRE FIGHTING MEASURES

Fire and Explosion Hazards: Batteries may burst and release hazardous decomposition products when exposed to a fire situation.

Extinguishing Media: Use any extinguishing media that is appropriate for the surrounding fire.

Special Fire Fighting Procedures: Firefighters should wear positive pressure self-contained breathing apparatus and full protective clothing. Fight fire from a distance or protected area. Cool fire exposed batteries to prevent rupture. Use caution when handling fire-exposed containers (batteries may explode in heat of fire).

Hazardous Combustion Products: Thermal degradation may produce hazardous fumes of lithium and manganese; oxides of carbon and other toxic by-products.

Detailed information on fighting a lithium metal battery fire can be found in Gide 138 of the US DOT Emergency Response Guide (http://phmsa.dot.gov/hazmat/library.erg).

SECTION 6: ACCIDENTAL RELEASE MEASURES

Notify safety personnel of large spills. Irritating vapors and flammable may be released from leaking or ruptured batteries. Eliminate all ignition sources. Evacuate the area and allow the vapors to dissipate. Clean-up personnel should wear appropriate protective clothing to avoid eye and skin contact and inhalation of vapors or fumes. Increase ventilation. Carefully collect batteries and place in an appropriate container for disposal. Remove spilled liquid with absorbent and contain for disposal.

SECTION 7: HANDLING AND STORAGE

Avoid mechanical or electrical abuse. DO NOT short circuit or install incorrectly. Batteries may explode, pyrolize or vent if disassembled, crushed, recharged or exposed to high temperatures. Install batteries in accordance with equipment instructions. Replace all batteries in equipment at the same time. Do not carry batteries loose in a pocket or bag.

Storage: Store batteries in a dry place at normal room temperature.

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

Exposure Limits: No exposure to the battery components should occur during normal use.
Ventilation: No special ventilation is needed for normal use.
Respiratory Protection: None required for normal use.
Skin Protection: None required for normal use. Use butyl rubber gloves when handling leaking batteries.
Eye Protection: None required for normal use. Wear safety goggles when handling leaking batteries.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

Appearance and Odor: Coin cells.
Water Solubility: Insoluble
Flash Point: 29°F (-2°C) (1,2-Dimethoxyethane)

SECTION 10: STABILITY AND REACTIVITY

Stability: This product is stable.

Incompatibility/Conditions to Avoid: Contents are incompatible with strong oxidizing agents. Do not heat, crush, disassemble, short circuit or recharge.

Hazardous Decomposition Products: Thermal decomposition may produce hazardous fumes of lithium and manganese; oxides of carbon and other toxic by-products.

Hazardous Polymerization: Will not occur

SECTION 11: TOXICOLOGICAL INFORMATION

Potential Health Effects: The chemicals and metals in this product are contained in a sealed can. Exposure to the contents will not occur unless the battery leaks, is exposed to high temperatures or is mechanically, physically, or electrically abused.

Eye Contact: Contact with battery contents may cause irritation.

Skin Contact: Contact with battery contents may cause irritation.

Inhalation: Inhalation of vapors or fumes released due to heat or a large number of leaking batteries may cause respiratory and eye irritation.

Ingestion: Seek immediate medical advice. Batteries lodged in the esophagus should be removed immediately since leakage, caustic burns and perforation can occur as soon as two hours after ingestion. Irritation to the internal/external mouth areas, may occur following exposure to a leaking battery.

SECTION 12: ECOLOGICAL INFORMATION

No ecotoxicity data is available. This product is not expected to present an environmental hazard.

SECTION 13: DISPOSAL INFORMATION

Disposal should be in accordance with national and local regulations. Do not incinerate for disposal except for in a controlled incinerator.

Duracell manganese dioxide lithium coin cell batteries are labeled in compliance with the EU Battery Directive 2006/66.

SECTION 14: TRANSPORT INFORMATION

Emergency Phone Number:

CHEMTREC 24-Hour Emergency Response Hotline
+703-527-3887 (United States of America)

Persons who prepare or offer lithium batteries for transport are required by regulation to be trained and certified. The information provided below is for informational purposes only.

DURACELL Primary Lithium Metal Batteries
UN3090 Primary lithium batteries – PI 968 **UN3091** Primary lithium batteries with or in equipment- PI 969 & 970
UN 38.3: DURACELL certifies that all of its lithium batteries meet the requirements of the UN Manual of Tests and Criteria, Part III subsection 38.3. If you assemble these batteries into larger battery packs, it is recommended that you perform the UN Tests to ensure the requirements are met prior to shipment.
US DOT: Special Provision 29, 188, 189, 190, A54, A55, A100, A101, A103, A104
Air Transport (IATA/ICAO): Packing Instruction 968-970
Marine/Water Transport (IMDG): Special Provision 188, 230, 310, 957
ADR: Special Provisions: 188, 230, 310, 957

DOT - Except for personal use, the shipment of lithium batteries aboard passenger aircraft is not allowed. Airline passengers may have non-rechargeable lithium batteries for their equipment and a reasonable amount of spare non-rechargeable lithium batteries for their equipment in their carry-on luggage – **NOT** in their checked baggage. For more information, air travelers should consult the US Department of Transportation (DOT) Safety Travel web site at http://safetravel.dot.gov.

Shipping packages containing non-rechargeable lithium batteries must be labeled, regardless of size or number of batteries, with the following statement: "PRIMARY LITHIUM BATTERIES – FORBIDDEN FOR TRANSPORT ABOARD PASSENGER AIRCRAFT."

The transportation of lithium metal batteries is regulated as UN3090 by ICAO, IATA, IMO and US DOT. DURACELL lithium manganese dioxide batteries cells and batteries are not subject to the other provisions of the Dangerous Goods regulations as long as they are packaged and marked in accordance with the ICAO regulations.

SECTION 15: REGULATORY INFORMATION

EU BATTERY DIRECTIVE: These batteries comply with the Directive substance limits and labeling requirements.

EU REACH REGISTRATION: These products are manufactured articles and not subject to REACH registration requirements.

EU REACH SVHC: These products contains 1,2-dimethoxyethane (ethylene glycol dimethyl ether) which is listed on the Candidate List of Substances of Very High Concern.

EU Labeling: Labeling is not required because batteries are classified as articles under the both REACH and the Dangerous Preparations Directive and as such are exempt from the requirement for labeling.

SECTION 16: OTHER INFORMATION

P&G Hazard Rating: Health: 0 Fire: 0 Reactivity: 0

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Data supplied is for use only in connection with occupational safety and health.

DISCLAIMER: This PSDS is intended to provide a brief summary of our knowledge and guidance regarding the use of this material. The information contained here has been compiled from sources considered by Procter & Gamble to be dependable and is accurate to the best of the Company's knowledge. It is not meant to be an all-inclusive document on worldwide hazard communication regulations.

This information is offered in good faith. Each user of this material needs to evaluate the conditions of use and design the appropriate protective mechanisms to prevent employee exposures, property damage or release to the environment. Procter & Gamble assumed no responsibility for injury to the recipient or third persons, or for any damage to any property resulting from misuse of the product.

