Cell-level IIISC, Nail Penetration, Hot Pad and ARC Tests for LVP65

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KEY FINDINGS

Introduction

The test plan covered in this report is an extended research work from previous UL/NTSB research contract (NTSBC13004). This work mainly focuses on the cell level abuse tests of the LVP65 Lithium-ion cells used in B787 Main/APU batteries, including indentation induced internal short-circuit (IIISC), nail penetration (NP), hot pad (HP) and accelerating rate calorimetry (ARC) thermal abuse tests.

In the tests, IIISC is to simulate a localized and small-scale internal short-circuit (ISC) condition; NP test is to simulate the ISC condition similar to the battery level NP test that has been implemented by UL[1]; HP test is to simulate the ISC condition caused by propagating heat from the adjacent cell; ARC thermal abuse test is to study the cell behaviors while the cell suffering a uniform overheating condition.

The purpose of these tests is to characterize the cell behaviors under different simulated abuse conditions to support the developing of cell-level safety assessment programs. Moreover, the failure mechanisms of these tests provide evidences for the forensic analysis of prior Boeing 787 battery incidences.

Basic Terms and Definition:

In order to specifically explain the observation and finding in cell level tests, some basic terms will need to be clearly identified. Below are the terminologies used in the report.

- W2: There are 3 windings connected in parallel inside of a LVP65 cell, W2 is the winding located in the center.
- W1: The winding adjacent to W2. There are 2 types of construction designs in LVP65 cells. To avoid confusion, W1 is defined as the windings that the initial ISC is first triggered in IIISC, side-penetrated NP[2] and HP test.
- W3: The winding adjacent to W2 and opposite to W1.
- Open fuse: melting of current collector to open the circuit in cathode (ex. aluminum)[3].

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[1] UL Final Report for 787 Battery (Asset 445) Tested at 15°C, Grounded, and Final Report for 787 Battery (Asset 436) Tested at 70°C, Ungrounded

[2] In this test plan, NP is conducted in two directions. Top-penetrated NP is to penetrate the cell from the center of cell top to induce the ISC condition. Side-penetrated NP is to penetrate the cell from center of the side with biggest area to trigger the ISC condition.

- FINDING 1: All abuse tests resulted in thermal runaway, venting and swollen cells.

DISCUSSION: With all 18 cells tested with different conditions, IIISC, NP and HP have caused the cells to have internal short circuit and thermal runaway; ARC have caused the cell to have thermal runaway as well. The vents of all 18 cells were opened after the thermal runaway, however the pressure due to thermal runaway has caused the cell to swell on all 18 cells. The cell behaviors measured in this report are very important information to evaluate the validity of battery system design and to verify if the battery design is able to mitigate the worst-condition failures of the cells.

- **FINDING 2:**ISC triggered at W1 (in IIISC, side-penetrated NP and HP tests) have open fuse in W1

DISCUSSION: Figure 1 shows the failure mechanism when an ISC is triggered at W1. In a LVP65 cell, the three windings are connected in parallel so the voltage readings for them are identical. When an ISC is triggered at W1, cell voltage of W1 will drop immediately. Because the three windings are connected in parallel, W2 and W3 will start to charge W1 in order to balance the overall cell voltage. The charge current could be up to more than 3,000 Amp[4], which is able to melt the current collector in W1 within a few seconds. After the open fuse in W1, although the charge from W2 and W3 stopped immediately, the heat generated by the thermal runaway of W1 has already propagated to W2 and W3 and causes ISC and thermal runaway of W2 and W3.

Figure 2 shows the cell voltage profile of an ISC simulation test. It takes only 4-5 seconds to melt down the current collectors in W1. The cell voltage recovers very fast after the open fuse as the electrical load (i.e. W1) for W2 and W3 has been disconnected. In about 20 to 30 seconds, the cell voltage will drop again due to two potential reasons: 1) the heat propagated from W1 causes the melting of separator in W2 and/or W3 to trigger further ISC and thermal runaway; 2) The heat propagated from W1 leads to materials decomposition in W2 or/and W3 and causes thermal runaway of them.

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[3] The current collector in anode side is impossible to be melted due to 2 reasons: (1) the melting point of copper (1085°C) is much higher than aluminum (660.3°C); and (2) after open fuse at cathode side, the circuit is open so there will be no current flow any more through copper.

[4] See the maximum current calculation on page 28 for details.

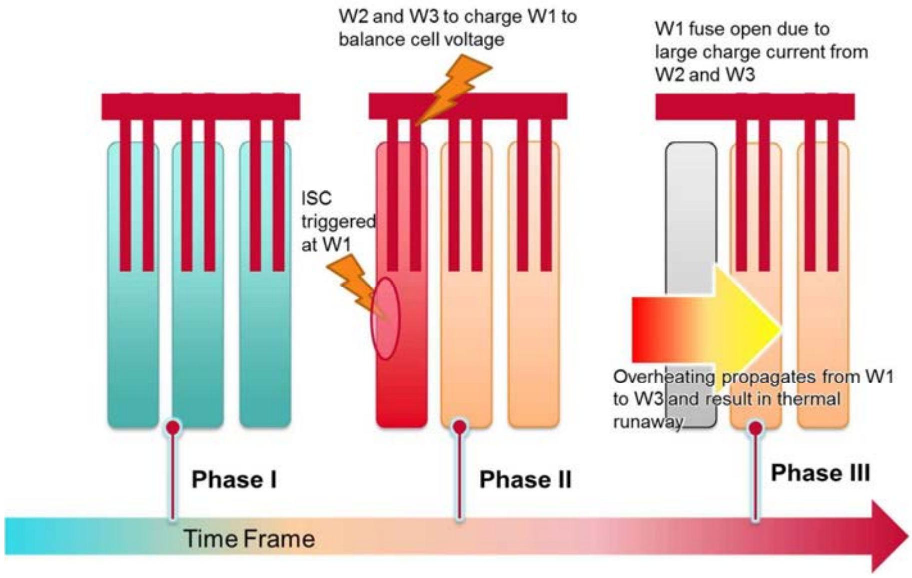

Figure 1. Failure Mode of ISC tests (Open fuse in W1 only)

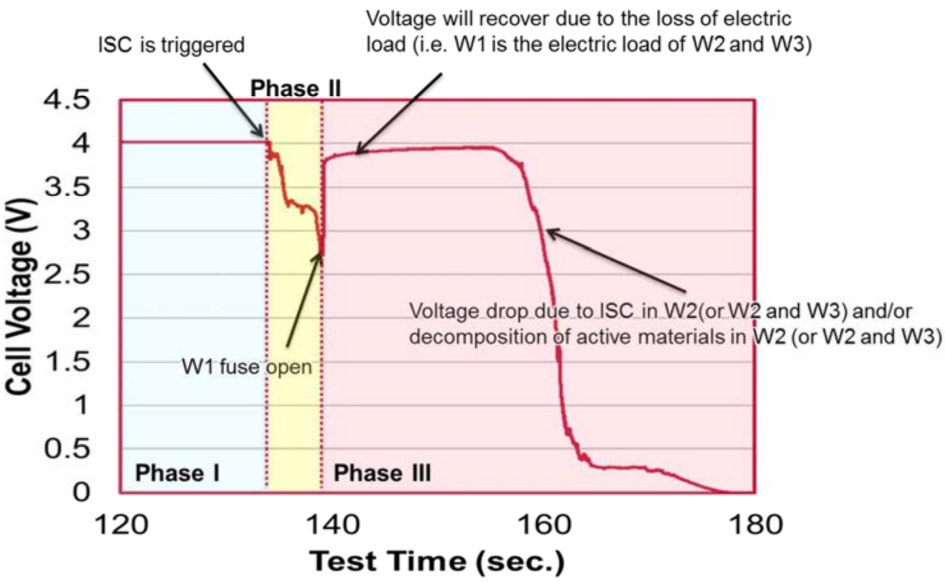

Figure 2. Cell voltage change under ISC (open fuse in W1 only)

There is also a possibility that both W1 and W2 have open fuse after the cell abuse tests. Figure 3 and Figure 4 show the mechanisms. Similar to the previous case, open fuse in W1 happened due to the ISC of W1 and charging from W2 and W3. After that, the heat propagation in W1 caused W2 to have ISC earlier than W3. In this case, because of the voltage drop on W2, W3 starts to charge W2. The heat propagated from the thermal runaway of W1 and the charging of W3 further causes the melting of current collector in W2 before W3 eventually goes thermal runaway.

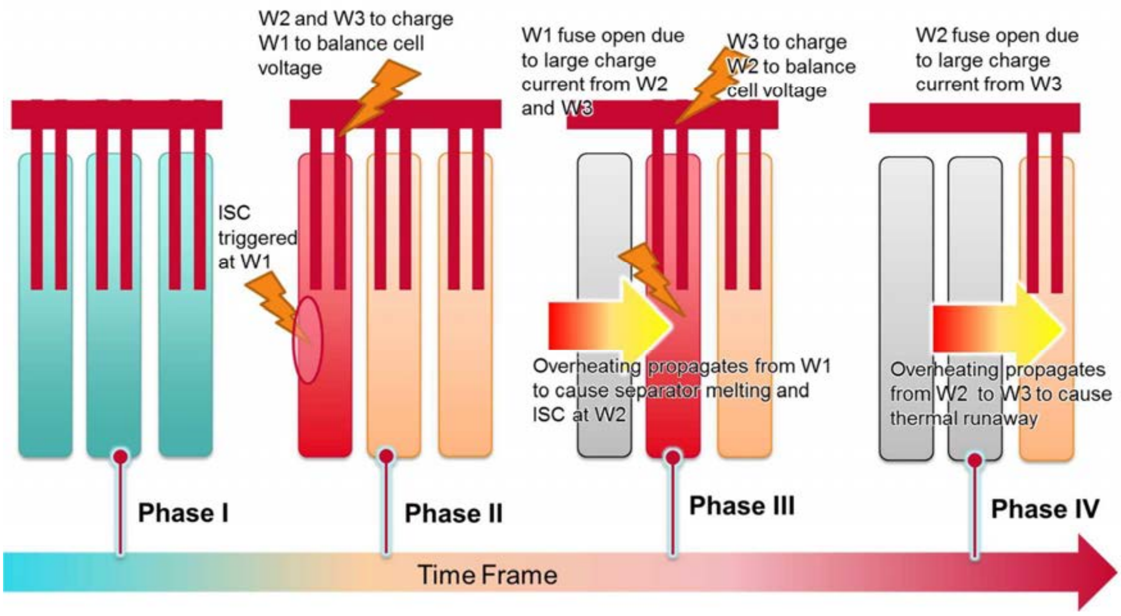

Figure 3. Failure Mode of ISC tests (Open fuse in both W1 and W2)

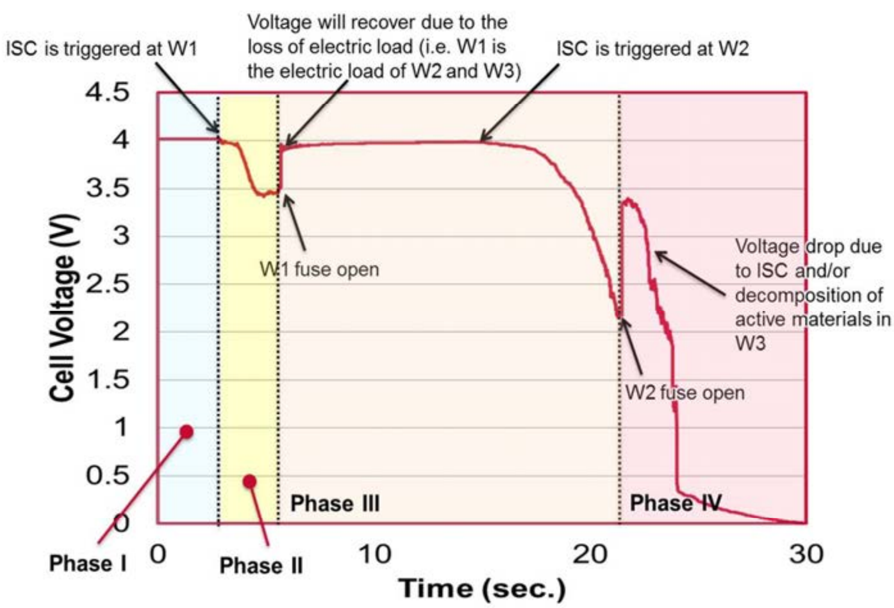

Figure 4. Cell voltage change under ISC (open fuse in W1 and W2)

- **FINDING 3**: Under higher test temperature, open fuse is more likely to occur in both W1 and W2 when the ISC is triggered in W1.

DISCUSSION: In all abuse tests under 25°C, only the open fuse in W1 can be observed. The open fuse in both W1 and W2 can only be observed in IIISC and side-penetrated NP tests under 70°C. Hence, test temperature is a critical factor that can potentially lead to open fuse in more windings.

- FINDING 4: In all the tests performed in this report, open fuse in W2 can only be observed at the top-penetrated NP tests.

DISCUSSION: For the top-penetrated NP tests, the initial ISC is triggered at W2 by the nail, therefore the short circuit in W2 will cause immediate voltage drop, followed by the two parallel connected windings W1 and W3 to start charging W2, as shown in Figure 5. The high current flow from W1 and W3 to W2 will cause the current collector in W2 to melt, and the heat generated by the thermal runaway of W2 will then cause W1 and W3 to go thermal runaway.

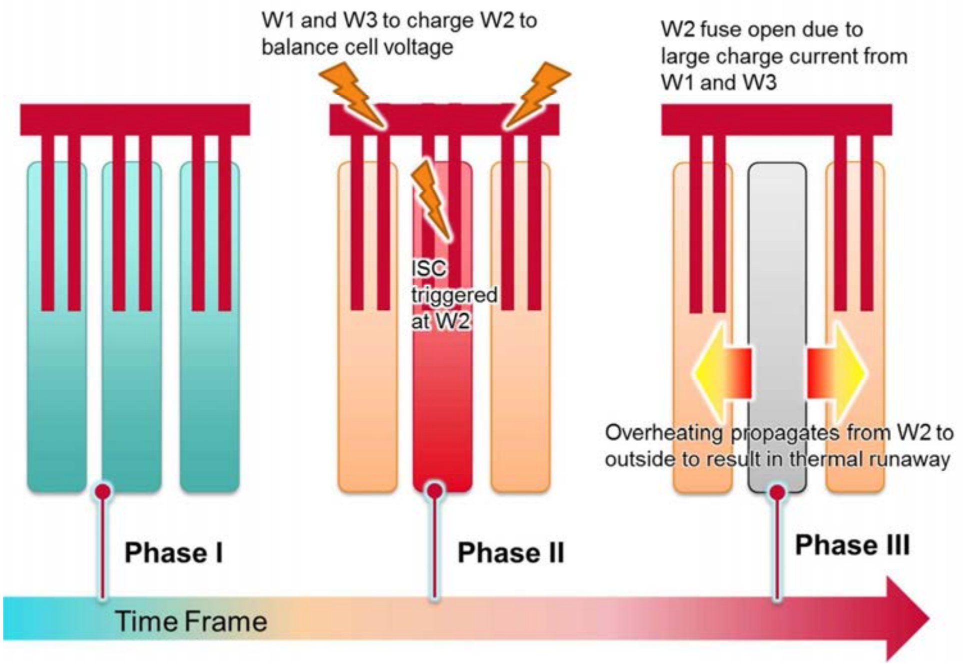

Figure 5. Failure Mode of top-penetrated NP test (Open fuse in W2 only)

- FINDING 5: Heating LVP65 cell uniformly (ex. ARC test) will result in no open fuse. However, heating from one side of LVP65 cell (ex. HP test) will have open fuse in W1.

DISCUSSION: In an ARC thermal abuse test, the heat within the cell increases slowly and evenly, so before the first separator melts down to cause ISC, the separators in all three windings are at similar temperature, which is already above the shutdown temperature of the separator. Therefore even short-circuit happens in one of the three windings, the other two windings will not have enough electricity to charge the short-circuited winding because the separators have already shut down the ion transfer. Therefore there is no open fuse in ARC tests.

However for the HP test, because the heat resource is on one side of the cell, the overheating in HP test will initially cause an ISC in one winding only. The detailed mechanism of the failure mechanism in HP is the same as Figure 1 and Figure 2. In our limited test samples via HP tests, we can observe open fuse in W1 only. However based on our experiences in IIISC and NP tests, it is also possible to have open fuse in both W1 and W2 due to the situation of heat propagation.

- FINDING 6: Examining open fuses on the LVP65 cells in a failed battery can provide information on how the cell failures might be propagated.

DISCUSSION: From the tests performed in this report, we can conclude the dependency of the first short-circuit winding and the location of open fuse. We also have learned from the HP tests that if the cell failure is caused by the heat propagation from an adjacent cell, the open fuse should be on the side where the heat is coming from. Therefore if the open fuse(s) in the cell is on the side, or both center and one side, then we know the heat source is very likely to come from that direction. If the open fuse is at the center winding only, then we can suspect that the internal short circuit was initiated from the center winding, and not likely to be a result of heat propagation from another cell or the environment.

Contents

INTRODUCTION

NTSB requested UL to conduct cell-level abuse tests on the lithium-ion batteries of Boeing 787 to understand the failure mechanisms of the cells under various abuse conditions. Lithium-ion batteries are known to have three major aspects of safety concerns[5]: short-circuit, thermal abuse, and overcharge. These three concerns are frequently discussed in battery industries and have been widely studied by battery researchers.

A short-circuit event can be triggered internally or externally. In practice, the concerns of external short-circuit are easier to be addressed through safety devices, such as a fuse or positive temperature coefficient (PTC) resistor within a cell/pack or even in the battery power system. However, internal short-circuit is usually a much more challenging safety issue. The internal short-circuit bypasses most of the safety devices outside and inside of the cell, and the heat generated by internal short-circuit has an extremely rapid rate that will result in thermal runaway under a worst-case scenario.

In the LVP65 cells of the Lithium-ion battery used in Boeing 787, the working voltage is between 2.75V and 4.025V with the cell balancing design to avoid the overcharge condition. With the protection of battery management unit (BMU), and that no strong evidence to show the Boeing 787 incidents were caused by any overcharge condition. This project focuses on thermal abuse tests and both external and internal triggered internal short-circuit tests.

Literature Overview

As lithium-ion battery is promoted for a wide variety of applications, it has undergone numerous enhancements and upgrades by chemical or physical means to improve its energy or power density, runtimes and application temperature range since its commercial introduction in 1991[6]. These advances have also increased the safety risks of lithium-ion battery — including fires and explosions — which, while rare, have resulted in product recalls and negative publicity[7]. Consequently, to analyze the failure mode and mechanism is essential and significant to get more insight into the safety behaviors in a lithium-ion cell. As the ISC is believed to be one of the most challenging safety

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[5] "Abuse Testing of Lithium-Ion Batteries: Characterization of the Overcharge Reaction of LiCoO2/Graphite Cells", R. A. Leising et al., Journal of The Electrochemical Society 148, A838-844, 2001

[6] "Lithium-ion Safety Concerns," Battery University, 2013. Web: 03 July 2013.

[7] "A review of hazards associated with primary lithium and lithium-ion batteries", D. Lisbona et al., Process Safety and Environmental Protection 89, pp434–442, 2011.

issues among all battery failure scenarios, there are some battery research organizations all over the world that have studied the ISC behaviors and proposed some test methods to simulate an ISC in a lithium-ion single-cell. H. Maleki et al. used the thermal model approach to characterize the features in an ISC event[8]. The key characteristics in an ISC are: (1) only few layers of electrodes are directly involved in the ISC reactions; and (2) side reactions, such as material decomposition, can be activated around the ISC point due to the local heating around the ISC point. To simulate the general situation that could happen in an ISC event, a localized and small scale of ISC shall be created. Consider the feasibility of ISC test on commercial cell products, UL[9], NASA[10] and ORNL have developed indentation type ISC tests that have been proved effectively to create a localized ISC and to trigger the subsequent localized heating within a single cell.

In some of the battery safety standards, NP test is used to simulate the mechanical abuse condition[11] that triggers the ISC in a single cell. Basically, the ISC condition and severity are always depend on the trigger mechanism[12] and thus this is very challenging to develop an appropriate test method to represent a real field ISC event. NP test is the most popular method in the field because it is very easy to conduct. However, there are some intrinsic drawbacks in NP test that have been discussed in some technical articles[13]: (1) Heat can be dissipated easily via the nail during NP test; (2) Excess pressure can be released through the penetrated hole on cell casing; (3) Metal nail will get involved in ISC reaction; and (4) Test results is related to penetration speed. Besides, NP test may create the penetration through multi-layer electrode sheets to get big area of electrochemistry reaction. To minimize the effect, appropriate cell voltage drop should be set as the threshold to stop the penetration of nail on test samples. By setting appropriate voltage threshold, the initial electrochemistry reaction can be controlled within a very small scale.

In addition to the IIISC and NP tests this project focuses on to simulate ISC, there are also some other ISC test methods proposed as below.

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[8] "Internal short circuit in Li-ion cells"; H. Maleki et al., Journal of Power Sources 191, pp568-574, 2009

[9] "Test Method to Simulate Internal Short-Circuit in Lithium-ion Cells", A. Wu, Presentation at IEEE ISPCE2014 conference, May, 2014, San Jose, USA

[10] "NASA and Underwriters Laboratories Collaboration on Simulated Internal Short Test for Lithium-ion Cells", J. Jeevarajan, Presentation at NASA Aerospace Battery Workshop, 2011, Huntsville, USA

[11] UL subject 2271, Section 8.7; SAE J2464

[12] "Analysis of internal short-circuit in a lithium ion cell", S. Santhanagopalan et al., Journal of Power Sources, Volume 194, pp 550-557, 2009

[13] "The safety characteristics of lithium-ion batteries for mobile phones and the nail penetration test", M. Ichimura, Telecommunication Energy Conference, 2007, Rome, Italy

A. Forced Internal Short-Circuit Test (FISC)[14]:

This method was proposed by Battery Association of Japan (BAJ). A fully charged cell is to be disassembled and the cell casing is removed. The jelly-roll or the electrode sheets assembly was then opened to insert a very small L-shape nickel particle (Figure 6; 0.2mm in height and 1mm in length) in the location between anode and cathode or anode and aluminum foil. The ISC was triggered by applying a force on test sample to bridge opposite electrodes via the L-shape nickel particle.

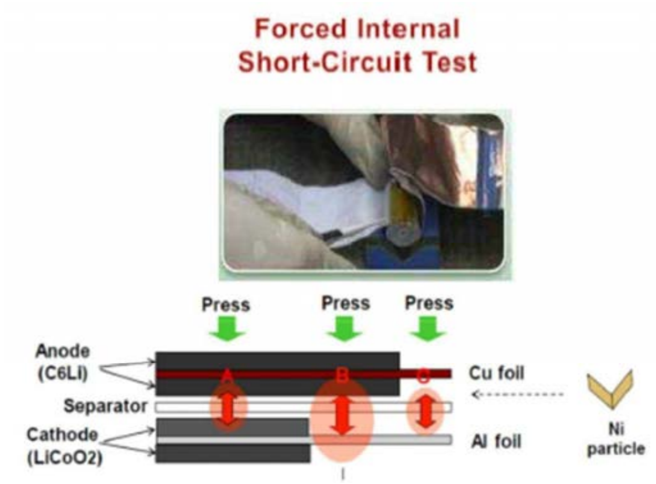


Figure 6. Forced Internal Short Circuit test by BAJ

- Strength of the test: can very accurately simulate a small scale ISC condition
- Weakness of the test: (1) Complicated sample preparation procedure; (2) safety concerns while disassembly of fully charged cell; (3) Jelly-roll or electrode sheet assembly without the case enclosure may not represent a real cell product

B. Experimental Triggered ISC Test[15]:

This method was proposed by US Sandia National Lab. A special made test sample will be required to conduct this test. The preparation procedure is more complicated than FISC test. The test sample shall be prepared during cell assembly process. A metal alloy with low melting point (i.e. 60-65°C) is to be embedded between opposite electrodes (Figure 7). At the location of alloy

[14] JIS C8714

[15] "Experimental triggers for internal short circuits in lithium-ion cells", C. J. Orendorff et al., Journal of Power Sources, Volume 196, pp 6554-6558, 2011

particle, a hole shall be made on separator so that the melted alloy can bridge opposite electrodes easily to create the ISC condition after the test sample is to be heated up to 65°C.

Figure 7. Experimental Triggered ISC test by US Sandia National Lab

- Strength of the test: can very accurately simulate a small scale ISC condition
- Weakness of the test: (1) Complicated sample preparation procedure; (2) Cannot be performed by 3rd party lab

C. Pinch Test[16]:

This method was proposed by Motorola Inc. and US Oak Ridge National Lab. The test setup is shown in Figure 8. To conduct this test, 2 pinch balls are used to compress test sample from both sides to trigger the ISC condition.

- Strength of the test: (1) can be easily conducted; (2) can create a localized ISC condition
- Weakness of the test: (1) need to select the appropriate pinch ball size to avoid punching through cell; (2) test result may be related to cell construction design

[16] "Experimental simulation of internal short circuit in Li-ion and Li-ion-polymer cells", W. Cai et al., J of Power Sources, Volume 196, pp 7779-7783, 2011

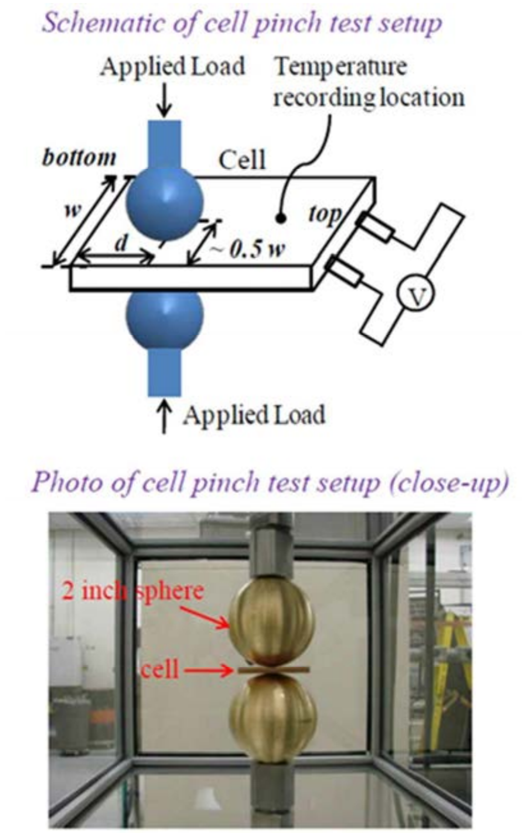


Figure 8. Pinch Test by Motorola Inc. and ORNL

Regarding the thermal abuse of lithium-ion batteries, accelerating rate calorimeter (ARC) is one of the popular approaches to characterize the battery thermal behaviors under a simulated adiabatic condition[17]. This test method is ideal for detecting the self-heating behaviors on a cell under a certain temperature range. Hence some key reactions within a battery, such as SEI decomposition, anode/electrolyte reactions, cathode/electrolyte reactions, separator melting and battery disintegration, can be detected in a very sensitive way. However, to reflect the real safety behaviors of batteries under overheating situation, a hot pad (HP) test will be sometimes more appropriate to show a real case when cell undergoes an overheating abuse due to the condition of thermal propagation.

[17] "Thermal abuse performance of high-power 18650 Li-ion cells", E. P. Roth et al., Journal of Power Sources 128, pp308-318, 2004

SUMMARY OF TEST PLAN

There are two ISC tests and two thermal abuse tests covered in this test plan. IIISC test is the approach to simulate the localized overheating due to the localized ISC condition. NP test is to duplicate the ISC situation in battery-level NP test, in order to analyze the cell behavior. Boeing have developed HP test to study the thermal propagation mechanism between cells at battery level. In this study, UL is to conduct HP test at cell level, in order to study in detail about how a cell may react to the thermal propagation from another failed cell. ARC thermal abuse test is to study the thermal stability of the cell design under adiabatic overheating condition. As the detailed ARC test results have already been addressed in document "UL Final Report NTSBC130004 2014.pdf". Hence in this report, only the failure mode of ARC thermal test is to be reviewed again to compare the test results of HP test.

All test samples for each test item are summarized in Table 1 below. In the sample code, the first 3 digits represent the battery asset number and the last digit is the cell position. For example, 149-1 means cell 1 from battery 149.

Table 1 Test Samples versus Test Items in LVP65 cell abuse test plan

Sample	149-1 241-1	149-2 241-2	149-3 241-4	149-5 241-3	149-4 241-5	149-6 241-6	149-7 241-7	149-8 241-8	171-8	412-4
Test	IIISC		NP test				Hot Pat test			ARC
Test condition	25 °C 0.1mm/s 20mV	70 °C 0.1mm/s 20mV	25 °C Side 20mm/s	25 °C Top 20mm/s	70 °C Side 20mm/s	70 °C Top 20mm/s	25 °C No load	70 °C No load	25 °C 8A load	50-305 °C 5 °C step 0.02 °C/m

TEST DESCRIPTIONS

This section describes the detailed test procedure, key test variables, and sample requirements for IIISC, NP, HP and ARC tests.

IIISC test

IIIS test was developed by the Corporate Research department of UL. It is an ISC simulation test to effectively create a localized and small-scale ISC condition in lithium-ion cells. Figure 9 shows the detailed test procedure, test setup and the indenter to conduct this test. Test sample is usually single cell with 100% SOC.

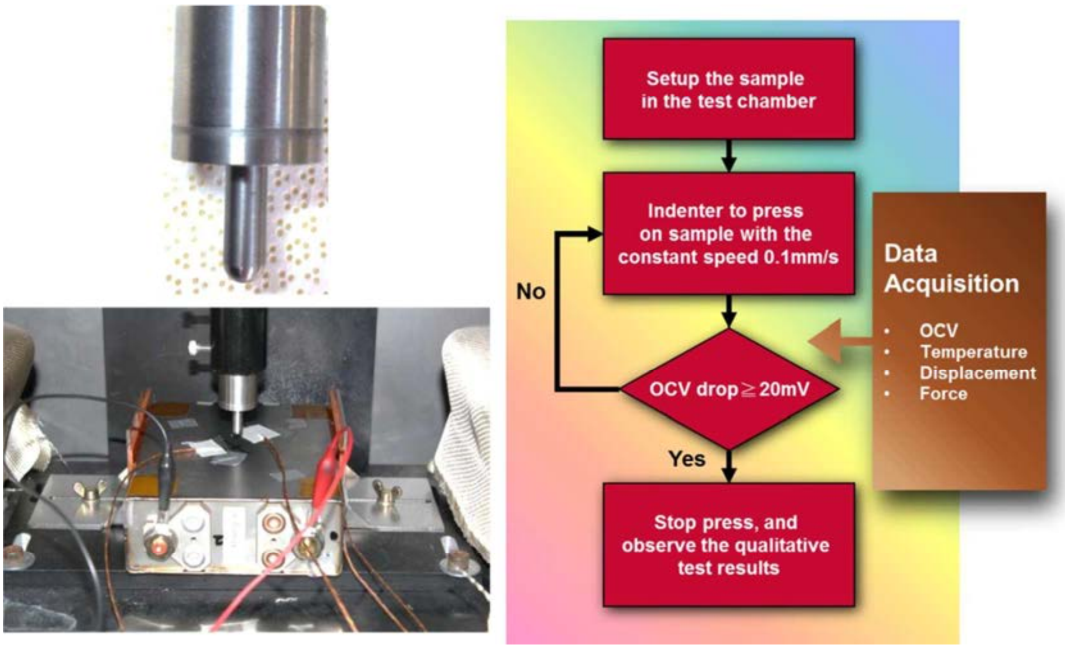


Figure 9. Test Setup, Indenter and Detailed Procedure in IIISC test

Before testing, the sample cell has to be set up in the test chamber and condition at the specified temperature[18] for at least two hours but no more than six hours before test. A voltage-meter is connected to the cell terminals and the signal of cell voltage reading is monitored and recorded by the control unit of the system. For the purpose of data analysis, the load applied on cell casing, displacement of indenter head and temperature reading on the cell case are also recorded during testing.

[18] The temperature of the test chamber can be set between -30°C and 100°C.

When the test starts, the indenter start to press on the cell casing with a constant speed of 0.1mm/s until the drop on cell voltage reading is larger than 20mV. When the system detects the voltage drop threshold (i.e. 20mV), the indenter stops immediately and keeps the position to make sure the ISC condition is sustained. The geometry of the indenter for LVP65 cell is 7mm with ball-end tip (Figure 9). The head of the indenter is rounded so it does not penetrate through cell case before the ISC was triggered. However the cell case can still be penetrated after ISC occurs because the swelling of the cell due to the gaseous products generated during high temperature.

