Li-Ion Battery By-Pass Removal Qualification

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Photos D.R.

Agenda

- **Why some by-pass on satellite batteries ?**
- **Li-Ion reversal**
- **Mathematical Model**
- **Qualification Tests**
- **Conclusion**

Why have by-pass on satellite batteries ?

- **To avoid the loss of the power due to :**
  - a battery open circuit
  - a low voltage cut off : battery performance

- **NiCd batteries : no by-pass**

- **NiH_2 batteries : charge and discharge diodes to cope with H_2 leak leading to a cell open circuit.**

- **Li-Ion GEO/LEO batteries :**
  - Use of a NEA by-pass based on Stentor program
  - However ….

Li-Ion open circuit failure

- **Contrary to NiCd and NiH_2 , Li-Ion can be assembled in parallel.**

- **Thanks to parallel assembly, the risk of sudden current interruption due to cell open circuit failure is clearly avoided with Li-Ion batteries (P>1).**

Li-ion open circuit failure transitory scenarios

- **If the open circuit occurs at low state of charge .**

- **Depending on the DOD and the P , the failed module could be self shorted or not :**
  - If DoD> 1.15* (P-1)/P, the failed module is self short circuited, the group of cells behaves as a resistor
  - If DoD< 1.15* (P-1)/P , the failed module is not self short circuited, the module has an energy reduced to (P - 1)/ P but still able to fulfill the mission .

    - DOD<76 % for P=3
    - DOD<87 % for P=6

Li-ion open circuit failure transitory scenarios

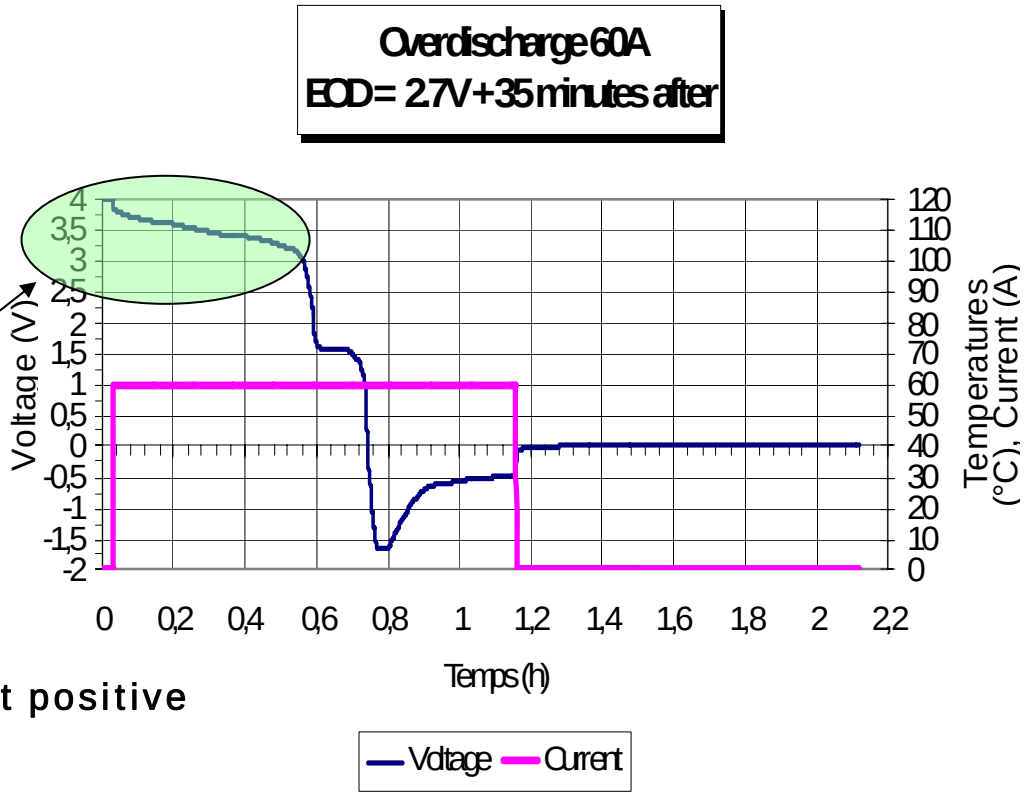
- **If the failure occurs while charging:**
  - The failing group of cells reaches the EOCV before all the other groups
  - This would result in undercharging the battery by (P- 1)/P
  - If need be, to compensate this imbalance, some higher-voltage charging of the failing group (up to 4.3V) may be immediately allowed and balancing resistor could be put on to rebalance.

Li-ion short circuit failure

- **Two possible events :**
  - if short current lower than the balancing current :
    - continuous activation of the balancing
    - compensation of the short by the balancing
  - if short current higher than balancing current :
    - reversal during discharge : soft shorting of cells
    - battery operating with one cell package less

Li-ion cell over-discharge or reversal

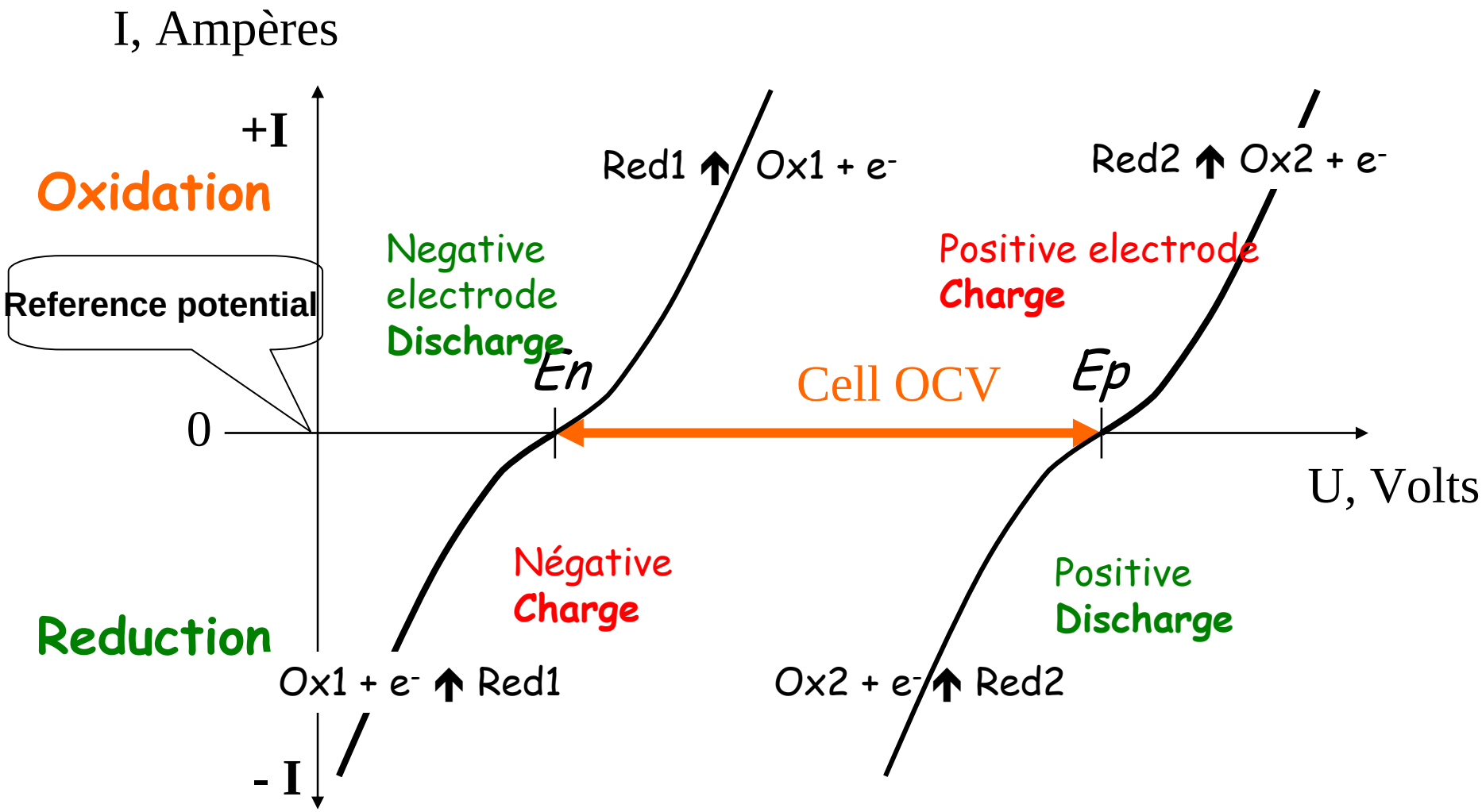
- **The prolonged discharge curve shows 4 steps**
  - Normal discharge
  - Second step discharge
  - Reversal
  - Short-circuit



