

Limitations of Internal Protective Devices in Commercial Low Capacity Cylindrical Lithium-ion Cells

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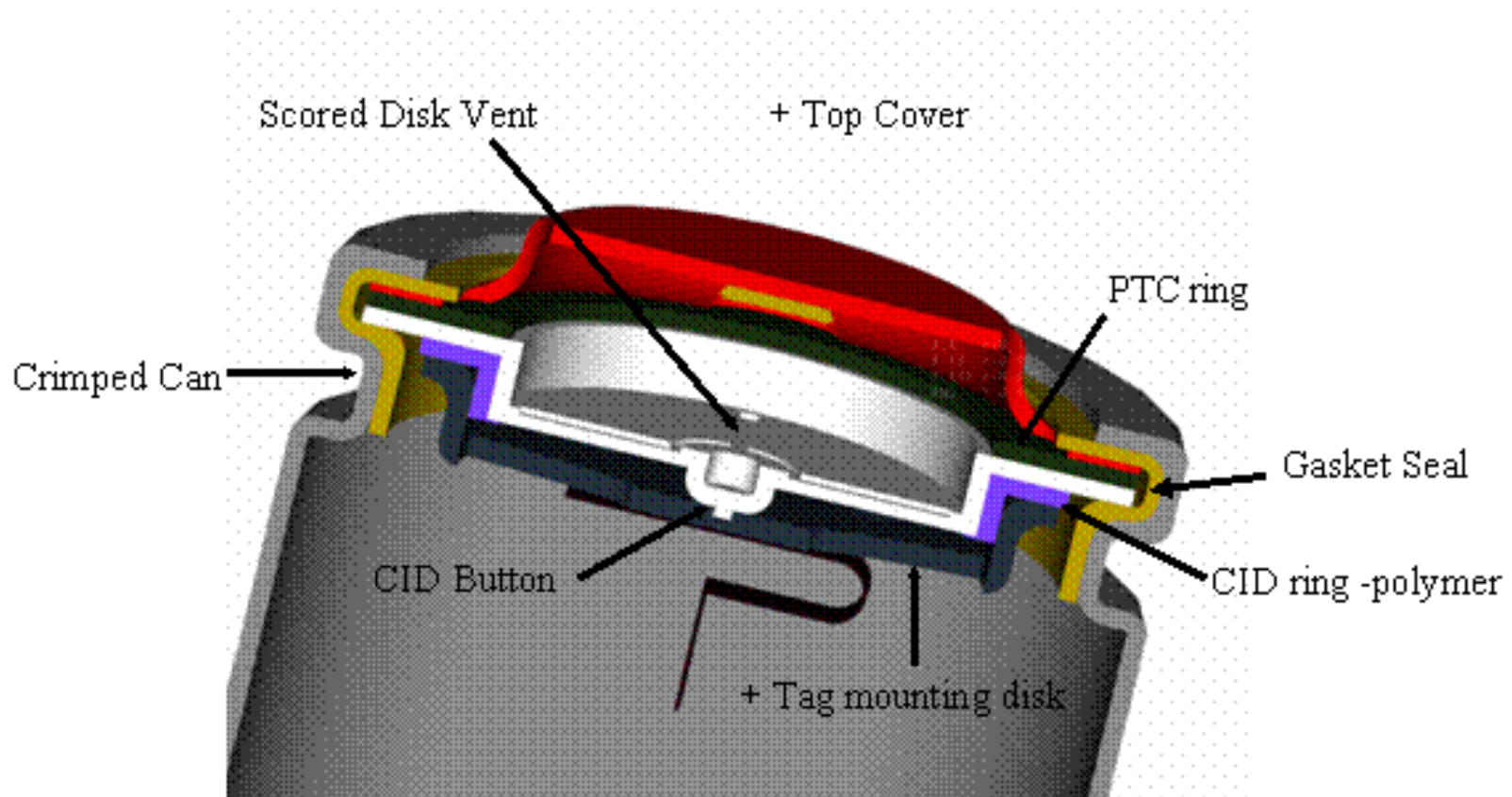
Test Team

- **Internal :**
 - NASA-JSC – Eric Darcy, Pranav Patel, Gilberto Varela and Frank Davies
 - NASA-JSC Energy Systems Test Area team
- **External:**
 - Ramesh Shah, Chuck Weitzel, Casey Keen
 - Mobile Power Solutions
 - Walt Tracinski
 - Applied Power International

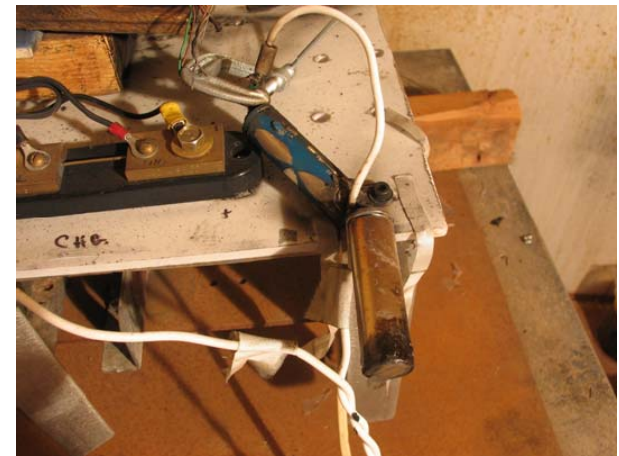
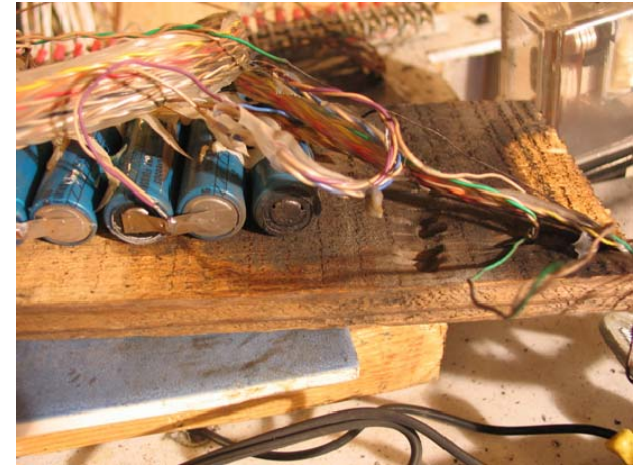
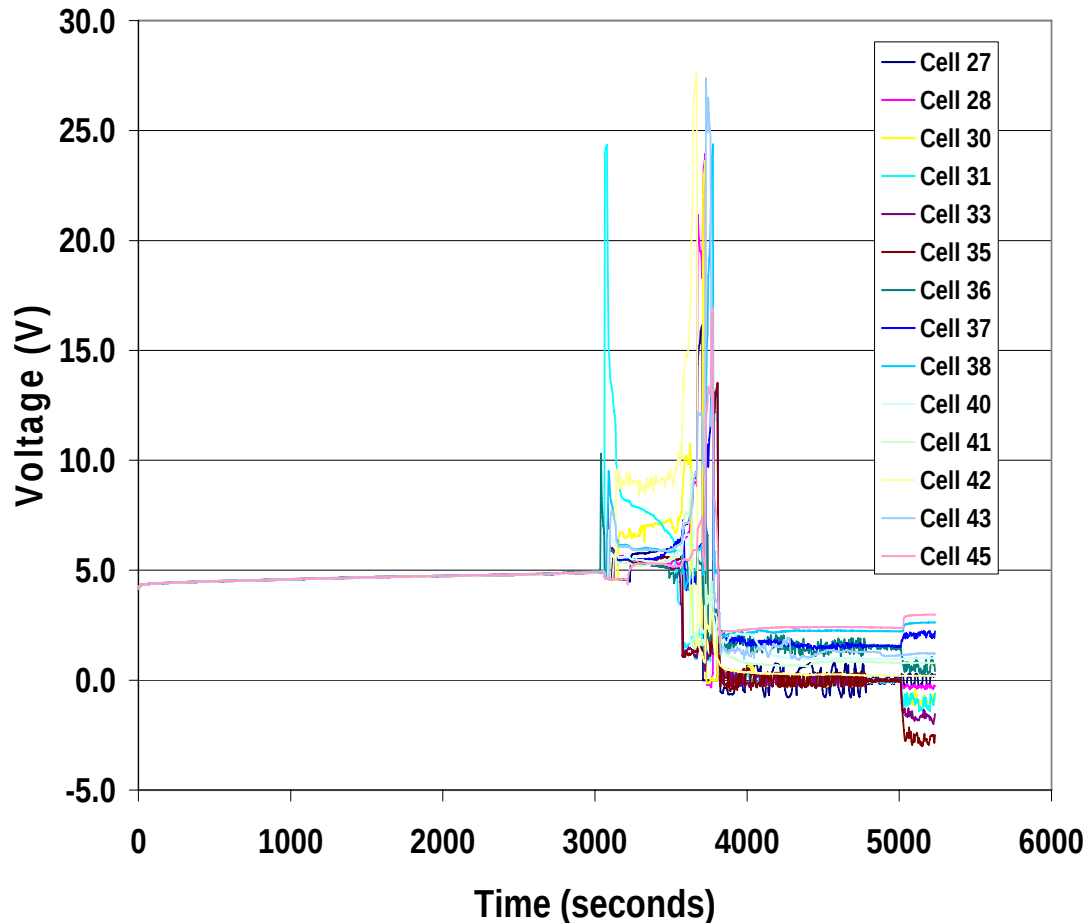
Background