<u>Test Variables</u>:

- Cell SOC%: 100% (i.e. charge to 4.025V for LVP65 cell)
- Indenter speed: 0.1mm/s
- Cell voltage drop threshold: 20mV
- Test Temperature: 25°C and 70°C
- Location to indent: center of the cell's flat side (the side with maximum area)

<u>Test Equipment</u>:

Press equipment (Figure 10) is used to conduct ISC simulation tests. A servo-motor is used to control the speed of the indenter. All of the detailed specifications are also given in the figure. The response time of the control unit is 0.01s to make sure the accuracy of the position of the indenter. All of the test parameters can be set by a controller so that the test can be set and conducted automatically and precisely.

Item	Spec.
Response time of Control Trigger	10^{-2} sec. or less
Maximum load capacity	10000N or more
Sampling rate for load measurement	100Hz or more
Sampling rate for Open Circuit Voltage (OCV)	100Hz or more
Press speed	0.1±0.005 mm/sec
Noise on OCV reading	+/- 5mV or less

Figure 10. Press equipment and design specifications to conduct IIISC test

NP Test

The NP test is a very popular test method to study ISC behavior in lithium-ion cells. In this project, a traditional approach was taken to conduct NP test with setting the cell voltage-drop threshold to control the initial ISC scale.

Figure 11 shows the detailed test procedure and test setup to conduct the test. The test sample is usually single cell with 100% SOC.

Before the test, the sample has to be set up in the test chamber and condition the cell at specified temperature for two hours but no more than six hours. A voltage-meter is connected to the cell terminals and the signal of cell voltage reading is monitored and recorded by the control unit of the system. For the purpose of data analysis, the load applied on the cell case, displacement of nail head, and temperature reading on the cell case are recorded during the test.

When the test starts, the nail is set with a constant speed of 20mm/s to penetrate through the cell case until the drop on cell voltage reading is bigger than 20mV. After the system detects the voltage drop threshold (i.e. 20mV), the nail will stop immediately and keep the position to make sure the ISC condition is sustained. The geometry of the nail for use in LVP65 cell is the same as LVP65 battery NP test (Figure 12).

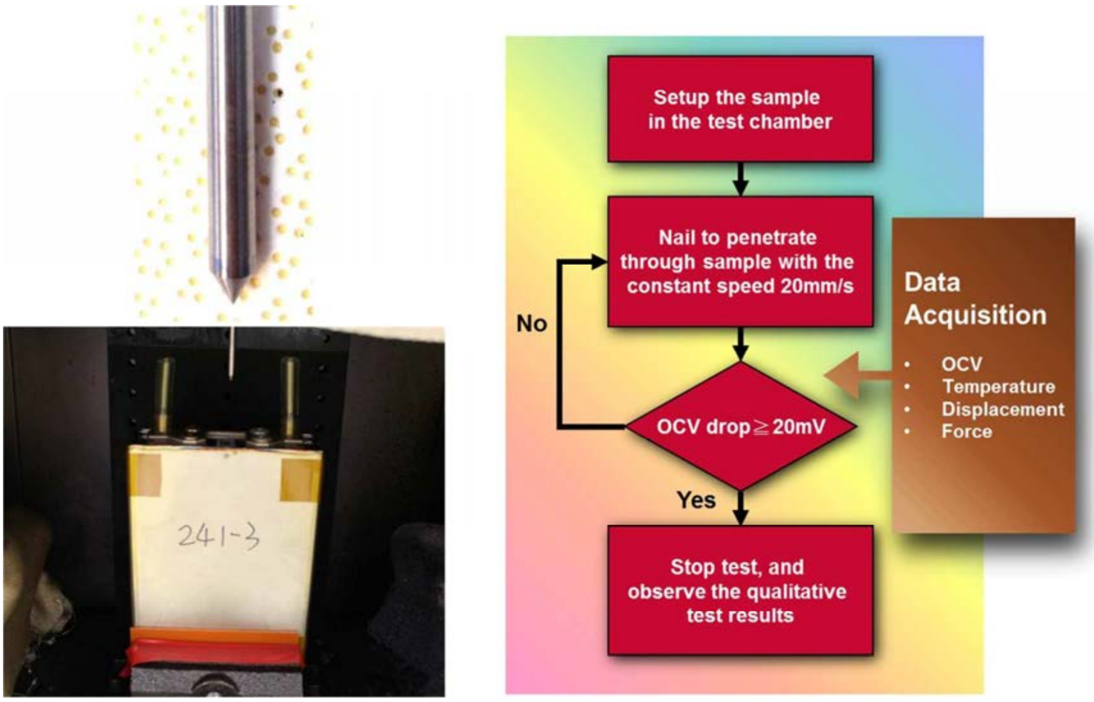


Figure 11. Test setup, nail and detailed procedure for IIISC test

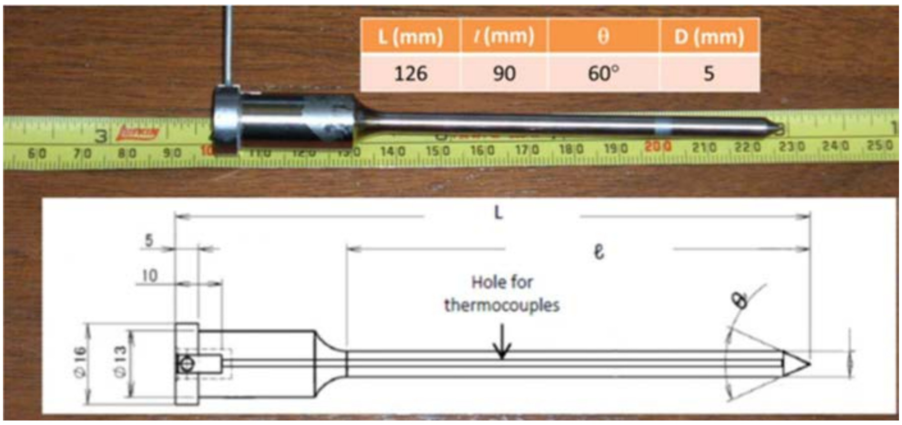


Figure 12. Standard nail used in NP test for LVP65 Battery

<u>Test Variables</u>:

- Cell SOC%: 100% (i.e. charge to 4.025V for LVP65 cell)
- Penetration speed: 20mm/s
- Cell voltage drop threshold: 20mV
- Test Temperature: 25°C and 70°C
- Location to penetrate: center of cell flat side (the side with maximum area) and the center of cell top (Figure 13)

Figure 13. Side-penetrated NP test (left) and Top-penetrated NP test (right)

<u>Test Equipment</u>: Same as IIISC test

HP Tests

The HP test in this project is to duplicate Boeing's HP test method for cell heat propagation but focusing on the single cell behaviors. The hot pad (Figure 14) used in this project is the same as the test fixture used in Boeing's study. The detailed test procedure of HP test for cell is:

1. A 250W hot pad is attached to one side of LVP65 cell.
2. The test sample is to be setup inside a test chamber (Figure 15). The hot pad is under the test cell. Sample is to be conditioned at specified temperature for at least 2 hours but no more than 6 hours before test.
3. Connect the cell to MACCOR 4000 series system if an electrical load is required.
4. During the test, cell voltage and the temperature on the cell case are monitored and recorded.
5. Turn on the hot pad to heat the sample up to 160°C and turn off the power if no event occurs. Turn on the power again when the temperature decreases down to 150°C. Then wait until thermal runaway occurs.

Figure 14. The hot pad (250W) used in HP test

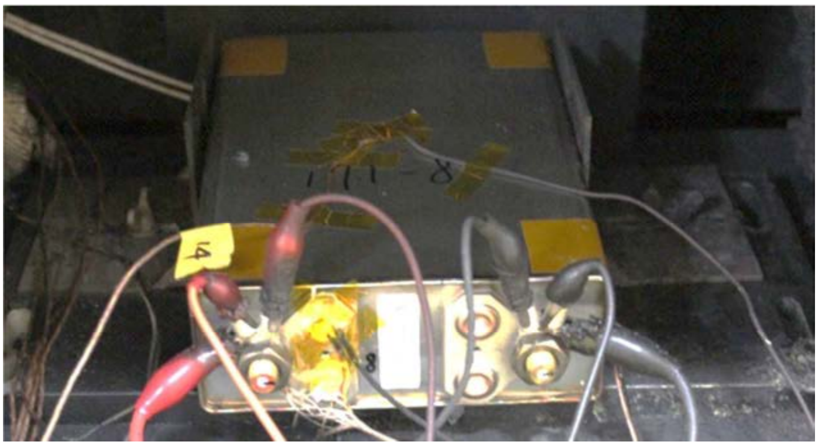


Figure 15. Test stup of HP test

<u>Test Variables</u>:

- Cell SOC%: 100% (i.e. charge to 4.025V for LVP65 cell)
- Cell Electric Load: no load and 8A constant current load
- Test Temperature: 25°C and 70°C

<u>Test Equipment</u>:

- Press Equipment: same as IIISC test
- MACCOR 4000 Series System: 10V/10A maximum rating (Figure 16)

Figure 16. MACCOR 4000 battery conditioning system

Thermal Abuse ARC test

ARC is the equipment that enables the characterization of lithium-ion cells under thermal abuse conditions. It creates adiabatic conditions so that all self-heating reactions generating more than 0.02 °C/min temperature-rise can be detected. For example, the initial on-set temperature (of self-heating) can be detected when SEI decomposition is triggered. Also the temperature range for the separator melting can be detected, along with thermal runaway behavior can be observed. The adiabatic condition creates a worst case for cell heating as the effect of heat dissipation is compensated by the ARC.

LVP65 cell with 100% SOC is used in the ARC tests. The ARC uses a heat-wait-seek mode to characterize the cell behaviors as the cell is heated. The test procedure is shown in Figure 17. The detection of temperature rate sensitivity is calibrated down to 0.01°C/min but the temperature rate threshold for tracing is set at 0.02°C/min. The temperature scan range is from 50°C to 305°C and the temperature rise step 5°C with 40 minutes waiting time for each waiting stage.

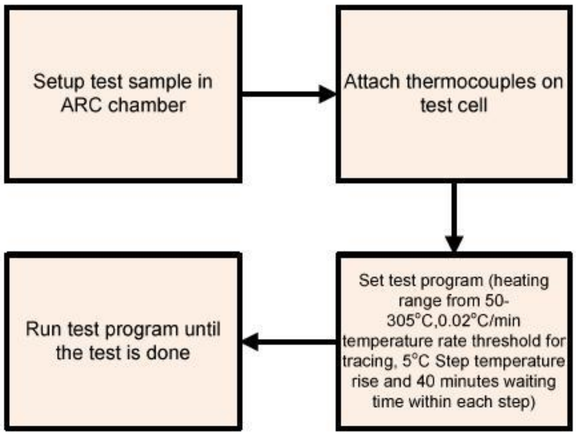


Figure 17. Test procedure of ARC Thermal Abuse (heat-wait-seek) test

Test Variables:

- Cell SOC%: 100% (i.e. charge to 4.025V for LVP65 cell)
- Temperature scan range: 50–305°C
- Self-heating tracking threshold: 0.02°C/min
- Temperature step: 5°C
- Waiting time for each step: 40 minutes

Test Equipment

The THT EV+ ARC System (Figure 18) is used for the test. The specification of the equipment is given below:

- Temperature range: room temperature to 300°C
- Temperature measurement: Type N thermocouple
- Temperature sensitivity: 0.01°C
- Temperature accuracy: 0.02°C
- Exotherm detection sensitivity: 0.02 °C/min
- Exotherm tracking rate: to 20 °C/min
- Pressure measurement range: 0-50 bar
- Pressure measurement accuracy: 0.5%

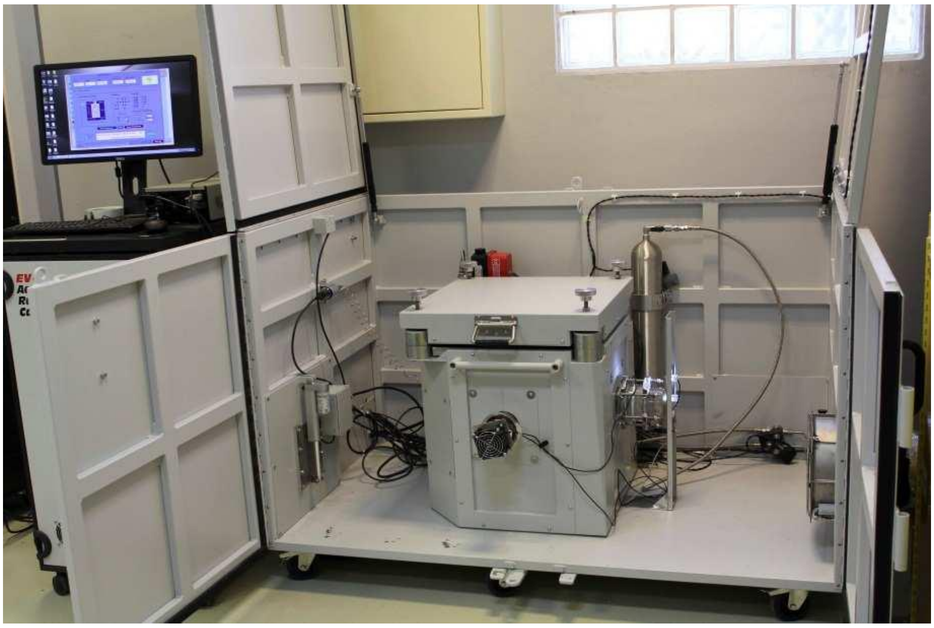


Figure 18. THT EV+ ARC System

Test Results and Discussion

In this section, the test results of four IISC tests, eight NP tests (including four from the top and four from the side), five HP tests, and one thermal abuse tests are presented and discussed.

IIISC

The results of IIISC test at both 25℃ and 70℃ are listed in Table 2. In most cases, the maximum temperature can be detected near the vent, which is located at the narrow side of LVP65 cells. The maximum temperature among all IIISC tests is between 290℃ and 336℃. However, the maximum temperature on the cell may not present the severity of test result as the temperature variation is affected largely by the failure modes so the locations of maximum temperature may differ. Under higher test temperature (i.e. 70℃), the test results show quicker heat release rate: The time from the triggering of ISC to the time the cell reaches to the maximum temperature is 146.1s and 28.2s under 70℃; 219.1s and 192.7s under 25°C. Most of cells have open fuse in W1 only but one tested under 70℃. It has open fuse in both W1 and W2.

Table 2 Test Result Summary of IIISC tests on LVP65 Cells

Test	IIISC test	
Sample	149-1 241-1	149-2 241-2
Condition	25 C	70 C
Test Result	Venting, Smoke	Venting, Smoke
Max T	322$_0$C 331 C	336$_0$C 290 C
Max T near vent	294$_0$C 331 C	336$_0$C 290 C
Max T at Indenter/Nail/Pad	322$_0$C 314 C	313$_0$C 283 C
Time from ISC to Max Vent T (seconds)	219.1 192.7	146.1 28.2
Open fuse?	W1 (149-1) W1 (241-1)	W1 (149-2) W1 and W2 (241-2)
Note	Cell case was not penetrated before the ISC occurs according to the indication of load profile.	

Note*1: Maximum temperature on cell may not represent the severity of test result as the temperature variation is affected largely by failure modes, so the locations of maximum temperature may differ. After cell failed, cell swelling and deformation is inevitable so the thermocouples may be detached and that will also cause error to the temperature readings

#149-1: IIISC at 25℃

Figure 19 shows the consolidated data of the IIISC test on sample 149-1, which is conducted under 25℃. In the data, we can see a drop on the load marked in the figure. The cause of this drop is an unbalancing force among support points between test sample and the base to hold test sample. At the force around 4500N to 5000N, the applied force is sufficient to clear the weakest supporting point. This situation occurs sometimes if the base to hold sample or the side of cell facing to the base is not uniformly flat. Also the test samples may be slightly deformed during the test.

In the test data, the temperature reading near the ISC point (i.e. TC3) shows the fastest response on temperature rise. It indicates that the over-heating is initially generated around ISC point, then the heat will propagate to surrounding area.

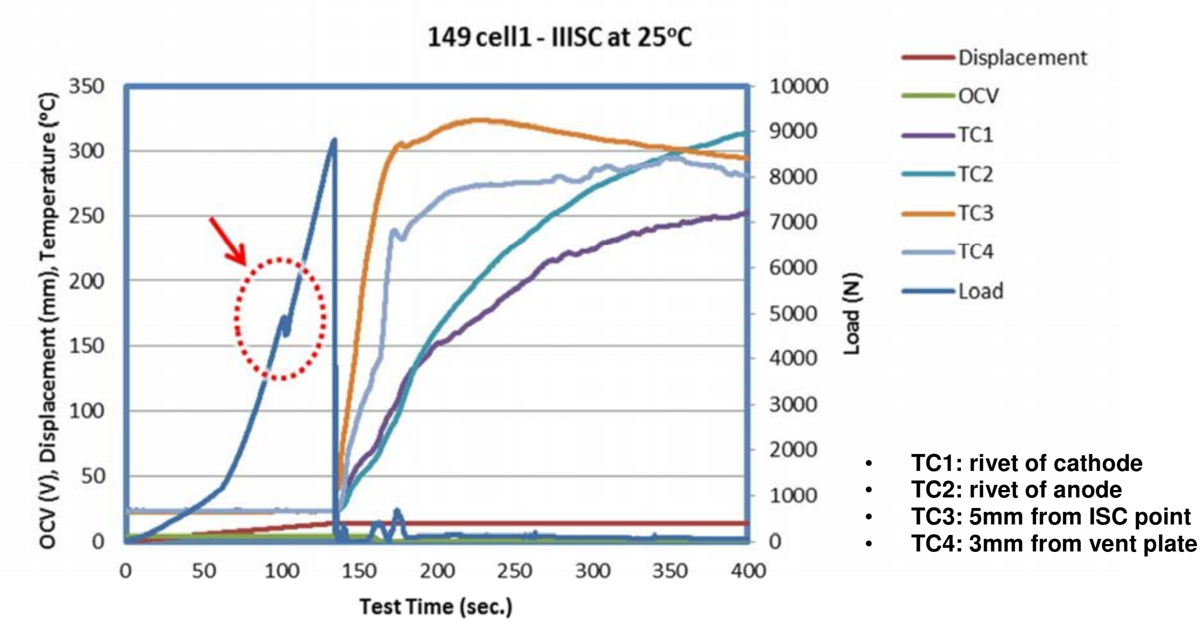


Figure 19. Cell voltage, cell temperature, load and displacement profiles of IIISC test (Sample: 149-1)

The cell voltage and the load profiles are shown in Figure 20. We can observe the cell volatge drop occurs first (i.e. at 134.15s) and the drop in the load (i.e. 134.17s) right after. It demonstrates that the cell case was not penetrated by the indenter before the ISC is triggered.

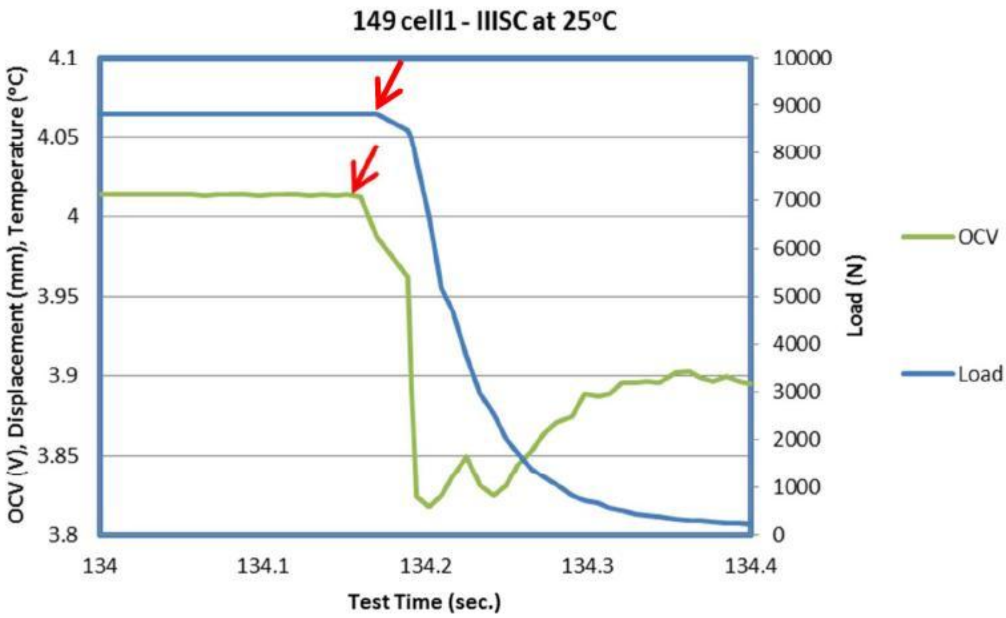


Figure 20. Cell voltage and load profiles of IIISC test (Sample: 149-1)

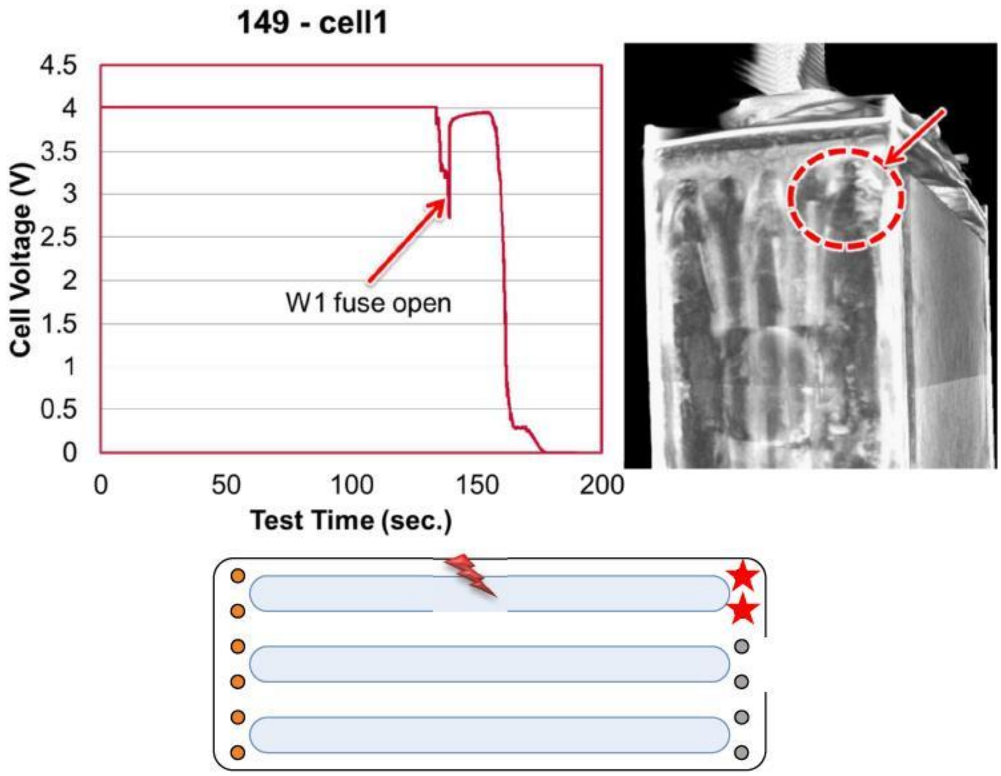


Figure 21. Cell voltage profile and the status of open fuse in IIISC test (Sample: 149-1)

In order to understand the implications of the voltage profile, the voltage measurements of the test sample 149-1 is shown in Figure 21. From the voltage profile, we can see a drop in cell voltage reading and it is then recovered sharply within few seconds, which shows the signal of open fuse in W1. In this case, the initial cell voltage is about 4.02V, which is about 100%SOC according to GS-Y's specification. After the open fuse in W1, cell voltage is recovered to about 3.95V, which is about 85%SOC. The time between the triggering of ISC and open fuse in W1 is about 5.1s. That is, the cell SOC decreases from 100% to 85% within 5.1s to cause the open fuse in W1. So the current to cause the melting in current collector in W1 can be roughly estimated as below:

$$\text{70Ah (Rate Capacity of LVP65 cell)} \times (100-85)SOC\% \times \frac{2}{3}(W2\ and\ W3\ to\ charge\ W1) = 7Ah$$

$$\frac{7Ah}{5.1s/3600s \cdot hr^{-1}} = 4941.2A$$

The calculated current, 4941.2A, is an estimated current for the W2 and W3 to charge W1 in order to balance the cell voltage as the 3 windings are connected in parallel. The value is far enough to cause the melting in aluminum current collectors in the cathode of LVP65 cell.

Some images are captured in Figure 22 form the video of IIIS test of sample 149-2. We can see the test cell swelling right after the ISC is triggered and the cell venting can also be observed.

Figure 22. Failure Mode observed in IIISC test (Sample: 149-1)

Figure 23 shows the cell voltage and load profiles for the IIISC test on sample 149-1. We can see the quick increase in load profile before open fuse in W1 and it will drop after W1 open fuse. The rise in load profile shows the expansion of winding due to thermal runaway. The first rise in load is apparently the thermal runaway of W1, where the second and third increase in load profile can be observed after the cell voltage gets to the second drop. The second and third peaks in load profile are likely the thermal runaway of W2 and W3 respectively.

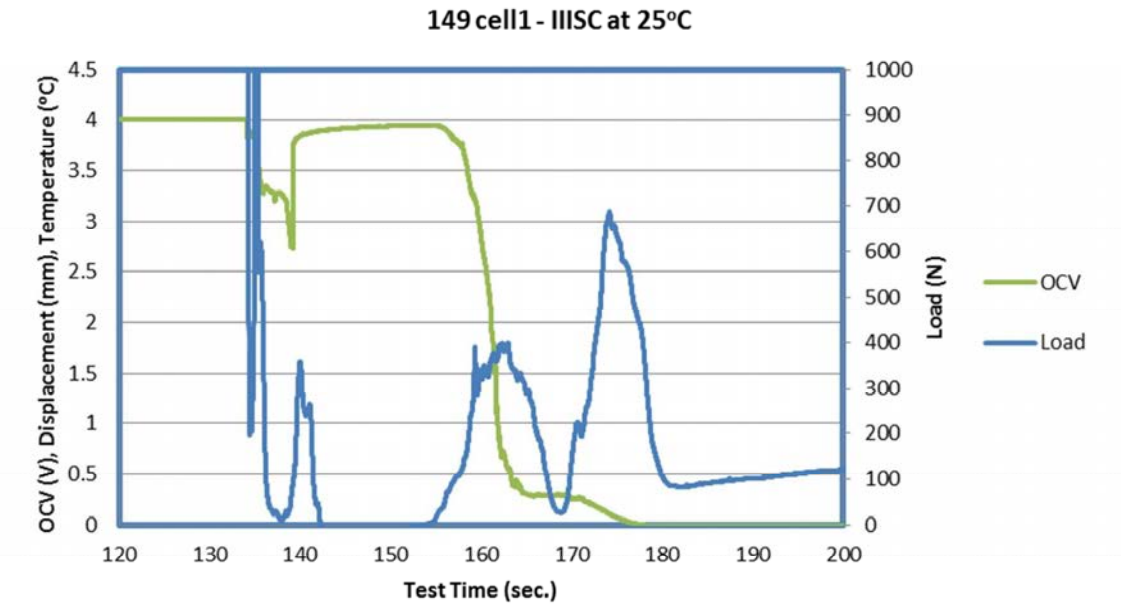


Figure 23 Cell voltage vs. load profiles of IIISC test (Sample: 149-1)

The pictures of tested sample 149-1 and the CT scan images are shown in Figure 24 . This sample is swollen after the ISC test and W1 is penetrated by the indenter because the indenter was kept at the location after the ISC was triggered. According to the appearance of tested sample, the vent plate is burned and the insulation material (i.e.[redacted]) between the rivet and terminals is melted and deformed.

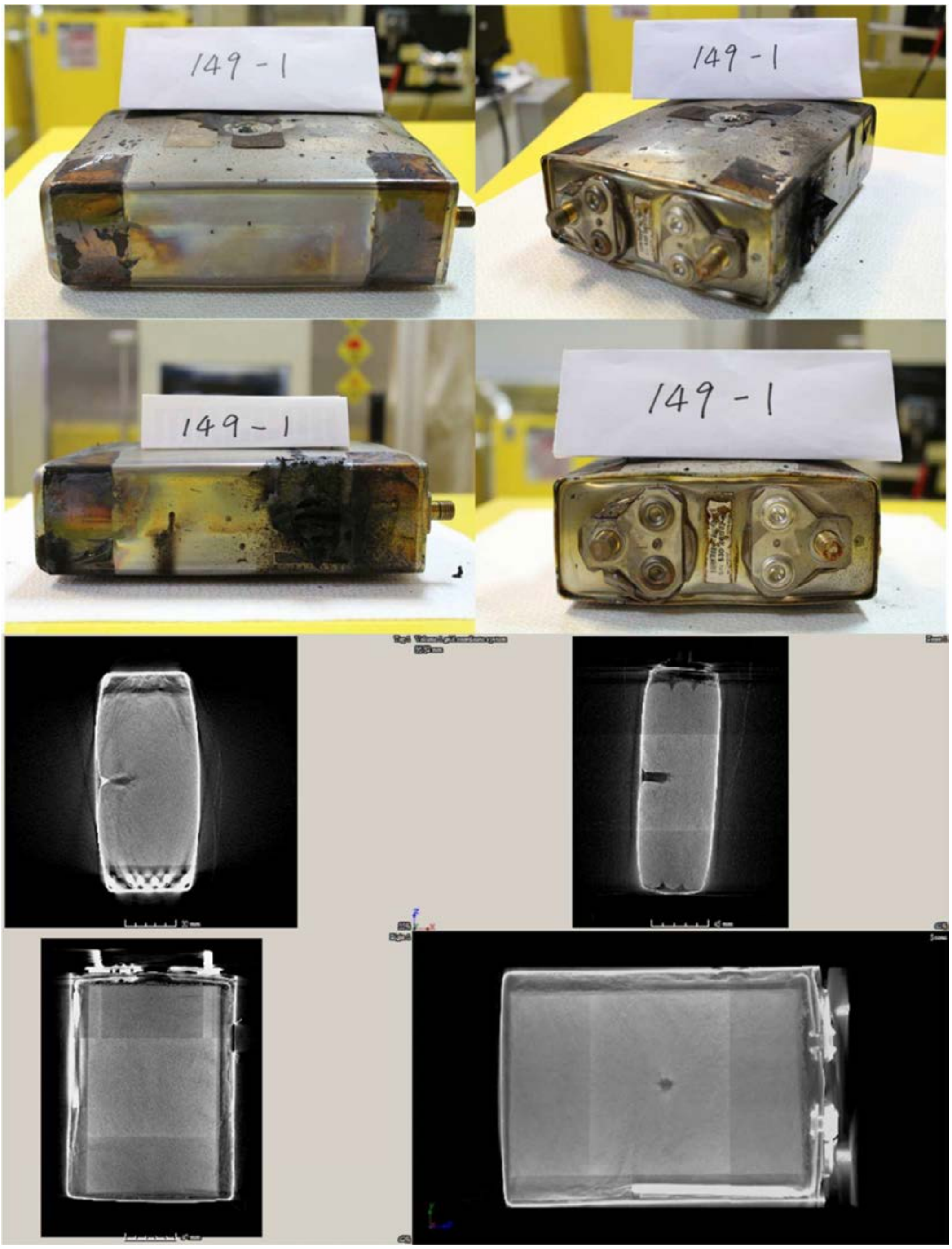


Figure 24. Appearance of tested sample and CT scan after IIISC test (Sample: 149-1)

#241-1: IIISC at 25℃

Similar to 149-1, for sample 241-2 tested by IIISC under 25ºC, it also shows the same behavior. The test results and profiles of all IIISC tests are shown in Figure 25 to Figure 29.