Lithium intercalation takes place at positive
Reduction of Ni4+ into Ni3+

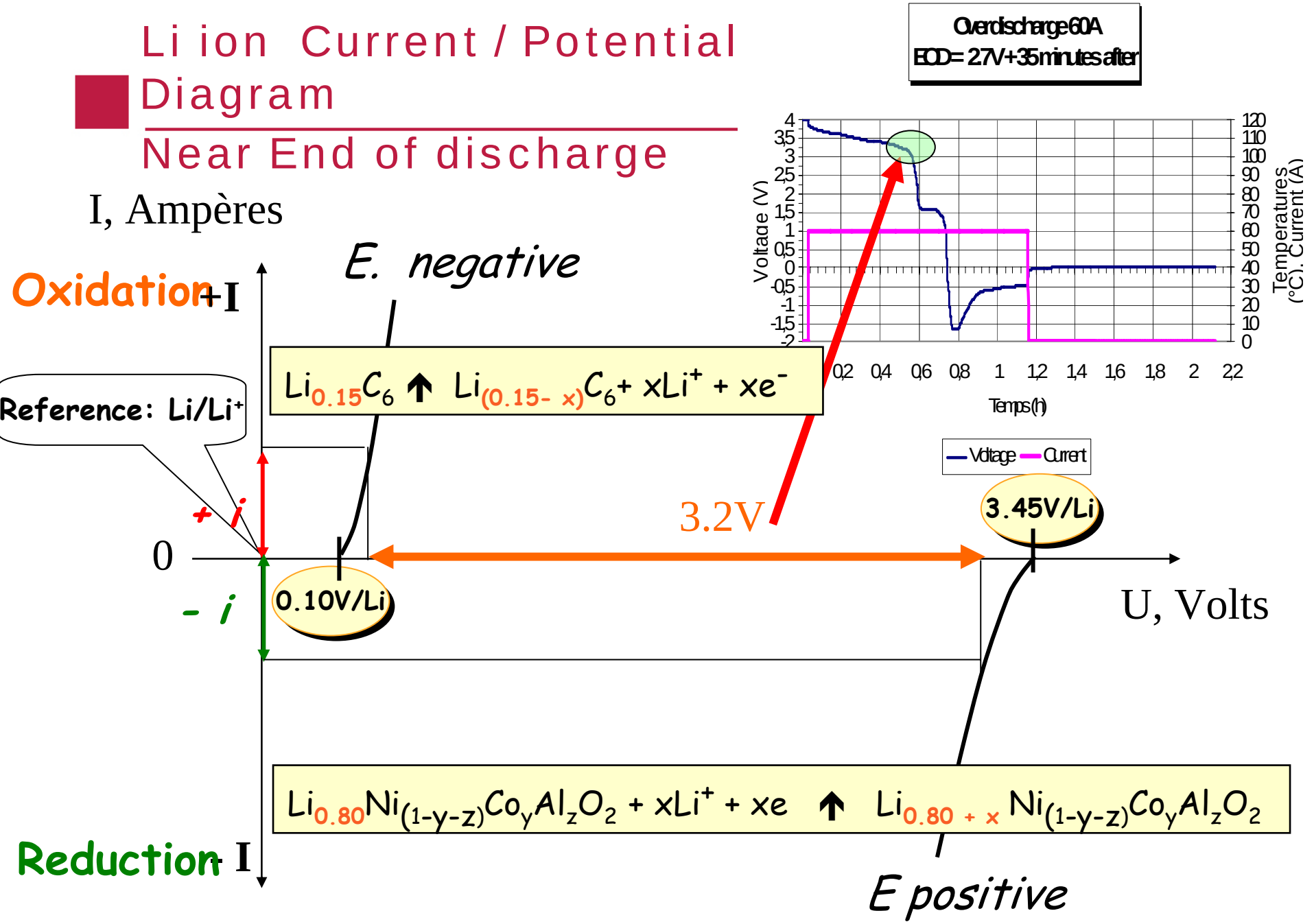
Inserted lithium oxidizes at negative

General Current / Potential Diagram of electrochemical couple : Negative (1) / Positive (2)

