THERMAL PROPAGATION TEST EXPERIENCE

November 2016

OICA Submission to EVS-GTR Task Force 5

Agenda

- Objective & key messages
- Thermal propagation testing
    - Initiation methods
    - Repeatability
    - Propagation behavior
    - DUT modifications
- Additional Discussion Topics
    - Engineering standard compared to regulatory requirement
    - Current practice of one OEM

Objective

- Share vehicle manufacturer thermal runaway and thermal propagation test experience, illustrating that the currently proposed thermal propagation test method is not sufficiently mature for regulation

Key Messages

- Proposed initiation methods are not equivalent and are not repeatable
- Performance criteria are inconsistent and largely unrelated to propagation behavior
- Necessary DUT modifications are extensive and affect test outcomes
- Wide variation in allowable test parameters creates opportunity for manufacturers to select most advantageous conditions which may not reflect intended purpose of test
- Continues to be very limited evidence suggesting that this issue is a significant field concern for automobiles

Extent of Recent Test Experience – One OEM

- 126 tests conducted over past 18 months
  - Single cell (no enclosure): 63
  - 4-cell "module" (enclosure and no enclosure): 53
  - Simulated pack (enclosure): 10
- 4 Cell types
  - Two energy cells (26-60 A-hr): 46 tests
  - Two power cells (5-7 A-hr): 80 tests
- 4 Initiation Methods
  - Heating: 79 tests
    - Constant temperature increase rate (5 rates)
    - Constant power (2 rates)
  - Overcharge: 24 tests
    - Varying constant rates (C/3 to 3C)
  - Nail penetration: 21 tests
    - Varying speeds and nail sizes
  - Other potential methods: 2 tests

Thermal Propagation Testing Initiation methods Part 1

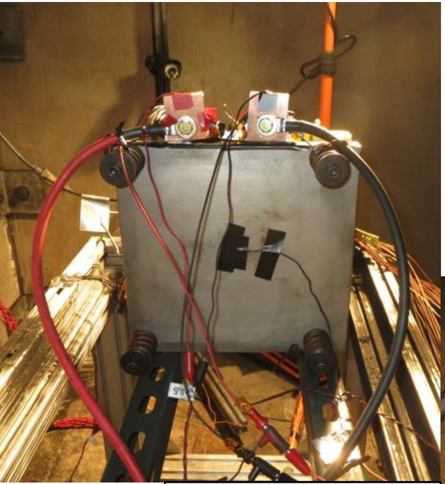
Key message: Proposed initiation methods are not equivalent

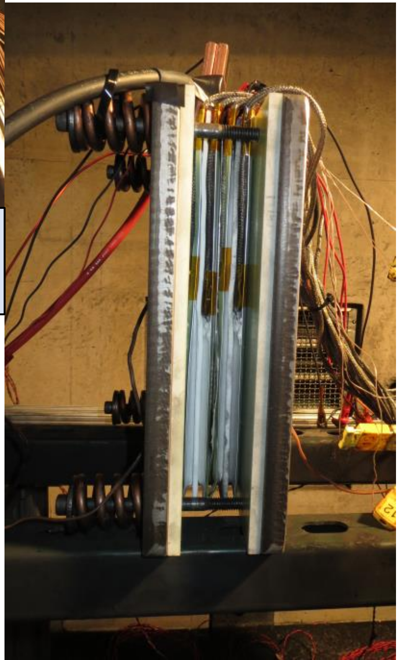
[Expanded detail on information shared in EVSTF-08-64e.pdf]

Initiation Method Comparison
Heating vs Overcharge

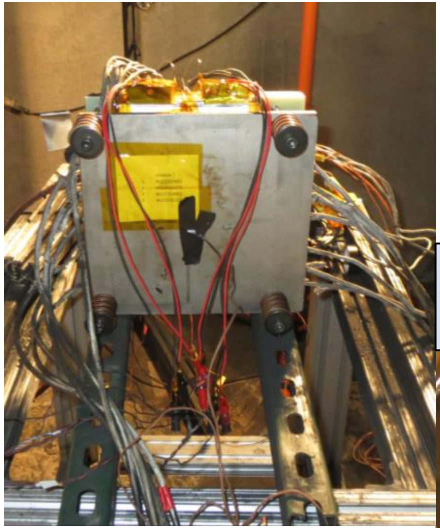
- DUT
  - Non-production “modules”
    - **Identical** except for presence of heater
    - Four pouch cells
    - No enclosure
- Test Methods
  - Heating
    - 0.5degC/s
    - One side of end cell
  - Overcharge
    - 3C Rate
    - No voltage limit