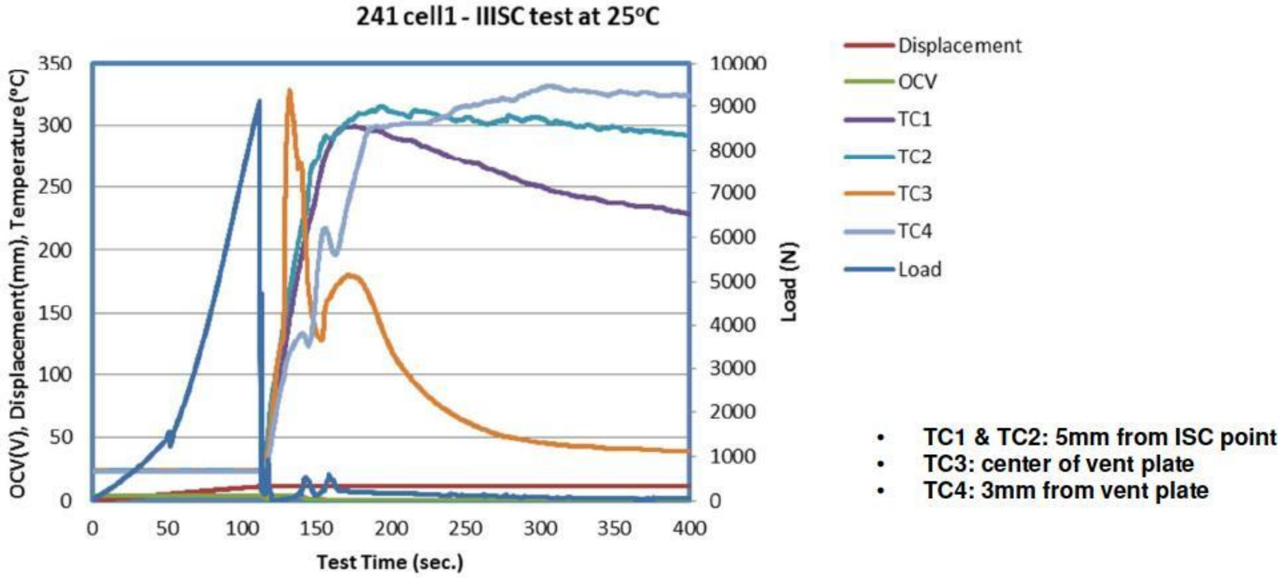


Figure 25. Cell voltage, cell temperature, load and displacement profiles of IIISC test (Sample: 241-1)

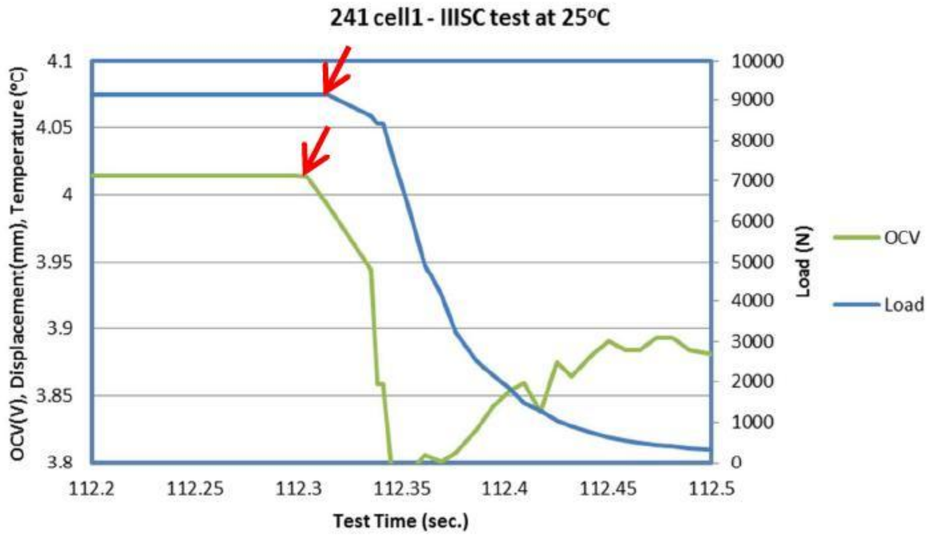


Figure 26. Cell voltage and load profiles of IIISC test (Sample: 241-1)

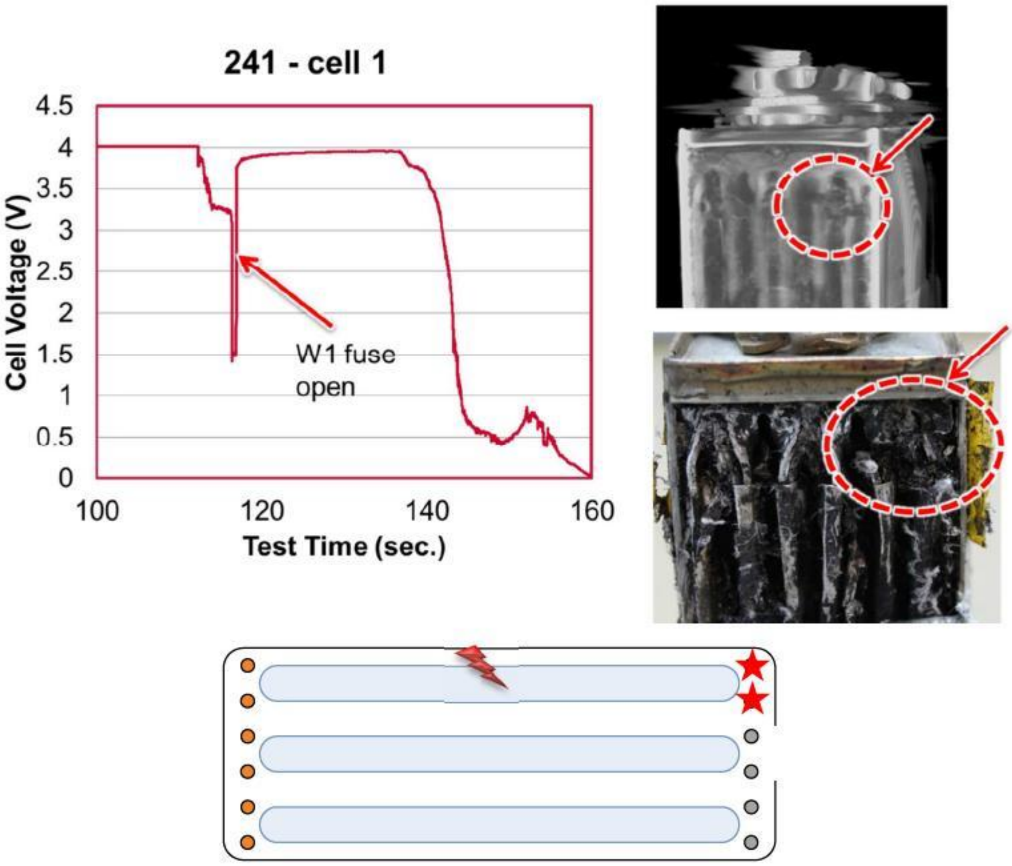


Figure 27. Cell voltage profile and the status of open fuse in IIISC test (Sample: 241-1)

Figure 28. Failure Mode observed in IIISC test (Sample: 241-1)

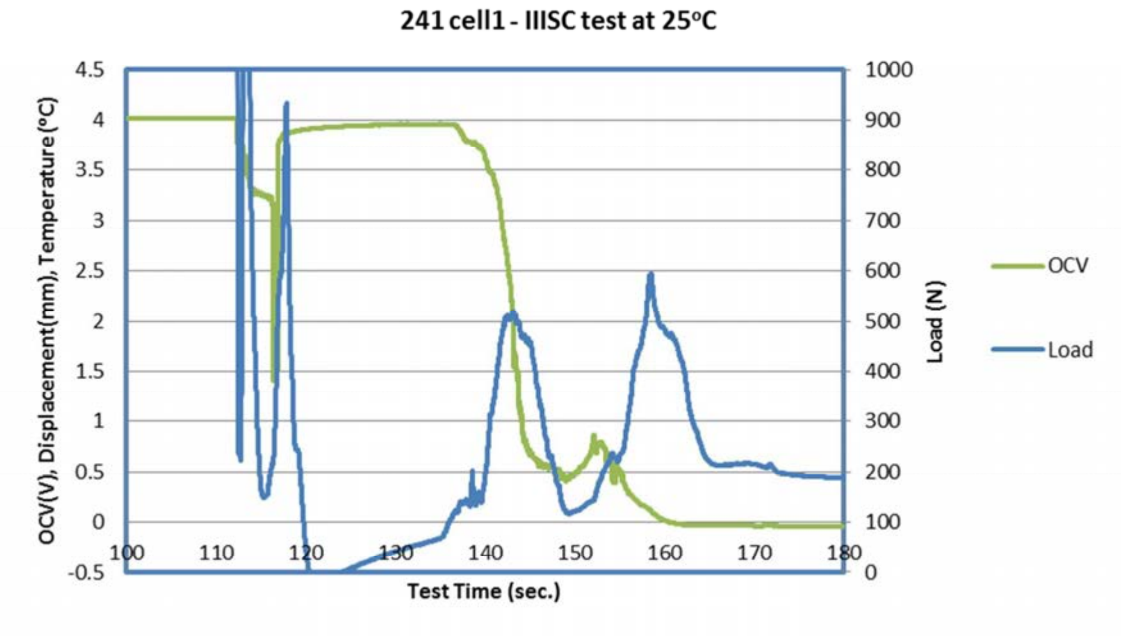


Figure 29. Cell voltage vs. Load profiles of IIISC test (Sample: 241-1)

The pictures of tested sample 241-1 and the CT scan images are shown in Figure 30. This sample is swollen after the ISC test and W1 is penetrated by the indenter because the indenter was kept at the location after the ISC was triggered. According to the appearance of tested sample, the vent plate is burned and the insulation material (i.e. [redacted] between the rivet and terminals is melted and deformed.

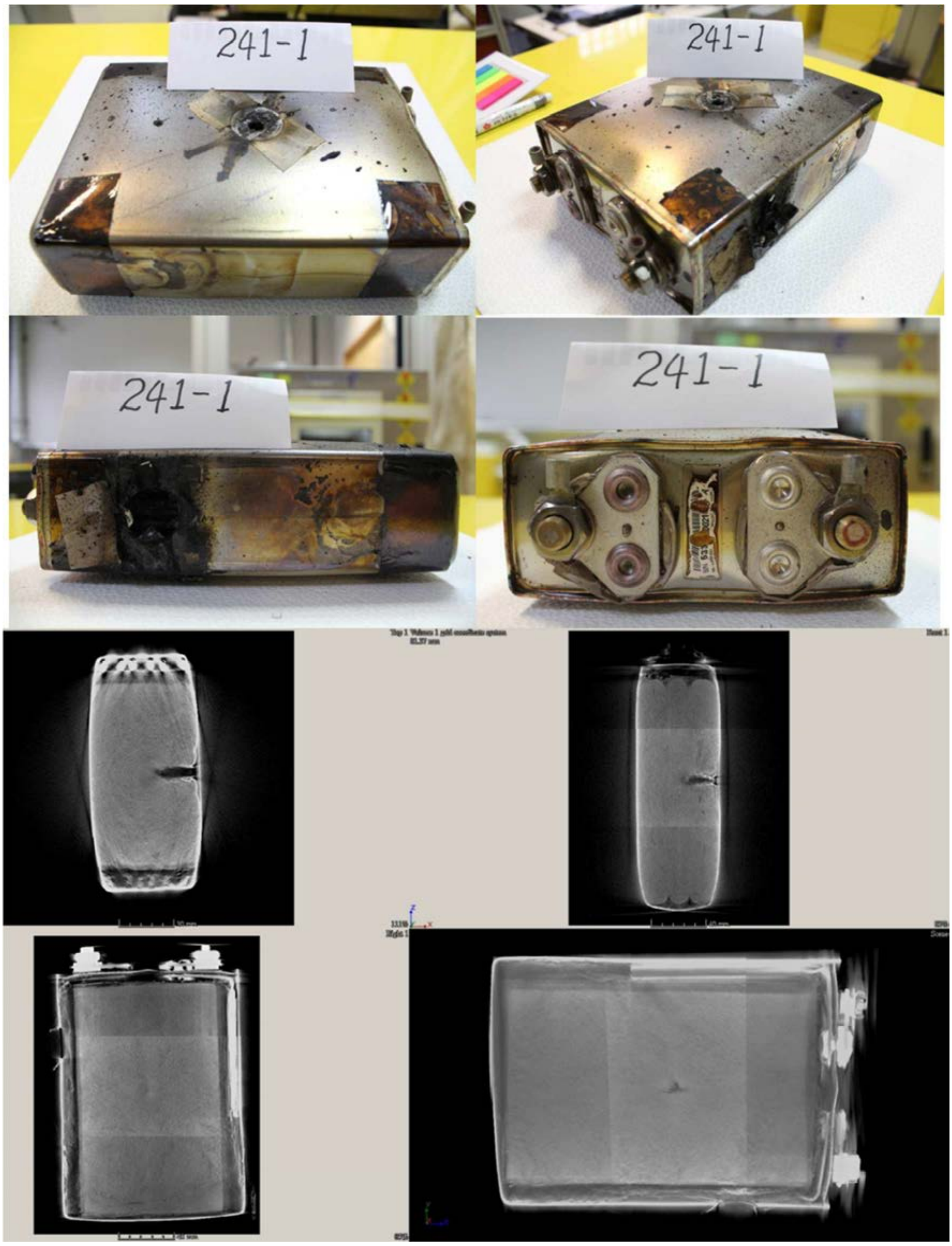


Figure 30. Appearance of tested sample and CT scan after IIISC test (Sample: 241-1)

#149-2: IIISC at 70 ℃

Figure 31 to Figure 36 show the detailed data profiles, status of open fuse, and appearance of tested sample and the CT scan images of sample 149-2 for IIISC test under 70 ℃.

The cell behavior is also very similar to the IIISC test at 25 ℃, but the overheating rate is faster. The open fuse can only be observed in W1.

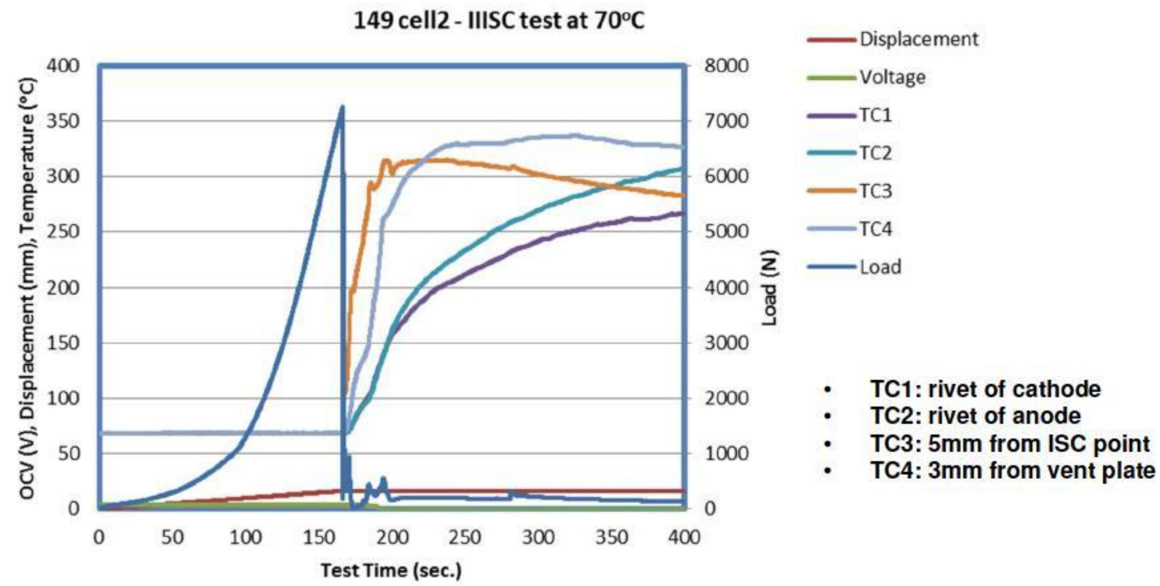


Figure 31. Cell voltage, cell temperature, load and displacement profiles of IIISC test (Sample: 149-2)

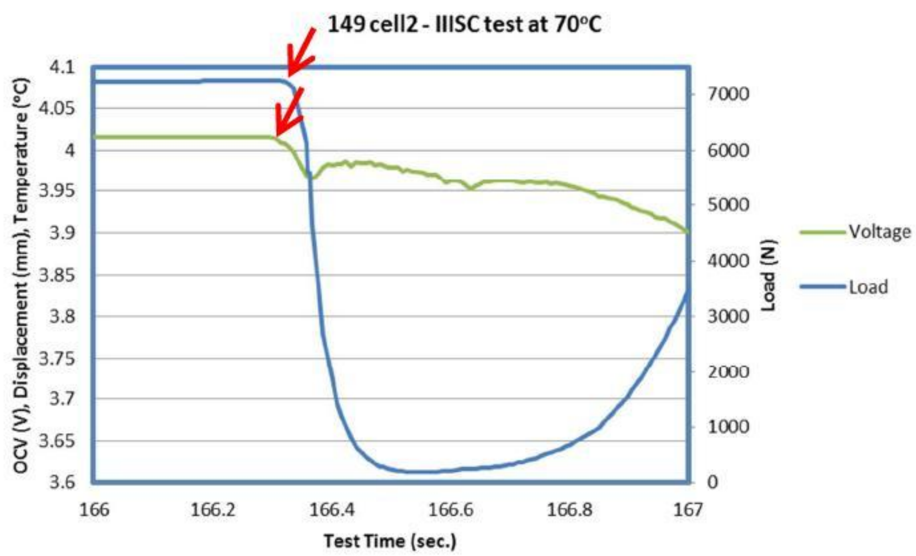


Figure 32. Cell voltage and Load profiles of IIISC test (Sample: 149-2)

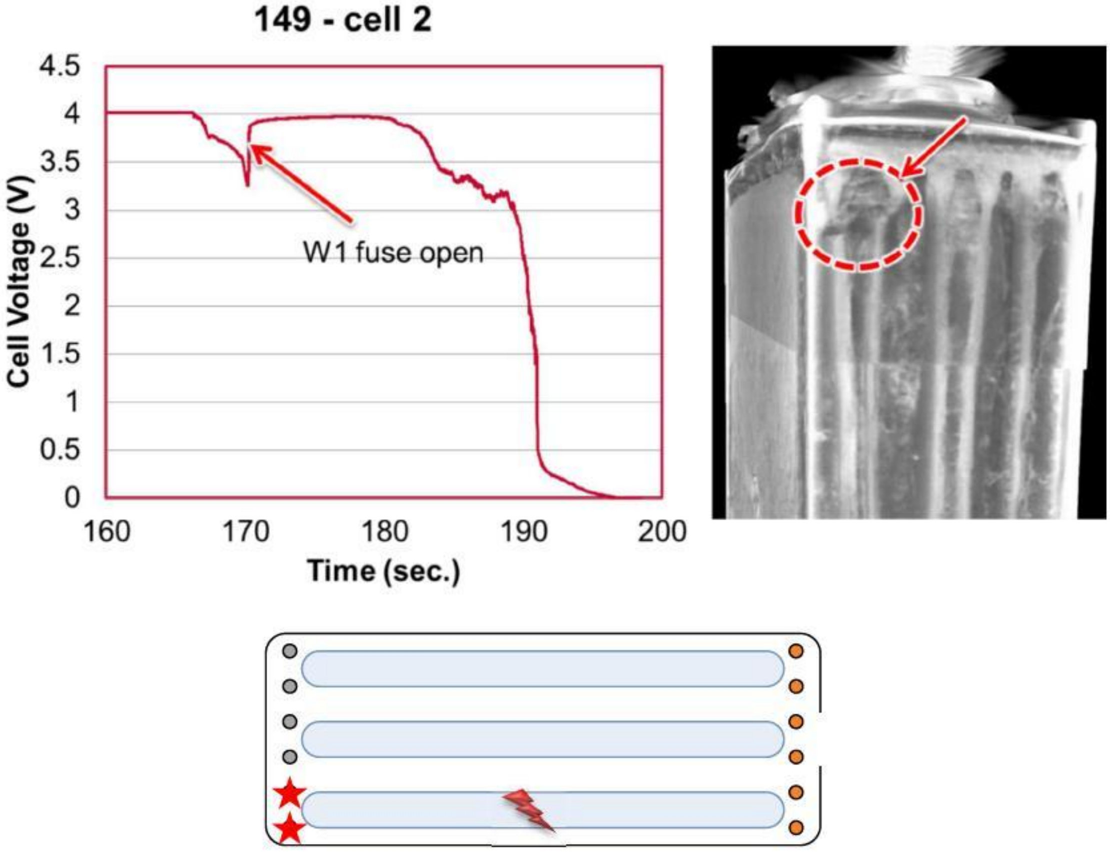


Figure 33. Cell voltage profile and the status of open fuse in IIISC test (Sample: 149-2)

Figure 34. Failure mode observed in IIISC test (Sample: 149-2)

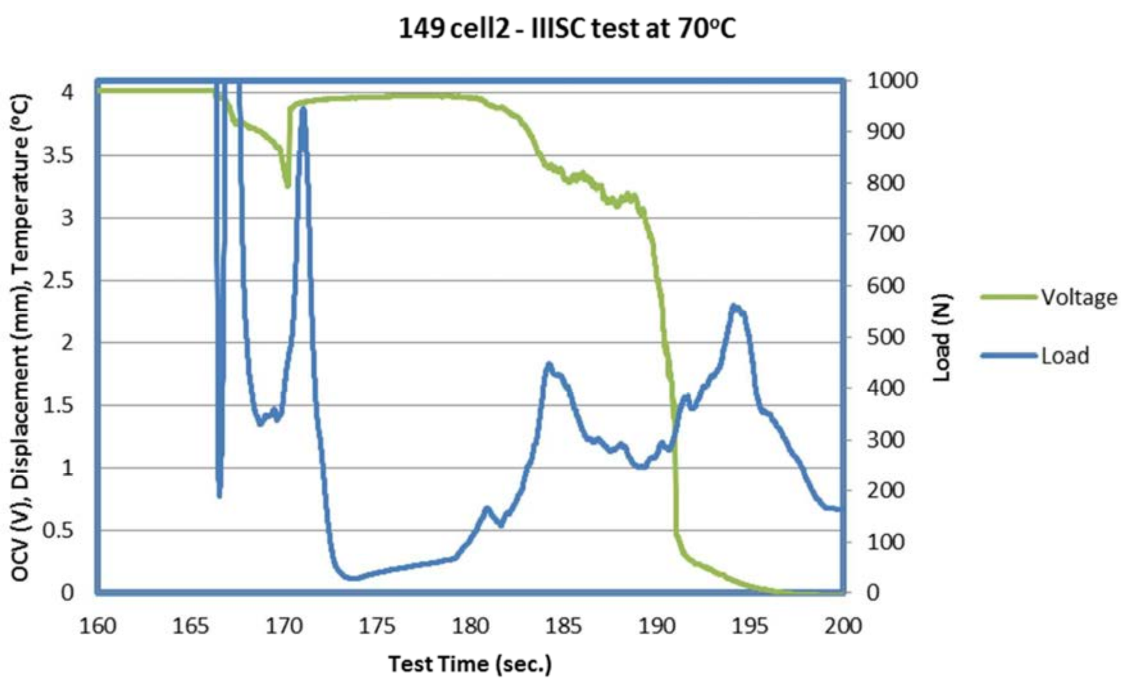


Figure 35. Cell voltage vs. Load profiles in IIISC test (Sample: 149-2)

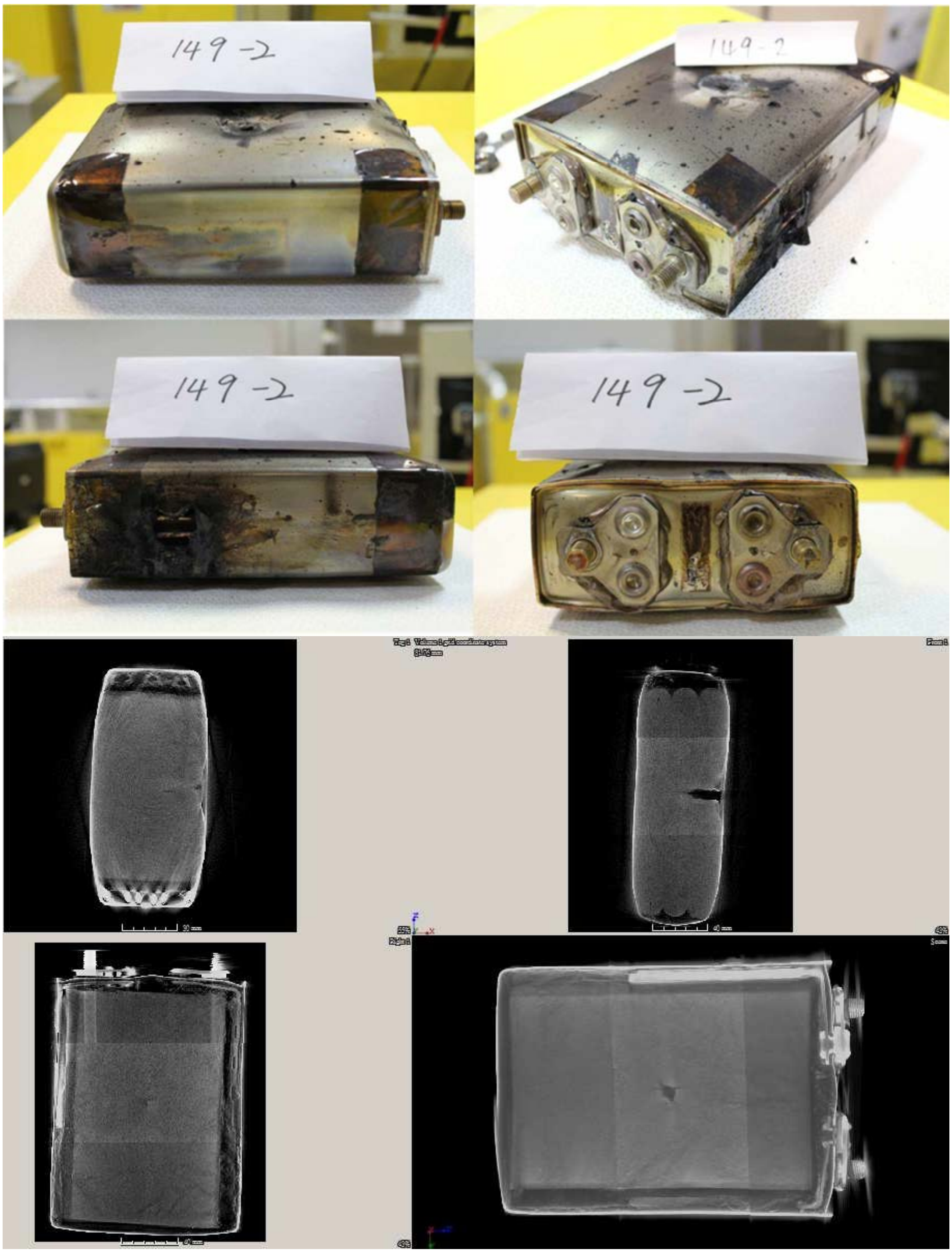


Figure 36. Appearance of tested sample and CT scan after IIISC test (Sample: 149-2)

#241-2: IIISC at 70℃

Figure 37 to Figure 42 show the detailed data profiles, status of open fuse, appearance of tested sample and the CT scan images of sample 241-2, which is the second test for IIISC under 70℃. The cell behavior is also very similar to the IIISC at 25℃ but the overheating rate is faster. Besides, the open fuse can be observed at both W1 and W2. Under a higher test temperature, the IIISC test can cause more fuses to open. It's likely that the W2 got an ISC due to the overheating propagated from W1 before the trigger of material decomposition chain reaction in W2.

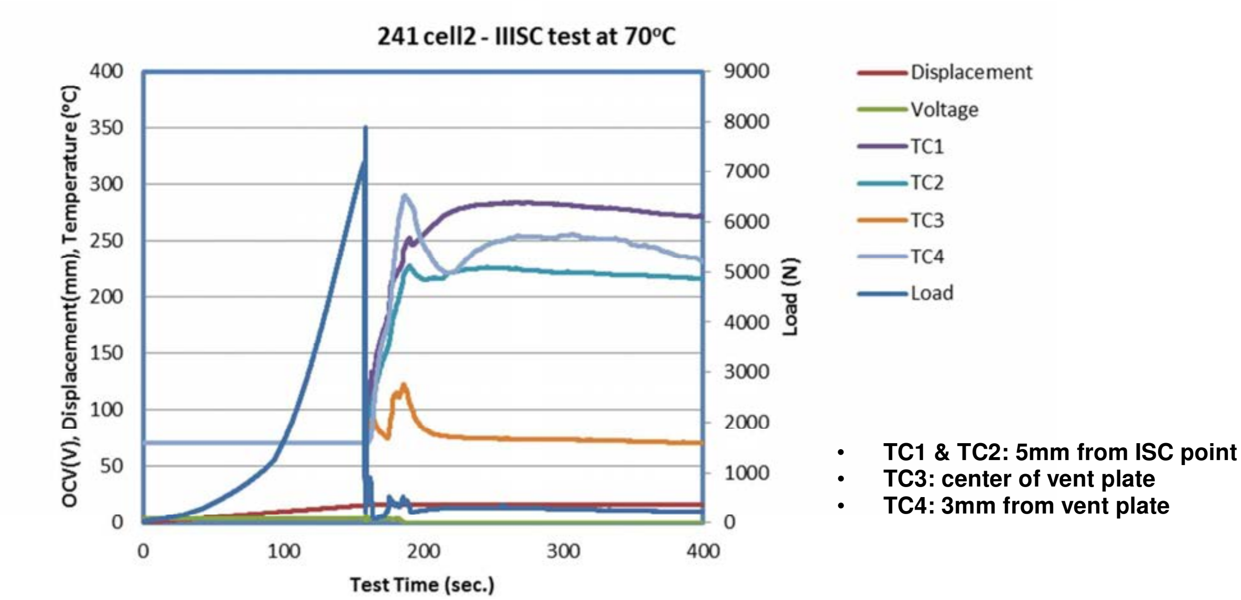


Figure 37. Cell voltage, cell temperature, load and displacement profiles of IIISC test (Sample: 241-2)

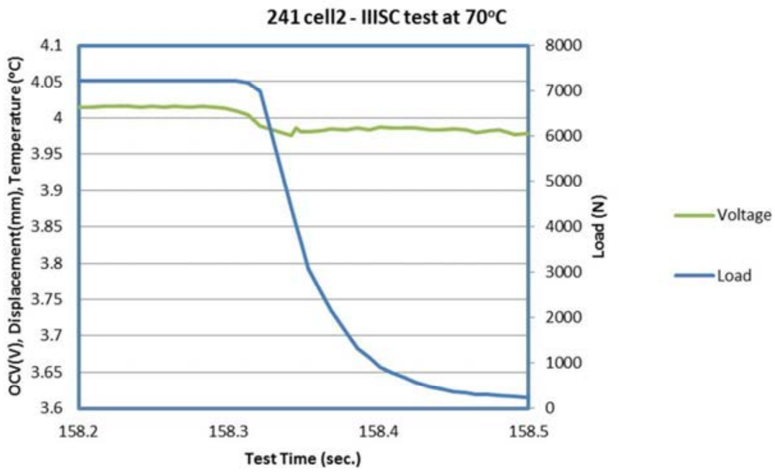


Figure 38. Cell voltage and load profiles of IIISC test (Sample: 241-2)