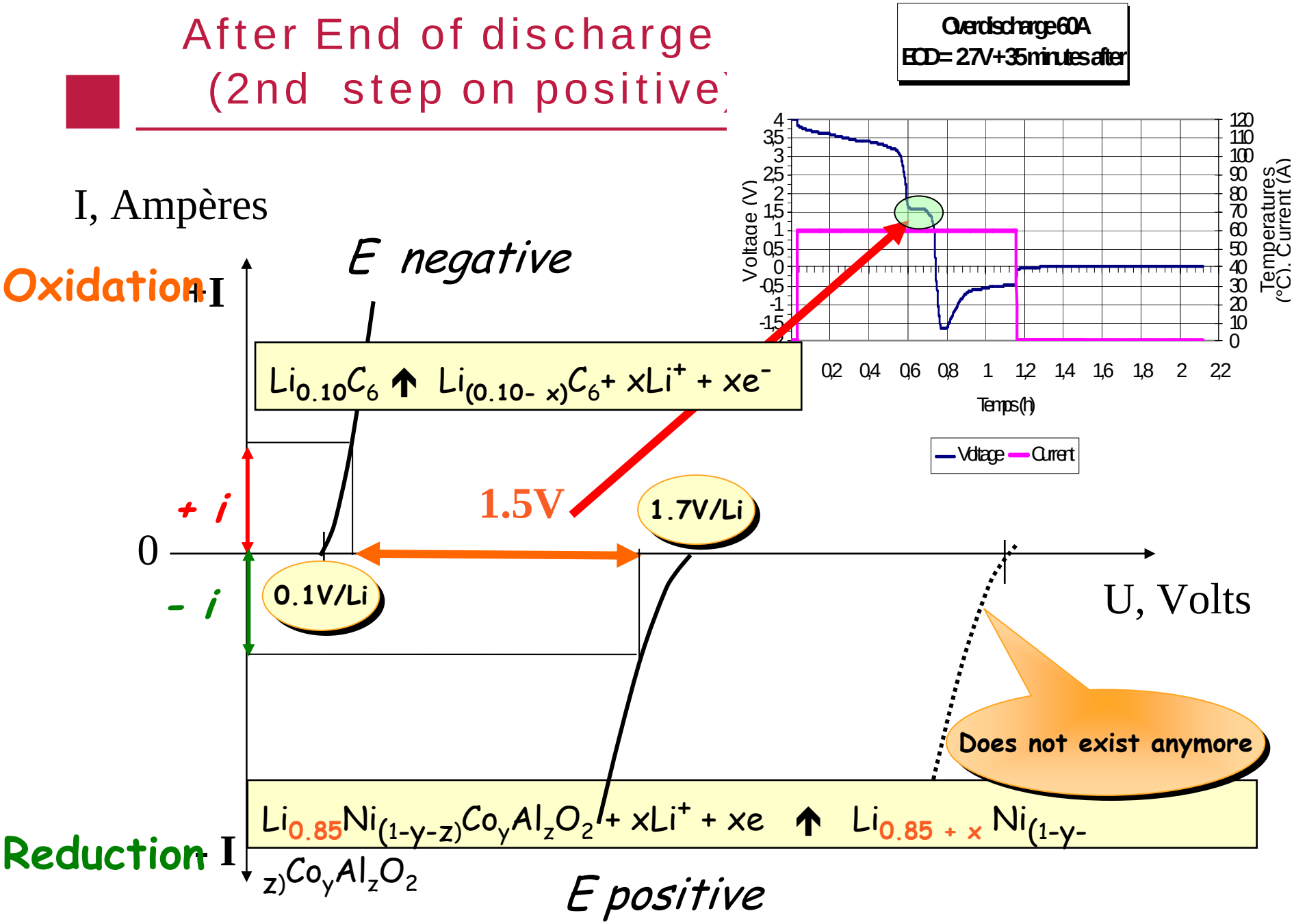


Li ion Current / Potential Diagram

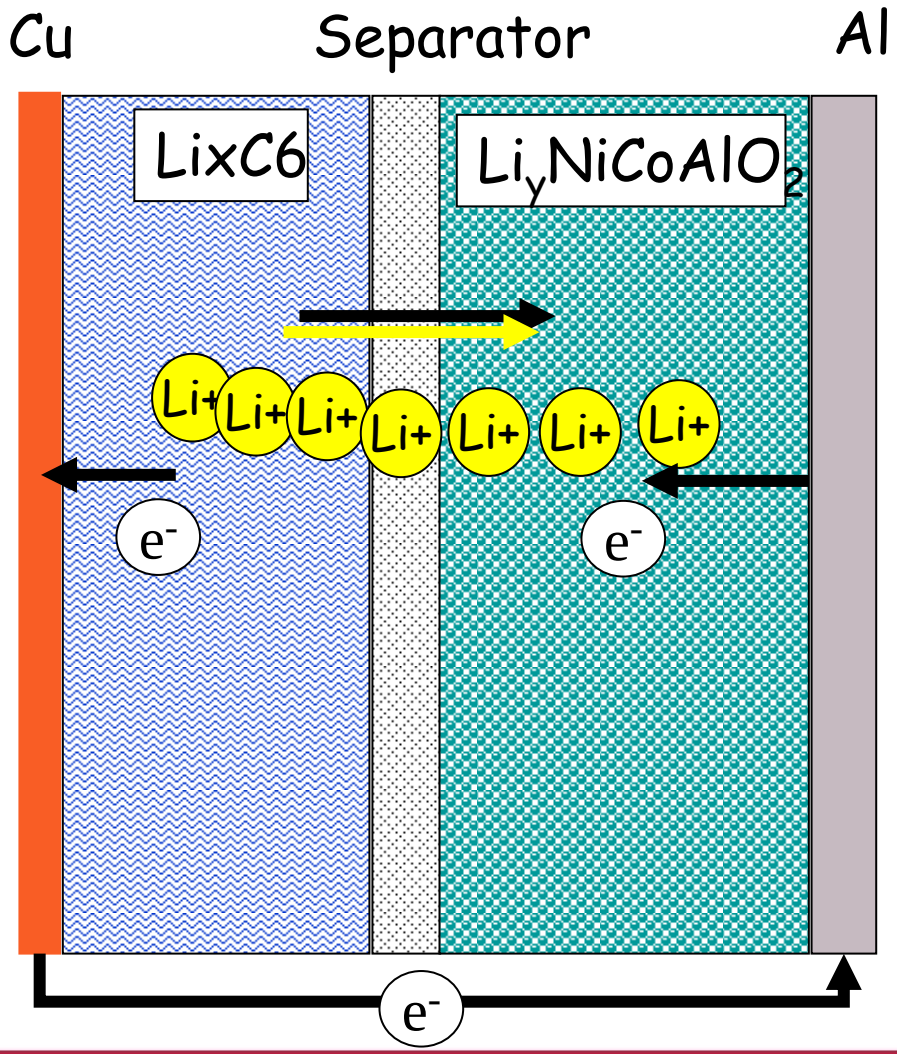
Near End of discharge



After End of discharge (2nd step on positive)

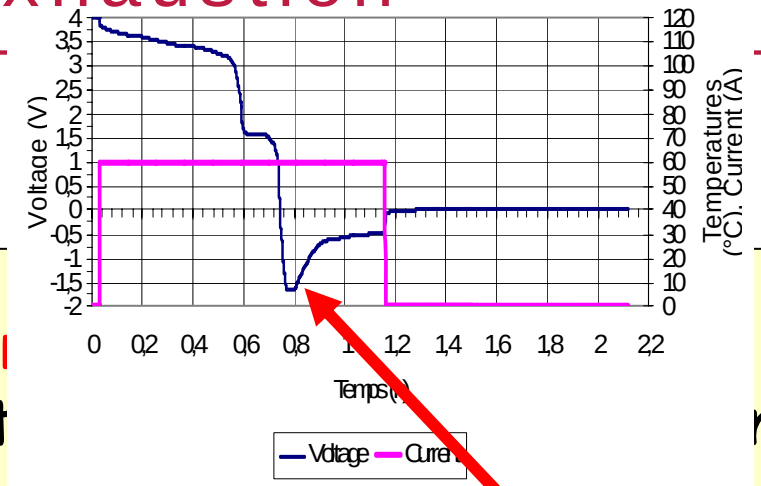


Schematic view of cell stack
End of Discharge



* Porous and electronically conductive electrodes

Overdischarge, after Li exhaustion



I, Ampères

Oxidation +I

Does no
any

- No ma… electrode:
  negat… ncreases
  to reach next oxidation reaction: Copper, at about 3V
  = Cell potential reversal (1.5 - 3 = -1.5V)
- Copper, oxidized and … lved at the negative.

1.6V/Li

-1.5V

+ i

0

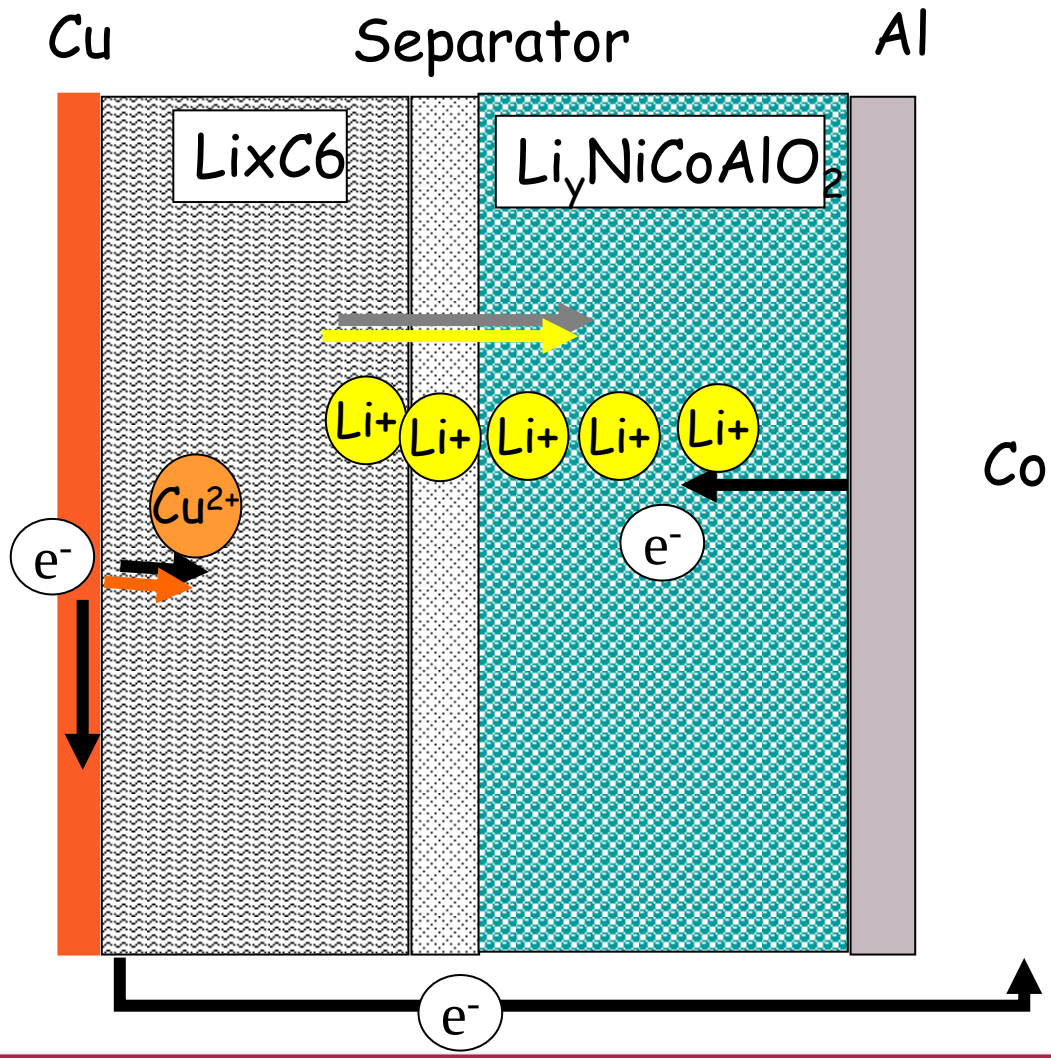
- i

U, Volts

$Li_1Ni_{(1-y-z)}Co_yAl_zO_2 + xLi^+ + xe \uparrow Li_{1+x}Ni_{(1-y-z)}Co_yAl_zO_2$

