Office for Product
Safety & Standards

Testing of Vape Batteries

The development and review of tests for assessing the safety of 18650 batteries for vaping

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Acknowledgements

This independent research report was produced by Jonathan Buston, Steve Goddard and Gemma Howard at the Health and Safety Executive (HSE) Science and Research Centre.

The views expressed in this report are those of the authors, not necessarily those of the Office for Product Safety and Standards or the Department for Business, Energy & Industrial Strategy (nor do they reflect Government policy).

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Executive Summary

Lithium ion cells are commonly used to power vapes (e-cigarettes). Many vape devices allow for use of interchangeable batteries, so the purchasing of additional or replacement batteries is common. Furthermore, some vapers seek to modify their devices, and demand higher current flows from their batteries to enable this.

Lithium ion batteries can, under a range of conditions, enter an uncontrolled condition known as thermal runaway. This can often lead to a fire, and the cell rupturing and/or ejecting its hot contents. During thermal runaway events, cell surface temperatures of 700 °C are typical.

The Office of Product Safety and Standards (OPSS) approached HSE in order to define a suite of tests that could indicate if a cell was fit for the purposes of vaping.

HSE proposed a number of tests to OPSS that might allow the identification of lithium ion cells which were less safe for use in vapes. Some of these were selected by OPSS for initial screening.

OPSS arranged the purchase of ten batches of 18650 sized cells, which were delivered to HSE-SRC, Buxton. The cells procured were a mixture of those claiming to be from reputable manufacturers, and rebranded products. Cells were sourced online, from a range of suppliers including dedicated retailers and a variety of sellers on an online marketplace.

Since some of these cells came with unclear provenance, and unrealistic claims about their capacity, all testing was performed remotely within the battery testing facilities at HSE-SRC by experienced staff so in order to protect personnel and provide mitigation in the event of any adverse cell failure events.

Outcomes

‘Cycling’ tests (repeated charge/discharge at different rates) clearly indicated that cells that claimed clearly implausible advertised capacities did indeed fall far short of their claims. Indeed, these cells tended to be the worst performing cells on test. Furthermore, not all of the cells tested were found able to deliver capacity at the higher discharge current rates often demanded from vapes.

Using a ‘pulsed discharge’ to better mimic real-life vape use was, in general observed to allow more charge to be extracted from the cells.

Overcharge tests (allowing a two amp current, but with no upper voltage limit) demonstrated that all of the cells procured had some kind of internal protection built in. The minimum level of protection typically found in a cell of this type is a combined pressure relief and current interrupt device (CID). These protection components prevented all the cells tested (one from each batch) from entering a potentially dangerous thermal runaway condition which, more often than not would lead to a fire. However, high surface temperatures and damage to the cell packaging was observed in some cases; it could not be ruled out that any repetition of those tests on other cells might lead to cell failures involving fire.

Short-circuit tests (allowing the maximum current to be drained from the cells) once again demonstrated that all of the cells tested had some kind of internal protection built in. These protection components prevented all the cells tested (one from each batch) from entering a dangerous thermal runaway condition which, more often than not would lead to a fire. During testing, high surface temperatures and damage to the cell packaging was observed in some cases, with electrolyte being extruded from the cell in one case; it could not be ruled out that repetition of those tests on other cells might lead to cell failures involving fire.

Recommendations

Of the tests undertaken during this work, it is recommended that a future test suite should include:

- **A capacity test**. This may not need to be as extensive as performed here, but should include both low and high rates of charge and discharge - cell capacities are often quoted at low rates where capacity is greater, and higher rates are more representative of cell performance in a vape device. Any marked drop-off in capacity at higher currents may suggest a cell is not suited for use with vape devices. Capacity testing could include a portion where the discharge is not continuous, but has an intermittent or pulsed profile.
- **An overcharge test**. This will help identify and verify protection mechanisms built into the cell. Where higher temperatures are observed for a particular cell type, consideration should be given to repeating the test on other specimens of that cell.
- **A short circuit test**. Again, this will help to help identify and verify protection mechanisms built into the cell. Where higher temperatures are observed for a particular cell type, consideration should be given to repeating the test on other specimens of that cell.

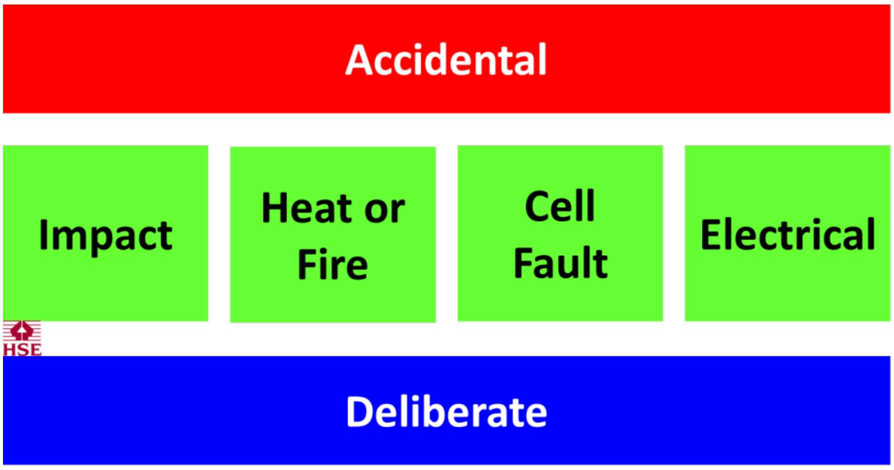
During testing, a number of cases showing significantly elevated temperatures were observed. Whilst it was not determined at which temperature these cells undergo final failure at, it is **strongly recommended** that some kind of **temperature test** is employed to determine this. Several options for determination of this value are provided.

Two other questions remain. Firstly, does a cell become more or less ‘safe’ with age and continued use? As a cell ages, the capacity of that cell tends to drop, and therefore it might be expected that the severity of any failure event will decrease. However, the likelihood of any failure event will reasonably increase with cell age, making the cell more prone to failure. The second question relates to the cells with dramatically over claimed capacities. Typically, the more exaggerated the claim, the more poorly performing the cell behaved in capacity measurement. But how does this translate to safety? Is the cell safer as it actually contains less electrical energy to dissipate (although the electrical energy is typically about a third of the energy released in a flaming failure event)? Or is the cell more likely to fail? Again, the testing strategies above may provide further insight.

1 Introduction

Lithium ion cells have been well documented to have dramatic failure modes, often (but not always) including small jet flames. The manner of the initiation of these failures is varied, but most will progress through generation of a small internal short circuit within the cell (Figure 1). This short circuit allows large currents to flow in small areas, leading to heat generation, which accelerates the failure, leading to a thermal runaway (a self-accelerating reaction which is difficult, if not impossible to bring under control).

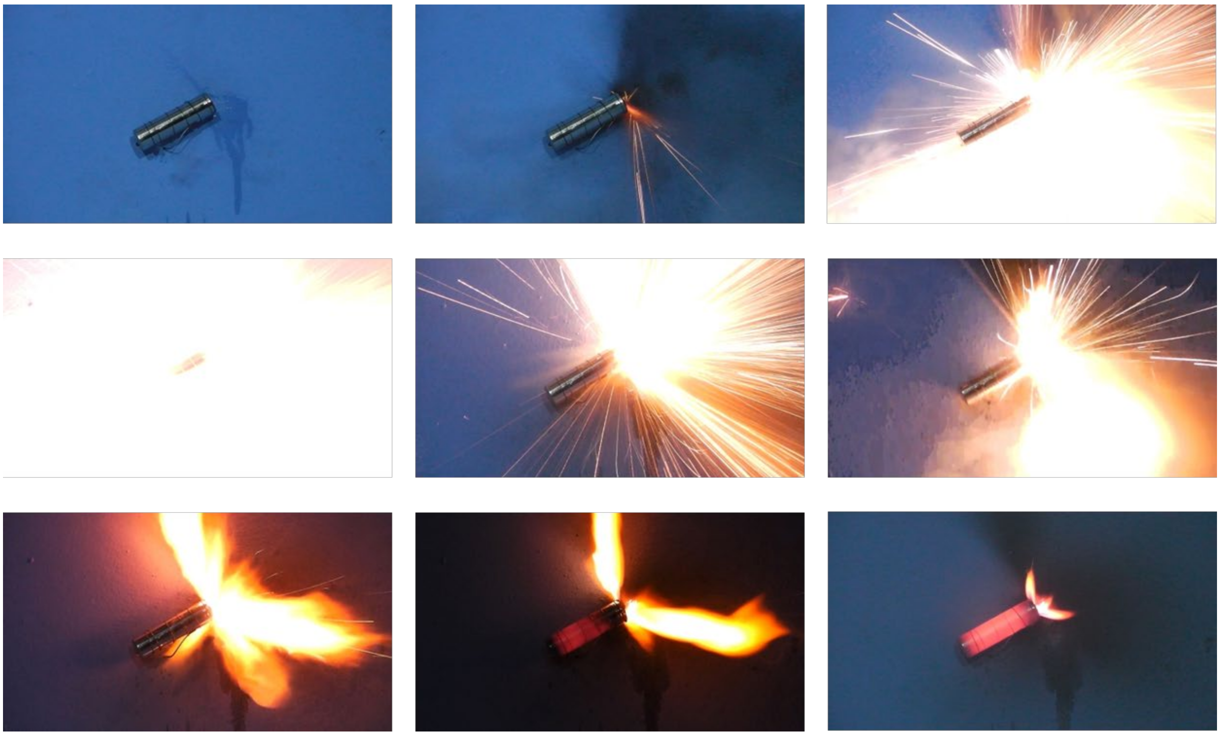
Figure 1 Causes of cell failure



Thermal runaway creates flammable gas within the cell, which eventually builds up sufficient pressure to escape through the vent or by rupturing the cell. At higher states of charge (SoC), this will most often be accompanied by self-ignition of the flammable gas produced. Figure 2 shows the typical progression of this type of thermal runaway process for an 18650 sized cell. In this test, the cell was not allowed to move, and most of the contents of the cells stayed within it; however the forces generated are able to propel the cells some distance, and cell casings rupture. These images were not captured as part of this piece of work.

Pertinent to this project, it is noted that manufacturing process can create cells with internal debris present or other means that leaves them more prone to generating internal short circuits in normal use. These faults might manifest immediately, but (due to production quality control testing) more likely only once a cell has been in use for some time. As a result, the work described in this report is not looking directly at user-generated abuse conditions, but those which might unearth or indicate internally flawed cells or design processes.

Figure 2 Thermal runaway process of a typical 18650 cell, showing the progression of the event. This cell was physically restrained during the test so that it could not move. (Images were generated during previous project work).



Vapes generally enclose their batteries further in a metal casing. This may mitigate the severity of very low level failures, but may enhance the effect of thermal runaways by confining flame, heat and gas generation into a fixed volume. Should the item rupture the casing could lead to an increased risk of generating high energy metal fragments during failure. Generation of such fragments in vape cell failure are reported to have caused serious harm (in addition to the burn injuries most commonly encountered), and, *in extremis* fatalities.

Cylindrical cells such as tested within this project may be designed with a variety of strategies to prevent these adverse outcomes. These include:

- A positive temperate coefficient (PTC) device, which increases the resistance of the device (and therefore reduces current flow) as its temperature increases. These are most often reversible; hence the cell will continue to function when it has cooled.
- A gas vent, to allow any pressure that builds up within the cell to escape in a planned manner, rather than through rupturing the cell casing.
- A current interruption device (CID) that breaks the current path once activated. These are generally combined with the gas vent, and activate at the same time. They are generally designed to be irreversible if functioning correctly, rendering the cell permanently unusable.
- Cells can be designed with different internal ‘separators’ (an electrically insulating membrane that separates the electrodes but allows lithium ions and often electrolyte to pass through). Some (more expensive) separators are coated with materials (often ceramic) to make them more resilient to some causes of internal short circuit. Others so-called ‘shut-down’ separators employ membranes that

undergo a partial melt at elevated temperatures. This blocks the pores in the membrane, stopping the passage of lithium ions, and hence current. However with continued heating from external sources, these separators fully melt, allowing uncontrolled short circuits.

- Some cells, particularly those for the consumer market, have additional ’protection‘. Often this is a small round circuit board that is fitted to the end of the cell and then packaged within the plastic wrapping present on all of these cells. This circuitry can incorporate many functions, but typically will limit the voltages that can be applied to the cell (aiming to prevent both over-charge and over-discharge), and limit the current that can flow. These most often operate reversibly.

A more complete coverage of failure modes and effects of lithium ion batteries, and approaches to controlling these is provided in a recent publication[1].

Cylindrical lithium ion cells, predominantly of the ‘18650’ size, are commonly used in vapes (e-Cigarettes). The Office of Product Safety and Standards (OPSS) approached HSE in order to define a suite of tests that could indicate if a cell was fit for the purposes of vaping.

HSE proposed a number of tests to OPSS that might allow the identification of lithium ion cells which were less safe for use in vapes. Some of these were selected by OPSS for initial screening.

- **Cell cycling.** This would test the capacity (both charge and discharge) of the cells at a variety of different rates, whilst monitoring cell surface temperature. (Note that use in vapes is often associated with high current requirements, but only for short bursts). This test determines actual capacity of the cell against claimed capacity. *Selected by OPSS for initial screening.*
- **Pulsed discharge.** A fully charged cell would be discharged using short, high current bursts, interspersed by rest periods, whilst measuring cell surface temperature. This test is more representative of the duty cycle under vaping conditions than a continuous discharge test. *Selected by OPSS for initial screening*
- **Cell aging.** A sample set of cells would be cycled (a charge/discharge loop) at a fixed rate, in order to see how quickly capacity fades with use. Lower cell life is often an indicator of degradation at an electrode level. *Not selected by OPSS for initial screening.*
- **Overcharge.** Cells would be overcharged at 2 A (to simulate standard USB charge current levels), but without the normal maximum voltage limit being applied, to determine the response to poorly controlled chargers. Cell surface temperature also being monitored. *Selected by OPSS for initial screening*
- **Short circuit.** Cells would be subjected to a short circuit pathway, leading to high current flow. Cell surface temperature would be monitored. *Selected by OPSS for initial screening*
- **Temperature test.** Cells would be slowly heated to determine at what temperature the internal self-heating process that eventually leads to thermal runaway start. This test would aim to understand how close to the thermal limits cells are coming within

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[1] Li-Battery Safety, edited J. Garche and K. Brandt. Part of the Electrochemical Power Sources: Fundamentals, Systems and Applications series. 2019

the other tests, and to understand if cells with a less illustrious pedigree display lower onset temperatures. *Not selected by OPSS for initial screening.*

OPSS arranged the purchase of ten batches of 18650 sized cells, which were delivered to HSE-SRC, Buxton. Each batch consisted of ten cells, except for the first, where twenty cells were supplied to allow any extra development of testing protocols. The cells procured were a mixture of those claiming to be from reputable manufacturers, and rebranded products. Cells were sourced online, from a range of suppliers including dedicated retailers and a variety of sellers on an online marketplace.

Since some of these cells came with unclear provenance, and unrealistic claims about their capacity, all testing was performed remotely so in order to provide mitigation. Typically this meant that cells were in a ventilated blast chamber, with HSE staff initiating and monitoring tests from a separate room.

2 Physical Characterisation

2.1 Initial Characterisation

2.1.1 Packaging

OPSS arranged for the supply of 10 cells of each type to HSE (20 of cell type A). For the purposes of this project, these have been designated as cells OPSS-A to OPSS-J, as shown in Table 1. When received at HSE-SRC, the cells were unpacked. It should be noted that OPSS-C cells were supplied with chargers (HSE do not believe that these were specifically ordered; it may be that these allowed the shipper to claim the supply of 'lithium ion batteries with equipment' a different shipping class).

Three of the cells (B, D and H) were found to be 'double wrapped'- that is having two separate layers of PVC wrap on each cell. Whilst it is not unusual for cells to be 'rebranded' by a proprietary wrap, the inner wrap may provide some indication of the origin of the cell.

Two of the cells (H and I) were evidently 'protected' cells- having a small round circuit board attached to the cell at the negative end. This was discernible through the packaging, both by the extra length of these cells, and by the slight ridge seen in the cell wrap.

NB: All tools used to assist in the unwrapping of the cells were non-conductive (e.g. ceramic scissors).

Table 1: Cell Identification and Source

Designation	Claimed Nominal Capacity	Supplier
OPSS-A	2500 mAh	Online retailer
OPSS-B	4200 mAh	Online marketplace seller
OPSS-C	9900 mAh	Online marketplace seller
OPSS-D	4800 mAh	Online marketplace seller
OPSS-E	2600 mAh	Online marketplace seller
OPSS-F	6000 mAh	Online marketplace seller
OPSS-G	3350 mAh	Online retailer

OPSS-H	3500 mAh	Online retailer
OPSS-I	3500 mAh	Online retailer
OPSS-J	3000 mAh	Online retailer

2.1.2 Physical Measurement

All cells were weighed and measured on arrival. The initial open cell voltage (OCV) and internal resistance was measured using an Applent AT526B internal resistance meter. A summary of the average results obtained for each cell type is shown in Table 2; the full dataset is reported in Appendix A, in which anomalous values are also highlighted.

Table 2: Initial Recorded Measurements of Received Cell Types

Cell Type	Average or Range	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-A	*Average*	65.0	18.2	43.8	3.52	13.2
	Range	-	-	0.2	0	1.4
OPSS-B	*Average*	66.8	18.4	43.9	3.86	53.7
	Range	-	-	0.9	0.25	11
OPSS-C	*Average*	67.5	18.0	34.5	3.96	52.8
	Range	-	-	1.3	0.27	22.3
OPSS-D	*Average*	66.6	18.2	41.4	3.51	36.9
	Range	-	-	2.9	2.97	11.1
OPSS-E	*Average*	65.0	18.2	46.0	3.23	11.2
	Range	-	-	0.6	2.82	0.9

OPSS-F	*Average*	67.7	18.0	35.3	3.93	39.2
	Range	-	-	0.7	0.04	7.2
OPSS-G	*Average*	65.0	18.2	45.5	3.53	36.9
	Range	-	-	0.2	0.01	2.6
OPSS-H	*Average*	68.7	18.5	49.1	3.50	44.7
	Range	-	-	0.1	0	6.4
OPSS-I	*Average*	69.2	18.2	48.1	3.83	36.8
	Range	-	-	0.3	0.03	4.1
OPSS-J	*Average*	65.0	18.2	45.9	3.45	13.0
	Range	-	-	0.2	0	5.5

2.2 Observations

Variations in the cell length between different types of cells are because some of the cells are ‘button topped’ or are ‘protected’ cells, having the extra circuit board welded onto the bottom of the cell. Variations in the weight are less easy to explain. The two cells (Cells C and F) which are markedly lighter (*ca.* 10 g / >20% lighter) than the others should arouse suspicion.

Two cells (one each from type D and E) arrived with an OCV of less than 1 V- this would be a concern since a normal operating range for lithium ion cells is 4.2 V (100% SoC (state-of-charge)) to 2.5 or 2.75 V (0% SoC). It is not recommended to discharge cells below these lower voltage limits, and certainly not to recharge cells from such a low voltage.

The range of internal resistance values between cell types is to be expected. This is a function of cell design and construction; in general, cells designed for high power applications would have a lower internal resistance.

3 Cell Cycling

The aim of this initial test was to determine if cells meet their nameplate capacity (or how close they come) and are suitable and safe for further testing. Three cells of each type supplied were selected at random to be tested, so that variation within a batch supplied could be probed.

3.1 Cell Cycling Test Method

The cells were cycled using a Neware BTS4000 5 V, 12 A, 8 channel cell cycler (Figure 3). The cells were held in Arbin cell holders (rated for 200 A current). Due to the unexalted provenance of some of the cells, each cell was placed within a separate enclosure constructed from a fire-resistant material (Figure 4), designed to stop any fire related failure mode from propagating to other cells, each cell being contained in its own section of the enclosure. The test enclosure was positioned within a blast cell to protect staff and mitigate any energetic failure modes; in addition, the blast cell could be ventilated in the case of any adverse event. Temperatures on the surface of each cell were recorded using type-T thermocouples.

Figure 3 Cell cycler- Control and temperature unit on top, power unit (beige) showing power cable bundle going into blast cell

Figure 4 Custom built cell holding enclosure (1 cell per section)

Three cells of each type were cycled, each using two different routines, routine 1 and routine 2, which are shown in Table 3. These routines were performed sequentially on the cells but with an undefined period of rest between them –operators would manually initiate the start of routine 2 after routine 1 had completed. Routine 2 contains the more aggressive cycles; these were only initiated once the safe performance of the cell during the less aggressive routine 1 had been assessed.

Charging steps were performed using a standard constant current constant voltage (CCCV) step: charging firstly at the stated constant current to 4.2 V, then holding the voltage at 4.2 V whilst reducing the current. Charging was stopped when the current reduced to 100 mA.