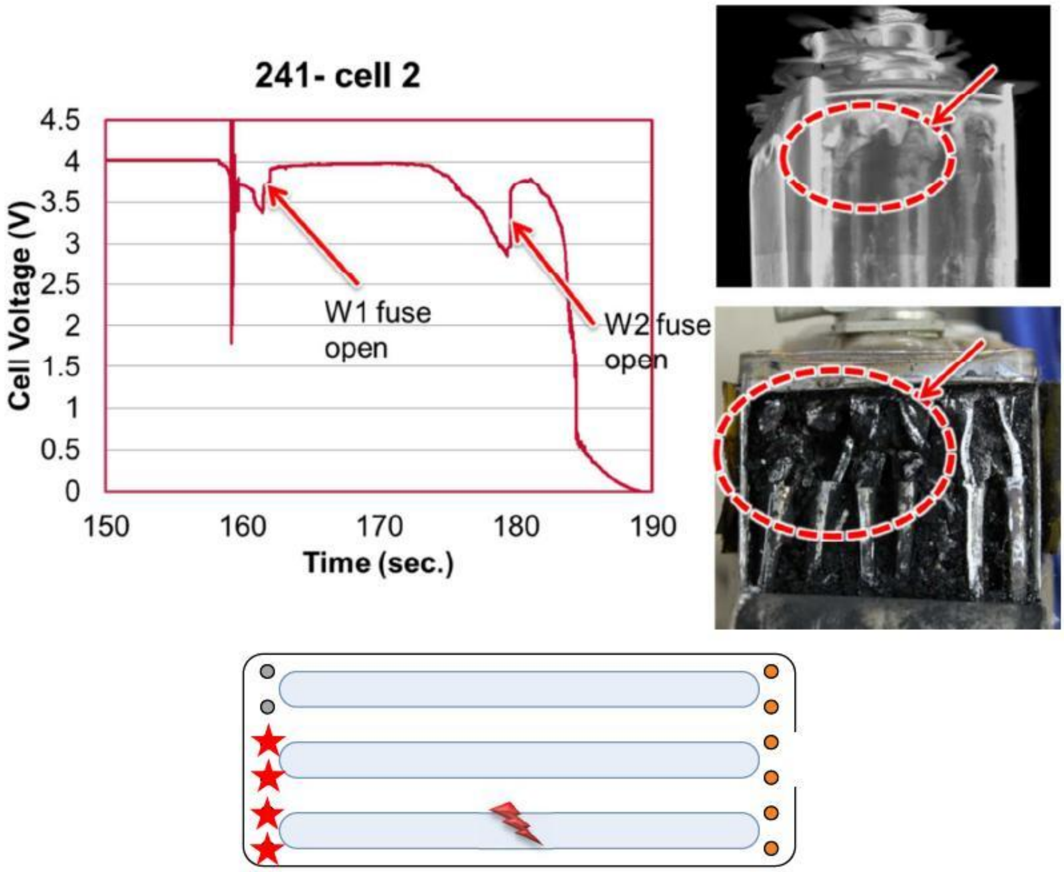


Figure 39. Cell voltage profile and the status of open fuse of IIISC test (Sample: 241-2)

Figure 40. Failure mode observed in IIISC test (Sample: 241-2)

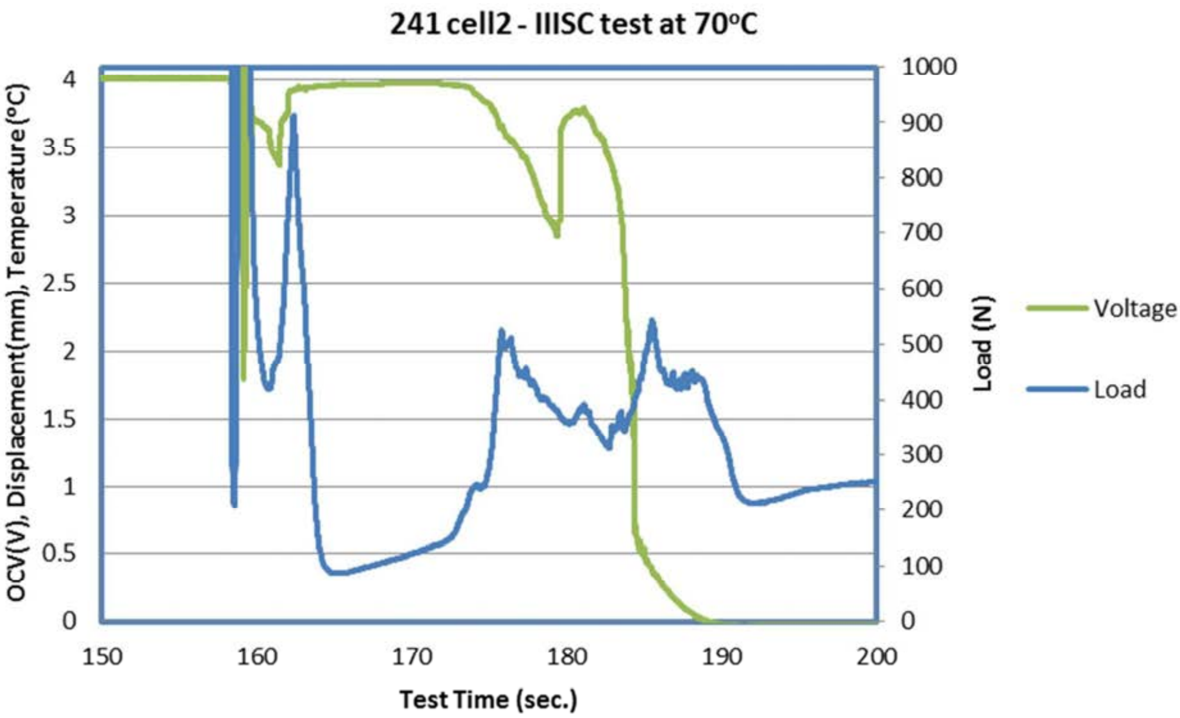


Figure 41. Cell voltage vs. load profiles of IIISC test (Sample: 241-2)

Figure 42 Appearance of tested sample and CT scan after IIISC test (Sample: 241-2)

NP test

The test results of side-penetrated and top-penetrated NP tests at both 25℃ and 70℃ are summarized in Table 3. In side-penetrated NP tests, the maximum temperature can be detected around vent plate, which is located at the narrow side of LVP65 cells. For top-penetrated test, most of the maximum temperature can be detected at NP point, which is the center of cell head. Comparing to the maximum temperature in IIISC tests, which are between 305℃ and 366℃, the maximum temperature is 409℃ on sample 241-3 for top-penetrated NP test under 25℃. It is the highest among all as 241-3 is the only cell to catch fire during the test[19].

Table 3. Summary of NP tests on LVP65 Cells

Test	Side-Penetrated NP test		Top-penetrated NP test	
Sample	149-3 241-4	149-4 241-5	149-5 241-3	149-6 241-6
Condition	25°C	70°C	25°C	70°C
Test Result	Venting, Smoke	Venting, Smoke	Venting, Smoke (149-5) **Fire (241-3)**	Venting, Smoke
Max T*1	305°C 340°C	366°C 330°C	314°C **409°C**	325°C 346°C
Max T near vent	305°C 242°C	366°C 330°C	193°C 290°C	292°C 231°C
Max T at Indenter/Nail/Pad	271°C 340°C	264°C 242°C	314°C 355°C	325°C 346°C
Time from ISC to Max Vent T (seconds)	141.8 70.5	149 16.6	52.6 26.9	38.1 19.4
Open fuse?	W1 (149-3) W1 (241-4)	W1 and W2 (149-4) W1 (241-5)	None (149-5) None (241-3)	W2 (149-6) None (241-6)
Note	For Top-penetrated NP test, cell top casing usually got more deformation that will cause more noise on cell voltage reading.			

Note*1: Maximum temperature on cell may not present the severity of test result as the temperature variation is affected largely by failure modes so the locations of maximum temperature may differ

There is no obvious difference in heating rate when comparing the NP test results between 25℃ and 70℃. For side-penetrated NP tests, 3 out of 4 cells have open fuse in W1 and only one has open fuse

[19] During the test on 241-3, the suddenly pressure increase due to thermal runaway has opened the door of the chamber and followed by a fire in the chamber.

in both W1 and W2, which is under 70℃. It may imply the higher testing temperature may be more likely to have open fuse in two windings.

For top-penetrated NP tests, the only cell to have open fuse is 149-6, which is tested under 70℃, and the opened fuse is W2. In all the tests conducted by this project, top-penetrated NP is the only test that generates open fuse in W2 only. The reason is because it is the only test that starts the ISC in W2.

#149-3: Side NP at 25℃

Figure 43 shows the recorded data for sample 149-3, which is the side-penetrated NP test conducted under 25°C. Among the temperature profiles, the locations near to the ISC point and vent plate (i.e. TC3 and TC4) show similar and the fastest response of temperature rise. That means the test sample got ISC triggered and vent almost at the same time as the ISC reaction is extremely fast under side-penetrated NP test. That might be because that nail has become part of the circuit in the ISC reaction that will provide a low impedance ISC condition. Therefore in this case, the electrochemistry reaction in side-penetrated NP test is faster comparing to an IIISC test.

In a side-penetrated NP test, the thermal runaway is too fast so that we are not able to observe clearly the propagation of overheating from the ISC point to vent plate.

Figure 44 shows the cell voltage and load profiles. Unlike the behavior we could observe in an IIISC test, we cannot tell the sequence of heat propagation in the 3 windings as there is no apparent peak in load profile can be observed.

Figure 45 shows the cell voltage and the status of open fuse in test sample 149-3. It also shows a quick drop in cell voltage reading and sharp recovery due to the open fuse in W1. And the second drop in cell voltage is likely the thermal runaway of W2 and W3 after the thermal runaway of W1.

Figure 46 shows the images captured form the video of 149-3 test. Similar to IIISC test, we can clearly see the swelling of the cell right after the ISC is triggered and the cell vents at the same time.

The tested sample of 149-3 and the CT scan images are shown in Figure 47. The test sample is swollen after the ISC test and W1 is penetrated through by the nail because the nail was kept at the location after the ISC was triggered. According to the appearance of the sample, the vent plate is burned and the insulation material (i.e. [redacted]) between rivet to terminals is melted and deformed.

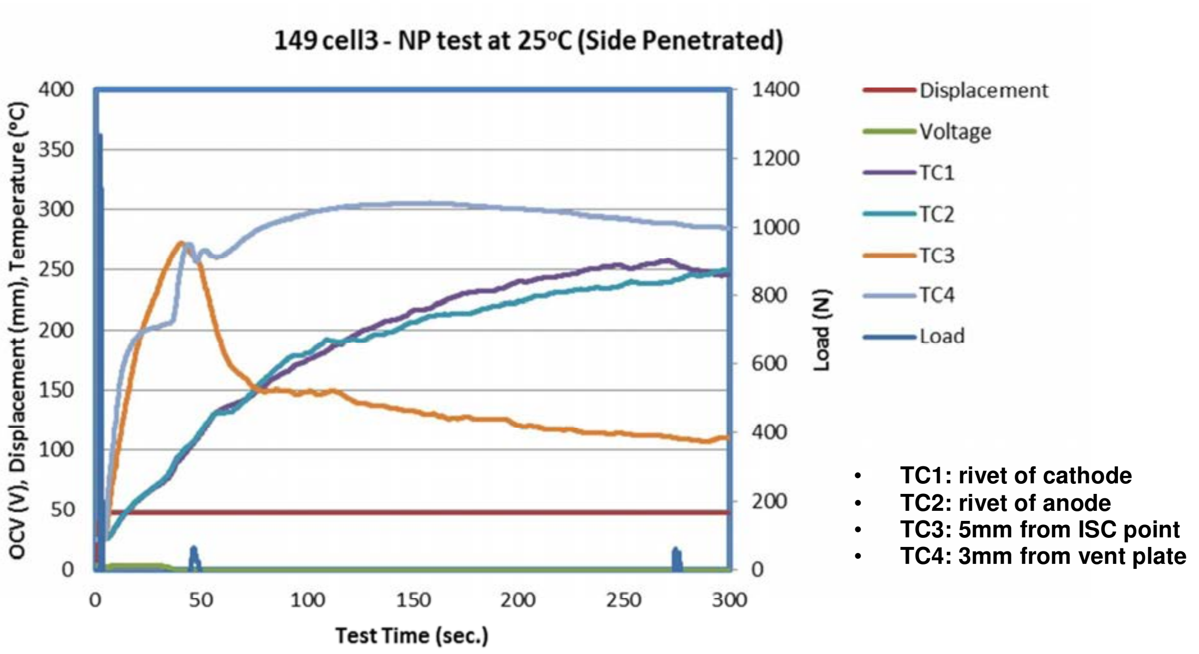


Figure 43. Cell voltage, cell temperature, load and displacement profiles in side-penetrated NP test (Sample: 149-3)

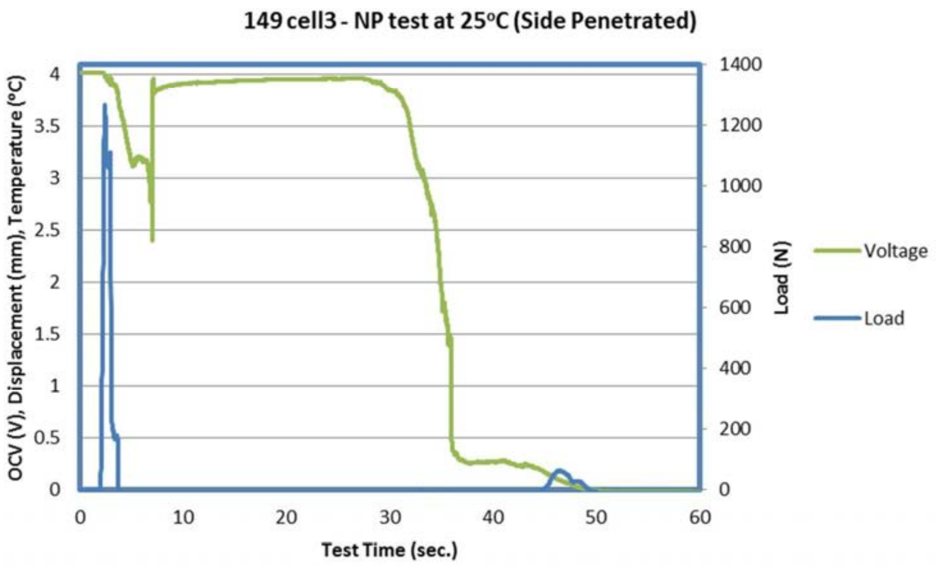


Figure 44. Cell voltage vs. load profiles in side-penetrated NP test (Sample: 149-3)

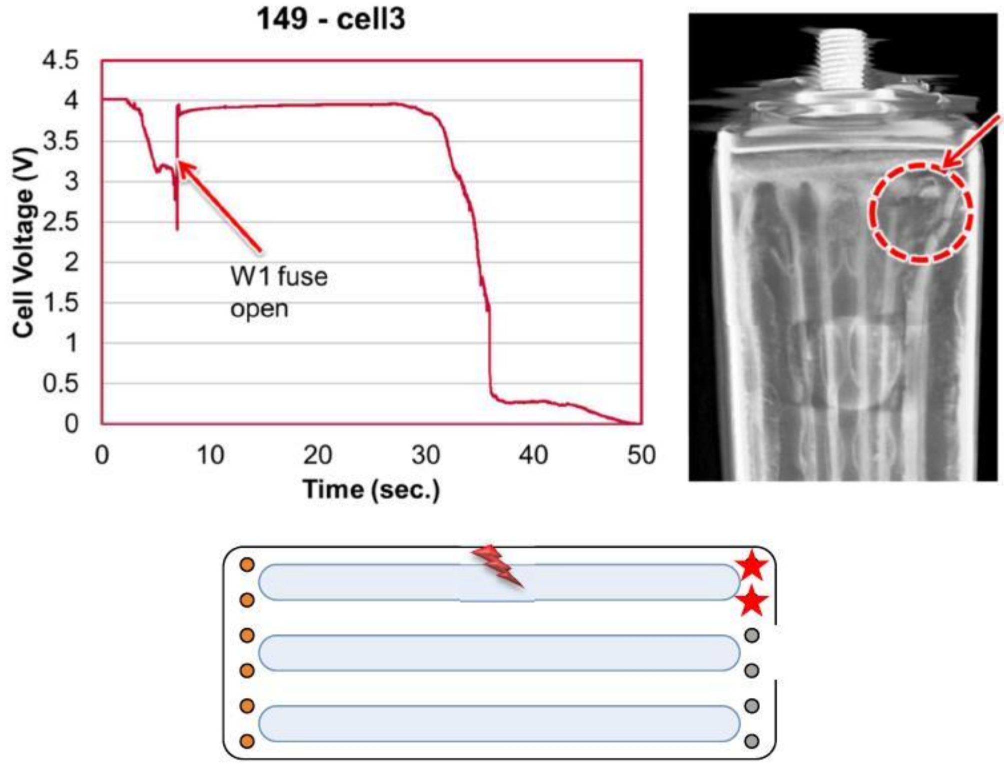


Figure 45. Cell voltage profile and the status of open fuse in side-penetrated NP test (Sample: 149-3)

Figure 46. Failure mode observed in side-penetrated NP test (Sample: 149-3)

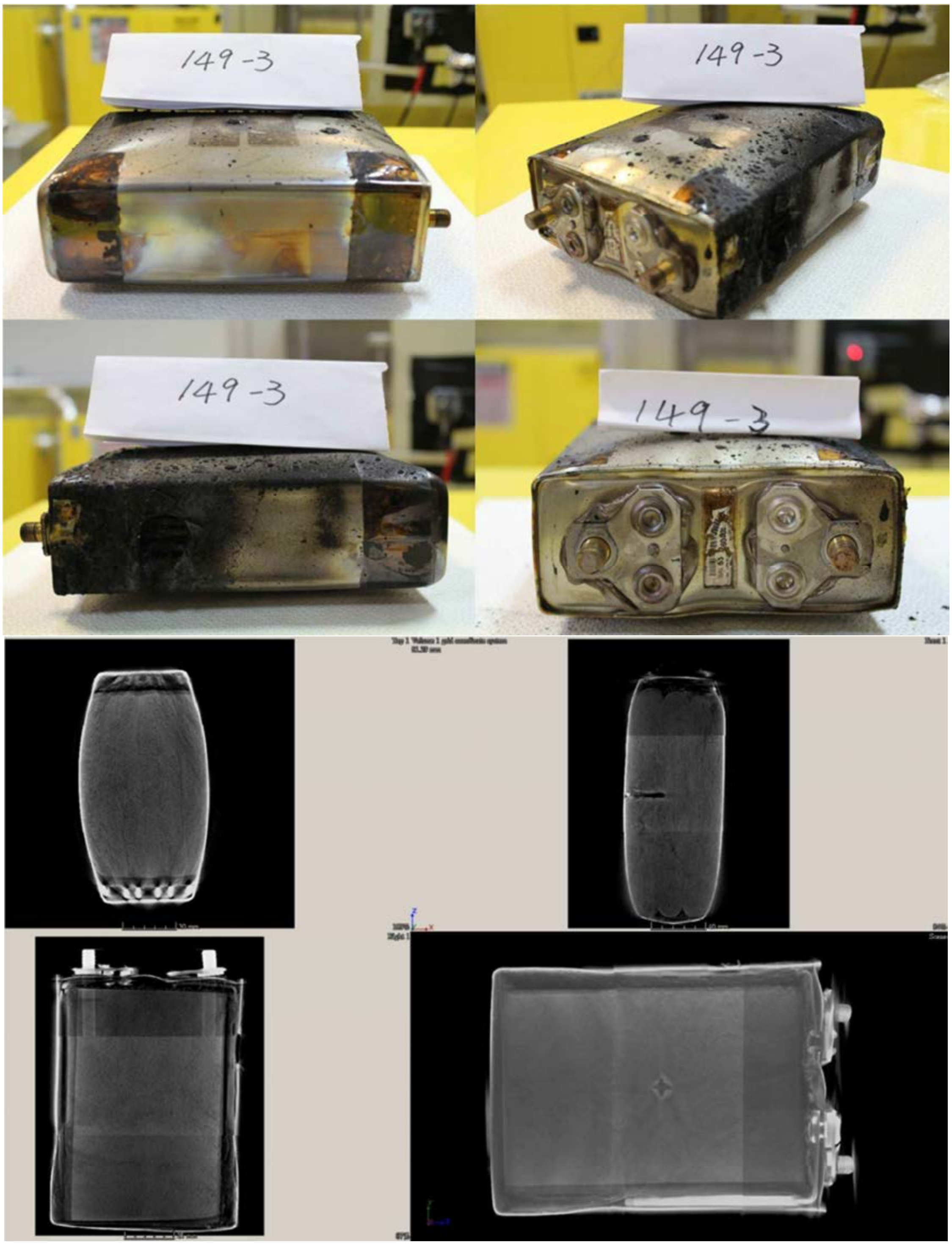


Figure 47. Appearance of tested sample and CT scan after side-penetrated NP test (Sample: 149-3)

#241-4: Side NP at 25℃

The data of sample 241-4 is shown in Figure 48, which is the side-penetrated NP test conducted under 25℃.

Among the temperature profile, the location near the ISC point (i.e. TC3) shows the fastest response of temperature rise. The heat is initially generated around ISC point then propagated to surrounding areas. This side-penetrated NP test is more similar to an IIISC test and it also shows more test variations in NP test as the 2 samples (i.e. 149-3 and 241-4) for side-penetrated NP test have more variations in temperature profiles.

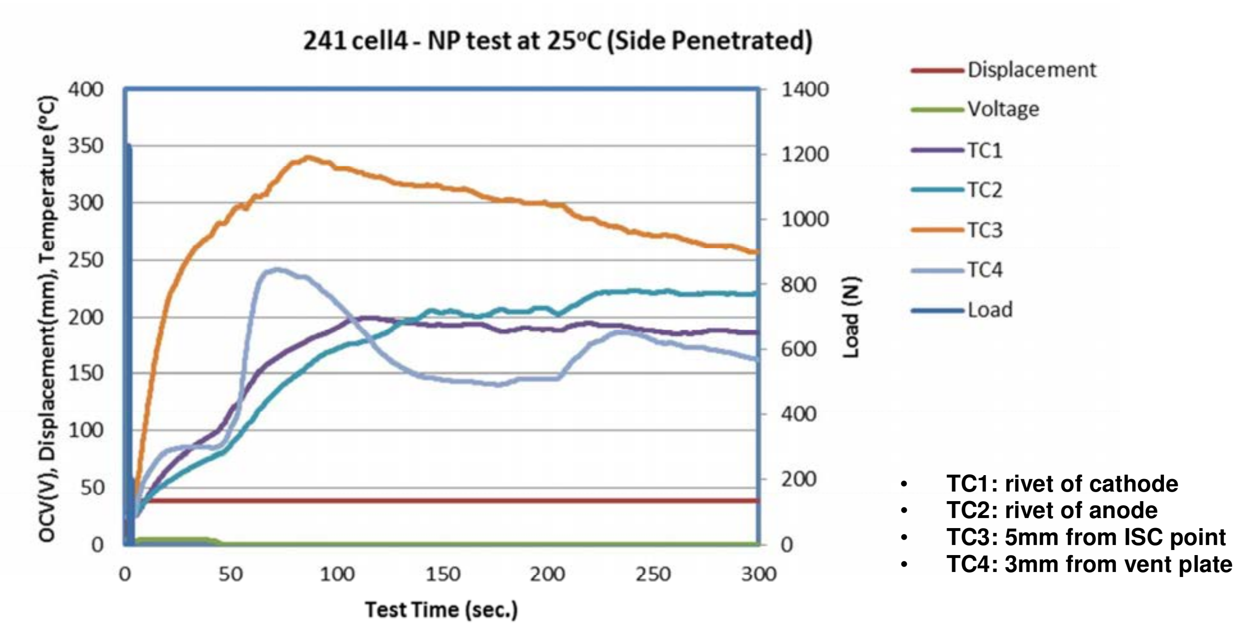


Figure 48. Cell voltage, cell temperature, load and displacement profiles in side-penetrated NP test (Sample: 241-4)

Figure 49 to Figure 52 are the cell voltage versus load data profiles, status of open fuse, appearance of tested sample and the CT scan images of sample 241-4. The test results are similar to previous test sample (149-3) and open fuse is also observed in W1 only.

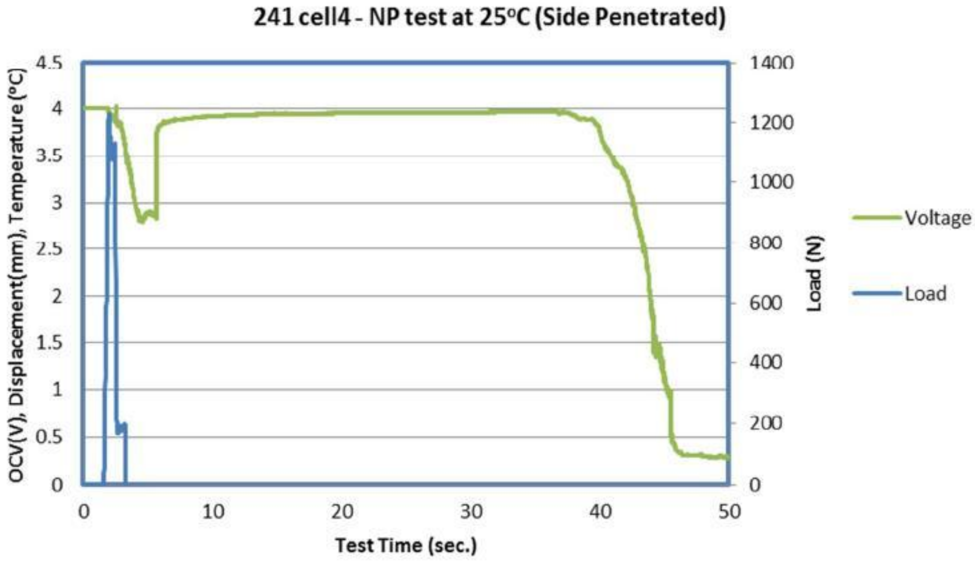


Figure 49. Cell voltage vs. Load profiles in side-penetrated NP test (Sample: 241-4)

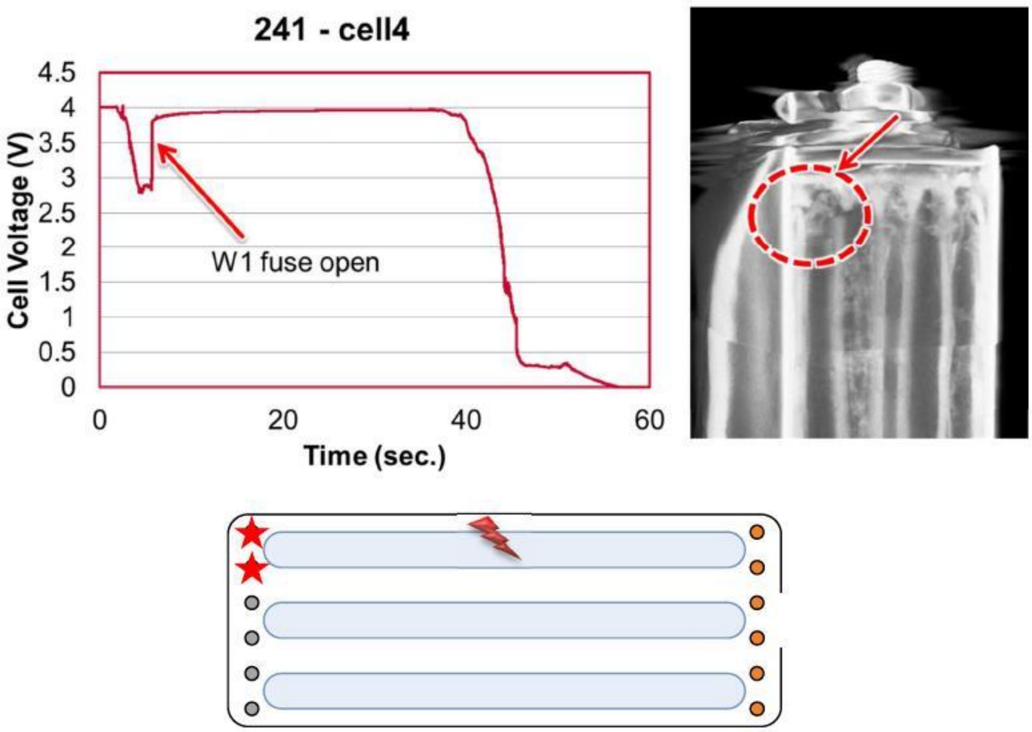


Figure 50. Cell voltage profile and the status of open fuse in side-penetrated NP test (Sample: 241-4)

Figure 51. Failure mode observed in side-penetrated NP test (Sample: 241-4)

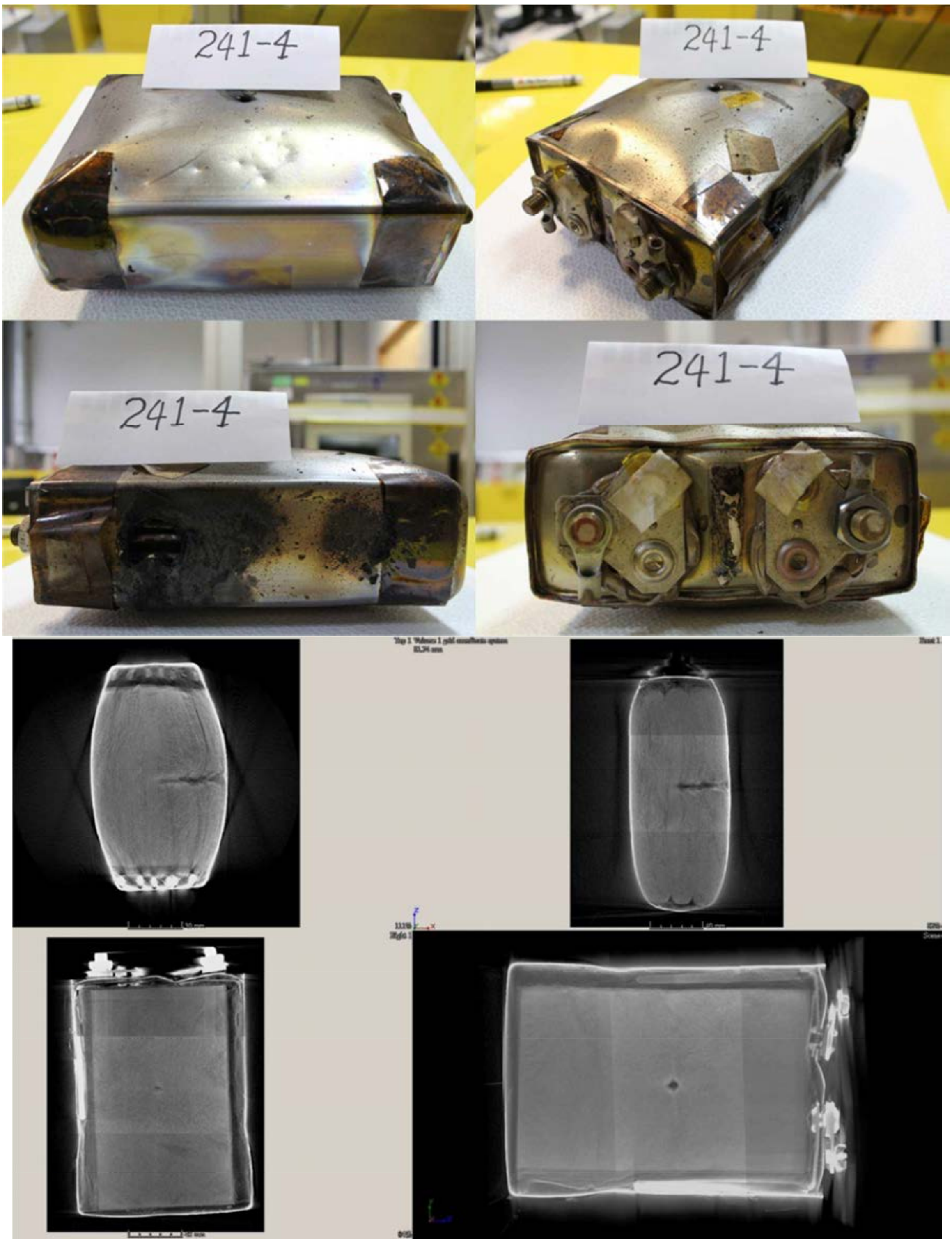


Figure 52. Appearance of tested sample and CT scan after side-penetrated NP test (Sample: 241-4)

#149-4: Side NP at 70℃

The data of sample 149-4 is shown in Figure 53, which is the side-penetrated NP test conducted under 70℃.

In the temperature profile, the location near the ISC point (i.e. TC3) shows the fastest response of temperature rise, which means the heat is initially generated around ISC point then propagates to surrounding areas. This side-penetrated NP test is also more similar to an IIISC test.