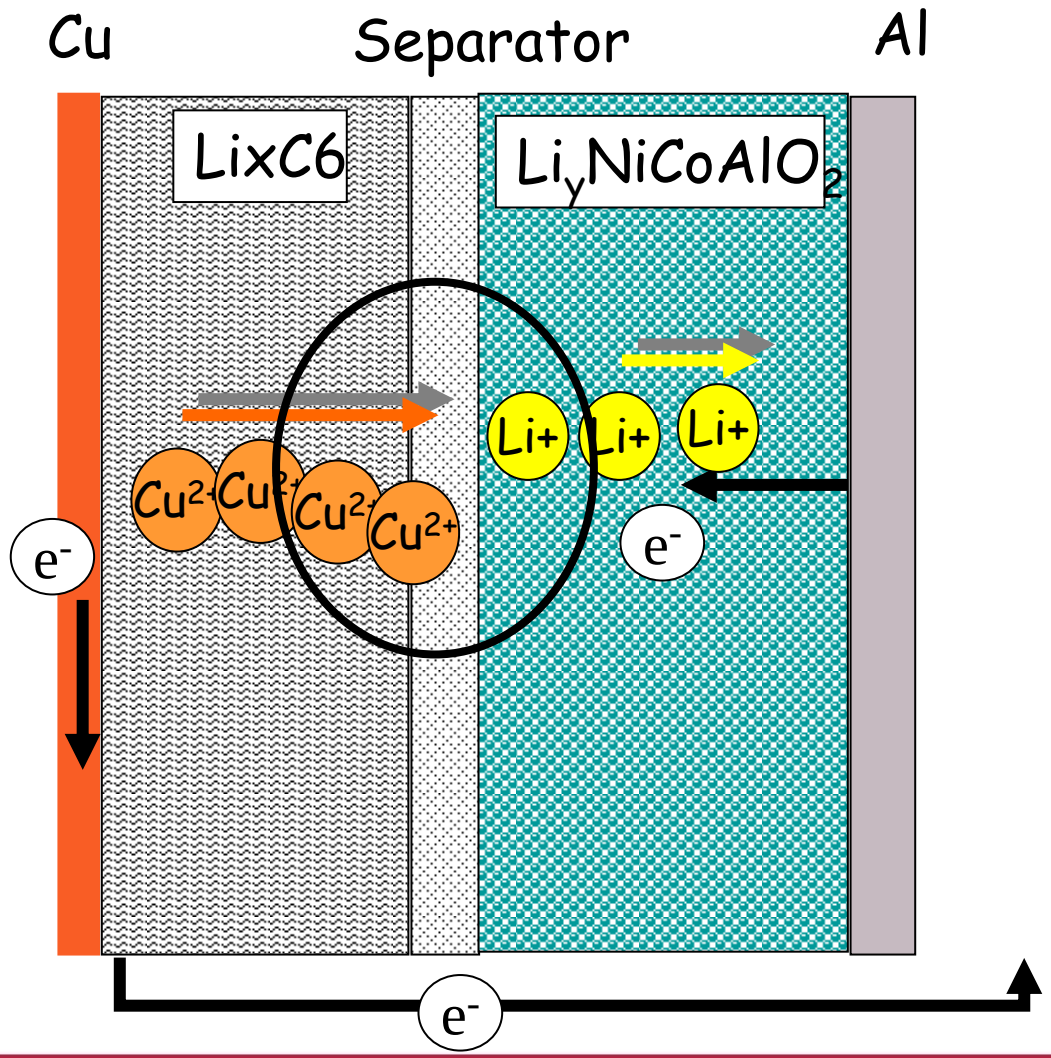
Reduction - I

Schematic view of cell stack
After Li Exhaustion from negative



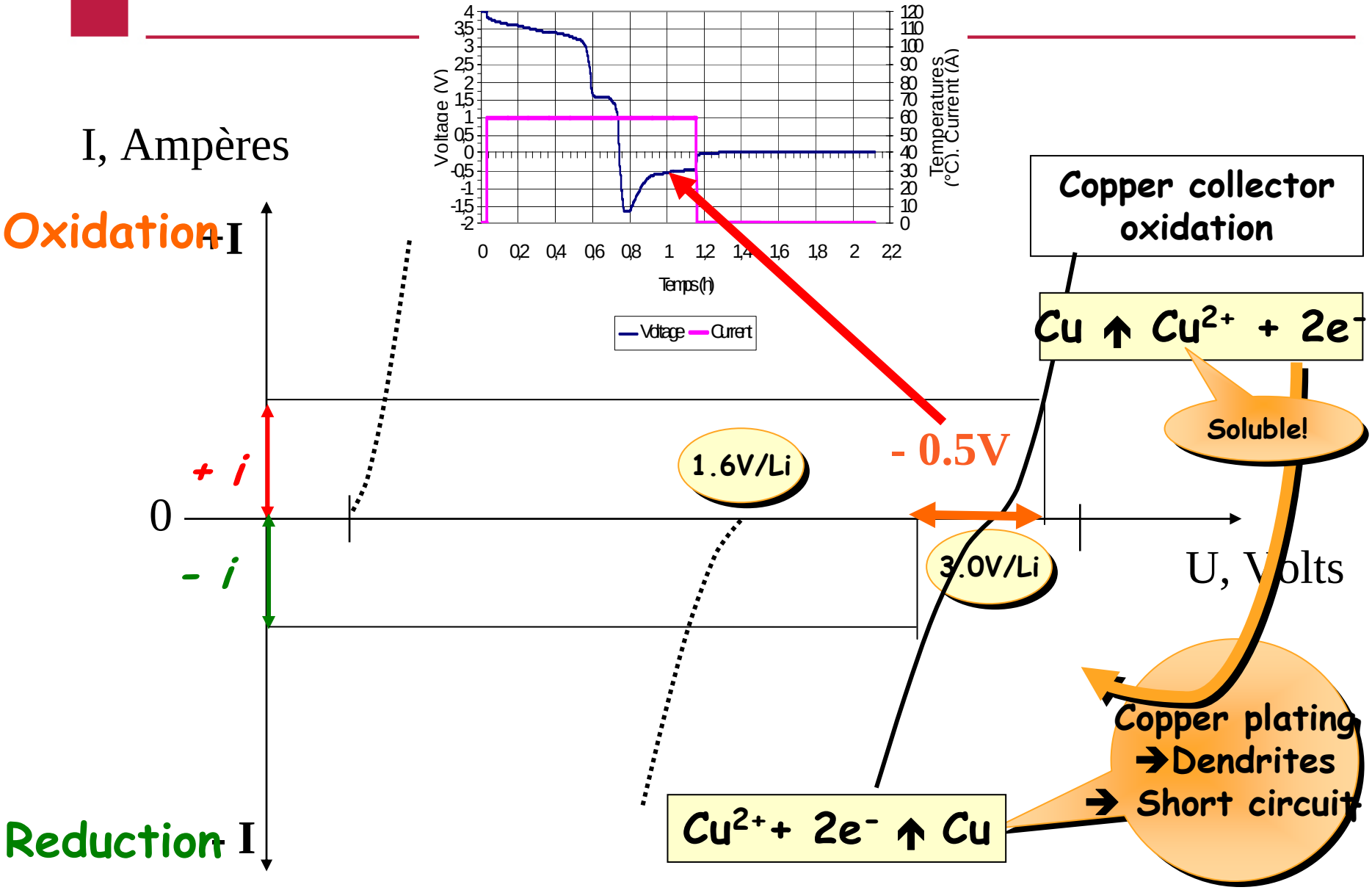
Copper starts to corrode

Schematic view of cell stack
Copper corrosion

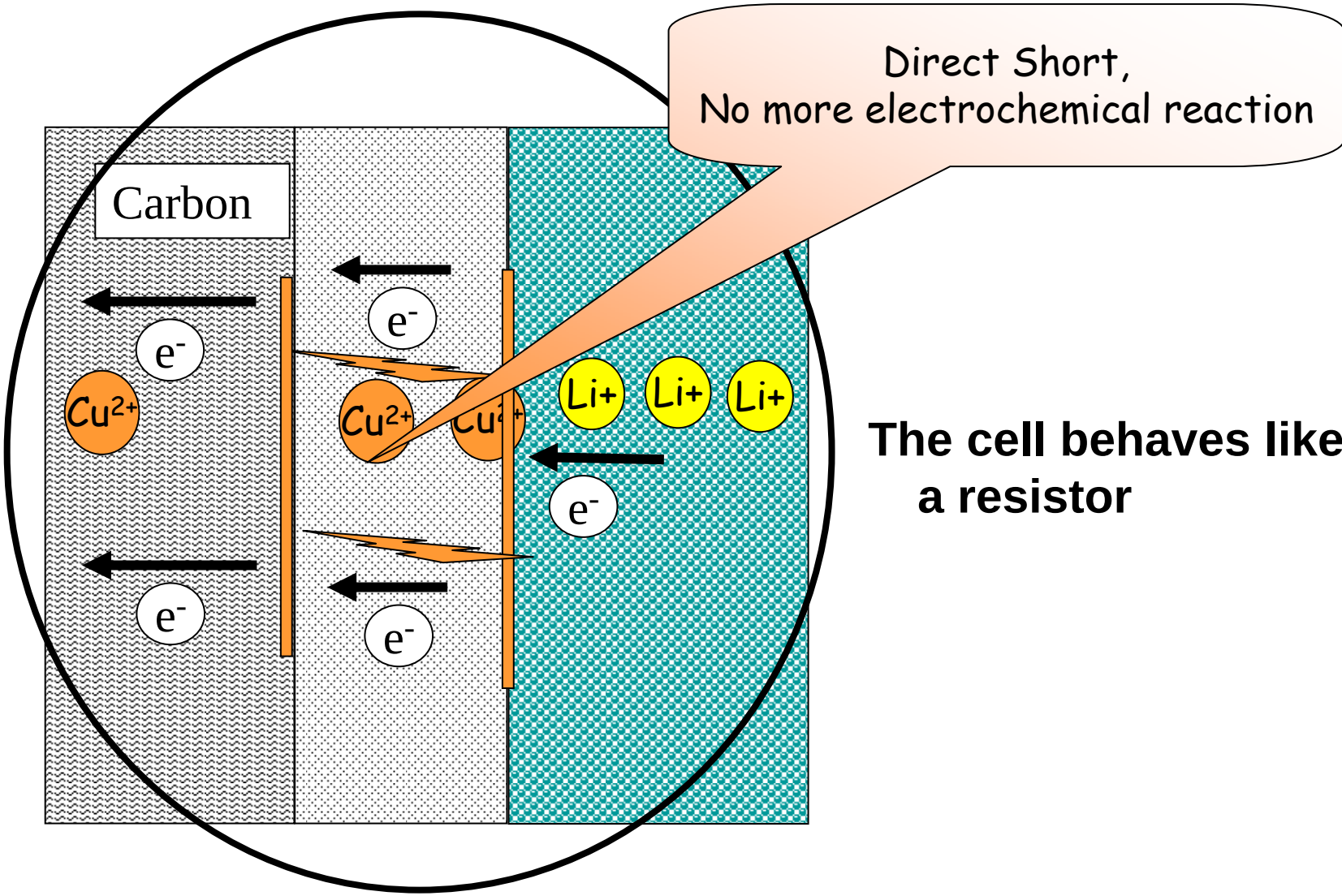


Copper ions migrate to positive electrode

Overdischarge, after Li exhaustion