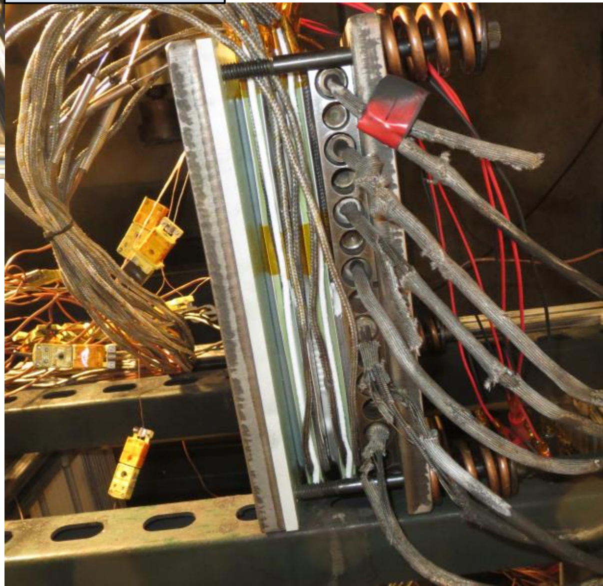
Initiation methods are not equivalent





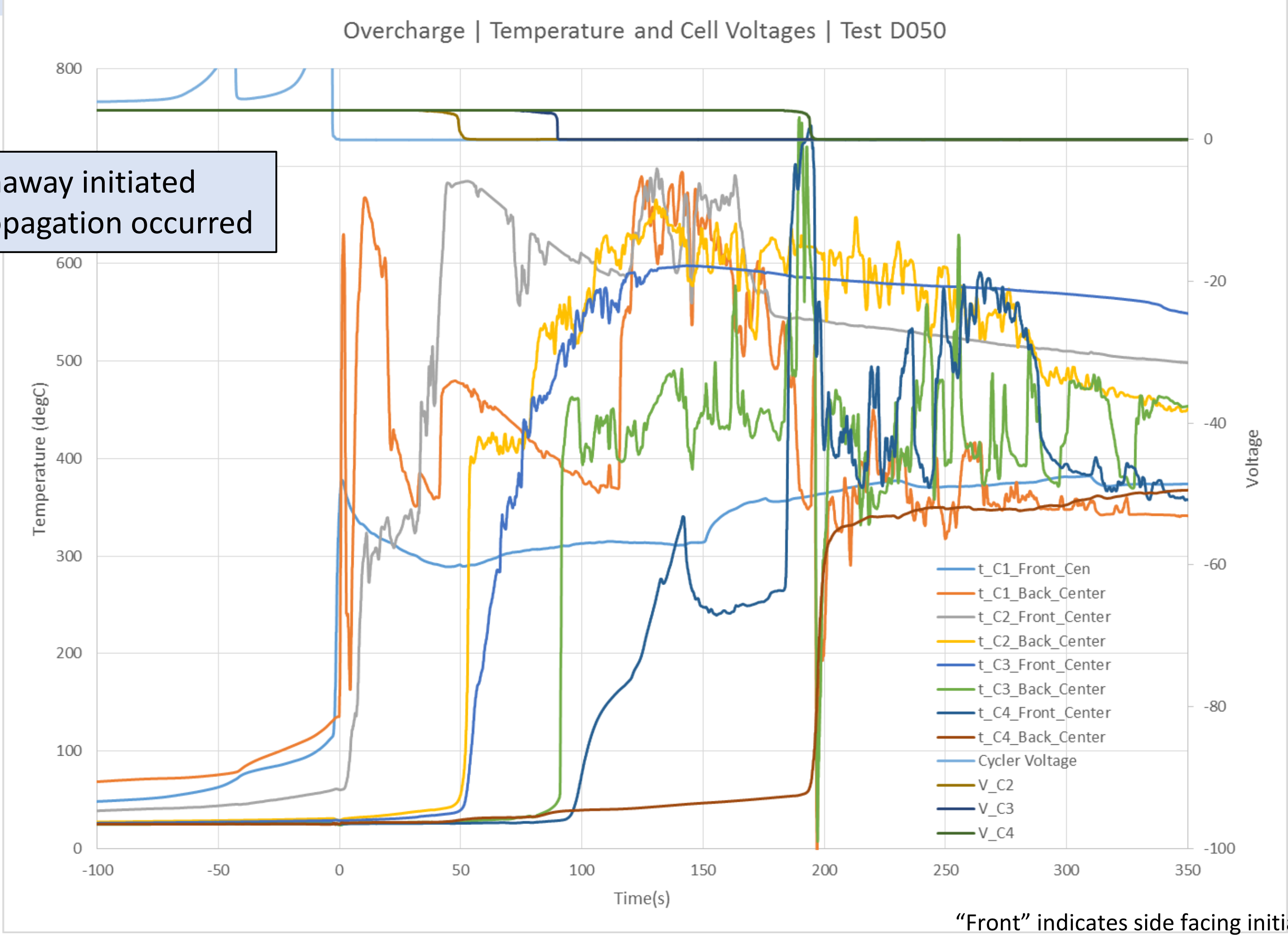
Overcharge Test Set-up



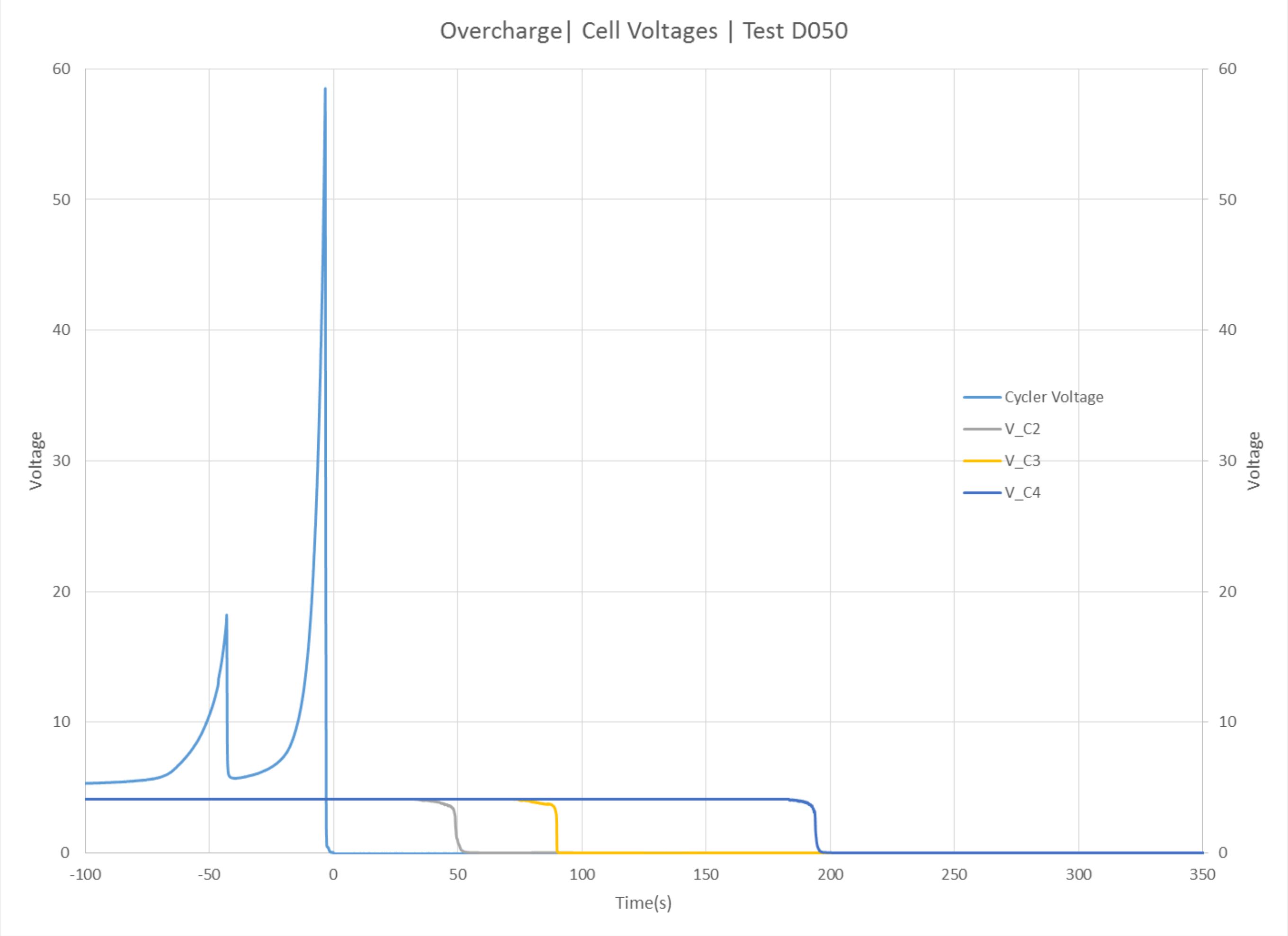


Heating Test Set-up

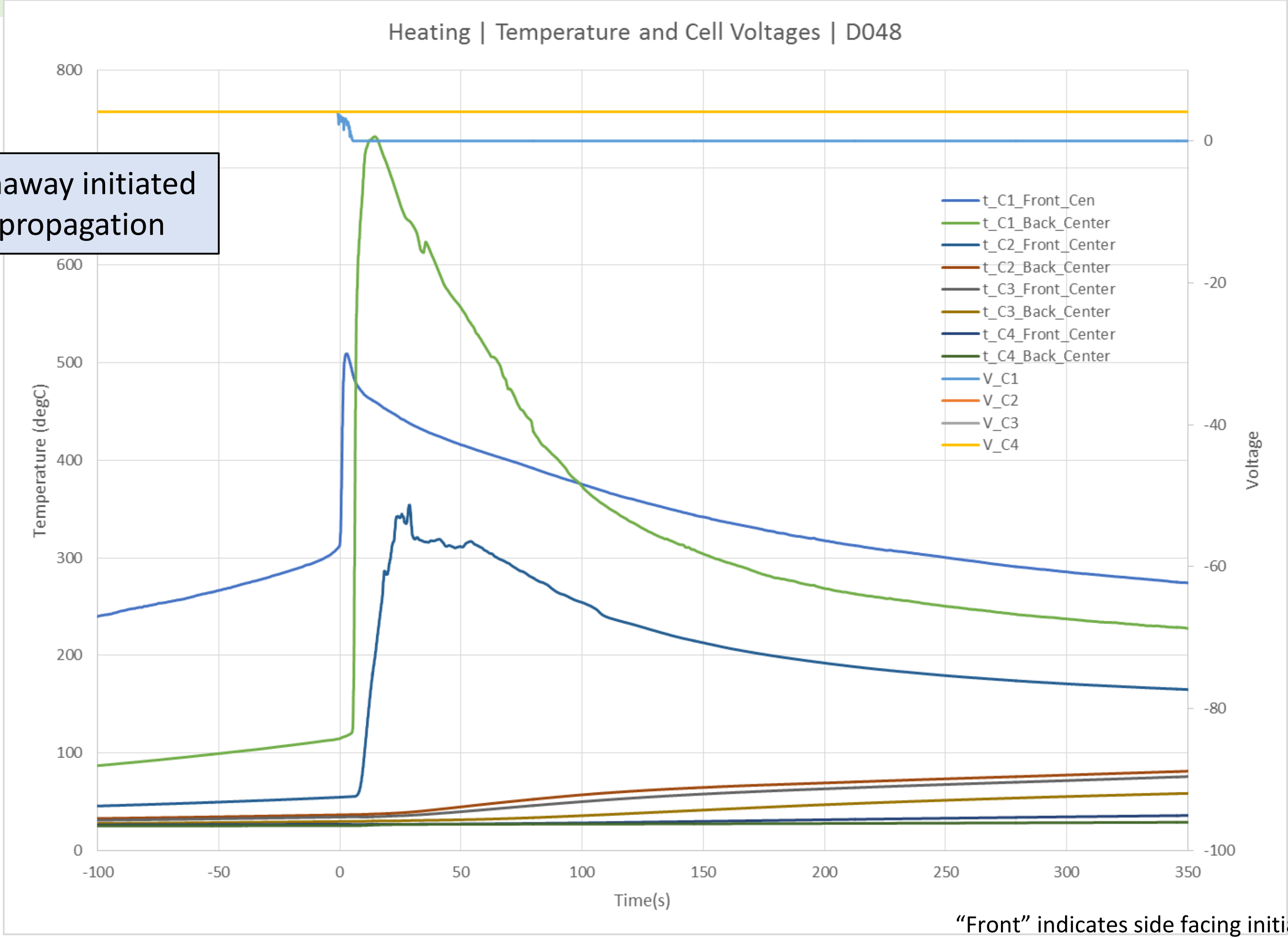
Thermal runaway initiated
Thermal propagation occurred



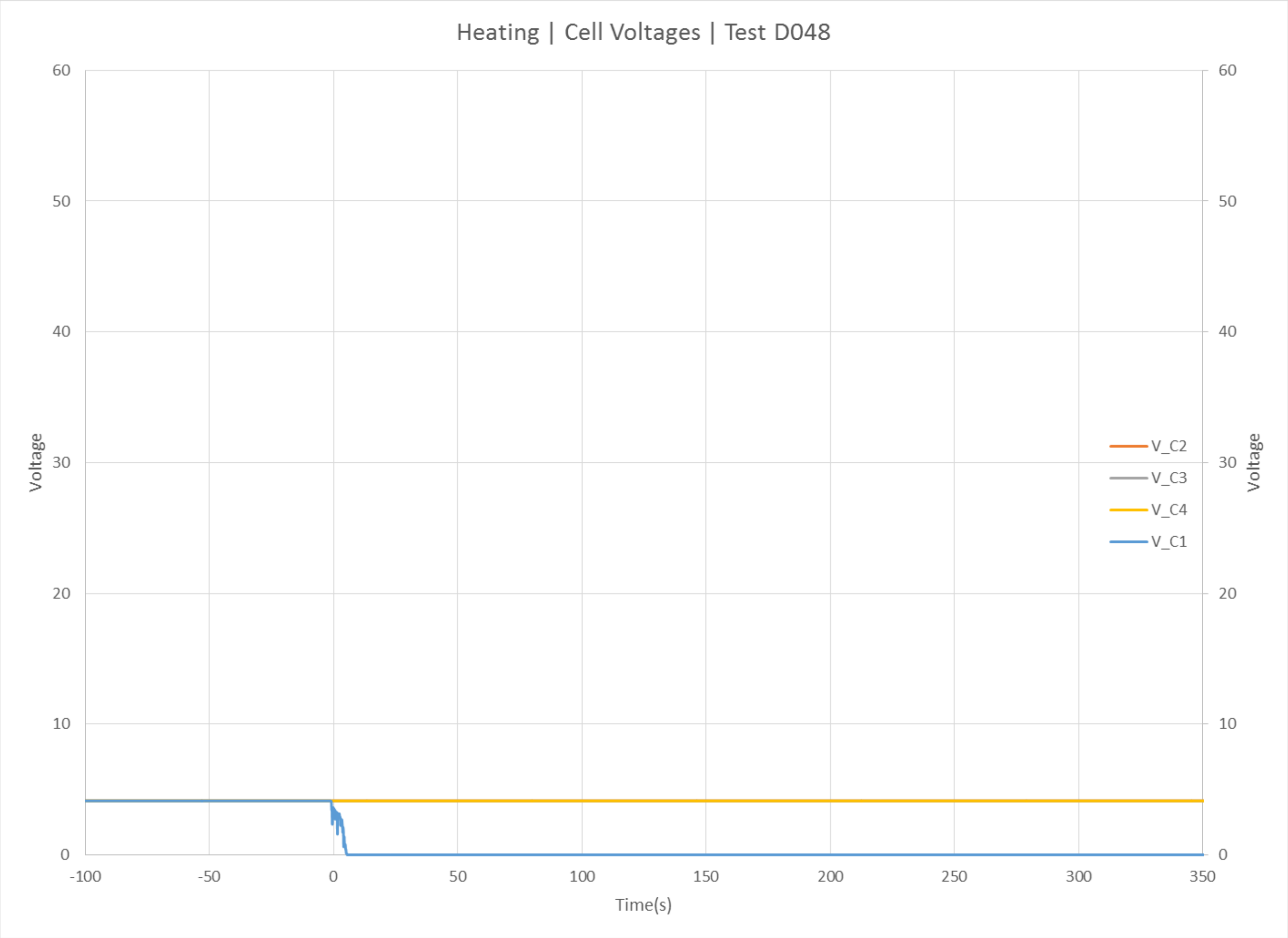
"Front" indicates side facing initiating end of module
"Back" indicates side facing non-initiating end of module


Overcharge| Cell Voltages | Test D050
Voltage
Voltage
Time(s)
60
50
40
30
20
10
0
-100
-50
0
50
100
150
200
250
300
350
Cycler Voltage
V_C2
V_C3
V_C4

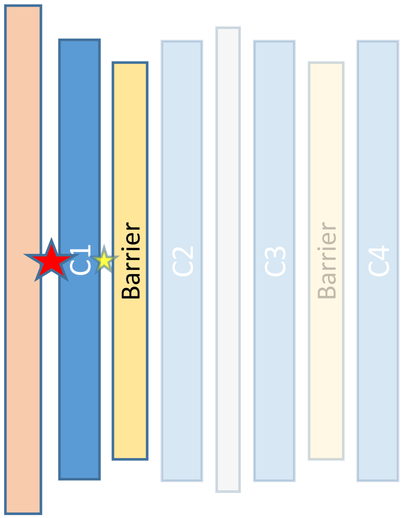
Thermal runaway initiated
No thermal propagation



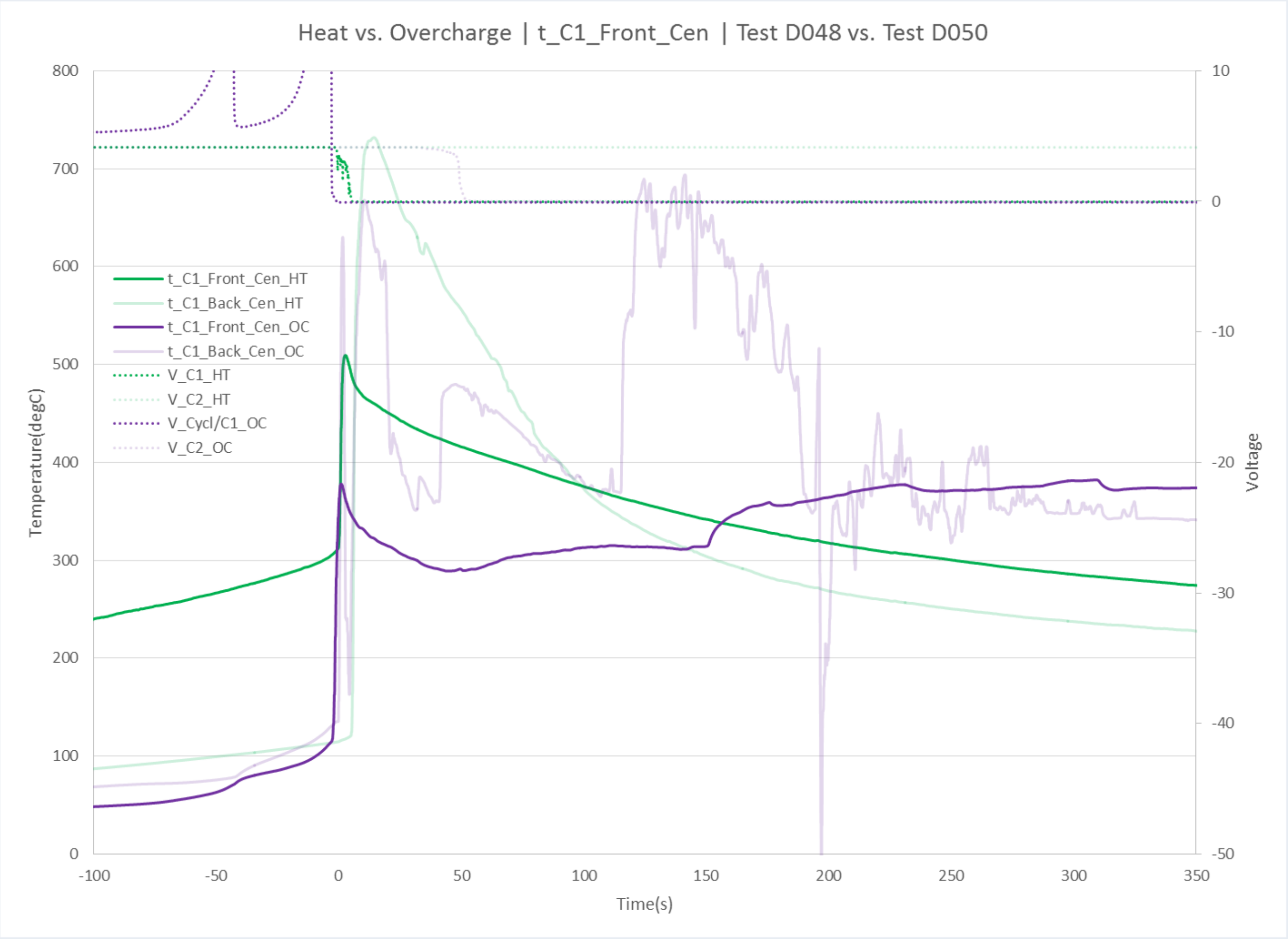
"Front" indicates side facing initiating end of module
"Back" indicates side facing non-initiating end of module