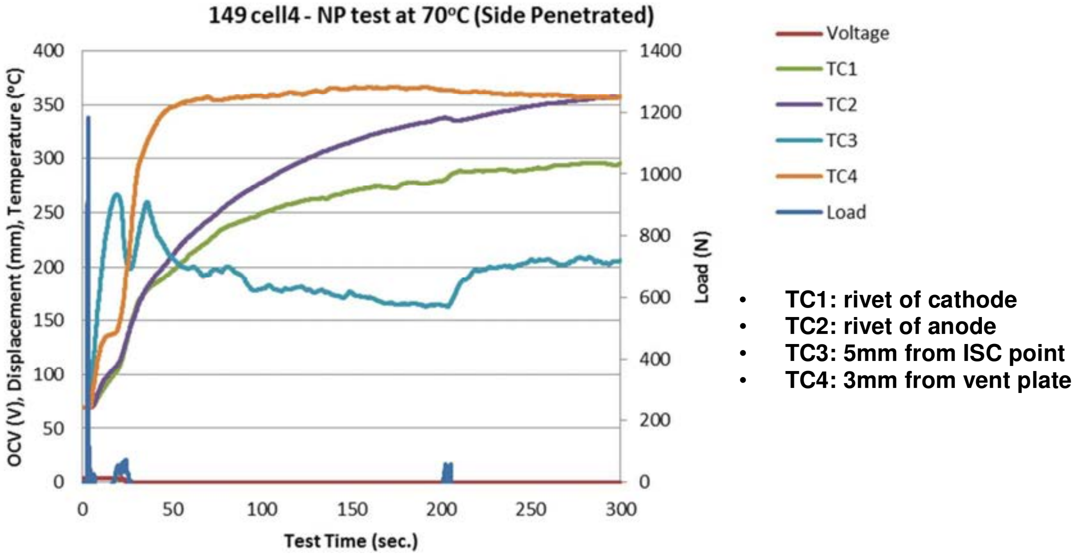


Figure 53. Cell voltage, cell temperature, load and displacement profiles in side-penetrated NP test (Sample: 149-4)

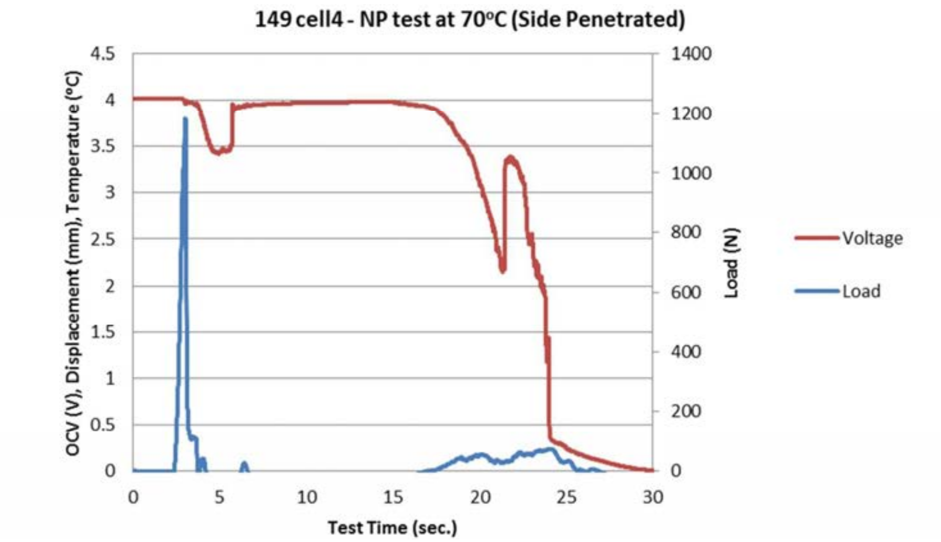


Figure 54. Cell voltage vs. load profiles in side-penetrated NP test (Sample: 149-4)

The cell voltage versus load profile is shown in Figure 54. In this test, we can observe the increase in load when the cell got voltage drop due to the trigger of ISC. Figure 55 shows that there are fuses open in both W1 and W2. Similar to other samples, the test cell also got swelling and venting after the occurrence of ISC. The failure mode, the appearance and the CT scan images of the tested sample, 149-4, are shown in Figure 56 and Figure 57.

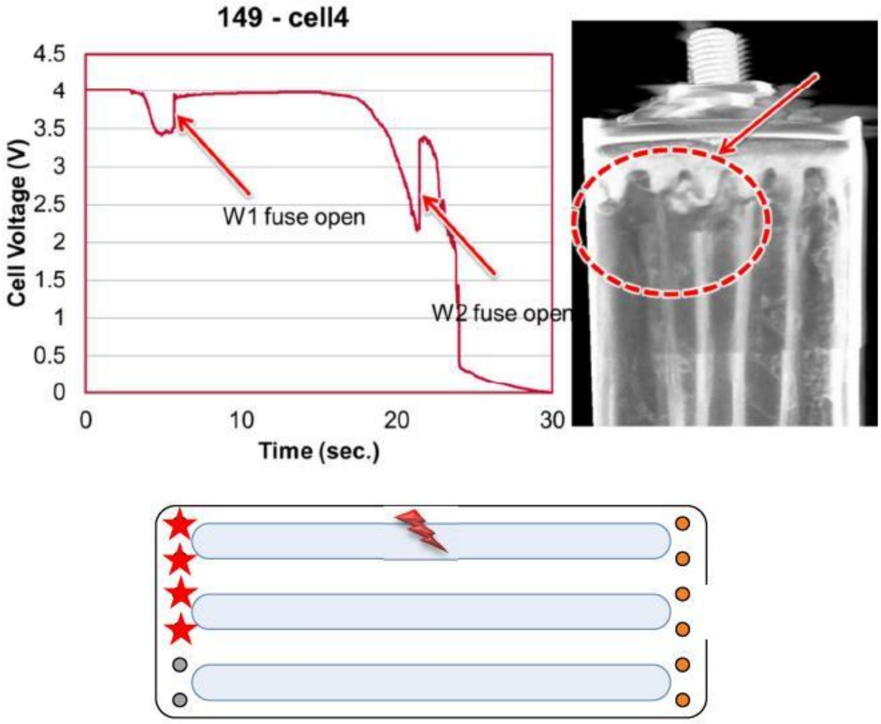


Figure 55 Cell voltage profile and the status of open fuse in side-penetrated NP test (Sample: 149-4)

Figure 56 Failure Mode observed in side-penetrated NP test (Sample: 149-4)

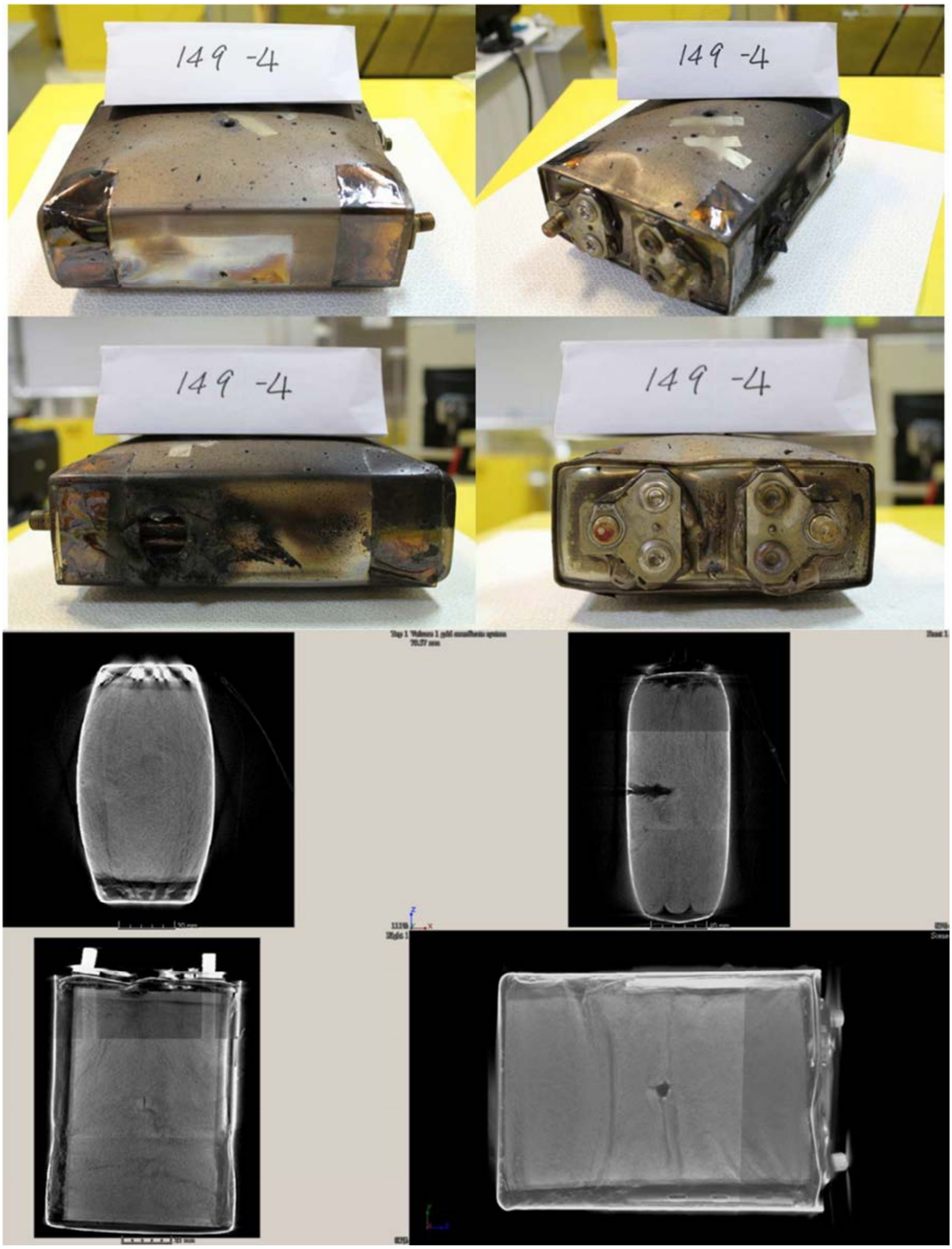
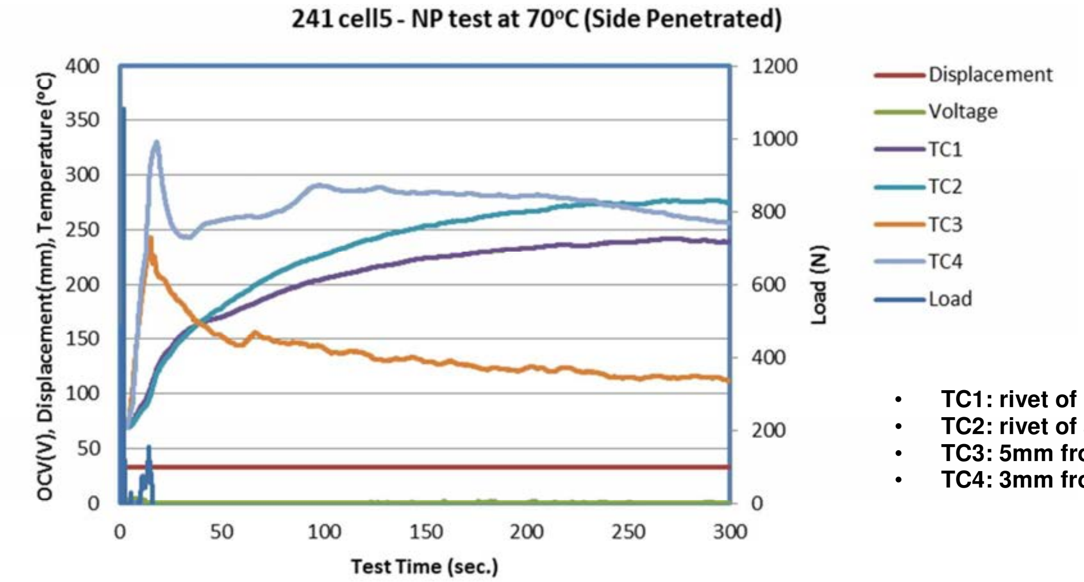


Figure 57. Appearance of tested sample and CT scan after side-penetrated NP test (Sample: 149-4)

#241-5: Side NP at 70℃

Figure 58 to Figure 62 show the detailed data profiles, status of open fuse, appearance of tested sample and the CT scan images of sample 241-5, which is the second test sample for side-penetrated NP under 70℃. The cell behavior is also very similar to other samples in side-penetrated NP tests. In this case, the open fuse can be observed in W1 only.



- TC1: rivet of cathode
- TC2: rivet of anode
- TC3: 5mm from ISC point
- TC4: 3mm from vent plate

Figure 58. Cell voltage, cell temperature, load and displacement profiles in side-penetrated NP test (Sample: 241-5)

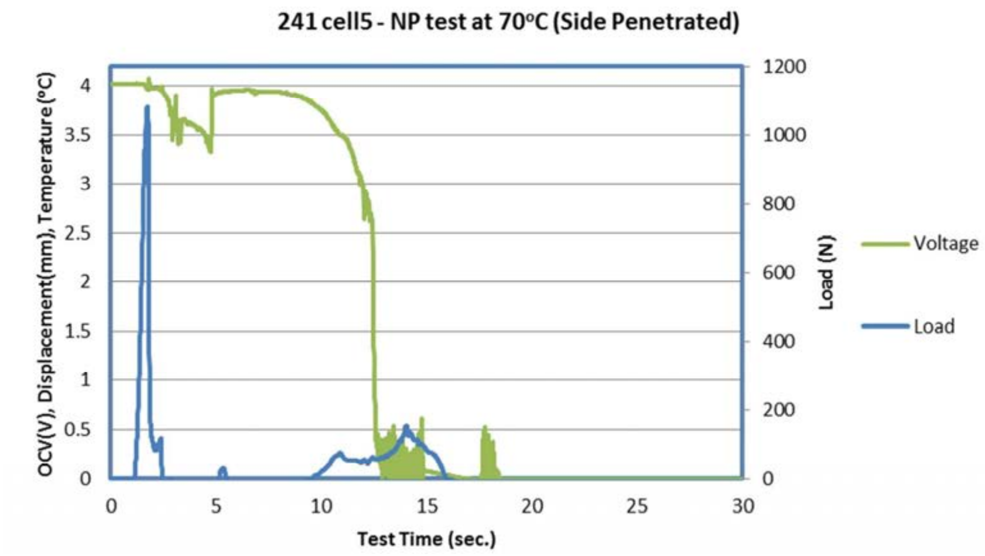


Figure 59. Cell voltage vs. load profiles in side-penetrated NP test (Sample: 241-5)

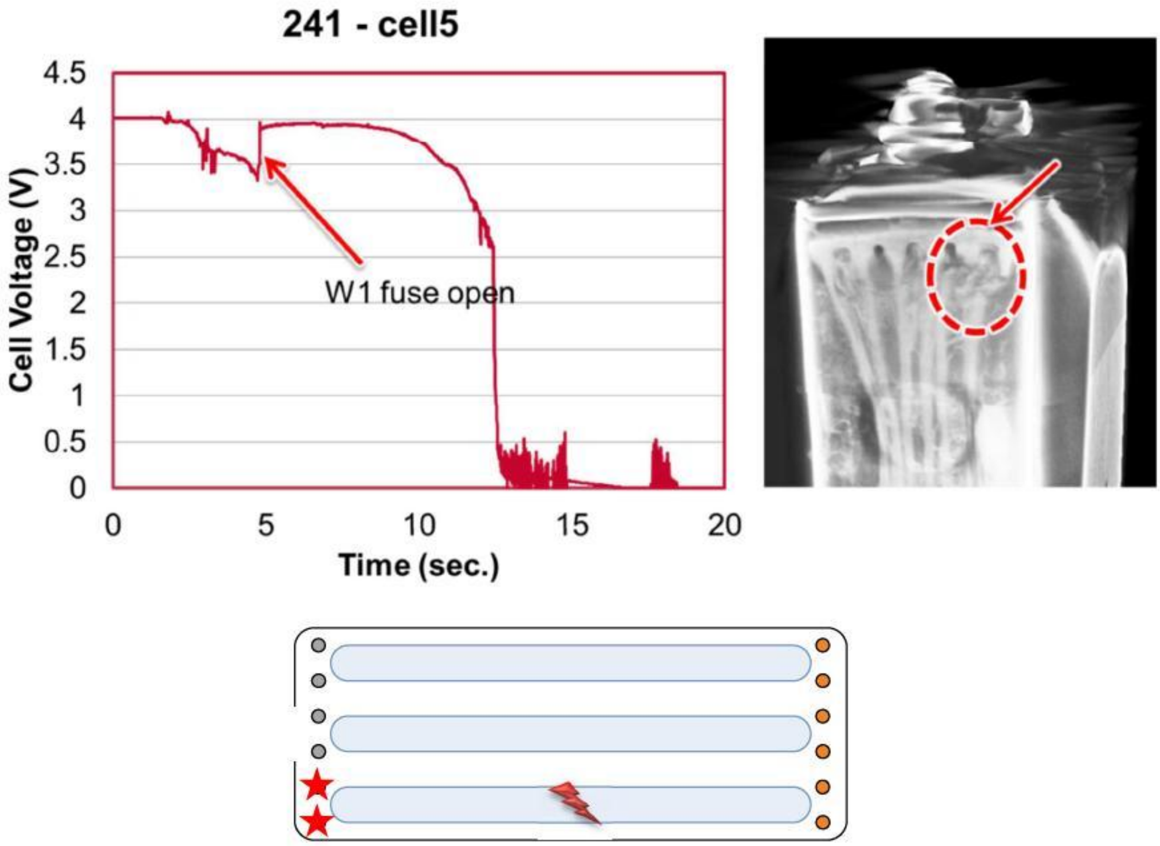


Figure 60. Cell voltage profile and the status of open fuse in side-penetrated NP test (Sample: 241-5)

Figure 61. Failure mode observed in side-penetrated NP test (Sample: 241-5)

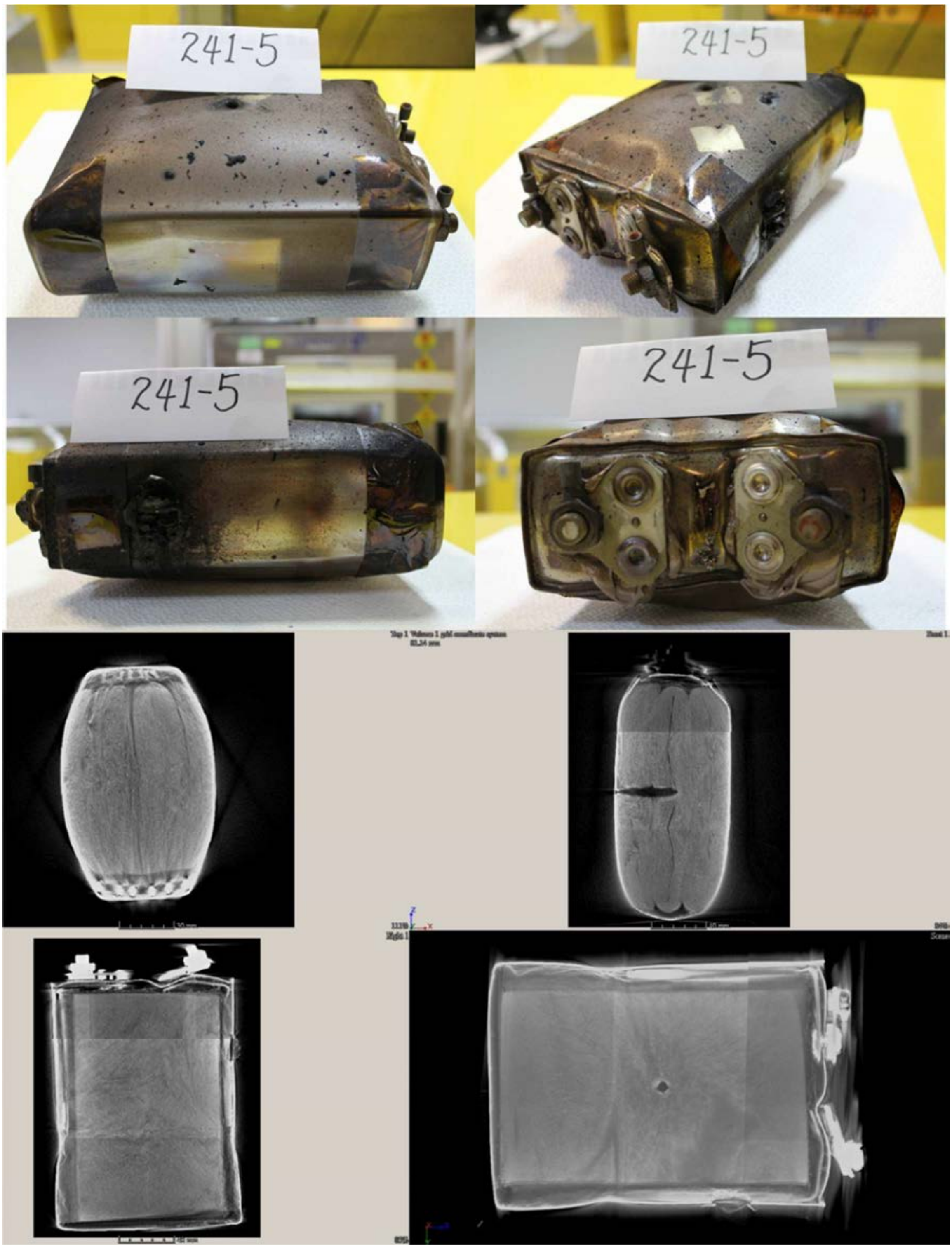


Figure 62. Appearance of tested sample and CT scan after side-penetrated NP test (Sample: 241-5)

#149-5: Top NP at 25℃

Figure 63 is the test result of sample 149-5, which is the top-penetrated NP test under 25℃. According to the temperature profile, only TC3 (i.e. the thermocouple attached next the penetration point) shows continuous high temperature. The temperature reading from other thermocouples (i.e. TC1, TC2 and TC4) shows a peak signal then decrease to below 100℃. That is probably because those thermocouples were blown off as the cell was swollen and deformed after the cell vented.

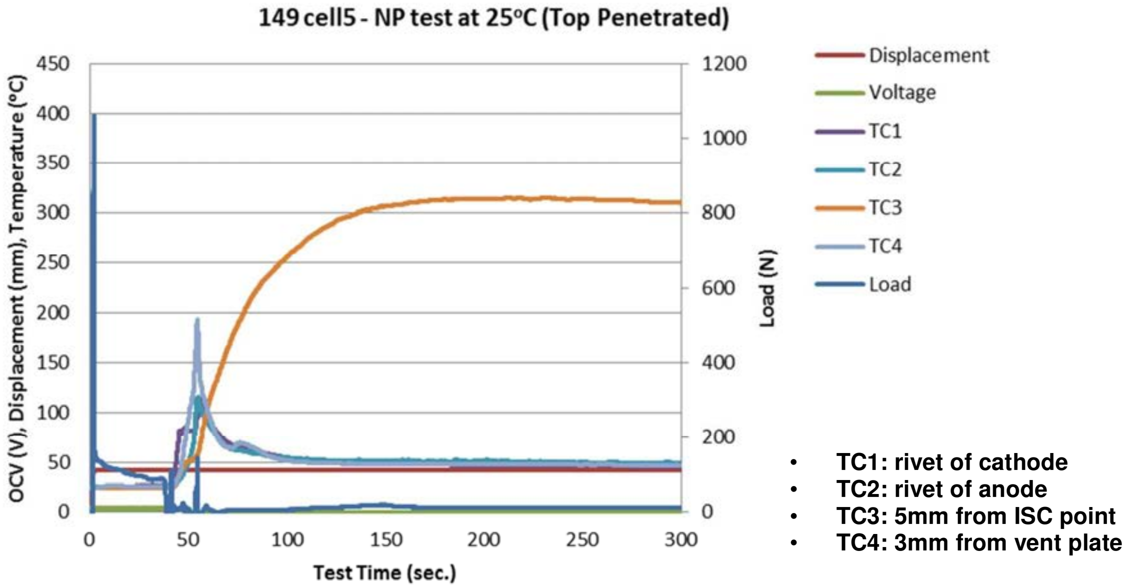


Figure 63. Cell voltage, cell temperature, load and displacement profiles in top-penetrated NP test (Sample: 149-5)

Figure 64 and Figure 65 show the cell voltage versus load profile and the status of current collector at cathode. We can see more noise in cell voltage reading because more deformatiin Was made on the cell head. Similar to the introduced earlier, we can also see the rise of load profile while cell voltage decreases due to ISC. There is no open fuse in this test.

In Figure 66 and Figure 67, we can see the failure mode, the appearance and CT scan images of tested sample, 149-5, after the top-penetrated NP test under 25˚C. Similar to the cases introduced previously, the cell vents and also has deformation and swelling after the test.

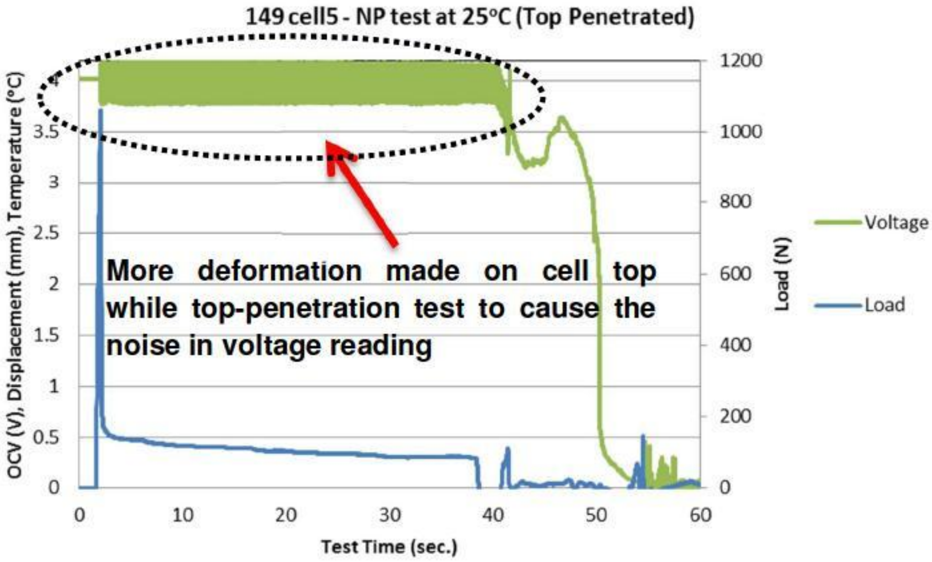


Figure 64. Cell voltage vs. Load profiles in top-penetrated NP test (Sample: 149-5)

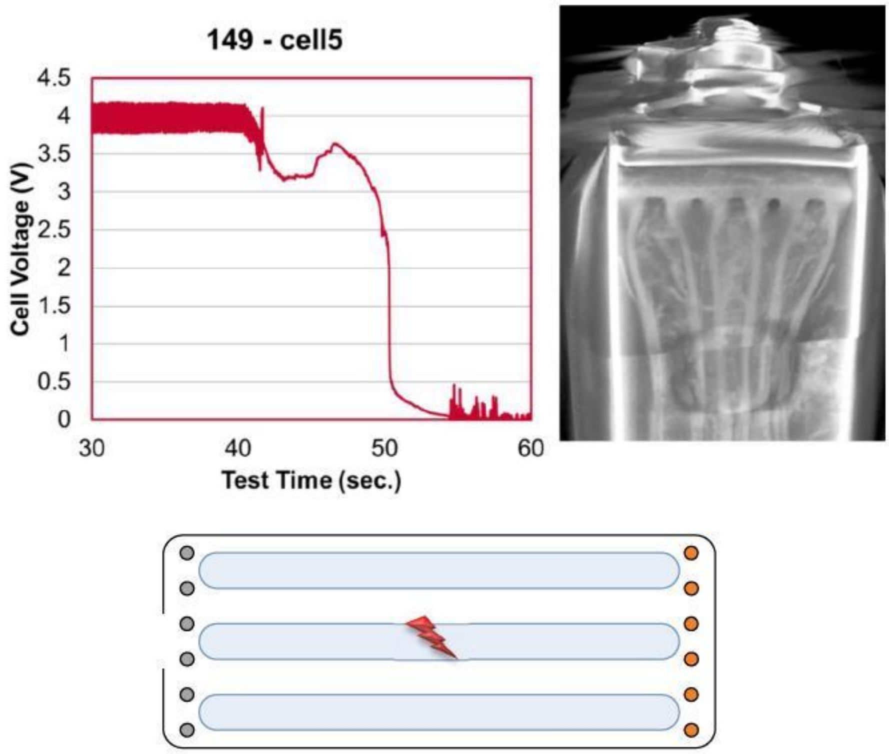


Figure 65. Cell voltage profile and the status of open fuse in top-penetrated NP test (Sample: 149-5)

Figure 66. Failure mode observed in top-penetrated NP test (Sample: 149-5)

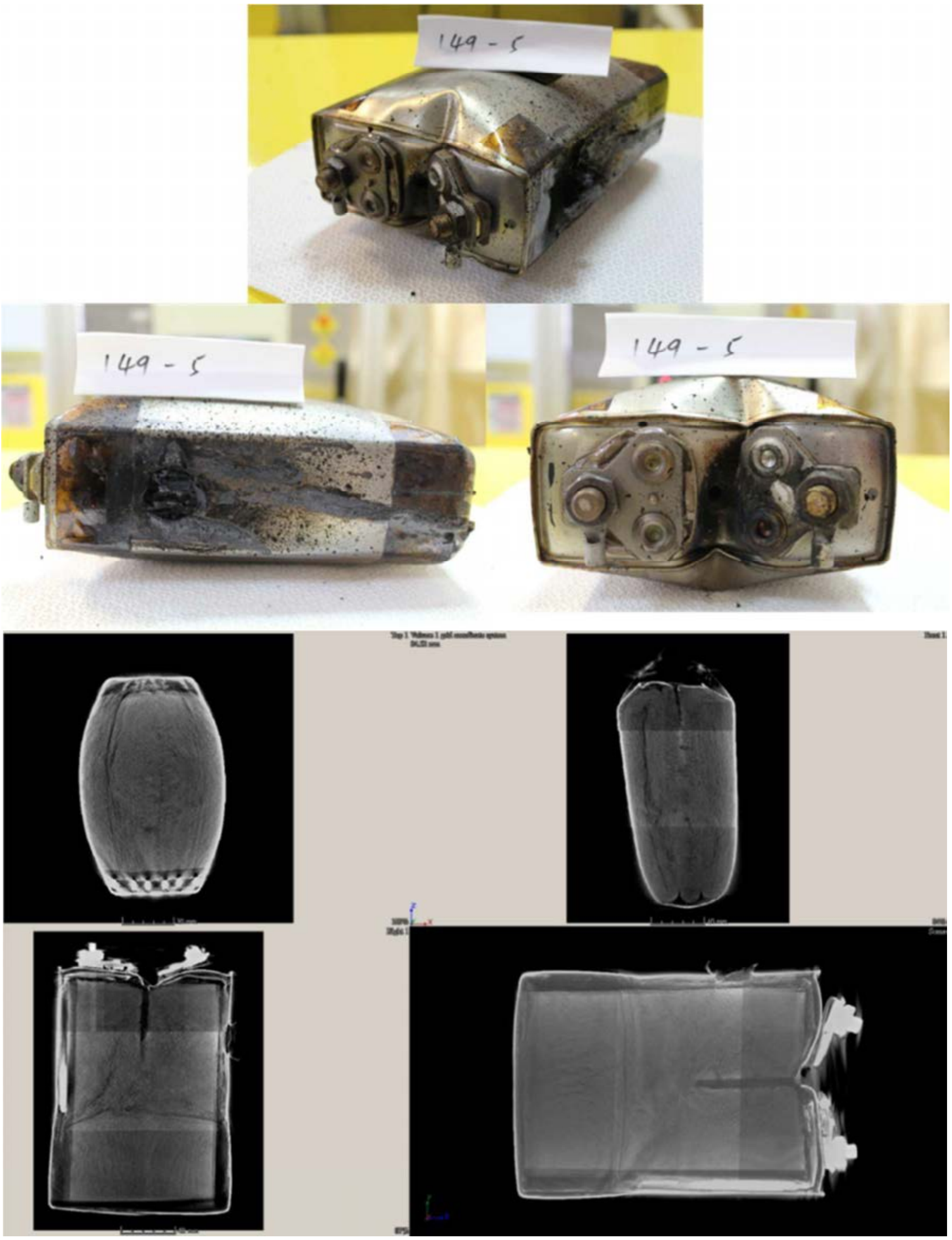


Figure 67. Appearance of tested sample and CT scan after top-penetrated NP test (Sample: 149-5)

#241-3: Top NP at 25℃

Figure 68, to Figure 70 show the test result, cell voltage, load profiles and status of current collector of sample 241-3 that was also tested by top-penetrated NP under 25℃. The data shows similar behavior to the previous sample, 149-5. No open fuse can be observed.