- Testing in the past indicated that internal protective devices in small cylindrical COTS (commercial-off-the-shelf) Li-ion cells failed to protect when the battery module designs included multi-cell series and/or parallel configurations.
- Testing carried out was mostly overcharge and external shorts.
- Tests were carried out with cells in series and cells in parallel
- The tests carried out were off-nominal and were carried out under worst-case conditions to determine the worst-case failures that could occur.
- Tests also included determination of PTC (Positive Temperature Coefficient) limitations for cells from different manufacturers, CID (Current Interrupt Device) tests in header assemblies as well as single cells and choice of diode for prevention of catastrophic hazards in multi-cell strings.
- Cells used for this test program were only test vehicles to provide data for the issue being discussed and also due to ease of availability. The test results do not infer any type of endorsement and are presented for information purposes only.
- All Tests were performed with cells in a single row configuration (picket-fence / fence-post type); all cells extracted from Canon battery unless indicated as new cells (obtained as loose fresh cells)

Schematic of Cell Header Portion



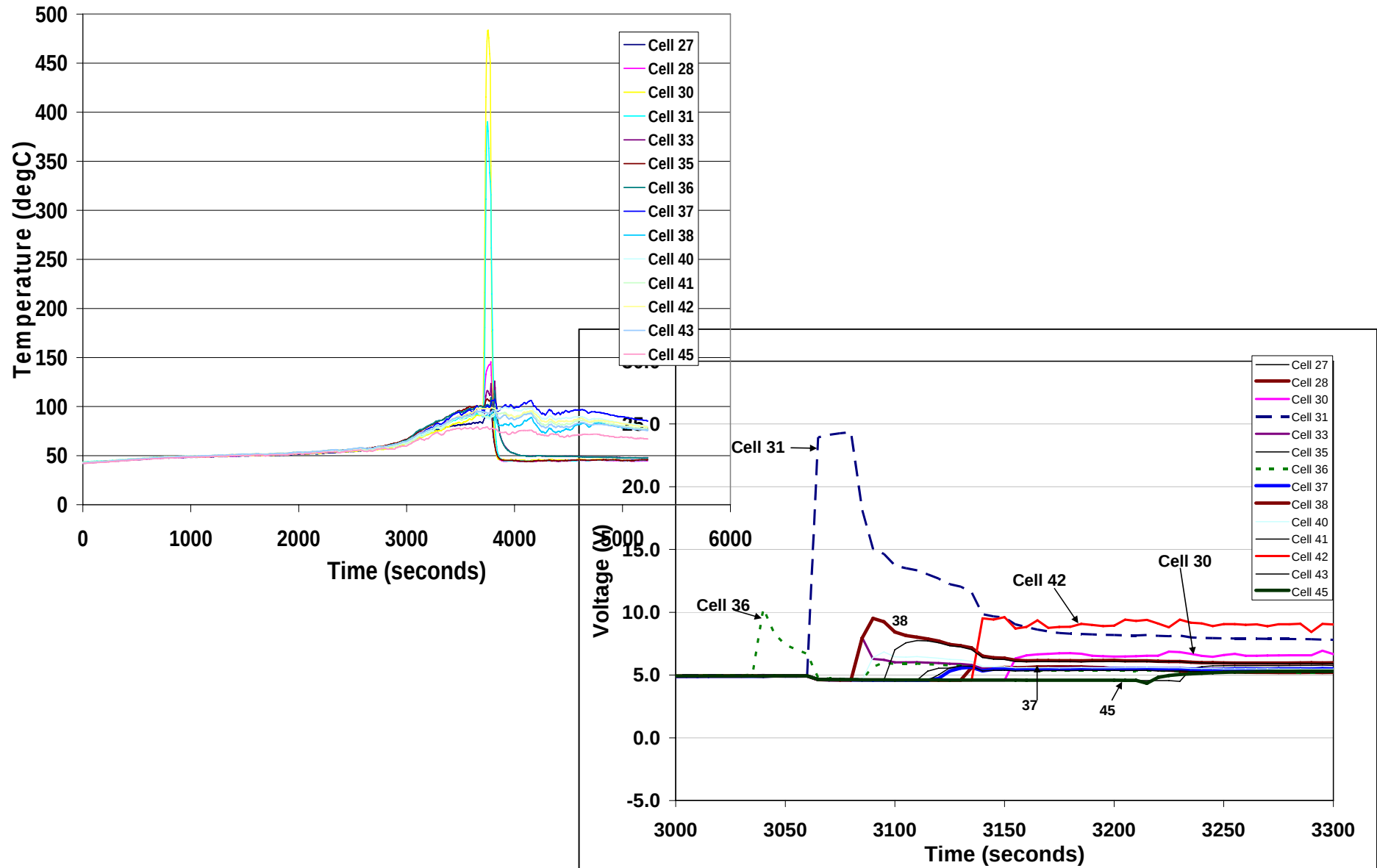
Overcharge Test on a 14-Cell String Showing Cell Voltages for the Sony Li-ion Cells