Appendix B. Raw Data Collected from Cell Acceptance Testing

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
001	16.3	3.239	2.893	0.316	16.43	34.22	
002	16.33	3.353	2.932	0.329	16.45	34.31	
003	16.34	3.351	2.984	0.329	16.41	34.26	
004	16.51	3.358	2.936	0.396	16.39	34.4	
005	16.3	3.357	2.932	0.36	16.39	34.31	
006	16.37	3.214	2.774	0.438	16.43	34.26	
007	16.3	3.350	2.868	0.496	16.4	34.29	
008	16.23	3.353	2.974	0.334	16.49	34.29	
009	16.31	3.355	2.928	0.471	16.41	34.29	
010	16.34	3.354	2.940	0.406	16.49	34.29	
011	16.32	3.378	2.990	0.441	16.43	34.33	
012	16.35	3.381	2.917	0.373	16.49	34.21	
013	16.35	3.373	2.994	0.315	16.42	34.13	
014	16.21	3.375	2.986	0.31	16.47	34.2	
015	16.33	3.378	2.975	0.326	16.46	34.23	
016	16.31	3.377	2.991	0.319	16.39	34.22	
017	16.28	3.377	2.954	0.414	16.48	34.32	
018	16.4	3.375	2.978	0.294	16.5	34.29	
019	16.4	3.376	2.991	0.297	16.48	34.22	
020	16.28	3.372	2.967	0.286	16.43	34.28	
021	16.31	3.257	2.883	0.321	16.45	34.28	
022	16.29	3.254	2.888	0.307	16.44	34.3	
023	16.27	3.255	2.866	0.328	16.42	34.23	
024	16.32	3.254	2.859	0.335	16.42	34.39	
025	16.3	3.258	2.816	0.311	16.48	34.28	
026	16.29	3.255	2.882	0.369	16.48	34.33	
027	16.25	3.255	2.862	0.318	16.43	34.36	
028	16.32	3.251	2.879	0.471	16.5	34.34	
029	16.29	3.255	2.880	0.545	16.47	34.22	
030	16.31	3.254	2.883	0.297	16.42	34.22	Indention on sleeving on positive side
031	16.29	3.253	2.881	0.348	16.42	34.24	
032	16.28	3.257	2.893	0.283	16.42	34.22	
033	16.19	3.252	2.885	0.333	16.42	34.2	
034	16.33	3.254	2.877	0.291	16.41	34.26	
035	16.32	3.253	2.893	0.292	16.42	34.35	
036	16.22	3.252	2.889	0.287	16.4	34.22	
037	16.32	3.253	2.861	0.294	16.42	34.34	
038	16.36	3.256	2.881	0.296	16.49	34.18	
039	16.29	3.254	2.832	0.303	16.41	34.25	
040	16.32	3.257	2.884	0.286	16.53	34.31	
041	16.27	3.252	2.876	0.308	16.39	34.21	
042	16.29	3.252	2.838	0.298	16.41	34.22	
043	16.44	3.256	2.882	0.294	16.41	34.28	
044	16.38	3.252	2.878	0.284	16.42	34.25	
045	16.4	3.258	2.849	0.298	16.46	34.25	
046	16.36	3.253	2.861	0.316	16.4	34.28	
047	16.33	3.255	2.876	0.311	16.42	34.29	
048	16.48	3.259	2.894	0.327	16.49	34.28	
049	16.3	3.256	2.891	0.295	16.48	34.2	
050	16.28	3.253	2.878	0.316	16.49	34.24	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
051	16.38	3.260	2.875	0.316	16.42	34.22	Indention on positive side
052	16.44	3.258	2.877	0.312	16.43	34.13	
053	16.38	3.257	2.871	0.343	16.4	34.28	
054	16.25	3.256	2.876	0.333	16.43	34.24	
055	16.25	3.256	2.860	0.285	16.42	34.26	
056	16.27	3.256	2.862	0.403	16.41	34.28	
057	16.34	3.257	2.882	0.311	16.42	34.37	
058	16.39	3.261	2.877	0.33	16.47	34.26	
059	16.29	3.256	2.877	0.389	16.43	34.23	
060	16.42	3.258	2.882	0.323	16.47	34.32	
061	16.19	3.255	2.875	0.303	16.4	34.29	
062	16.5	3.256	2.890	0.347	16.45	34.2	
063	16.32	3.258	2.860	0.355	16.4	34.23	
064	16.24	3.253	2.877	0.294	16.4	34.22	
065	16.24	3.255	2.866	0.309	16.42	34.3	
066	16.39	3.257	2.888	0.284	16.41	34.18	
067	16.41	3.257	2.879	0.306	16.4	34.23	
068	16.36	3.255	2.885	0.317	16.41	34.15	
069	16.36	3.257	2.896	0.284	16.46	34.2	
070	16.33	3.256	2.870	0.297	16.38	34.27	
071	16.29	3.257	2.879	0.328	16.4	34.22	
072	16.43	3.258	2.862	0.322	16.39	34.19	
073	16.32	3.257	2.876	0.307	16.42	34.27	
074	16.39	3.258	2.880	0.299	16.39	34.19	
075	16.22	3.252	2.850	0.331	16.47	34.19	
076	16.34	3.256	2.887	0.323	16.47	34.22	
077	16.28	3.255	2.875	0.294	16.48	34.38	
078	16.3	3.145	2.817	0.285	16.48	34.24	
079	16.38	3.259	2.887	0.31	16.4	34.31	
080	16.35	3.254	2.888	0.301	16.44	34.33	
081	16.49	3.257	2.885	0.298	16.48	34.26	
082	16.33	3.258	2.827	0.354	16.4	34.22	
083	16.27	3.256	2.876	0.334	16.4	34.37	
084	16.41	3.259	2.884	0.321	16.42	34.21	
085	16.18	3.253	2.861	0.44	16.46	34.2	
086	16.34	3.255	2.836	0.298	16.4	34.19	
087	16.3	3.259	2.886	0.344	16.47	34.28	
088	16.35	3.253	2.885	0.301	16.41	34.11	
089	16.4	3.258	2.892	0.315	16.44	34.23	
090	16.29	3.254	2.884	0.288	16.47	34.2	
091	16.23	3.254	2.874	0.338	16.41	34.2	
092	16.37	3.246	2.887	0.309	16.47	34.22	
093	16.22	3.257	2.875	0.346	16.42	34.34	
094	16.27	3.255	2.881	0.355	16.4	34.22	
095	16.29	3.258	2.872	0.366	16.44	34.27	
096	16.32	3.252	2.887	0.301	16.4	34.15	
097	16.54	3.260	2.882	0.37	16.41	34.26	
098	16.27	3.253	2.873	0.317	16.41	34.22	
099	16.33	3.255	2.894	0.285	16.48	34.2	
100	16.34	3.258	2.885	0.302	16.48	34.25	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
101	16.39	3.250	2.873	0.309	16.36	34.15	
102	16.39	3.251	2.859	0.384	16.39	34.3	
103	16.31	3.248	2.860	0.326	16.4	34.16	
104	16.4	3.253	2.867	0.355	16.47	34.29	
105	16.38	3.252	2.867	0.315	16.39	34.15	
106	16.29	3.249	2.853	0.311	16.46	34.22	Indention on positive side
107	16.44	3.253	2.869	0.332	16.45	34.17	
108	16.43	3.253	2.855	0.305	16.4	34.16	
109	16.35	3.250	2.868	0.318	16.45	34.29	
110	16.44	3.251	2.832	0.338	16.4	34.13	
111	16.3	3.250	2.868	0.307	16.4	34.11	
112	16.35	3.250	2.838	0.331	16.39	34.19	
113	16.26	3.250	2.868	0.291	16.41	34.2	
114	16.24	3.249	2.862	0.317	16.38	34.13	
115	16.46	3.253	2.857	0.287	16.4	34.18	Indention on positive side
116	16.24	3.247	2.862	0.339	16.4	34.18	
117	16.57	3.254	2.869	0.335	16.4	34.18	
118	16.34	3.251	2.855	0.323	16.38	34.19	
119	16.34	3.252	2.870	0.313	16.43	34.13	
120	16.42	3.250	2.865	0.317	16.5	34.19	
121	16.51	3.253	2.874	0.296	16.41	34.24	
122	16.35	3.250	2.859	0.296	16.44	34.19	
123	16.38	3.252	2.878	0.29	16.44	34.22	
124	16.32	3.249	2.856	0.307	16.48	34.17	
125	16.39	3.251	2.866	0.323	16.42	34.2	
126	16.37	3.251	2.864	0.313	16.43	34	
127	16.21	3.247	2.849	0.346	16.5	34.28	
128	16.36	3.248	2.868	0.314	16.48	34.15	
129	16.24	3.249	2.870	0.328	16.43	34.24	
130	16.07	3.246	2.859	0.324	16.47	34.19	
131	16.45	3.251	2.864	0.322	16.42	34.19	
132	16.5	3.252	2.877	0.294	16.51	34.24	
133	16.37	3.251	2.871	0.295	16.41	34.12	
134	16.36	3.250	2.874	0.308	16.42	34.14	
135	16.35	3.251	2.818	0.323	16.5	34.17	
136	16.48	3.252	2.865	0.362	16.41	34.24	
137	16.33	3.249	2.875	0.301	16.49	34.18	
138	16.26	3.250	2.865	0.317	16.5	34.26	
139	16.41	3.252	2.874	0.349	16.47	34.15	
140	16.43	3.253	2.880	0.293	16.41	34.26	
141	16.49	3.255	2.855	0.312	16.41	34.24	
142	16.33	3.250	2.871	0.311	16.42	34.21	
143	16.46	3.254	2.874	0.33	16.42	34.29	
144	16.22	3.248	2.867	0.34	16.48	34.28	
145	16.29	3.251	2.854	0.303	16.49	34.22	
146	16.46	3.254	2.852	0.335	16.45	34.29	
147	16.22	3.246	2.866	0.298	16.44	34.42	
148	16.3	3.252	2.862	0.346	16.42	34.14	
149	16.41	3.254	2.869	0.311	16.43	34.24	
150	16.38	3.249	2.864	0.313	16.41	34.19	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
151	16.29	3.248	2.873	0.325	16.48	34.1	Small indention on positive side
152	16.34	3.250	2.865	0.317	16.41	34.27	Small indention on positive side
153	16.36	3.253	2.880	0.307	16.4	34.24	Small indention on positive side
154	16.43	3.251	2.872	0.313	16.41	34.21	
155	16.38	3.252	2.869	0.317	16.48	34.19	
156	16.33	3.249	2.873	0.305	16.4	34.14	
157	16.2	3.245	2.875	0.312	16.44	34.23	
158	16.29	3.250	2.867	0.311	16.42	34.18	
159	16.43	3.253	2.881	0.315	16.48	34.19	
160	16.35	3.249	2.865	0.305	16.49	34.2	
161	16.26	3.250	2.873	0.308	16.46	34.15	
162	16.37	3.251	2.863	0.311	16.5	34.15	
163	16.37	3.247	2.876	0.316	16.42	34.17	
164	16.52	3.253	2.874	0.308	16.44	34.21	Small indention on positive side
165	16.29	3.252	2.866	0.313	16.43	34.23	
166	16.38	3.252	2.856	0.371	16.43	34.24	
167	16.33	3.247	2.870	0.323	16.49	34.18	
168	16.43	3.250	2.880	0.309	16.49	34.2	
169	16.18	3.248	2.878	0.305	16.41	34.23	
170	16.48	3.253	2.849	0.31	16.48	34.23	
171	16.4	3.253	2.864	0.32	16.49	34.25	Small indention on positive side
172	16.3	3.249	2.877	0.295	16.51	34.29	
173	16.44	3.253	2.881	0.305	16.43	34.21	
174	16.28	3.248	2.872	0.307	16.42	34.12	
175	16.38	3.249	2.870	0.324	16.45	34.18	
176	16.29	3.249	2.877	0.328	16.44	34.14	
177	16.42	3.250	2.872	0.303	16.51	34.17	
178	16.38	3.252	2.860	0.321	16.44	34.27	
179	16.37	3.251	2.875	0.316	16.43	34.2	
180	16.49	3.250	2.875	0.31	16.44	34.11	
181	16.4	3.252	2.873	0.311	16.46	34.25	
182	16.45	3.254	2.859	0.317	16.51	34.15	
183	16.48	3.250	2.882	0.313	16.47	34.3	
184	16.32	3.252	2.873	0.317	16.48	34.24	Small indention on positive side
185	16.4	3.252	2.866	0.315	16.47	34.26	
186	16.23	3.248	2.870	0.311	16.49	34.25	
187	16.3	3.251	2.860	0.367	16.41	34.21	
188	16.31	3.248	2.866	0.339	16.42	34.13	Small indention on positive side
189	16.53	3.251	2.857	0.346	16.44	34.18	
190	16.54	3.254	2.873	0.364	16.45	34.27	
191	16.38	3.249	2.878	0.322	16.53	34.14	
192	16.32	3.251	2.860	0.325	16.45	34.25	
193	16.29	3.251	2.878	0.322	16.44	34.1	
194	16.43	3.253	2.877	0.304	16.49	34.18	
195	16.44	3.252	2.877	0.307	16.48	34.18	
196	16.48	3.249	2.875	0.313	16.43	34.15	
197	16.33	3.250	2.872	0.311	16.41	34.12	
198	16.5	3.252	2.877	0.302	16.43	34.24	
199	16.38	3.252	2.875	0.316	16.16	34.41	
200	16.29	3.253	2.867	0.321	16.13	34.15	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
201	16.23	3.248	2.875	0.32	16.42	34.24	
202	16.23	3.250	2.853	0.324	16.67	34.17	
203	16.3	3.250	2.876	0.322	16.58	34.42	
204	16.21	3.248	2.869	0.312	16.59	34.19	
205	16.42	3.251	2.877	0.333	16.51	34.23	
206	16.33	3.251	2.867	0.305	16.43	34.27	
207	16.46	3.251	2.879	0.303	16.42	34.17	
208	16.46	3.253	2.870	0.311	16.27	34.43	
209	16.28	3.250	2.872	0.312	16.42	34.17	
210	16.26	3.248	2.861	0.305	16.49	34.21	
211	16.39	3.252	2.880	0.305	16.41	34.12	Small indention on positive side
212	16.49	3.252	2.865	0.321	16.46	34.31	
213	16.33	3.252	2.865	0.319	16.49	34.14	
214	16.47	3.250	2.863	0.337	16.48	34.17	
215	16.35	3.250	2.867	0.34	16.43	34.18	
216	16.34	3.246	2.878	0.303	16.41	34.29	
217	16.77	3.249	2.879	0.308	16.5	34.15	
218	16.31	3.250	2.868	0.304	16.42	34.1	
219	16.32	3.250	2.863	0.311	16.43	34.23	
220	16.47	3.251	2.843	0.312	16.42	34.08	
221	16.35	3.252	2.860	0.304	16.47	34.19	
222	16.45	3.251	2.865	0.308	16.41	34.2	
223	16.16	3.246	2.876	0.287	16.42	34.15	
224	16.2	3.250	2.879	0.307	16.44	34.16	
225	16.45	3.253	2.879	0.308	16.44	34.25	
226	16.41	3.250	2.879	0.293	16.48	34.19	
227	16.36	3.250	2.876	0.312	16.48	34.23	
228	16.34	3.249	2.875	0.308	16.47	34.2	
229	16.36	3.254	2.875	0.306	16.43	34.16	
230	16.31	3.249	2.879	0.301	16.49	34.15	
231	16.34	3.248	2.876	0.303	16.42	34.1	
232	16.51	3.248	2.885	0.305	16.43	34.18	
233	16.43	3.251	2.884	0.291	16.41	34.14	
234	16.42	3.249	2.875	0.335	16.42	34.29	
235	16.38	3.252	2.838	0.341	16.42	34.28	
236	16.31	3.250	2.859	0.317	16.42	34.16	
237	16.44	3.250	2.879	0.302	16.23	34.2	
238	16.43	3.251	2.879	0.313	16.26	34.3	
239	16.38	3.250	2.872	0.314	16.51	34.19	
240	16.56	3.253	2.874	0.32	16.51	34.23	
241	16.33	3.250	2.865	0.318	16.49	34.2	
242	16.28	3.250	2.876	0.321	16.44	34.27	
243	16.39	3.250	2.881	0.312	16.48	34.27	
244	16.3	3.250	2.885	0.305	16.49	34.28	
245	16.51	3.255	2.879	0.311	16.49	34.24	
246	16.37	3.250	2.878	0.313	16.45	34.16	
247	16.25	3.246	2.874	0.301	16.5	34.26	
248	16.39	3.251	2.872	0.32	16.49	34.17	
249	16.25	3.250	2.880	0.299	16.49	34.12	
250	16.34	3.249	2.874	0.31	16.42	34.16	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
251	16.3	3.249	2.868	0.309	16.49	34.13	
252	16.42	3.251	2.871	0.306	16.43	34.21	
253	16.21	3.250	2.875	0.316	16.48	34.17	
254	16.4	3.251	2.879	0.335	16.47	34.15	
255	16.4	3.251	2.872	0.317	16.49	34.19	Small indention on positive side
256	16.42	3.253	2.823	0.399	16.44	34.12	
257	16.37	3.251	2.872	0.307	16.49	34.21	
258	16.24	3.249	2.875	0.338	16.41	34.12	
259	16.31	3.250	2.876	0.338	16.5	34.12	
260	16.36	3.248	2.867	0.307	16.49	34.16	
261	16.33	3.249	2.883	0.308	16.49	34.19	
262	16.34	3.251	2.864	0.349	16.42	34.12	
263	16.36	3.251	2.881	0.296	16.48	34.15	
264	16.4	3.251	2.884	0.31	16.44	34.17	
265	16.38	3.252	2.875	0.314	16.49	34.23	
266	16.52	3.249	2.882	0.298	16.41	34.23	
267	16.39	3.250	2.886	0.299	16.48	34.26	
268	16.39	3.250	2.872	0.304	16.48	34.18	
269	16.36	3.251	2.872	0.309	16.42	34.07	
270	16.38	3.248	2.867	0.303	16.4	34.12	
271	16.44	3.251	2.885	0.297	16.42	34.14	
272	16.31	3.249	2.820	0.331	16.41	34.25	
273	16.43	3.253	2.883	0.31	16.54	34.12	
274	16.31	3.251	2.882	0.313	16.49	34.14	
275	16.37	3.249	2.877	0.331	16.48	34.22	
276	16.41	3.252	2.882	0.302	16.5	34.32	
277	16.33	3.251	2.882	0.342	16.42	34.13	
278	16.48	3.253	2.883	0.318	16.41	34.29	
279	16.37	3.250	2.882	0.347	16.46	34.1	
280	16.37	3.250	2.875	0.348	16.47	34.15	
281	16.28	3.250	2.884	0.308	16.42	34.17	
282	16.37	3.251	2.821	0.331	16.46	34.14	
283	16.53	3.253	2.881	0.307	16.48	34.27	
284	16.36	3.252	2.877	0.305	16.44	34.13	
285	16.46	3.250	2.887	0.324	16.42	34.12	
286	16.39	3.248	2.875	0.336	16.49	34.26	
287	16.41	3.250	2.881	0.306	16.43	34.24	
288	16.32	3.250	2.880	0.313	16.42	34.23	
289	16.48	3.251	2.873	0.316	16.47	34.26	
290	16.22	3.246	2.871	0.354	16.4	34.04	
291	16.44	3.251	2.886	0.297	16.43	34.18	
292	16.5	3.256	2.868	0.339	16.49	34.14	
293	16.44	3.251	2.886	0.302	16.49	34.12	
294	16.45	3.252	2.882	0.319	16.41	34.2	
295	16.38	3.251	2.872	0.312	16.41	34.34	
296	16.46	3.251	2.876	0.302	16.47	34.13	
297	16.31	3.250	2.876	0.322	16.43	34.2	
298	16.43	3.253	2.880	0.333	16.42	34.33	
299	16.31	3.250	2.874	0.308	16.5	34.23	
300	16.42	3.253	2.877	0.308	16.48	34.22	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
301	16.27	3.252	2.868	0.304	16.41	34.23	
302	16.31	3.249	2.879	0.31	16.46	34.17	
303	16.35	3.251	2.877	0.335	16.47	34.17	
304	16.22	3.248	2.877	0.334	16.47	34.07	
305	16.21	3.250	2.875	0.307	16.42	34.13	
306	16.38	3.250	2.885	0.299	16.4	34.26	
307	16.31	3.251	2.872	0.303	16.4	34.09	
308	16.44	3.253	2.870	0.311	16.4	34.08	
309	16.42	3.253	2.887	0.308	16.4	34.14	
310	16.22	3.248	2.864	0.336	16.39	34.04	
311	16.29	3.250	2.879	0.314	16.45	34.28	
312	16.28	3.249	2.870	0.311	16.43	34.13	
313	16.34	3.252	2.880	0.313	16.5	34.29	
314	16.25	3.249	2.873	0.32	16.48	34.18	Small indention on positive side
315	16.37	3.251	2.882	0.315	16.43	34.3	
316	16.42	3.250	2.884	0.303	16.43	34.22	
317	16.31	3.248	2.879	0.293	16.5	34.19	
318	16.49	3.253	2.878	0.328	16.44	34.15	
319	16.22	3.251	2.868	0.323	16.43	34.17	
320	16.43	3.251	2.850	0.32	16.42	34.17	
321	16.2	3.250	2.888	0.289	16.43	34.26	
322	16.25	3.249	2.881	0.29	16.41	34.14	
323	16.45	3.251	2.885	0.304	16.49	34.27	
324	16.46	3.250	2.881	0.321	16.43	34.27	
325	16.36	3.251	2.879	0.31	16.4	34.14	
326	16.41	3.251	2.879	0.312	16.43	34.23	
327	16.36	3.252	2.886	0.322	16.49	34.25	
328	16.46	3.255	2.870	0.313	16.43	34.17	
329	16.42	3.253	2.873	0.316	16.46	34.19	
330	16.37	3.252	2.877	0.301	16.42	34.25	
331	16.36	3.250	2.887	0.309	16.43	34.15	
332	16.43	3.250	2.817	0.303	16.51	34.14	
333	16.42	3.251	2.875	0.303	16.43	34.09	
334	16.41	3.250	2.878	0.321	16.47	34.17	
335	16.34	3.250	2.855	0.313	16.48	34.19	
336	16.47	3.250	2.875	0.297	16.43	34.13	
337	16.21	3.247	2.874	0.322	16.43	34.11	
338	16.27	3.249	2.860	0.317	16.46	34.19	
339	16.47	3.250	2.887	0.301	16.5	34.13	
340	16.27	3.249	2.882	0.31	16.41	34.23	
341	16.2	3.248	2.878	0.304	16.52	34.28	
342	16.31	3.250	2.867	0.316	16.42	34.15	
343	16.35	3.249	2.884	0.309	16.42	34.23	
344	16.38	3.252	2.876	0.364	16.41	34.17	
345	16.56	3.253	2.887	0.319	16.49	34.18	
346	16.35	3.248	2.867	0.307	16.42	34.22	
347	16.44	3.250	2.872	0.295	16.42	34.17	
348	16.42	3.252	2.877	0.295	16.45	34.18	
349	16.27	3.249	2.878	0.315	16.47	34.22	
350	16.41	3.252	2.854	0.323	16.48	34.22	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
351	16.4	3.250	2.884	0.304	16.49	34.29	
352	16.31	3.247	2.860	0.314	16.42	34.23	
353	16.35	3.251	2.878	0.312	16.43	34.16	
354	16.28	3.250	2.875	0.297	16.44	34.16	
355	16.48	3.250	2.886	0.329	16.43	34.21	
356	16.4	3.251	2.871	0.311	16.54	34.29	
357	16.42	3.250	2.874	0.303	16.43	34.16	
358	16.42	3.252	2.875	0.307	16.5	34.19	Small indention on positive side
359	16.46	3.252	2.879	0.323	16.44	34.23	
360	16.43	3.251	2.879	0.322	16.5	34.21	
361	16.32	3.248	2.881	0.315	16.43	34.18	
362	16.44	3.250	2.881	0.327	16.51	34.28	
363	16.3	3.250	2.877	0.303	16.49	34.21	
364	16.17	3.250	2.875	0.299	16.5	34.19	
365	16.44	3.255	2.881	0.299	16.54	34.27	
366	16.34	3.251	2.881	0.308	16.43	34.19	
367	16.33	3.250	2.871	0.318	16.43	34.1	
368	16.31	3.250	2.877	0.295	16.48	34.15	
369	16.41	3.252	2.872	0.297	16.42	34.21	
370	16.34	3.250	2.873	0.306	16.43	34.23	
371	16.36	3.249	2.891	0.325	16.43	34.15	
372	16.55	3.254	2.880	0.307	16.5	34.28	
373	16.34	3.250	2.882	0.304	16.49	34.38	Small indention on positive side
374	16.31	3.252	2.877	0.305	16.44	34.26	
375	16.31	3.249	2.884	0.312	16.43	34.1	
376	16.44	3.251	2.887	0.314	16.49	34.1	
377	16.42	3.250	2.883	0.301	16.49	34.29	Small indention on positive side
378	16.33	3.251	2.873	0.32	16.51	34.12	
379	16.37	3.251	2.880	0.294	16.49	34.29	
380	16.35	3.250	2.879	0.304	16.49	34.17	
381	16.39	3.250	2.882	0.296	16.42	34.24	
382	16.33	3.251	2.872	0.309	16.51	34.19	
383	16.23	3.248	2.879	0.298	16.5	34.18	Small indention on positive side
384	16.31	3.251	2.875	0.303	16.44	34.26	Small indentions on positive side
385	16.18	3.248	2.871	0.313	16.43	34.23	
386	16.3	3.250	2.882	0.286	16.51	34.22	
387	16.44	3.251	2.868	0.317	16.42	34.23	Small indention on positive side
388	16.49	3.250	2.881	0.292	16.5	34.15	
389	16.16	3.248	2.887	0.287	16.47	34.25	
390	16.35	3.250	2.886	0.3	16.43	34.23	
391	16.38	3.253	2.888	0.287	16.5	34.16	
392	16.35	3.251	2.874	0.303	16.42	34.2	
393	16.32	3.250	2.867	0.312	16.5	34.14	Small indentions on positive side
394	16.25	3.249	2.874	0.32	16.43	34.25	
395	16.26	3.250	2.877	0.316	16.51	34.23	Small indention on positive side
396	16.27	3.247	2.888	0.319	16.42	34.23	
397	16.39	3.253	2.873	0.322	16.47	34.28	
398	16.28	3.246	2.892	0.297	16.5	34.15	
399	16.37	3.251	2.885	0.302	16.14	34.2	
400	16.37	3.248	2.882	0.319	16.44	34.21	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
401	16.3	3.252	2.875	0.304	16.42	34.23	
402	16.39	3.251	2.878	0.282	16.43	34.06	
403	16.51	3.255	2.863	0.302	16.37	34.38	
404	16.4	3.254	2.866	0.325	16.45	34.25	
405	16.33	3.250	2.868	0.315	16.45	34.11	
406	16.38	3.253	2.871	0.297	16.48	34.28	
407	16.37	3.250	2.869	0.292	16.41	34.36	
408	16.4	3.250	2.872	0.305	16.42	34.29	
409	16.24	3.248	2.872	0.305	16.37	34.17	
410	16.3	3.251	2.869	0.285	16.48	34.24	
411	16.22	3.248	2.859	0.32	16.37	34.23	
412	16.26	3.249	2.872	0.293	16.38	34.22	
413	16.39	3.250	2.865	0.299	16.47	34.24	
414	16.36	3.251	2.863	0.311	16.38	34.21	
415	16.25	3.252	2.865	0.311	16.44	34.1	
416	16.33	3.250	2.874	0.293	16.42	34.34	
417	16.32	3.250	2.867	0.322	16.47	34.21	
418	16.47	3.251	2.872	0.302	16.42	34.25	
419	16.39	3.253	2.871	0.296	16.42	34.35	
420	16.48	3.252	2.849	0.308	16.42	34.2	
421	16.32	3.250	2.869	0.317	16.46	34.22	
422	16.35	3.250	2.863	0.308	16.47	34.08	
423	16.35	3.251	2.878	0.316	16.39	34.39	
424	16.39	3.253	2.877	0.298	16.43	34.21	
425	16.42	3.251	2.862	0.279	16.44	34.21	
426	16.44	3.253	2.877	0.311	16.4	34.47	
427	16.49	3.250	2.884	0.285	16.43	34.17	
428	16.28	3.253	2.871	0.319	16.43	34.36	
429	16.26	3.250	2.869	0.289	16.48	34.14	
430	16.38	3.250	2.830	0.291	16.46	34.11	
431	16.43	3.251	2.875	0.3	16.47	34.23	
432	16.36	3.248	2.882	0.326	16.43	34.16	
433	16.31	3.248	2.870	0.331	16.4	34.25	
434	16.24	3.247	2.872	0.312	16.4	34.16	
435	16.41	3.250	2.884	0.298	16.4	34.2	
436	16.37	3.251	2.862	0.293	16.4	34.15	
437	16.21	3.245	2.879	0.304	16.41	34.28	
438	16.46	3.252	2.877	0.315	16.47	34.24	
439	16.37	3.251	2.861	0.306	16.42	34.29	
440	16.26	3.249	2.866	0.309	16.46	34.14	
441	16.43	3.252	2.875	0.301	16.41	34.39	Sleeving damage near top of cell and can is slightly exposed
442	16.24	3.247	2.870	0.298	16.43	34.15	
443	16.45	3.250	2.879	0.311	16.43	34.22	
444	16.38	3.249	2.879	0.321	16.41	34.28	
445	16.28	3.250	2.872	0.32	16.47	34.25	
446	16.37	3.251	2.878	0.316	16.43	34.21	
447	16.28	3.249	2.878	0.315	16.38	34.22	
448	16.36	3.249	2.876	0.313	16.44	34.33	
449	16.47	3.251	2.882	0.311	16.5	34.17	
450	16.39	3.249	2.879	0.323	16.41	34.31	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
451	16.33	3.251	2.881	0.296	16.35	34.13	Slight sleeving damage near top of cell
452	16.35	3.245	2.874	0.303	16.41	34.11	
453	16.22	3.248	2.874	0.304	16.41	34.15	Slight sleeving damage near top of cell
454	16.42	3.252	2.873	0.313	16.41	34.26	
455	16.31	3.249	2.876	0.32	16.46	34.22	
456	16.46	3.251	2.874	0.288	16.42	34.13	
457	16.25	3.249	2.860	0.313	16.45	34.15	
458	16.24	3.246	2.876	0.278	16.46	34.13	
459	16.38	3.253	2.879	0.32	16.39	34.07	
460	16.34	3.251	2.875	0.306	16.46	34.07	
461	16.36	3.249	2.881	0.332	16.47	34.16	
462	16.37	3.252	2.874	0.317	16.38	34.15	
463	16.33	3.249	2.885	0.303	16.4	34.14	
464	16.48	3.252	2.879	0.283	16.4	34.27	
465	16.51	3.253	2.878	0.308	16.48	34.12	
466	16.48	3.248	2.882	0.315	16.42	34.05	Sleeving damage near top of cell
467	16.37	3.249	2.869	0.316	16.39	34.05	
468	16.36	3.250	2.871	0.302	16.4	34.17	
469	16.35	3.250	2.873	0.313	16.46	34.05	
470	16.27	3.250	2.849	0.311	16.46	34.23	
471	16.27	3.250	2.872	0.295	16.46	34.17	
472	16.27	3.252	2.871	0.308	16.4	34.2	Indention near top and can slightly exposed
473	16.43	3.251	2.885	0.292	16.47	34.15	
474	16.33	3.250	2.863	0.315	16.39	34.15	
475	16.45	3.250	2.883	0.294	16.47	34.18	
476	16.43	3.251	2.875	0.294	16.39	34.22	Sleeving damage near top and slight can exposed
477	16.28	3.249	2.876	0.296	16.39	34.2	
478	16.46	3.249	2.876	0.295	16.46	34.15	
479	16.4	3.249	2.876	0.303	16.46	34.22	
480	16.31	3.249	2.877	0.291	16.39	34.21	
481	16.3	3.252	2.859	0.31	16.46	34.13	
482	16.33	3.252	2.864	0.305	16.4	34.14	
483	16.5	3.253	2.874	0.314	16.39	34.21	
484	16.34	3.250	2.874	0.301	16.38	34.11	
485	16.3	3.251	2.876	0.303	16.4	34.21	Sleeving damage near top and can slightly exposed
486	16.4	3.253	2.882	0.295	16.4	34.09	Indention near top and dent near the bottom
487	16.34	3.249	2.876	0.297	16.46	34.12	
488	16.3	3.250	2.885	0.299	16.4	34.16	
489	16.36	3.251	2.878	0.304	16.47	34.14	Indentions on sleeve
490	16.4	3.251	2.870	0.3	16.46	34.1	
491	16.4	3.253	2.876	0.303	16.42	34.1	Indention on sleeve
492	16.39	3.249	2.884	0.298	16.39	34.16	Indention on sleeve
493	16.49	3.251	2.880	0.297	16.41	34.25	
494	16.32	3.252	2.881	0.305	16.39	34.17	
495	16.59	3.254	2.876	0.319	16.46	34.2	
496	16.33	3.250	2.879	0.306	16.38	34.05	
497	16.33	3.239	2.890	0.281	16.46	34.27	
498	16.47	3.245	2.883	0.29	16.5	34.12	
499	16.38	3.243	2.887	0.293	16.48	34.23	
500	16.29	3.240	2.852	0.338	16.5	34.09	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
501	16.23	3.241	2.859	0.309	16.38	34.14	
502	16.39	3.245	2.886	0.3	16.38	34.15	
503	16.42	3.241	2.878	0.289	16.42	34.17	
504	16.5	3.242	2.881	0.316	16.38	34.19	
505	16.4	3.248	2.876	0.308	16.44	34.08	
506	16.28	3.246	2.882	0.286	16.43	34.18	Slight sleeving damage near top of cell
507	16.25	3.238	2.878	0.282	16.43	34.15	
508	16.17	3.240	2.879	0.288	16.37	34.26	Slight sleeving damage near top of cell
509	16.29	3.246	2.890	0.304	16.43	34.13	Slight sleeving damage near top of cell
510	16.24	3.242	2.860	0.304	16.45	34.05	
511	16.29	3.243	2.854	0.315	16.4	34.12	
512	16.26	3.246	2.882	0.272	16.4	34.1	
513	16.33	3.245	2.882	0.285	16.44	34.18	
514	16.46	3.245	2.881	0.298	16.38	34.25	
515	16.32	3.243	2.883	0.293	16.39	34.12	
516	16.38	3.243	2.874	0.307	16.44	34.15	
517	16.31	3.240	2.872	0.295	16.44	34.11	
518	16.24	3.243	2.882	0.277	16.46	34.19	
519	16.38	3.247	2.872	0.29	16.4	34.15	
520	16.43	3.241	2.884	0.304	16.38	34.11	
521	16.48	3.249	2.874	0.286	16.44	34.15	
522	16.5	3.242	2.882	0.291	16.38	34.07	
523	16.2	3.238	2.873	0.313	16.38	34.1	
524	16.21	3.238	2.870	0.278	16.42	34.11	
525	16.19	3.243	2.885	0.277	16.45	34.05	
526	16.45	3.248	2.879	0.282	16.39	34.16	
527	16.47	3.245	2.883	0.28	16.45	34.17	
528	16.39	3.246	2.880	0.279	16.39	34.09	
529	16.39	3.240	2.890	0.261	16.39	34.13	
530	16.29	3.241	2.854	0.286	16.39	34.11	
531	16.33	3.246	2.882	0.297	16.38	34.12	
532	16.36	3.246	2.869	0.284	16.44	34.15	
533	16.34	3.243	2.875	0.288	16.44	34.14	
534	16.26	3.244	2.864	0.296	16.44	34.1	
535	16.34	3.248	2.885	0.286	16.46	34.09	
536	16.34	3.240	2.878	0.324	16.37	34.09	
537	16.37	3.247	2.879	0.321	16.44	34.07	
538	16.43	3.248	2.867	0.302	16.39	34.22	
539	16.35	3.245	2.879	0.282	16.43	34.1	
540	16.24	3.241	2.873	0.283	16.44	34.19	Slight sleeving damage near top of cell
541	16.16	3.240	2.873	0.28	16.44	34.12	
542	16.42	3.250	2.798	0.33	16.42	34.1	
543	16.42	3.246	2.873	0.313	16.38	34.09	
544	16.46	3.247	2.872	0.293	16.43	34.24	
545	16.28	3.243	2.875	0.286	16.39	34.16	
546	16.16	3.241	2.861	0.311	16.45	34.19	Slight sleeving damage near top of cell
547	16.26	3.238	2.875	0.271	16.45	34.16	
548	16.33	3.244	2.883	0.285	16.38	34.12	
549	16.39	3.247	2.895	0.269	16.46	34.14	
550	16.24	3.245	2.886	0.269	16.39	34.21	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
551	16.24	3.240	2.884	0.27	16.39	34.13	
552	16.26	3.245	2.880	0.279	16.37	34.16	
553	16.41	3.241	2.879	0.276	16.46	34.19	
554	16.33	3.247	2.877	0.302	16.39	34.15	
555	16.18	3.246	2.872	0.3	16.39	34.21	
556	16.42	3.246	2.882	0.278	16.46	34.1	
557	16.47	3.245	2.874	0.295	16.46	34.15	
558	16.15	3.244	2.872	0.273	16.45	34.13	
559	16.43	3.243	2.875	0.287	16.39	34.17	
560	16.39	3.245	2.884	0.276	16.4	34.13	
561	16.35	3.248	2.878	0.283	16.37	34.3	
562	16.37	3.242	2.883	0.273	16.44	34.19	
563	16.32	3.242	2.884	0.275	16.38	34.17	
564	16.29	3.243	2.881	0.268	16.4	34.15	
565	16.34	3.247	2.882	0.295	16.44	34.15	
566	16.31	3.246	2.882	0.272	16.37	34.13	
567	16.25	3.240	2.882	0.287	16.43	34.18	Slight sleeving damage neat the top of cell and the bottom
568	16.32	3.248	2.886	0.319	16.38	34.16	
569	16.21	3.240	2.857	0.296	16.39	34.13	
570	16.31	3.246	2.871	0.311	16.45	34.1	
571	16.32	3.246	2.887	0.336	16.38	34.13	
572	16.22	3.243	2.874	0.296	16.45	34.1	
573	16.19	3.237	2.887	0.273	16.44	34.15	
574	16.4	3.248	2.887	0.275	16.38	34.06	
575	16.3	3.243	2.878	0.285	16.43	34.1	
576	16.5	3.242	2.888	0.291	16.38	34.21	
577	16.3	3.247	2.886	0.292	16.39	34.08	
578	16.38	3.245	2.877	0.261	16.47	34.14	
579	16.4	3.248	2.882	0.302	16.38	34.13	
580	16.42	3.242	2.874	0.306	16.45	34.11	
581	16.44	3.249	2.892	0.25	16.44	34.12	
582	16.42	3.240	2.870	0.29	16.43	34.11	
583	16.26	3.246	2.872	0.283	16.38	34.13	
584	16.16	3.240	2.867	0.297	16.38	34.19	
585	16.4	3.246	2.878	0.282	16.38	34.18	
586	16.29	3.249	2.882	0.305	16.38	34.1	
587	16.44	3.245	2.862	0.309	16.38	34.17	
588	16.27	3.242	2.875	0.282	16.45	34.12	
589	16.34	3.240	2.869	0.29	16.38	34.17	
590	16.34	3.240	2.886	0.312	16.39	34.17	
591	16.4	3.247	2.875	0.308	16.45	34.18	
592	16.23	3.240	2.875	0.293	16.39	34.15	
593	16.35	3.241	2.884	0.271	16.39	34.17	
594	16.34	3.241	2.876	0.293	16.39	34.1	
595	16.31	3.241	2.825	0.385	16.38	34.12	
596	16.2	3.245	2.890	0.292	16.38	34.17	
597	16.35	3.247	2.888	0.326	16.44	34.04	
598	16.33	3.243	2.878	0.322	16.39	34.17	
599	16.31	3.243	2.889	0.295	16.37	34.16	
600	16.34	3.247	2.873	0.288	16.38	34.16	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
601	16.36	3.244	2.868	0.309	16.46	34.22	
602	16.36	3.243	2.849	0.309	16.42	34.19	
603	16.34	3.249	2.866	0.318	16.4	34.21	
604	16.31	3.247	2.866	0.303	16.44	34.15	
605	16.23	3.241	2.864	0.301	16.4	34.25	
606	16.31	3.245	2.876	0.3	16.44	34.22	
607	16.31	3.246	2.877	0.305	16.41	34.12	
608	16.18	3.241	2.841	0.314	16.46	34.21	
609	16.41	3.242	2.881	0.314	16.41	34.11	
610	16.4	3.248	2.875	0.324	16.47	34.07	
611	16.39	3.244	2.880	0.279	16.39	34.13	
612	16.44	3.248	2.860	0.297	16.42	34.19	
613	16.36	3.245	2.878	0.303	16.47	34.08	
614	16.29	3.242	2.870	0.277	16.4	34.16	
615	16.33	3.247	2.869	0.282	16.48	34.16	
616	16.46	3.248	2.864	0.302	16.42	34.18	
617	16.24	3.241	2.856	0.296	16.43	34.21	
618	16.48	3.247	2.877	0.283	16.47	34.19	
619	16.42	3.241	2.881	0.273	16.4	34.08	
620	16.32	3.241	2.856	0.29	16.4	34.17	
621	16.22	3.243	2.865	0.295	16.41	34.14	
622	16.36	3.246	2.872	0.291	16.39	34.19	
623	16.36	3.243	2.864	0.29	16.41	34.13	
624	16.46	3.245	2.885	0.28	16.45	34.16	
625	16.41	3.248	2.877	0.372	16.39	34.18	
626	16.3	3.243	2.861	0.319	16.39	34.26	
627	16.55	3.247	2.862	0.308	16.38	34.11	
628	16.38	3.248	2.861	0.329	16.41	34.15	
629	16.38	3.242	2.864	0.281	16.44	34.13	
630	16.49	3.244	2.870	0.294	16.45	34.07	
631	16.41	3.243	2.871	0.29	16.42	34.19	
632	16.29	3.241	2.870	0.289	16.47	34.12	
633	16.39	3.245	2.883	0.309	16.39	34.17	
634	16.35	3.243	2.885	0.305	16.39	34.09	
635	16.31	3.242	2.877	0.293	16.38	34.13	
636	16.31	3.242	2.864	0.305	16.45	34.18	
637	16.28	3.240	2.864	0.301	16.4	34.21	
638	16.53	3.246	2.880	0.296	16.43	34.13	
639	16.52	3.248	2.887	0.306	16.4	34.17	
640	16.15	3.246	2.859	0.313	16.45	34.25	
641	16.34	3.243	2.879	0.29	16.41	34.14	
642	16.34	3.243	2.840	0.289	16.48	34.18	
643	16.31	3.244	2.883	0.317	16.5	34.24	
644	16.41	3.243	2.878	0.286	16.48	34.29	
645	16.27	3.248	2.870	0.295	16.42	34.2	
646	16.34	3.243	2.867	0.295	16.42	34.22	
647	16.26	3.240	2.865	0.309	16.4	34.11	
648	16.28	3.240	2.884	0.264	16.41	34.16	
649	16.39	3.247	2.853	0.297	16.42	34.25	
650	16.31	3.242	2.867	0.285	16.46	34.14	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
651	16.31	3.241	2.866	0.283	16.39	34.19	
652	16.42	3.242	2.862	0.286	16.45	34.13	
653	16.37	3.245	2.861	0.294	16.38	34.11	
654	16.41	3.243	2.879	0.272	16.48	34.11	
655	16.2	3.247	2.868	0.289	16.41	34.13	
656	16.48	3.244	2.880	0.287	16.4	34.22	
657	16.15	3.245	2.861	0.315	16.49	34.15	
658	16.27	3.241	2.872	0.3	16.4	34.15	
659	16.35	3.240	2.873	0.279	16.4	34.16	
660	16.33	3.241	2.870	0.277	16.49	34.14	
661	16.35	3.244	2.875	0.292	16.47	34.18	
662	16.3	3.239	2.857	0.284	16.42	34.21	
663	16.51	3.242	2.881	0.277	16.44	34.16	
664	16.42	3.248	2.871	0.291	16.4	34.08	
665	16.47	3.241	2.876	0.291	16.48	34.25	
666	16.44	3.243	2.869	0.285	16.4	34.17	
667	16.37	3.247	2.869	0.304	16.44	34.15	
668	16.45	3.249	2.881	0.334	16.4	34.15	
669	16.32	3.240	2.875	0.299	16.4	34.1	
670	16.26	3.244	2.867	0.295	16.4	34.17	
671	16.35	3.243	2.875	0.295	16.39	34.12	
672	16.24	3.240	2.871	0.325	16.43	34.36	
673	16.44	3.249	2.883	0.325	16.46	34.13	
674	16.37	3.247	2.876	0.3	16.38	34.13	
675	16.34	3.246	2.888	0.278	16.47	34.2	
676	16.46	3.249	2.870	0.295	16.38	34.13	
677	16.3	3.240	2.865	0.305	16.49	34.23	
678	16.47	3.247	2.882	0.313	16.38	34.17	
679	16.3	3.240	2.871	0.31	16.48	34.11	
680	16.18	3.237	2.871	0.309	16.44	34.16	
681	16.24	3.244	2.881	0.28	16.42	34.15	
682	16.51	3.249	2.869	0.299	16.45	34.17	
683	16.37	3.247	2.885	0.273	16.46	34.21	
684	16.31	3.242	2.859	0.294	16.45	34.09	
685	16.26	3.246	2.878	0.3	16.43	34.18	
686	16.2	3.238	2.867	0.281	16.44	34.11	
687	16.27	3.240	2.856	0.294	16.45	34.21	
688	16.24	3.240	2.881	0.258	16.39	34.08	
689	16.35	3.240	2.875	0.273	16.47	34.07	
690	16.33	3.248	2.858	0.276	16.38	34.21	
691	16.24	3.240	2.868	0.267	16.46	34.14	
692	16.24	3.246	2.856	0.288	16.37	34.14	
693	16.32	3.250	2.865	0.287	16.38	34.1	
694	16.37	3.249	2.865	0.279	16.38	34.2	
695	16.45	3.243	2.880	0.294	16.46	34.13	
696	16.31	3.240	2.883	0.265	16.45	34.13	
697	16.41	3.243	2.878	0.255	16.38	34.2	
698	16.3	3.249	2.873	0.274	16.36	34.19	
699	16.47	3.245	2.865	0.287	16.43	34.16	
700	16.4	3.243	2.855	0.285	16.44	34.11	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
701	16.3	3.247	2.871	0.272	16.44	34.13	
702	16.35	3.242	2.872	0.26	16.41	34.08	
703	16.32	3.248	2.854	0.291	16.37	34.1	
704	16.23	3.242	2.850	0.306	16.39	34.08	
705	16.43	3.243	2.887	0.253	16.36	34.2	
706	16.39	3.243	2.868	0.279	16.37	34.16	
707	16.24	3.242	2.865	0.281	16.44	34.09	
708	16.41	3.245	2.867	0.293	16.45	34.2	
709	16.35	3.246	2.866	0.311	16.39	34.14	
710	16.27	3.241	2.875	0.285	16.41	34.1	
711	16.17	3.240	2.859	0.313	16.39	34.29	
712	16.25	3.245	2.883	0.261	16.35	34.06	
713	16.35	3.248	2.869	0.286	16.46	34.06	
714	16.33	3.245	2.861	0.297	16.37	34.17	
715	16.3	3.246	2.866	0.295	16.37	34.09	
716	16.12	3.241	2.886	0.272	16.34	34.13	
717	16.3	3.240	2.879	0.3	16.37	34.13	
718	16.35	3.244	2.869	0.303	16.36	34.26	
719	16.29	3.245	2.869	0.311	16.36	34.14	
720	16.33	3.243	2.856	0.294	16.47	34.16	
721	16.26	3.247	2.887	0.266	16.42	34.19	
722	16.25	3.241	2.843	0.304	16.37	34.22	Two indentions on sleeving near top of cell
723	16.26	3.242	2.863	0.311	16.43	34.06	
724	16.38	3.247	2.883	0.297	16.37	34.1	Small indention on sleeving near top of cell
725	16.2	3.242	2.855	0.307	16.42	34.02	Small indention on sleeving near top of cell
726	16.38	3.247	2.887	0.261	16.43	34.14	
727	16.35	3.241	2.884	0.282	16.37	34.01	
728	16.37	3.249	2.886	0.288	16.41	34.17	
729	16.39	3.241	2.872	0.304	16.44	34.01	
730	16.23	3.240	2.876	0.268	16.44	34.17	Small indention on sleeving near top of cell
731	16.37	3.243	2.877	0.308	16.47	34.14	
732	16.15	3.240	2.861	0.294	16.45	34.11	
733	16.39	3.243	2.883	0.267	16.45	34.14	Two indentions on sleeving near top of cell
734	16.3	3.241	2.865	0.292	16.4	34.07	Small indention on sleeving near top of cell
735	16.26	3.244	2.875	0.288	16.44	34.21	
736	16.3	3.246	2.867	0.314	16.38	34.14	Small indention on sleeving near top of cell
737	16.28	3.242	2.883	0.328	16.4	34.16	
738	16.19	3.245	2.849	0.291	16.39	34.18	
739	16.34	3.243	2.867	0.295	16.45	34.15	
740	16.46	3.240	2.882	0.266	16.4	34.14	Small indention on sleeving near top of cell
741	16.25	3.242	2.862	0.29	16.38	34.09	
742	16.56	3.246	2.862	0.3	16.48	34.09	Small indention on sleeving near top of cell
743	16.35	3.245	2.885	0.262	16.46	34.15	
744	16.25	3.243	2.865	0.283	16.39	34.24	
745	16.46	3.250	2.872	0.289	16.45	34.14	
746	16.35	3.246	2.870	0.298	16.46	34.09	
747	16.33	3.250	2.848	0.301	16.45	34.18	
748	16.42	3.248	2.869	0.282	16.46	34.09	
749	16.32	3.242	2.882	0.282	16.48	34.24	
750	16.27	3.241	2.876	0.267	16.37	34.16	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
751	16.29	3.246	2.886	0.266	16.47	34.19	Small indention on sleeving near top of cell
752	16.37	3.247	2.870	0.3	16.44	34.18	Small indention on sleeving near top of cell
753	16.38	3.244	2.857	0.31	16.38	34.23	Small indention on sleeving near top of cell
754	16.24	3.242	2.860	0.345	16.46	34.06	Small indention on sleeving near top of cell
755	16.36	3.248	2.865	0.319	16.45	34.19	
756	16.41	3.242	2.884	0.269	16.38	34.44	Small indention on sleeving near top of cell
757	16.3	3.246	2.880	0.274	16.47	34.25	Small indention on sleeving near top of cell
758	16.13	3.238	2.876	0.276	16.39	34.15	Small indention on sleeving near top of cell
759	16.37	3.245	2.875	0.289	16.37	34.08	Small indention on sleeving near top of cell
760	16.32	3.246	2.886	0.274	16.4	34.18	Small indention on sleeving near top of cell
761	16.34	3.243	2.880	0.281	16.47	34.2	Small indention on sleeving near top of cell
762	16.31	3.244	2.866	0.293	16.45	34.19	Small indention on sleeving near top of cell
763	16.19	3.241	2.865	0.274	16.39	34.26	Small indention on sleeving near top of cell
764	16.12	3.238	2.867	0.27	16.4	34.16	Small indention on sleeving near top of cell
765	16.37	3.244	2.887	0.251	16.43	34.12	Small indention on sleeving near top of cell
766	16.36	3.243	2.874	0.281	16.39	34.17	Small indention on sleeving near top and bottom of cell, can exposed in bottom
767	16.26	3.241	2.884	0.264	16.39	34.13	Small indention on sleeving near top of cell
768	16.26	3.240	2.863	0.29	16.36	34.09	
769	16.23	3.242	2.876	0.281	16.45	34.11	Small indention on sleeving near top of cell
770	16.18	3.243	2.864	0.283	16.39	34.16	Small indention on sleeving near top and bottom of cell
771	16.3	3.243	2.857	0.266	16.39	34.09	Small indention on sleeving near top of cell
772	16.38	3.240	2.865	0.27	16.39	34.15	Small indention on sleeving near top of cell
773	16.43	3.244	2.866	0.278	16.42	34.1	Small indention on sleeving near top of cell
774	16.42	3.241	2.860	0.298	16.48	34.12	Small indention on sleeving near top of cell
775	16.53	3.248	2.859	0.273	16.4	34.15	Sleeving damage near top of cell with can exposed and indention near bottom
776	16.23	3.243	2.857	0.288	16.4	34.33	Small indentions on sleeving near top of cell
777	16.33	3.245	2.867	0.278	16.47	34.19	
778	16.26	3.248	2.858	0.313	16.38	34.29	
779	16.09	3.242	2.868	0.268	16.4	34.05	Small indentions on sleeving near top of cell
780	16.35	3.246	2.854	0.28	16.42	34.16	Small indentions on sleeving near top of cell
781	16.42	3.245	2.875	0.268	16.39	34.19	Small indention on sleeving near top of cell
782	16.38	3.249	2.836	0.299	16.39	34.13	Small indentions on sleeving near top of cell
783	16.3	3.243	2.855	0.283	16.46	34.2	Small indention on sleeving near top of cell
784	16.35	3.244	2.852	0.287	16.46	34.18	Small indention on sleeving near top of cell
785	16.38	3.248	2.861	0.274	16.47	34.19	Small indention on sleeving near top of cell
786	16.36	3.247	2.875	0.271	16.4	34.23	
787	16.11	3.239	2.853	0.278	16.44	34.21	
788	16.4	3.244	2.849	0.286	16.39	34.24	
789	16.33	3.245	2.877	0.269	16.39	34.2	
790	16.28	3.246	2.858	0.284	16.45	34.11	
791	16.39	3.245	2.848	0.308	16.38	34.12	
792	16.19	3.243	2.848	0.281	16.4	34.12	Small indention on sleeving near top of cell
793	16.33	3.240	2.849	0.288	16.44	34.18	
794	16.49	3.247	2.867	0.288	16.44	34.17	
795	16.21	3.243	2.870	0.281	16.39	34.12	Small indentions on sleeving near top of cell
796	16.2	3.241	2.827	0.305	16.39	34.11	Small indentions on sleeving near top of cell
797	16.43	3.245	2.874	0.286	16.45	34.12	Small indention on sleeving near top of cell
798	16.19	3.244	2.868	0.275	16.38	34.13	Small indention on sleeving near top of cell
799	16.59	3.249	2.884	0.264	16.41	34.22	Small indention on sleeving near top of cell
800	16.26	3.247	2.857	0.274	16.45	34.16	Small indention on sleeving near top of cell