However, Figure 71 shows the sample got quite different in failure mode as the cell, 241-3, It eventually caught fire and this is also the only sample in the project to get the failure mode of fire.

In Figure 72, we can see the appearance and the CT scan images of the test sample, 241-3. We can easily tell that there is more deformation and swelling. More deformation on the top of the cell can also be observed as the initial ISC was triggered at the top area of W2.

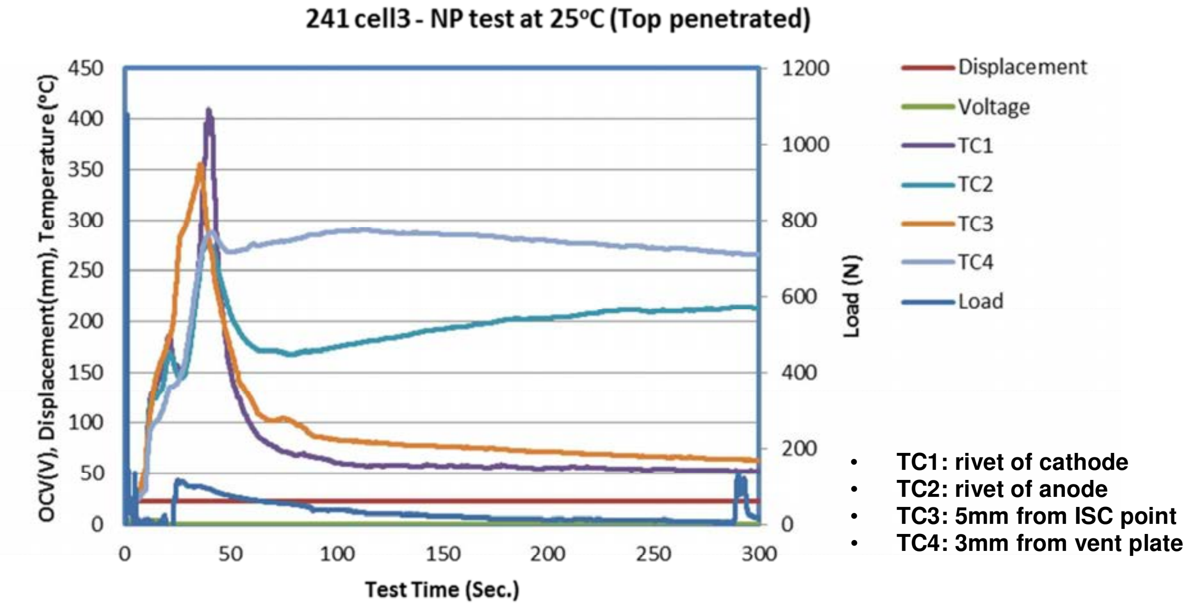


Figure 68. Cell voltage, cell temperature, load and displacement profiles in top-penetrated NP test (Sample: 241-3)

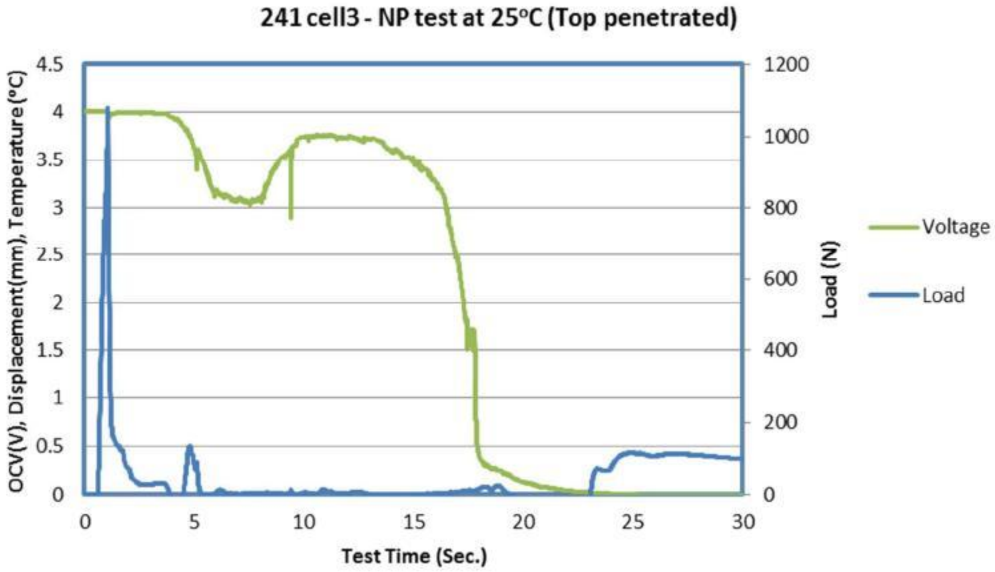


Figure 69 Cell voltage vs. Load profiles in top-penetrated NP test (Sample: 241-3)

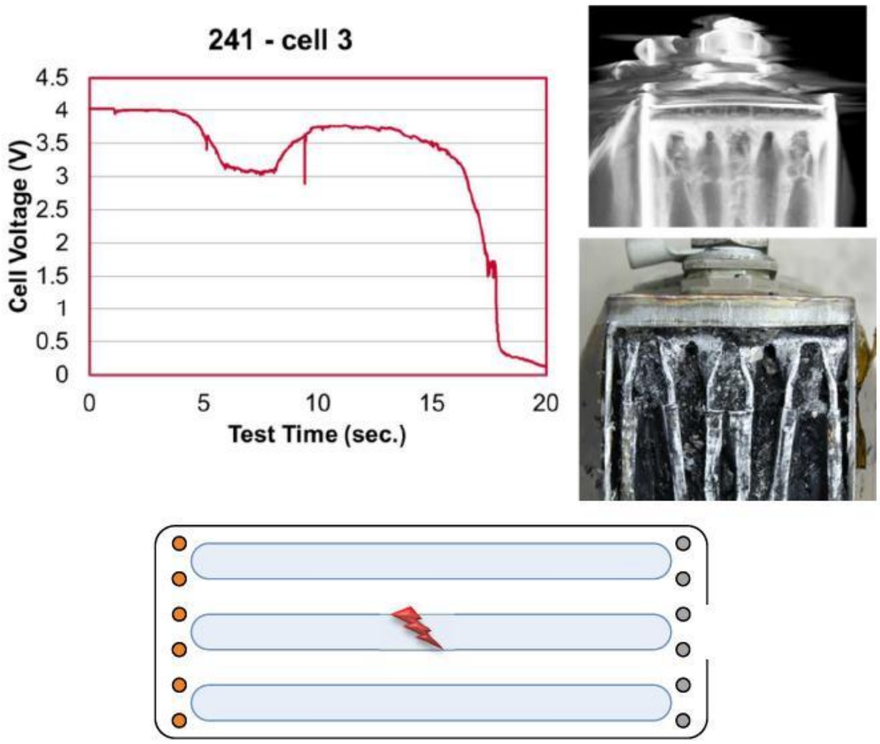


Figure 70. Cell voltage profile and the status of open fuse in top-penetrated NP test (Sample: 241-3)

Figure 71. Failure Mode observed in top-penetrated NP test (Sample: 241-3)

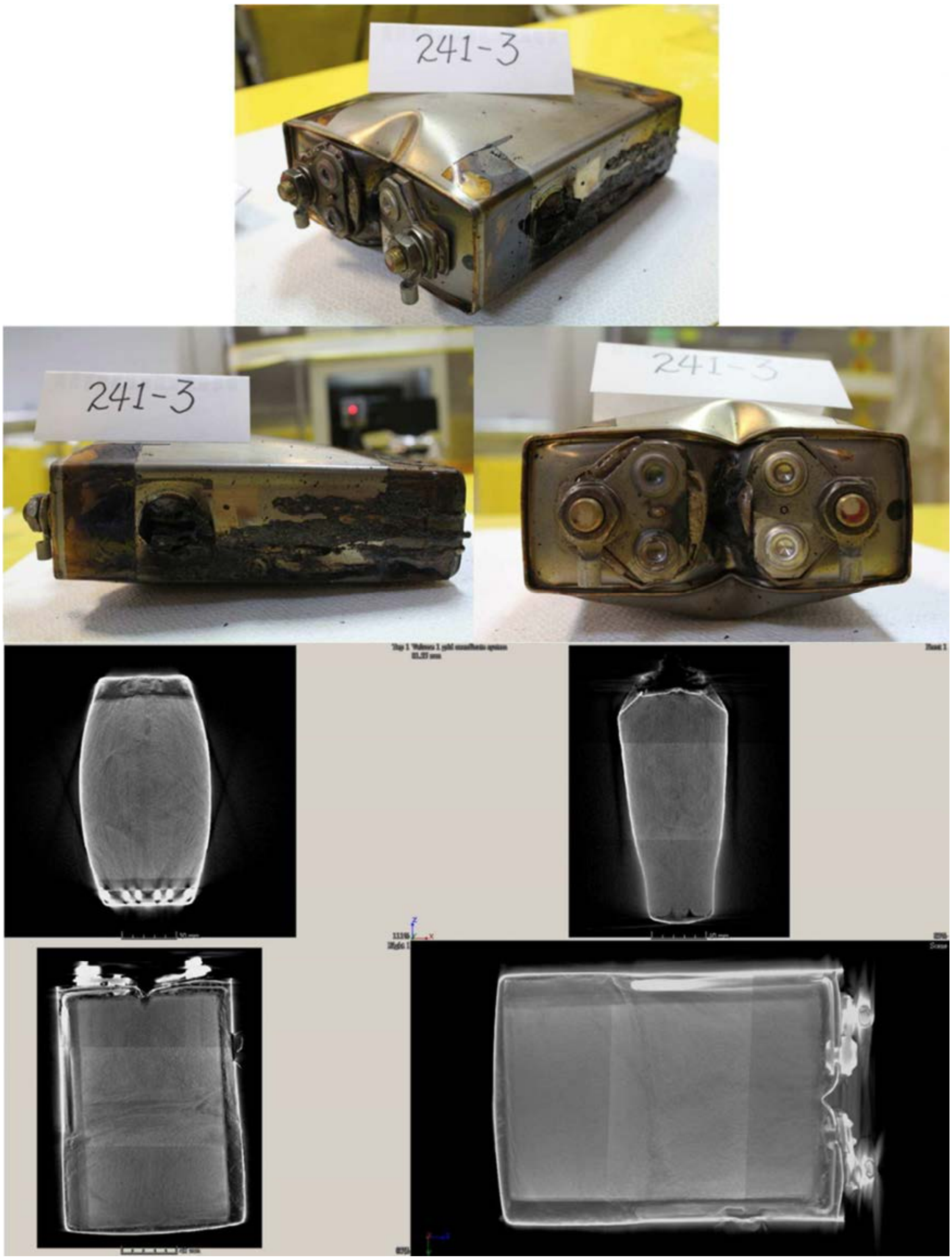


Figure 72 Appearance of Tested Sample and CT scan after top-penetrated NP test (Sample: 241-3)

#149-6: Top NP at 70℃

Figure 73 to Figure 77 show the detailed data profiles, status of open fuse, appearance of tested sample and the CT scan images of sample 149-6, which is tested by top-penetrated NP test under 70°C.

The cell behaviors are similar to the top-penetrated NP test under 25°C. In this case, we can also observe big noise in cell voltage reading due to the excess deformation on the cell header. This is the only cell among all that shows the open fuse in W2.

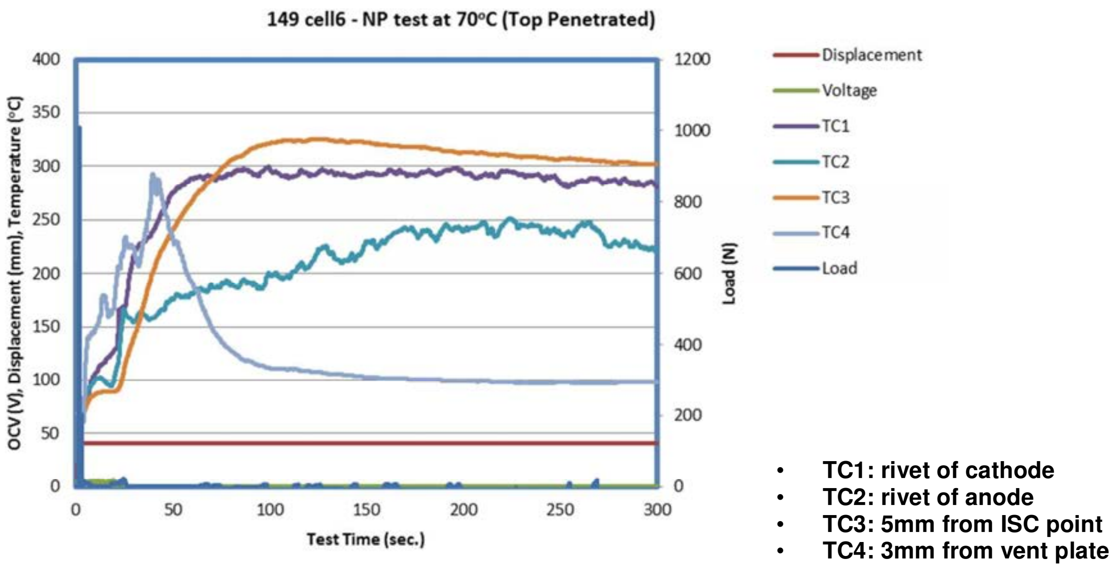


Figure 73. Cell voltage, cell temperature, load and displacement profiles in top-penetrated NP test (Sample: 149-6)

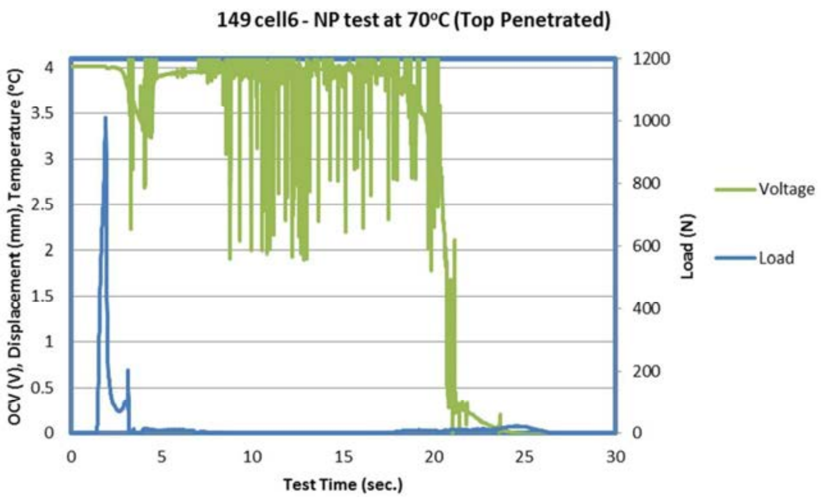


Figure 74. Cell voltage vs. Load profiles in top-penetrated NP test (Sample: 149-6)

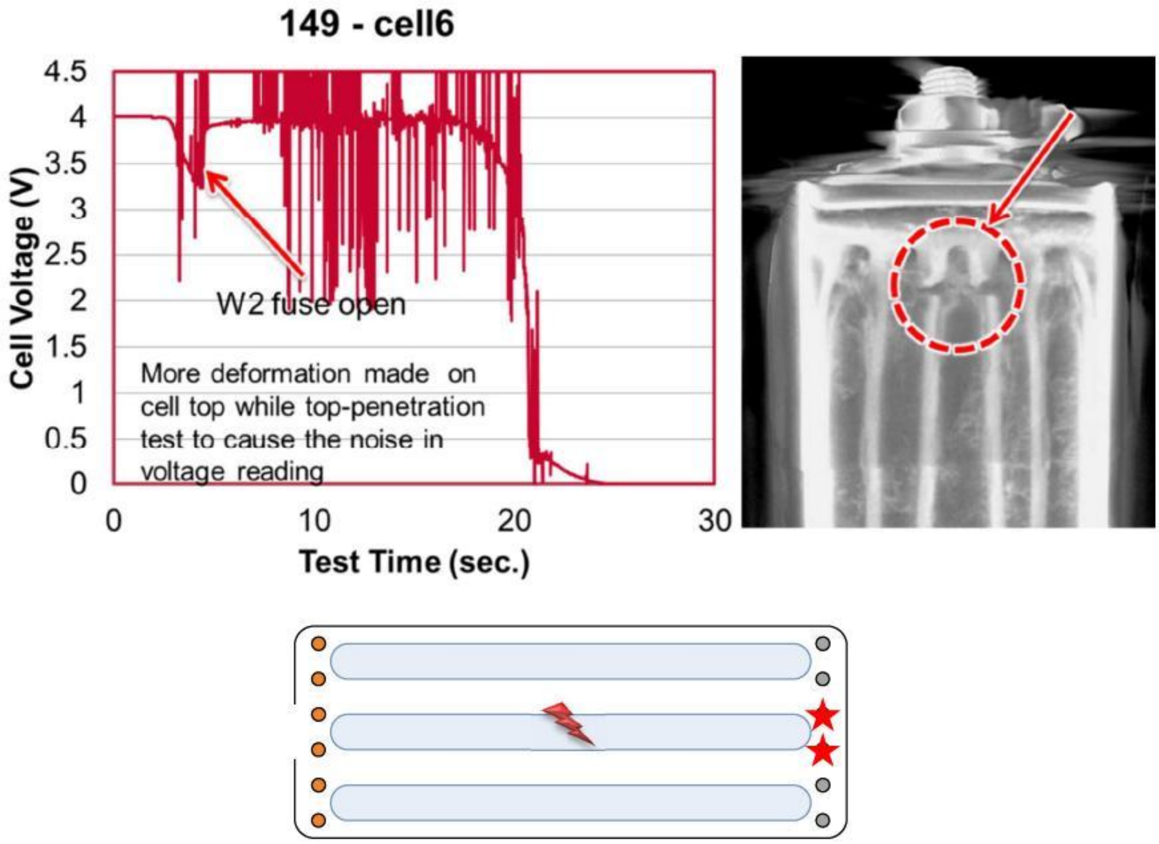


Figure 75. Cell voltage profile and the status of open fuse in top-penetrated NP test (Sample: 149-6)

Figure 76. Failure Mode observed in top-penetrated NP test (Sample: 149-6)

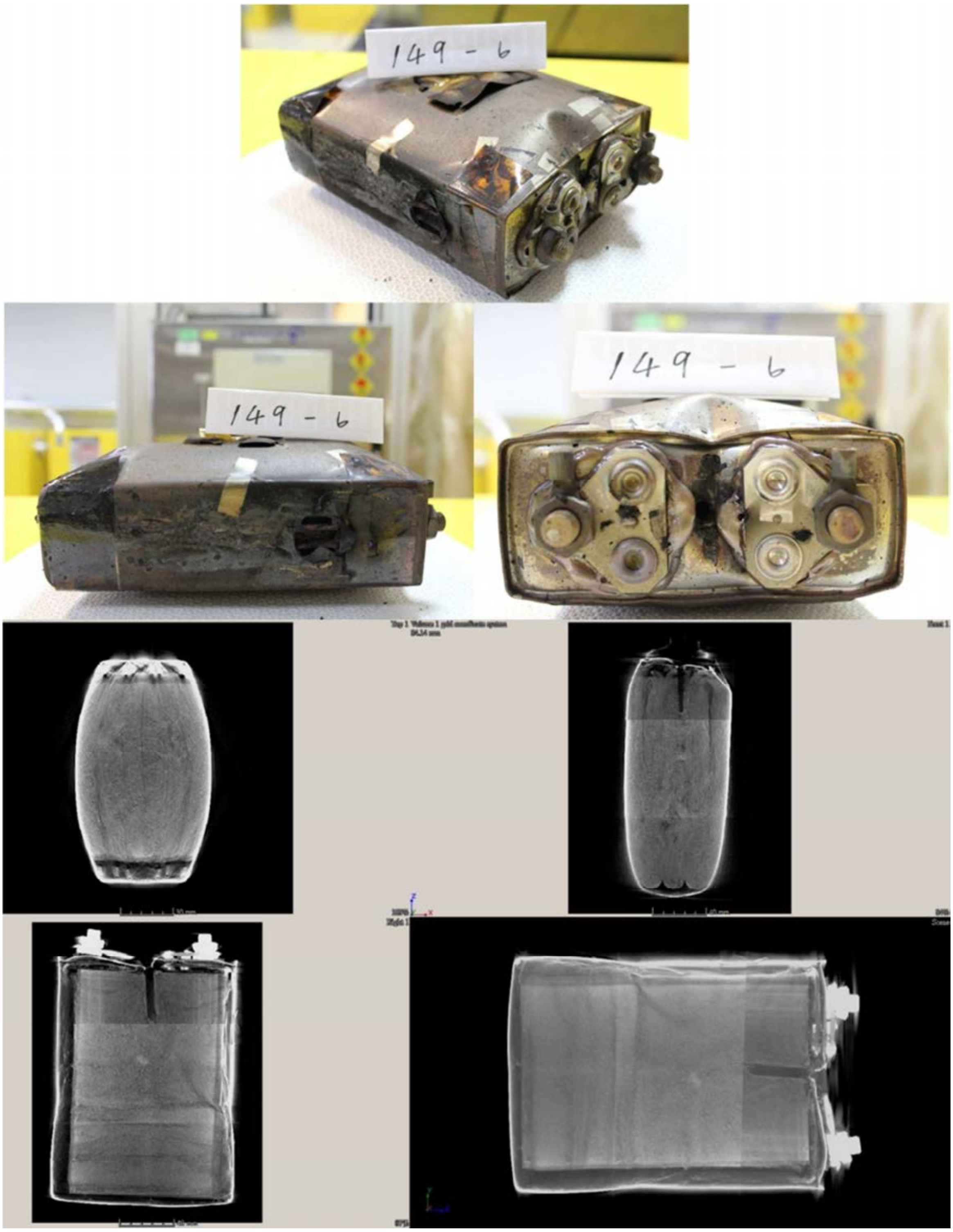
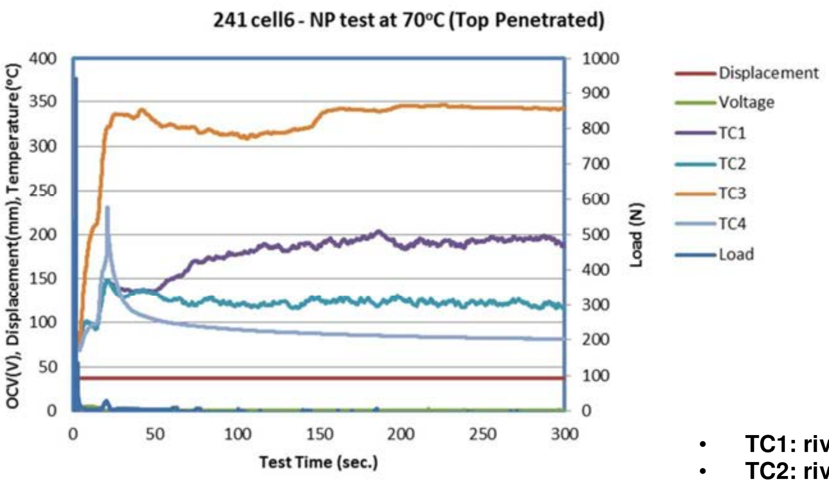


Figure 77. Appearance of tested sample and CT scan after top-penetrated NP test (Sample: 149-6)

#241-6: Top NP at 70℃

Figure 78 to Figure 82 show the detailed data profiles, status of open fuse, appearance of tested sample and the CT scan images of sample 241-6, which is the second test sample of top-penetrated NP test under 70℃. The cell behaviors are similar to the first sample. In this case, we can also observe big noise in cell voltage reading due to the excess deformation on cell head. The video also shows the test conducted at higher temperature (i.e. 70℃) usually leads to more violent vent comparing to the test done under 25℃. However, no open fuse can be observed in the second tested sample, 241-6.



- TC1: rivet of cathode
- TC2: rivet of anode
- TC3: 5mm from ISC point
- TC4: 3mm from vent plate

Figure 78. Cell voltage, cell temperature, load and displacement profiles in top-penetrated NP test (Sample: 241-6)

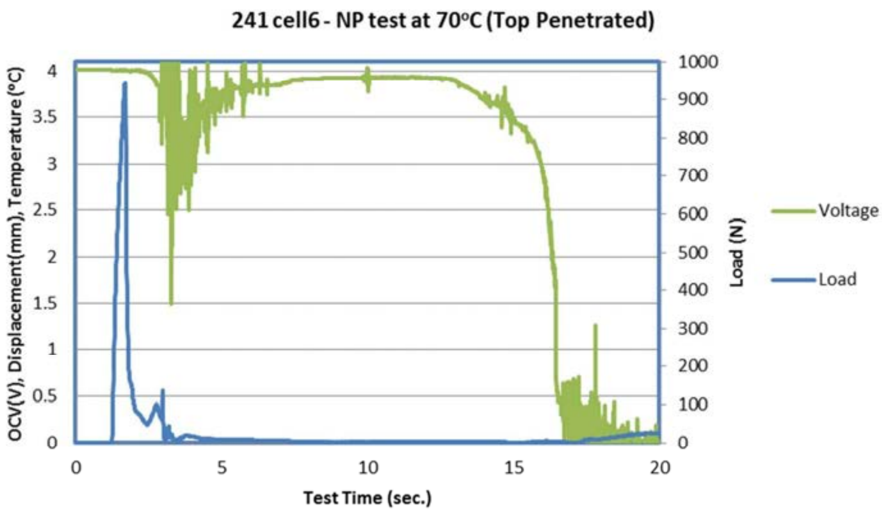


Figure 79. Cell voltage vs. Load profiles in top-penetrated NP test (Sample: 241-6)

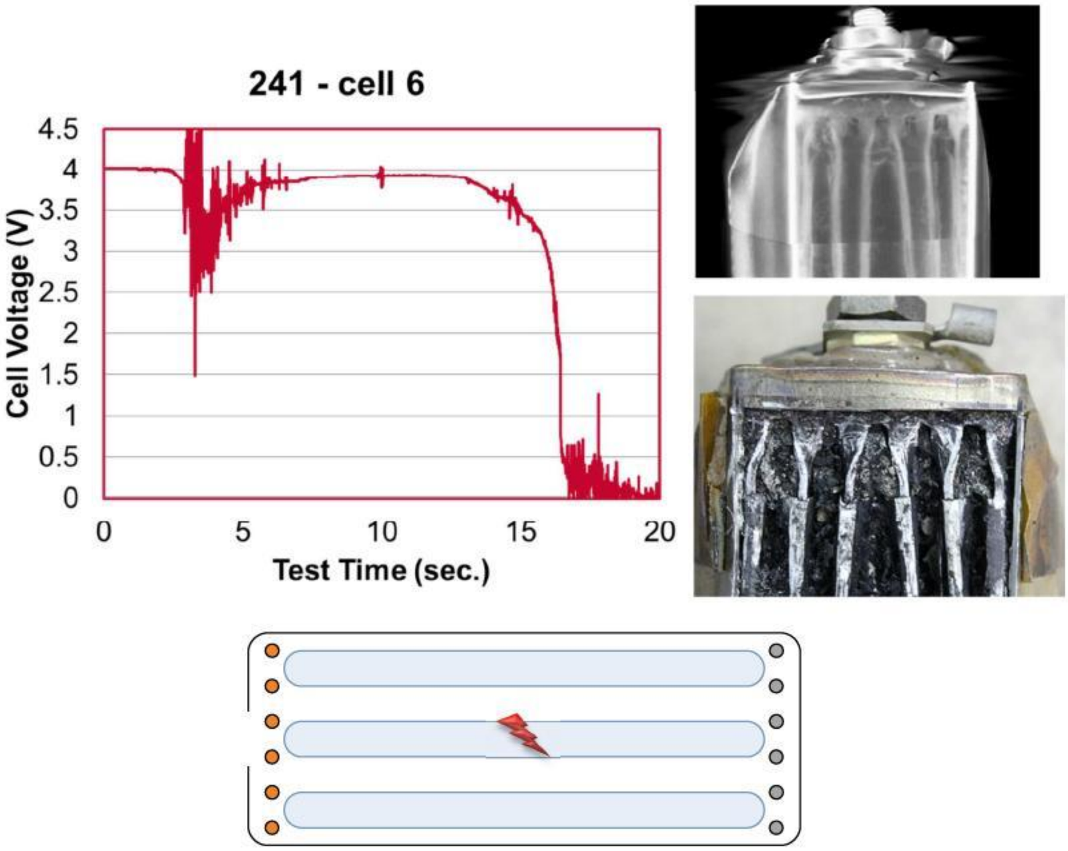


Figure 80. Cell voltage profile and the status of open fuse in top-penetrated NP test (Sample: 241-6)

Figure 81. Failure mode observed in top-penetrated NP test (Sample: 241-6)

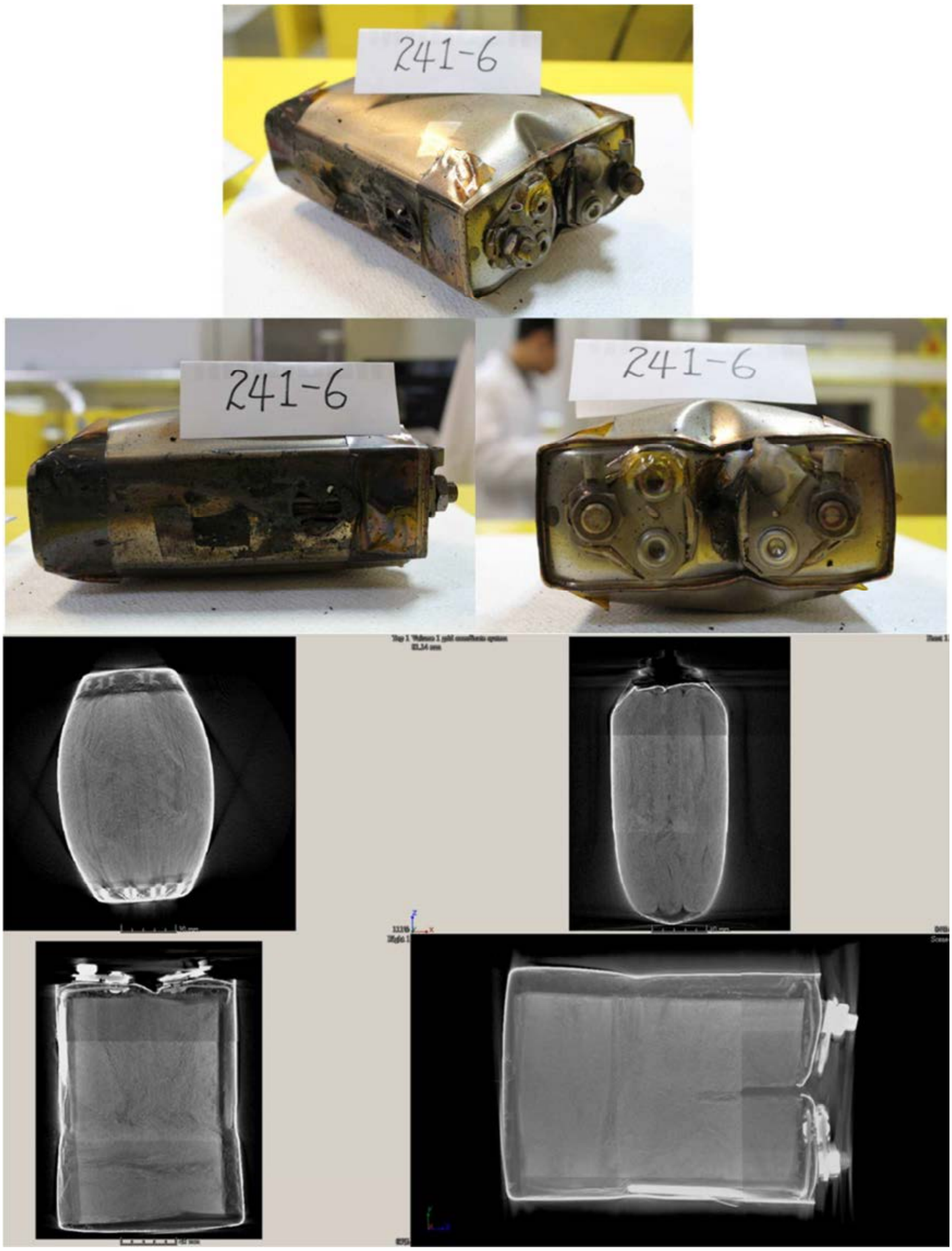


Figure 82 Appearance of Tested Sample and CT scan after top-penetrated NP test (Sample: 241-6)

HP test

The results of HP tests at both 25℃ and 70℃ are summarized in Table 4. Two different conditions under 25℃ were developed: one without electrical load and another with 8A electrical load for comparison. Among all tests, the maximum temperature is between 409℃ and 508℃. The maximum temperature is always between the hot pat and test sample. The test results of HP tests show very good consistency as all of the cells have a same failure mode with open fuse in W1 only.