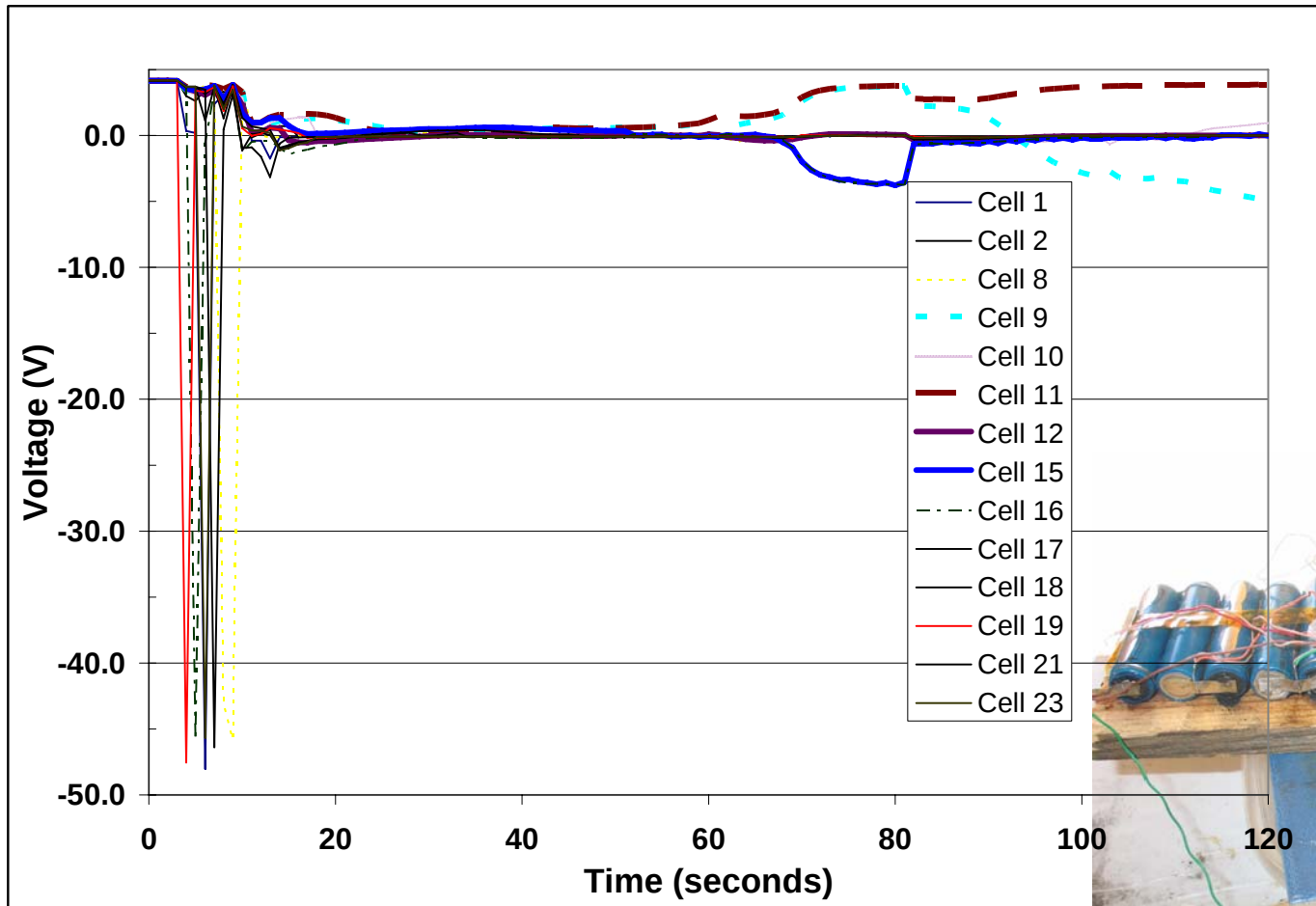
Missing : 27, 28, 30 and 31

Cells 37, 38 and 45 showed no visible
Signs of venting

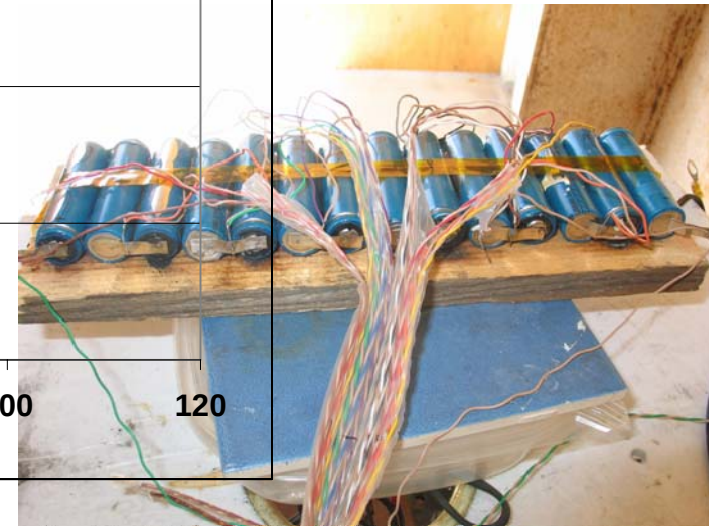
Overcharge Test on 14S set of Sony Lithium-ion Cells



14-Cell String Short Circuit Test on Sony Li-ion Cells



Only venting observed,
no fire
Cell Voltages in bold –
No visible signs of
Venting or damage,
but no voltage;
All others vented with
Obvious leakage or
discoloration



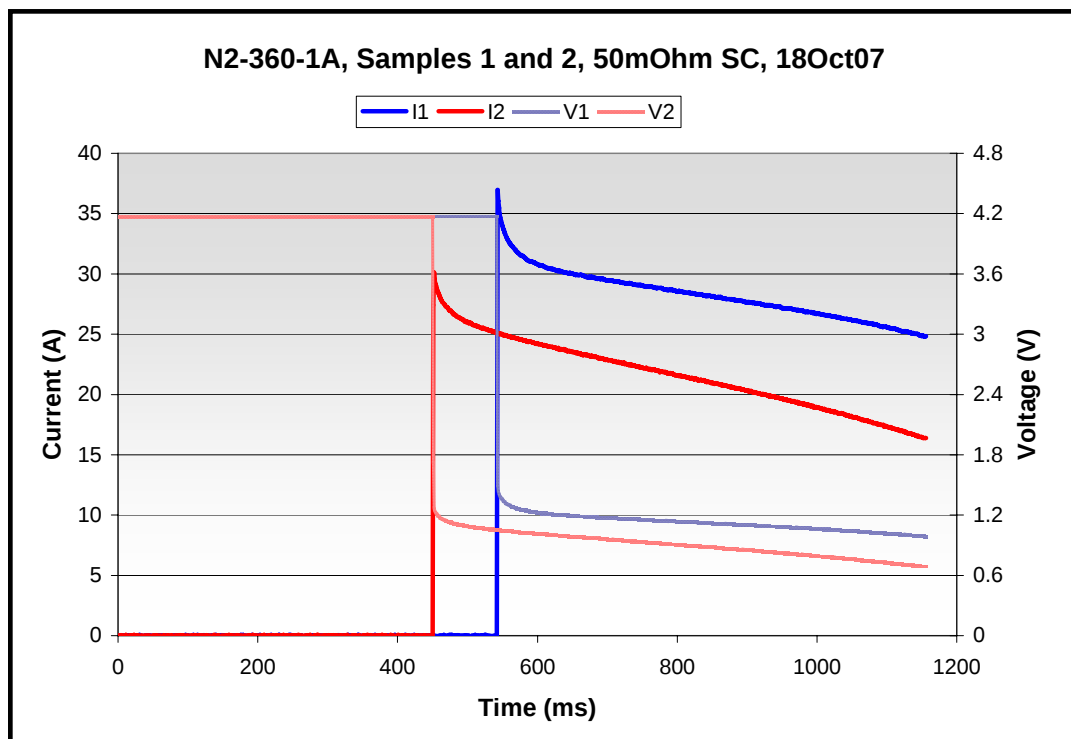
Rapid cell venting within the first 10 seconds