Heading | Cell Voltages | Test D048
Voltage
Time(s)
V_C2
V_C3
V_C4
V_C1
60
50
40
30
20
10
0
-100
-50
0
50
100
150
200
250
300
350

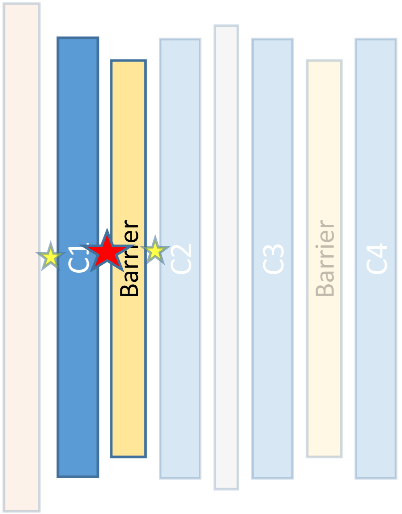
t_C1_FRONT



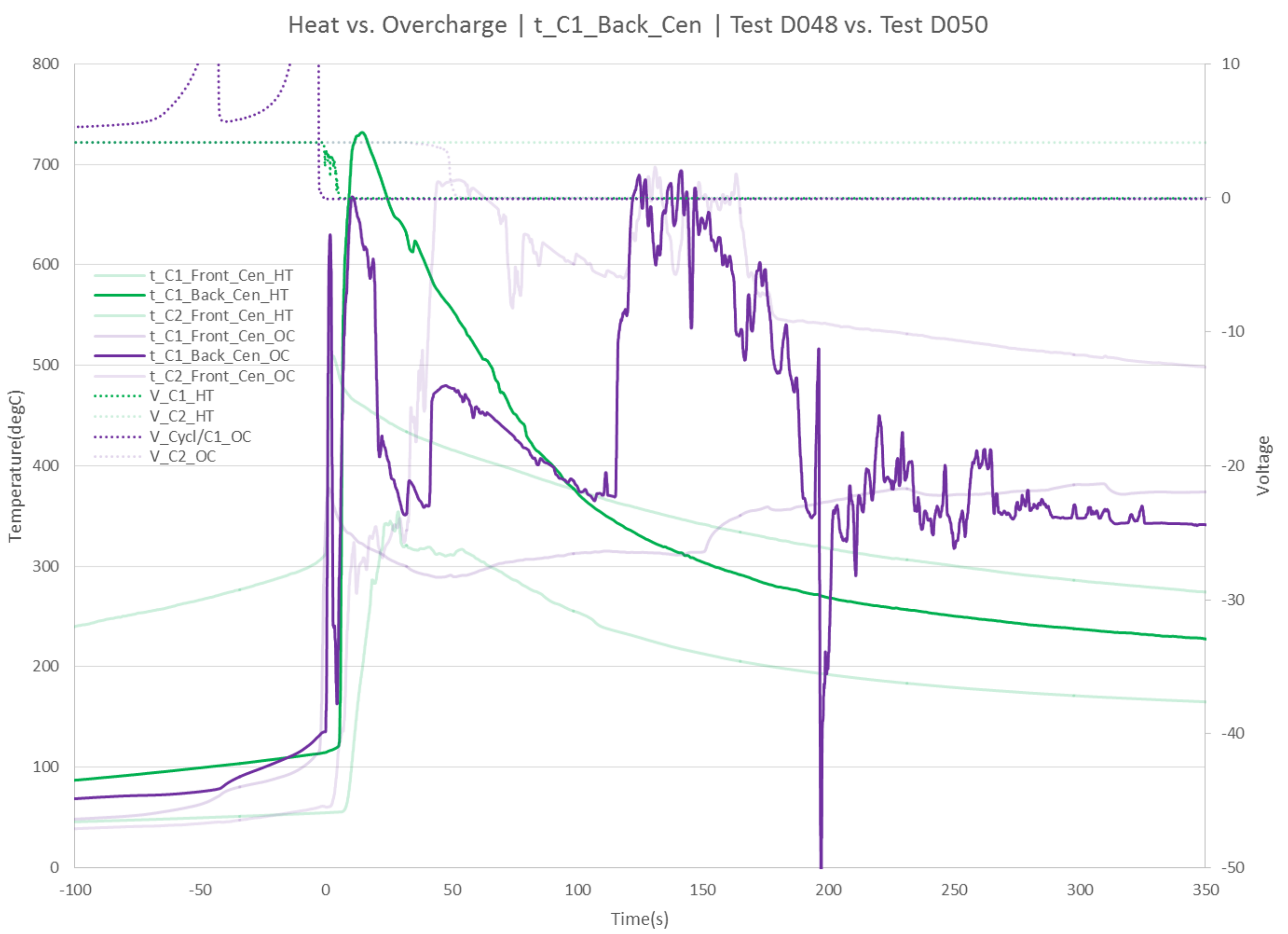
C1
Barrier
C2
C3
Barrier
C4

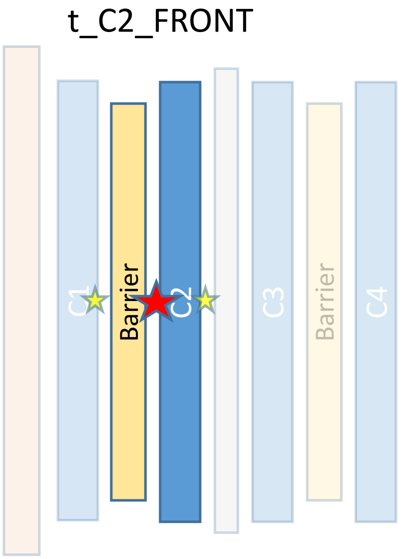


Heat vs. Overcharge | t_C1_Front_Cen | Test D048 vs. Test D050
Temperature(degC)
Voltage
Time(s)
t_C1_Front_Cen_HT
t_C1_Back_Cen_HT
t_C1_Front_Cen_OC
t_C1_Back_Cen_OC
V_C1_HT
V_C2_HT
V_Cycl/C1_OC
V_C2_OC

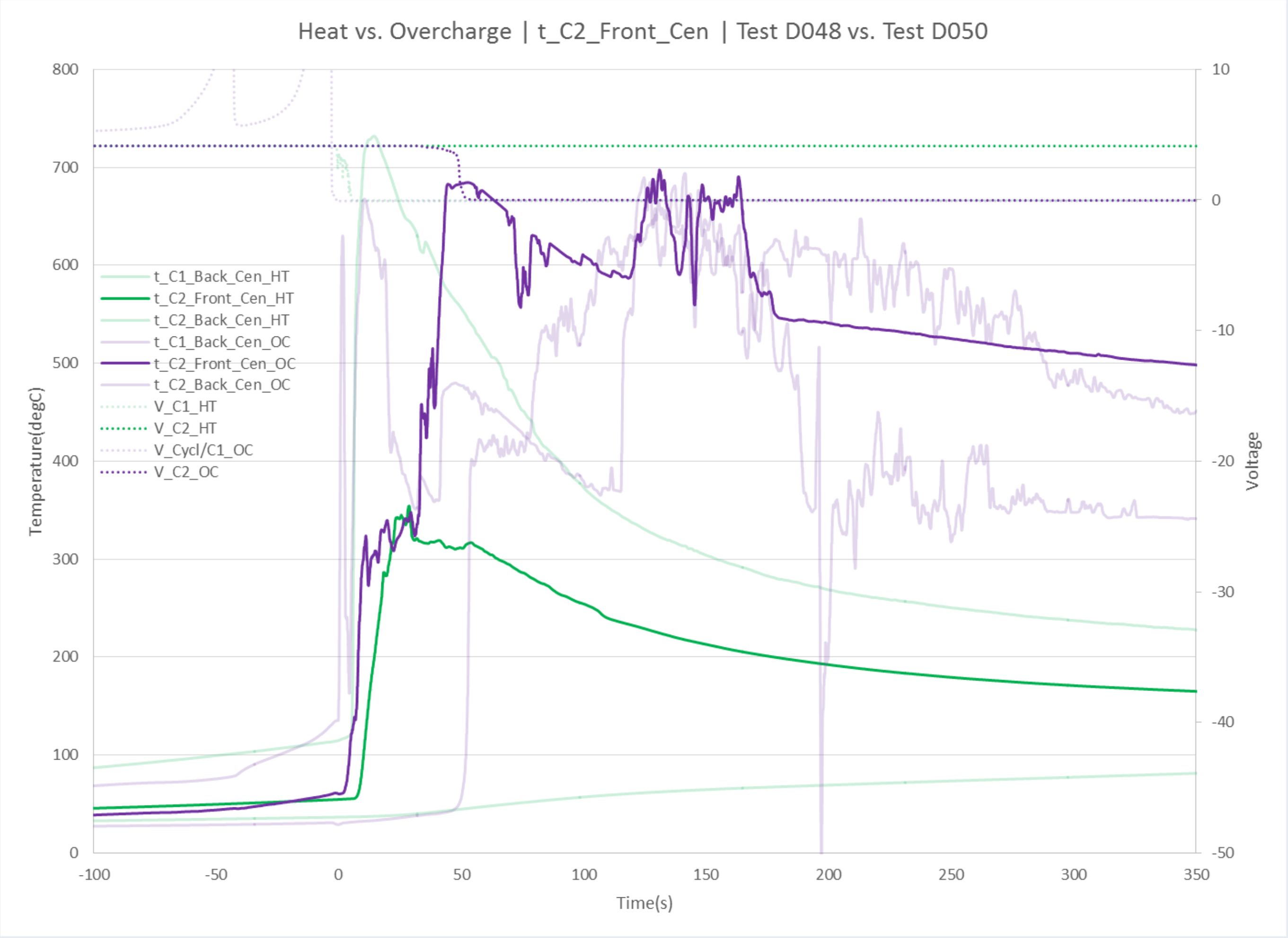

C1
Barrier
C2
C3
Barrier
C4

t_C1_BACK

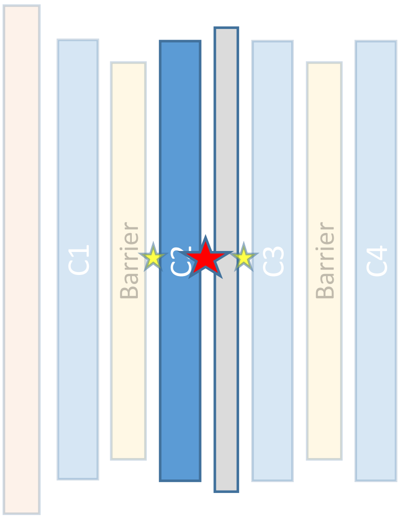

Heat vs. Overcharge | t_C1_Back_Cen | Test D048 vs. Test D050
Temperature(degC)
Voltage
Time(s)
t_C1_Front_Cen_HT
t_C1_Back_Cen_HT
t_C2_Front_Cen_HT
t_C1_Front_Cen_OC
t_C1_Back_Cen_OC
t_C2_Front_Cen_OC
V_C1_HT
V_C2_HT
V_Cycl/C1_OC
V_C2_OC
800
700
600
500
400
300
200
100
0
10
0
-10
-20
-30
-40
-50
-100
-50
0
50
100
150
200
250
300
350