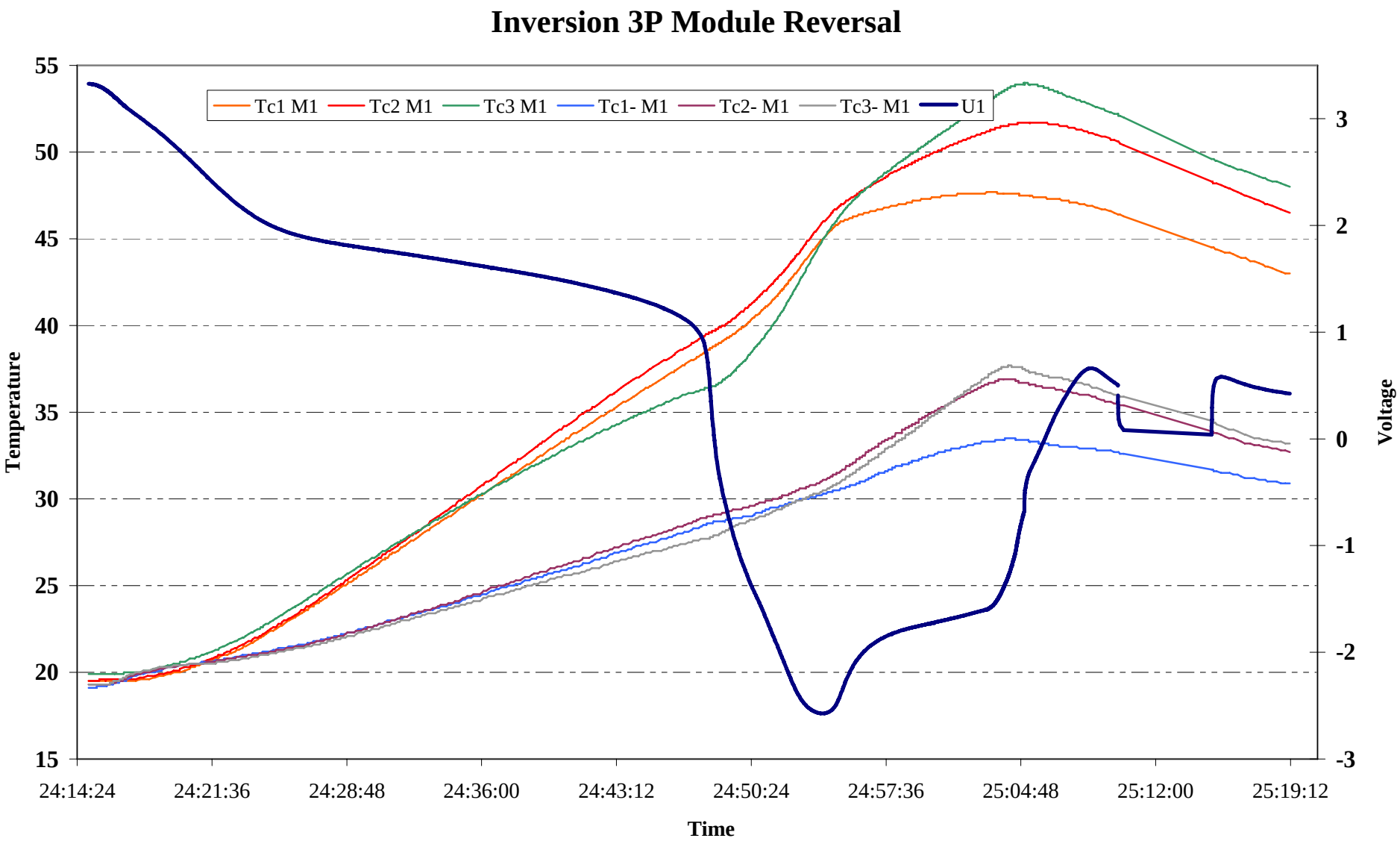


Schematic view of cell stack
After Li Exhaustion from negative



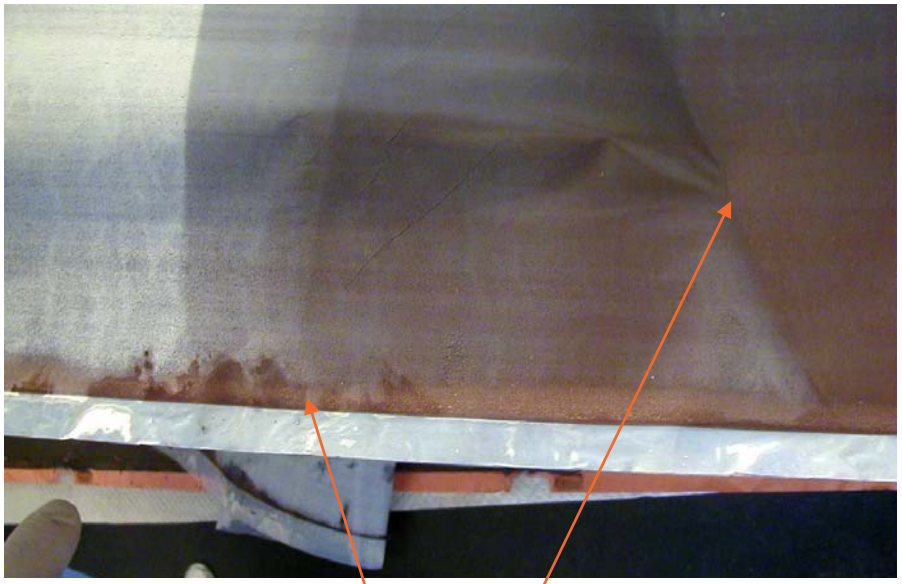
The cell behaves like a resistor

Overdischarge on to a 3P module at C/2



DPA on VES cell (after reversal)

Copper deposition



Copper deposition on separator

DPA on VES cell (after reversal)