Variable Bank Size Test Summary Table

Status	Test Code	Date	Old Cells	New Cells	Description	Volts	Amps	Reference
Complete	1A	18-Oct	2		Single cell short, 2X			SoW
Complete	2A	19-Oct	2		Single cell overcharge, 2X	12	6	SoW
Complete	4A	26-Oct	4		4P overcharge, 48V, 6A	48	6	SoW
Complete	4A2	24-Oct	4		4P overcharge, 12V, 6A	12	6	10/29 e-mail
Complete	4A3	31-Oct	4		4P overcharge, 12V, 4A	12	4	10/29 e-mail
Complete	4A4	1-Nov		4	4P overcharge, 12V, 6A	12	6	10/31 e-mail
Complete	4B	2-Nov		16	16P overcharge, 48V, 24A	48	24	SoW
Complete	4A5	15-Nov	4		4P overcharge, 12V, 6A	12	6	11/5 e-mail
Complete	4B2	19-Nov		16	16P overcharge, 12V, 24A	12	24	11/9 e-mail
Complete	4B3	19-Dec		16	16P overcharge, 12V, 12A	12	12	12/5 e-mail
Complete	3B	31-Jan		16	16P short circuit			SoW

- Test 1A- 50mOhm Short Circuit on Single Cells
- Test 2A- 12V, 1.5A Overcharge on Single Cells
- Test 4A- Overcharge on 4 parallel cells
- Test 4B- Overcharge on 16 parallel cells
- Test 3B- Short Circuit on 16 parallel connected cell battery

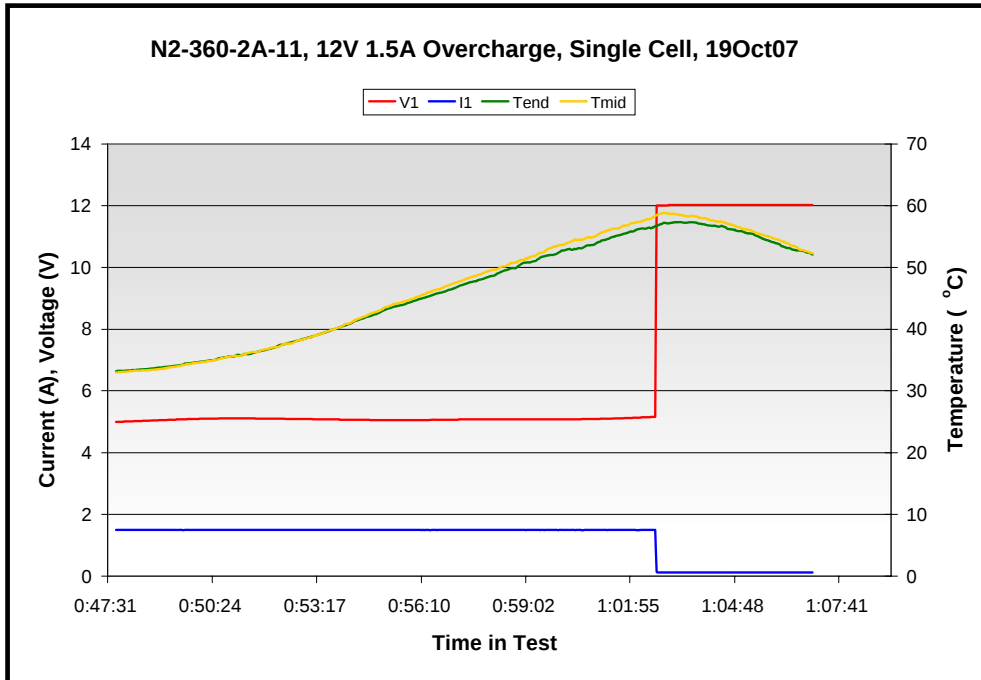
50mOhm Short Circuit, Single Cell (1000 Hz Chart)



- Short circuit concluded on each sample without event
- Operation consistent with typical 18650 cell PTC performance

	Peak Current (A)	Peak Temp (°C)	Peak Temp Time (minutes)
N2-360-1A-1	37	78	43
N2-360-1A-2	30	82	49

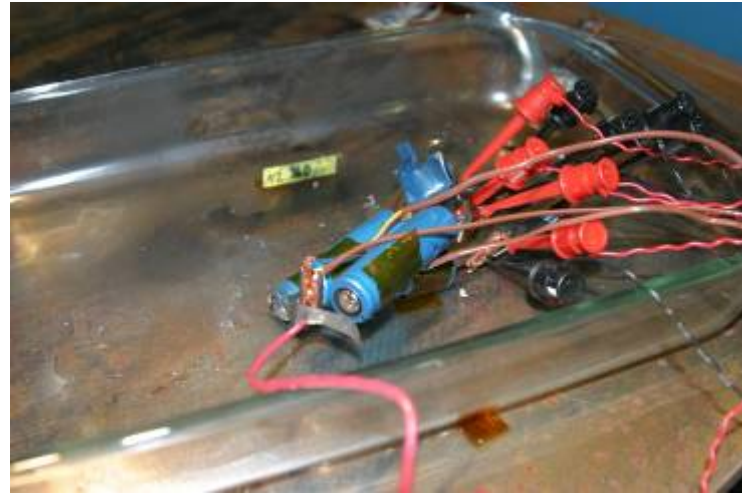
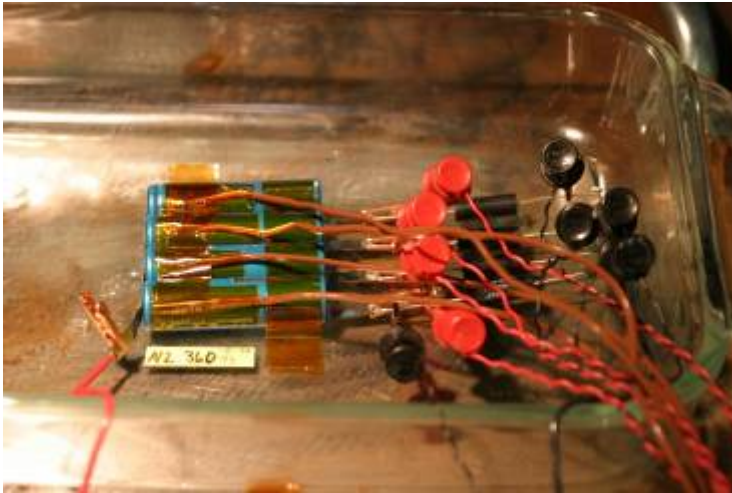
12V 1.5A Overcharge on Single Cells



- CID devices activated in both samples at 1 hour and 2 minutes into the overcharge.

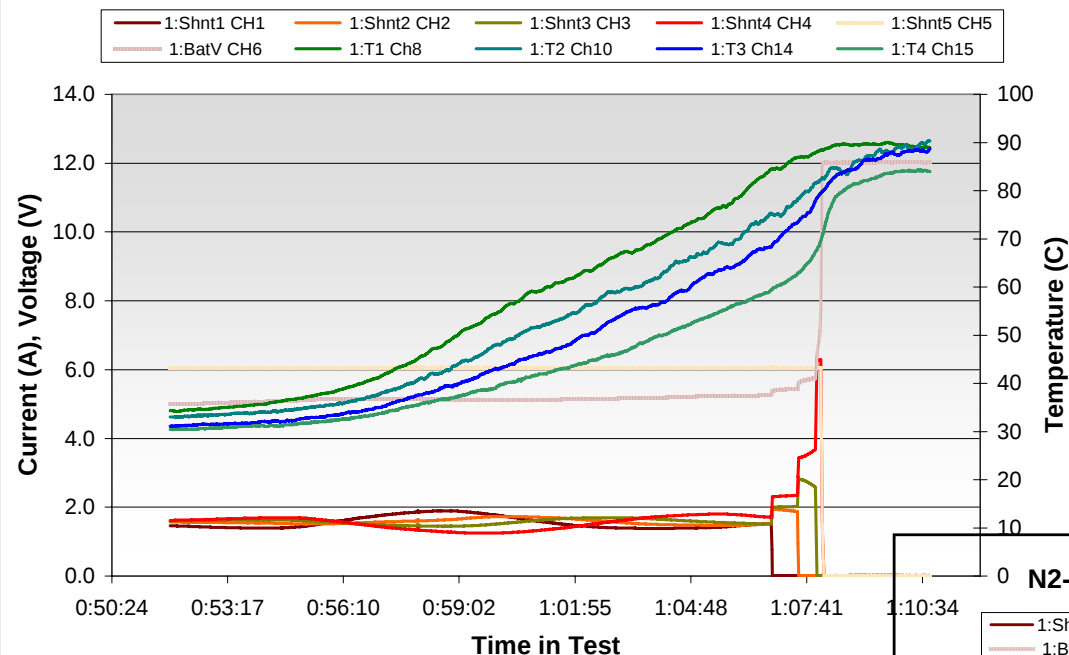
	CID Open Time (approximate)	Sample Temp. at CID Open (°C)
N2-360-2A-11	1:02:38	59
N2-360-2A-12	1:02:28	73