Discharge steps were performed with a constant current (CC), and terminated when the cell voltage dropped to 2.75 V under load. The voltage was generally observed to recover once the load was removed.

Rest periods of 20 minutes were allowed between all charge and discharge cycles.

Note that parameters used within these routines are representative of industry specifications. Some cells have specified discharge limits of 2.5 V, and there is considerable variation in the current limits in the charge cycles. The values used here are representative and uniform.

Table 3: Cycling Routines 1 and 2

Step	Type	Charge current / A	Discharge current / A	Time (minutes)
Routine 1				
1	CC Discharge		1	
2	Rest			20
3	CCCV Charge	1		
4	Rest			20
5	CC Discharge		1	

6	Rest			20
7	CCCV Charge	1		
8	Rest			20
9	CC Discharge		1	
10	Rest			20
11	CCCV Charge	1		
12	Rest			20
13	CC Discharge		0.2	
14	Rest			20
15	CCCV Charge	0.2		
16	Rest			20
17	CC Discharge		0.5	
18	Rest			20
19	CCCV Charge	0.5		
20	Rest			20
21	CC Discharge		1	
22	Rest			20
23	CCCV Charge	1		
24	Rest			20
25	CC Discharge		2	
26	Rest			20
27	CCCV Charge	2		
28	Rest			20
29	CC Discharge		3	
30	Rest			20
31	CCCV Charge	2		
32	Rest			20
33	CC Discharge		5	
34	Rest			20
35	CCCV Charge (NB: limited to 1Ah max)	1		
36	Rest			20
Routine 2				
1	CCCV Charge	2		
2	Rest			20
3	CC Discharge		10	
4	Rest			5
5	CC Discharge		1	
6	Rest			20
7	CCCV Charge	2		
8	Rest			20
9	CC Discharge		12	
10	Rest			5
11	CC Discharge		1	
12	Rest			20
13	CCCV Charge	5		
14	Rest			20
15	CC Discharge		1	

16	Rest			20
17	CCCV Charge (NB: limited to 1Ah max)	1		
18	Rest			20

3.2 Cell Cycling Results

Table 4 shows selected outcomes of the discharge capacities measured (average value from testing three cells of each type), and how they compare to the declared nominal capacity.

Table 4: Discharge Capacity Profiles for Cells A-J

Cell Type	Declared Nominal Capacity (mAh)*	Measured Capacity at 1A Discharge (mAh)	% of Nominal	Measured Capacity at 10A Discharge (mAh)	% of Nominal
Cell A	2500	2440	98	2410	96
Cell B	4200	1535	37	155	4
Cell C	9900	920	9	35	0
Cell D	4800	1220	25	115	2
Cell E	2600	2415	93	2400	92
Cell F	6000	1245	21	70	1
Cell G	3350	2995	89	2405	72
Cell H	3500	3265	93	2765	79
Cell I	2900	3185	91	2542	73
Cell J	3000	2895	97	2805	93

* This nominal capacity is defined by the manufacturer and is often measured at very low charge/discharge rates where the apparent capacity will be maximised.

More detailed summaries are shown in Table 5 (average value from testing three cells of each type); full details are reported in Appendix B.

Table 5: Charge/Discharge Capacity Profiles at Varying Rates for Cells A-J.

Cell Type	Nominal Capacity (mAh)	Charge and Discharge Capacities (mAh) at different rates				
		Rate (A)	Charge	%	Discharge	%
Cell A	2500	0.2	2526	101	2525	101
		0.5	2467	99	2466	99
		1	2450	98	2442	98
		2	2387	84	2382	95
		3			2371	95
		5	2505	100	2386	95
		10			2410	96
		12			2410	96
Cell B	4200	0.2	1588	38	1572	37
		0.5	1556	37	1569	37
		1	1542	37	1535	37
		2	1340	30	1410	34
		3			1199	29
		5	1454	35	841	20
		10			155	4
		12			150	4
Cell C	9900	0.2	963	10	963	10
		0.5	927	9	931	9
		1	964	10	923	9
		2	443	3	605	6
		3			228	2

		5	696	7	53	1
		10			37	0
		12			18	0
Cell D	4800	Rate (A)	Charge	%	Discharge	%
		0.2	1333	28	1310	27
		0.5	1320	28	1311	27
		1	1234	26	1221	25
		2	1150	24	1170	24
		3			1096	23
		5	1314	27	1083	23
		10			116	2
		12			90	2
Cell E	2600	Rate (A)	Charge	%	Discharge	%
		0.2	2566	99	2559	98
		0.5	2459	95	2460	95
		1	2411	93	2416	93
		2	2358	80	2362	91
		3			2338	90
		5	2543	98	2324	89
		10			2397	92
		12			2428	93
Cell F	6000	Rate (A)	Charge	%	Discharge	%
		0.2	1288	21	1283	21
		0.5	1272	21	1278	21
		1	1234	21	1247	21
		2	1030	13	1100	18

		3			924	15
		5	1091	18	263	4
		10			71	1
		12			59	1
Cell G	3350	Rate (A)	Charge	%	Discharge	%
		0.2	3143	94	3134	94
		0.5	3004	90	2994	89
		1	3013	90	2994	89
		2	2848	73	2873	86
		3			2787	83
		5	3055	91	2643	79
		10			2405	72
		12			1895	57
Cell H	3500	Rate (A)	Charge	%	Discharge	%
		0.2	3364	96	3361	96
		0.5	3300	94	3289	94
		1	3269	93	3264	93
		2	3232	78	3228	92
		3			3200	91
		5	3281	94	3154	90
		10			2763	79
		12			2494	71
Cell E	2600	Rate (A)	Charge	%	Discharge	%
		0.2	2566	99	2559	98
		0.5	2459	95	2460	95
		1	2411	93	2416	93

		2	2358	80	2362	91
		3			2338	90
		5	2543	98	2324	89
		10			2397	92
		12			2428	93
Cell F	6000	Rate (A)	Charge	%	Discharge	%
		0.2	1288	21	1283	21
		0.5	1272	21	1278	21
		1	1234	21	1247	21
		2	1030	13	1100	18
		3			924	15
		5	1091	18	263	4
		10			71	1
		12			59	1
Cell G	3350	Rate (A)	Charge	%	Discharge	%
		0.2	3143	94	3134	94
		0.5	3004	90	2994	89
		1	3013	90	2994	89
		2	2848	73	2873	86
		3			2787	83
		5	3055	91	2643	79
		10			2405	72
		12			1895	57
Cell H	3500	Rate (A)	Charge	%	Discharge	%
		0.2	3364	96	3361	96
		0.5	3300	94	3289	94

		1	3269	93	3264	93
		2	3232	78	3228	92
		3			3200	91
		5	3281	94	3154	90
		10			2763	79
		12			2494	71
Cell I	2900	Rate (A)	Charge	%	Discharge	%
		0.2	3300	94	3288	94
		0.5	3228	92	3231	92
		1	3190	91	3183	91
		2	3160	70	3166	90
		3			3129	89
		5	3203	92	3081	88
		10			2542	73
		12			50	1
Cell J	3000	Rate (A)	Charge	%	Discharge	%
		0.2	2978	99	2969	99
		0.5	2940	98	2940	98
		1	2903	97	2896	97
		2	2900	83	2895	96
		3			2879	96
		5	2942	98	2855	95
		10			2803	93
		12			2791	93

The maximum temperature seen in several of the more demanding cycles was also recorded, and is shown in Table 6. Generally the highest temperature was seen just before the discharge/charge ended.

Table 6: Average Cell-Surface Temperatures for Cells A-J During Charge/Discharge.

	Average T_{max} (°C)		
Cell Type	**10 A Discharge**	**12 A Discharge**	**5 A Charge**
A	42	48	31
B	27	30	27
C	25	23	25
D	29	27	29
E	37	42	29
F	24	24	26
G	57	59	32
H	61	67	37
I	58	23	36
J	44	49	31

3.3 Cell Cycling Observations

- The highest capacities on the market from the traditionally reputable brands have an upper capacity limit of around 3500 mAh for an 18650 sized cell; often less if the cell is designed to be a ‘power’ cell - providing higher currents. None of the cells tested exceeded that limit, whatever the claimed capacity of the cell.
- The cells that made the more outrageous capacity claims delivered the least; they were not even average cells.
- The cell types which were anomalously light (Cells C and F) had very low capacities.
- Not all cells were capable of delivering higher currents with reasonable capacity; some showed a marked drop off as the current increased. This observation could be used as being indicative that a cell is distinctly unsuited for use within a vape.

- Cell I performed well at currents up to 10 A; at 12 A the capacity was much reduced; this is likely a feature of the included extra protection circuitry limiting the discharge voltage.
- Cell C showed a significant variation between the three cells evaluated. One individual cell had a capacity *ca*. 40% higher than the other cells of the same type (albeit all were much less than the nominal capacity). With this cell type, the capacity also appeared to fade even within the relatively few cycles used.
- Cells were generally supplied at an initial SoC of 15-25% (based on nominal capacity, where the nominal capacity was reasonable, much less in those cases where the nominal capacity was unreasonably over claimed). Measured SoC appeared to be consistent across the three cells of each type evaluated. However, Cell B showed one cell with a notably higher initial SoC than the other two. This is only likely to be an issue if a device used several cells at once; having imbalanced cells would increase the strain on all cells.
- Cell I was supplied at *ca*. 55% SoC. This may be permissible for road transport, but would have been a breach of aviation shipping rules, which limits SoC to a maximum of 30% nominal capacity.
- Some of the cells reached temperatures of up to 70 °C during the most demanding discharge cycles. This should be considered close to a temperature of concern for most cells. However, it should be noted that this occurred during a continuous discharge cycle where there is no time to dissipate heat, and is therefore a worst case event.

3.4 Cell Cycling Recommendations

- Some kind of capacity check would be an essential part of any assessment of cells. It may not need to be as exhaustive as that carried out here, but should encompass both low and high rate discharge phases, as well as charging at up to 2 A (as would be typical when using a USB charger).
- This testing should be carried out as a first test on any new batch of cells to determine both if it is safe to continue other testing, and as a determination of the actual capacity of the cell type.
- A number of cells from each batch should be tested to look for batch to batch variations. This would be of particular value where it was suspected that the cell was second-hand or a ‘re-wrap’.
- Consideration should be given to acquiring cells in several separate purchases a few weeks apart to determine if the cells originate from a single bulk batch, of if an expedient re-wrap and dispatch of whatever cells are at hand is occurring.
- It is recommended that the ageing of cells is investigated- how quickly the capacity of a cell fades with repeated charge/discharge cycles, particularly if rates typical of vape use are employed, rather than those recommended by the cell manufacturer (where given).
- It is not known if the failure of an ‘aged’ cell is more or less violent than that of a new cell (as capacity fades), nor if it is more or less likely (as internal damage that contributes to that reduced capacity) increases.

4 Pulsed Discharge

The pulsed discharge test is designed to be representative of real life use of cells in vapes, in which high currents are drawn sporadically for short periods of time. Vapes are likely to draw over 5 A in each pulse, with some ‘sub-ohm’ vapes drawing much more (over 15 A). It should be noted that not all 18650 cells are designed to deliver these current levels. This test was designed to probe if a cell could deliver high currents on an intermittent basis, even if it could not on a continuous discharge. It is not clear if the intermittent use would allow heat to dissipate more readily, or impose extra burdens on the cell.

4.1 Pulsed Discharge Test Method

These tests were performed within the same Neware BTS4000 cell cycler as detailed in section 3.1.

A fully charged cell was set to discharge at either 5 A or 12 A for two seconds, followed by an eight second rest period. Discharge voltage limits were as the standard cycling process. Cell surface temperature was measured by a type-T thermocouple.

4.2 Pulsed Discharge Results

The results obtained are shown in Table 7 for a 5 A discharge rate, and Table 8 for the 12 A discharge rate. The capacities for a continuous discharge are also shown for reference.

Table 7: Pulsed Discharge Capacities at 5 A Discharge Rates

Cell Type	Number of pulses	Average power in first pulse (W)	Average power last full pulse (W)	Total Discharged (mAh)	% of Nominal Capacity	Continuous Discharge (mAh)	% of Nominal Capacity
A	883	20.6	14.1	2460	(98 %)	2386	(95 %)
B	461	19.1	14.2	1284	(30 %)	841	(20 %)
C	349	18.8	14.6	972	(10 %)	53	(0.5 %)
D	424	19.6	14.3	1182	(25 %)	1083	(23 %)
E	881	20.6	14.9	2454	(94 %)	2324	(89 %)
F	364	18.9	15.0	1015	(17 %)	263	(4 %)

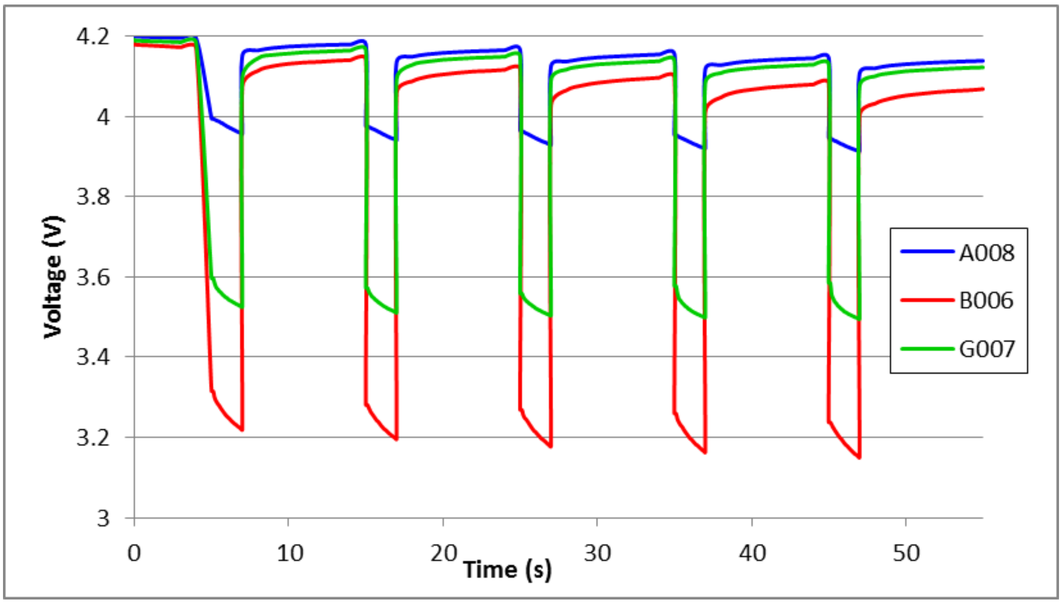
G	1067	19.6	14.4	2974	(89 %)	2643	(79 %)
H	1134	19.6	14.0	3161	(90 %)	3154	(90 %)
I	1100	19.4	14.0	3064	(106 %)	3081	(106 %)
J	1038	20.6	14.0	2893	(96 %)	2855	(95 %)

Table 8: Pulsed Discharge Capacities at 12 A Discharge Rates.

Cell Type	Number of pulses	Average power in first pulse (W)	Average power last full pulse (W)	Total Discharged (mAh)	% of Nominal Capacity	Continuous Discharge (mAh)	% of Nominal Capacity
A	363	47.8	33.9	2424	(97 %)	2410	(96 %)
B	157	39.2	33.9	1049	(25 %)	150	(3.6 %)
C	91	37.0	34.7	608	(6 %)	18	(0.2 %)
D	137	41.3	34.2	915	(19 %)	60	(1.3 %)
E	352	47.9	35.1	2352	(90 %)	2428	(93 %)
F	120	39.1	34.9	801	(13 %)	59	(1 %)
G	398	42.7	33.4	2659	(79 %)	1895	(57 %)
H	282	38.4	33.3	1884	(54 %)	2763	(79 %)
I	150	41.6	39.7	1002	(35 %)	50	(1.7 %)
J	415	47.7	33.6	2772	(92 %)	2791	(93 %)

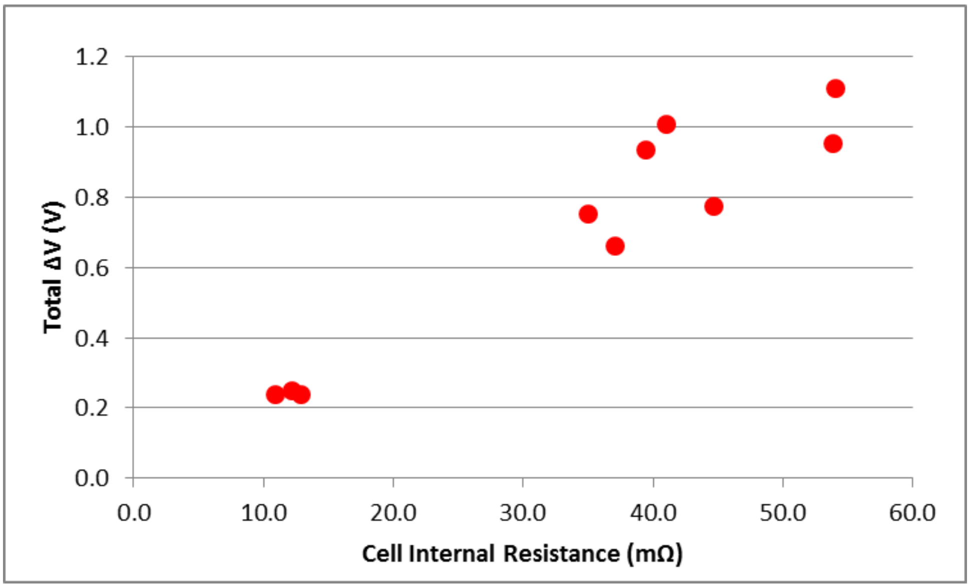
Figure 5 shows how the voltage of several of these cells decays within each of the first 5 pulses. Once the load is applied there is an immediate voltage drop (which varies depending on the cell design and composition), followed by a slower drop in voltage until the load is removed. During this testing, this sequence was repeated until a voltage of 2.75 V was observed, at which point the test was automatically curtailed.

Figure 5 Voltage decay during pulsed discharge at 12 A for three cells- first 5 pulses



One of the main drivers to the voltage drop is the internal resistance of the cell. Figure 6 shows the correlation between the internal resistance (for the actual cell) and the voltage drop of the pulse for the 12 A tests.

Figure 6 Voltage drop in the first pulse of each cell type and internal resistance (12 A pulses)



The temperature of the cell surface was measured during these tests; the maximum temperatures observed for the 12 A pulsed discharge are shown (Table 9), together with the maximum temperatures for the corresponding continuous discharge. It should be noted that the ambient temperature of the environment was neither measured nor controlled; it was, however, an unusually warm time. Care should therefore be taken in interpreting these results.

Table 9: Cell Surface Temperatures During Pulsed Discharge

Cell Type	Maximum observed temperature, pulsed discharge (°C)	When observed	Maximum observed temperature, continuous discharge (°C)
A	30	End of test	48
B	40	End of test	30
C	40	End of test	23
D	37	End of test	27
E	27	End of test	42
F	39	End of test	24
G	23	End of test	59
H	20	Mid test- ambient cooled overnight	67
I	34	End of test	23
J	22	Mid test- ambient cooled overnight	49

4.3 Pulsed Discharge Observations

- Most cells showed greater capacities during pulsed discharge than during continuous discharge. This appears to be because the rest steps allow the voltage to recover, allowing more discharge to occur before reaching the 2.75 V minimum voltage cut-off.
- Maximum observed temperatures were found not to be of concern during the pulsed discharge test. It is presumed that the additional rest time between the pulses allows heat to dissipate more effectively.
- It is not yet clear what impact pulsed discharge has on the cycle life of a cell; *i.e.* whether this method of discharge poses greater, lesser or just different strain on a cell.