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
801	16.28	3.245	2.861	0.278	16.44	34.16	
802	16.15	3.240	2.857	0.28	16.43	34.18	
803	16.36	3.242	2.872	0.27	16.37	34.18	
804	16.52	3.247	2.872	0.269	16.44	34.18	Small indention on sleeving on bottom of cell with can slightly exposed
805	16.45	3.251	2.807	0.338	16.4	34.14	
806	16.36	3.245	2.870	0.279	16.38	34.09	
807	16.27	3.247	2.878	0.293	16.45	34.13	
808	16.33	3.244	2.866	0.311	16.39	34.11	
809	16.38	3.239	2.872	0.278	16.42	34.13	
810	16.33	3.241	2.856	0.271	16.41	34.18	
811	16.34	3.242	2.881	0.267	16.36	34.14	
812	16.35	3.242	2.870	0.275	16.49	34.21	Small indentions on sleeving near top of cell
813	16.24	3.243	2.863	0.279	16.38	34.12	
814	16.39	3.251	2.871	0.286	16.45	34.25	
815	16.34	3.244	2.889	0.253	16.39	34.02	
816	16.17	3.238	2.860	0.283	16.44	34.14	
817	16.32	3.248	2.877	0.276	16.45	34.25	
818	16.46	3.248	2.875	0.271	16.44	34.23	
819	16.34	3.247	2.835	0.313	16.38	34.13	
820	16.31	3.248	2.864	0.301	16.43	34.25	
821	16.28	3.245	2.876	0.273	16.44	34.13	
822	16.32	3.246	2.886	0.271	16.44	34.18	
823	16.29	3.242	2.865	0.278	16.39	34.29	
824	16.37	3.242	2.867	0.285	16.39	34.23	Small indentions on sleeving near top of cell
825	16.26	3.239	2.882	0.278	16.39	34.14	
826	16.31	3.246	2.885	0.268	16.45	34.15	
827	16.34	3.241	2.891	0.253	16.46	34.1	
828	16.39	3.248	2.866	0.293	16.45	34.26	
829	16.38	3.246	2.880	0.273	16.46	34.09	
830	16.15	3.235	2.880	0.256	16.45	34.2	
831	16.41	3.247	2.880	0.269	16.39	34.21	
832	16.26	3.243	2.874	0.28	16.46	34.13	
833	16.34	3.242	2.869	0.287	16.39	34.17	
834	16.3	3.242	2.870	0.302	16.38	34.15	
835	16.55	3.245	2.891	0.278	16.38	34.09	
836	16.28	3.247	2.887	0.285	16.45	34.16	
837	16.33	3.241	2.882	0.286	16.45	34.17	
838	16.22	3.240	2.880	0.279	16.38	34.19	
839	16.47	3.244	2.882	0.269	16.38	34.22	
840	16.38	3.241	2.887	0.253	16.39	34.25	
841	16.44	3.242	2.884	0.269	16.39	34.25	
842	16.19	3.242	2.881	0.262	16.39	34.23	
843	16.24	3.242	2.869	0.294	16.46	34.23	
844	16.39	3.242	2.872	0.283	16.44	34.2	
845	16.4	3.246	2.878	0.291	16.44	34.17	
846	16.24	3.245	2.890	0.28	16.38	34.17	
847	16.15	3.240	2.874	0.286	16.38	34.28	
848	16.22	3.244	2.887	0.271	16.38	34.12	
849	16.32	3.244	2.874	0.289	16.37	34.06	
850	16.29	3.246	2.873	0.286	16.37	34.2	