48V 6A Overcharge on 4P Battery



12V 6A Overcharge on 4P Battery (Repeated)

N2-360-B-4A4-69, 4P Battery, 12V, 6A Overcharge, 01Nov07



Cells from DPAed Battery:

Test 4A2 was repeated with 4 cells from the original lot

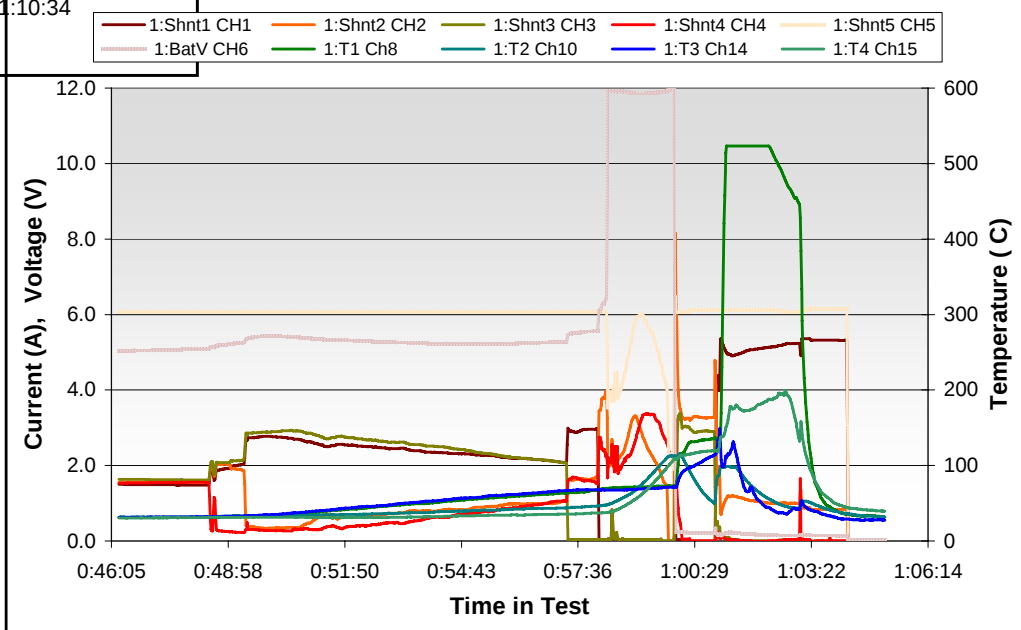
The CID on cell 3 activated at 0:57:21

The CID on cell 1 activated at 0:58:07

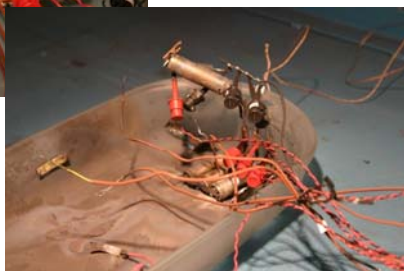
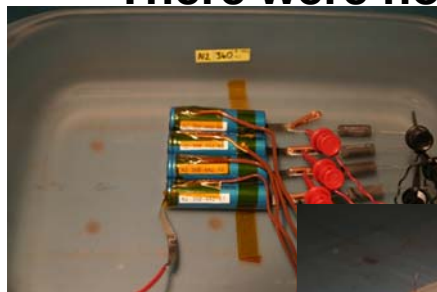
Cells 2 and 4 split the 6A current. Cell 2 rose from 48°C to 110°C in 2 minutes. A large current spike was recorded on shunt 2 and cell 2 vented sparks and flame.

Cells 3, 4, and 1 also vented, likely due to thermal propagation from the initial event. ↓

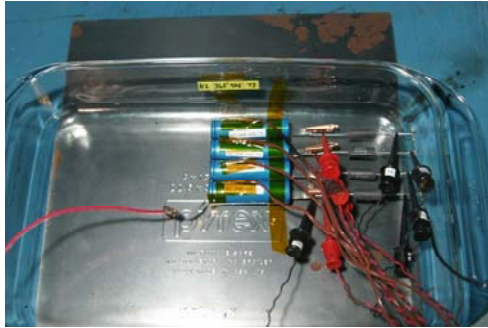
N2-360-B-4A5-73, 4P Battery, 12V, 6A Overcharge, 15Nov07



- New Loose Cells ↑
- There were no events



12V 6A Overcharge on 4P Battery



Note: The Pyrex dish shattered due to thermal stress minutes after the cell events.



Cells from old DPAed Pack with compromised PTCs:

Cell 1: OCV: 4.062V, PTC resistance: 30.9mohm – **indicates compromised PTC**

Cell 2: OCV: 4.051V, PTC resistance: 21.2mohm - **uncompromised PTC**

Cell 3: OCV: 4.033V, PTC resistance: 26.7mohm : **indicates compromised PTC**

New Loose Cells:

PTC resistances: 21.1 mohm to 24.1 mohm;

Cells from New Canon Pack:

Cell 1: OCV: 3.511V, PTC resistance: 24.4mohm

Cell 2: OCV: 3.512V, PTC resistance: 24.0mohm

Cell 3: OCV: 3.500V, PTC resistance: 25.1mohm

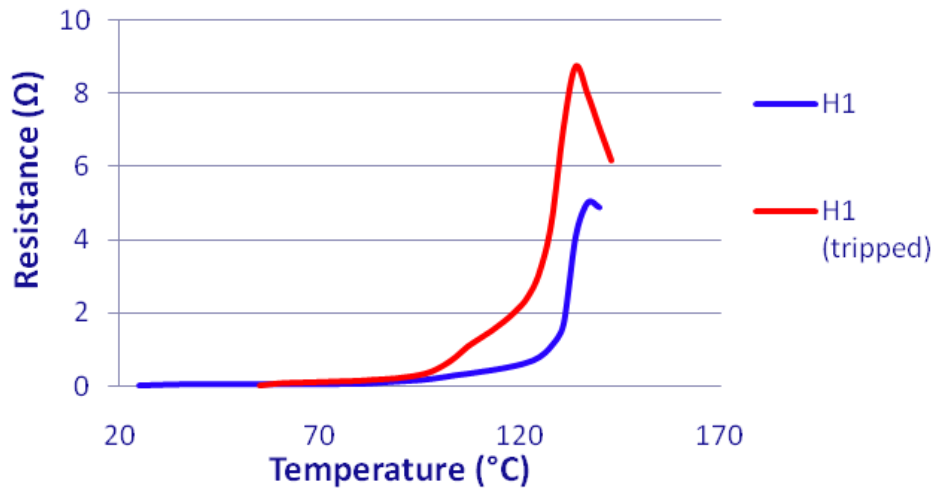
Cell 4: OCV: 3.500V, PTC resistance: 24.9mohm