4.4 Pulsed Discharge Recommendations

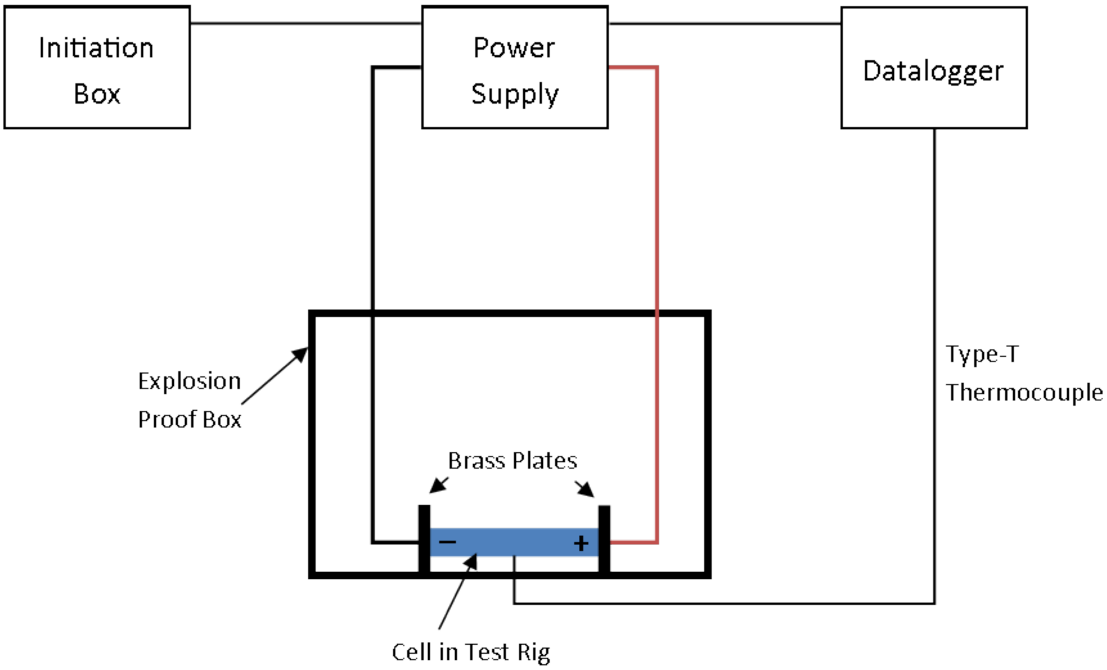
- Pulsed discharge (being representative of real-life usage) should be included in any suite of tests for vape batteries. This test could be incorporated as part of an extended cell cycling routine.
- It is recommended that ageing of cells be compared between those aged through continuous and pulsed discharge methods. The capacity change after ageing could be compared, possibly with comparison of ‘’point-of-no-return’ temperature values from an oven or accelerating rate calorimetry (ARC) test.

5 Overcharge Test

5.1 Overcharge Test Set-Up

The aim of the overcharge tests was to investigate the behaviour of each cell when charged at a constant current of 2 A from an initial state of charge of 50%. A schematic of the overcharge test rig is shown in Figure 7.

Figure 7 Schematic of overcharge test rig.



Individual, single cells were placed in the test rig horizontally, between two brass plates, and secured at the positive and negative terminals using brass screws. The cell under test was supported along its base with vertical pieces of insulating fireboard. Ring terminals were used to connect the power supply to the test rig *via* the brass screws at each end.

The power supply was set to provide a constant current of 2 A; the supplied current and cell voltage were recorded throughout the test using a Graphtec GL240 datalogger. The cell surface temperature was also measured and logged using a type-T thermocouple attached to the top of the surface of the cell. All data channels were recorded at a sampling frequency of 2 Hz.

Once initiated, the end of test was determined by the point at which the cell voltage matched the set power supply voltage (14 V). At this point, the current interrupt device (CID) of the cell was assumed to have activated, thus disconnecting the cell and forming an open-circuit with the power supply.

The overcharge test-rig is shown in Figure 8, Figure 9, Figure 10 and Figure 11.

Figure 8 Frontal view of overcharge test rig.

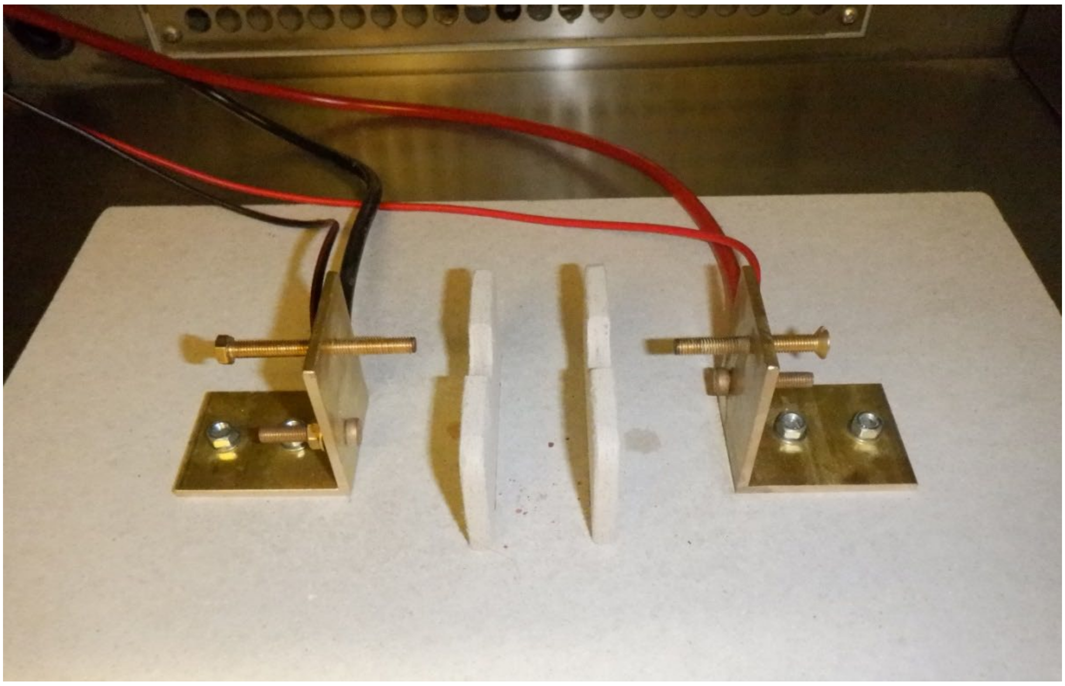


Figure 9 Initiation box, power supply and Graphtec datalogger used for the overcharge tests.

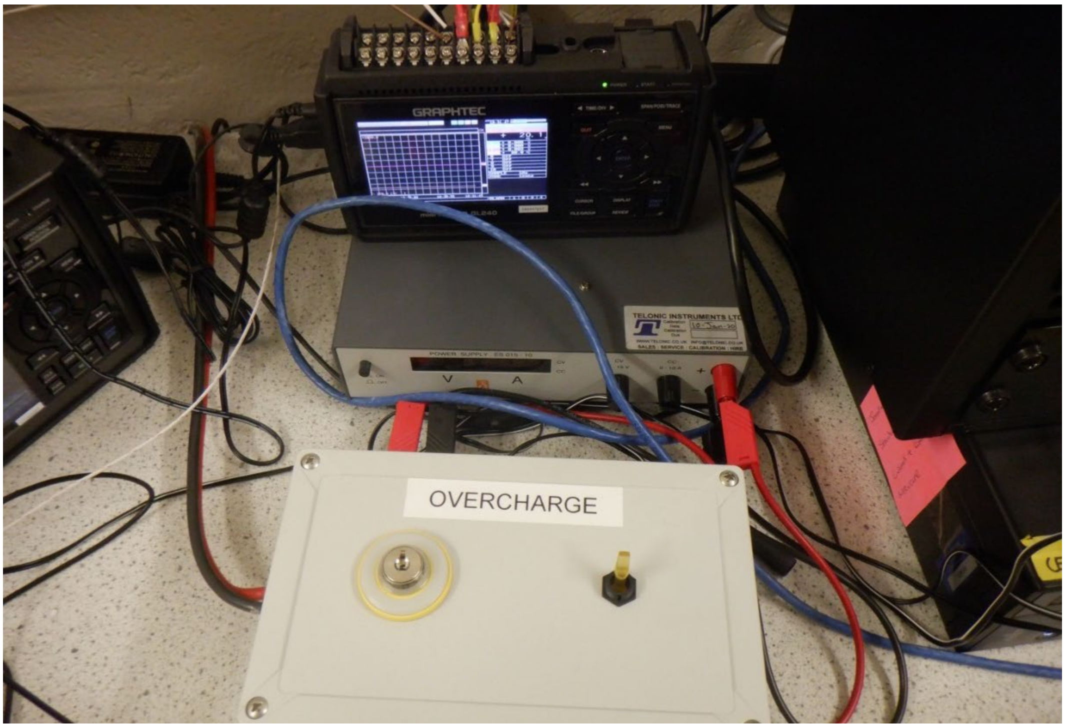


Figure 10 Explosion-proof box containing the test rig for the overcharge tests.

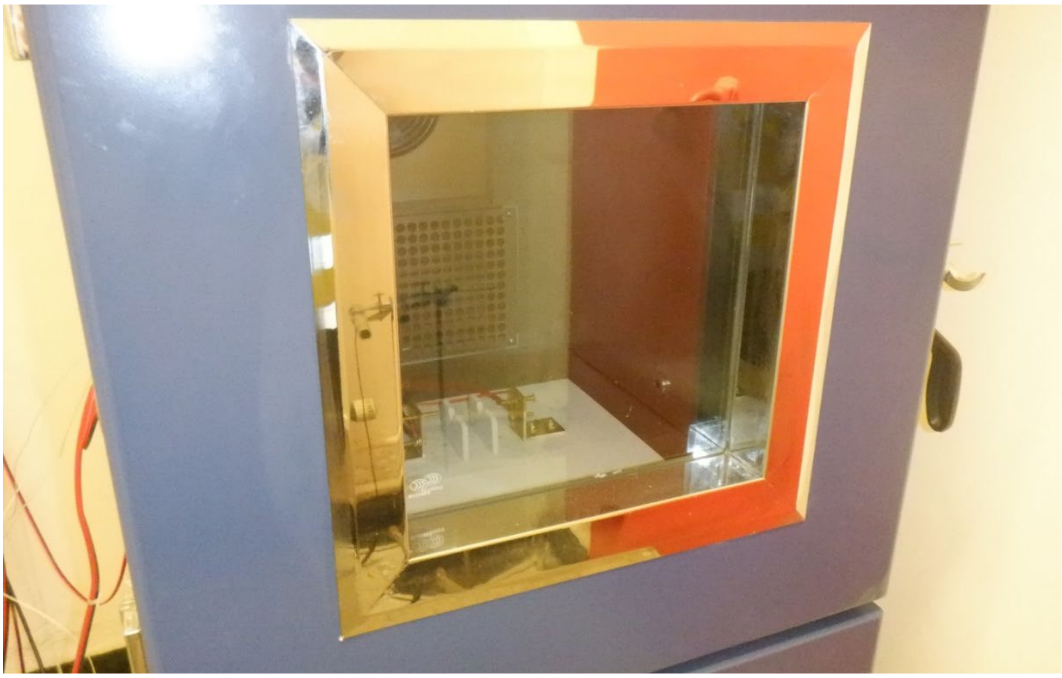
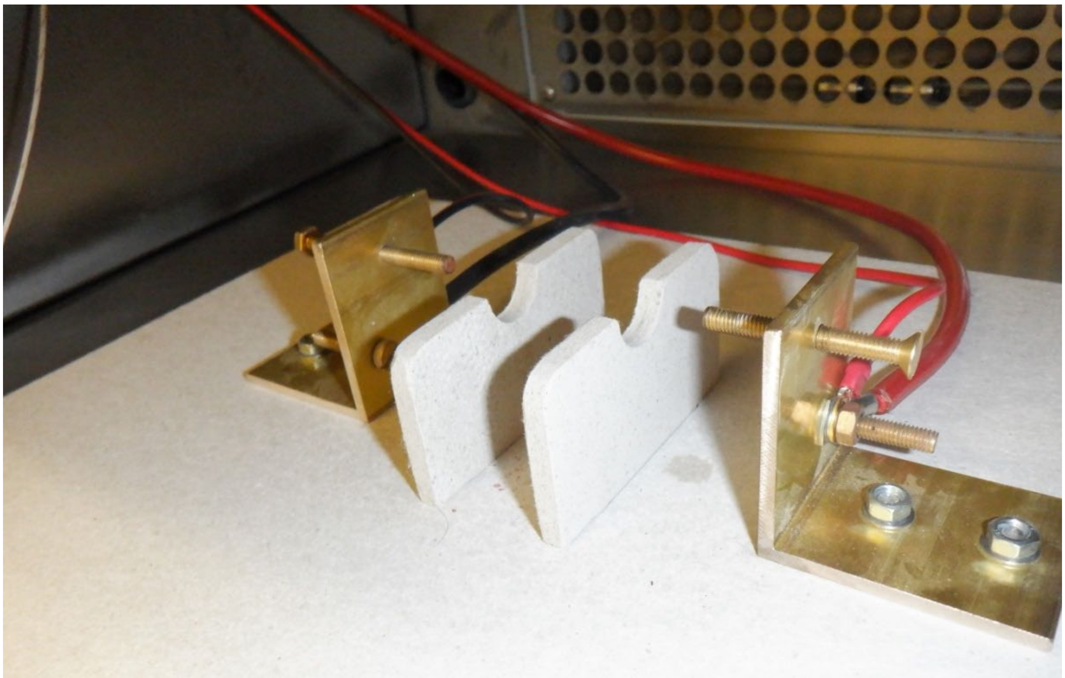


Figure 11 Side view of the overcharge test rig, showing the brass screws used to connect the positive and negative terminals of the cell



5.2 Overcharge Test Results

Table 10: Maximum Recorded Values Obtained from Overcharge Tests for Cells A-J.

Cell type	Maximum cell voltage (V)	Maximum temperature (°C)	Max. State of Charge based on capacity recorded prior to test (%)	Maximum cell capacity (Ah)
Cell A	4.99	35	128	3.2
Cell B	13.34	76	170	2.6
Cell C	13.43	110	142	1.3
Cell D	11.46	103	193	2.4
Cell E	5.11	45	129	3.1
Cell F	13.83	107	123	1.5
Cell G	5.17	61	137	4.1
Cell H	4.40	26	102	3.3
Cell I	4.34	26	101	3.0
Cell J	5.04	44	125	3.6

Table 11: Cell measurements at the point of Current Interrupt Device (CID) activation.

Cell Type	Charging time until the CID cut in (s)	Voltage (V)	Temperature (°C)	State of charge based on cell capacity recorded prior to test (%)	Cell capacity (Ah)
Cell A	3507	4.99	34	128	3.2
Cell B	3249	13.84	59	171	2.6
Cell C	1455	13.43	105	140	1.3

Cell D	3141	11.46	95	196	2.3
Cell E	3409	5.06	44	129	3.1
Cell F	1561	13.83	94	123	1.5
Cell G	4697	5.01	59	137	4.1
Cell H	2925	4.40	26	100	3.3
Cell I	2797	4.33	25	101	3.0
Cell J	3889	5.04	43	125	3.6

All the cells tested displayed behaviours which can be categorised in one of the following four ways:

1. Cells A, E, G and J showed a quick cut off in terms of voltage when the CID activated. However, once the CID had cut in the cells failed to recover to a similar voltage as before, instead showing no voltage reading or in some cases a much lower voltage. The current was also observed to drop back to zero once the CID had cut in, remaining at 0 A even when the power supply was switched back on. Each of these cells (A, E ,G and J) showed smaller increases in cell temperature and there was no visible damage to the outside of the cell. The cells showing this type of behaviour included the more reputable branded cells A and G. Data traces for each of the cell types A, E, G and J are shown in Figure 12, Figure 13, Figure 14, and Figure 15 respectively. Note: The spikes in the voltage trace after the CID has activated show the voltage of the power supply- this was briefly turned on again to probe if the CID had permanently disconnected and allowed no further current to flow.

Figure 12 Cell temperature, cell voltage, state of charge and current supplied for OPSS-A-19

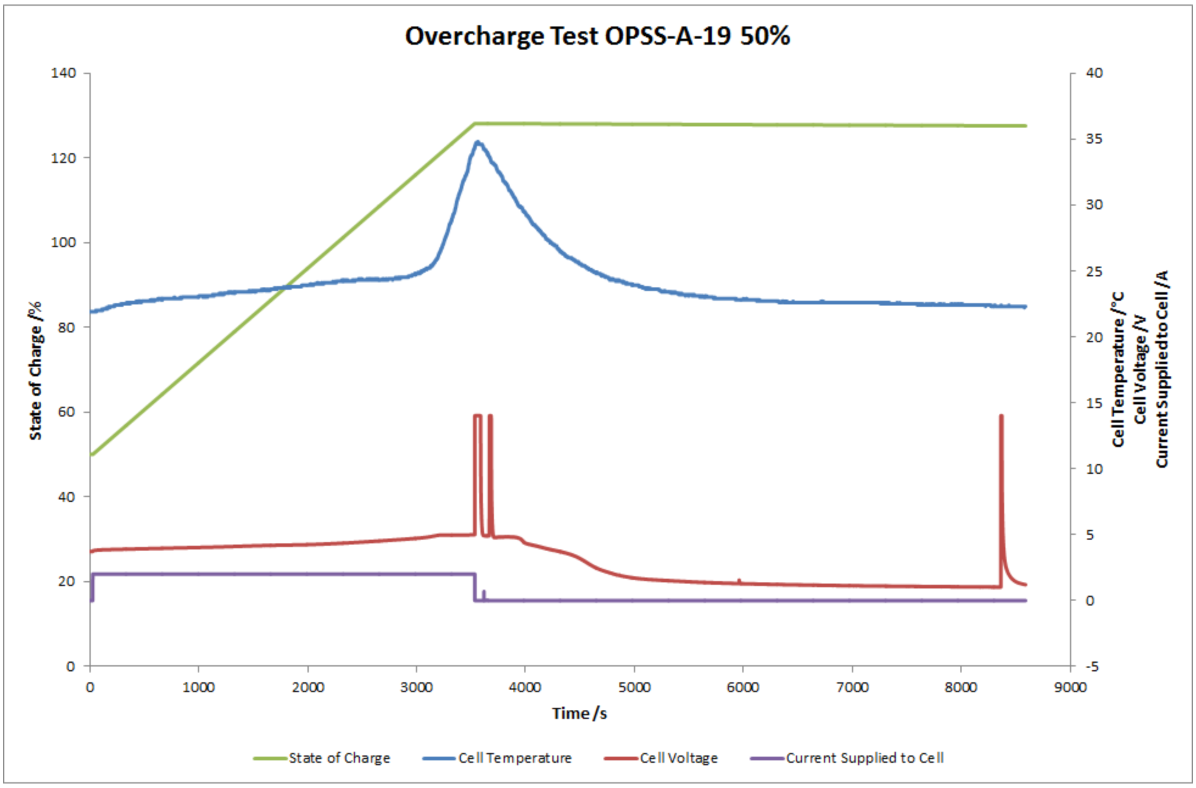


Figure 13 Cell temperature, cell voltage, state of charge and current supplied for OPSS-E-8

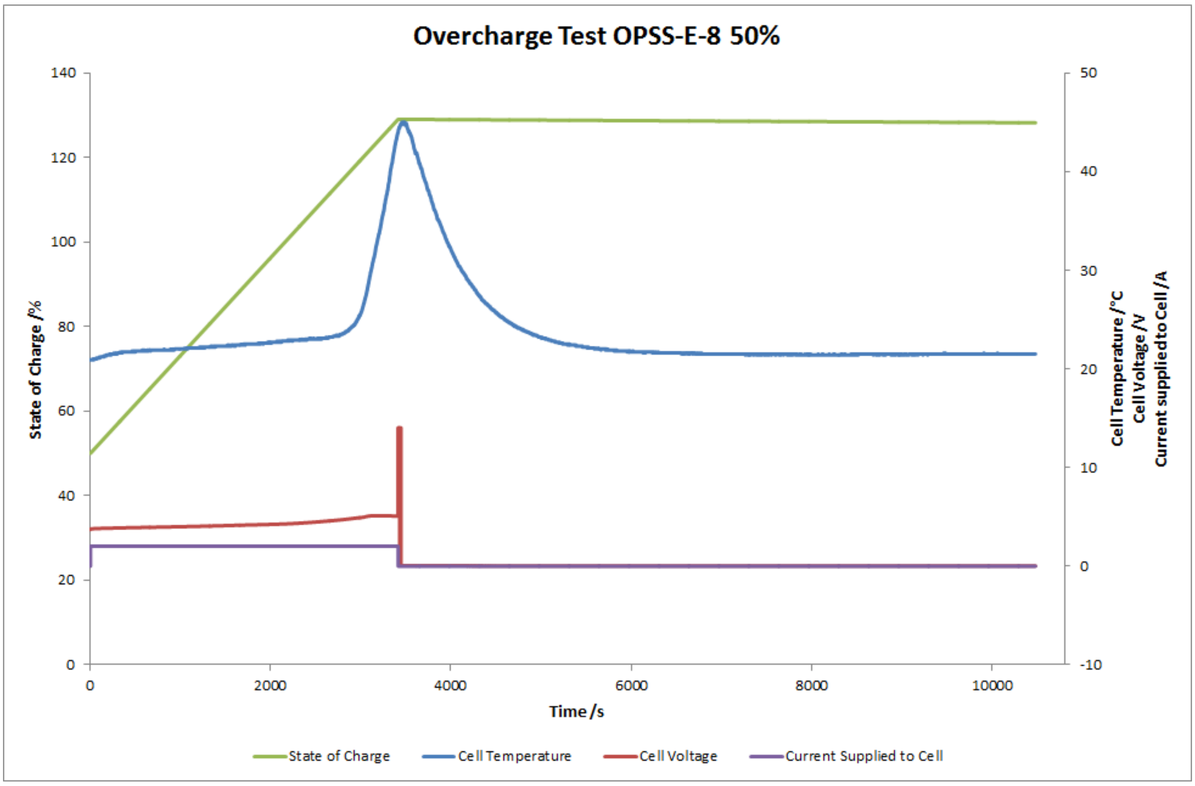


Figure 14 Cell temperature, cell voltage, state of charge and current supplied for OPSS-G-9