Copper deposition on positive electrode

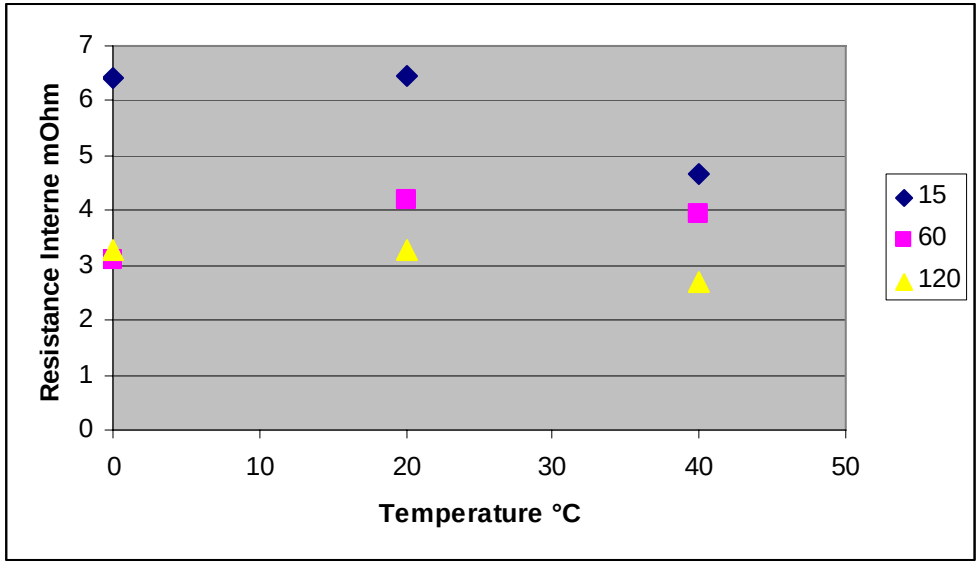
Copper deposition on negative electrode

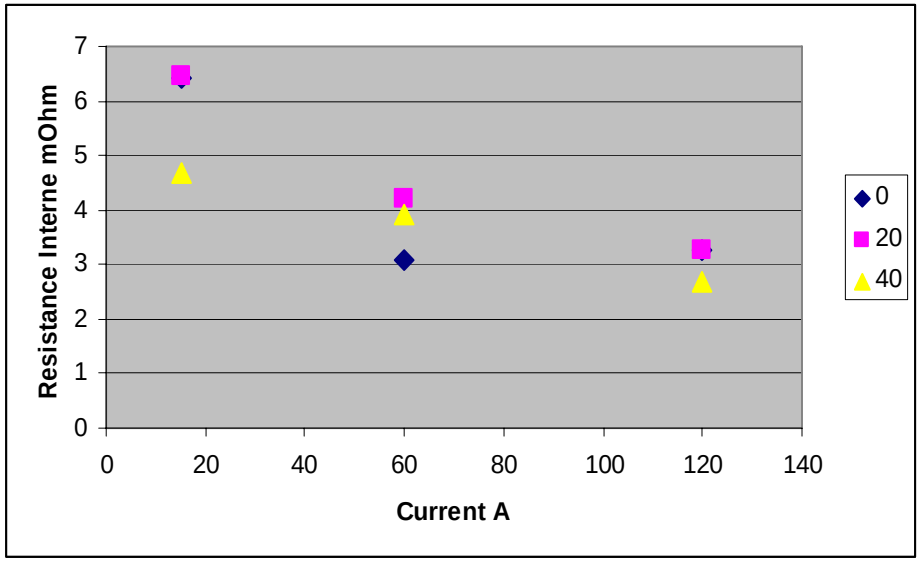
ARTES3 : By-pass removal test plan

Test	§ RD1 test plan	Procedure §	2P 1	2P 2	2P 3	2P 4	2P 5	2P 6	2P 7	2P 8	2P 9	2P 10	3P 1	3P 2	3P 3	3P 4	3P 5	3P 6	3P 7	3P 8	3P 9	3P 10	3P 11	6P 1	6P 2	3P3S	3P3S
Used as tool			0						0					0											0		
Open circuit one cell at EOD	5,2,1	RD2; 4.2.1						1																		1	
Open circuit one cell at EOD with max peak 4,3V excursion	5,2,2	RD2; 4.2.2			1																						
Open circuit one cell caused by leaking cell	5,2,3	RD2; 4.6		1					1 repeated																		
Open circuit one cell at EOD	5,2,4	RD4; 4.2																						1			
Short circuit one cell (soft) 2,6 ohm	5,3,1	RD2; 4.3.1 to 4.3.4				1																					1
Short circuit one cell (soft) 5,1 ohm										1																	
Short circuit one cell (soft) 20,5 ohm							1																				
2 GEO seasons cycling; 20°C		RD2;4.3.5 to 4.3.8				2	2			2																	
Reversal; 0°C; C/8	5,4,1	RD3; 4.2.1 to 4.2.3											1														
Reversal; 0°C; C/2															1												
Reversal; 0°C; C																					1						
Reversal; 20°C, C/8																	1										
Reversal; 20°C; C/2																				1							
Reversal; 20°C; C																		1									
Reversal; 40°C; C/8																						1					
Reversal; 40°C; C/2																							1				
Reversal; 40°C; C																1											
Rapid cycling ; 20°C; 900 cycles		RD3; 4.2.4 to 4.2.5											2		2	2	2	2		2	2	2	2				
Progressive reversal	5,4,3	RD3; 4.5																	1								
Storage of reversed cells 6 months	5,4,4	RD3; 4.6																	2								
Life cycling GEO ; DOD 80%; 22 Yrs	5,4,2	RD2; 4.4									1																
Cycling of reversed cells 7,5 yrs	N/A											1															
Pulse 3C/250ms on reversed cells	5,6	RD2; 4.5 RD4; 4.3						2			2	2												2			

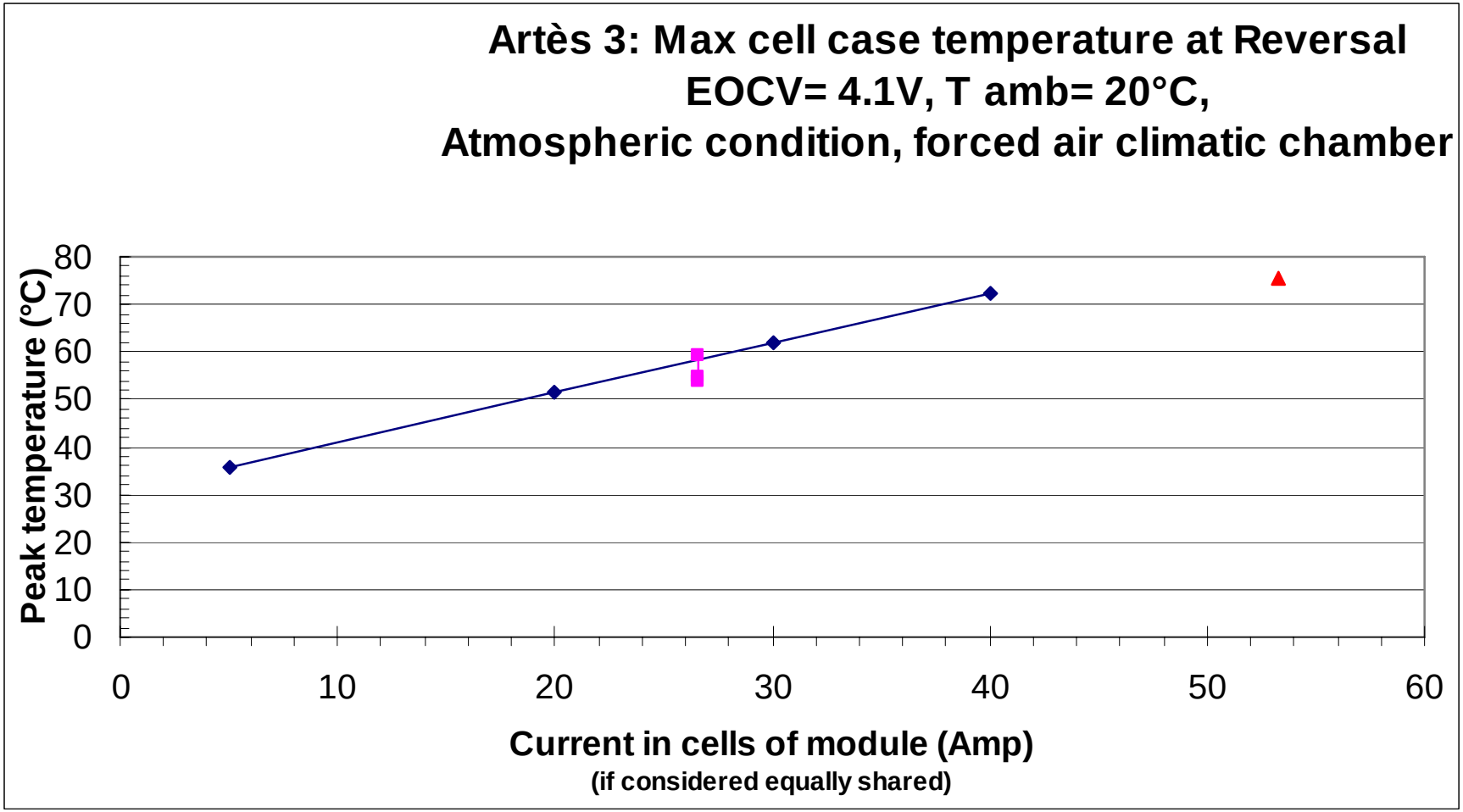
Self Short characterization on 3P modules : resistance after stabilization

	Current (A)		
Temperature	**15 (C/8)**	**60 (C/2)**	**120 C**
0°C	6,41	3,09	3,27
20°C	6,45	4,2	3,27
40°C	4,68	3,93	2,7