Summary Of Tests and Results

Description	Volts	Amps	Load (Ohms)	Notes
Single cell overcharge, 2X	12	1.5		CID operates; Canon / fresh
4P overcharge, 48V, 6A	48	6		Thermal runaway; Canon
4P overcharge, 12V, 6A	12	6		CID operates; fresh
4P overcharge, 12V, 6A	12	6		Thermal runaway / Canon
4P overcharge, 12V, 4A	12	4		CID operates / Canon
16P overcharge, 48V, 24A	48	24		Thermal runaway / fresh
16P overcharge, 12V, 24A	12	24		Thermal runaway / fresh
16P overcharge, 12V, 12A	12	12		CID operates /fresh
16 P external short			2	No thermal runaway /Canon
Single Cell external shorts				No failures; PTC trips / Canon
4S External short			50	No failures; PTC trips / Canon
14S External short			50	PTC fails; venting and sparks / Canon
4S Overcharge	48	1.5		No failure; CID activates / Canon
14S Overcharge	84	1.5		Thermal runaway / Canon

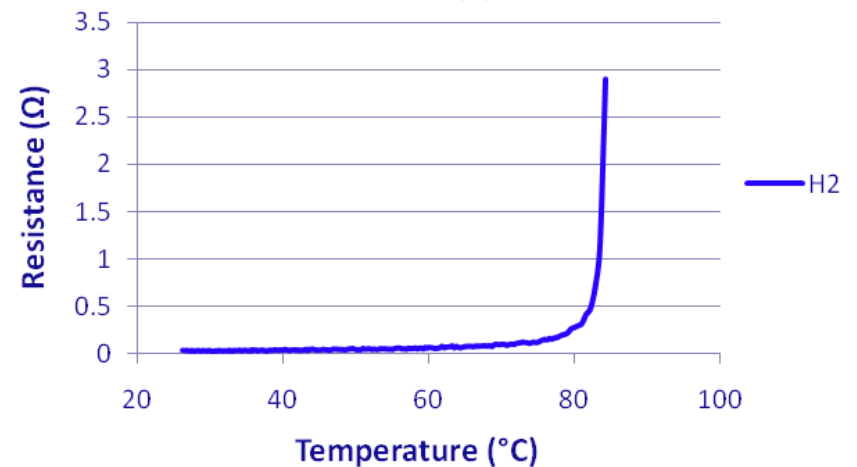
PTC Test in Cell Header

PTC Thermal Test in Cell Header
PCT Resistance versus Temperature



PTC Thermal and Current Test in Cell Header

PTC Resistance versus Temperature; 1.5A Current Applied

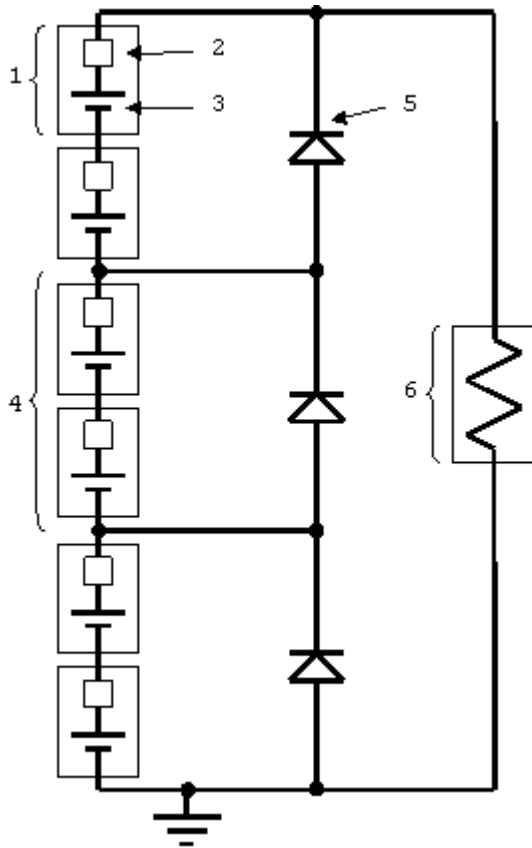


Summary of PTC Results

- Moli results
 - 7S is maximum series count to prevent PTC damage and leakage (n=3)
 - 4S is maximum series count to prevent slight odor from seal (n=3)
- Sanyo results
 - 3S is maximum series count to prevent PTC damage (n=3)
 - 8S is maximum series count to prevent odor from seal (n=3)
- Sony results
 - 3S is maximum series count to prevent PTC electrical damage (n=3)
 - 10S is maximum series count to prevent smoking the PTC (n=1)
 - at 11S, seal damage led to an internal short (n=1)
 - at 12S, rapid, severe electrical damage to PTC without seal damage (n=1)
 - Its PTC has the slowest tripping transition
- Panasonic results
 - 7S yields no odor, no leakage, but slight electrical damage (n=3)
 - 11S and 15S yields no odor, no leakage, but some electrical damage (n=1)

n=sample number; PTC damage: defined as 3X growth in resistance

Diode Scheme



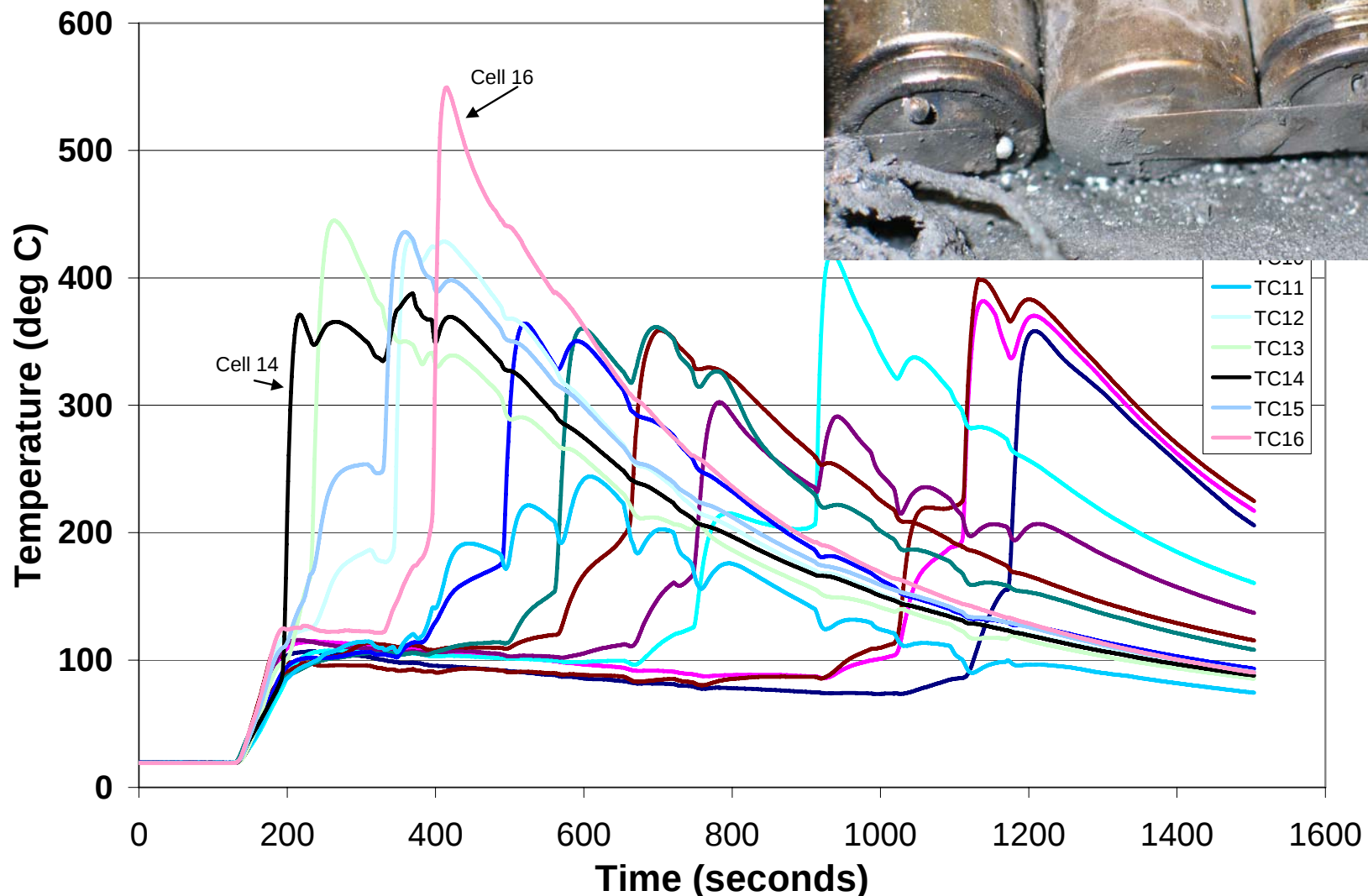
1. Battery cell with built-in short circuit protection.
2. Internal short circuit protection device (PTC). May be similar to Raychem Polyswitch.
3. Electrochemical part of cell (provides electromotive force)
4. Substring
5. Diode
6. Load