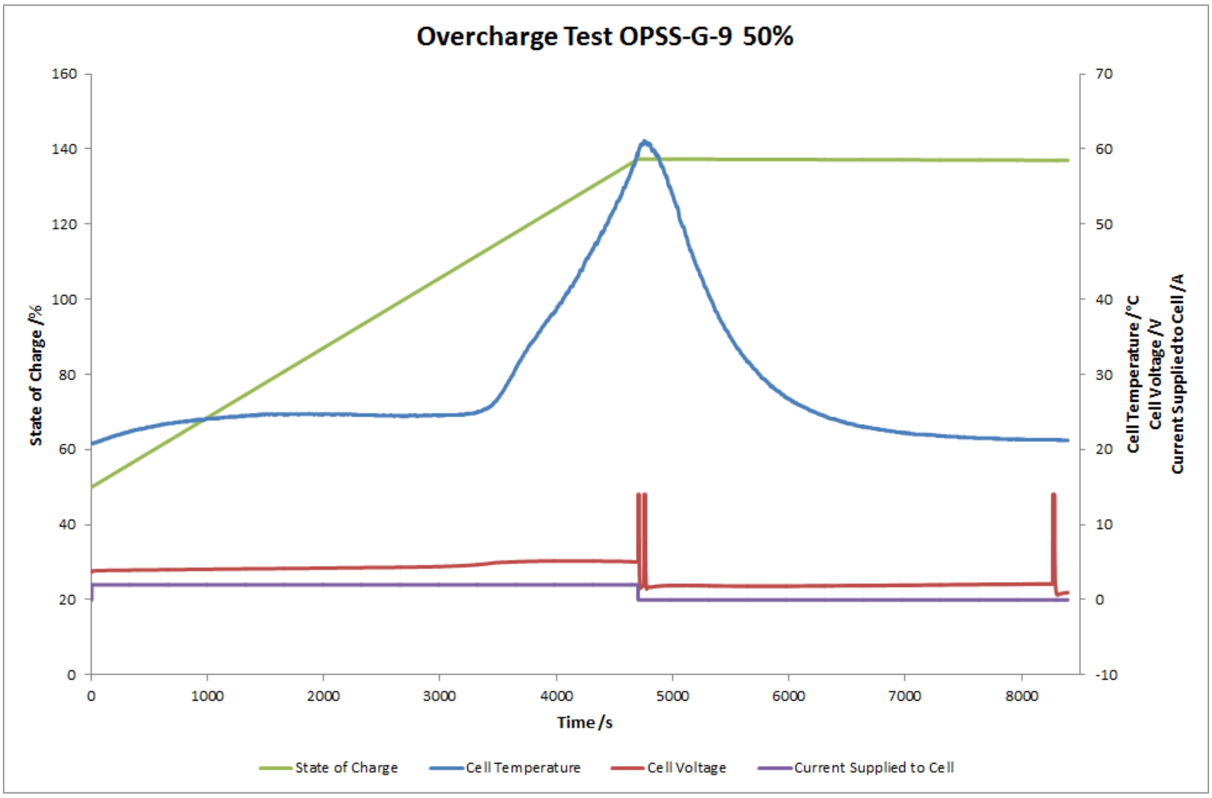
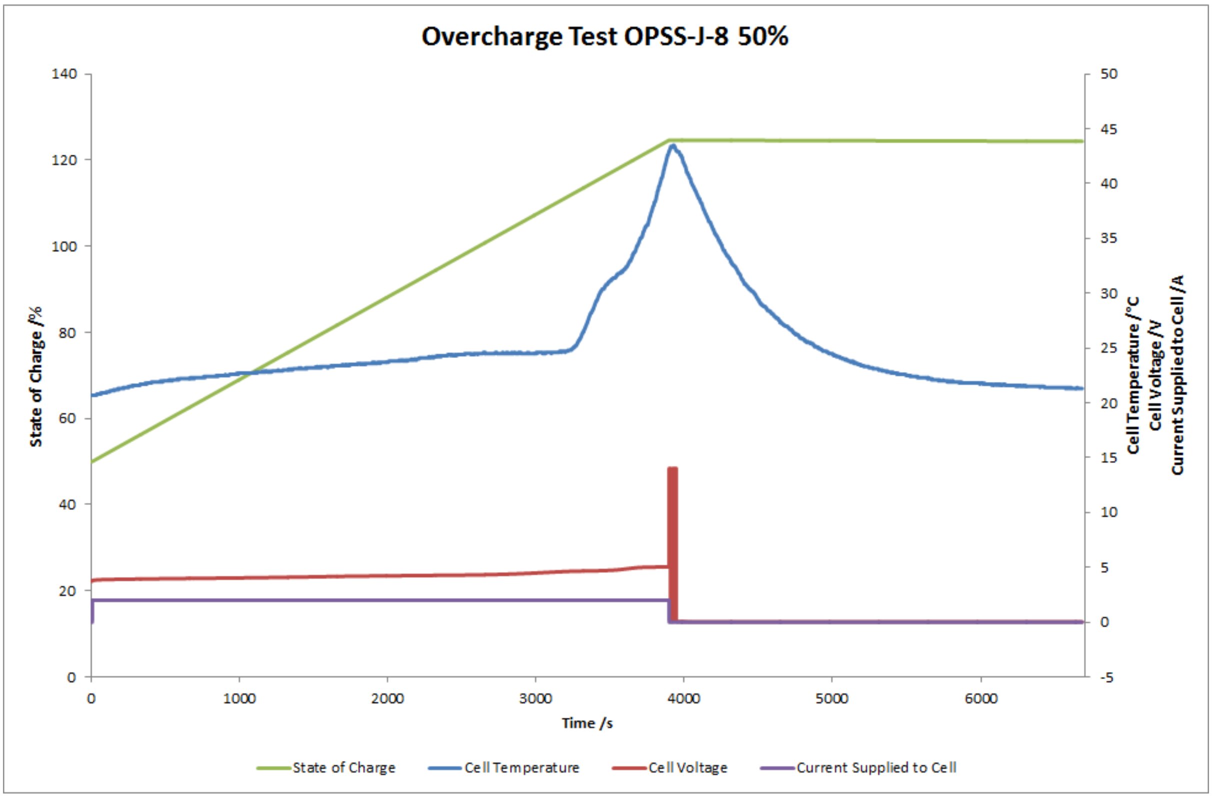


Figure 15 Cell temperature, cell voltage, state of charge and current supplied for OPSS-J-8



2. When charging cells B, C and F, the voltage was observed to rise rose slowly: this allowed the cells to reach a higher voltage before the CID activated (Figure 16, Figure 17, Figure 18). After the power supply had been turned off, the cell voltage recovered to a level similar to what was measured prior to CID activation; however the current remained at 0 A even when the power supply was turned back on. Cells B, C and F all showed a significant increase in temperature throughout the test, with the cell B reaching a temperature sufficient enough to result in the melting of the plastic wrapper (see Figure 19). Cells C and F showed no visible damage to the outside of the cell.

Figure 16 Cell temperature, cell voltage, state of charge and current supplied for OPSS-B-8

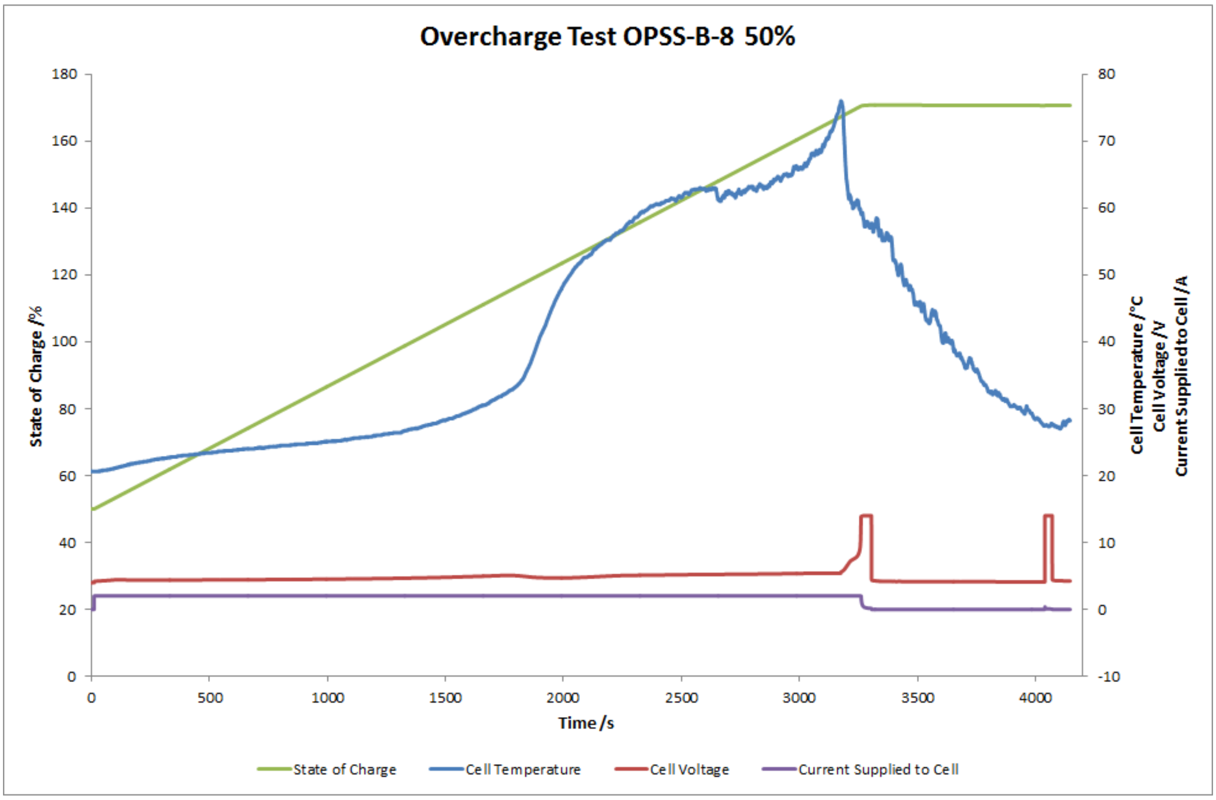


Figure 17 Cell temperature, cell voltage, state of charge and current supplied for OPSS-C-9

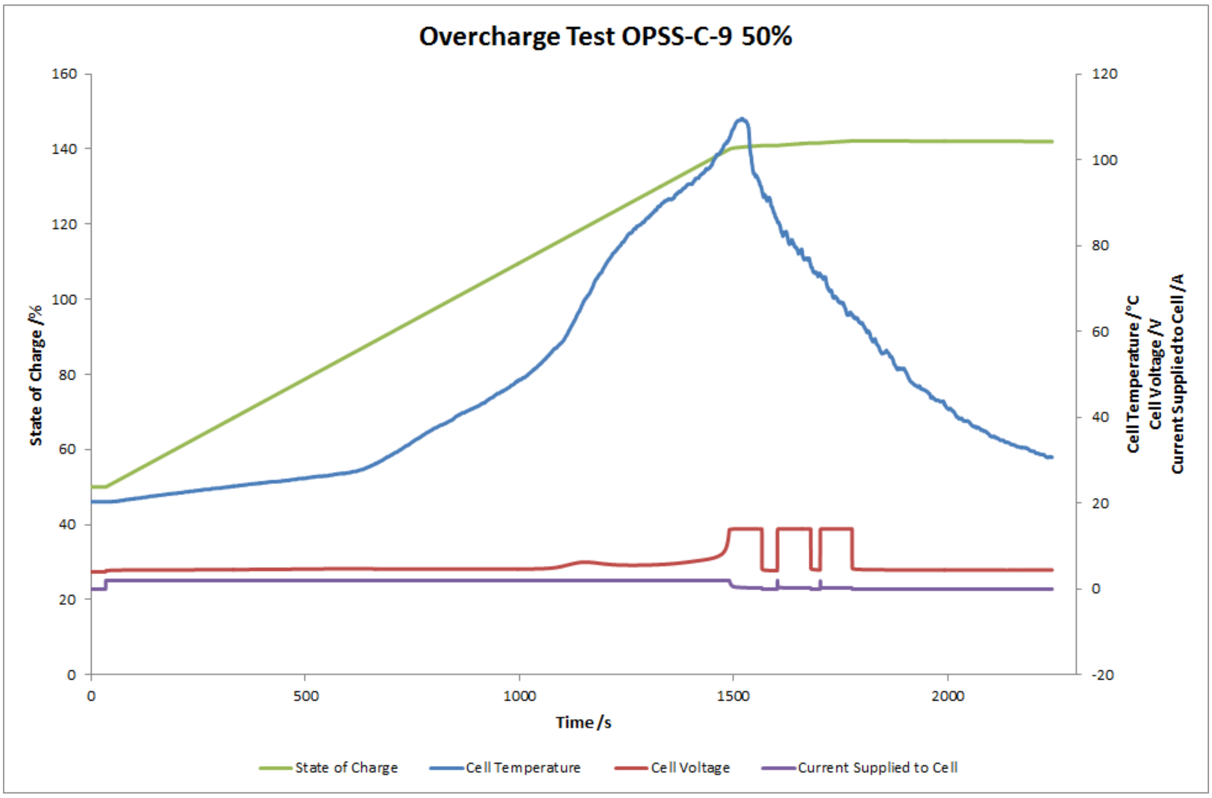


Figure 18 Cell temperature, cell voltage, state of charge and current supplied for OPSS-F-8

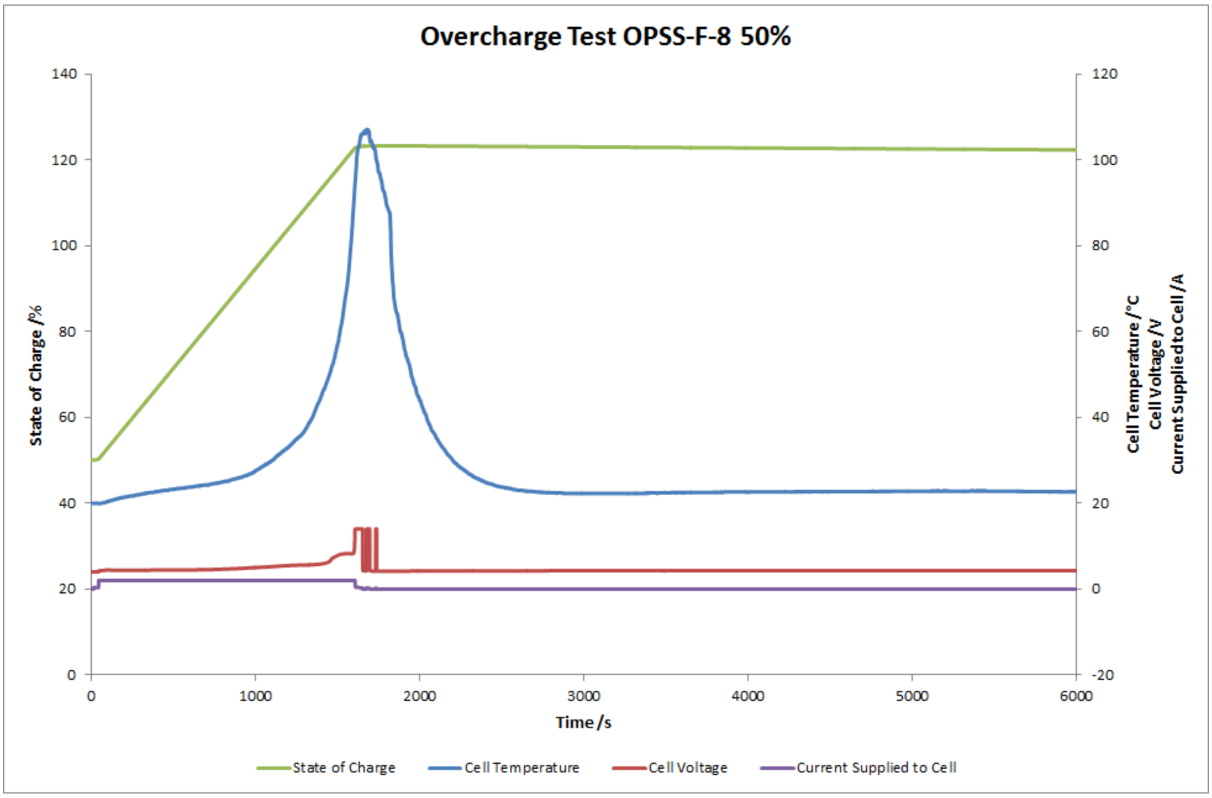
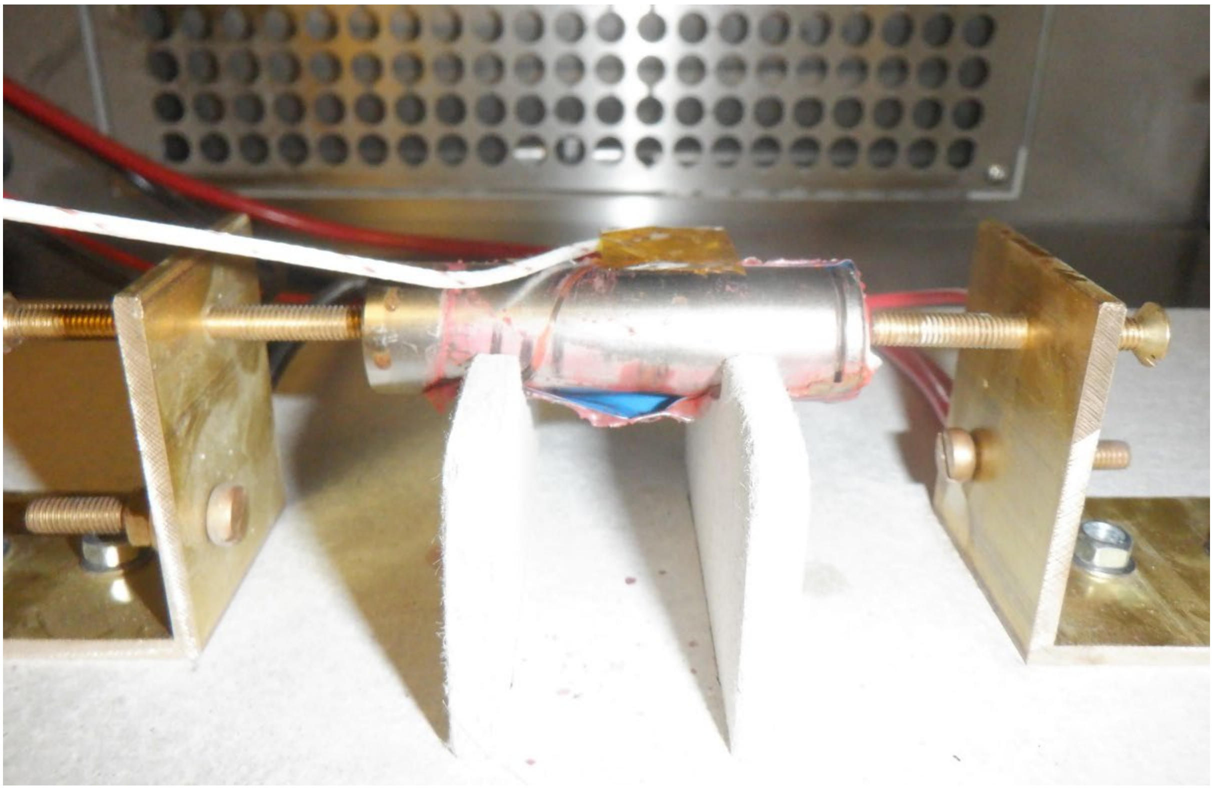


Figure 19 Damage to the plastic casing on OPSS-B-8



3. Cells I and H possessed additional protection in the form of a printed circuit board (PCB) to further protect the cell against overcharging. As a result of this added mitigation, the cell voltage rose quickly before cutting off when the cell reached a certain voltage; this prevented the CID from being activated (Note: with the experimental set-up used, this shows as the maximum set voltage of the power supply (15 V). Notably, when the power supply was switched off, the cell voltage was observed to recover to a similar level observed prior to PCB activation. The current, however, cut out and remained at 0 A, even after the power supply was turned on again. In both cell types, there was little increase in temperature, presumably due to the presence of the PCB, which prevented further charging after reaching a 100% SoC (Figure 20, Figure 21). As such, there was no visible damage to the cells.