t_C2_FRONT
C1
Barrier
C2
C3
Barrier
C4

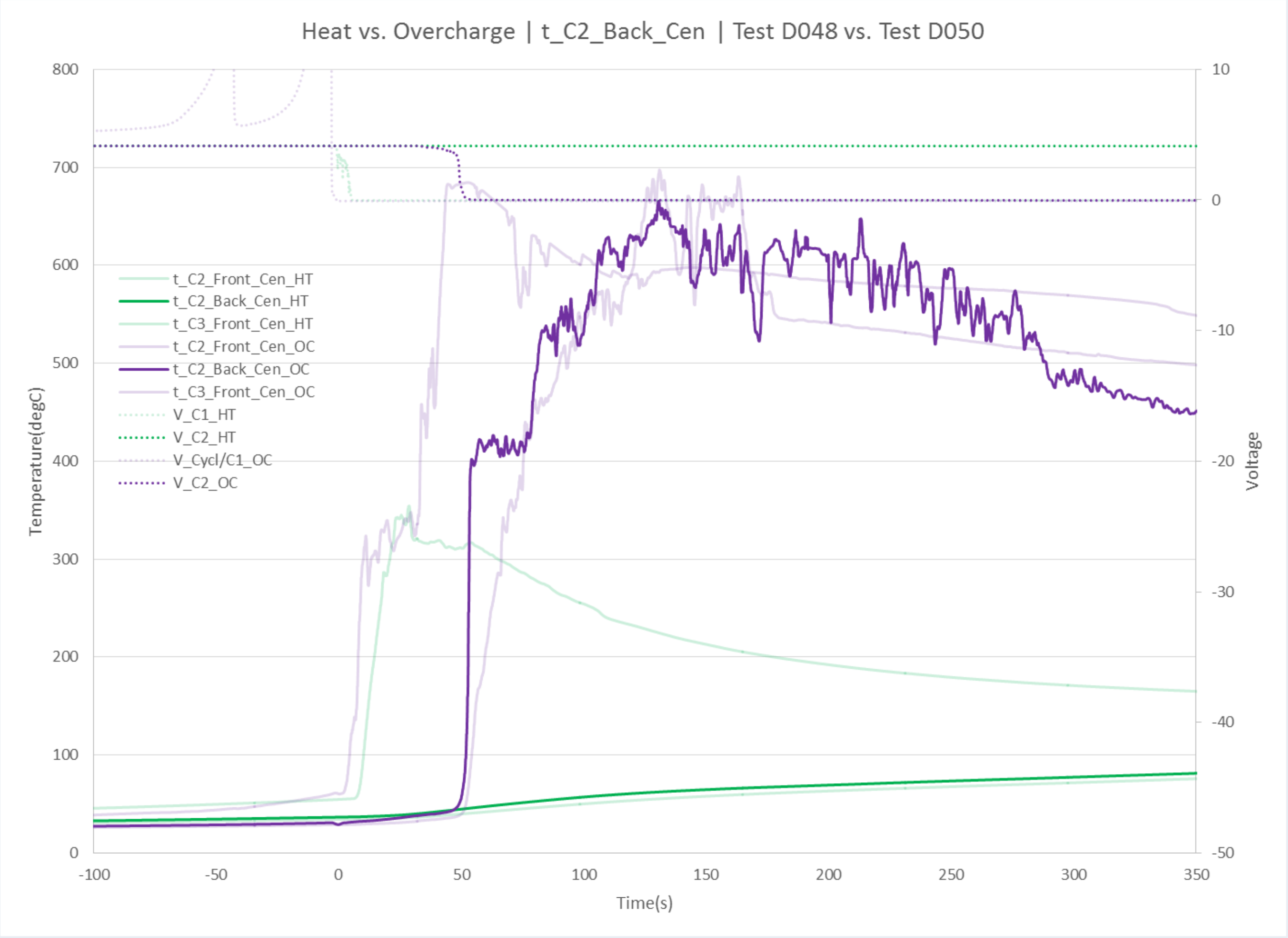


Heat vs. Overcharge | t_C2_Front_Cen | Test D048 vs. Test D050
Temperature(degC)
Voltage
Time(s)
800
700
600
500
400
300
200
100
0
10
0
-10
-20
-30
-40
-50
-100
-50
0
50
100
150
200
250
300
350
t_C1_Back_Cen_HT
t_C2_Front_Cen_HT
t_C2_Back_Cen_HT
t_C1_Back_Cen_OC
t_C2_Front_Cen_OC
t_C2_Back_Cen_OC
V_C1_HT
V_C2_HT
V_Cycl/C1_OC
V_C2_OC



C1
Barrier
C2
C3
Barrier
C4

t_C2_BACK



Heat vs. Overcharge | t_C2_Back_Cen | Test D048 vs. Test D050
Temperature(degC)
Voltage
Time(s)
t_C2_Front_Cen_HT
t_C2_Back_Cen_HT
t_C3_Front_Cen_HT
t_C2_Front_Cen_OC
t_C2_Back_Cen_OC
t_C3_Front_Cen_OC
V_C1_HT
V_C2_HT
V_Cycl/C1_OC
V_C2_OC

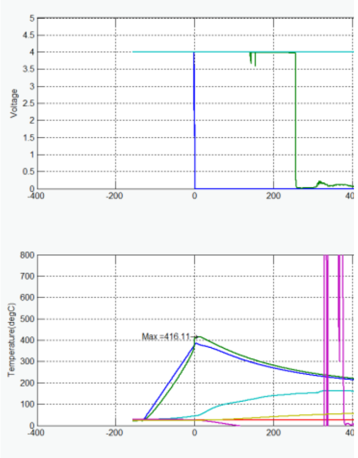
Thermal Propagation Testing
Initiation methods Part 2

Key message: Proposed initiation methods are not repeatable

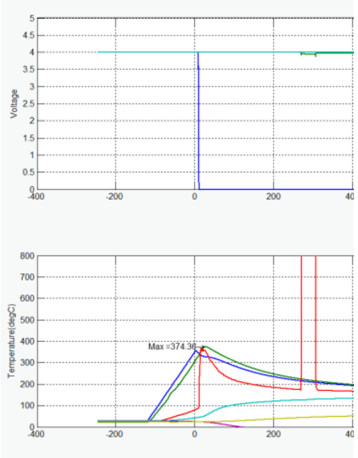
[New information not previously shared.]

Cell Heating Test Repeatability

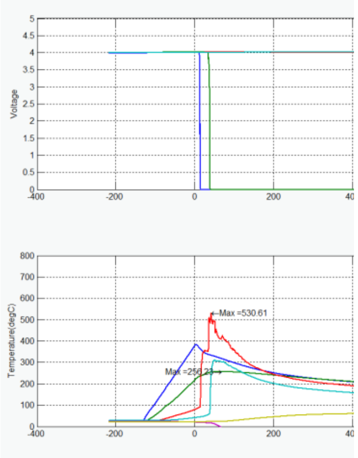
- Test article:
  - 4-cell stack, face to face
  - 6.8 Ahr pouch cell
- Initiation method:
  - Block heater – 2.75degC/sec



30112_X001



30112_X002



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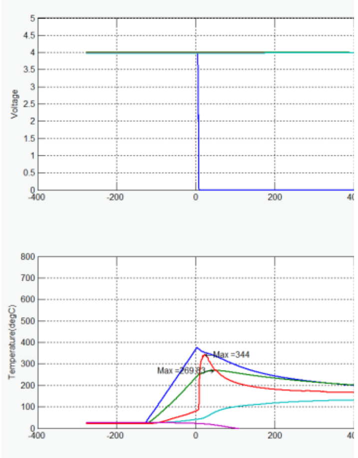
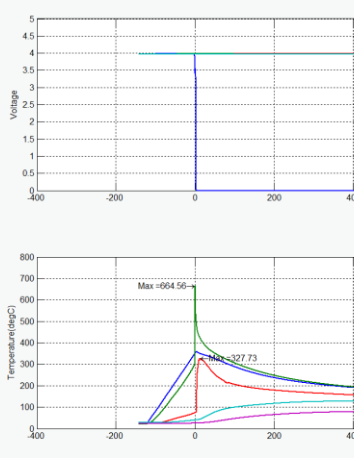
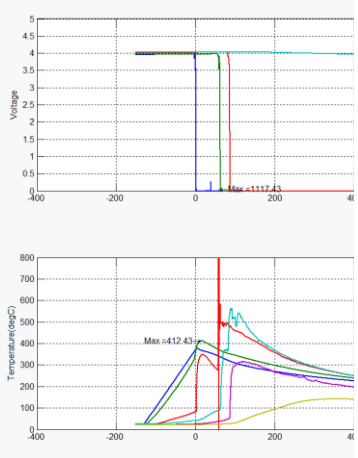


30112_X004

Out of 6 tests run the same way:
2 propagate, 4 do not.



30112_X008



30112_X010

Test Number	Cells in Thermal Runaway
001	1
002	1
003	2
004	1
008	1
010	3

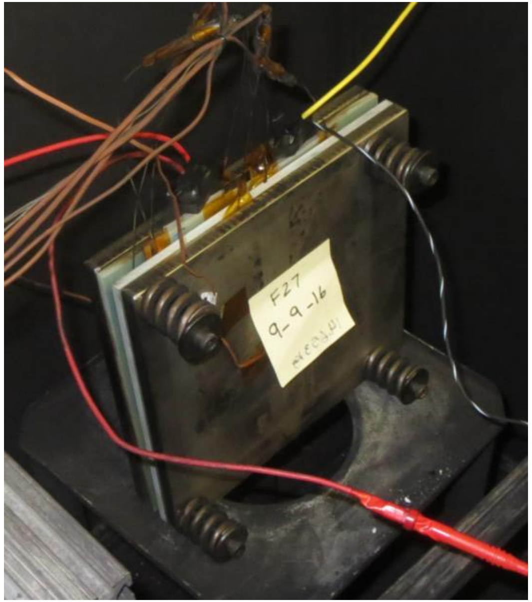
Thermal Propagation Testing Initiation methods Part 3

Key message: Wide variation in allowable test parameters creates opportunity for manufacturers to select most advantageous conditions which may not reflect intended purpose of test

[New information not previously shared.]

Single cell overcharge

Charge rate variation



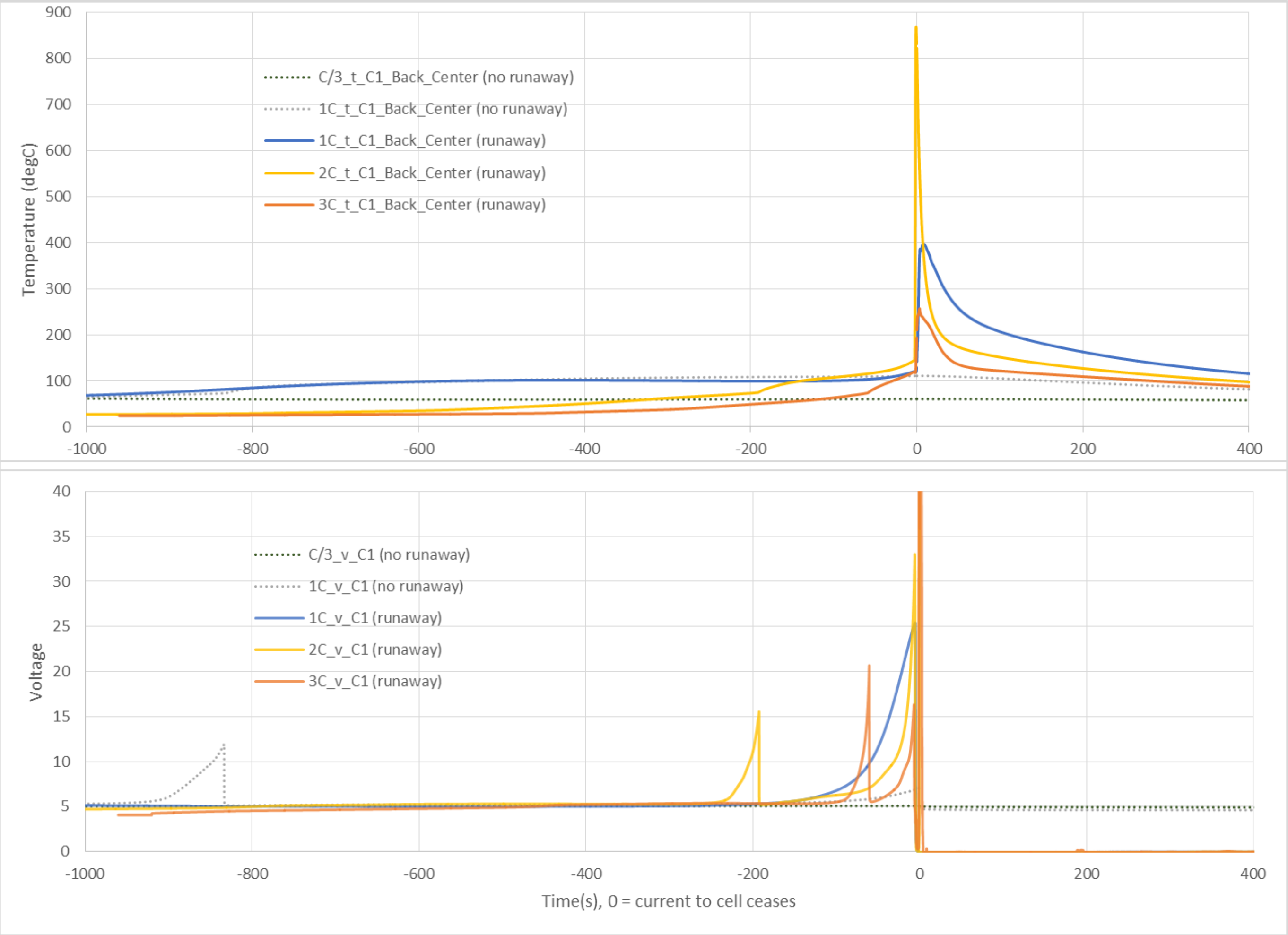
Variation in test parameters allows manufacturers to select advantageous conditions

Single cell overcharge summary:

Test #	Rate	Charge time (seconds)	Thermal runaway?	Approx. %SOC (based on charge time and rate)
F26	C/3	11028	No	202%
F27	1C	3646	No	201%
F29	2C	1519	Yes	184%
F28	3C	920	Yes	177%

Significant outcome variation within allowable range.

Single cell overcharge



....