Notes:

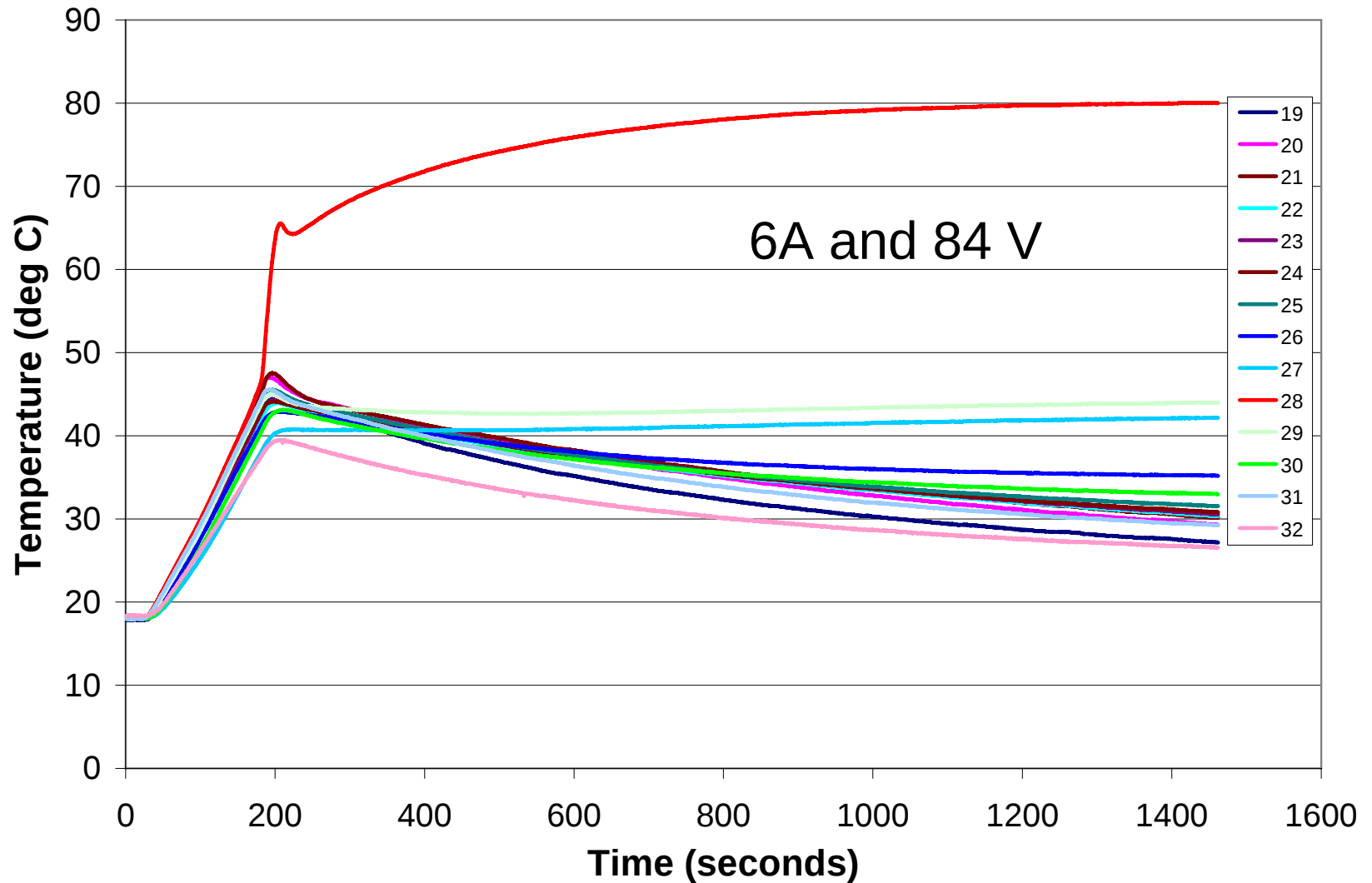
- More than two battery cells per substring may be used.
- More than 3 substrings may be used.
- The example battery system presented here is of limited size and complexity for clarity.