Figure 20 Cell temperature, voltage (of cell during charge, and of maximum power supply voltage when protection circuit active and power supply still switched on), state of charge and current supplied for OPSS-I-8

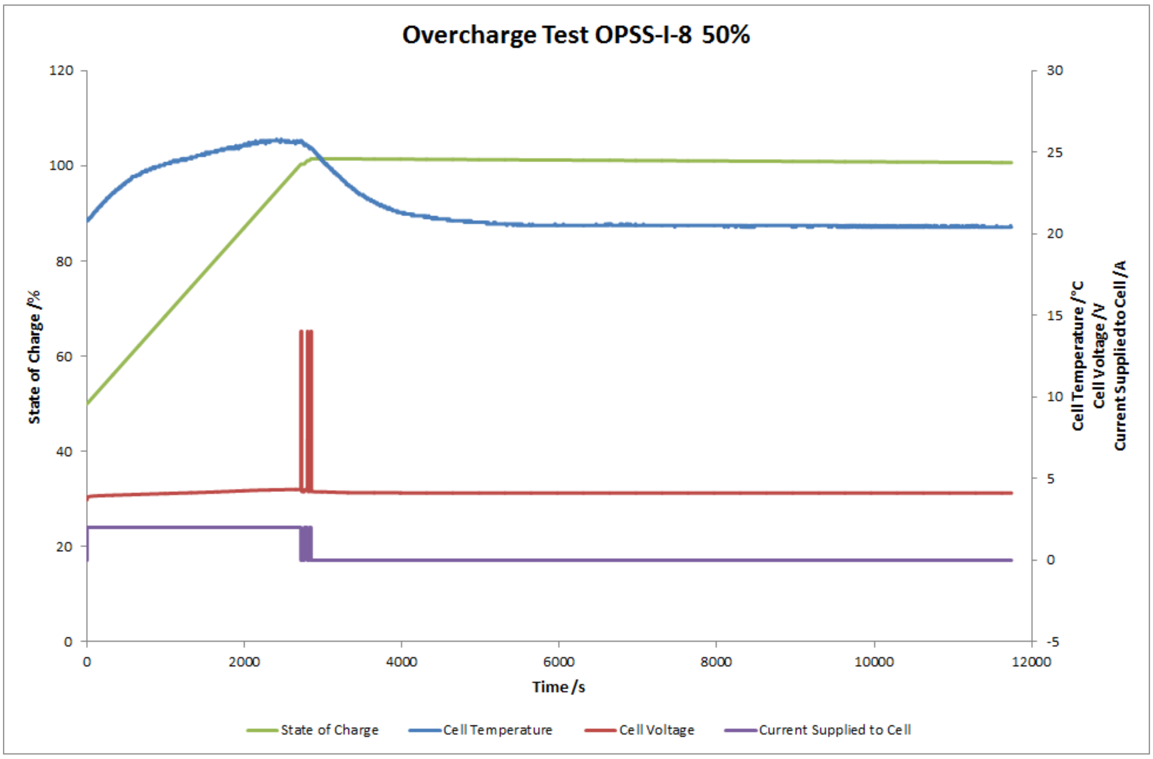
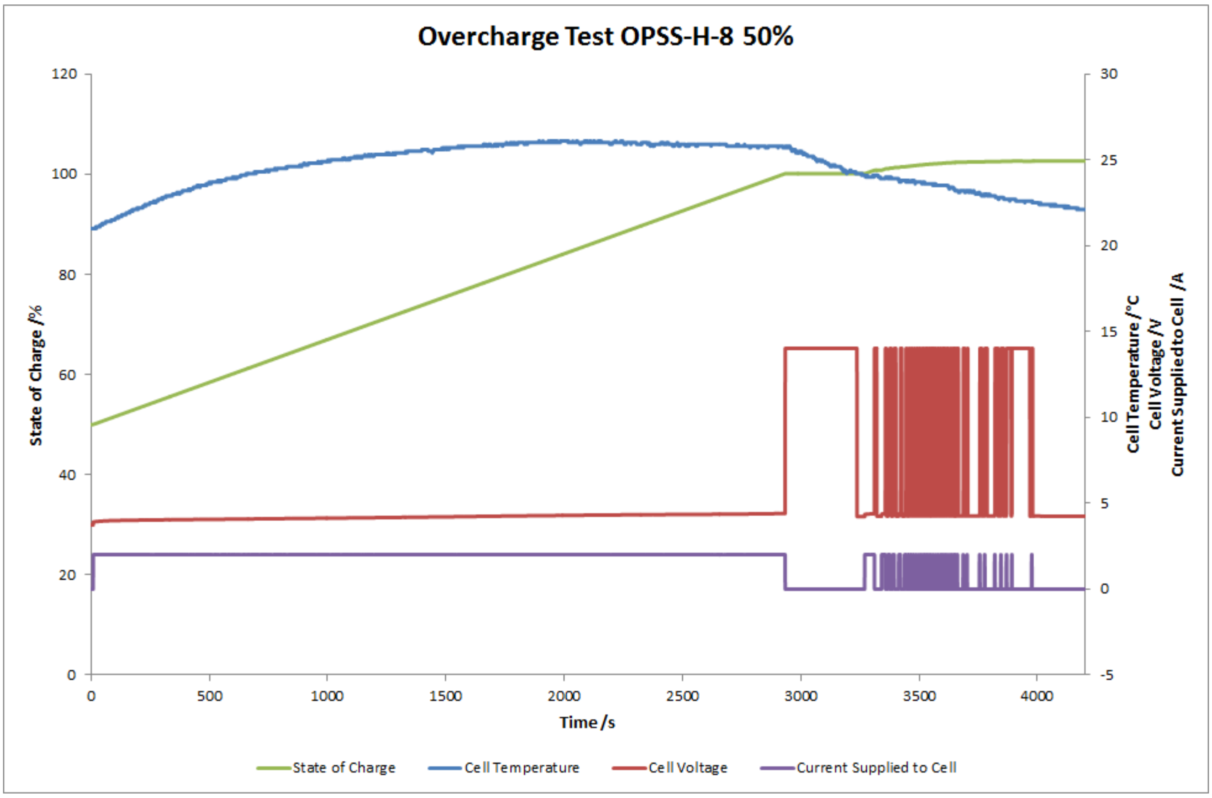
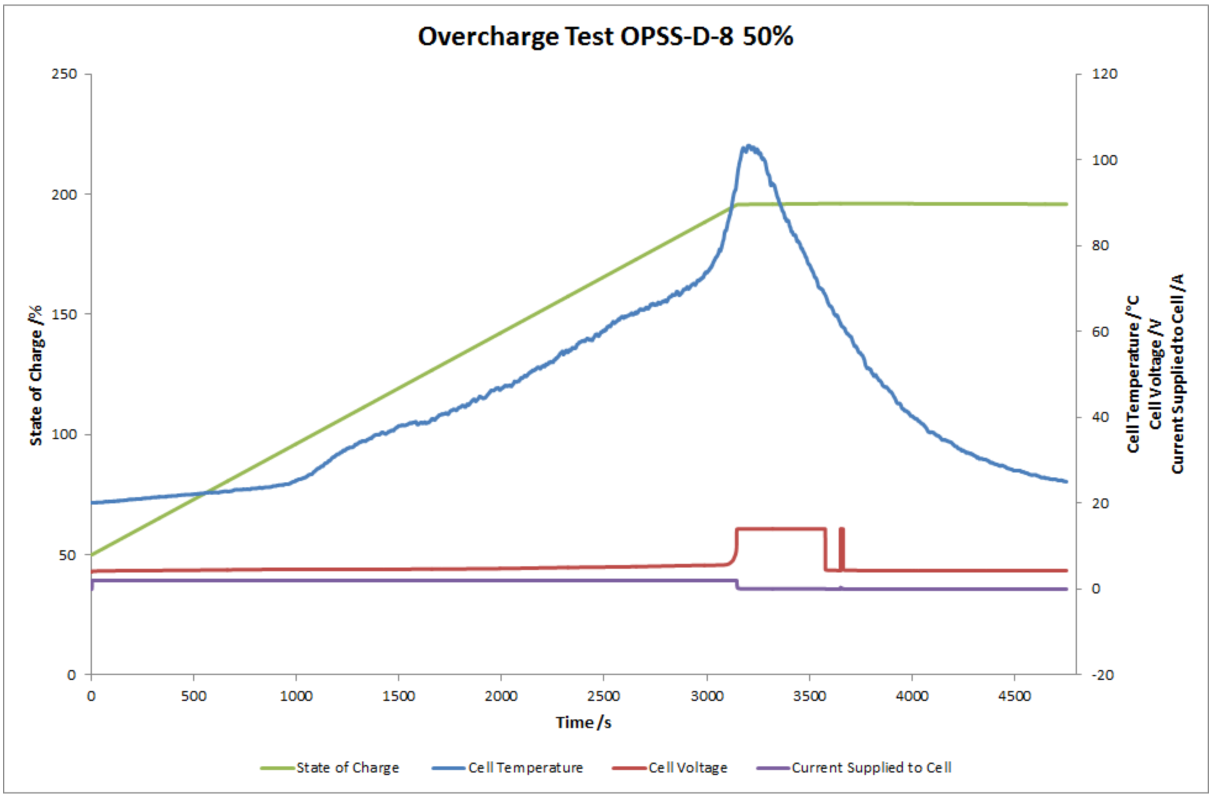


Figure 21 Cell temperature, cell voltage, state of charge and current supplied for OPSS-H-8



4. During testing of cell D, the cell voltage rose steadily until the CID activated. Once the power supply was turned off, the cell voltage recovered to a similar level observed prior to CID activation. The current dropped to 0 A after the CID was activated and continued to remain at this level for the rest of the test, even after the power supply was turned back on. Although there was no visible damage to the outside of the cell, a significant increase in temperature was observed throughout the test (Figure 22).

Figure 22 Cell temperature, cell voltage, state of charge and current supplied for OPSS-D-8



5.3 Overcharge Test Observations

- The functioning of a variety of cell protection mechanisms were observed within these tests.
- During testing, some temperatures high enough to cause electrolyte leakage and damage to the wrapping of the cells were observed, giving cause for concern. It should be noted that tests were not repeated.
- No cell entered a final failure condition.
- The cell surface temperature is likely to be lower than the maximum internal temperature, as the heat is generated locally within the cell and then equilibrates to the whole cell. Hence the maximum observed temperatures did not occur when the current was highest.
- It should be noted that these tests were performed with a single, uniform current (2 A, typical of the maximum designed to be seen by USB based chargers).

5.4 Overcharge Test Recommendations

- An overcharge test of this nature should be included within the suite used to characterise cells for vaping.
- Any cell which reaches a high temperature (for example 100 °C) or voltage (12 V) during testing should be repeated.

- Overcharge testing should be coupled with an additional test to determine the thermal runaway onset temperature for each cell type to see how close the observed maximum temperature is to that of the temperature where the cell is likely to enter thermal runaway.
- No testing was undertaken looking at higher rate charging within the permissible voltage envelopes (often called an ‘over-current’ test). This should be considered, but is perhaps less likely to be representative of the electrical abuse considered likely in a domestic setting.

6 Short Circuit Test

6.1 Short Circuit Test Method

The aim of the short circuit tests was to investigate cell behaviour when subjected to a low electric impedance pathway at a 100% SoC. A schematic and picture of the test rig are shown in Figure 23 and Figure 24. The conducting pathway comprised of 35 mm^2 cables (rated to 240 A continuous current), a bespoke cell holder (Figure 20) and a contactor (high current relay, Albright ALT/CONT19-5014) rated to 725 A DC. Every effort was made to minimise the resistance of this pathway.

Figure 23 Schematic of short circuit test set-up.

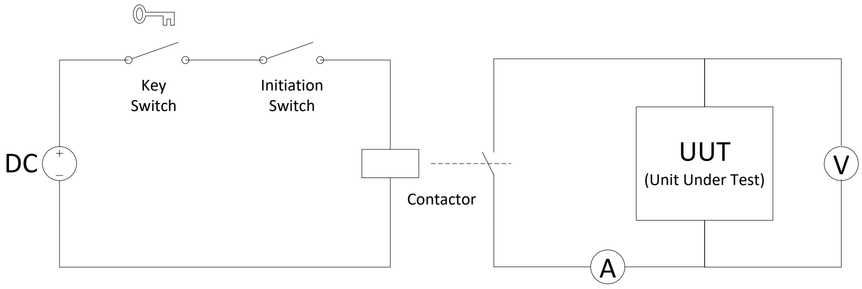
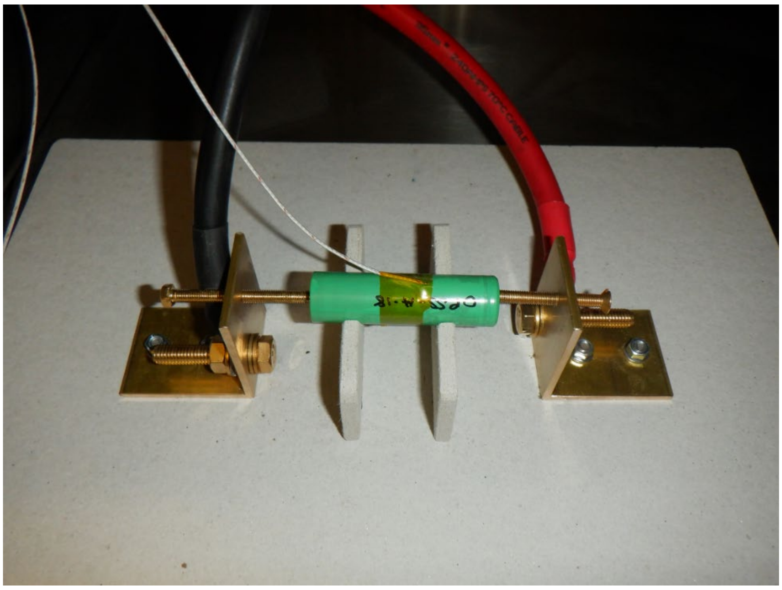


Figure 24 Short circuit cell holder



Individual cells were placed in the rig horizontally and were secured into place at both cell terminals using brass screws. The cell was supported along its base with insulating fireboard, which had been pre-cut to accommodate the cell diameter. Two 35 mm^2 cables were connected to each terminal, along with two separate cables to measure the cell voltage. The rig was confined inside a blast enclosure, (Figure 25), situated within a blast chamber.

Figure 25 Ventilated test enclosure within blast chamber

A current transducer (rated to 300 A) was placed on the positive 35 mm^2 cable leading to the contactor. Prior to testing, the resistance of the cell and cabling was measured, and the initial cell voltage was noted. The cell surface temperature was measured using a type-T thermocouple. All data was logged using a Graphtec GL2000 high-speed data logger, recording at a frequency of 10 Hz (see Figure 26).

Figure 26 Graphtec GL2000 data logger and control system for the initiation of the short circuit

Test initiation was controlled by a double switch protocol, one of which is key switch. This ensured the safety of those setting up the test (and in control of the key).

A single cell of each type was tested in this work package. Each cell was secured into the test rig inside the blast chamber. The terminals of the cell were then connected using the initiator box in an adjacent room. The current flow, cell voltage and cell temperature were monitored as the tests progressed. When the current flow reached 0 A, the test operator turned off the initiation box, which removed the connection between the positive and negative terminals of the cell under test. After approximately ten seconds the operator would turn the initiation box on again to see if any more current would flow from the cell. This process was repeated multiple times to see if the cell protective mechanisms were having a permanent or only temporary effect. After the tests were completed the cell voltage was measured to see whether it had recovered to a similar level to that which it was before the short circuiting. The cell surface temperature is likely to be less than that achieved inside the cell, however the cell surface temperature data are likely to reflect those that occurred internally and are useful to make comparisons between different cell behaviours.

6.2 Short Circuit Test Results

A summary of the results from the short circuit tests are shown in Table 12

Table 12: Summary of Results from the Testing

Cell Type	Maximum Cell Surface Temperature / ˚C	Maximum Current / A	Duration of Current / s	Charge extracted / Ah	Final cell voltage* / V	Resistance pathway during test** / mΩ	Nominal charge extracted*** / %	Any observed damage?
Cell A	84	160	16.5	0.45	0.45	2.3	18	NO
Cell B	108	51	71	0.49	0.0	25.5	33	YES
Cell C	105	49	100	0.38	3.5	21.9	42	NO
Cell D	132	54	79	0.47	0.60	22.5	39	YES
Cell E	57	189	3	0.11	0.0	12.3	5	NO
Cell F	133	50	100	0.41	3.8	21.0	34	NO
Cell G	48	56	26	0.033	4.1	17.1	1	NO
Cell	51	5	0.4	0.00035	1.5	17.1	0.01	NO
Cell I	39	1.3	0.1	0.000037	3.1	7.2	0.001	NO

Cell J	97	167	13	0.40	0.3	25.7	14	NO

* Final cell voltage – This was measured at the end of the testing for each cell, when the short circuit pathway was removed, to see if the voltage recovered to pre-test levels.
** The resistance pathway is the resistance of the circuitry external to the cell which was used in the process of short circuiting. The cables that formed the resistance pathway were 35 mm^2 which ran through the current transducer.
*** This is based on the figure calculated from the cell cycling part of this work package, not the capacity stated on the cell itself.

All the cells tested displayed behaviours which can be categorised in one of the following four ways:

5. Cells A, B, E and J had evidence of irreversible change after the short circuit test. This is demonstrated by final open cell voltage after the short circuit was applied of close to 0 V (Figure 27, Figure 28, Figure 29 and Figure 30 respectively). They reached temperatures of around 100 ˚C (except cell E) and had a current draw of around 180 A (except cell B). The current profiles of cells A, E and J and also the fact that the voltage didn’t recover are evidence that a CID operated and quickly terminated the current flow, whilst that of B would be indicative of a PTC device since the current declined gradually. Cell B also suffered some physical damage, including leakage of electrolyte (Figure 31).