The purpose of HP test is to study the LVP65 cell failure mode while the heat is propagated from one side of the cell. In the five tests conducted in this report, fuse only open in W1. However, there is still a possibility that more open fuse can occur in if the environmental temperature is higher in a real event as the heat might not be easily dissipated.

Table 4. Summary of HP tests on LVP65 Cells

Test	HP test		
Sample	149-7 241-7	171-8	149-8 241-8
Condition	25°C, No load	25°C, 8A load	70°C, No load
Test Result	Venting, Smoke	Venting, Smoke	Venting, Smoke
Max T[1]	507°C 417°C	508°C	409°C 417°C
Max T near vent	107°C 373°C	216°C	358°C 298°C
Max T at Indenter/Nail/Pad	507°C 417°C	508°C	409°C 417°C
Time from ISC to Max Vent T (seconds)	94.7 112.6	45.5	212.1 159.8
Open fuse?	W1 (149-7) W1 (241-7)	W1 (171-8)	W1 (149-8) W1 (241-8)
Note	Heat cannot be conducted quickly to the other sides of hot Pad. At higher test temperature, the cell got earlier thermal runaway		

#149-7: HP at 25℃, No load

Figure 83 is the cell voltage and temperature profiles of sample 149-7, which is the HP test without load under 25°C. In the temperature readings, only TC3, the thermocouple between hot pat and test cell, shows much higher reading than others. There is a plastic film on the surface of hot pad and extra tapes were used when fixing TC3, so the plastic materials will have phase changes or even melted and vaporized during heating causing endothermic or exothermic reactions. Therefore the reading in TC3 is not that stable after the temperature is higher than 210℃. TC1, TC2 and TC4 show much lower temperature reading than TC3 and it takes about 25 to 30 minutes to cause the separator to melt and then lead to the ISC in W1.

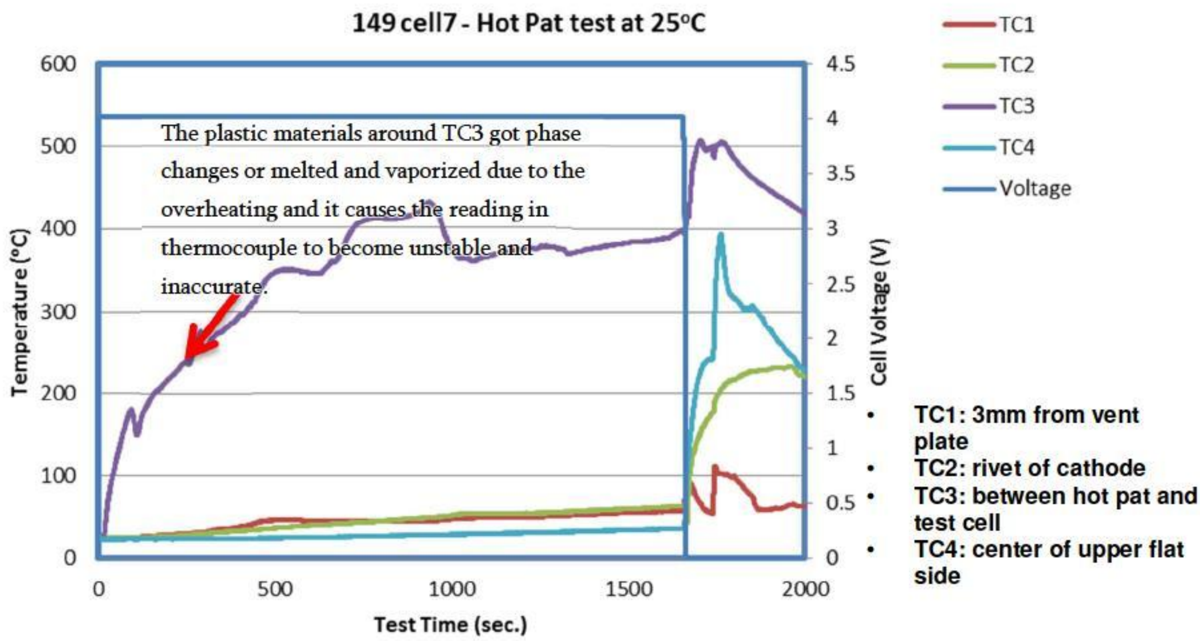


Figure 83 Temperature and cell voltage profiles in HP test (Sample: 149-7)

Figure 84 shows the cell voltage profile and the status of open fuse in the test samples. This cell has open fuse in W1 only.

Figure 85 is the failure mode captured from the video during test. Figure 86 shows the appearance of tested samples and CT scan images 149-7.

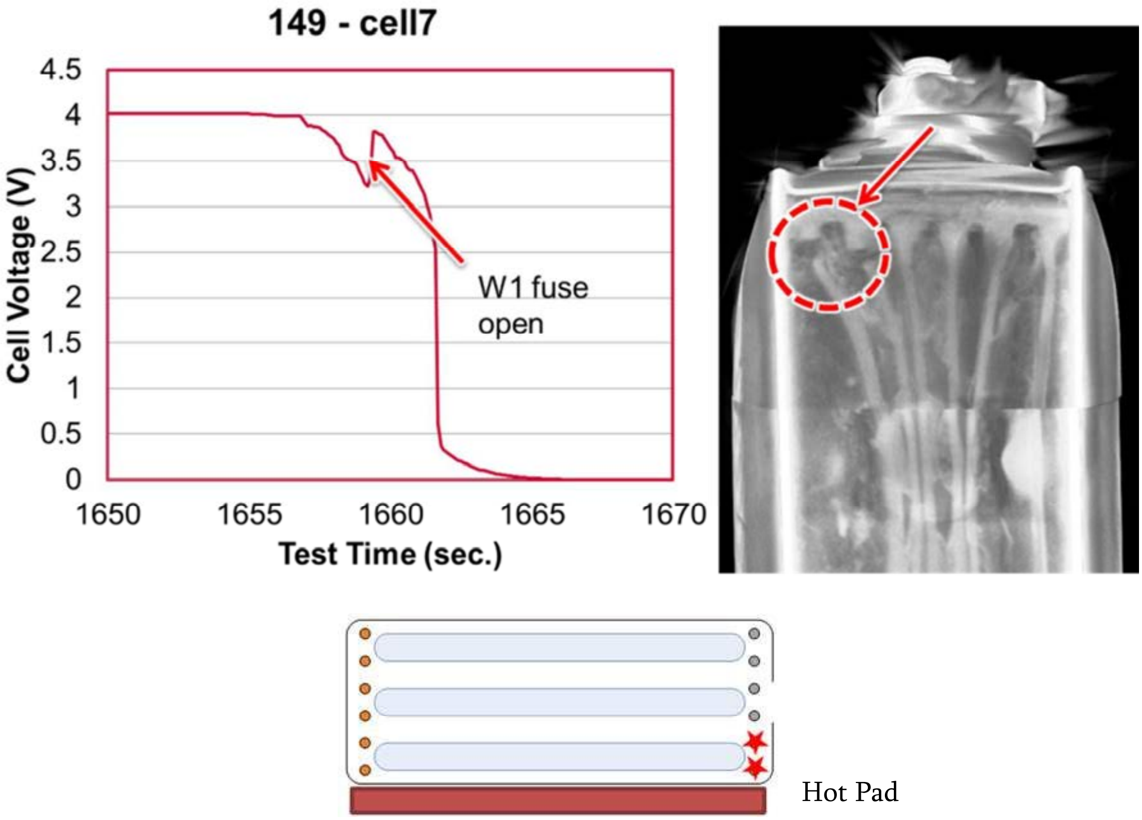


Figure 84. Cell voltage profile and the status of open fuse in HP test (Sample: 149-7)

Figure 85. Failure Mode observed in HP test (Sample: 149-7)

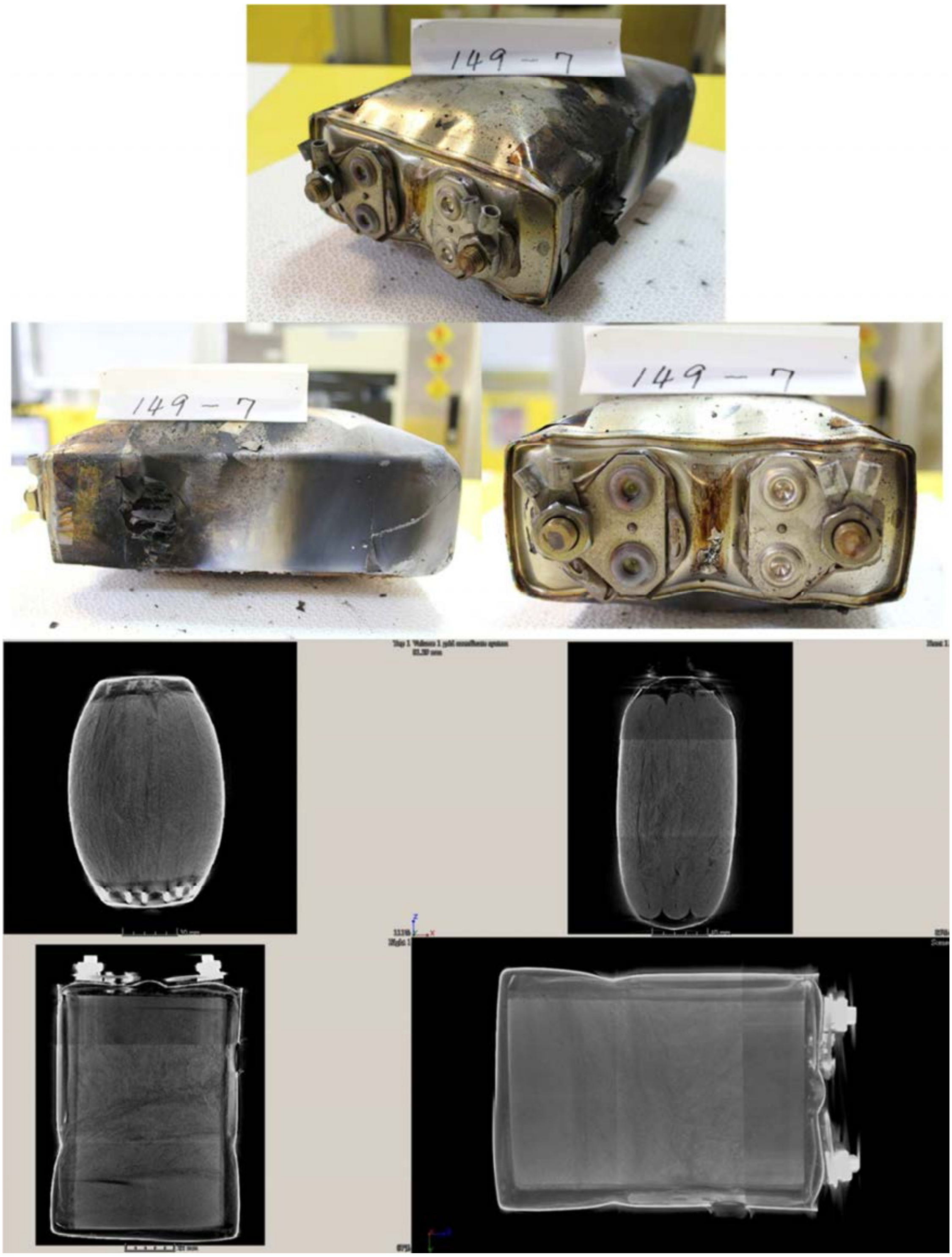


Figure 86. Appearance of Tested Sample and CT scan after HP test (Sample: 149-7)

#241-7: HP at 25℃, No Load

Figure 87 is the test result of 241-7, which is tested for HP under 25 ℃ with no load.

Figure 88 shows the cell voltage profile and the status of open fuse in the test samples. This cell has open fuse in W1 only.

Figure 89Figure 85 is the failure mode captured from the video during test. Figure 90 shows the appearance of tested samples and CT scan images 241-7.

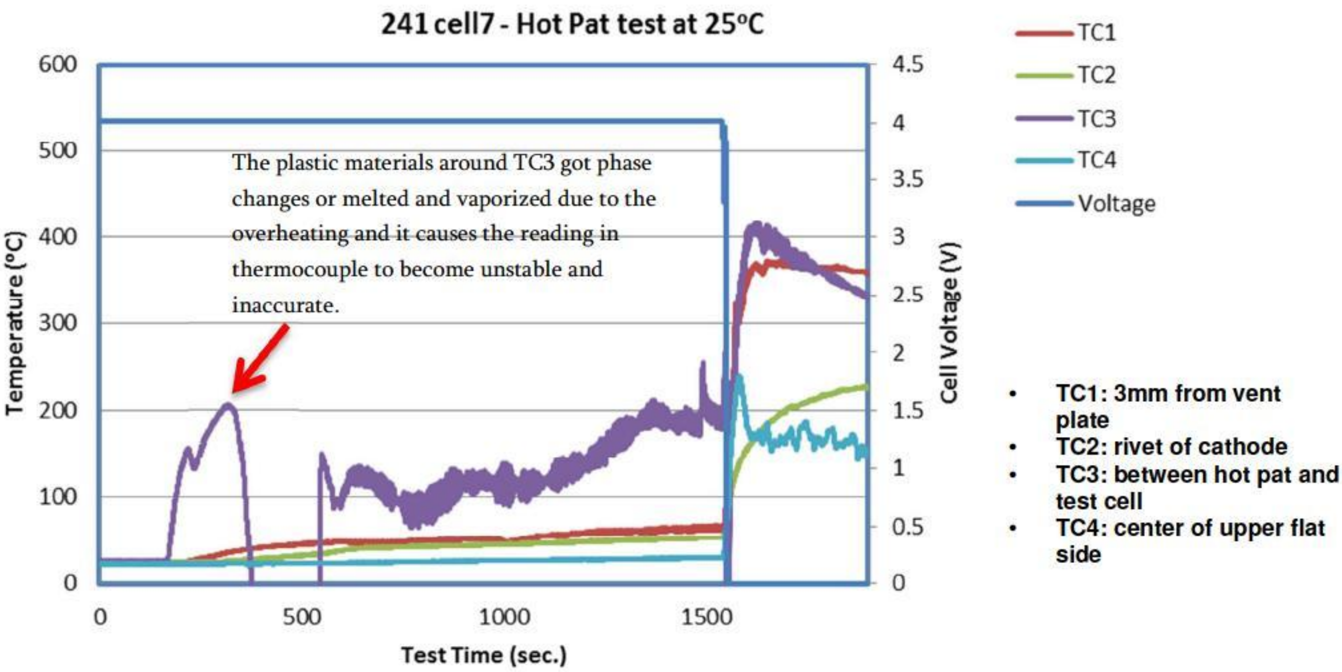


Figure 87. Temperature and cell voltage profiles in HP test (Sample: 241-7)

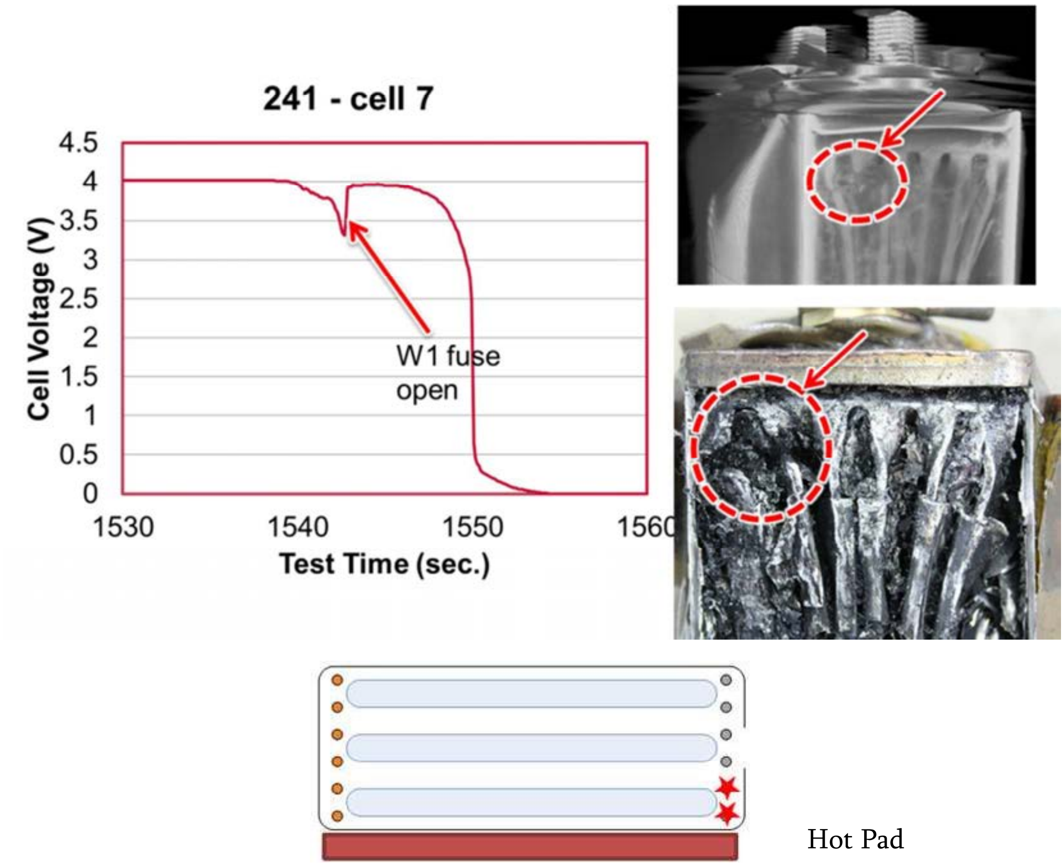


Figure 88 Cell voltage profile and the status of open fuse in HP test (Sample: 241-7)

Figure 89. Failure Mode observed in HP test (Sample: 241-7)

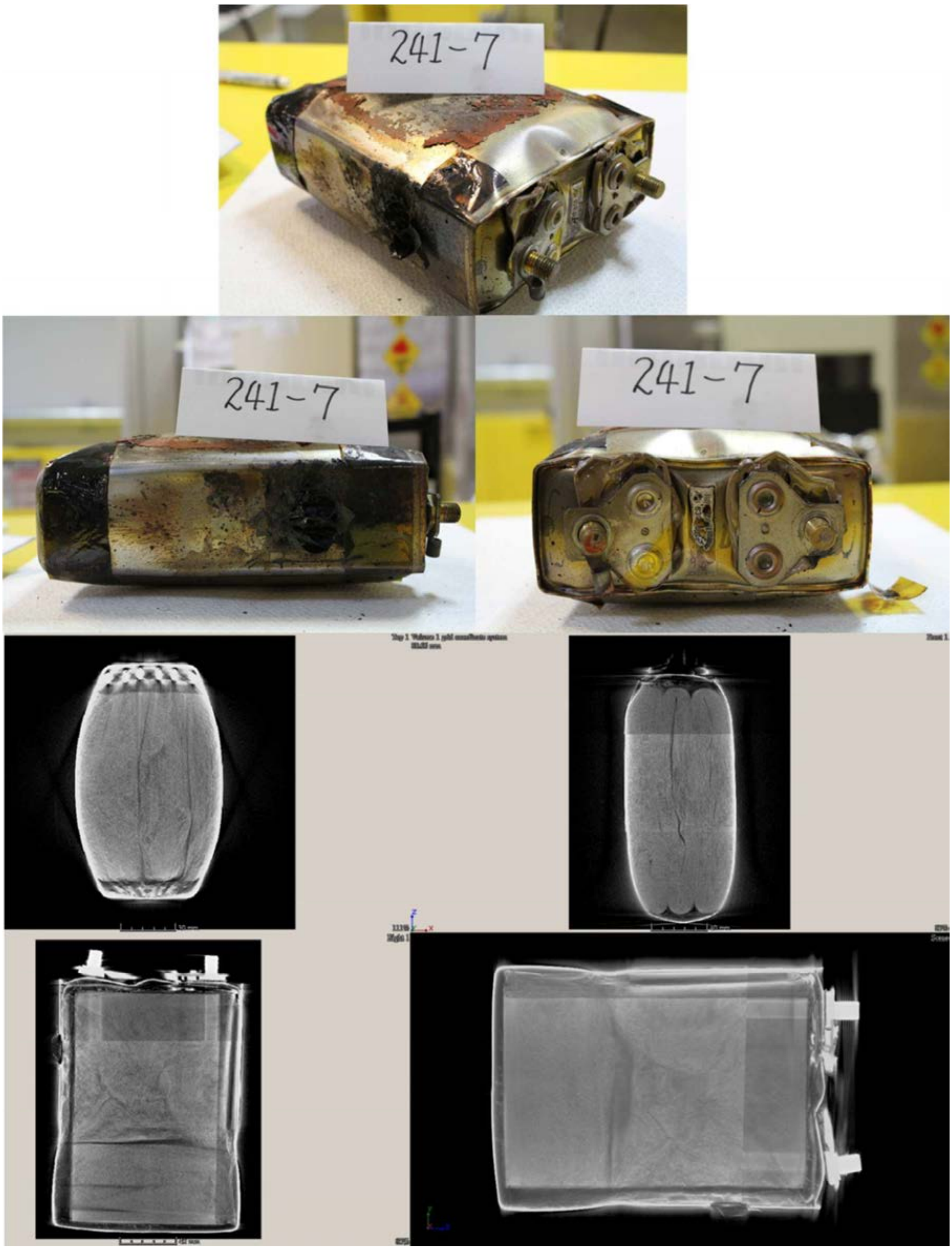


Figure 90. Appearance of Tested Sample and CT scan after HP test (Sample: 241-7)

#171-8: HP at 25℃, 8A Load

Figure 91 is the test result of test sample, 171-8, which is the cell for HP test with 8A electrical load under 25°C. The test result profile shows very similar cell behaviors to the previous cells under 25℃.

Figure 92 shows the cell voltage profile and the status of open fuse in the test samples. This cell has open fuse in W1 only.

Figure 93Figure 85 is the failure mode captured from the video during test. Figure 94 shows the appearance of tested samples and CT scan images 171-8.

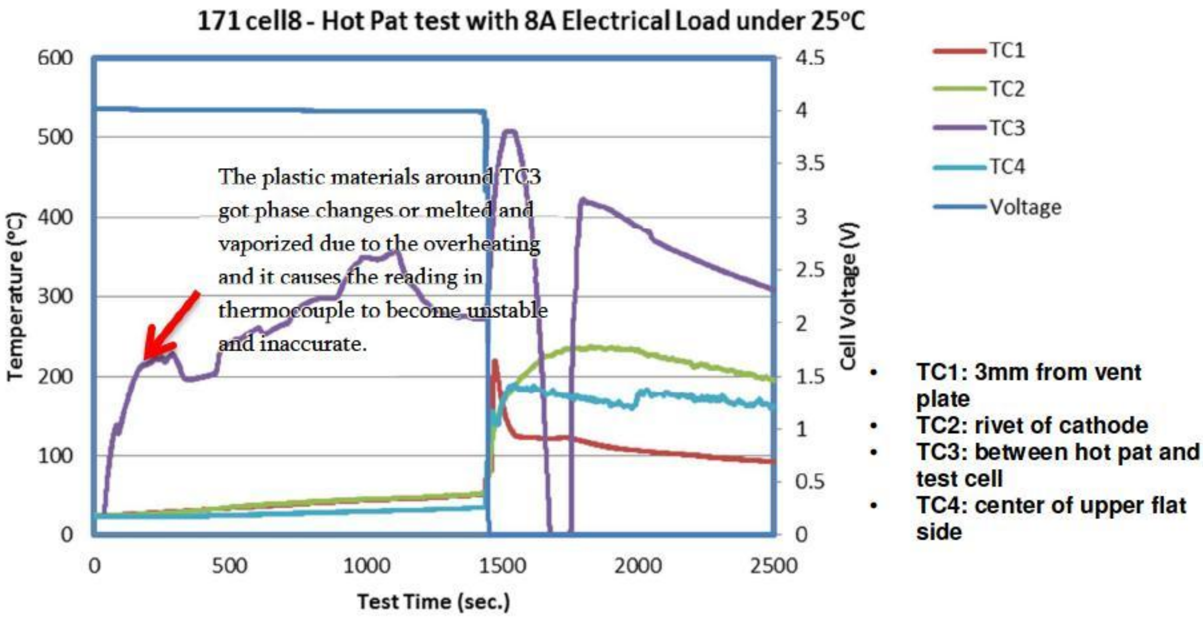


Figure 91 Temperature and cell voltage profiles in HP test with 8A load (Sample: 241-7)

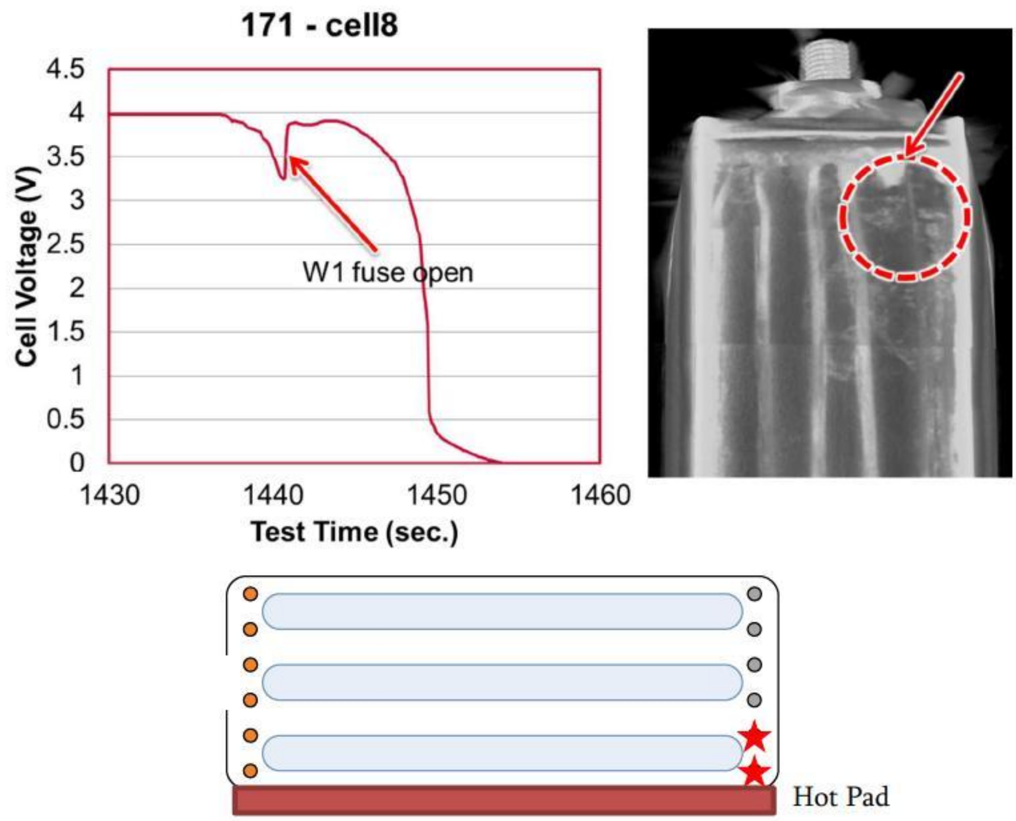


Figure 92. Cell voltage profile and the status of open fuse in HP test with 8A load (Sample: 171-8)

Figure 93. Failure mode observed in HP test with 8A load (Sample: 171-8)

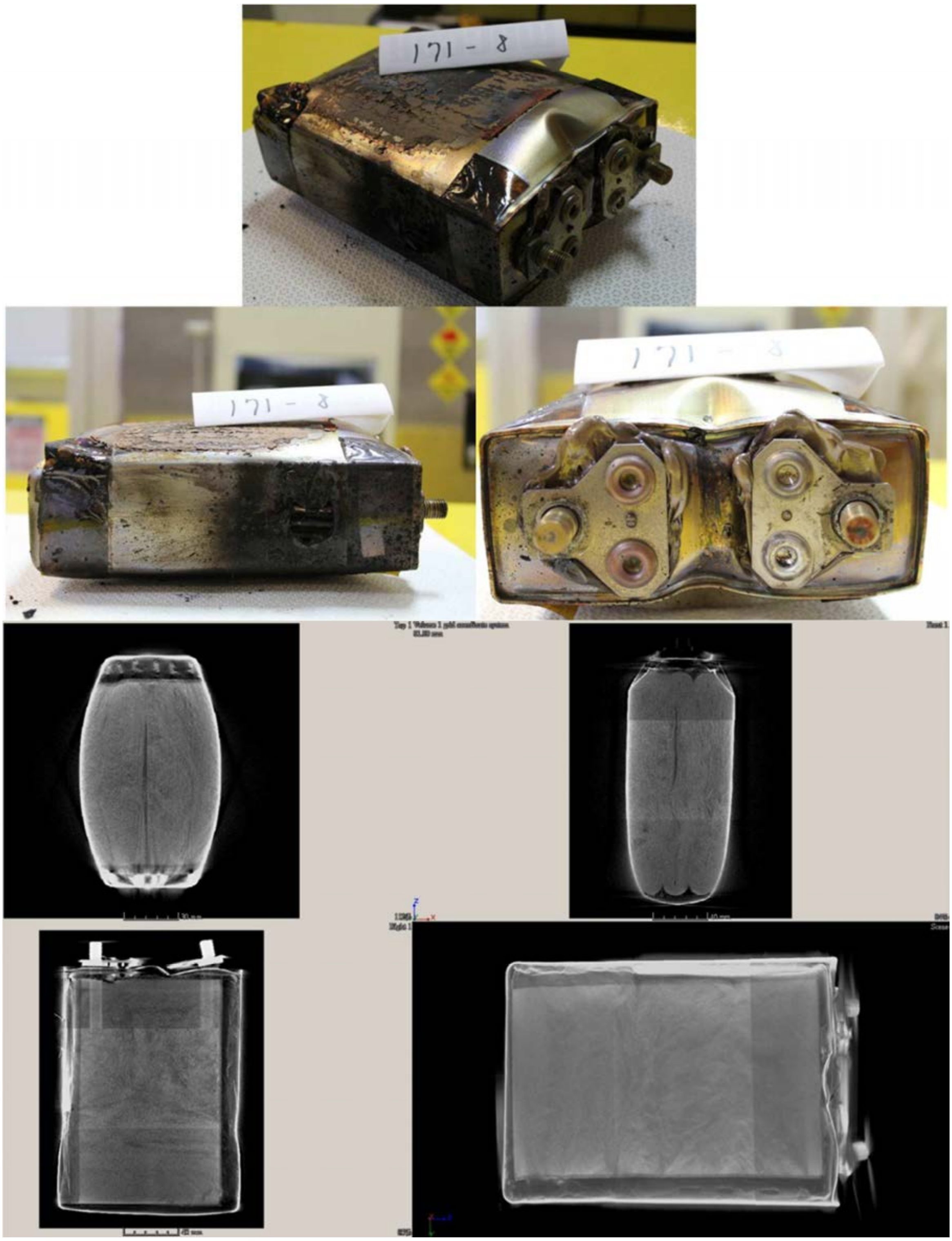


Figure 94 Appearance of Tested Sample and CT scan after HP test (Sample: 171-8)

#149-8: HP at 70℃, No Load

Figure 95 shows the test result of 149-8 for HP test under 70℃ with no current load. The test results are similar to the test under 25℃, but it took shorter time, only 13-15 minutes to cause the ISC in W1.

Figure 96 shows the cell voltage profile and status of current collector after HP test under 70℃. The open fuse can be observed at W1 only.

Figure 97 and Figure 98 show the failure mode, appearance of tested samples and the CT scan images. Same as the tests under 25℃, the failure mode is swelling and venting.