Dotted line indicates test that did <u>not</u> go into thermal runaway

Thermal Propagation Testing
Propagation behavior

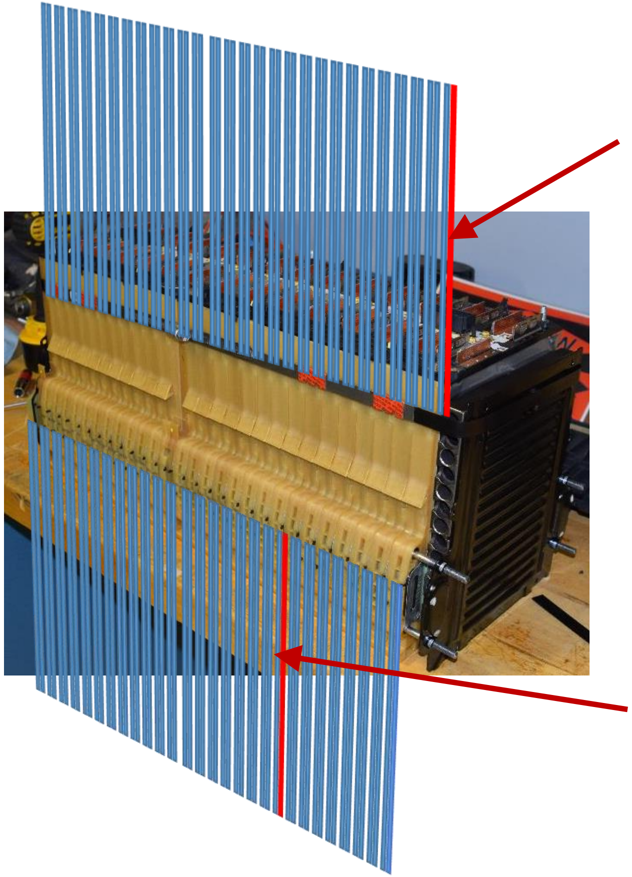
Key message: Performance criteria are inconsistent and largely unrelated to propagation behavior

[Expanded detail on information shared in EVSTF-09-40-TF5-19.pdf]

Large Scale DUT Tested within bounds of Draft Regulation

- Test article:
  - Non-production battery pack configuration
  - Pouch cell in a 2p28s arrangement
  - Voltage: ~116 V
  - Nominal capacity: ~52 A-hr (2 x 26 A-hr cells in parallel)
- Initiation method:
  - Block heater – 1.6 kW, constant power
  - Overcharge – 1 C rate (less than 1 hour)
- Initiation Cell Location (see following page)
  - End of pack
  - Mid pack

Initiation Cell Locations



End of Pack
Initiation Cell Location

Mid Pack
Initiation Cell Location

Results Summary

	End of pack	Mid pack
Heating	Flame visible for approx. 1 second; Visible smoke (D76)	Visible smoke (D78)
Overcharge	Visible smoke (D77)	Flame visible for >160 seconds; Visible smoke (D79)

Inconsistent results

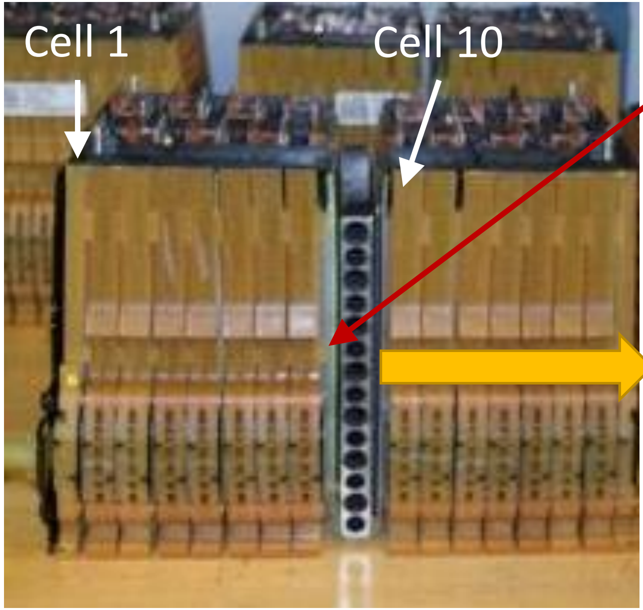
Results Summary

	D76 Heating – End	D77 Overcharge – End	D78 Heating – Mid	D79 Overcharge - Mid
Mode				
Results				
Time to all cells vent (approx. secs)	2550	2750	1950	1700
Cell groups vented* @ 300 seconds (# cells)	4	4	5	10
Cell groups vented* @ 600 seconds (# cells)	8	7	12	>13
Cell groups vented* @ 900 seconds (# cells)	12	10	14	Unknown
Cell groups vented* @1200 seconds (# cells)	15	14	16	Unknown
Cell groups vented* @ 1500 seconds (# cells)	16	16	19	Unknown
Order of voltage loss *Voltage loss of the cell group is assumed indicative of cell venting	Sequential (C1 to C28)	Sequential (C1 to C28)	C9, C10, C11, C12, C13, C8, C14, C7, C15, C6, C16, C5, C4, C3, C1, C17, C18, C19, C20, C21, C22, C23, C24, C25, C28, C26, C27	C9, C8, C10, C7, C11, C6, C5, C12, C4, C3…cannot be distinguished.

Results unrelated to intended assessment

Example of influence of test set-up on results

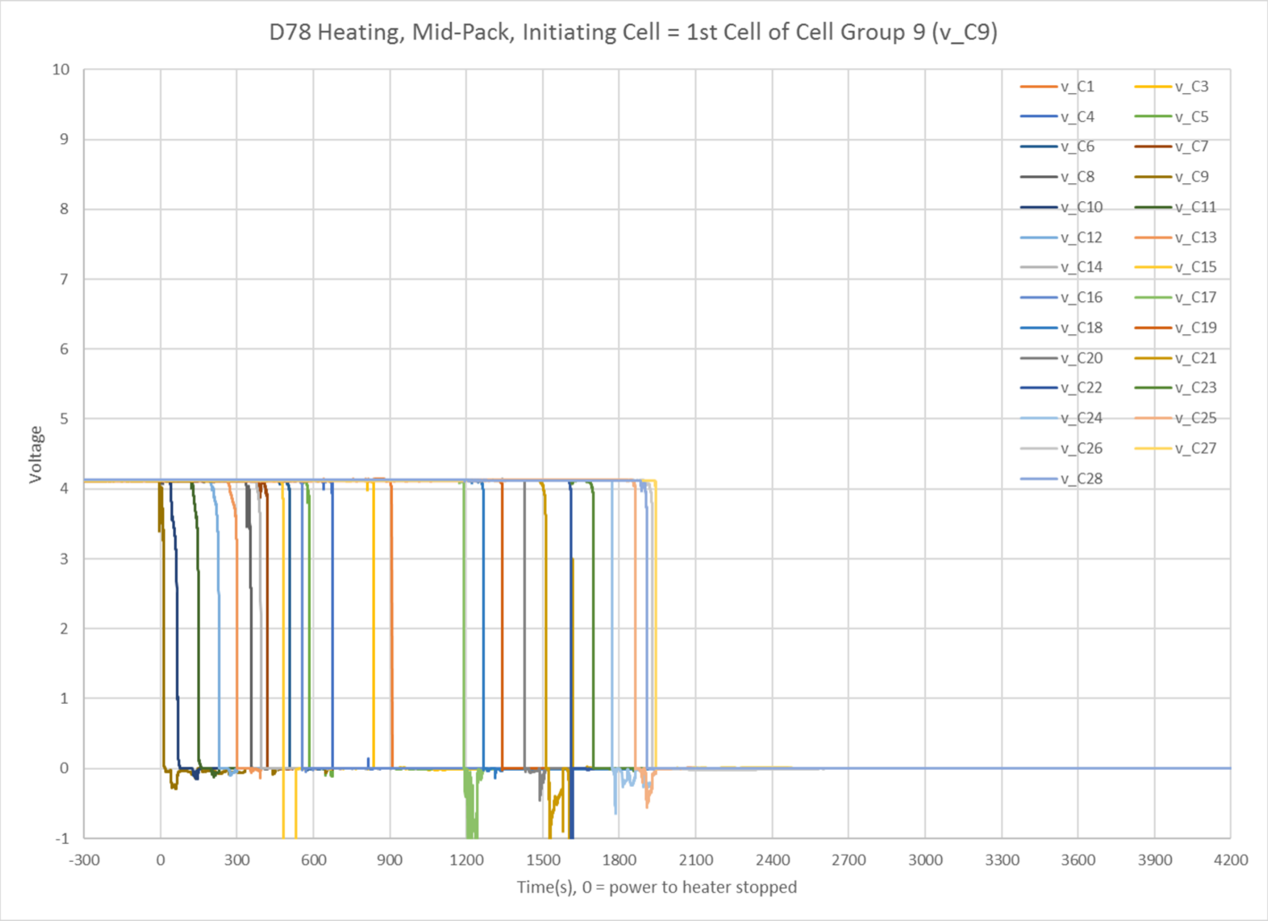
D78 Mid pack, Heater



Insulating plate to prevent heater from initiating 2 cells.

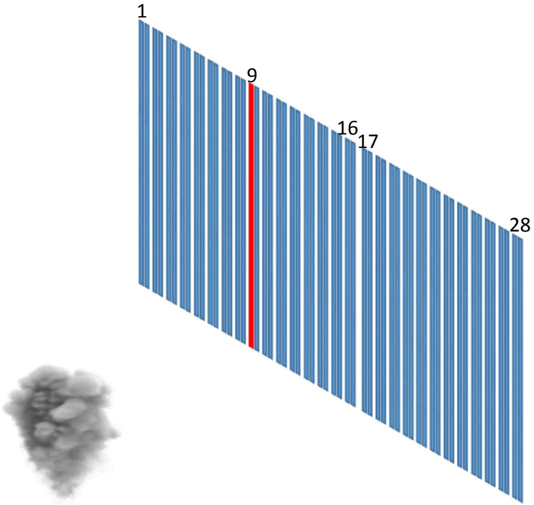
Initial propagation direction (4 cells)