Figure 27 Cell temperature, current, contactor voltage and cell voltage for OPSS-A-5

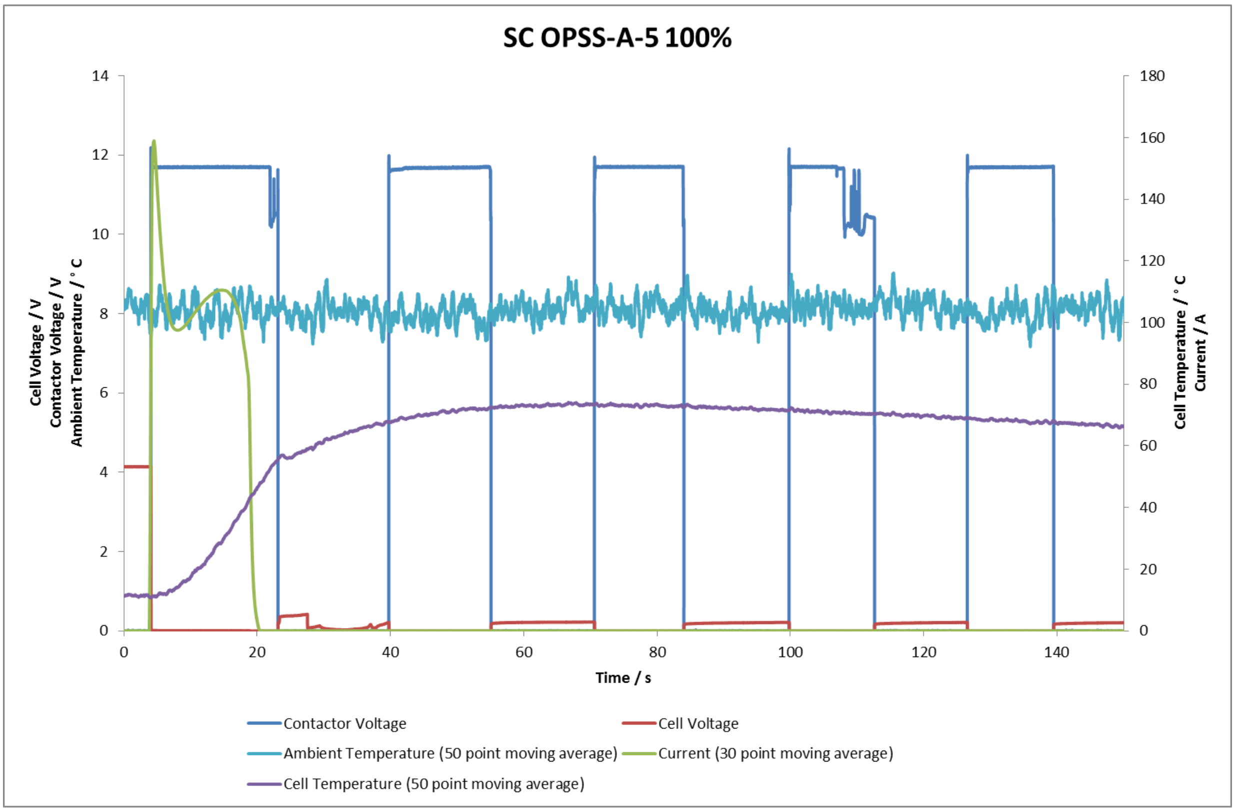


Figure 28 Cell temperature, current, contactor voltage and cell voltage for OPSS-B-3

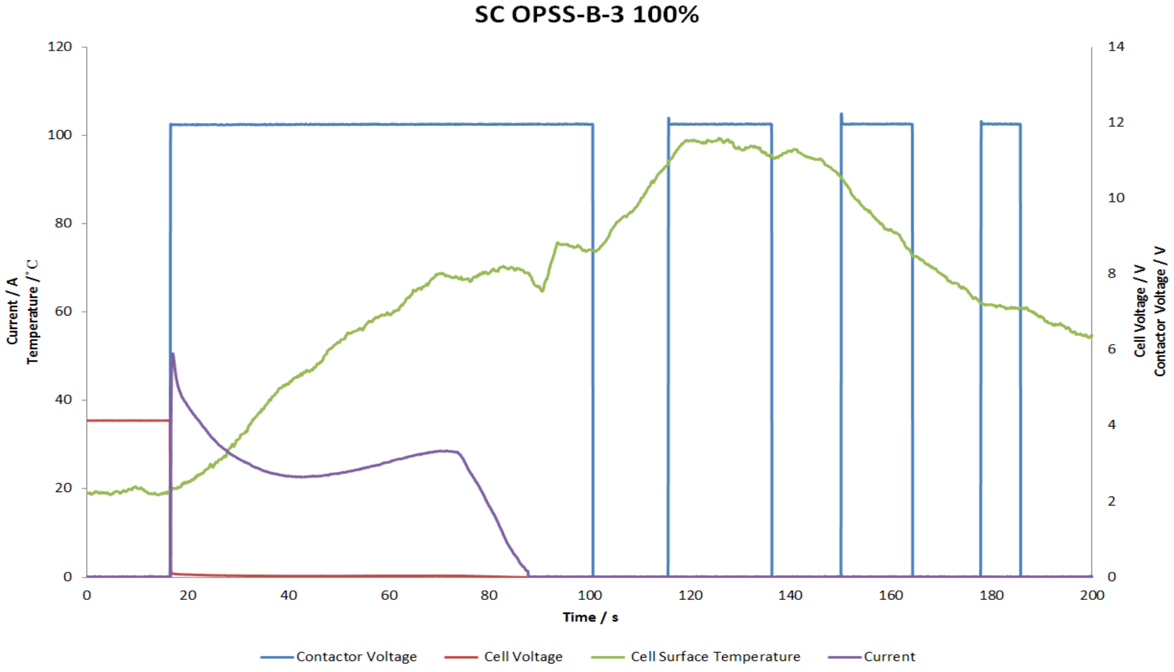


Figure 29 Cell temperature, current, contactor voltage and cell voltage for OPSS-E-6

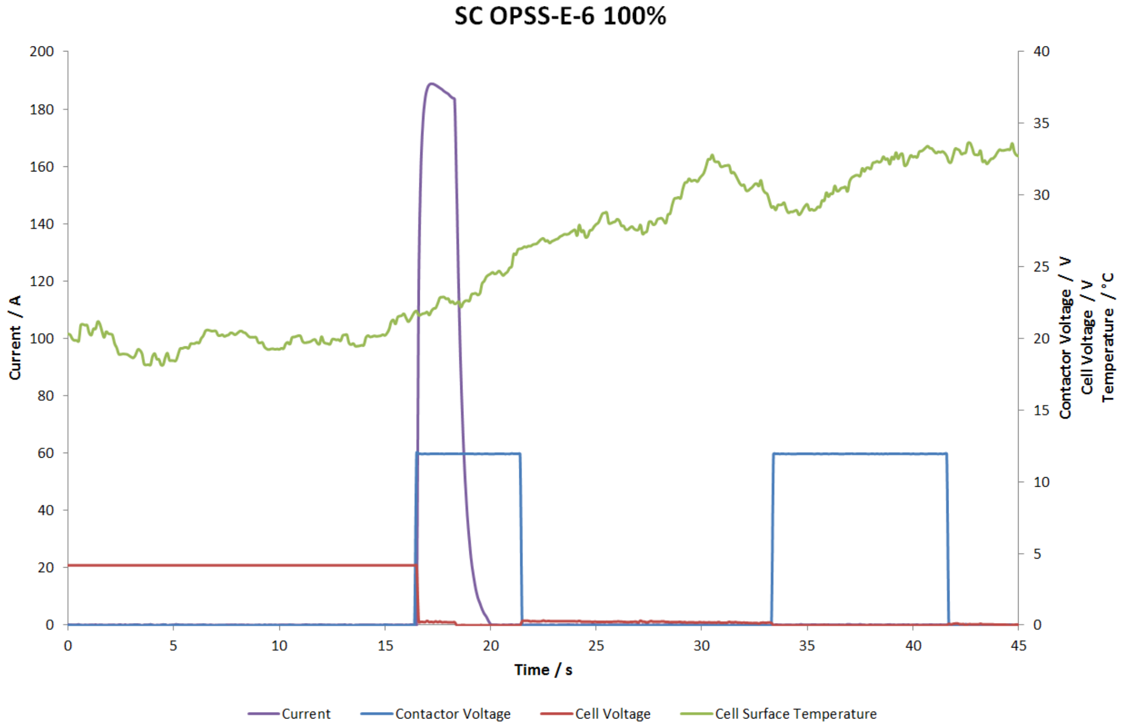


Figure 30 Cell temperature, current, contactor voltage and cell voltage for OPSS-J-3

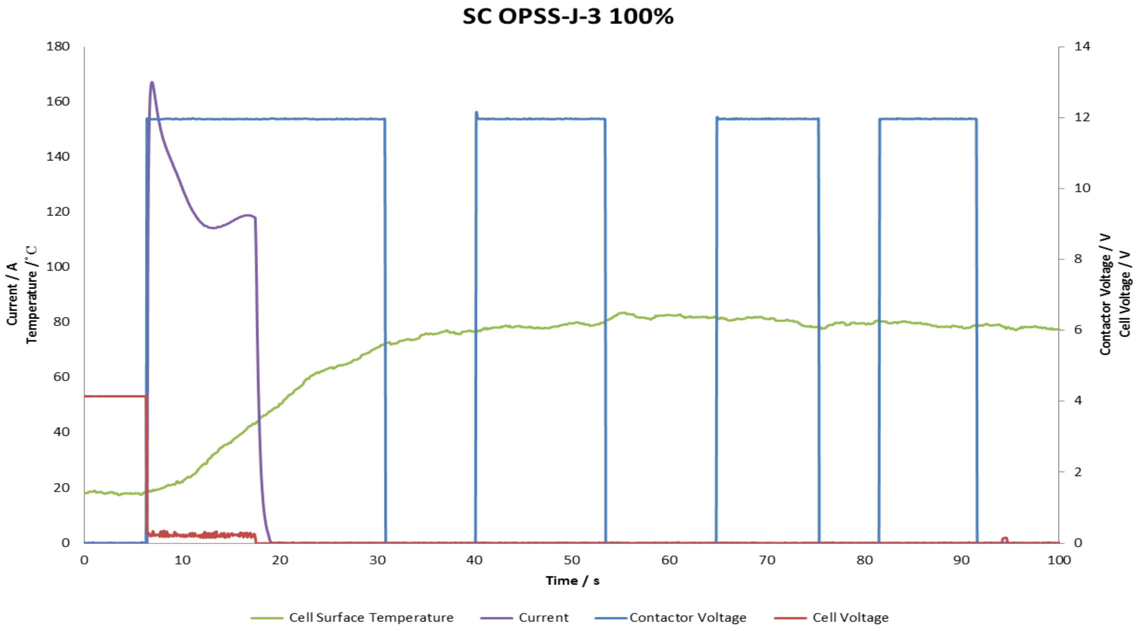
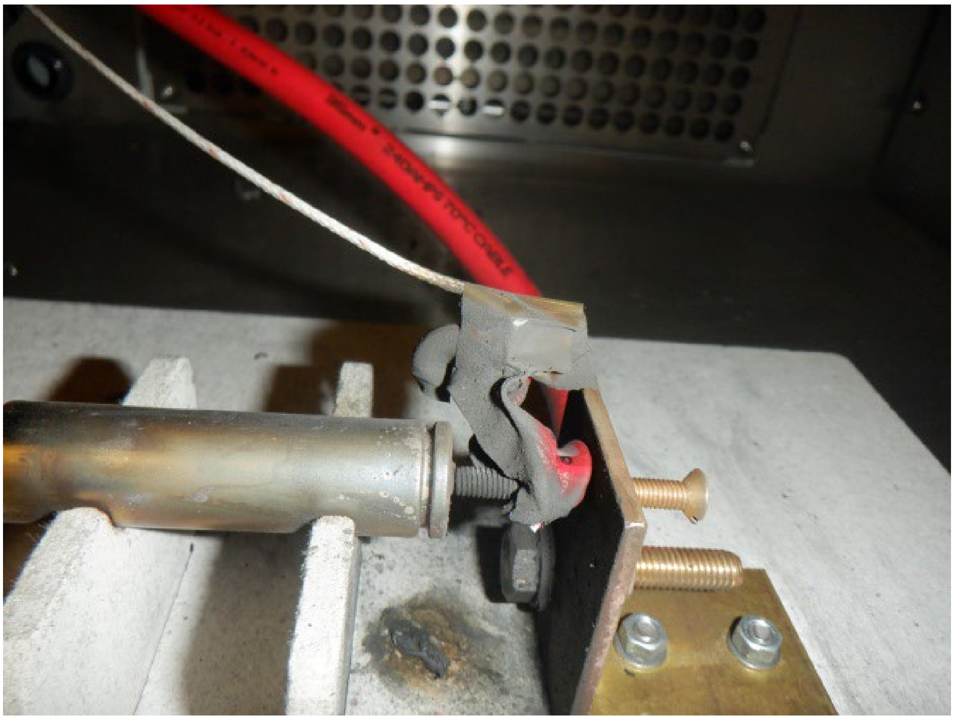


Figure 31 Cell B post-test. A different B cell was weighed (unwrapped) and had a mass of 43.33g. After the test, this cell had a mass of 32.55g, indicating that electrolyte was lost.



6. Cells C, D and F displayed a post-test cell voltage slightly lower than pre-test levels (not 0 V). Each of cells C, D and F reached a temperature in the range 100 ˚C – 120 ˚C and displayed a current draw of *ca*. 50 A (Figure 32, Figure 33 and Figure 34). In all 3 cases the current was observed to: initially spike before dropping, followed sequentially by gradual increase ahead of a more rapid decline (as the temperature increased and the resistance increased). This might be typical of a PTC device operating. After the first short circuiting no further current would flow. The cell label wrap was damaged in the case of cell D (Figure 35).

Figure 32 Cell temperature, current, contactor voltage and cell voltage for OPSS-C-4

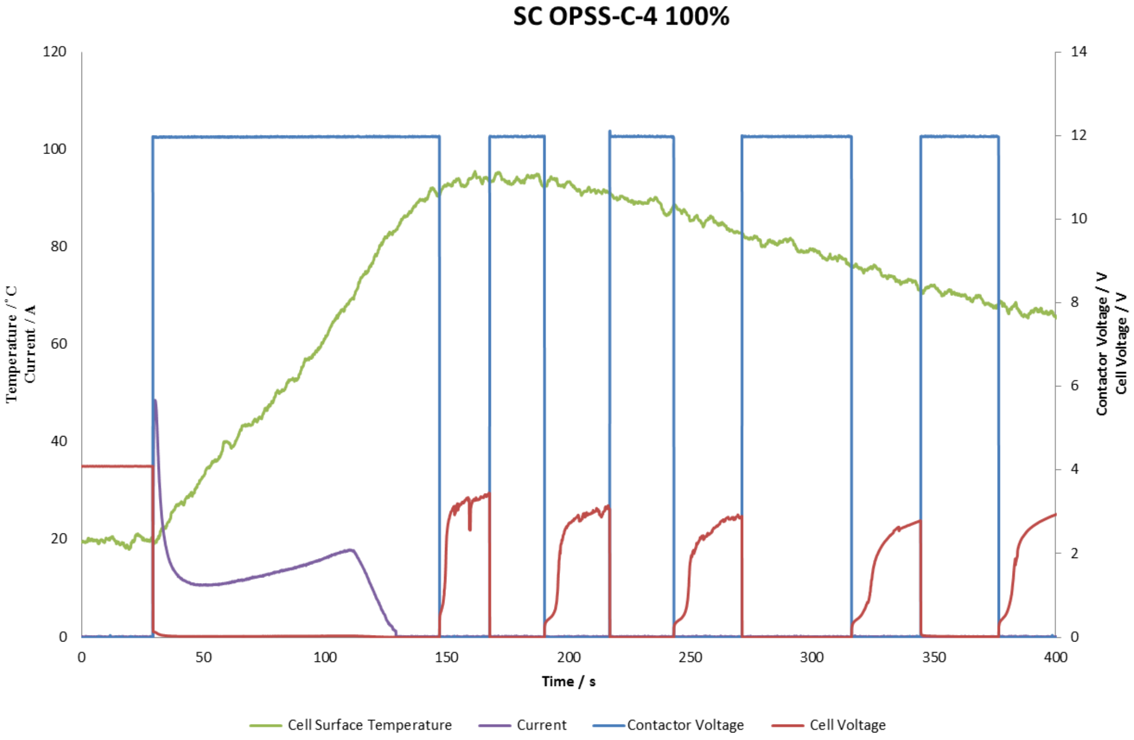


Figure 33 Cell temperature, current, contactor voltage and cell voltage for OPSS-D-3

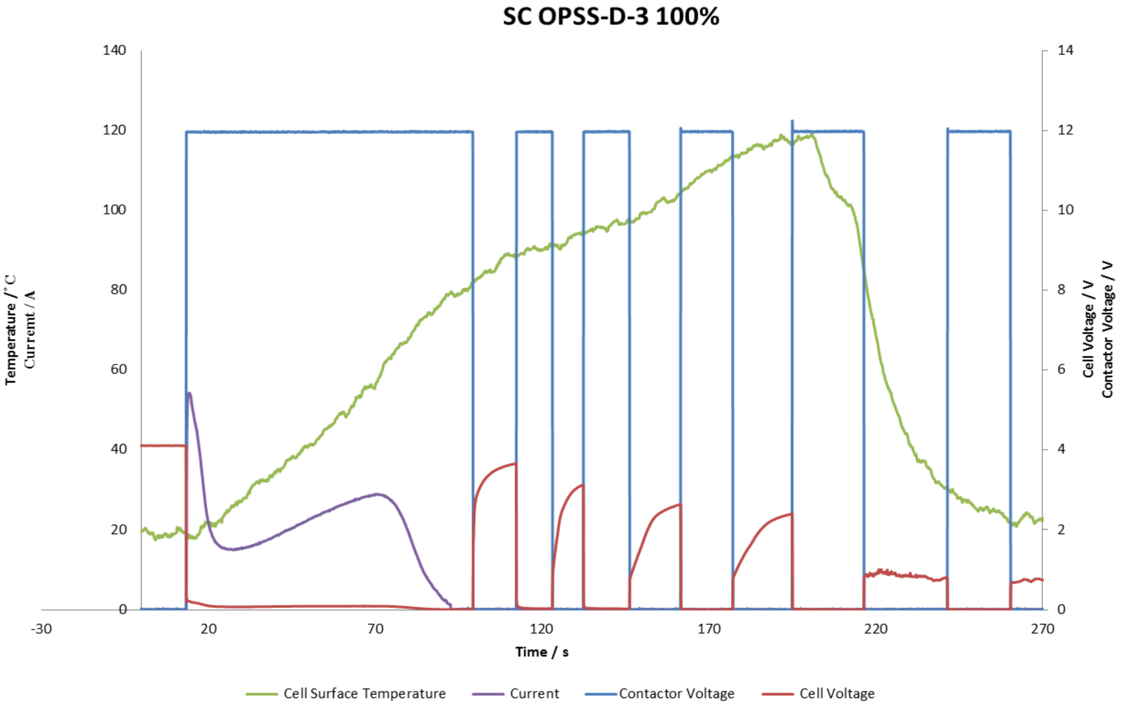


Figure 34 Cell temperature, current, contactor voltage and cell voltage for OPSS-F-6

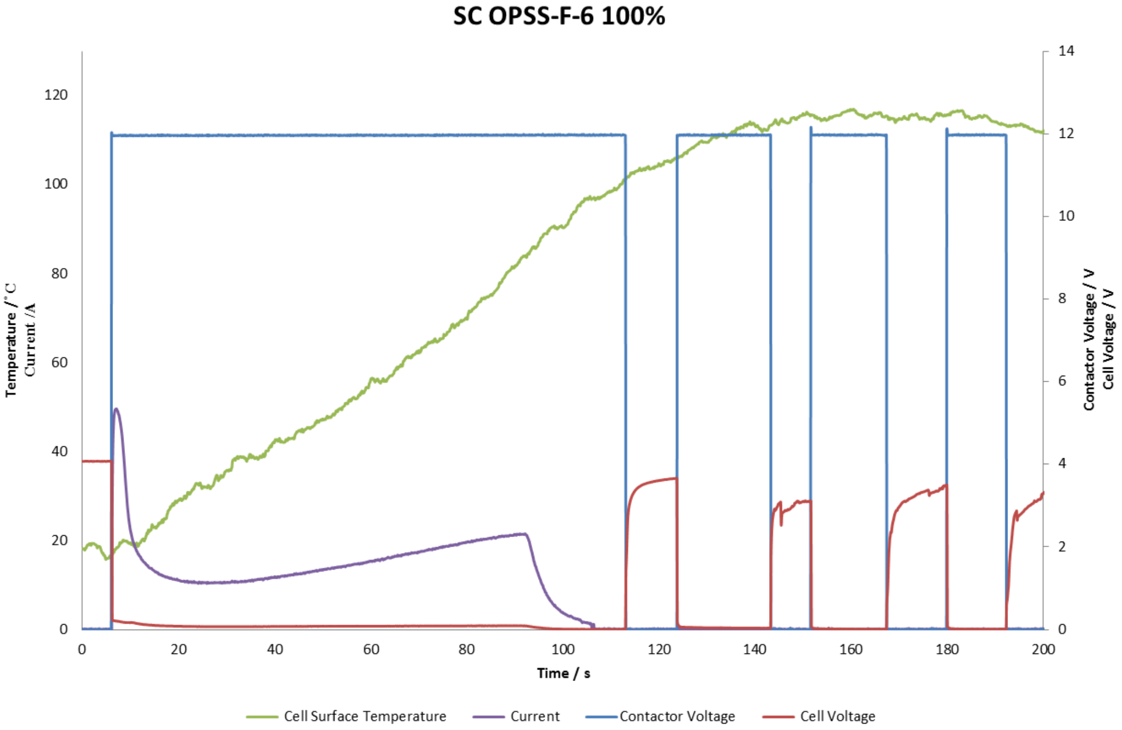


Figure 35 Cell D post-test

7. Cells H and I had additional inbuilt protection so only a very small current flow occurred. The cell voltage recovered each time the operator removed the short circuit pathway and the temperature changed very little (Figure 36 and Figure 37).