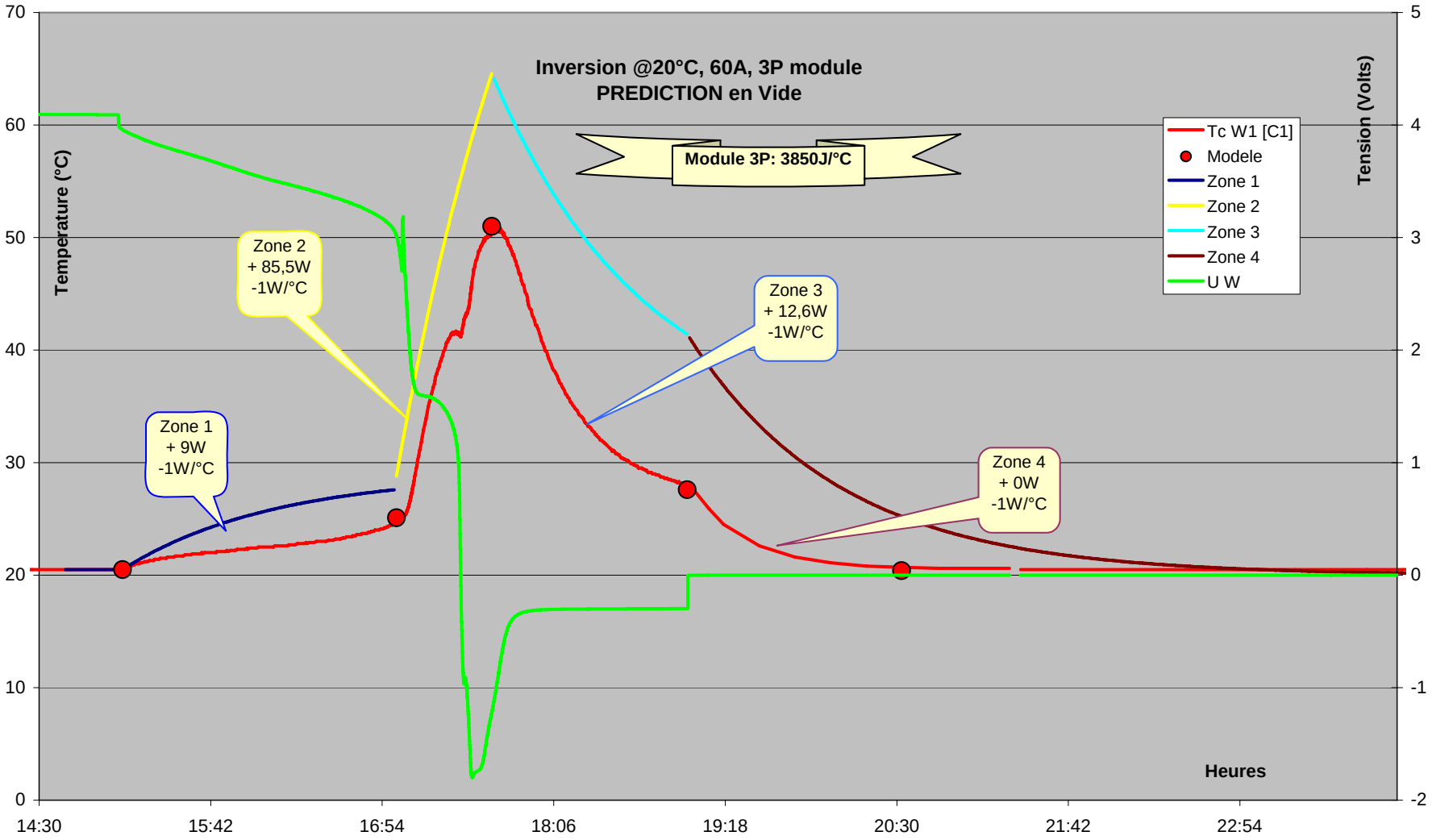




Thermal effect: test results summary

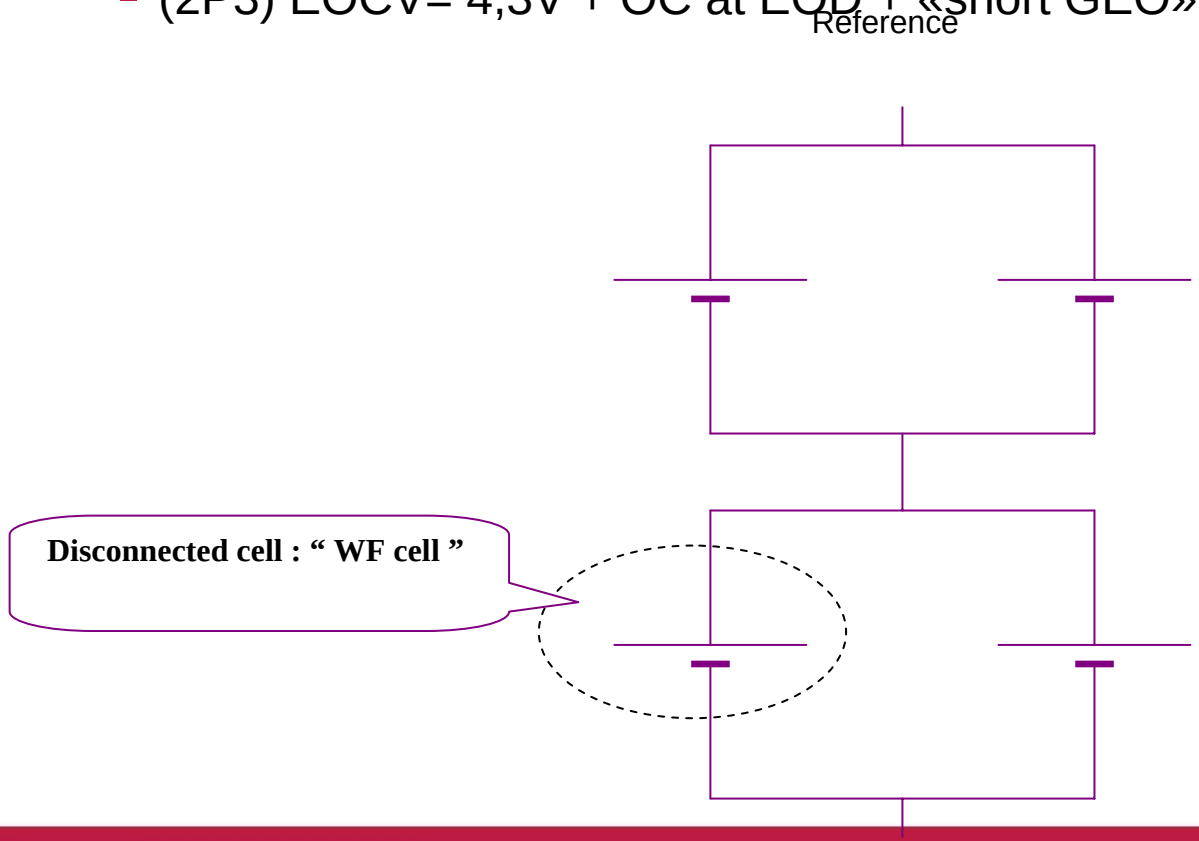


Thermal effect: test results analysis



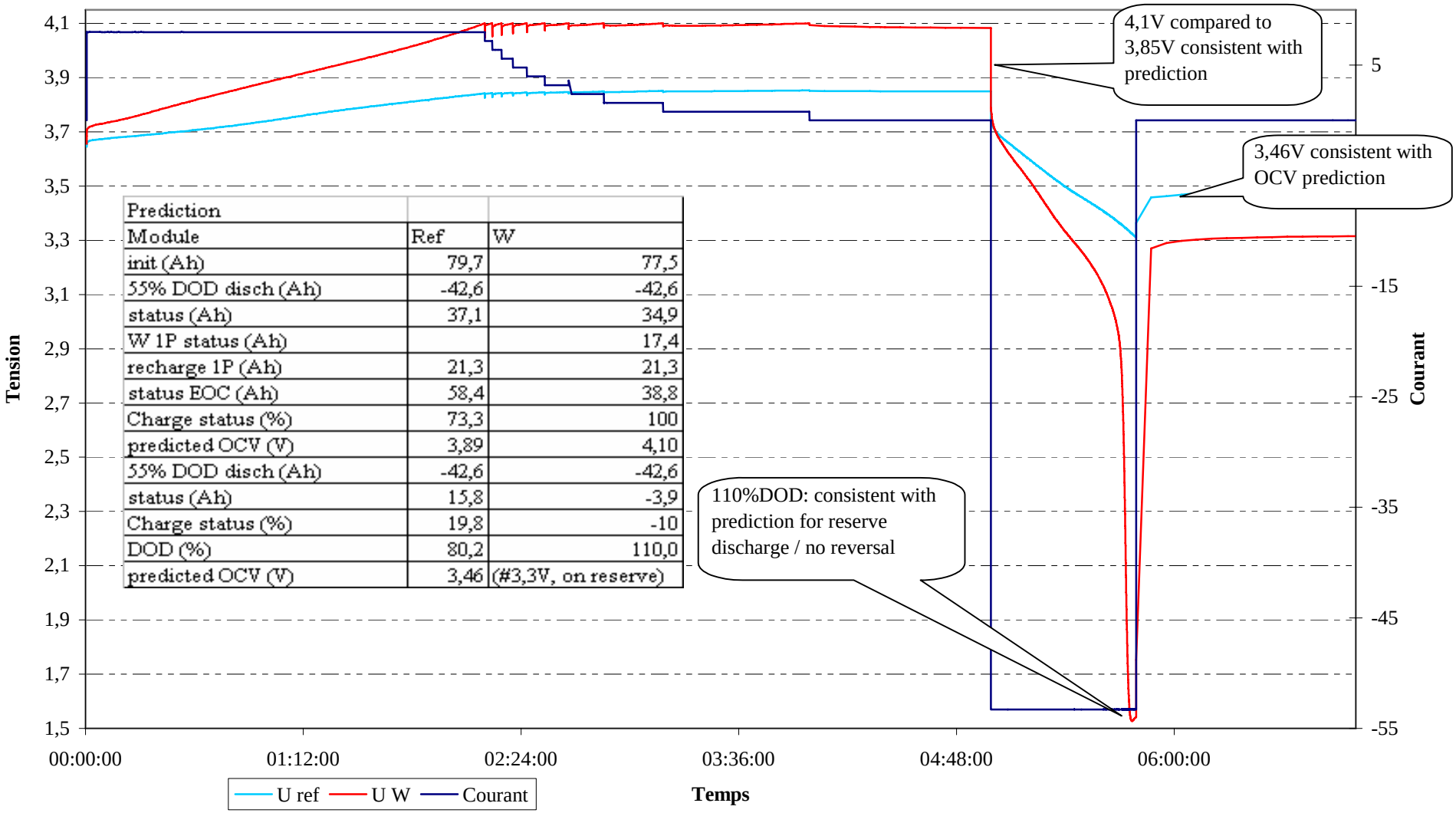
2P Modules: Open circuit test at End Of Discharge