Cell ID#	Mass (g)	OCV (V)	CCV (V)	AC Impedance (ohm)	Diameter (mm)	Length (mm)	Visual Inspection (Physical/Defects/Observations)
851	16.46	3.247	2.885	0.278	16.37	34.25	
852	16.25	3.245	2.854	0.284	16.37	34.23	Small indention on sleeving near top of cell
853	16.5	3.248	2.860	0.294	16.45	34.14	
854	16.35	3.241	2.878	0.284	16.37	34.11	
855	16.13	3.238	2.872	0.289	16.37	34.1	
856	16.27	3.245	2.878	0.291	16.38	34.1	
857	16.37	3.242	2.885	0.275	16.36	34.1	
858	16.3	3.246	2.879	0.288	16.35	34.16	
859	16.33	3.243	2.882	0.285	16.38	34.14	
860	16.15	3.243	2.871	0.301	16.36	34.15	
861	16.3	3.240	2.886	0.271	16.4	34.1	
862	16.56	3.243	2.882	0.276	16.36	34.17	
863	16.24	3.243	2.879	0.283	16.42	34.27	
864	16.34	3.243	2.893	0.294	16.39	34.13	
865	16.26	3.238	2.890	0.269	16.35	34.18	
866	16.21	3.245	2.865	0.293	16.45	34.06	
867	16.42	3.242	2.880	0.281	16.35	34.15	
868	16.3	3.242	2.874	0.303	16.41	34.08	
869	16.22	3.245	2.890	0.295	16.42	34.26	
870	16.21	3.241	2.874	0.288	16.44	34.2	
871	16.56	3.245	2.900	0.253	16.46	34.14	
872	16.32	3.241	2.871	0.285	16.45	34.08	
873	16.29	3.239	2.872	0.288	16.38	34.18	
874	16.1	3.249	2.887	0.274	16.42	34.28	
875	16.16	3.239	2.868	0.294	16.45	34.12	
876	16.34	3.245	2.889	0.283	16.45	34.14	
877	16.25	3.240	2.878	0.27	16.4	34.18	
878	16.16	3.241	2.862	0.298	16.48	34.27	
879	16.3	3.240	2.881	0.288	16.47	34.14	
880	16.33	3.245	2.878	0.282	16.38	34.2	
881	16.27	3.247	2.882	0.272	16.45	34.25	
882	16.27	3.239	2.893	0.258	16.44	34.23	
883	16.34	3.243	2.883	0.282	16.39	34.18	
884	16.27	3.243	2.881	0.283	16.4	34.11	Small indention on sleeving near top of cell
885	16.32	3.241	2.883	0.273	16.41	34.1	Small indention on sleeving near top of cell
886	16.31	3.240	2.866	0.29	16.48	34.15	
887	16.32	3.242	2.877	0.291	16.47	34.16	
888	16.45	3.246	2.887	0.278	16.41	34.13	Small indention on sleeving near top of cell
889	16.44	3.242	2.871	0.296	16.46	34.1	Small indention on sleeving near top of cell
890	16.21	3.241	2.878	0.288	16.38	34.28	Small indentions on sleeving near top of cell
891	16.33	3.247	2.879	0.277	16.41	34.16	
892	16.41	3.248	2.878	0.282	16.46	34.21	Small indentions on sleeving near top of cell
893	16.33	3.242	2.878	0.286	16.4	34.12	Small indentions on sleeving near top of cell
894	16.22	3.244	2.885	0.273	16.14	34.39	

Appendix C. Cell Selection Statistical Analysis (Outside Values)

Serial Number of Outside Value Cells. (XLData/Li_MnO2/ NASA_NESC_SAFER/ SAFER_TestBattCellATP.xlsx/Outside Values/AL3)

Mass (g)	Diameter (mm)	Length (mm)	OCV (V)	CCV (V)	AC Impedance (ohms)
117	199	4	2	2	4
130	200	24	3	3	5
217	202	57	4	4	6
495	203	77	5	5	7
716	204	83	6	6	9
764	208	126	7	8	10
779	237	147	8	9	11
787	238	199	9	10	12
799	399	203	10	11	17
874	894	208	11	12	26
		373	12	13	28
		403	13	14	29
		423	14	15	56
		426	15	16	59
		441	16	17	63
		756	17	18	82
		894	18	19	85
			19	20	94
			20	25	95
			78	39	97
				42	102
				78	104
				82	136
				86	166
				110	187
				112	190
				135	256
				220	290
				235	344
				256	595
				272	625
				282	
				332	
				430	
				542	
				595	
				608	
				642	
				722	
				782	
				796	
				805	
				819	

Appendix D. PolySwitch® PTC Device Specifications

Tyco / Electronics
Raychem Circuit Protection
308 Constitution Drive
Menlo Park, CA 94025-1164
Phone: 800-227-4856
Fax: 800-227-4866

PolySwitch®
PTC Devices
Overcurrent Protection Device

PRODUCT: SRP200
DOCUMENT: SCD 21790
PCN: 194020
REV LETTER: G
REV DATE: JULY 25, 2002
PAGE NO.: 1 OF 1

Specification Status: RELEASED

Electrical Rating
Voltage: 30V MAX
Current: 100A MAX

Leads:
Nickel: 0.125 mm nom.