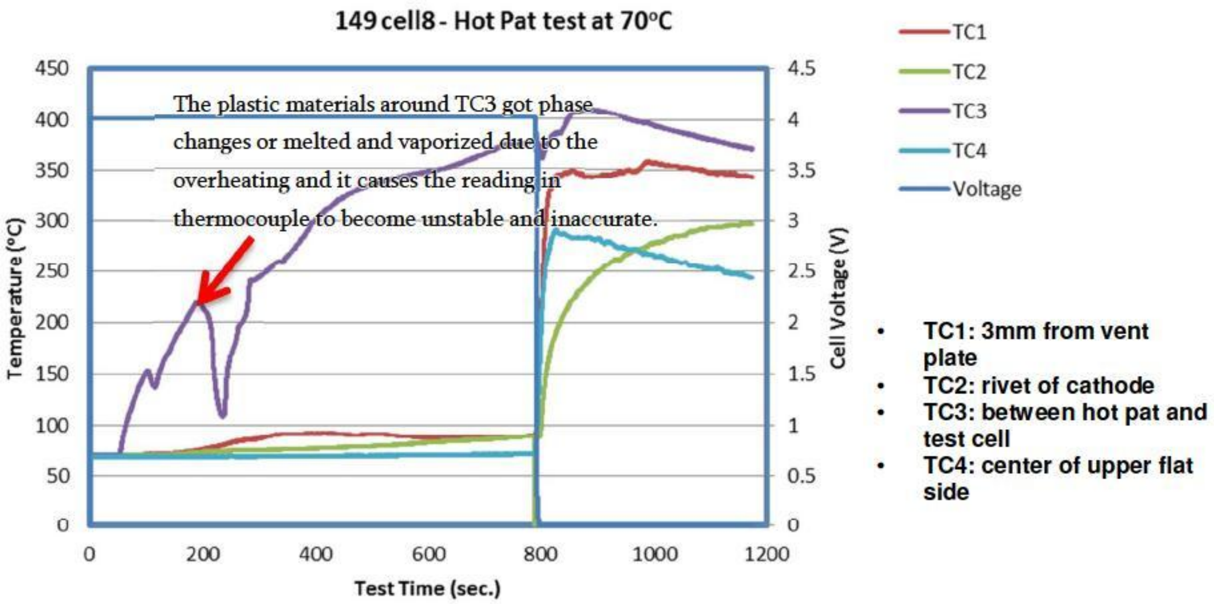


Figure 95 Temperature and cell voltage profiles in HP test (Sample: 149-8)

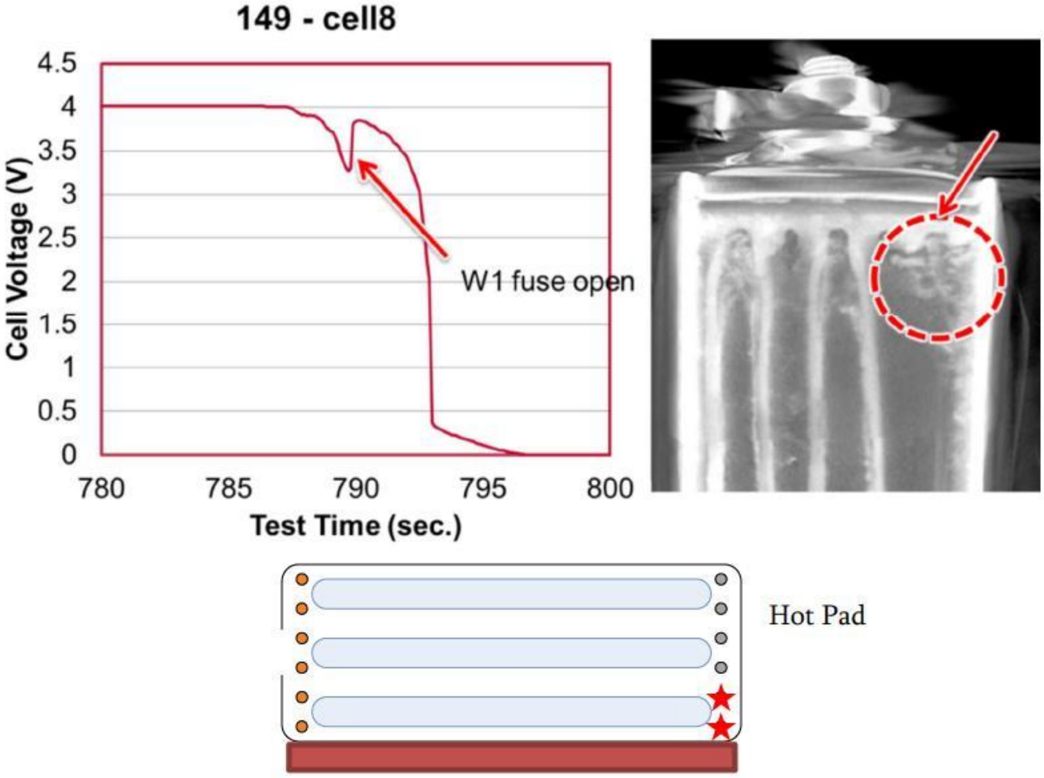


Figure 96 Cell voltage profile and the status of open fuse in HP test (Sample: 149-8)

Figure 97 Failure Mode observed in HP test (Sample: 149-8)

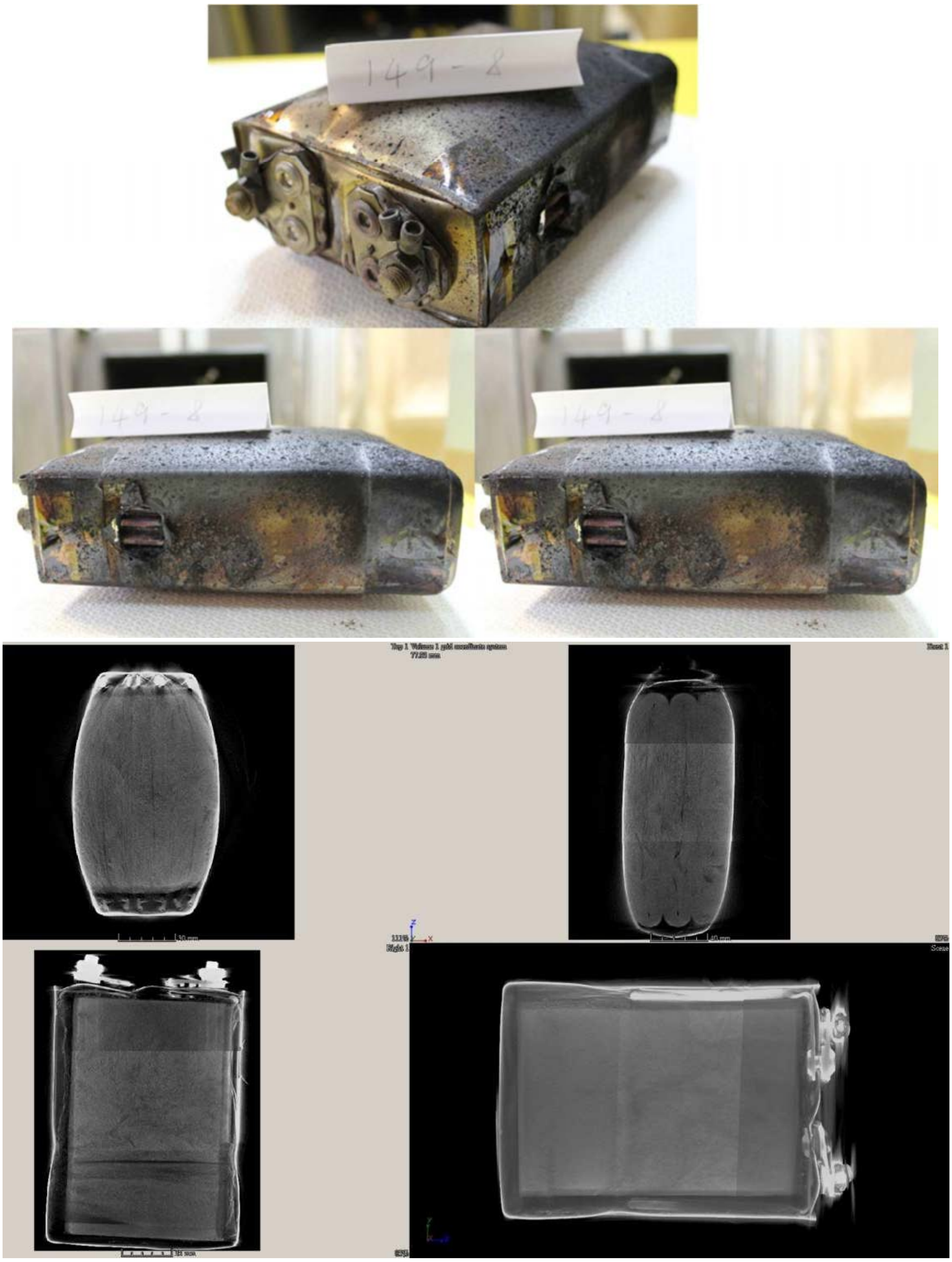


Figure 98. Appearance of tested sample and CT scan after HP test (Sample: 149-8)

#241-8: HP at 70℃, No Load

Figure 99 shows the test result of 241-8 for HP test under 70℃ with no current load. The test results are similar to 149-8.

Figure 100 shows the cell voltage profile and status of current collector after HP test under 70℃. The open fuse can be observed at W1 only.

Figure 101 and Figure 102 show the failure mode, appearance of tested samples and the CT scan images. Same as the tests of 149-8, the failure mode is swelling and venting.

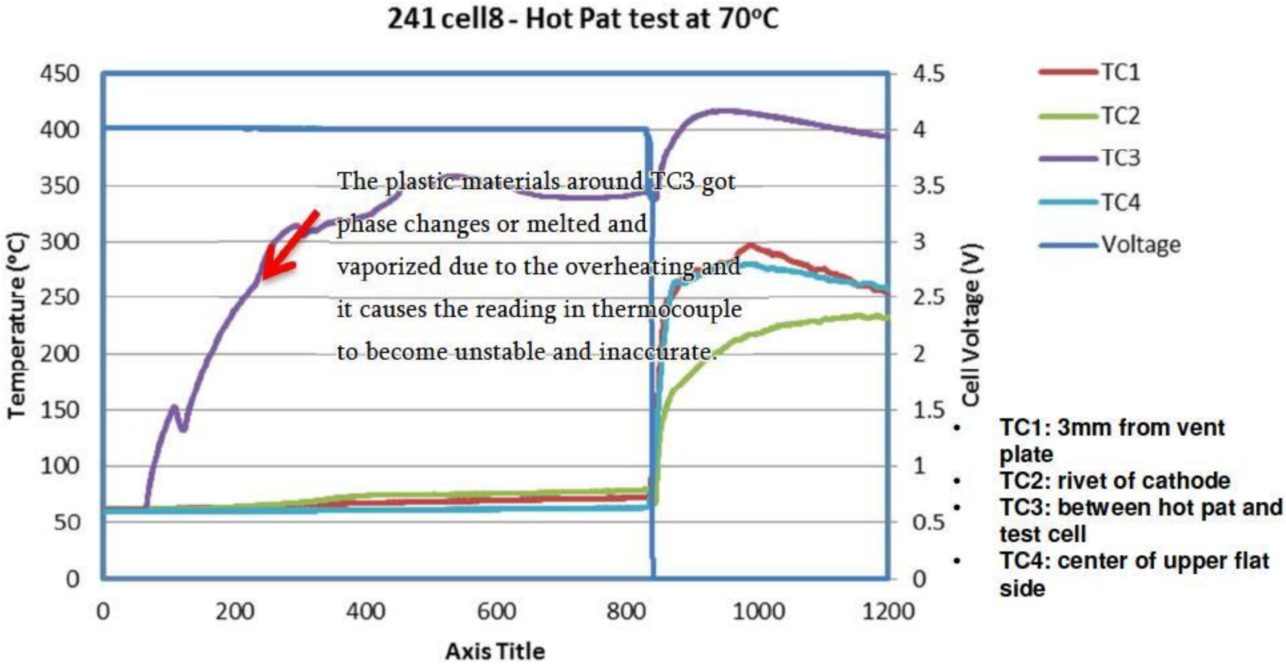


Figure 99 Temperature and cell voltage profiles in HP test (Sample: 241-8)

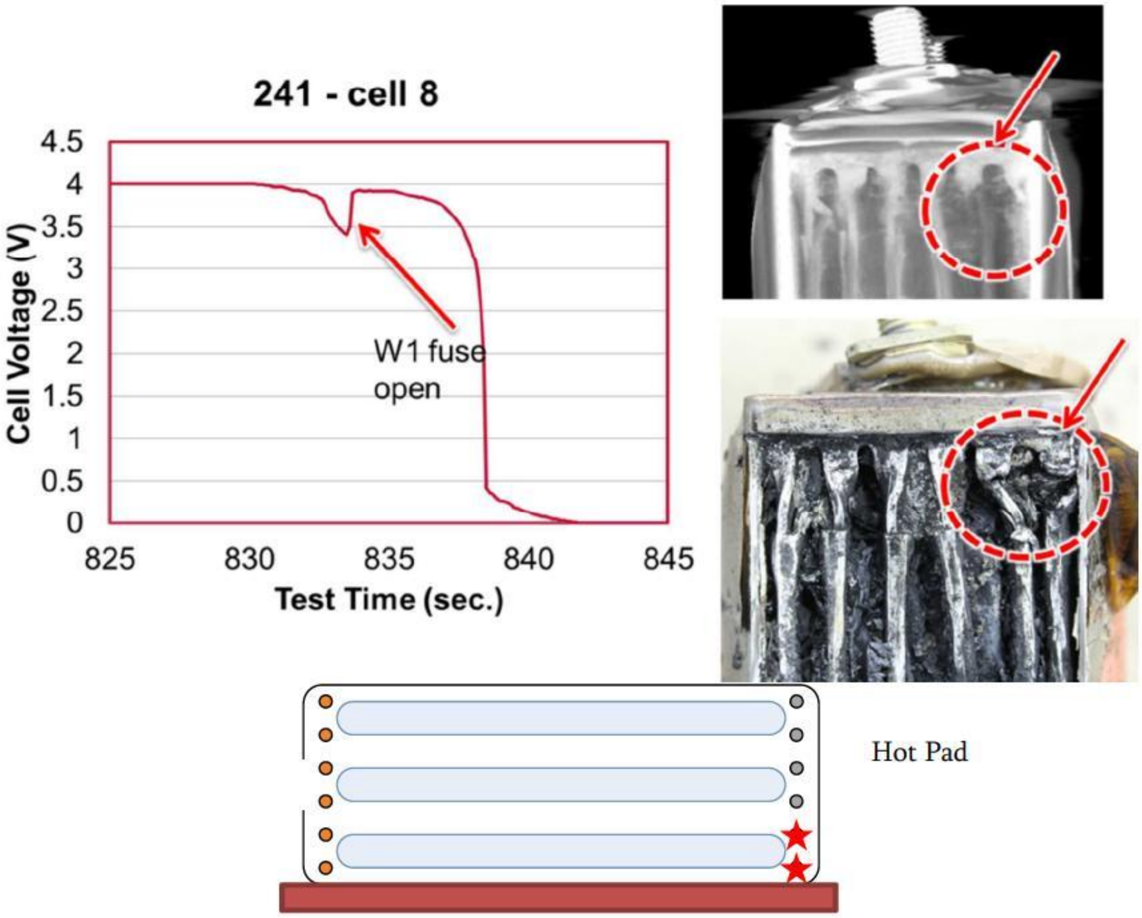


Figure 100 Cell voltage profile and the status of open fuse in HP test (Sample: 241-8)

Figure 101 Failure Mode observed in HP test (Sample: 241-8)

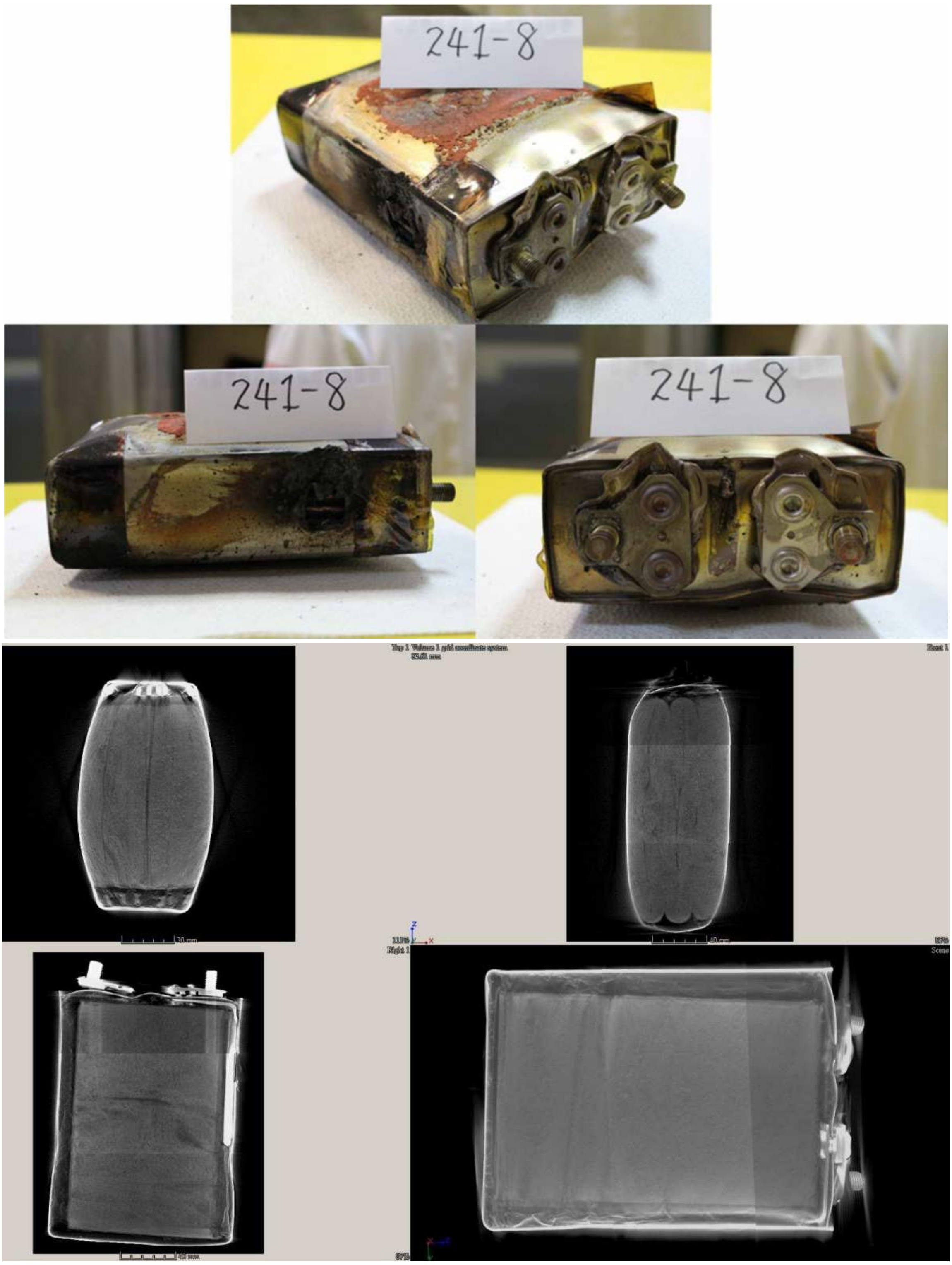


Figure 102 Appearance of tested sample and CT scan after HP test (Sample: 241-8)

Thermal Abuse Simulation Through ARC

The ARC is programmed to run a heat-wait-seek procedure to maintain adiabatic conditions by matching the heating rate of the cell, which is measured by the temperature reading on the surface of the cell.

The test result of sample 412-4 under 100%SOC is shown in Figure 103 and the specific self-heating rate at each temperature step is shown in Figure 104. In this test, the self-heating rate starts to exceed 0.02℃/min at temperatures around 80-85℃. The separator melted around 130℃ followed by ISC, then thermal runaway.

In the self-heating rate data, the self-heating appears at around 60℃. This suggests that from a safety point of view, 60℃ may be an appropriate application limit for cell usage. These results do not imply that there will be immediate safety issue if the cells are exposed to conditions within 60 to 70℃. However, there may be long-term safety concerns for the cells as damage may happen to the SEI layer between electrode and electrolyte reducing the protection function of this important layer[20].

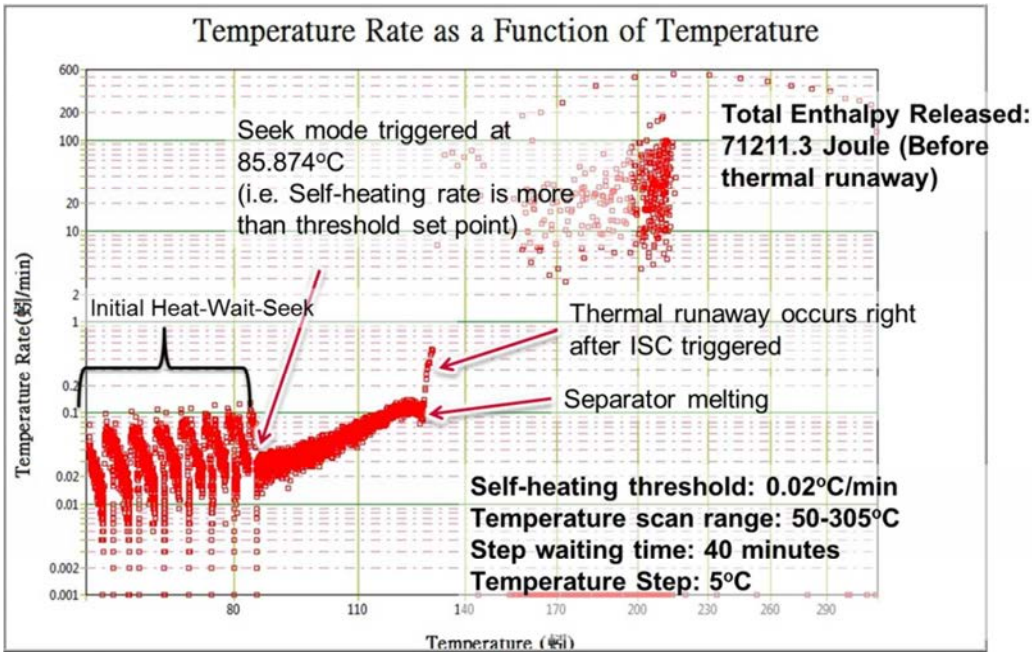


Figure 103. ARC heat-wait-seek test on LVP65 cell 412-4

[20] P. Verma et al., "A review of the features and analyses of the solid electrolyte interphase in Li-ion batteries", Electrochimica Acta, vol. 55, pp. 6332-6341, 2010.

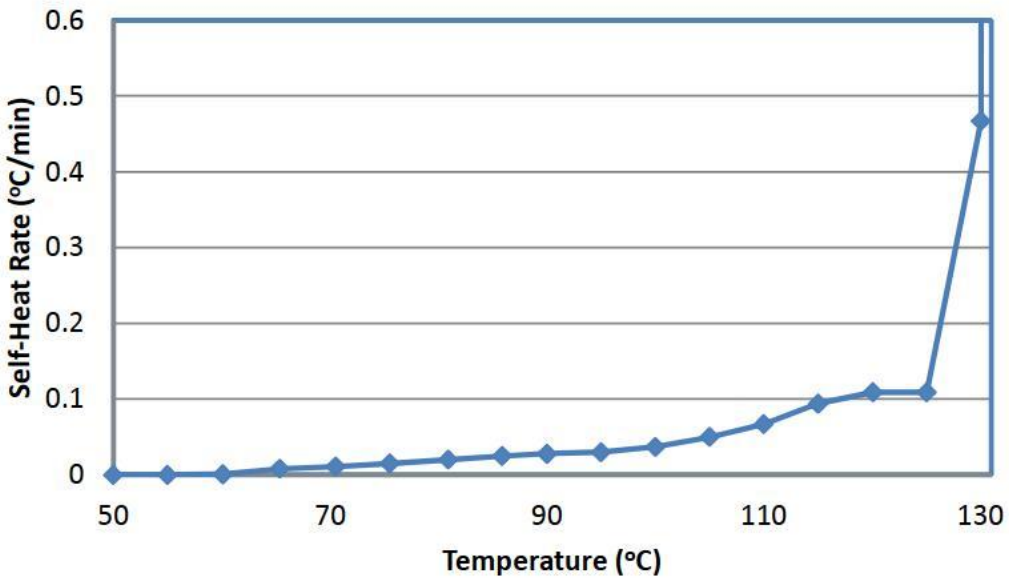


Figure 104. Self-heating Rate under ARC (Sample: 412-4, 100% SOC)

The CT scan images of sample 412-4 after the ARC thermal abuse test are shown in Figure 105. In this case, swelling of the cell is observed without any rupture of the metal casing. Thermal runaway burned most of the active materials in the cell.

Figure 106 shows the status of aluminum current collectors in the cathode. No open fuse can be observed after the ARC thermal abuse test. The reason is because in ARC test, the heat within the cell increases slowly and evenly. Therefore before the first separator melts down, the separators in all three windings are at similar temperature, which is above the shutdown temperature. Therefore even short-circuit happens in one of the three windings, the other two windings will not have enough electricity to charge the short-circuited winding because the separators have already shut down the ion transfer.

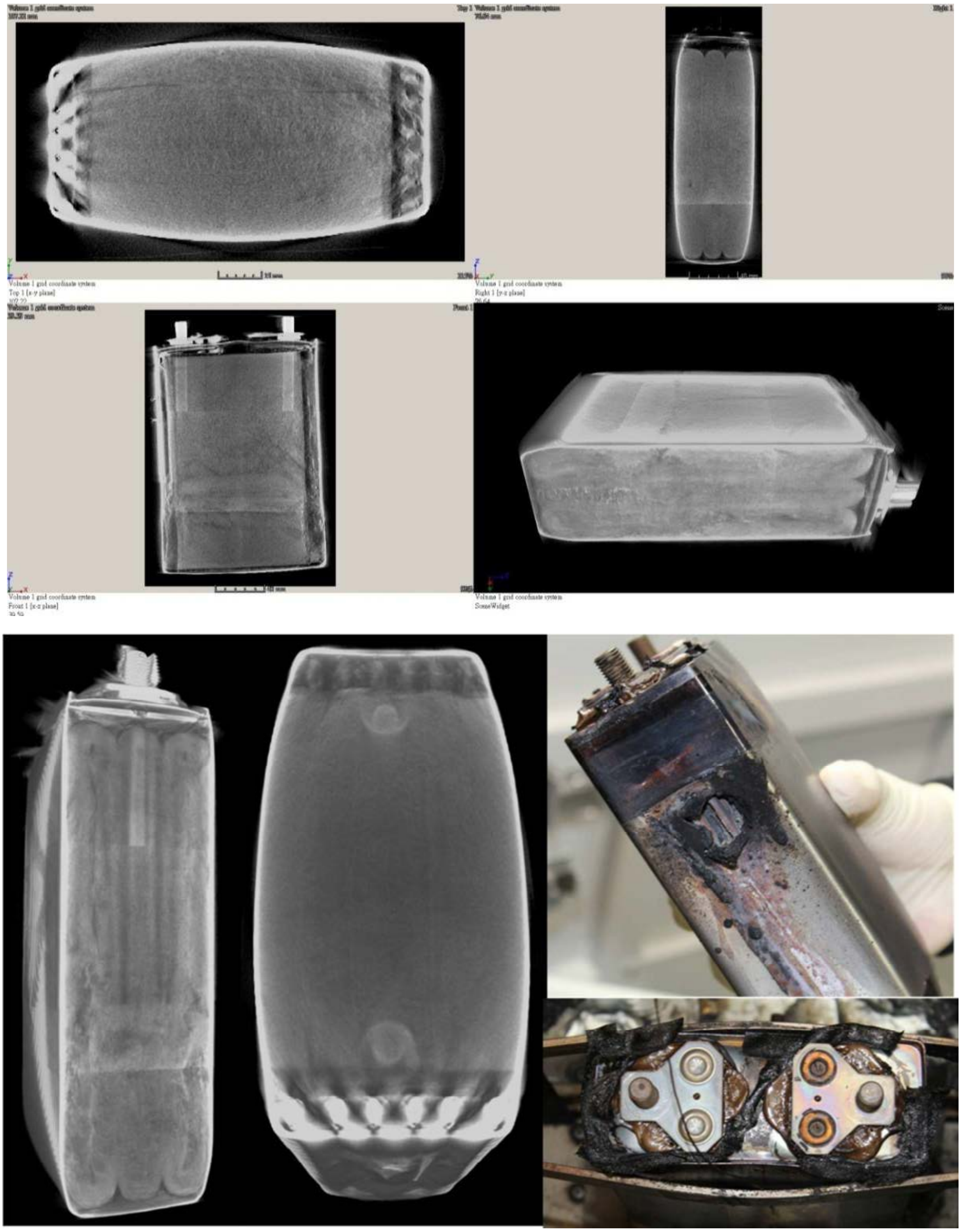


Figure 105. CT scan images of cell 412-4 after ARC test

Figure 106. Status of current collectors in LVP65 cell 412-4 after ARC thermal abuse test

CONCLUSION

In summary, the test results of the 18 cell-level abuse tests in this project are shown in Table 5.

Table 5 Test results of LVP65 cell-level abuse tests

Sample	149-1 241-1	149-2 241-2	149-3 241-4	149-5 241-3	149-4 241-5	149-6 241-6	149-7 241-7	149-8 241-8	171-8	412-4
Test	IISC		NP test				Hot Pat test			ARC
Test condition	25°C 0.1mm/s 20mV	70°C 0.1mm/s 20mV	25°C Side 20mm/s	25°C Top 20mm/s	70°C Side 20mm/s	70°C Top 20mm/s	25°C No load	70°C No load	25°C 8A load	50-305°C 5°C step 0.02°C/m
Test Result	Venting, Smoke	Venting, Smoke	Venting, Smoke	Venting, Smoke	Venting, Smoke (149-5) **Fire (241-3)**	Venting, Smoke	Venting, Smoke	Venting, Smoke	Venting, Smoke	N/A
Max T [*1]	322°C 331°C	336°C 290°C	305°C 340°C	366°C 330°C	314°C **409°C**	325°C 346°C	507°C 417°C	508°C	409°C 417°C	N/A
Max T near vent	294°C 331°C	336°C 290°C	305°C 242°C	366°C 330°C	193°C 290°C	292°C 231°C	107°C 373°C	216°C	358°C 298°C	N/A
Max T at Indenter/ Nail/Pad	322°C 314°C	313°C 283°C	271°C 340°C	264°C 242°C	314°C 355°C	325°C 346°C	507°C 417°C	508°C	409°C 417°C	N/A
Time from ISC to Max Vent T (s)	219.1 192.7	146.1 28.2	141.8 70.5	149 16.6	52.6 26.9	38.1 19.4	94.7 112.6	45.5	212.1 159.8	N/A
Open fuse?	W1 (149-1) W1 (241-1)	W1 (149-2); W1 and W2 (241-2)	W1 (149-3) W1 (241-4)	W1 and W2 (149-4) W1 (241-5)	None (149-5) None (241-3)	W2 (149-6) None (241-6)	W1 (149-7) W1 (241-7)	W1 (171-8)	W1 (149-8) W1 (241-8)	None

Note*1: Maximum temperature on cell may not present the severity of test result as the temperature variation is affected largely by failure modes and the locations of maximum temperature may differ

Although all 18 tests have similar results with thermal runaway, venting and swollen cells, these different types of tests still represent different means of abuse conditions:

- IIISC simulates localized internal short circuit without changing too much on the integrity of the cell construction. It represents the short circuit initiated within the cell such as dendrites, impurities, separator defects, etc.
- NP simulates larger-scale internal short circuit such as the internal short circuit caused by mechanical intrusion of external subjects, or by physical damage of the cells.
- HP simulates the internal short circuit caused by heat, such as the heat propagation from another failed cell, or from the fire.
- ARC simulates the thermal abuse in an ideal adiabatic environment, so the thermal stability performances, such as self-heating rate, can be understood.

The safety of a lithium-ion battery system has to be guarded by different levels of attention - from the materials of the cell, the cell, module, pack, to the system. Therefore for a lithium-ion battery system designer, it is imperative to consider all possible failure mechanisms from the cell level, in order to understand the safety boundary of the cells and try to mitigate all possible failures in the system design.

On the other hand, for the safety assessment of a lithium-ion battery system, it is very critical to understand the cell-level performances so that the safety boundary of the very basic unit of the battery system – the cells, can be fully addressed when developing appropriate evaluation criterion for a battery system. A well-defined lithium-ion battery safety assessment system has to evaluate the safety performances from materials, cells, modules, to the battery systems, and to address the safety concerns from both external and internal causes.