Figure 36 Cell temperature, current, contactor voltage and cell voltage for OPSS-H-6

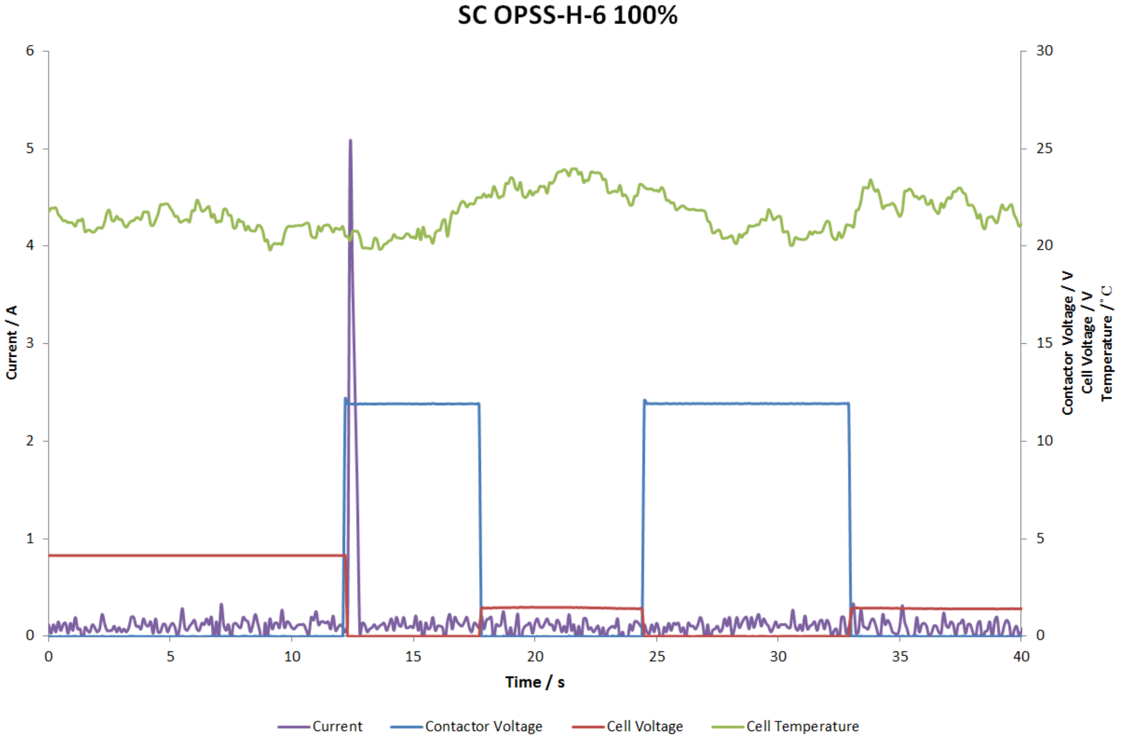
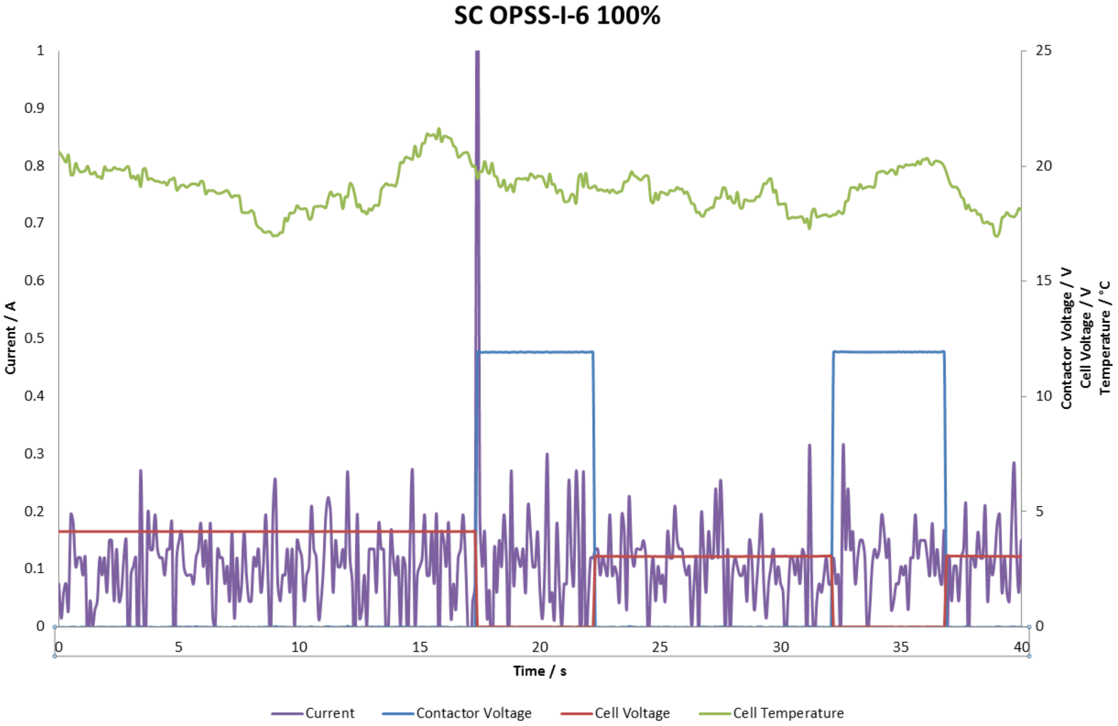
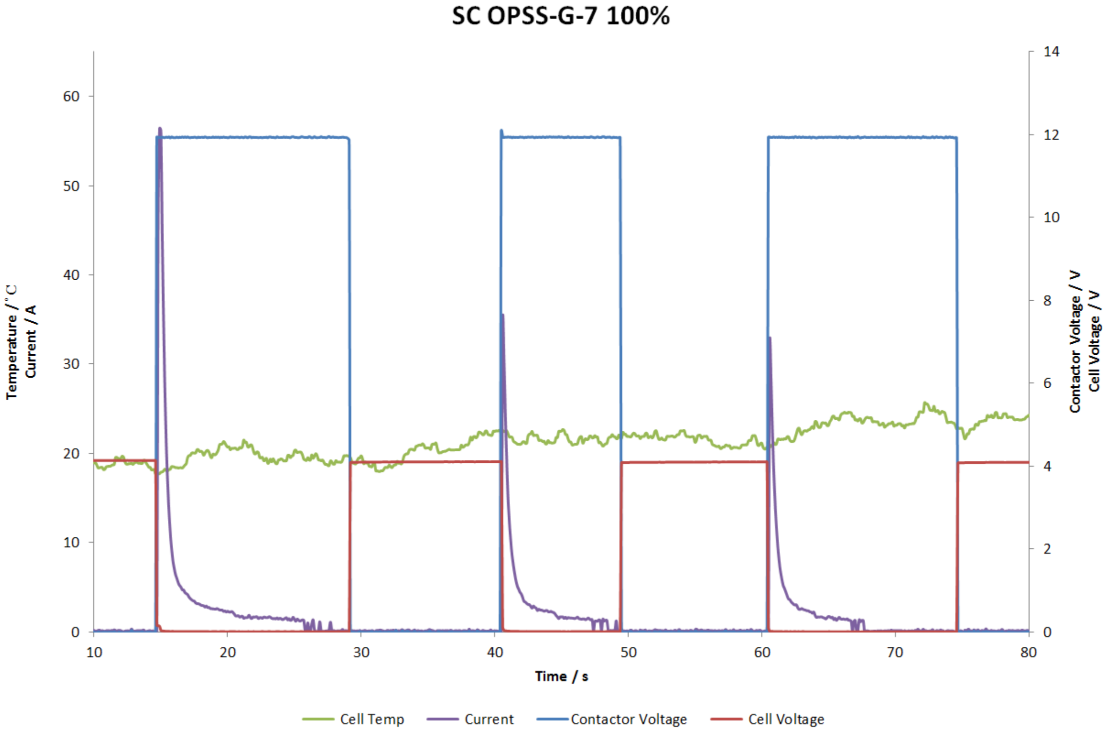


Figure 37 Cell temperature, current, contactor voltage and cell voltage for OPSS-I-6



8. Cell G – The test operator initiated the connection between the positive and negative terminals. There was a large spike in current followed by an initial rapid decline, followed by a period of gradual decline until the current reached 0 A. The operator then removed the short circuit pathway and the voltage was observed to recover. The operator then re-initiated the short circuit, and the current profile matched the first (but with diminished magnitude). On subsequent removal of the short circuit pathway, the cell voltage again recovered. A third short circuiting event was initiated, producing a further current flow profile similar to that following the second short circuit, with voltage recovering once again on removal of the short circuit pathway (Figure 38).

Figure 38 Cell temperature, current, contactor voltage and cell voltage for OPSS-G-7



6.3 Short Circuit Test Observations

- The functioning of a variety of cell protection mechanisms were observed within these tests.
- Some temperatures high enough to cause electrolyte leakage and damage to the wrapping of the cells were observed. This should be of concern. These tests were not repeated.
- No cell entered final failure.
- It is worth noting that the observed cell surface temperatures are very likely to be lower than the maximum internal temperature within the cell, as heat is generated locally within the cell and then radiates / equilibrates throughout the whole cell. As a result maximum observed temperatures do not coincide with when the highest recorded current value occurred.

6.4 Short Circuit Test Recommendations

- A short circuit test should be included within any suite of tests used to characterise cells for vaping.
- In any cases where high cell surface temperatures are observed, the test should be repeated with other specimens of the same cell type.
- It may be that allowing the lowest possible resistance pathway does not lead to the worst case outcome as this allows the early activation of any protection mechanisms. Higher resistance paths may lead to current flows which, although lower than some recorded peak values, are significantly over the safe designed current for the cell. Any long duration, high current flow event is deemed likely to lead to elevated cell temperatures being observed. The extent of the relationship between high current flow and cell temperature could be established through a series of tests carried out at fixed resistance values in order to determine the likely maximum cell temperatures observed.
- Short circuit testing should be carried out in conjunction with a test to determine the thermal runaway onset temperature for each cell type to see how close the observed maximum temperature is to that of the temperature where the cell is likely to enter thermal runaway.

7 Conclusions

This series of tests performed on a range of cell types have provided some insight into the variety of cells available on the UK market for vaping. It is clear that not all cells are entirely authentic, and do not deliver the advertised power or energy; indeed some of the advertised capacities are simply not plausible.

Of the tests undertaken in this work, it is recommended that any future test suite to evaluate cells being used in vapes should include:

- **A capacity test**. This may not need to be as extensive as performed here, but should include both low rates of charge and discharge (as cell capacities are often quoted at low rates where they are greatest), and higher rates which are more relevant to cell performance in a vape device. Any marked drop-off in capacity at higher currents may suggest a cell is not suited for use with vape devices. The capacity test could include an element where the discharge is not continuous, but has an intermittent or pulsed profile.
- **An overcharge test**. This will help identify and verify protection mechanisms built into the cell. Where higher temperatures were seen for a particular cell type, consideration should be given to repeating the test on other specimens of that cell.
- **A short circuit test**. Again, this will help to help identify and verify protection mechanisms built into the cell. Where higher temperatures were seen for a particular cell type, consideration should be given to repeating the test on other specimens of that cell.

Significantly elevated temperatures were observed in a number of cases during the testing performed. It has not been determined for these cells at what temperature these cells undergo final failure. At this point, it is strongly recommended that some kind of temperature test is employed to help inform / determine this. Several options for this are possible:

- **An ARC test** in an adiabatic calorimeter system. Likely to be the most accurate option, ARC testing will allow measurement of the onset temperature leading to self-heating and thermal runaway. ARC will also aid the determination of likely maximum cell temperature values and an estimation of the total heat evolved.
- **A heat ramp test**, where the cell is heated at a set rate. Likely to be quicker than an ARC test, but less accurate at determining onset temperatures.
- **An open-field test** where the cell is heated by heating element. Less accurate at determining onset temperatures, but would allow filming of the event. This could help to qualitatively indicate the severity of an event.

Two further questions remain.

Firstly, does a cell become more or less ‘safe’ with age and/or continued use? As a cell ages, the capacity of that cell tends to drop, therefore it might be expected that the severity of any failure event decrease. However, the likelihood of that event may increase with age as the cell may before more prone to failure. The capacity fade of a cell is fairly easy to measure through repeated cycling (although some consideration would have to be given to the charge/discharge rates employed). Characterising the severity of the final failure is also tricky- either an ARC type test can be employed, or an open field test with subjective descriptions.

The second question relates to how to deal with cells with dramatically over claimed capacities. Typically, the more exaggerated the claim, the more poorly performing the cell in the capacity measurement. But how does this translate to safety? Is the cell safer as it actually contains less electrical energy to dissipate (although the electrical energy is typically about a third of the energy released in a flaming failure event)? Or is the cell more likely to fail? Again, the testing strategies outlined above may give some indications here.

Appendix A Physical Measurements on Cells

A.1 OPSS-A

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-A-1	65.0	18.2	43.9	3.52	12.9
OPSS-A-2	65.0	18.2	43.9	3.52	13.3
OPSS-A-3	65.0	18.2	43.8	3.52	13.0
OPSS-A-4	65.0	18.2	43.8	3.52	12.5
OPSS-A-5	65.0	18.2	43.8	3.52	13.5
OPSS-A-6	65.0	18.2	43.7	3.52	13.0
OPSS-A-7	65.0	18.2	43.9	3.52	13.9
OPSS-A-8	65.0	18.2	43.8	3.52	12.9
OPSS-A-9	65.0	18.2	43.9	3.52	13.1
OPSS-A-10	65.0	18.2	43.7	3.52	12.8
OPSS-A-11	65.0	18.2	43.9	3.52	13.6
OPSS-A-12	65.0	18.2	43.8	3.52	13.3
OPSS-A-13	65.0	18.2	43.8	3.52	13.2
OPSS-A-14	65.0	18.2	43.7	3.52	13.1
OPSS-A-15	65.0	18.2	43.7	3.52	13.3

OPSS-A-16	65.0	18.2	43.9	3.52	13.6
OPSS-A-17	65.0	18.2	43.7	3.52	13.3
OPSS-A-18	65.0	18.2	43.8	3.52	12.6
OPSS-A-19	65.0	18.2	43.8	3.52	13.8
OPSS-A-20	65.0	18.2	43.9	3.52	13.5
Average	65.0	18.2	43.8	3.52	13.2
Range	N/A	N/A	0.2	0	1.4

A.2 OPSS-B

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-B-1	66.8	18.4	44.0	3.85	55.0
OPSS-B-2	66.9	18.4	43.8	3.86	54.7
OPSS-B-3	66.7	18.4	43.9	4.03	61.1
OPSS-B-4	66.8	18.4	44.2	3.83	50.1
OPSS-B-5	66.8	18.4	43.8	3.86	52.1
OPSS-B-6	66.9	18.4	44.0	3.84	53.9
OPSS-B-7	66.9	18.4	43.3	3.84	50.3
OPSS-B-8	66.8	18.4	43.9	3.83	52.1
OPSS-B-9	66.8	18.5	43.8	3.86	51.2
OPSS-B-10	66.8	18.4	43.9	3.78	56.2
Average	66.8	18.4	43.9	3.86	53.7
Range	N/A	N/A	0.9	0.25	11

A.3 OPSS-C

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-C-1	67.5	18.0	34.5	3.73	56.8
OPSS-C-2	67.5	18.0	35.4	4.00	49.4
OPSS-C-3	67.7	18.0	34.3	3.99	62.1
OPSS-C-4	67.7	18.0	34.3	3.98	55.4
OPSS-C-5	67.5	17.9	34.4	3.99	54.1
OPSS-C-6	67.5	18.0	34.5	3.97	51.3
OPSS-C-7	67.5	18.0	34.4	3.99	54.6
OPSS-C-8	67.5	18.0	34.6	3.99	39.8
OPSS-C-9	67.5	18.0	34.1	3.97	51.1
OPSS-C-10	67.5	18.0	34.9	3.98	53.6
Average	67.5	18.0	34.5	3.96	52.8
Range	N/A	N/A	1.3	0.27	22.3

A.4 OPSS-D

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-D-1	66.4	18.2	42.3	3.87	37.4
OPSS-D-2	66.6	18.2	41.3	3.86	34.8
OPSS-D-3	66.7	18.2	41.1	3.83	40.6
OPSS-D-4	66.5	18.2	41.6	3.87	37.9
OPSS-D-5	66.6	18.2	39.4	0.90	35.0
OPSS-D-6	66.6	18.1	41.5	3.40	33.6
OPSS-D-7	66.6	18.2	41.6	3.82	44.7
OPSS-D-8	66.5	18.2	41.7	3.83	35.1
OPSS-D-9	66.5	18.2	41.4	3.85	36.2
OPSS-D-10	66.6	18.2	41.7	3.83	33.6
Average	66.6	18.2	41.4	3.51	36.9
Range	N/A	N/A	2.9	2.97	11.1

A.5 OPSS-E

Cell	Length (mm)	Diameter (mm) (wrapped)	Weight (g) (wrapped)	Voltage (V) (as received)	Internal Resistance (mΩ) (as received)
OPSS-E-1	65.0	18.2	46.0	3.52	11.0
OPSS-E-2	65.1	18.2	45.8	3.52	10.9
OPSS-E-3	65.0	18.3	46.4	3.52	11.0
OPSS-E-4	65.0	18.2	46.1	0.71	11.8
OPSS-E-5	65.0	18.2	46.0	3.53	11.3
OPSS-E-6	65.1	18.2	46.1	3.52	11.1
OPSS-E-7	65.0	18.2	46.0	3.52	10.9
OPSS-E-8	65.1	18.3	45.9	3.52	11.7
OPSS-E-9	65.0	18.2	45.8	3.52	11.2
OPSS-E-10	65.0	18.3	45.8	3.42	11.2
Average	65.0	18.2	46.0	3.23	11.2
Range	N/A	N/A	0.6	2.82	0.9

A.6 OPSS-F

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-F-1	67.7	18.0	35.5	3.92	35.4
OPSS-F-2	67.7	18.0	35.3	3.90	38.1
OPSS-F-3	67.7	18.0	35.3	3.94	38.9
OPSS-F-4	67.7	18.0	35.0	3.94	39.4
OPSS-F-5	67.8	18.0	35.3	3.93	39.5
OPSS-F-6	67.5	18.1	35.1	3.94	38.9
OPSS-F-7	67.7	18.1	35.6	3.93	40.2
OPSS-F-8	67.5	18.0	35.3	3.93	40.5
OPSS-F-9	67.7	18.1	35.3	3.94	42.6
OPSS-F-10	67.8	18.0	35.7	3.92	38.9
Average	67.7	18.0	35.3	3.93	39.2
Range	N/A	N/A	0.7	0.04	7.2

A.7 OPSS-G

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-G-1	65.0	18.2	45.5	3.53	37.2
OPSS-G-2	65.0	18.2	45.6	3.52	38.1
OPSS-G-3	65.0	18.2	45.5	3.53	36.5
OPSS-G-4	65.0	18.2	45.6	3.52	36.5
OPSS-G-5	65.0	18.2	45.5	3.53	37.0
OPSS-G-6	65.0	18.2	45.5	3.53	37.3
OPSS-G-7	65.0	18.2	45.6	3.53	37.1
OPSS-G-8	65.0	18.2	45.4	3.53	36.8
OPSS-G-9	65.0	18.2	45.5	3.53	36.9
OPSS-G-10	65.2	18.2	45.5	3.53	35.5
Average	65.0	18.2	45.5	3.53	36.9
Range	N/A	N/A	0.2	0.01	2.6

A.8 OPSS-H

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-H-1	68.7	18.6	49.1	3.50	42.7
OPSS-H-2	68.8	18.5	49.0	3.50	41.2
OPSS-H-3	68.7	18.5	49.0	3.50	47.4
OPSS-H-4	68.7	18.6	49.1	3.50	47.0
OPSS-H-5	68.7	18.5	49.1	3.50	43.9
OPSS-H-6	68.7	18.5	49.1	3.50	41.0
OPSS-H-7	68.8	18.5	49.1	3.50	43.7
OPSS-H-8	68.8	18.5	49.1	3.50	45.5
OPSS-H-9	68.8	18.6	49.1	3.50	47.3
OPSS-H-10	68.7	18.6	49.0	3.50	46.9
Average	68.7	18.5	49.1	3.50	44.7
Range	N/A	N/A	0.1	0	6.4

A.9 OPSS-I

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-I-1	69.2	18.3	48.0	3.83	35.8
OPSS-I-2	69.1	18.1	48.0	3.84	36.8
OPSS-I-3	69.2	18.2	48.1	3.82	37.9
OPSS-I-4	69.2	18.2	48.0	3.83	39.1
OPSS-I-5	69.2	18.2	48.1	3.82	35.4
OPSS-I-6	69.2	18.0	47.9	3.83	36.7
OPSS-I-7	69.3	18.2	48.2	3.85	35.0
OPSS-I-8	69.1	18.2	48.1	3.84	36.3
OPSS-I-9	69.1	18.2	48.1	3.83	38.2
OPSS-I-10	69.2	18.1	48.0	3.84	36.8
Average	69.2	18.2	48.1	3.83	36.8
Range	N/A	N/A	0.3	0.03	4.1

A.10 OPSS-J

Cell	Length (mm)	Diameter (wrapped) (mm)	Weight (wrapped) (g)	Voltage (as received) (V)	Internal Resistance (as received) (mΩ)
OPSS-J-1	65.0	18.2	45.9	3.45	17.3
OPSS-J-2	65.0	18.2	46.0	3.45	11.8
OPSS-J-3	65.0	18.2	45.9	3.45	12.1
OPSS-J-4	65.0	18.2	45.9	3.45	11.8
OPSS-J-5	65.0	18.2	45.9	3.45	12.1
OPSS-J-6	65.0	18.2	45.9	3.45	11.9
OPSS-J-7	65.0	18.2	45.9	3.45	12.2
OPSS-J-8	65.0	18.2	46.0	3.45	12.1
OPSS-J-9	65.0	18.2	45.8	3.45	16.8
OPSS-J-10	65.0	18.2	46.0	3.45	11.8
Average	65.0	18.2	45.9	3.45	13.0
Range	N/A	N/A	0.2	0	5.5