External Short Test on 14S Under Vacuum Conditions

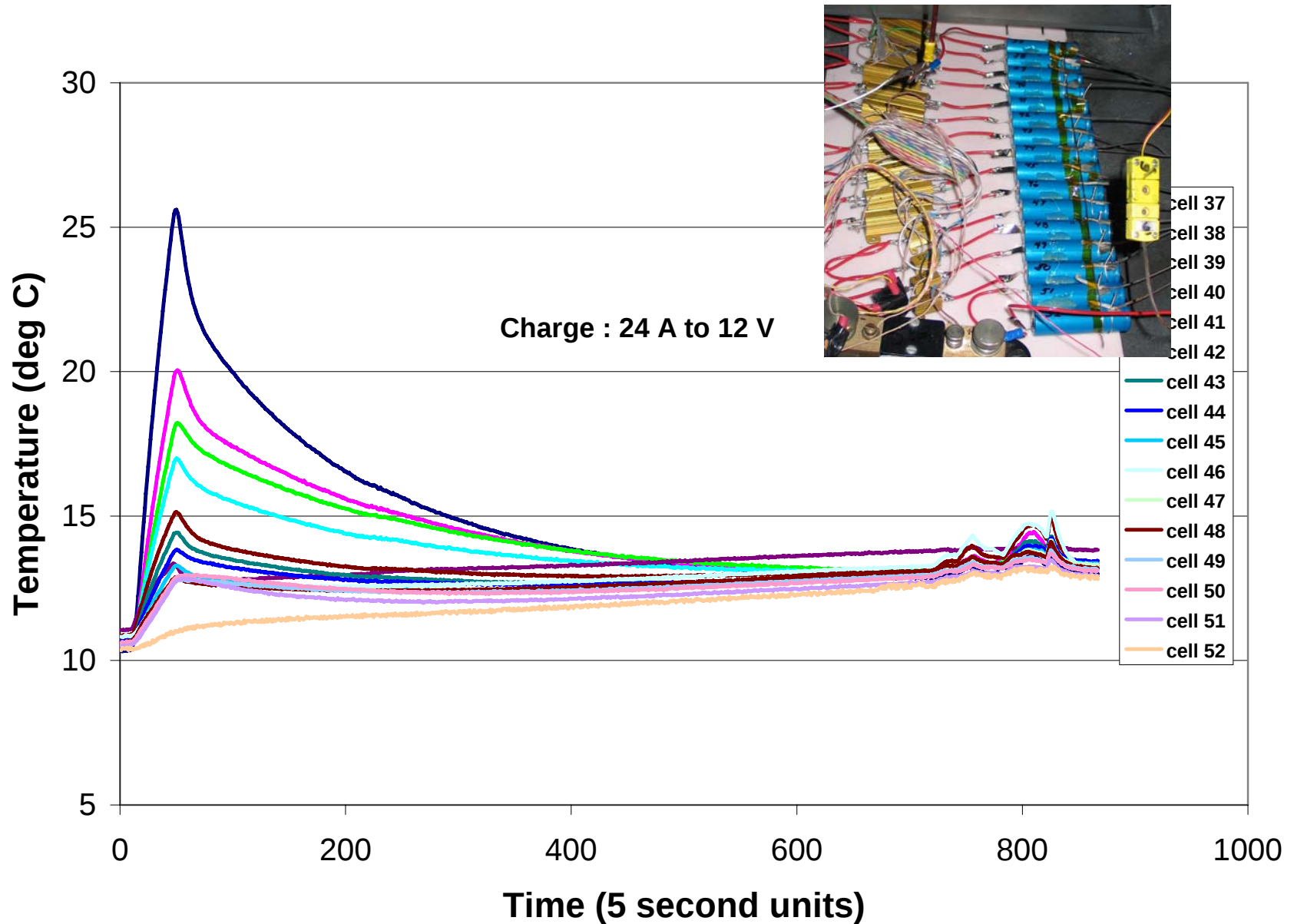
50 mohm



Overcharge Test on 14S Li-ion Cells Under Vacuum Condition



Overcharge of 16P Sony Li-ion Cells in Vacuum Conditions



Summary and Conclusions

- **The PTC characteristics varies from manufacturer to manufacturer in their trip currents as well as withstanding voltages. The withstanding voltage of the PTCs implies that they have a voltage limitation.**
 - **Determine, by testing, the PTC withstanding voltage and trip current for the cell to be used in battery design. Cells from different manufacturer will have different PTC ratings and this information is not provided in a cell specification.**
- **Tripping cell PTCs irreversibly increases their electrical resistance by up to a factor of two. Compromised or high-resistance PTCs cause catastrophic failures under overcharge conditions.**
 - **The cell PTC should not be compromised (activated or subjected to a condition that causes a rise in its resistance), if needed to be used as safety control. Cell screening for battery build for engineering, qualification as well as flight testing should not cause inadvertent activation of the PTC. Any cells in which the PTC may have been inadvertently tripped should not be used in the fabrication of flight batteries.**

Summary and Conclusions

- **The CID did not protect or underwent incomplete opening and reset under some overcharge conditions.**
 - **The CID cannot always be depended upon as safety control in multicell series/parallel battery designs. To prevent cells from going into an overcharge condition, voltage monitoring should be implemented at a level that would allow reliable and accurate detection and prevention of an overcharge condition of even a single cell.**

Summary and Conclusions

- It was found that in a parallel bank of cells, catastrophic results were obtained if the charge current and the power supply voltage are set at high values. This helps to explain the thermal runaway in cases where the voltage limit and /or charge current were set at a very high value (48 V and 6A for a bank of four cells or 24A for a bank of 16 cells).
 - The charge current used to charge a string or a bank should be as low as possible. For charging of cell banks, the total charge current should be limited to a value that would not cause PTC activation in any single cell in the event that the CIDs of all the other cells have opened.
- Under Vacuum conditions, the external short test caused thermal runaway in all the 14S (14 series) cells, but the overcharge condition in the series and parallel configurations did not result in a thermal runaway.
 - This indicates that under the overcharge condition, if the heat is isolated, the hazard is reduced, whereas for the short circuit condition, the heat should be dissipated.

Acknowledgment

NESC for the funding

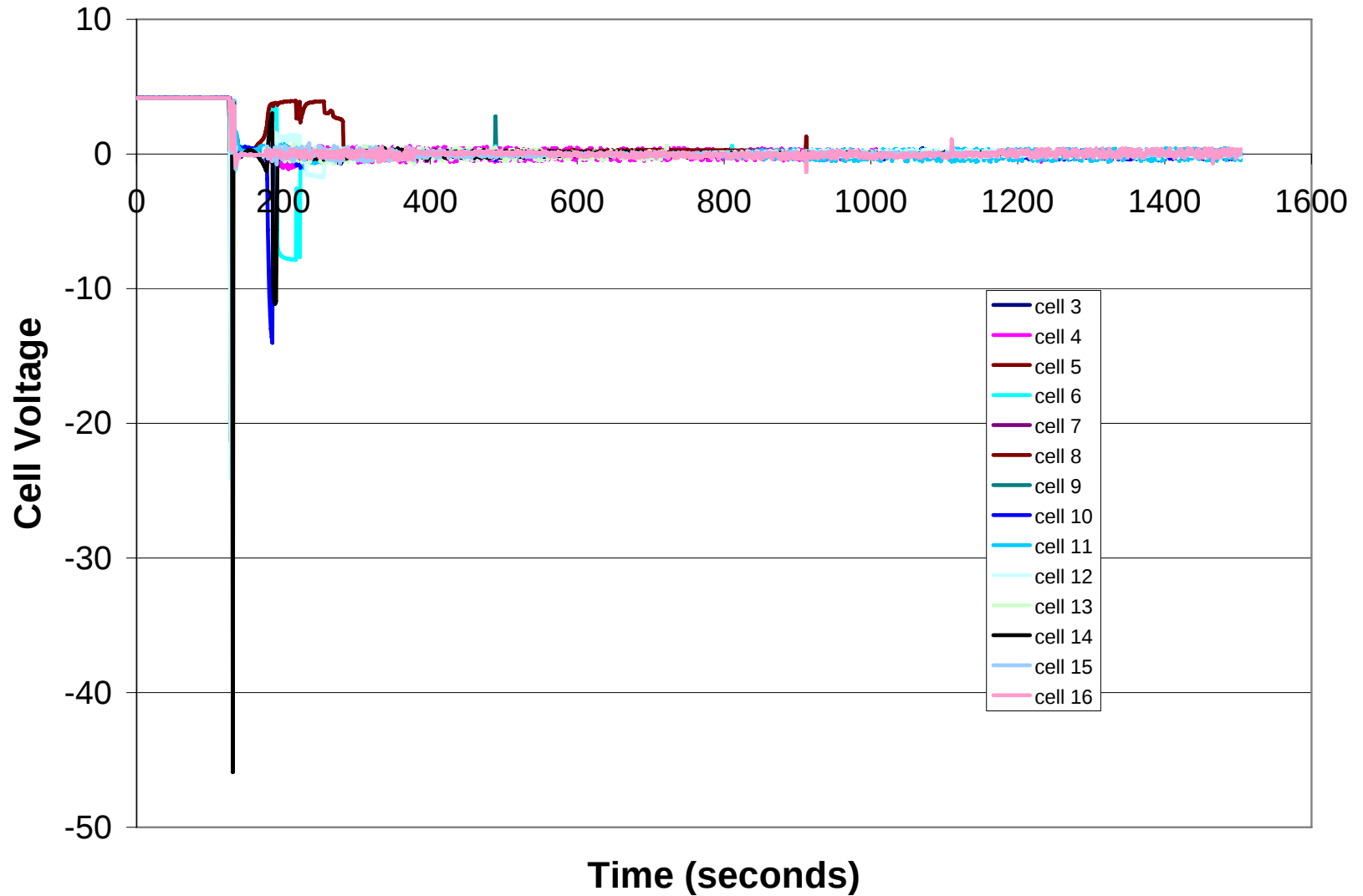
NASA-GRC - Lead on overall NESC task

NASA-JSC team

MPS and API for the all the work performed

Backup

External Short of 14S string in Vacuum



Overcharge of 14S string in Vacuum