Tape:
Polyester

Marking:
XX 200 — Manufacturer's Mark; Part Identification
□□□□ — Lot Identification

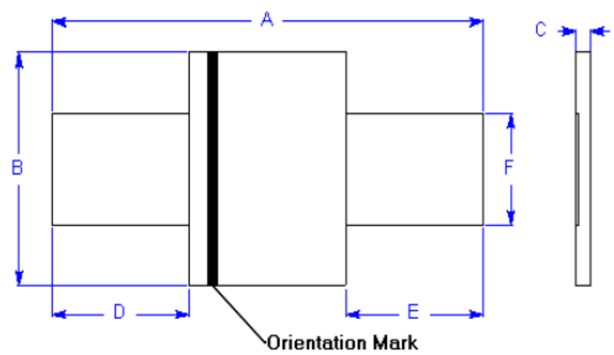

TABLE I. DIMENSIONS:

	A		B		C		D		E		F	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
mm:	21.3	23.4	10.2	11.0	0.5	1.1	5.0	7.6	5.0	7.6	4.8	5.4
in*:	(0.84)	(0.92)	(0.40)	(0.43)	(0.02)	(0.04)	(0.20)	(0.30)	(0.20)	(0.30)	(0.19)	(0.21)

*Rounded off approximation

TABLE II. PERFORMANCE RATINGS:

I HOLD	CURRENT TRIP LIMITS								TIME TO TRIP		REFERENCE RESISTANCE		ONE-HOUR POST-TRIP RESISTANCE		TRIPPED-STATE POWER DISSIPATION	
AMPS 20°C	AMPS AT 0°C		AMPS AT 20°C		AMPS AT 60°C		AMPS AT 80°C		SECONDS AT 20°C, 10 A		OHMS AT 20°C		OHMS AT 20°C		WATTS AT 20°C, 15V	
HOLD	HOLD	TRIP	HOLD	TRIP	HOLD	TRIP	HOLD	TRIP	TYP	MAX	MIN	MAX	MIN	MAX	TYP	MAX
2.0	2.5	5.1	2.0	4.4	1.4	3.0	--	--	1.8	4.0	0.030	0.060	0.030	0.100	1.6	1.9

Reference Documents: PS300
Precedence: This specification takes precedence over documents referenced herein.
Effectivity: Reference documents shall be the issue in effect on the date of invitation for bid.
CAUTION: Operation beyond the rated voltage or current may result in rupture, electrical arcing or flame.

Appendix E. NASA SAFER Battery Assessment Test Plan

	TITLE: NASA SAFER Battery Assessment Test Plan	
	☐ **FLIGHT DOCUMENTATION**	☒ **NON- FLIGHT DOCUMENTATION**

NASA Simplified Aid for EVA Rescue (SAFER) Battery

Assessment Test Plan

CHANGE REVISION RECORD

REVISION	PAGE #	CHANGE	DATE
Draft	All	Initial version	September 26, 2014
A	All	Minor update to Figure 1. Major updates to Tables V and VI.	December 1, 2014
B	All	Tables V and VI: Test duration updates. Section 3.6: Added requirement for photography and consideration of video and thermal imaging data collection. Added Section 4.1.1.2 to support cell selection using cell ATP data.	January 30, 2015
C	All	Added additional details to test plan for trigger cell over-temperature tests and heat-to-vent tests. Added Sections 4.1.1.3.2, 4.1.3.2, 4.1.3.3 and some references. Renumbered former Tables V and VI to VII and VIII, respectively; added new Tables V, VI, IX and Figure 4.	May 7, 2015
D	All	Updates to Tables V and IX. Figure 4 updated w/trigger cell test sequence locations. Added requirement to perform battery-level trigger testing with an interface plate.	January 14, 2016
E	4.1.3.2	Deletion of requirement to conduct battery-level thermal runaway (trigger testing) w/an interface plate. Addition of requirement to conduct battery-level thermal runaway trigger testing using a SAFER unit mass simulator.	April 19, 2016

+

SAFER Battery IRT

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1.0 General

1.1 Scope

This test plan defines the test requirements to be used for the NASA Engineering Safety Center (NESC) sponsored Simplified Aid for EVA Rescue (SAFER) Battery test program. Test scope may include performance, safety, abuse, and/or other types of testing to meet the stated objectives. The need to conduct Destructive Physical Analysis (DPA) will be determined on an as-needed basis.

1.2 Background

The NESC has identified a broad need to evaluate the technical risk associated with safety hazards which may impact the SAFER battery during nominal or off-nominal use. This need is, in part, motivated by recent lessons learned gained from in-service aerospace industry incidents with rechargeable (secondary) and non-rechargeable (primary) lithium batteries [1,2].

To best meet the NESC needs, an independent review team (IRT) has been composed from within the NESC Technical Discipline Team (TDT) for Electrical Power. IRT members are recognized subject matter experts who also represent various industry and government organizations.

As a goal and in order to best support the subject NASA SAFER Battery evaluation, IRT members were chosen from outside the NASA International Space Station (ISS) SAFER battery program. As such, IRT members shall not have direct technical/cost/schedule responsibility for the SAFER Battery product under review.

Dr. Chris Iannello, NASA Technical Fellow for Electrical Power, is the NESC TDT sponsor for this effort.

1.3 Test Objectives

The test program objectives are as follows:

1. Extend the existing heritage SAFER battery test database by performing updated safety tests representative of industry experience with similar battery power systems,

2. Conduct credible worst-case SAFER battery safety tests designed to quantify the severity of a thermal runaway condition which may result in cell-to-cell propagation, and

3. Develop technical recommendations based on the test results.

1.4 Test Approach

To the greatest extent possible, the subject test program will not "exactly duplicate" previous SAFER battery tests under the same cell, bundle, or battery-level configuration or test condition. However, certain tests may be repeated if certain "gaps" in test configurations, environments, or conditions are identified.

To the greatest extent possible, test articles will be representative of flight hardware. So as to not interrupt program plans for SAFER battery flight processing, use of designated flight hardware for testing will be avoided. For example, test cells will not be required to be flight certified (such as cells that may belong to a flight certified lot). However, test cells will be required to undergo cell acceptance testing [3,4].

Characterization testing is broadly defined as any testing whose objectives are to further quantify certain performance or safety characteristics. Characterization testing is not conducted for the purposes of flight article qualification or certification.

Figure 1 shows the general test sequence flow diagram. Initial cell-level characterization (Phase I) will include a cell ATP per program requirements. Phase II testing will be conducted at the bundle level of cell integration. Bundles may be configured in either a 4-cell (4 cells connected electrically in series) or 10-cell (10 cells connected electrically in series) architecture with (or without) PTC's and/or diodes. Finally, Phase III testing will be conducted at the SAFER battery-level (three 14-cell bundles electrically connected in parallel) consistent with the ISS relevant configuration.

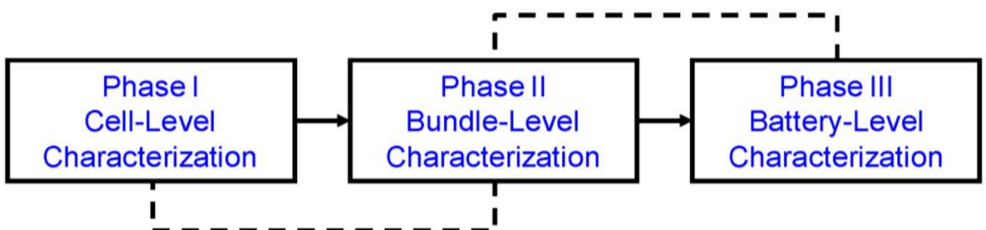


Figure 1: Generalized test flow diagram for SAFER battery characterization testing. Dotted lines represent test opportunities to repeat certain tests if required.

1.5 Test Article Description

Unless otherwise specified, all test articles will be procured and supplied by the NASA/JSC. In addition all test articles used in this test program will be classified as non-flight engineering hardware.

1.5.1 Duracell Ultra 123 Li/MnO_2 Primary Cylindrical Cell

The Duracell Ultra 123 cell (IEC type CR17345) is a spirally-wound cylindrical primary lithium cell designed for high-current pulse as well as continuous high-rate discharge operation [5]. It is assumed that the Duracell Ultra 123 cell is designed to be anode-limited. The Duracell Ultra 123 cell contains certain internal safety devices designed to protect the cell under various abuse conditions. The cell contains a safety vent (located on the positive (top) side of the cell designed to relieve internal pressure in the event of an abuse condition) and a resettable positive temperature coefficient (PTC) device designed to protect the cell under over-temperature conditions created by over-discharge, short-circuit, or other condition. Figure 2 shows a cross-sectional view of the Duracell Ultra 123 Li/MnO_2 spirally-wound cylindrical cell [6].

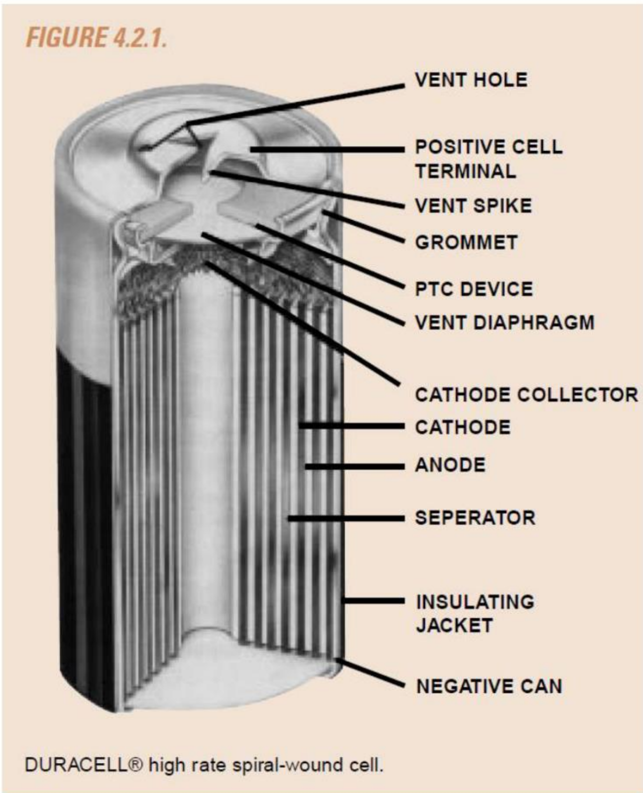


Figure 2: Cross-sectional view of the Duracell Ultra 123 Li/MnO_2 spiral-wound cell [6].

1.5.2 Polyswitches (PTC)'s and Schottky Diodes

SAFER battery SRP200F polyswitch (PTC) and 1N5819 diodes will be employed for this test program. Appendix B contains the SRP200F PTC manufacturer specification. Figure 3 shows the effect of temperature on the hold and trip currents for the SRP200F PTC [7,8]. These data may be used to design bundle or battery-level tests whose objective is to characterize the SRP200F PTC margins.

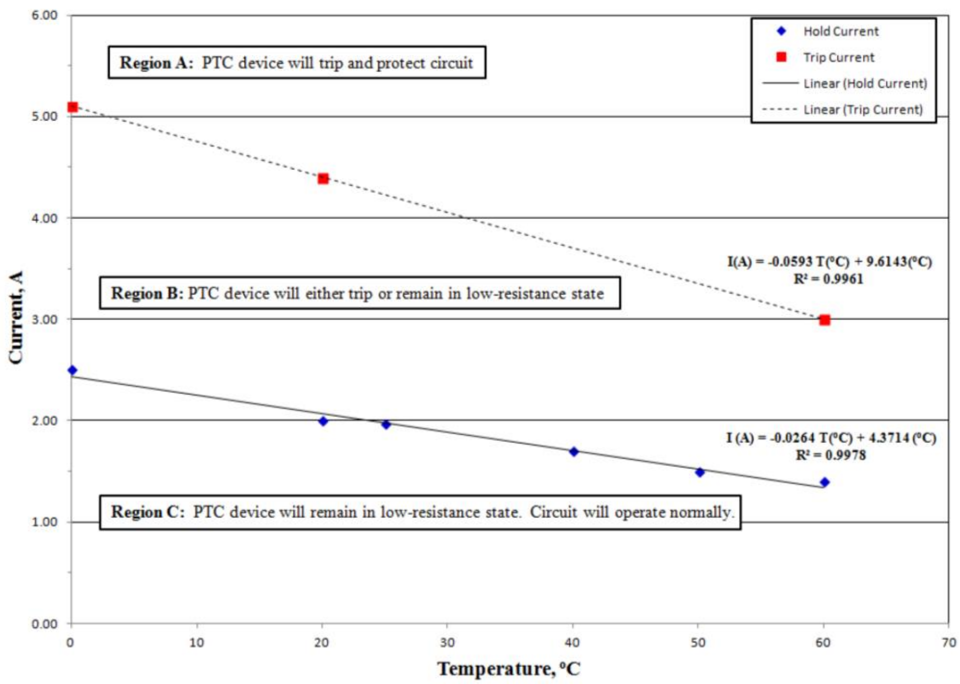


Figure 3: Effect of Temperature on hold and trip current for SAFER battery PTC (SRP200F) [7,8].

Blocking Schottky diodes are employed on the battery gauge board to provide each cell string protection from charge current. Each cell bundle utilizes a bypass Schottky diodes (IN5819) on each cell to shunt discharge current around "weak" cells during discharge. These blocking diodes are supplied by Vishay General Semiconductor (Sheldon, CT).

Table I summarizes key mechanical, electrical, thermal, and safety characteristics of the Duracell Ultra 123 cell design [9,10].

Table I: Selected design, electrical, and safety performance characteristics of the Duracell Ultra 123 cell design [9,10].

Cell Characteristic	*Duracell Ultra 123*
Electrical	
Chemistry	Cathode: MnO_2 Anode: Lithium metal Electrolyte/Separator: See Ref. 5.
Lithium Content	*0.55g*
Nominal Operating Voltage	*3.00V*
Nominal Internal Impedance (@1kHz)	*0.25ohm*
Capacity (C/30 discharge at RT to 1.55V)	*1500mAh*
Thermal	
Nominal Operating Range	-20°C to +75°C
Mechanical	
Terminal Design	*Flat, Recessed Negative Terminal, Nickel Plated Steel*
Dimension (h x d)	*34.5-mm x 17.0-mm (w/terminal)*
Ave. Weight	*17g*
Safety	
Internal PTC Device	Yes
External Vent	Yes
Product Safety Data Sheets (PSDS)	See Appendix A

2.0 Notices

2.1 Applicable Documents and Data

The performing test organization is responsible for developing and implementing a test procedure based on the test plan. The test procedure will be maintained and updated as required.

3.0 Test Requirements

A test readiness review (TRR) shall be conducted prior to testing. Successful completion of the TRR is required prior to beginning test. The objective of the TRR is to establish the objective evidence for test readiness in order to meet safety, quality, and other test criteria. The outcome of the TRR supports the determination of the ability of the test to fulfill stated objectives and test requirements.

The TRR content will include:

1. Test Management Overview and Sequence Of Activities
2. Test Requirements/Objectives and Success Criteria
3. Test Documentation and Test Article Description
5. Instrumentation
6. Test Fixture/Support Equipment
7. Software, Scripts, and Fault Detection
8. Facility and Resources
9. Test Personnel and Schedule
10. Safety Assessment and Hazard Controls

3.1 Standard Environmental Test Conditions

Unless otherwise specified, all measurements and tests will be performed as follows:

Temperature	20°C +/- 3°C
Pressure	Ambient
Humidity	Ambient (Non-condensing)

3.2 Test Limits and Setup

To be determined by NASA/ESTA organization.

3.3 Test Article Configuration

The primary objective of proper test article configuration is to ensure safe test environment for personnel, test articles, and facilities. Secondly, when practically feasible, bundle and battery-level test articles shall be electrically, thermally, and mechanically configured to best represent the expected SAFER battery operating conditions.

Requirements for test article restraints shall be evaluated relative to maintain a representative SAFER battery operating environment. Cell safety pressure relief vents shall not be obstructed in any manner.

3.4 Test Tolerances

Table II lists the test parameter tolerances required to conduct the cell tests.

Table II: Test parameter control and data recording tolerances.

Test Parameter	Controlled To:	Recorded To:
Temperature	+/- 3°C	N/A
Current	+/- 10mA	+/- 1mA
Voltage	+/- 5mV	+/- 1mV
Weight	+/- 1%	+/- 0.1g

3.5 Test Equipment

The performing test organization is responsible for defining, selecting, calibrating, maintaining, operating, and utilizing all test and measurement equipment. Table III list the preliminary list of test equipment required to conduct the subject testing.