Appendix B Cycling Capacities

B.1 OPSS-A

		OPSS-A-1			OPSS-A-2			OPSS-A-3			OPSS-A Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	445	18	1459	436	17	1430	428	17	1403	436	17	1430
1 A	Charge	2476	99	9463	2470	99	9443	2474	99	9455	2473	99	9454
1 A	Discharge	2460	98	9026	2451	98	8998	2453	98	9009	2454	98	9011
1 A	Charge	2460	98	9394	2451	98	9364	2454	98	9372	2455	98	9377
1 A	Discharge	2458	98	9020	2448	98	8989	2449	98	8996	2452	98	9002
1 A	Charge	2456	98	9379	2447	98	9347	2448	98	9352	2450	98	9359
0.2 A	Discharge	2529	101	9370	2522	101	9351	2524	101	9364	2525	101	9362
0.2 A	Charge	2530	101	9525	2522	101	9498	2524	101	9502	2526	101	9509

0.5 A	Discharge	2473	99	9133	2462	98	9099	2463	99	9103	2466	99	9112
0.5 A	Charge	2474	99	9375	2463	99	9344	2463	99	9344	2467	99	9355
1 A	Discharge	2428	97	8907	2418	97	8873	2417	97	8875	2421	97	8885
1 A	Charge	2428	97	9285	2417	97	9252	2417	97	9251	2421	97	9263
2 A	Discharge	2389	96	8679	2379	95	8645	2379	95	8650	2382	95	8658
2 A	Charge	2399	96	9293	2390	96	9261	2387	95	9251	2392	96	9268
3 A	Discharge	2378	95	8550	2367	95	8513	2367	95	8514	2371	95	8526
2 A	Charge	2390	96	9255	2379	95	9222	2377	95	9212	2382	95	9230
5A	Discharge	2393	96	8465	2384	95	8431	2382	95	8430	2386	95	8442
Break	Evaluate												
10 A	Discharge	2414	97	8316	2406	96	8290	2412	96	8316	2410	96	8307
12 A	Discharge	2411	96	8212	2406	96	8201	2412	96	8229	2410	96	8214
5 A	Charge	2509	100	9813	2502	100	8927	2505	100	9795	2505	100	9512

B.2 OPSS-B

		OPSS-B-1			OPSS-B-2			OPSS-B-3			OPSS-B Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	456	11	1599	1317	31	4821	490	12	1729	754	18	2716
1 A	Charge	1512	36	6242	1609	38	6664	1534	37	6325	1552	37	6410
1 A	Discharge	1496	36	5546	1607	38	5987	1520	36	5656	1541	37	5730
1 A	Charge	1509	36	6226	1603	38	6638	1530	36	6301	1547	37	6388
1 A	Discharge	1502	36	5573	1588	38	5908	1523	36	5673	1538	37	5718
1 A	Charge	1508	36	6226	1584	38	6566	1528	36	6296	1540	37	6362
0.2 A	Discharge	1537	37	5951	1623	39	6304	1556	37	6039	1572	37	6098
0.2 A	Charge	1561	37	6208	1628	39	6494	1576	38	6272	1588	38	6325
0.5 A	Discharge	1548	37	5907	1596	38	6100	1563	37	5980	1569	37	5996
0.5 A	Charge	1538	37	6221	1576	38	6405	1553	37	6278	1556	37	6301

1 A	Discharge	1510	36	5602	1537	37	5696	1528	36	5689	1525	36	5663
1 A	Charge	1513	36	6250	1540	37	6393	1531	36	6311	1528	36	6318
2 A	Discharge	1404	33	4983	1384	33	4914	1443	34	5150	1410	34	5016
2 A	Charge	1442	34	6053	1407	34	5912	1484	35	6225	1444	34	6063
3 A	Discharge	1181	28	4105	1161	28	3902	1255	30	4387	1199	29	4131
2 A	Charge	1216	29	5107	1196	28	5026	1295	31	5433	1235	29	5189
5A	Discharge	905	22	2869	685	16	2101	932	22	3015	841	20	2662
Break	Evaluate												
10 A	Discharge	149	4	461	170	4	528	147	3	468	155	4	486
12 A	Discharge	140	3	427	146	3	447	164	4	511	150	4	462
5 A	Charge	1468	35	6170	1498	36	4971	1396	33	5873	1454	35	5671

B.3 OPSS-C

		OPSS-C-1			OPSS-C-2			OPSS-C-3			OPSS-C Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	5	0	16	598	6	2136	473	5	1653	359	4	1268
1 A	Charge	1004	10	4199	1245	13	5175	943	10	3948	1064	11	4441
1 A	Discharge	825	8	2941	1232	12	4556	880	9	3178	979	10	3559
1 A	Charge	868	9	3627	1246	13	5155	898	9	3755	1004	10	4179
1 A	Discharge	778	8	2835	1257	13	4675	776	8	2832	937	9	3447
1 A	Charge	781	8	3271	1251	13	5178	769	8	3227	934	9	3892
0.2 A	Discharge	831	8	3185	1280	13	4954	777	8	2981	963	10	3707
0.2 A	Charge	838	8	3373	1286	13	5122	764	8	3088	963	10	3861
0.5 A	Discharge	784	8	2927	1275	13	4862	733	7	2737	931	9	3509
0.5 A	Charge	783	8	3237	1268	13	5132	731	7	3034	927	9	3801

1 A	Discharge	685	7	2474	1222	12	4549	648	7	2339	852	9	3121
1 A	Charge	692	7	2901	1216	12	5030	658	7	2763	855	9	3565
2 A	Discharge	409	4	1320	991	10	3364	414	4	1341	605	6	2008
2 A	Charge	449	5	1889	1012	10	4254	440	4	1850	634	6	2664
3 A	Discharge	80	1	271	525	5	1670	80	1	271	228	2	737
2 A	Charge	108	1	453	547	6	2300	105	1	443	253	3	1066
5A	Discharge	45	0	147	67	1	230	47	0	151	53	1	176
Break	Evaluate												
10 A	Discharge	37	0	110	49	0	156	27	0	79	37	0	115
12 A	Discharge	12	0	34	37	0	112	5	0	15	18	0	54
5 A	Charge	543	5	2287	1074	11	2511	470	5	1979	696	7	2259

B.4 OPSS-D

		OPSS-D-1			OPSS-D-2			OPSS-D-3			OPSS-D Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	432	9	1519	357	7	1229	326	7	1142	371	8	1297
1 A	Charge	1279	27	5223	1175	24	4788	1188	25	4826	1214	25	4946
1 A	Discharge	1256	26	4692	1106	23	4149	1162	24	4372	1175	24	4404
1 A	Charge	1287	27	5246	1152	24	4697	1201	25	4880	1213	25	4941
1 A	Discharge	1283	27	4818	1158	24	4364	1201	25	4537	1214	25	4573
1 A	Charge	1291	27	5266	1173	24	4777	1216	25	4941	1227	26	4995
0.2 A	Discharge	1359	28	5261	1313	27	5063	1259	26	4878	1310	27	5067
0.2 A	Charge	1375	29	5448	1351	28	5352	1273	27	5042	1333	28	5280
0.5 A	Discharge	1360	28	5217	1311	27	5007	1261	26	4842	1311	27	5022
0.5 A	Charge	1366	28	5474	1328	28	5328	1266	26	5067	1320	28	5290

1 A	Discharge	1321	28	4976	1260	26	4750	1244	26	4704	1275	27	4810
1 A	Charge	1324	28	5389	1264	26	5140	1254	26	5084	1281	27	5204
2 A	Discharge	1232	26	4487	1124	23	4138	1156	24	4255	1170	24	4293
2 A	Charge	1251	26	5191	1139	24	4724	1176	25	4873	1189	25	4930
3 A	Discharge	1152	24	4110	1048	22	3786	1088	23	3924	1096	23	3940
2 A	Charge	1167	24	4850	1061	22	4405	1103	23	4579	1110	23	4612
5A	Discharge	1159	24	3814	958	20	3314	1131	24	3721	1083	23	3616
Break	Evaluate												
10 A	Discharge	114	2	372	132	3	427	102	2	339	116	2	379
12 A	Discharge	92	2	295	94	2	294	86	2	279	90	2	289
5 A	Charge	1333	28	5595	1345	28	4659	1265	26	5312	1314	27	5189

B.5 OPSS-E

		OPSS-E-1			OPSS-E-2			OPSS-E-3			OPSS-E Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	384	15	1260	374	14	1226	378	15	1239	379	15	1242
1 A	Charge	2421	93	9255	2405	92	9190	2401	92	9177	2409	93	9207
1 A	Discharge	2439	94	9004	2424	93	8951	2423	93	8954	2429	93	8969
1 A	Charge	2436	94	9288	2421	93	9222	2420	93	9221	2426	93	9244
1 A	Discharge	2409	93	8891	2396	92	8849	2395	92	8849	2400	92	8863
1 A	Charge	2405	92	9184	2392	92	9127	2391	92	9126	2396	92	9145
0.2 A	Discharge	2575	99	9564	2554	98	9489	2549	98	9478	2559	98	9510
0.2 A	Charge	2581	99	9701	2561	99	9622	2554	98	9589	2566	99	9637
0.5 A	Discharge	2473	95	9172	2456	94	9113	2453	94	9104	2460	95	9129
0.5 A	Charge	2472	95	9354	2455	94	9289	2451	94	9279	2459	95	9307

1 A	Discharge	2426	93	8955	2414	93	8913	2413	93	8915	2418	93	8928
1 A	Charge	2424	93	9243	2412	93	9186	2411	93	9186	2416	93	9205
2 A	Discharge	2370	91	8676	2358	91	8646	2359	91	8656	2362	91	8659
2 A	Charge	2377	91	9171	2366	91	9112	2365	91	9114	2369	91	9132
3 A	Discharge	2344	90	8510	2333	90	8485	2337	90	8495	2338	90	8497
2 A	Charge	2353	91	9090	2343	90	9033	2343	90	9037	2347	90	9053
5A	Discharge	2329	90	8325	2320	89	8317	2323	89	8322	2324	89	8322
Break	Evaluate												
10 A	Discharge	2400	92	8376	2391	92	8375	2401	92	8397	2397	92	8383
12 A	Discharge	2431	93	8401	2422	93	8402	2432	94	8427	2428	93	8410
5 A	Charge	2555	98	9937	2535	97	8871	2538	98	9848	2543	98	9552

B.6 OPSS-F

		OPSS-F-1			OPSS-F-2			OPSS-F-3			OPSS-F Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	512	9	1833	491	8	1753	495	8	1762	499	8	1783
1 A	Charge	1209	20	4997	1221	20	5056	1153	19	4787	1194	20	4947
1 A	Discharge	1214	20	4507	1231	21	4583	1178	20	4343	1208	20	4478
1 A	Charge	1225	20	5047	1244	21	5124	1187	20	4898	1219	20	5023
1 A	Discharge	1298	22	4873	1291	22	4852	1233	21	4606	1274	21	4777
1 A	Charge	1293	22	5300	1287	21	5284	1230	21	5064	1270	21	5216
0.2 A	Discharge	1310	22	5086	1301	22	5056	1238	21	4793	1283	21	4978
0.2 A	Charge	1312	22	5214	1305	22	5192	1246	21	4956	1288	21	5121
0.5 A	Discharge	1302	22	4993	1295	22	4972	1237	21	4724	1278	21	4896
0.5 A	Charge	1296	22	5212	1289	21	5191	1232	21	4973	1272	21	5125

1 A	Discharge	1281	21	4814	1278	21	4811	1216	20	4547	1258	21	4724
1 A	Charge	1277	21	5229	1274	21	5220	1211	20	4975	1254	21	5141
2 A	Discharge	1125	19	3970	1123	19	4016	1051	18	3713	1100	18	3900
2 A	Charge	1142	19	4774	1139	19	4768	1065	18	4462	1115	19	4668
3 A	Discharge	886	15	2991	986	16	3321	899	15	3007	924	15	3106
2 A	Charge	905	15	3796	1006	17	4216	922	15	3869	944	16	3960
5A	Discharge	154	3	528	459	8	1447	176	3	595	263	4	857
Break	Evaluate												
10 A	Discharge	69	1	224	65	1	207	80	1	258	71	1	230
12 A	Discharge	58	1	184	55	1	171	65	1	205	59	1	187
5 A	Charge	1102	18	4634	1100	18	3532	1072	18	4507	1091	18	4224

B.7 OPSS-G

		OPSS-G-1			OPSS-G-2			OPSS-G-3			OPSS-G Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	565	17	1798	564	17	1793	567	17	1802	565	17	1798
1 A	Charge	3070	92	11923	3076	92	11958	3067	92	11921	3071	92	11934
1 A	Discharge	3020	90	10836	3037	91	10885	3017	90	10819	3025	90	10846
1 A	Charge	3018	90	11703	3039	91	11783	3017	90	11705	3024	90	11730
1 A	Discharge	2973	89	10682	3011	90	10805	2980	89	10702	2988	89	10730
1 A	Charge	2970	89	11530	3007	90	11669	2975	89	11555	2984	89	11584
0.2 A	Discharge	3119	93	11521	3159	94	11676	3124	93	11553	3134	94	11584
0.2 A	Charge	3130	93	11853	3168	95	12002	3132	93	11880	3143	94	11912
0.5 A	Discharge	2982	89	10893	3027	90	11047	2975	89	10867	2994	89	10936
0.5 A	Charge	2989	89	11455	3038	91	11632	2985	89	11443	3004	90	11510

1 A	Discharge	2953	88	10627	3008	90	10815	2950	88	10612	2970	89	10685
1 A	Charge	2958	88	11454	3010	90	11646	2953	88	11447	2974	89	11516
2 A	Discharge	2860	85	10089	2908	87	10223	2851	85	10045	2873	86	10119
2 A	Charge	2869	86	11371	2926	87	11597	2867	86	11373	2887	86	11447
3 A	Discharge	2770	83	9533	2831	85	9729	2759	82	9490	2787	83	9584
2 A	Charge	2784	83	11063	2858	85	11347	2782	83	11060	2808	84	11157
5A	Discharge	2634	79	8720	2675	80	8847	2621	78	8680	2643	79	8749
Break	Evaluate												
10 A	Discharge	2313	69	7197	2480	74	7722	2420	72	7539	2405	72	7486
12 A	Discharge	1784	53	5428	1937	58	5909	1964	59	5974	1895	57	5770
5 A	Charge	3035	91	12360	3090	92	10473	3039	91	12380	3055	91	11738

B.8 OPSS-H

		OPSS-H-1			OPSS-H-2			OPSS-H-3			OPSS-H Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	594	17	1878	603	17	1907	595	17	1879	597	17	1888
1 A	Charge	3277	94	12764	3287	94	12797	3273	94	12779	3279	94	12780
1 A	Discharge	3258	93	11731	3262	93	11758	3235	92	11641	3251	93	11710
1 A	Charge	3257	93	12654	3261	93	12666	3232	92	12585	3250	93	12635
1 A	Discharge	3261	93	11753	3261	93	11768	3233	92	11656	3252	93	11725
1 A	Charge	3275	94	12686	3275	94	12687	3245	93	12599	3265	93	12657
0.2 A	Discharge	3370	96	12490	3367	96	12507	3345	96	12430	3361	96	12475
0.2 A	Charge	3374	96	12806	3370	96	12804	3349	96	12741	3364	96	12784
0.5 A	Discharge	3299	94	12107	3295	94	12109	3273	94	12029	3289	94	12082
0.5 A	Charge	3310	95	12673	3307	94	12667	3284	94	12593	3300	94	12644

1 A	Discharge	3297	94	11930	3295	94	11941	3271	93	11847	3288	94	11906
1 A	Charge	3292	94	12721	3291	94	12716	3266	93	12641	3283	94	12693
2 A	Discharge	3232	92	11453	3241	93	11498	3210	92	11358	3228	92	11436
2 A	Charge	3244	93	12793	3260	93	12846	3227	92	12745	3243	93	12795
3 A	Discharge	3203	92	11124	3216	92	11195	3181	91	11038	3200	91	11119
2 A	Charge	3217	92	12694	3240	93	12771	3203	92	12654	3220	92	12706
5A	Discharge	3160	90	10626	3182	91	10727	3121	89	10471	3154	90	10608
Break	Evaluate												
10 A	Discharge	2895	83	9145	2498	71	7776	2895	83	9186	2763	79	8702
12 A	Discharge	2429	69	7565	2796	80	8460	2257	64	7136	2494	71	7720
5 A	Charge	3290	94	13353	3294	94	11334	3258	93	13225	3281	94	12637

B.9 OPSS-I

		OPSS-I-1			OPSS-I-2			OPSS-I-3			OPSS-I Average		
Current	Charge/ Discharge	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh	Ah	% Nominal	Wh
1 A	Discharge	1929	55	6590	1958	56	6694	1923	55	6567	1937	55	6617
1 A	Charge	3209	92	12448	3211	92	12460	3218	92	12476	3213	92	12461
1 A	Discharge	3185	91	11502	3193	91	11523	3193	91	11533	3190	91	11519
1 A	Charge	3176	91	12321	3184	91	12353	3186	91	12356	3182	91	12343
1 A	Discharge	3158	90	11401	3167	90	11425	3168	91	11435	3164	90	11420
1 A	Charge	3160	90	12264	3168	91	12297	3169	91	12297	3166	90	12286
0.2 A	Discharge	3284	94	12167	3289	94	12187	3292	94	12209	3288	94	12188
0.2 A	Charge	3296	94	12512	3301	94	12531	3302	94	12525	3300	94	12523
0.5 A	Discharge	3227	92	11853	3231	92	11867	3234	92	11882	3231	92	11867
0.5 A	Charge	3224	92	12346	3229	92	12366	3231	92	12369	3228	92	12360

1 A	Discharge	3187	91	11533	3198	91	11562	3200	91	11579	3195	91	11558
1 A	Charge	3192	91	12341	3203	92	12386	3205	92	12383	3200	91	12370
2 A	Discharge	3158	90	11220	3170	91	11253	3171	91	11277	3166	90	11250
2 A	Charge	3170	91	12484	3183	91	12534	3180	91	12509	3178	91	12509
3 A	Discharge	3120	89	10846	3133	90	10880	3133	90	10899	3129	89	10875
2 A	Charge	3135	90	12367	3149	90	12420	3143	90	12385	3142	90	12391
5A	Discharge	3077	88	10325	3079	88	10328	3087	88	10383	3081	88	10346
Break	Evaluate												
10 A	Discharge	2506	72	7976	2256	64	7227	2865	82	9085	2542	73	8096
12 A	Discharge	29	1	97	14	0	47	108	3	363	50	1	169
5 A	Charge	3190	91	12943	3198	91	11173	3220	92	13049	3203	92	12388

B.10 OPSS-J

		OPSS-J-1			OPSS-J-2			OPSS-J-3			OPSS-J Average		
Current	Charge/	Ah	%	Wh	Ah	%	Wh	Ah	%	Wh	Ah	%	Wh
	Discharge		Nominal			Nominal			Nominal			Nominal	
1 A	Discharge	444	15	1391	421	14	1314	433	14	1353	433	14	1353
1 A	Charge	2919	97	11187	2888	96	11076	2935	98	11244	2914	97	11169
1 A	Discharge	2894	96	10506	2858	95	10389	2933	98	10665	2895	96	10520
1 A	Charge	2895	96	11094	2858	95	10964	2935	98	11218	2896	97	11092
1 A	Discharge	2892	96	10497	2857	95	10382	2923	97	10623	2891	96	10501
1 A	Charge	2897	97	11099	2862	95	10974	2924	97	11182	2894	96	11085
0.2 A	Discharge	2972	99	10984	2942	98	10880	2991	100	11060	2969	99	10975
0.2 A	Charge	2981	99	11265	2952	98	11158	3002	100	11343	2978	99	11255
0.5 A	Discharge	2942	98	10817	2911	97	10717	2967	99	10909	2940	98	10814
0.5 A	Charge	2941	98	11161	2911	97	11057	2968	99	11252	2940	98	11157

1 A	Discharge	2907	97	10576	2875	96	10471	2927	98	10655	2903	97	10567
1 A	Charge	2911	97	11129	2879	96	11015	2927	98	11185	2906	97	11110
2 A	Discharge	2900	97	10449	2870	96	10351	2914	97	10490	2895	96	10430
2 A	Charge	2910	97	11251	2879	96	11139	2926	98	11304	2905	97	11231
3 A	Discharge	2881	96	10287	2854	95	10199	2903	97	10373	2879	96	10286
2 A	Charge	2896	97	11200	2868	96	11097	2918	97	11268	2894	96	11188
5A	Discharge	2854	95	10006	2832	94	9940	2880	96	10126	2855	95	10024
Break	Evaluate												
10 A	Discharge	2805	94	9608	2785	93	9542	2819	94	9661	2803	93	9604
12 A	Discharge	2792	93	9466	2772	92	9401	2808	94	9533	2791	93	9466
5 A	Charge	2944	98	11560	2924	97	10419	2957	99	11602	2942	98	11193

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