Results influenced by test method

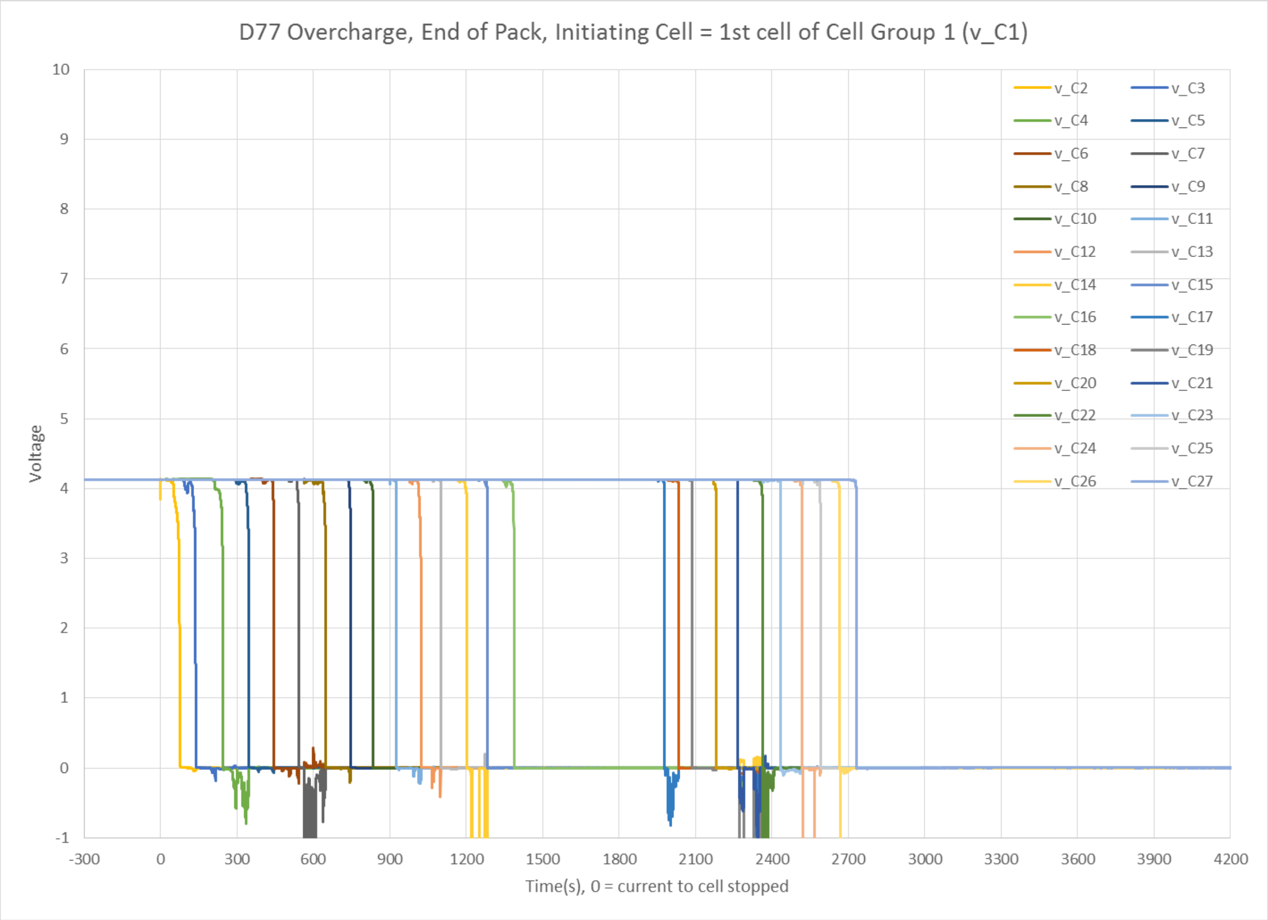


Cell heated (w/ 1.6kW) for approx. 1134 sec

v_C2 unavailable due to data acquisition anomaly

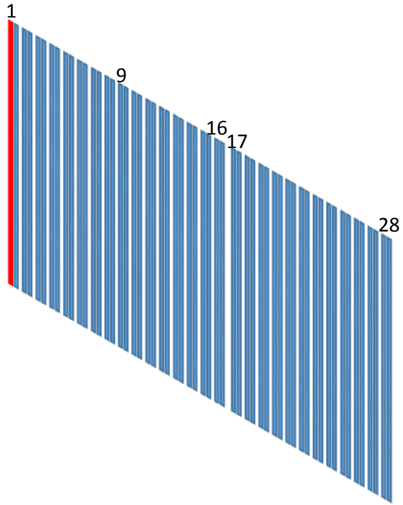


D78



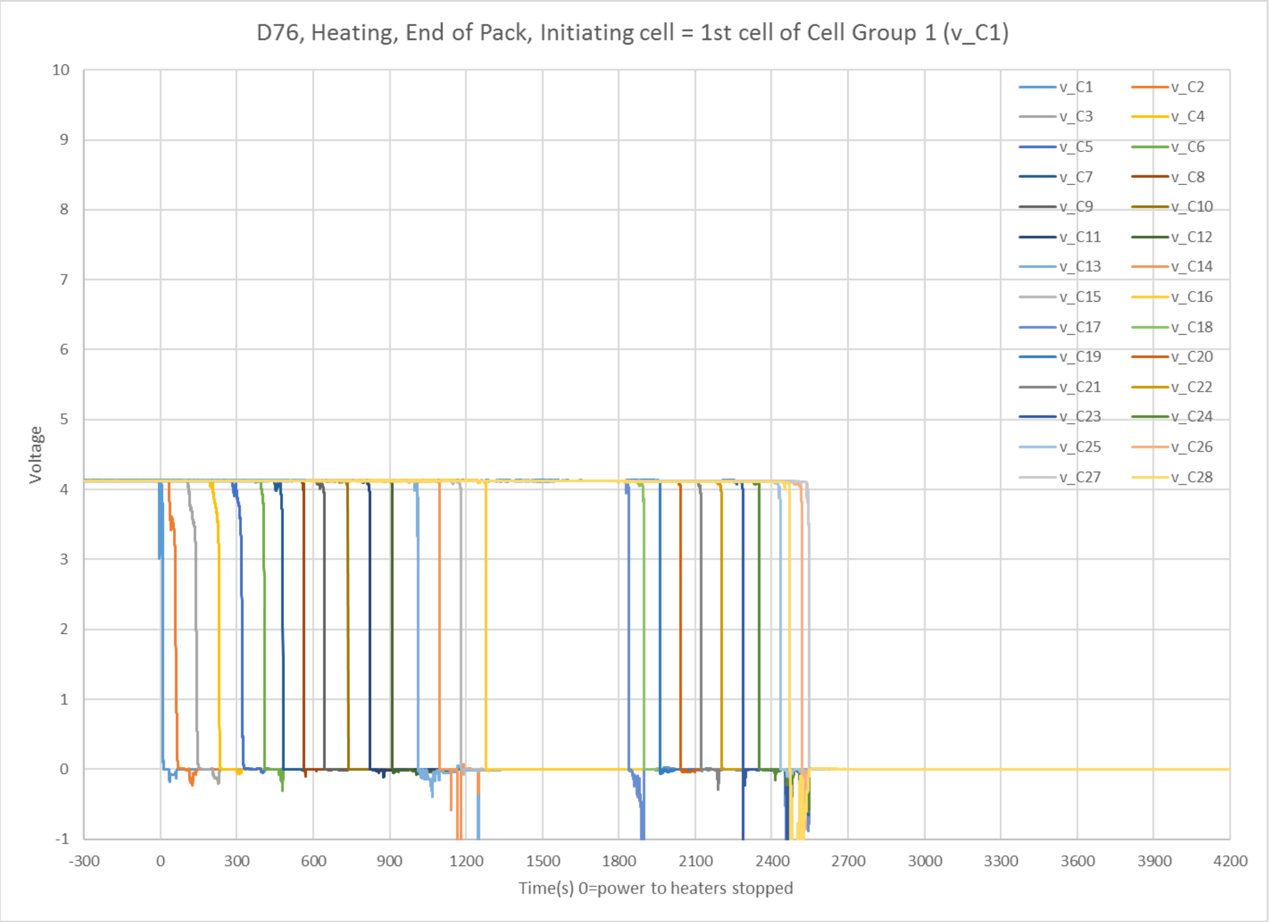
Overcharge time (@ 1C) = approx. 3230 sec

Data acquisition anomaly in v_C1 causes apparent oscillation of voltage. Real voltage does not oscillate. V_C1 not shown on graph.

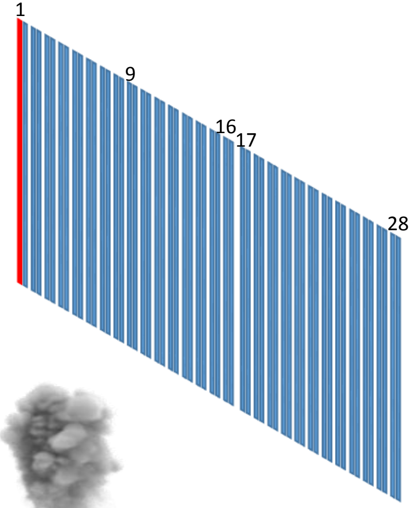


D77

Heating – End of pack



Cell heated (w/ 1.6kW) for approx. 967 sec



D76

Thermal Propagation Testing
DUT Modifications

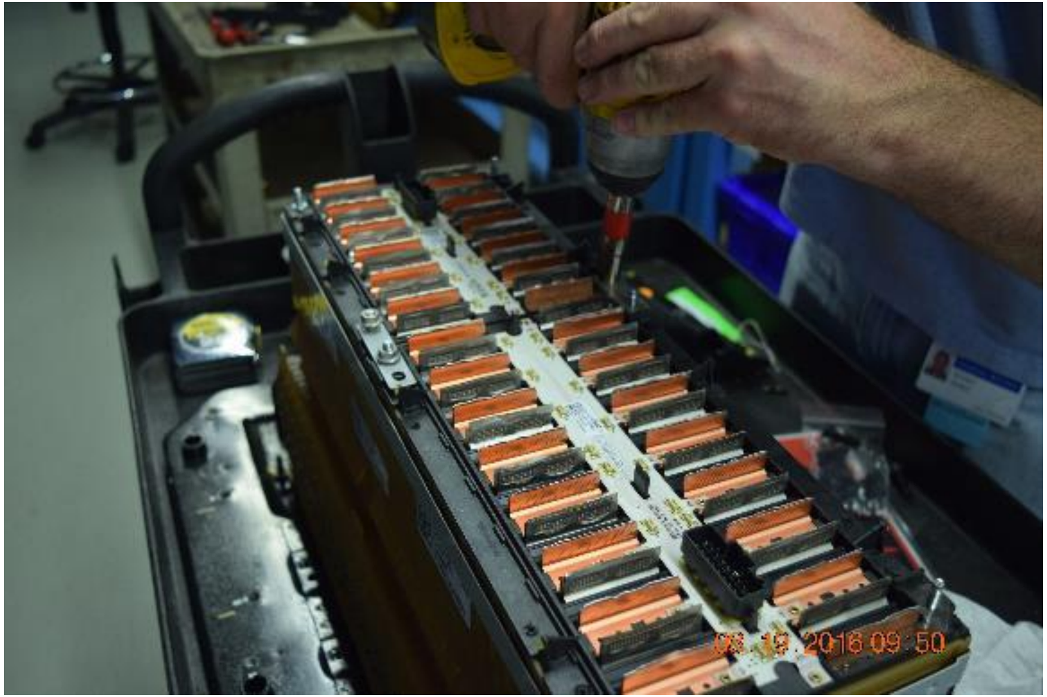
Key message: Necessary DUT modifications are extensive and affect test outcomes

[Information shared in EVSTF-09-40-TF5-19.pdf]

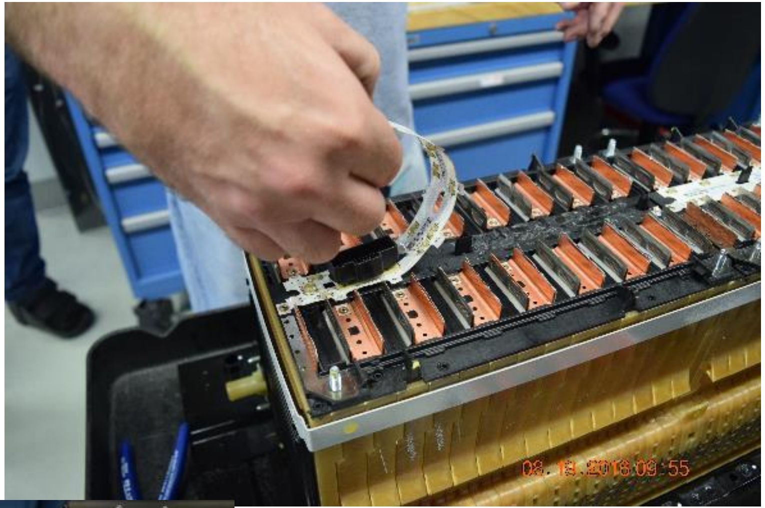
Remove cover for modification

Pack cover removed

Heating – mid-pack: Remove bus bars



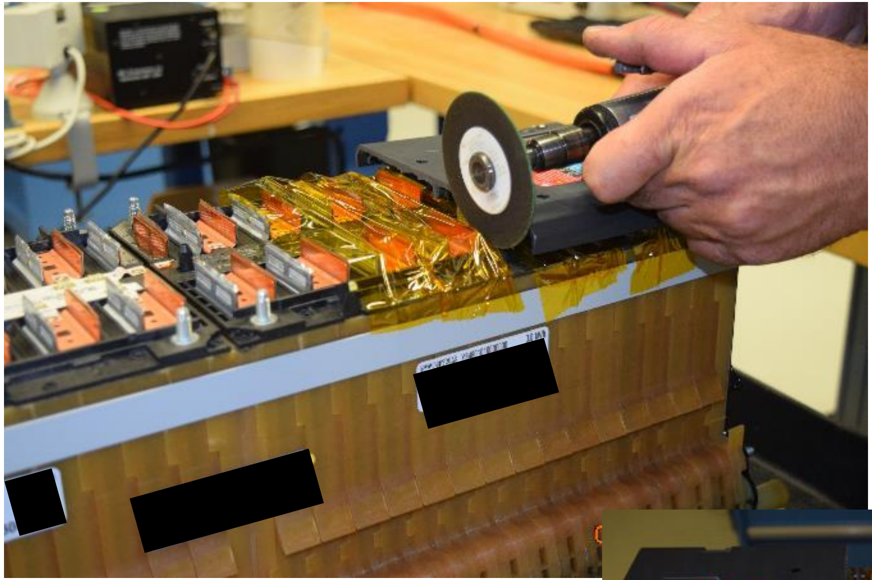
Heating – mid-pack:
Cell sensing circuit removed