Table III: Test equipment inventory.

Item Number	Test Equipment Description	Quantity	Location (TBR)
1			
2			
3			
4			
5			

3.6 Test Data Recording

Raw data for cell voltage, battery (bundle) voltage, current, and temperature shall be recorded for the total time period of each test. The minimum data recording rates shall be determined by certain data resolution requirements and data storage limitations.

Photographs of test articles, facilities, and configuration shall be recorded. Consideration to video recording and thermal imaging should be evaluated relative to expected results.

3.7 Test Anomalies

Any test anomaly shall be documented and is subject to engineering review.

3.7.1 Hardware Failure

A hardware failure is physical in nature. Examples are:

a. Evidence of damage to the cell case.
b. Evidence of electrolyte leakage.
c. Evidence of cell shorting or arcing.
d. Damage to cell seals.
e. Any other obvious physical anomaly.

3.7.2 Electrical Failure

An electrical failure is associated with the test articles inability to meet the electrical performance requirements defined herein. Examples are:

a. Cell voltage outside of specified ranges.
b. An obvious shift in DC resistance from prior measurements.
c. Any unexpected voltage discontinuity during tests.
d. Any other obvious electrical anomaly.

3.7.3 Test Failures

A significant test failure is one that exposes a test article to stress levels beyond those planned as part of the test procedure that can potentially cause damage to the test articles. Examples are:

a. Substantial deviations in test duration or magnitude.
b. A test abort that would result in a repeat of a stressful test sequence such as shock or vibration.

3.7.4 Incidental Failures

Incidental test failures are minor deviations to the test procedure that do not expose the test articles to excessive, potentially damaging levels. Examples are:

a. Minor deviations in time and temperature.

b. Test interruptions that can either be continued or restarted providing the cells do not become exposed to excessive test levels.

4.0 Test Procedure

A detailed test procedure shall be developed from the test plan. Deviations from the test procedure shall be documented and approved. A test log shall be maintained at all times. The test log shall document all test milestones, changes, anomalies, or other test events.

4.1 Test Sequence and Description

Per Figure 1, the test sequence for the SAFER battery characterization testing will start with cell-level testing and proceed thru higher levels of integration. External short testing at high and low impedance values will be included.

4.1.1 Phase I: Cell-Level Characterization

The performing test organization will conduct and complete cell-level characterization testing. The cell-level characterization testing will include a "tailored" cell ATP and safety testing.

4.1.1.1 Cell-Level Acceptance Testing (ATP)

Cell-level acceptance testing is required in order to characterize the baseline performance of the Duracell Ultra 123 cell engineering test articles. Cell-level acceptance testing will be "tailored" from the cell-level flight acceptance testing protocols described in Ref. 3. The tailored cell-level ATP testing will include, but is not limited to [3,4]:

(a). Visual Inspection
(b). Serialization
(c). Weight Check
(d). Dimensional
(e). Open-Circuit Voltage (OCV) Check
(f). Impedance (@ 1kHz)
(g). Closed-Circuit Voltage (CCV) Check

Pass/fail criteria will be consistent with Table I, Ref. 3. Cells which pass the tailored cell-level ATP will become candidates for further testing during Phase I, II, or III.

4.1.1.2 Cell Selection

Cells shall be screened using the results from the cell-level ATP. Cells which pass the screening criteria shall be selected for integration into battery bundles.

4.1.1.3 Cell-Level Safety Testing

Cell-level safety testing will be conducted in order to characterize certain safety margins associated with the Duracell Ultra 123 cell.

4.1.1.3.1 External Short Circuit Testing

Table IV shows the test type and conditions for the planned single-cell external short testing. The test cells shall be discharged until a fire or explosion is obtained or until it is completely discharged and the cell has returned to near ambient temperature. Unless otherwise specified, external short testing will be conducted at ambient temperature.

Table IV: Cell-level external short safety characterization test matrix.

Test No.	External Resistance, ohm	No. of Test Articles	Test Type
1	< 0.050	8	Low impedance short
2	if required	TBD	TBD

4.1.1.3.2 Thermal Runaway Testing

Table V and VI show the test type and conditions for the trigger cell over-temperature testing and the single cell heat-to-vent testing. Trigger cell over-temperature tests shall be conducted by placing a heater on the cell housing. Trials shall be run with the heater at various locations to determine its worst case position. Various heater powers shall also be used to experimentally determine the most effective heater power required to initiate thermal runaway. Optimizing the heater power will reduce the possibility of exciting the surrounding cells via conductive, convective, or radiative heating when bundle/battery-level testing is performed. Tests 1-6 shall be conducted and the data reviewed prior to proceeding to tests 7-10. Tests 7-10 shall be conducted as determined by the needs of the project and upon approval of the project lead. Similarly, tests 11-16 shall be conducted and the data reviewed prior to proceeding to tests 17-20. Tests 17-20 shall be conducted as determined by the needs of the project and upon approval of the project lead.

Single-cell over-temperature tests shall be conducted at the ambient temperature of the test facility and at 49°C. The 49°C test condition was derived from the 38°C maximum hot case thermal environment the battery could be exposed to during the mission, plus an 11°C thermal analysis uncertainty margin [11,12]. The test article shall be soaked at the test temperature for at least one hour prior to commencing the test. The test article shall be actively maintained at the test temperature +/- 3°C at least up to the point in time when the cell heaters are activated.

Unless otherwise specified, temperature sensors shall be placed in the same location(s) on the cell as they are placed for external short circuit testing. In addition to the test data recording requirements given in Section 3.6, heater voltage and current, and the temperature of the environment in close proximity to the test article shall be monitored and recorded. Video monitoring shall be performed for all trigger cell over-temperature testing. The cell shall be restrained in TBD manner.

As determined by the needs of the project and upon approval of the project lead, Accelerating Rate Calorimeter (ARC) testing shall be used to perform heat-to-vent testing at slow heating rates under adiabatic conditions to more precisely determine the onset of thermal runaway (Table VI). Cells shall initially be heated from room temperature to 70°C. A heat-wait-seek routine shall then execute during which the temperature within the ARC is increased in a stepwise fashion and held while the system waits for an exothermic reaction to occur. If no reaction occurs, the temperature is increased and the process repeats. Since these tests take several days to complete, fewer tests will be run. Data from the trigger cell over-temperature tests and the heat-to-vent tests shall be used to further define or modify the bundle/battery-level test matrix as needed.

Table V: Cell-level heater power, location, and temperature determination test matrix.[1]

Trial Run No.	Heater Power (W)	Heater Location	Temperature	Estimated Test Duration	No. of Test Articles	Status
1	15	Bottom	Ambient	1 hr	2	Completed
2	15	Side	Ambient	1 hr	2	Completed
3	10	Bottom	Ambient	1 hr	2	Completed
4	10	Side	Ambient	1 hr	2	Completed
5	20	Bottom	Ambient	1 hr	2	Completed
6	20	Side	Ambient	1 hr	2	Completed
7	25	Bottom	Ambient	1 hr	2	Completed
8	25	Side	Ambient	1 hr	2	Completed
9	5	Bottom	Ambient	1 hr	2	Postpone
10	5	Side	Ambient	1 hr	2	Postpone
11	15	Bottom	49°C	1 hr	2	Postpone
12	15	Side	49°C	1 hr	2	Completed
13	10	Bottom	49°C	1 hr	2	Postpone
14	10	Side	49°C	1 hr	2	Postpone
15	20	Bottom	49°C	1 hr	2	Postpone
16	20	Side	49°C	1 hr	2	Completed
17	25	Bottom	49°C	1 hr	2	Postpone
18	25	Side	49°C	1 hr	2	Completed
19	5	Bottom	49°C	1hr	2	Postpone
20	5	Side	49°C	1 hr	2	Postpone
21	30W	Side	Ambient	1 hr	2	Completed
22	35W	Side	Ambient	1 hr	2	Completed
23	40W	Side	Ambient	1 hr	2	Completed

Notes:

1. Reserved.

Table VI: Heat-to-Vent Test Matrix (ARC Testing)

Trial Run Number	State-of-Charge (%)	Temperature to Begin Heat-Wait-Seek (°C)	Estimated Test Duration	No. of Test Articles
1	100	70	1-2 days	1[1]
2	80	70	1-2 days	1
3	60	70	1-2 days	1
4	40	70	1-2 days	1
5	20	70	1-2 days	1
6	0	70	1-2 days	1

Notes:

1. Values are To Be Reviewed (TBR).

4.1.2 Phase II: Bundle-Level Characterization

The SAFER battery is constructed from 4-cell and 10-cell bundle assemblies. All cells within each bundle assembly are electrically connected in series. Each bundle has an external PTC installed [13,14]. Each cell within a bundle is also protected by a single Schottky diode.

4.1.2.1 4-Cell Bundle Testing

4-cell bundle testing shall be conducted in order to characterize certain safety margins in a given configuration. Table VII shows the test type and conditions for the 4-cell bundle testing. PTC location shall be consistent with the heritage SAFER battery 4-cell bundle configuration. External resistance values were chosen based on Fig.2 and previous SAFER battery test results [15]. Test 4-cell bundles shall be configured in a flight-like configuration with bypass diodes. The number of test articles and conditions may change based on test results as required. Unless otherwise specified, test 4-cell bundle testing will be conducted at ambient temperature.

4.1.2.2 10-Cell Bundle Testing

10-cell bundle testing shall be conducted in order to characterize certain safety margins in a given configuration. Table VIII shows the test type and conditions for the 10-cell bundle testing. PTC location shall be consistent with the heritage SAFER battery 10-cell bundle configuration. External resistance values were chosen based on Fig.2 and previous SAFER battery test results [15]. Test 10-cell bundles shall be configured in a flight-like configuration with bypass diodes. The number of test articles and conditions may change based on test results as required. Unless otherwise specified, test 10-cell bundle testing will be conducted at ambient temperature.

Table VII: 4-cell bundle safety characterization test matrix. Single cell mid-discharge voltage (@300mA) = 2.75V [15].

Test No.	Electrical Config.	Test Type	External Load (ohm)	Estimated Peak Current (A)	Load Type (high/med/low impedance)	PTC Region (See Fig. 3)	Estimated Test Duration [1]	ByPass Diodes	PTC	PTC Location [2]	No. of Test Articles [3]
1	4S	External Short	10	1.1	High	C	10-12 hr	Yes	No	Heritage	1
2	4S	External Short	10	1.1	High	C	10-12 hr	Yes	Yes	Heritage	1
3	4S	External Short	3.5	3.1	Med	B	10-12 hr	Yes	No	Heritage	1
4	4S	External Short	3.5	3.1	Med	B	10-12 hr	Yes	Yes	Heritage	1
5	4S	External Short	1	11.0	Low	A	3-5 hr	Yes	No	Heritage	1
6	4S	External Short	1	11.0	Low	A	3-5 hr	Yes	Yes	Heritage	1
7	4S	External Short	0.1	110.0	Low	A	3-5 hr	Yes	No	Heritage	1
8	4S	External Short	0.1	110.0	Low	A	3-5 hr	Yes	Yes	Heritage	1
9	4S	External Short	0.05	220.0	Low	A	3-5 hr	Yes	No	Heritage	1
10	4S	External Short	0.05	220.0	Low	A	3-5 hr	Yes	Yes	Heritage	1

Notes:

1. Test duration is an estimate based on previous test history experience. Test should be terminated following any event causing cell or battery-level venting, rupture, fire, smoke, or other catastrophic failure.

2. Heritage PTC location per drawing SED33109326 [14].

3. Number of test articles may change based on test results.

Table VIII: 10-cell bundle safety characterization test matrix. Single cell mid-discharge voltage (@300mA) = 2.75V [15].

Test No.	Electrical Config.	Test Type	External Load (ohm)	Estimated Peak Current (A)	Load Type (high/med/low impedance)	PTC Region (See Fig. 3)	Estimated Test Duration [(a)]	ByPass Diodes	PTC	PTC Location [(b)]	No. of Test Articles [(c)]
1	10S	External Short	25	1.1	High	C	10-12 hr	Yes	No	Heritage	1
2	10S	External Short	25	1.1	High	C	10-12 hr	Yes	Yes	Heritage	1
3	10S	External Short	9	3.1	Med	B	10-12 hr	Yes	No	Heritage	1
4	10S	External Short	9	3.1	Med	B	10-12 hr	Yes	Yes	Heritage	1
5	10S	External Short	1	27.5	Low	A	3-5 hr	Yes	No	Heritage	1
6	10S	External Short	1	27.5	Low	A	3-5 hr	Yes	Yes	Heritage	1
7	10S	External Short	0.5	55	Low	A	3-5 hr	Yes	No	Heritage	1
8	10S	External Short	0.5	55	Low	A	3-5 hr	Yes	Yes	Heritage	1
9	10S	External Short	3	9.2	Med	A	3-5 hr	Yes	No	Heritage	1
10 [(d)]	10S	External Short	3	9.2	Med	A	3-5 hr	Yes	No	Heritage	1

(a) Test duration is an estimate based on previous test history experience. Test should be terminated following any event causing cell or battery-level venting, rupture, fire, smoke, or other catastrophic failure.

(b) Heritage PTC location per drawing SED33109326.

(c) Number of test articles may change based on test results.

(d) Test 10 to be conducted with bundle contained inside SAFER battery housing.

4.1.3 Phase III: Battery-Level Testing - Preliminary

The SAFER battery-level configuration is defined as one each 4-cell and 10-cell bundle assemblies connected in series. There are three (3) of these 14-cell batteries electrically connected in parallel to provide a 14S-3P battery power system to the SAFER assembly.

4.1.3.1 External Short Circuit Testing

Table VIII shows the preliminary test type and conditions for the planned battery-level testing. PTC location and external resistance value(s) will be based on test results from Phase II. Unless otherwise specified, battery-level testing will be conducted at ambient temperature.

Table VIII will be updated pending results from the 4S and 10S test results.

Table VIII: Preliminary SAFER battery-level external short characterization test matrix.

Test No.		Electrical Configuration	Test Type	Bypass Diodes	PTC	No. of Test Articles
1		14S	External Short Circuit	Yes	Yes	TBD
2		14S	External Short Circuit	Yes	Yes	TBD
3		14S-3P	External Short Circuit	Yes	Yes	TBD
4		14S-3P	External Short Circuit	Yes	Yes	TBD
5		If required	TBD	TBD	TBD	TBD

4.1.3.2 Thermal Runaway Testing

Table IX shows the test type and condition for the battery-level trigger cell over-temperature testing. For each test run, one cell, the trigger cell, shall be heated to initiate thermal runaway while the battery is contained within its housing in the flight orientation. The heater power, heater location, and test temperature shall be determined based on the results of the single-cell trigger cell over-temperature tests (Section 4.1.1.3.2).

Trigger cell locations within the battery were selected based on the positions that would likely represent the worst case heating scenario for the battery if a single cell were to go in to thermal runaway. Five trigger cell locations are shown in Figure 4 (circled in red). The test number in Table IX corresponds to the location of the designated trigger cell for each test. Tests are numbered in order of priority. Tests 1-2 shall be conducted and the data reviewed prior to proceeding to tests 3-5. Tests 3-5 shall be conducted as determined by the needs of the project and upon approval of the project lead.

In order to best mimic the relevant SAFER battery flight unit configuration and environment, battery-level heater trigger testing with a SAFER unit mass simulator shall be conducted.

Unless otherwise specified, temperature sensors shall be placed in the same locations on the cells and within the battery as they are placed for external short circuit testing. In addition to the test data recording requirements given in Section 3.6, heater voltage and current, and the temperature of the environment in close proximity to the test article shall be monitored and recorded. Video monitoring shall be performed for all trigger cell over-temperature testing.

Table IX: 14S-3P battery-level TR trigger cell over-temperature characterization test matrix.

Test No.	Trigger Cell Location	Heater Power (W)[1]	Heater Location[1]	Temp[1]	Interface Plate	Estimated Test Duration	No. of Test Articles	Status
1	1	20	Side	Ambient	No	1 hr	1	Completed
2	1	30	Side	Ambient	No	1 hr	1	Completed
3	1	35	Side	Ambient	No	1 hr	1	
4	1	40	Side	Ambient	No	1 hr	1	If required
5	1	TBD	Side	Ambient	Yes	1 hr	1	
6	2	TBD	Side	Ambient	Yes	1 hr	1	
7	3	TBD	Side	Ambient	Yes	1 hr	1	If required
8	4	TBD	Side	Ambient	Yes	1 hr	1	If required
9	5	TBD	Side	Ambient	Yes	1 hr	1	If required

Notes:

1. Recommendations based on the results of the single-cell over-temperature trigger heater testing. Updated with Rev D.

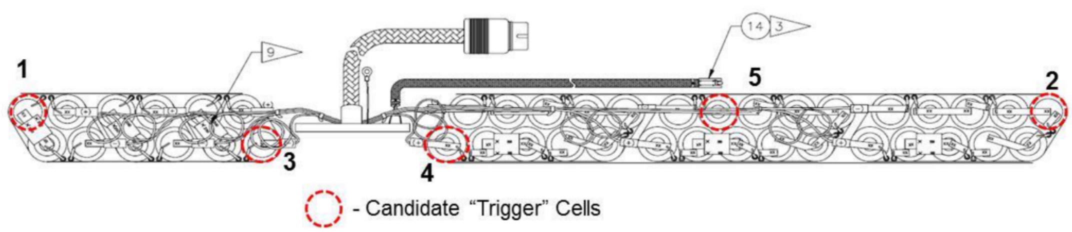


Figure 4: Trigger cell locations and test sequence for battery-level over-temperature testing.

4.1.3.3 Heat-to-Vent testing

As determined by the needs of the project and upon approval of the project lead, heat-to-vent testing shall be performed in the battery in an extended volume ARC. State-of-charge and the start temperature for heat-wait-seek shall be specified upon completion of the single-cell heat-to-vent testing. The estimated test duration is 1-2 days.

5.0 Test Evaluation Criteria

Test data will be analyzed using available industry accepted tools and processes. Test data analyses will be used to determine if test objectives have been met. Repeating a test, updating test conditions, or otherwise modifying a test case will be determined on an as needed basis. Consistency of results (repeatability) may create a need to repeat a given test so as to establish certain levels of confidence.

As required, criteria for "pass/fail" thresholds will be established as part of the success criteria.

6.0 Safety

Safety limits shall be established and implemented for all testing. Safety limits are established to ensure adequate test safety margin to personnel and hardware. Watchdog timers and other redundant safety features shall be implemented into the test stand.

6.1 Warning and Emergency (Termination) Safety Limits (if required)

To be determined by NASA/ESTA organization.

7.0 References

[1]. Hart, Christopher A., National Transportation Safety Board (NTSB) Safety Recommendations, A-14-032 through A-14-036, Washington, D.C., May 22, 2014.

[2]. Air Accidents Investigation Branch (AAIB) Special Bulletin S4/2014, AAIB Field Investigation, ET-AOP, EW/C2013/ 07/01, Farnborough House, Berkshire Copse Road, Aldershot, Hants GU11 2HH, June 18, 2014.

[3]. Randall, D., "*Specification for Acceptance and Lot Certification Testing of 2/3A Lithium-Manganese Dioxide Cells for the Batteries of the Simplified Aid for EVA Rescue (SAFER)*", NASA/Lyndon B. Johnson Space Center, Engineering Directorate, Propulsion and Power Division, Power Systems Branch, Houston, TX, SAFER-BAT-001, Rev. J., March 2012.

[4]. Graika, J, "*Certification/Acceptance Plan For the IVA Battery Assembly of the U.S.A. and I.S.S. Simplified Aid for EVA Rescue (SAFER)*", NASA/Lyndon B. Johnson Space Center, Engineering Directorate, Energy Systems Division, Houston, TX, SAFER-BAT-002, Rev. I., May 2013.

[5]. Linden, D., *ed.*, "*Handbook of Batteries*", 2nd *ed.*, McGraw-Hill, 1995.

[6]. Duracell Lithium Technical Bulletin (www.duracell.com).

[7]. Tyco Electronics RayChem Circuit Protection, "*PolySwitch PTC Device*", SRP200, SCD 21790, Rev. G, July 25, 2002.

[8]. Tyco Electronics RayChem Circuit Protection, "*PolySwitch Resettable Devices – Strap Battery Devices"*, p. 201.

[9]. Duracell Ultra 123 Specification Datasheet (www.duracell.com).

[10]. Duracell Declaration of Conformity (www.duracell.com), 12/31/2013.

[11] "ISS SAFER System Thermal Analysis Summary", Internal NASA Johnson Space Center/JACOBS Memorandum JETS-JE33-13-TAED-DOC-0004, June 3, 2013.

[12] Welch, John W., "Comparison of Recent Satellite Flight Temperatures with Thermal Model Predictions", SAE Technical Paper 2006-01-2278, 2006.

[13]. Battery Brick Assembly Drawing, SED33106061, Rev H.

[14]. Cell Bundle Assembly Drawing, SED33109326, Rev K.

[15]. Symmetry Resources, Inc., " *SAFER Cell Acceptance and Lot Certification : Duracell Ultra 123*", SRI Job #24F, June 29, 2012.

8.0 Reserved

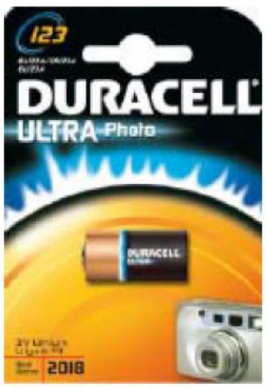
Appendix A

P&G

Product Safety Data Sheet (PSDS)

SECTION 1: IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

Product Name: DURACELL LITHIUM MANGANESE DIOXIDE BATTERIES AND CELLS



Representative Product Image/ Packaging

Identity: Lithium Batteries and Cells (HPL)
Description: Consumer Product

Size/Designation	Voltage	IEC Designation	Lithium Content (g) per Cell/Battery
CR-V3	3	CR-V3	1.4g (Battery)
123, 123A, 2/3A, PL123	3	CR17345	0.55g (Cell)
223/223A	6	CR-P2	1.1g (Battery)
245	6	2CR5	1.1g (Battery)
CR2	3	CR17355	0.3g (Cell)
28L	6	2CR13252	.12g (Battery)
1/3N	3	CR1108	0.06g (Cell)
DL1604	9		0.9g (Battery)

Product Use: Energy Source
PSDS Date of Preparation: March 28, 2013 (replaces November 29, 2012); Reaffirmed/Updated April 11, 2014
Company Identification:

EUROPEAN OFFICE
Procter& Gamble International Operations SA
47 route de Saint-Georges,
1213 Petit-Lancy, 1, Geneva,
Telephone: +41-58-004-6111

US Office
P&G - Duracell
Berkshire Corporate Park
Bethel, CT 06801 USA
Telephone: 203-796-4000

SECTION 2: HAZARDS IDENTIFICATION

These products are classified as Articles under REACH and are not subject to the requirements for Information in the Supply Chain (Safety Data Sheets and Labels). While batteries may release hazardous substances if damaged, this is not an intended release as defined under REACH. Batteries are not classified as hazardous under the CLP.

The following information is provided to assist in the safe use of our products.

CAUTION: Battery can explode or leak if heated, disassembled, shorted, recharged, exposed to fire or high temperature or inserted incorrectly. Keep in original package until ready to use. Do not carry batteries loose in your pocket or purse. Keep batteries away from children. If swallowed, consult a physician at once. Under certain misuse conditions and by abusively opening the battery, exposed lithium can react with water or moisture in the air causing potential thermal burns or fire.

SECTION 3: COMPOSITION/INFORMATION ON INGREDIENTS

Chemical Name	CAS Number	EINECS Number	Amount
1,2-Dimethoxyethane*	110-71-4	203-794-9	5-10 %
Carbon Black	1333-86-4	215-609-9	0-5%
Ethylene Carbonate	96-49-1	202-510-0	0-5%
Graphite	7782-42-5	231-955-3	0-5%
Lithium	7439-93-2	231-102-5	1-5 %
Lithium Perchlorate	7791-03-9	232-237-2	<1.5 %
Lithium Trifluoromethane Sulfonate	33454-82-9	251-528-5	0.5%
Manganese Dioxide	1313-13-9	215-202-6	15-45 %
Propylene Carbonate	108-32-7	203-572-1	1-10 %

*SVHC Substance per Candidate List Updated June 18, 2012

SECTION 4: FIRST AID MEASURES

General Advice: The chemicals and metals in this product are contained in a sealed can. Exposure to the contents will not occur unless the battery leaks, is exposed to high temperatures or is mechanically, physically, or electrically abused.

Eye Contact: If battery is leaking and material contacts the eye, flush thoroughly with copious amounts of running water for 30 minutes. Seek immediate medical advice.

Skin Contact: If battery is leaking and material contacts the skin, remove any contaminated clothing and flush exposed skin with copious amounts of running water for at least 15 minutes. If irritation, injury or pain persists, seek medical advice.

Inhaled: If battery is leaking, contents may be irritating to respiratory passages. Move to fresh air. If irritation persists, seek medical advice.

Swallowed: If battery is swallowed seek immediate medical advice. Batteries lodged in the esophagus should be removed immediately since leakage, caustic burns and perforation can occur as soon as two hours after ingestion. If mouth area irritation or burning has occurred, rinse the mouth and surrounding area with tepid water for at least 15 minutes. Do not give ipecac.

Note to Physician: Published reports recommend removal from the esophagus be done endoscopically (under direct visualization). Batteries beyond the esophagus need not be retrieved unless there are signs of injury to the GI tract or a large diameter battery fails to pass the pylorus. If asymptomatic, follow-up x-rays are necessary only to confirm the passage of larger batteries. Confirmation by stool inspection is preferable under most circumstances. Potential leakage of less than 50 milligrams of dimethoxyethane and propylene carbonate. Dimethoxyethane rapidly evaporates. Do not give ipecac.

SECTION 5: FIRE FIGHTING MEASURES

Fire and Explosion Hazards: Batteries may burst and release hazardous decomposition products when exposed to a fire situation.

Extinguishing Media: Use any extinguishing media that is appropriate for the surrounding fire.

Special Fire Fighting Procedures: Firefighters should wear positive pressure self-contained breathing apparatus and full protective clothing. Fight fire from a distance or protected area. Cool fire exposed batteries to prevent rupture. Use caution when handling fire-exposed containers (batteries may explode in heat of fire).

Hazardous Combustion Products: Thermal degradation may produce hazardous fumes of lithium and manganese; oxides of carbon and other toxic by-products.

Detailed information on fighting a lithium metal battery fire can be found in Gide 138 of the US DOT Emergency Response Guide (http://phmsa.dot.gov/hazmat/library.erg).

SECTION 6: ACCIDENTAL RELEASE MEASURES

Notify safety personnel of large spills. Irritating vapors and flammable may be released from leaking or ruptured batteries. Eliminate all ignition sources. Evacuate the area and allow the vapors to dissipate. Clean-up personnel should wear appropriate protective clothing to avoid eye and skin contact and inhalation of vapors or fumes. Increase ventilation. Carefully collect batteries and place in an appropriate container for disposal. Remove spilled liquid with absorbent and contain for disposal.

SECTION 7: HANDLING AND STORAGE

Avoid mechanical or electrical abuse. DO NOT short circuit or install incorrectly. Batteries may explode, pyrolize or vent if disassembled, crushed, recharged or exposed to high temperatures. Install batteries in accordance with equipment instructions. Replace all batteries in equipment at the same time. Do not carry batteries loose in a pocket or bag.

Storage: Store batteries in a dry place at normal room temperature.

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

Exposure Limits: No exposure to the battery components should occur during normal use.
Ventilation: No special ventilation is needed for normal use.
Respiratory Protection: None required for normal use.
Skin Protection: None required for normal use. Use butyl rubber gloves when handling leaking batteries.
Eye Protection: None required for normal use. Wear safety goggles when handling leaking batteries.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

Appearance and Odor: Coin cells.
Water Solubility: Insoluble
Flash Point: 29°F (-2°C) (1,2-Dimethoxyethane)

SECTION 10: STABILITY AND REACTIVITY

Stability: This product is stable.

Incompatibility/Conditions to Avoid: Contents are incompatible with strong oxidizing agents. Do not heat, crush, disassemble, short circuit or recharge.

Hazardous Decomposition Products: Thermal decomposition may produce hazardous fumes of lithium and manganese; oxides of carbon and other toxic by-products.

Hazardous Polymerization: Will not occur

SECTION 11: TOXICOLOGICAL INFORMATION

Potential Health Effects: The chemicals and metals in this product are contained in a sealed can. Exposure to the contents will not occur unless the battery leaks, is exposed to high temperatures or is mechanically, physically, or electrically abused.

Eye Contact: Contact with battery contents may cause irritation.

Skin Contact: Contact with battery contents may cause irritation.

Inhalation: Inhalation of vapors or fumes released due to heat or a large number of leaking batteries may cause respiratory and eye irritation.

Ingestion: Seek immediate medical advice. Batteries lodged in the esophagus should be removed immediately since leakage, caustic burns and perforation can occur as soon as two hours after ingestion. Irritation to the internal/external mouth areas, may occur following exposure to a leaking battery.

SECTION 12: ECOLOGICAL INFORMATION

No ecotoxicity data is available. This product is not expected to present an environmental hazard.

SECTION 13: DISPOSAL INFORMATION

Disposal should be in accordance with national and local regulations. Do not incinerate for disposal except for in a controlled incinerator.

Duracell manganese dioxide lithium coin cell batteries are labeled in compliance with the EU Battery Directive 2006/66.

SECTION 14: TRANSPORT INFORMATION

Emergency Phone Number:

CHEMTREC 24-Hour Emergency Response Hotline
+703-527-3887 (United States of America)

Persons who prepare or offer lithium batteries for transport are required by regulation to be trained and certified. The information provided below is for informational purposes only.

DURACELL Primary Lithium Metal Batteries
UN3090 Primary lithium batteries – PI 968 **UN3091** Primary lithium batteries with or in equipment- PI 969 & 970
UN 38.3: DURACELL certifies that all of its lithium batteries meet the requirements of the UN Manual of Tests and Criteria, Part III subsection 38.3. If you assemble these batteries into larger battery packs, it is recommended that you perform the UN Tests to ensure the requirements are met prior to shipment.
US DOT: Special Provision 29, 188, 189, 190, A54, A55, A100, A101, A103, A104
Air Transport (IATA/ICAO): Packing Instruction 968-970
Marine/Water Transport (IMDG): Special Provision 188, 230, 310, 957
ADR: Special Provisions: 188, 230, 310, 957

DOT - Except for personal use, the shipment of lithium batteries aboard passenger aircraft is not allowed. Airline passengers may have non-rechargeable lithium batteries for their equipment and a reasonable amount of spare non-rechargeable lithium batteries for their equipment in their carry-on luggage – **NOT** in their checked baggage. For more information, air travelers should consult the US Department of Transportation (DOT) Safety Travel web site at http://safetravel.dot.gov.

Shipping packages containing non-rechargeable lithium batteries must be labeled, regardless of size or number of batteries, with the following statement: "PRIMARY LITHIUM BATTERIES – FORBIDDEN FOR TRANSPORT ABOARD PASSENGER AIRCRAFT."

The transportation of lithium metal batteries is regulated as UN3090 by ICAO, IATA, IMO and US DOT. DURACELL lithium manganese dioxide batteries cells and batteries are not subject to the other provisions of the Dangerous Goods regulations as long as they are packaged and marked in accordance with the ICAO regulations.

SECTION 15: REGULATORY INFORMATION

EU BATTERY DIRECTIVE: These batteries comply with the Directive substance limits and labeling requirements.

EU REACH REGISTRATION: These products are manufactured articles and not subject to REACH registration requirements.

EU REACH SVHC: These products contains 1,2-dimethoxyethane (ethylene glycol dimethyl ether) which is listed on the Candidate List of Substances of Very High Concern.

EU Labeling: Labeling is not required because batteries are classified as articles under the both REACH and the Dangerous Preparations Directive and as such are exempt from the requirement for labeling.

SECTION 16: OTHER INFORMATION

P&G Hazard Rating: Health: 0 Fire: 0 Reactivity: 0

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Data supplied is for use only in connection with occupational safety and health.

DISCLAIMER: This PSDS is intended to provide a brief summary of our knowledge and guidance regarding the use of this material. The information contained here has been compiled from sources considered by Procter & Gamble to be dependable and is accurate to the best of the Company's knowledge. It is not meant to be an all-inclusive document on worldwide hazard communication regulations.

This information is offered in good faith. Each user of this material needs to evaluate the conditions of use and design the appropriate protective mechanisms to prevent employee exposures, property damage or release to the environment. Procter & Gamble assumed no responsibility for injury to the recipient or third persons, or for any damage to any property resulting from misuse of the product.

Appendix B

Tyco / Electronics
Raychem Circuit Protection
308 Constitution Drive
Menlo Park, CA 94025-1164
Phone: 800-227-4856
Fax: 800-227-4866

PolySwitch®
PTC Devices
Overcurrent Protection Device

PRODUCT: SRP200
DOCUMENT: SCD 21790
PCN: 194020
REV LETTER: G
REV DATE: JULY 25, 2002
PAGE NO.: 1 OF 1

Specification Status: RELEASED

Electrical Rating
Voltage: 30V MAX
Current: 100A MAX

Leads:
Nickel: 0.125 mm nom.