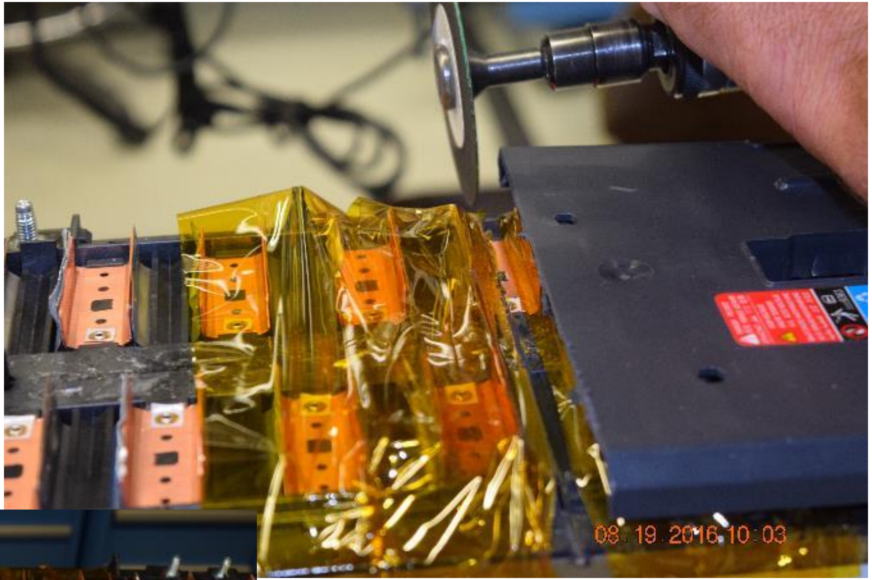


Heating – mid-pack:
Preparation to cut through cell connection board

Cell connection board must be cut to insert heater

Heating – mid-pack:
Cut through cell connection board

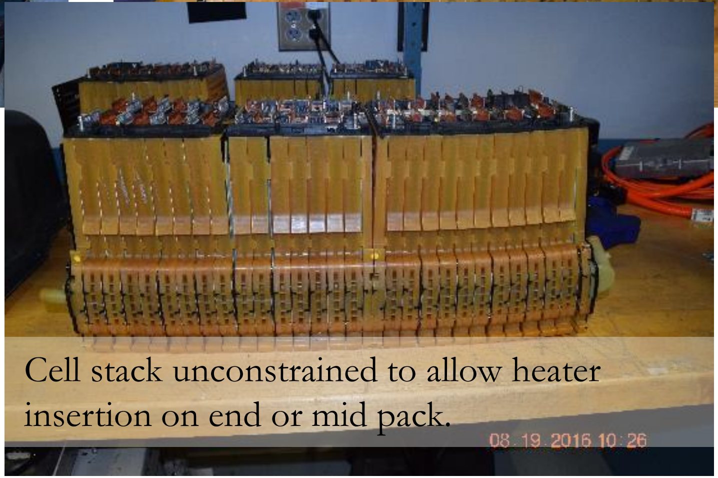




Cell connection board cut

Heating – mid-pack & end-pack: Remove cell constraint fasteners

1) Compress stack with clamps
2) Remove top "strap"
3) Remove fasteners



Cell stack unconstrained to allow heater insertion on end or mid pack.

Heating – mid-pack: Insertion of heater

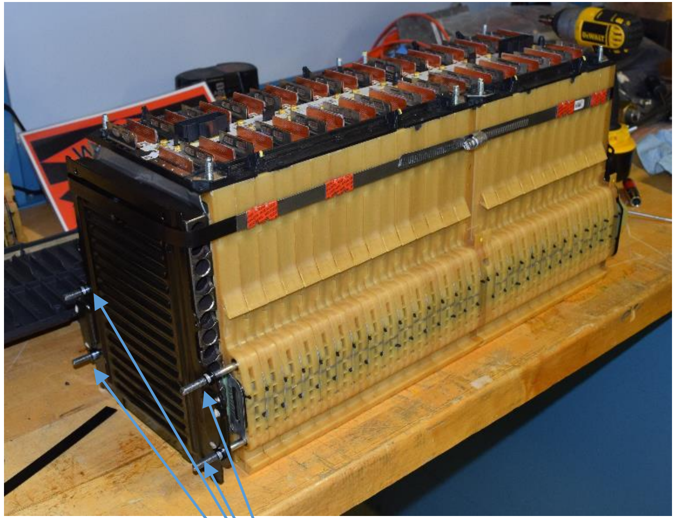
Separate cell stack, remove holding frame, insert heater

Separate cell stack

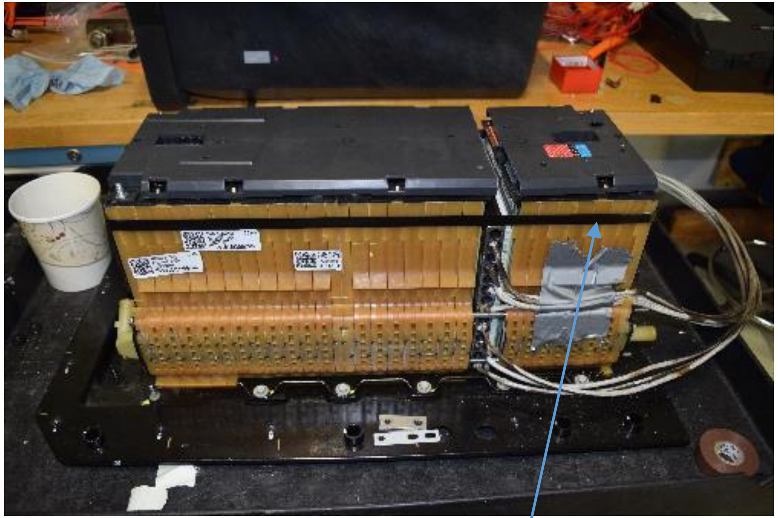
Remove holding frame to fit heater

Insert heater

Heating – mid-pack & end-pack: Modification/fabrication of parts required



End-pack

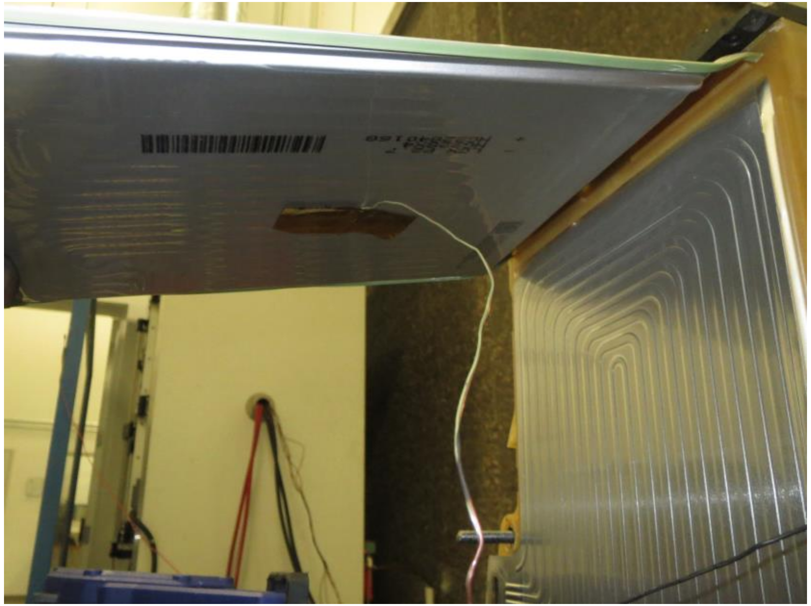


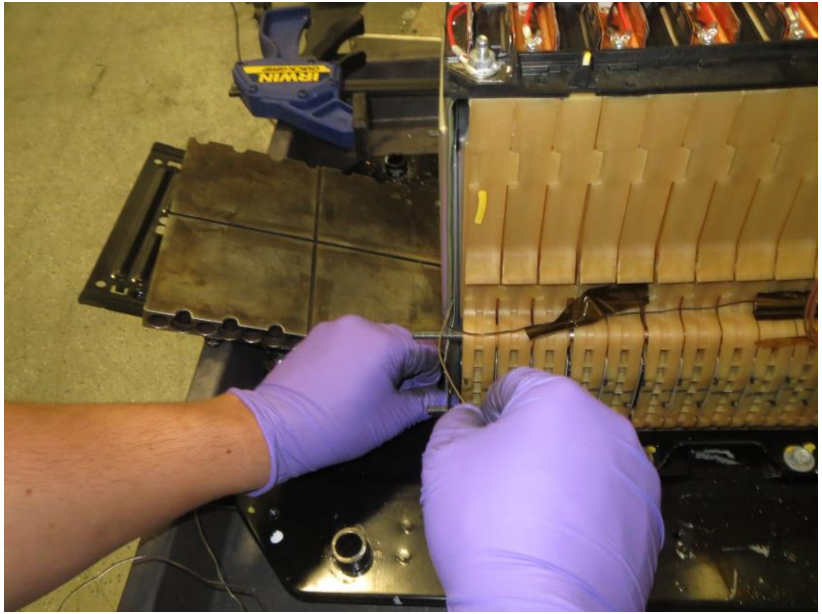
Mid-pack

Longer fasteners required (both heater positions)

Larger "strap" required (both heater positions)

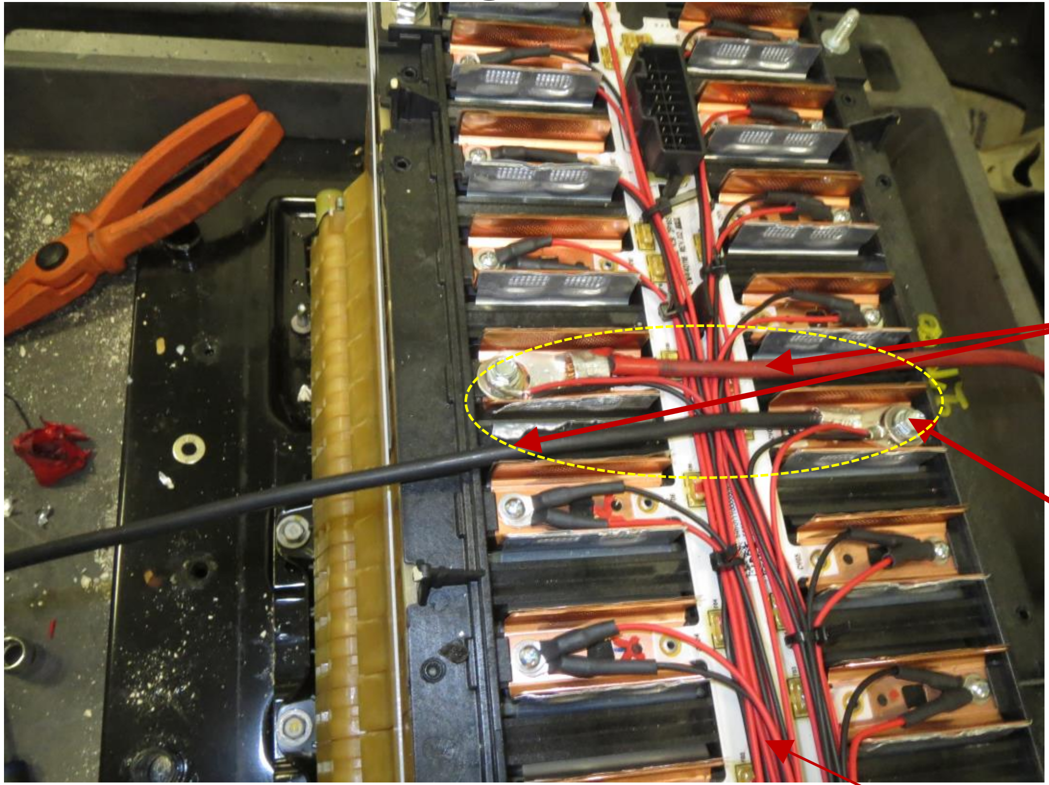
All packs:
Thermocouple fixed to target cell





Cell stack must be expanded to include thermocouple

Overcharge – mid-pack & end-pack
Install Charging Wires to Initiation Cell

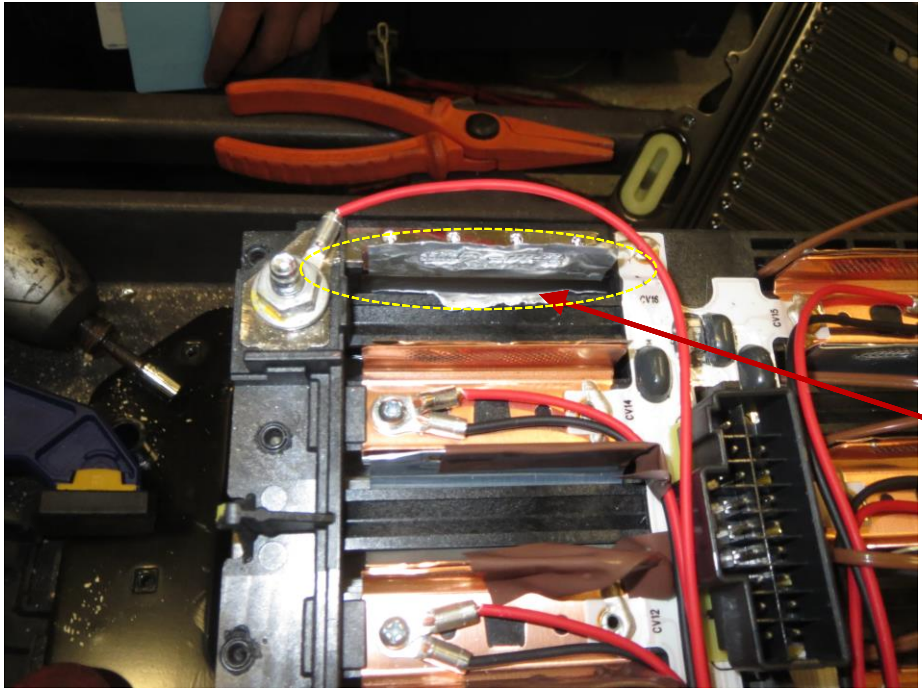


Charge wires

Install terminals for wire connection

Note: Voltage measurement wires for data collection.
(Not required part of test)

Overcharge – mid-pack & end-pack
Remove parallel cell from electrical circuit



Cell tab severed to disconnect target cell from parallel configured cell pair (a single cell tab is disconnected).

Conclusions

Conclusions

- Thermal propagation behavior depends on METHOD of initiating thermal runaway in a single cell
- Proposed allowable test method variation enable conditions which BOTH generate and do not generate thermal runaway in a single cell
- Thermal propagation appears UNCORRELATED to proposed test pass-fail criteria
- Proposed test methodology results in INCONSISTENT results
- SIGNIFICANT modification of DUT will likely be required and may affect test outcome
- Proposed thermal propagation test method is not sufficiently mature for regulation

Additional Points for Discussion

- Engineering standard compared to regulatory requirement
- How one OEM addresses thermal propagation risk

Engineering Standard vs Regulatory Requirement

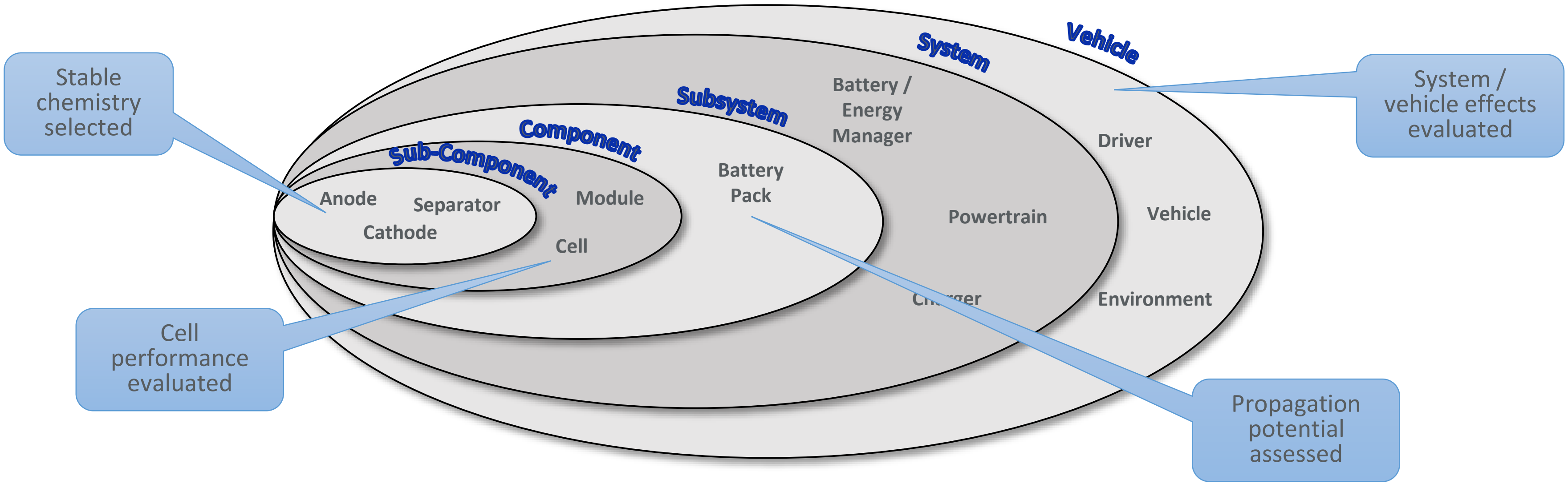
Comparing Engineering Standards and Regulations

Characteristic	Engineering Standard	Regulation
Purpose	Assist manufacturer in development of product and/or communication with suppliers	Assure public safety
Usage Requirement	Optional at manufacturer discretion	Mandatory
Procedure Robustness	Sufficient to suit manufacturer's needs	Repeatable and reproducible
DUT (including modification)	As determined by manufacturer	Must represent product as used by customer
Required technical merit	May be included in standard even if evidence supporting it is limited	Needs to be effective at assuring a product which complies is safe
Degree of detail	Can be vague/non-specific [manufacturer discretion]	Must be highly specific so minimize mis-interpretation
Acceptance criteria	Likely not part of standard; at manufacturer's discretion	Must be specified unambiguously

A test suitable for an engineering standard IS NOT necessarily appropriate for regulation.

Current Practice of One OEM

Application to thermal propagation Mitigation



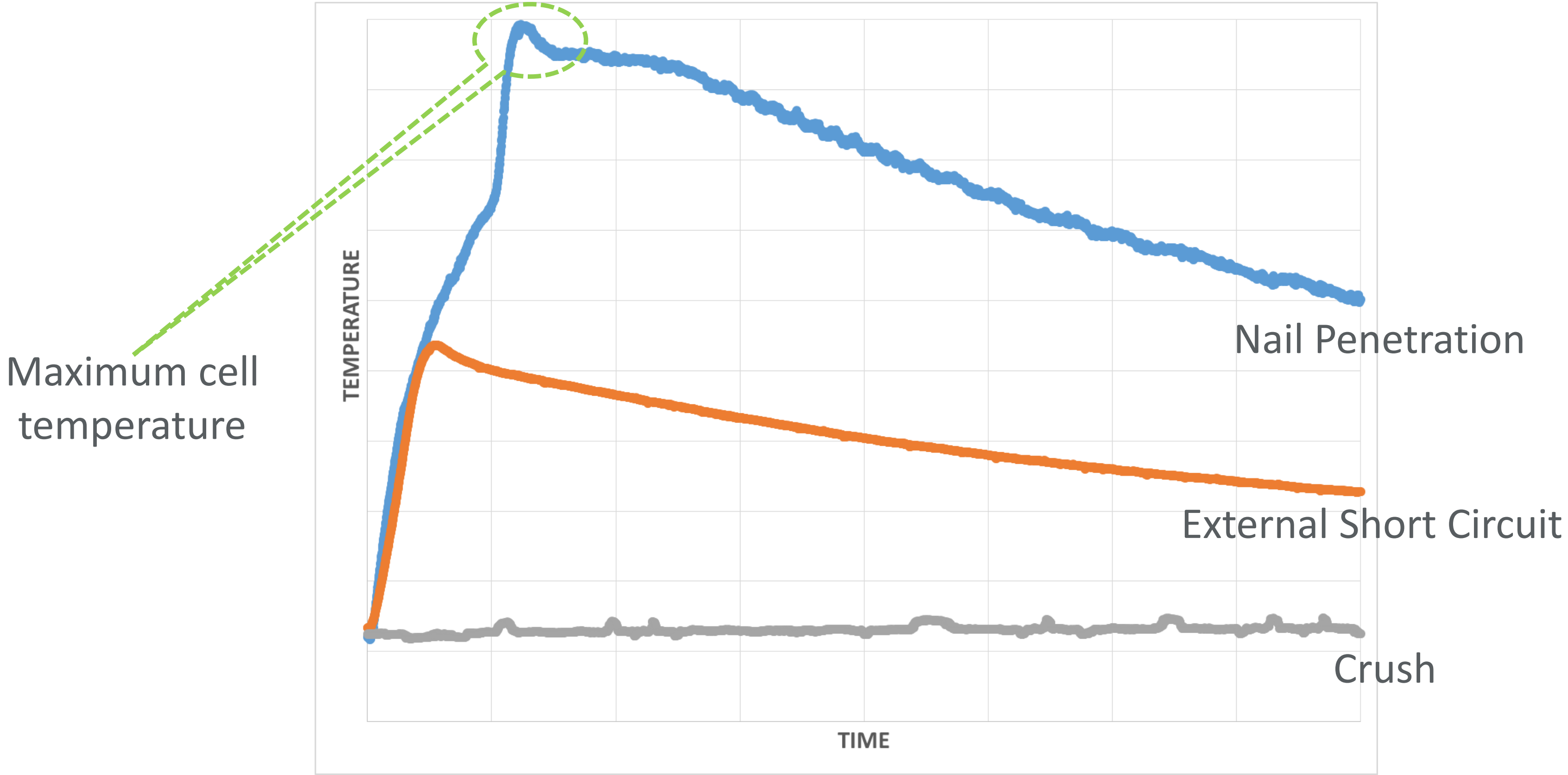
Safety designs at all levels contribute to total system safety

Cell performance evaluated

- Cell abuse tests have been used to assess performance to various simulated failure modes

- Selected methods simulate, to some degree, failure mode of interest
  - External short circuit
    - \+ Simulates high current event through current collectors
    - \- Current density low at electrodes
  - Nail penetration
    - \+ Electrode to electrode shorting possible
    - \- More distributed heating than internal short
  - Crush
    - \+ Electrode to electrode shorting possible
    - \- Robust mechanical design may prevent internal short

Cell test results example

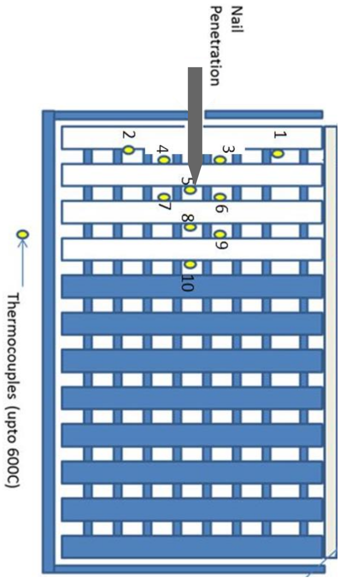


Propagation potential assessed

- Of the three tests considered, the highest thermal energy was released in the test with maximum peak temperature since all cell tests were conducted in similar environments.

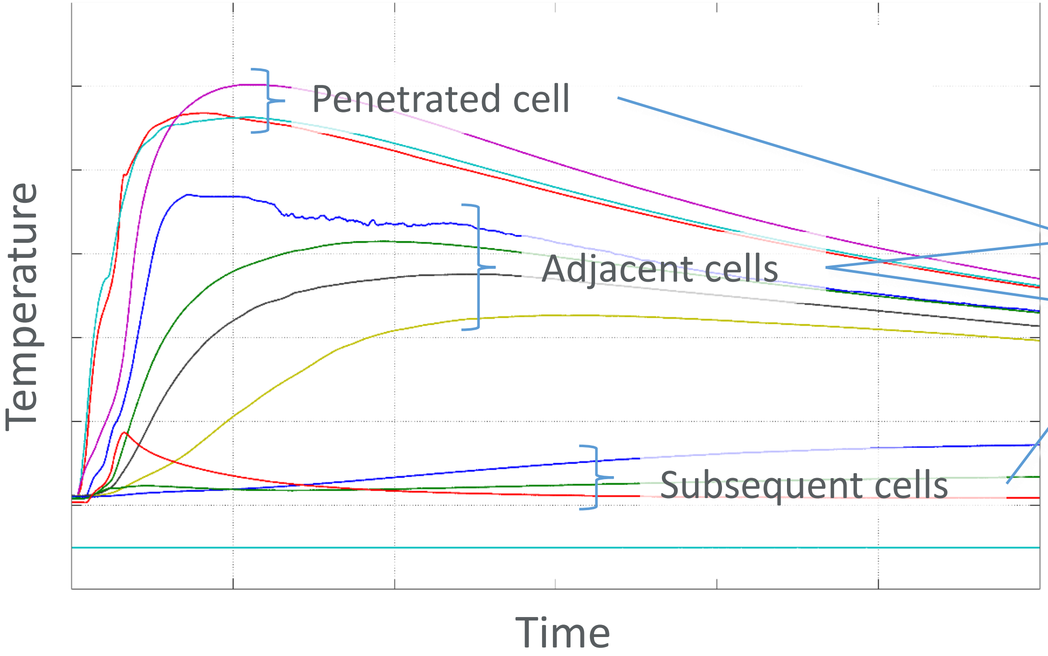
- Reproduce similar thermal energy event while cell in module
  - Observe for event propagation
    - Number of cells
  - Observe for type of thermal outcome
    - Benign temperature increase
    - Venting
    - Fire

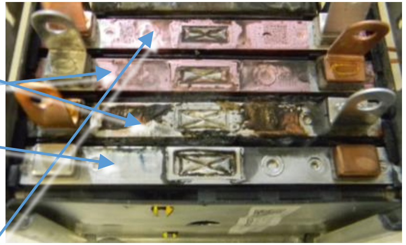
Thermal propagation assessment method



Test method example only. The illustrated test is NOT applicable for other REESS designs. Each module/pack design requires a unique test configuration or method. Such a method is not possible for ALL REESS designs.

Thermal propagation assessment example





System / vehicle effects evaluated

- Does amount of vent gas exceed allowable levels?
- Was fire / flame observed?
- Other system level effects noted?