Tape:
Polyester

Marking:
Manufacturer's Mark
XX 200 — Part Identification
□□□□ — Lot Identification

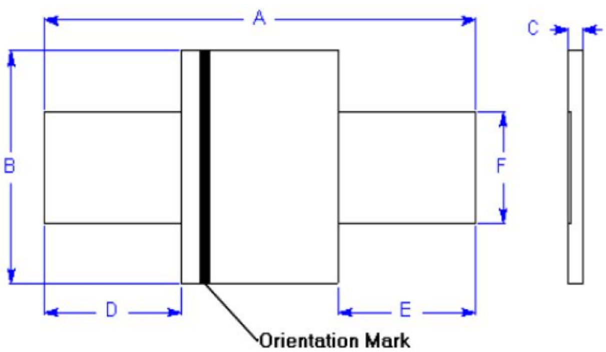


TABLE I. DIMENSIONS:

	A		B		C		D		E		F	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
mm:	21.3	23.4	10.2	11.0	0.5	1.1	5.0	7.6	5.0	7.6	4.8	5.4
in*:	(0.84)	(0.92)	(0.40)	(0.43)	(0.02)	(0.04)	(0.20)	(0.30)	(0.20)	(0.30)	(0.19)	(0.21)

*Rounded off approximation

TABLE II. PERFORMANCE RATINGS:

I HOLD	CURRENT TRIP LIMITS								TIME TO TRIP		REFERENCE RESISTANCE		ONE-HOUR POST-TRIP RESISTANCE		TRIPPED-STATE POWER DISSIPATION	
AMPS 20°C HOLD	AMPS AT 0°C		AMPS AT 20°C		AMPS AT 60°C		AMPS AT 80°C		SECONDS AT 20°C, 10 A		OHMS AT 20°C		OHMS AT 20°C		WATTS AT 20°C, 15V	
	HOLD	TRIP	HOLD	TRIP	HOLD	TRIP	HOLD	TRIP	TYP	MAX	MIN	MAX	MIN	MAX	TYP	MAX
2.0	2.5	5.1	2.0	4.4	1.4	3.0	--	--	1.8	4.0	0.030	0.060	0.030	0.100	1.6	1.9

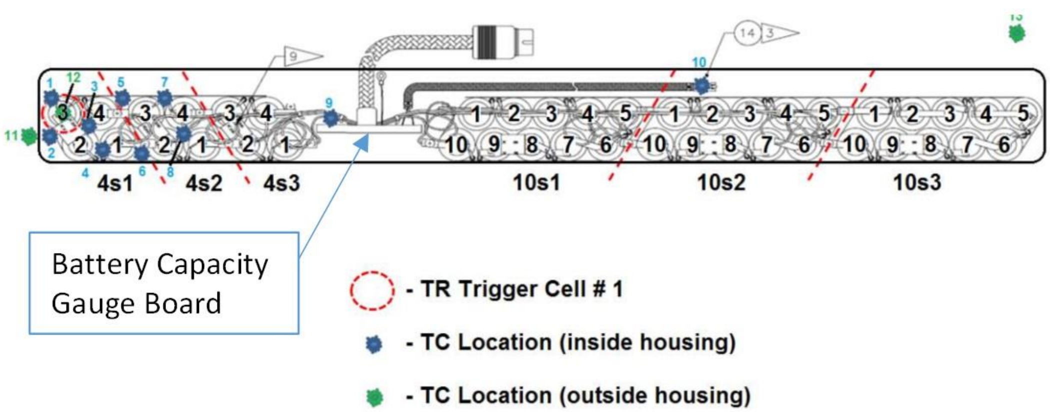
Reference Documents: PS300
Precedence: This specification takes precedence over documents referenced herein.
Effectivity: Reference documents shall be the issue in effect on the date of invitation for bid.
CAUTION: Operation beyond the rated voltage or current may result in rupture, electrical arcing or flame.

Appendix F. DPA Notes from Tests #1, #2, #3, and #4

DPA Notes from Test # 1 – 20W heater on trigger cell in Position 1 (6/18/15).

We performed a visual inspection of the cells from battery Test # 1 and made the following observations:

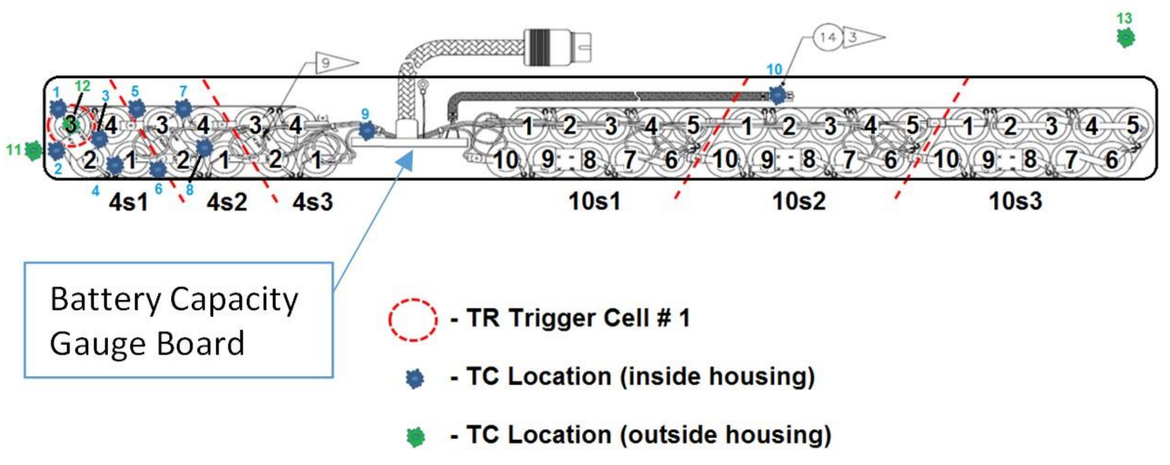
1. B4S1 (cell 1, trigger) – large hole and significant damage to side from mid-cell to positive terminal
2. B4S1 (cell 2) – hole on side near negative terminal
3. B4S1 (cell 3) – pin holes on cap & on side near positive terminal
4. B4S1 (cell 4) – hole on side near negative terminal
5. B4S2 (cell 1) – hole through cap
6. B4S2 (cell 2) – hole on side near negative terminal
7. B4S2 (cell 3) – hole on side near negative terminal
8. B4S2 (cell 4) – large hole on side near positive terminal
9. B4S3 (cell 1) – hole on side near positive terminal
10. B4S3 (cell 2) – hole on side near positive terminal
11. B4S3 (cell 3) – large hole on side between mid-cell and positive terminal
12. B4S3 (cell 4) – hole at positive terminal crimp
13. B10S1 (bundle 4) – no signs of stress on cells; OCV = 5.72 V
14. B10S2 (bundle 5) – no signs of stress on cells; OCV = 5.06 V
15. B10S3 (bundle 6) – no signs of stress on cells; OCV = 4.08 V



ISAFER Battery TR Test
Battery-Level Test # 2 – 6/30/2015
Post-test DPA – 7/9/2015

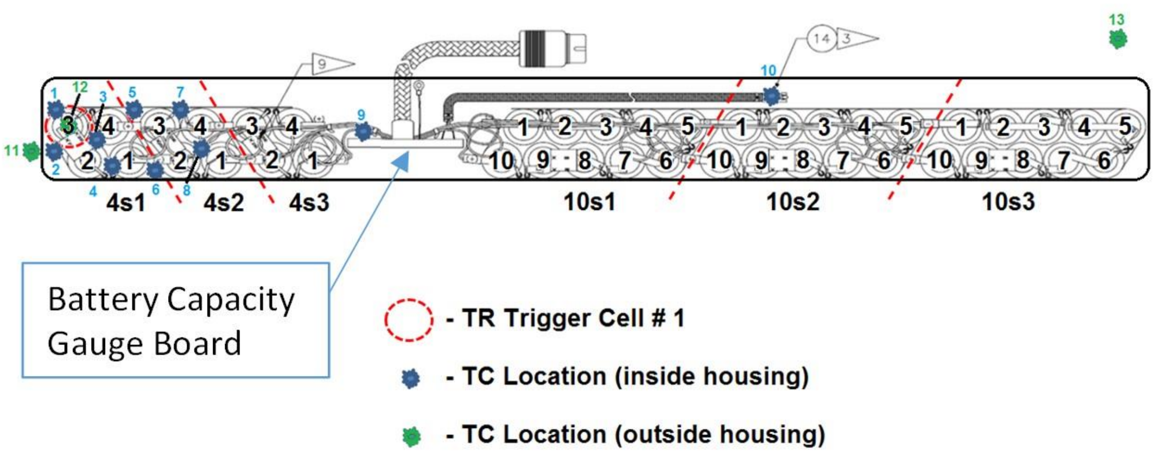
Bundle/Cell Location *	OCV	Notes
4S1-1 (trigger)	0	Sidewall breach near positive terminal (~3/8”×1/4”)
4S1-2	0	Pinhole near positive terminal; No sidewall breach
4S1-3	0	Top vent; No sidewall breach (~1/4” wide)
4S1-4	0	Top vent; No sidewall breach (~1/4” wide)
4S2-1	0	Two pinholes on positive terminal; No sidewall breach
4S2-2	0	Sidewall breach near positive terminal (~1/16”)
4S2-3	0	Sidewall breach near positive terminal (~1/16”)
4S2-4	0	Sidewall breach near positive terminal (~1/16” long) and near negative terminal (~1/4” wide)
4S3-1	0	Sidewall breach near middle of cell (~1/8”×1/4”)
4S3-2	0	Sidewall breach near positive terminal (~1/16”×1/32” wide)
4S3-3	0	Sidewall breach near positive terminal (~1/16”×1/8”)
4S3-4	0	Sidewall breach near negative terminal (~1/2”×1/8”)
10S1	12.64	Minor smoke stains
10S2	8.70	
10S3	8.27	

* - Bundles numbered per convention in drawing below (not latest numbering convention). Cell numbering does not follow drawing. Cell numbering likely reflects order of inspection and not location within bundles.



ISAFER Battery TR Test
Battery-Level Test # 3 – 4/27/2016
Post-test DPA – 5/3/2016

Bundle/Cell Location	OCV	Notes
4S1-1	0	Sidewall breach near bottom
4S1-2	0	Sidewall breach near top
4S1-3	0	Top vent; No sidewall breach
4S1-4	0	Top vent; No sidewall breach; Top cap slightly separated at crimp seal
4S2-1	0	Sidewall breach near top
4S2-2	0	No obvious vent holes; Cell lid slightly lifted (swollen) when compared to new cell
4S2-3	0	Sidewall breach near top; Top cap separated at crimp seal
4S2-4	0	Sidewall breach near top; Top cap separated at crimp seal
4S3-1	0	Sidewall breach near top; Top cap slightly separated at crimp seal
4S3-2	0	Fused to 4C3; Sidewall breach with further damage potentially resulting from cell separation; Top cap separated at crimp seal
4S3-3	0	Fused to 4C2; Sidewall breach near top
4S3-4	0	Sidewall breach near top
10S1	30.23	Significant amount of soot on cells under the shrink wrap and Kapton® tape
10S2	27.20	Less soot on cells than in bundle 10A
10S3	27.13	Less soot on cells than in bundle 10B

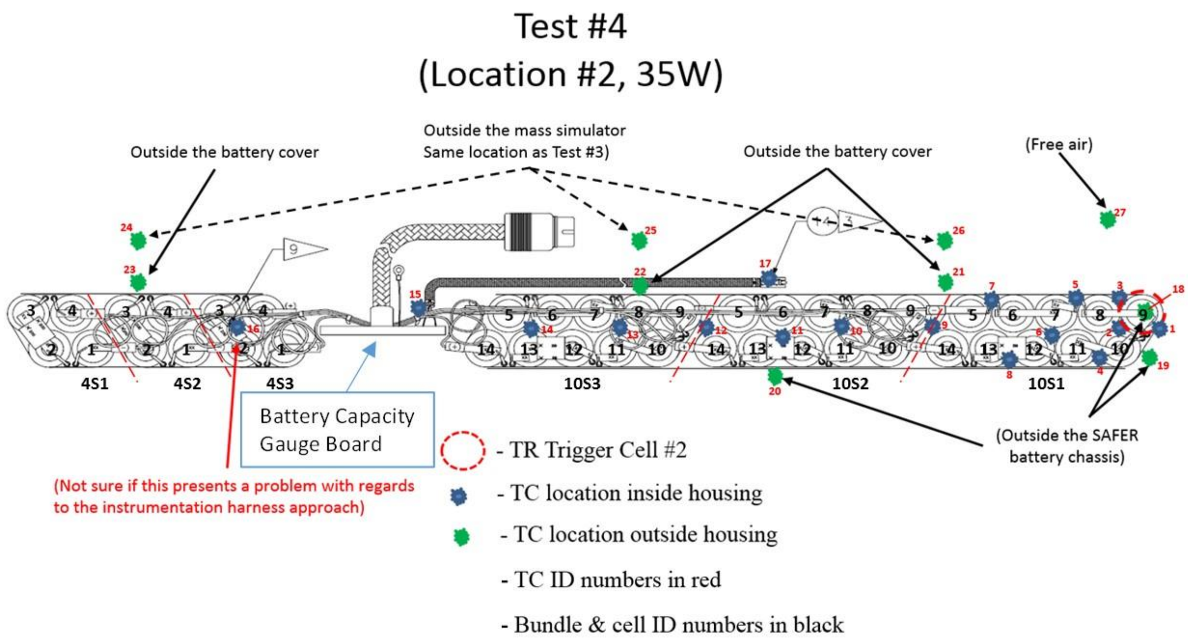


ISAFER Battery TR Test
Battery-Level Test # 4 – 5/24/2016
Post-test DPA – 5/24/2016

Bundle	**Pre-Test OCV**	**Post-Test OCV**	**Pre-Test Mass**	**Post-Test Mass**	**Notes**
4S1	12.34	3.21	72	69	**Minimal soot under Kapton® tape and shrink wrap. All cells show signs of swelling at cell lids. Cell jackets stretched and warped at cell ends.**
4S2	12.52	1.15	72	71	**Minimal soot under Kapton® tape and shrink wrap. All cells show signs of swelling at cell lids. Cell jackets stretched and warped at cell ends.**
4S3	12.58	5.65	72	71	**Minimal soot under Kapton® tape and shrink wrap. All cells show signs of swelling at cell lids. Cell jackets stretched and warped at cell ends.**
10S1	31.27	0.0	178	137	**Completely consumed.**
10S2	31.10	0.0	175	136	**Completely consumed.**
10S3	31.03	0.0	175	132	**Completely consumed.**

Cell	**Pre-Test OCV**	**Post-Test OCV**	**Pre-Test Mass**	**Post-Test Mass**	**Notes**
10S1-5	-	-	-	-	**At least 4 smaller sidewall perforations**. Slight separation at spin groove.
10S1-6	-	-	-	-	No obvious signs of venting. Minimal separation at spin groove.
10S1-7	-	-	-	-	**Large sidewall breach**. Slight separation at spin groove.
10S1-8	-	-	-	-	Significant separation at spin groove. **Top lid popped open.**
10S1-9 (trigger)	-	-	-	-	**Top vent at header button.**
10S1-10	-	-	-	-	**Sidewall breach near header** just under the spin groove.
10S1-11	-	-	-	-	**Two sidewall breaches near cell bottom.**
10S1-12	-	-	-	-	**Sidewall breach near header** just under the spin groove.
10S1-13	-	-	-	-	**Two sidewall breaches near cell bottom**. Slight separation at spin groove.
10S1-14	-	-	-	-	**Sidewall breach near header** just under the spin groove.
10S2-5	-	-	-	-	**Large sidewall breach near center of can**. Sidewall breach near cell bottom.

10S2-6	-	-	-	-	**Large sidewall breach near header** just under the spin groove. Some damage may have occurred during DPA.
10S2-7	-	-	-	-	**Fused to 10B11.** No obvious signs of venting. Minimal separation at spin groove.
10S2-8	-	-	-	-	**Sidewall breach near header** just under the spin groove.
10S2-9	-	-	-	-	**Top vent at header button**.
10S2-10	-	-	-	-	**Sidewall breach near header** just under the spin groove. Separation at spin groove.
10S2-11	-	-	-	-	Fused to 10S2#7. **Sidewall breach near cell bottom.**
10S2-12	-	-	-	-	Fused to 10S2#13. **Sidewall breach** (near header just under the spin groove) which may have been created or worsened during DPA.
10S2-13	-	-	-	-	Fused to 10S2#12. **Large sidewall breach** from center to bottom of can. **Sidewall breach near bottom of cell** which may have been created or worsened during DPA.
10S2-14	-	-	-	-	**Large sidewall breach near header** just under the spin groove. Sidewall breach near center of can.
10S3-5	-	-	-	-	**"Pinhole" sidewall breach near cell bottom**. Crack in sidewall near cell bottom.
10S3-6	-	-	-	-	**Sidewall breach near header.**
10S3-7	-	-	-	-	**Large sidewall breach from cell center to bottom**. Sidewall breach near cell bottom.
10S3-8	-	-	-	-	**Sidewall breach near header.**
10S3-9	-	-	-	-	**Sidewall breach in two spots near bottom of cell.**
10S3-10	-	-	-	-	**"Pinhole" sidewall breach near header**. Separation at spin groove.
10S3-11	-	-	-	-	Fused to 10S3#12. **Large sidewall breach near cell bottom.**
10S3-12	-	-	-	-	Fused to 10S3#11. **Large sidewall breach near header** just under the spin groove. Sidewall breach near center of can.
10S3-13	-	-	-	-	**Sidewall breach near cell bottom.**
10S3-14	-	-	-	-	**Sidewall breach near center of can.**


Test #4
(Location #2, 35W)
Outside the battery cover
Outside the mass simulator
Same location as Test #3)
Outside the battery cover
(Free air)
4S1
4S2
4S3
10S3
10S2
10S1
Battery Capacity
Gauge Board
(Outside the SAFER
battery chassis)
(Not sure if this presents a problem with regards
to the instrumentation harness approach)
- TR Trigger Cell #2
- TC location inside housing
- TC location outside housing
- TC ID numbers in red
- Bundle & cell ID numbers in black

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14. ABSTRACT
Mr. J. Leggett, International Space Station (ISS) Chief Engineer, requested the NASA Engineering and Safety Center (NESC) conduct an assessment of the ISS Simplified Aid for Extra-Vehicular Activity Rescue (SAFER) Battery against post Boeing Company model 787-8 Dreamliner commercial aircraft lithium (Li) battery failures lessons learned. Specifically, this task was focused on assessing the severity of a cell-to-cell propagating thermal runaway (TR) event in the SAFER non-rechargeable Li battery power system. This document contains the outcome of the NESC assessment.

15. SUBJECT TERMS
International Space Station; NASA Engineering and Safety Center; Simplified Aid for Extra-Vehicular Activity Rescue; SAFER; Extra-Vehicular Activity

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