- **Open on 1 cell:**
  - (2P6) EOCV= 4,1V + OC at EOD + «GEO» season with reversal
  - (2P9) EOCV= 4,1V + OC at EOD + «GEO» season with reversal on aged cells (45 saisons)
  - (2P3) EOCV= 4,3V + OC at EOD + «short GEO» season with reversal



2P6 Module: 55% discharge: no reversal

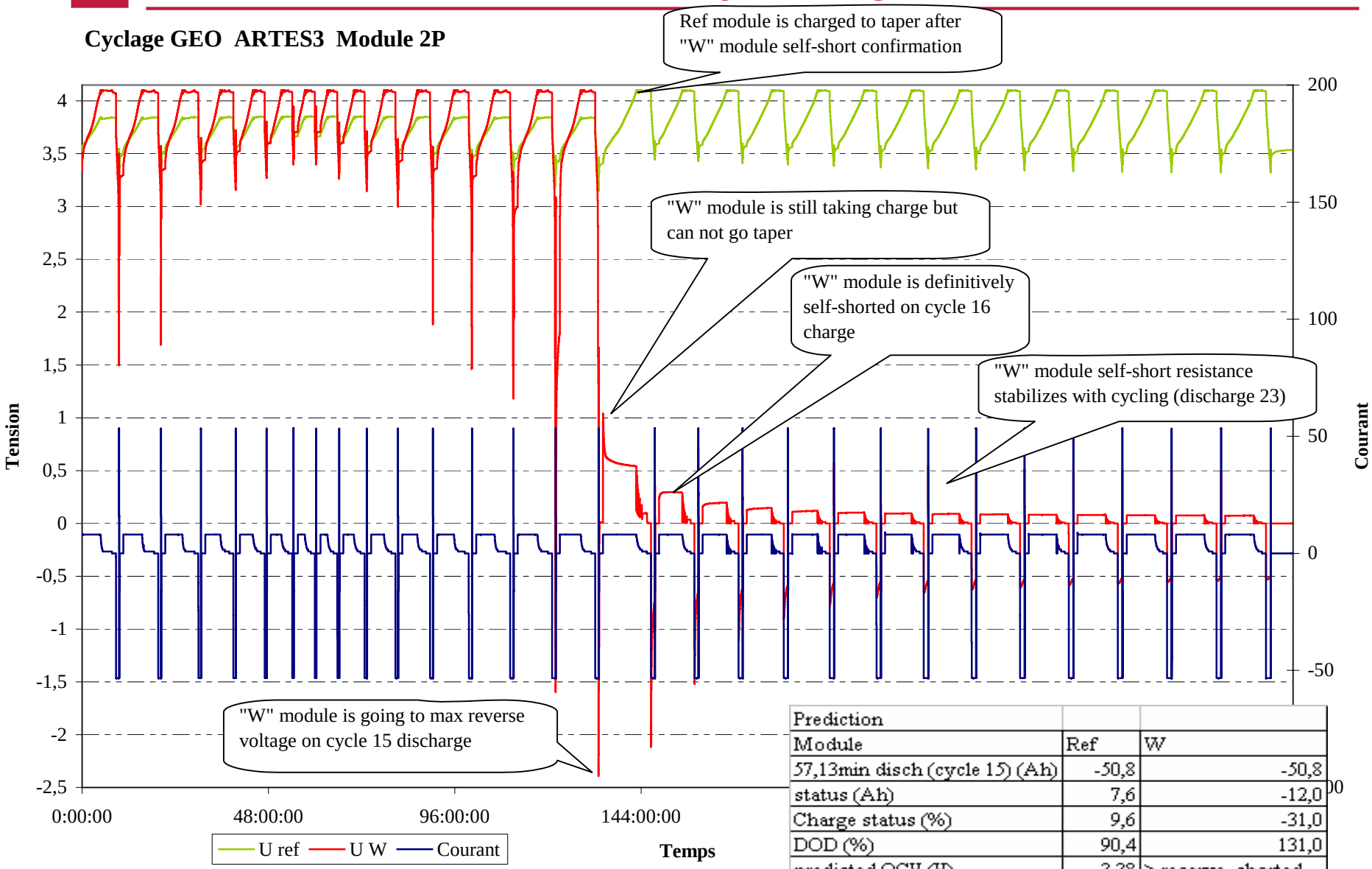
ARTES3: Charge to 4,1V/Discharge down to 55%DOD of 2P "W" after 1 open on 2P "W" module



Prediction		
Module	Ref	W
init (Ah)	79,7	77,5
55% DOD disch (Ah)	-42,6	-42,6
status (Ah)	37,1	34,9
W 1P status (Ah)		17,4
recharge 1P (Ah)	21,3	21,3
status EOC (Ah)	58,4	38,8
Charge status (%)	73,3	100
predicted OCV (V)	3,89	4,10
55% DOD disch (Ah)	-42,6	-42,6
status (Ah)	15,8	-3,9
Charge status (%)	19,8	-10
DOD (%)	80,2	110,0
predicted OCV (V)	3,46	(#3,3V, on reserve)

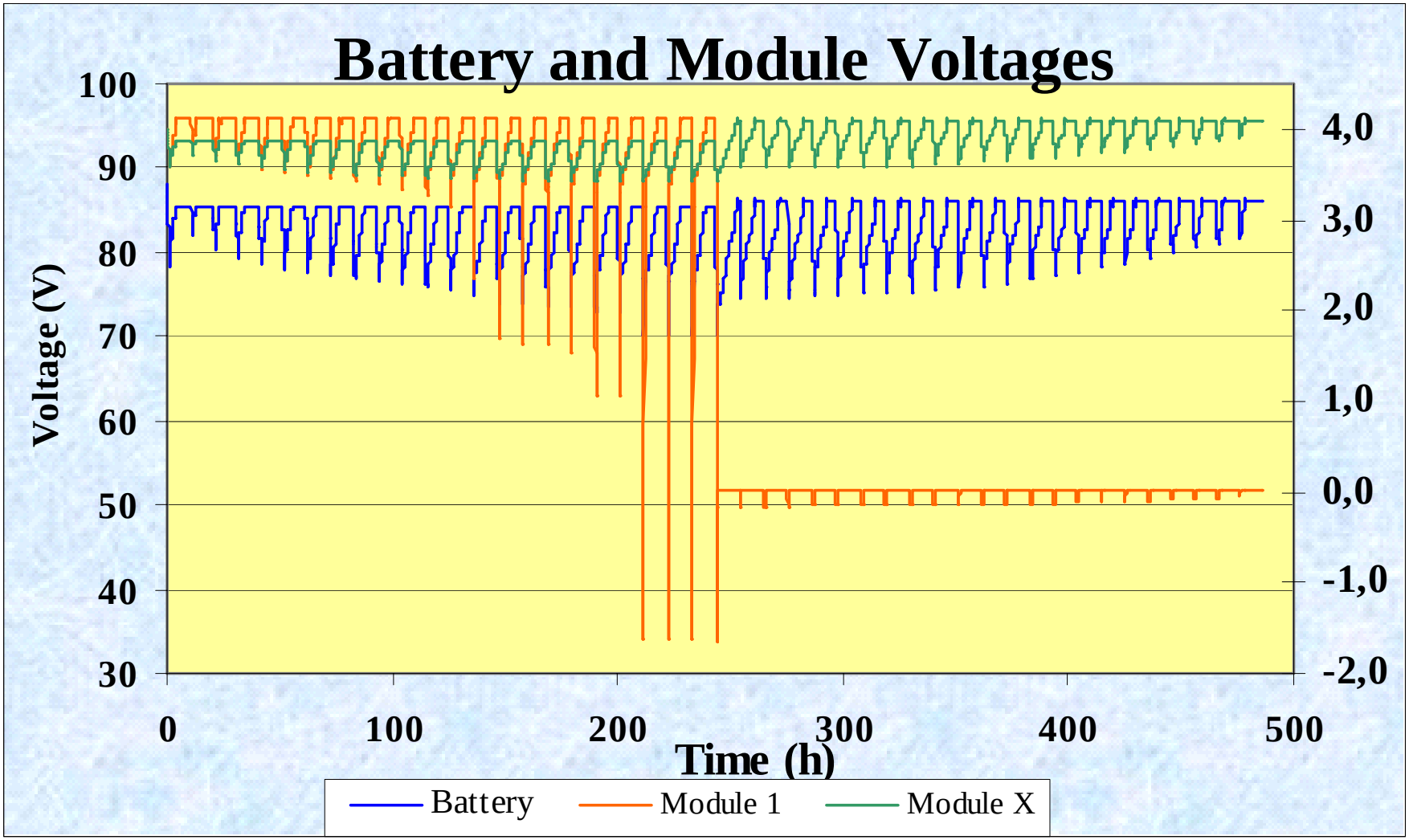
2P6 Module: GEO cycling -> reversal

Cyclage GEO ARTES3 Module 2P

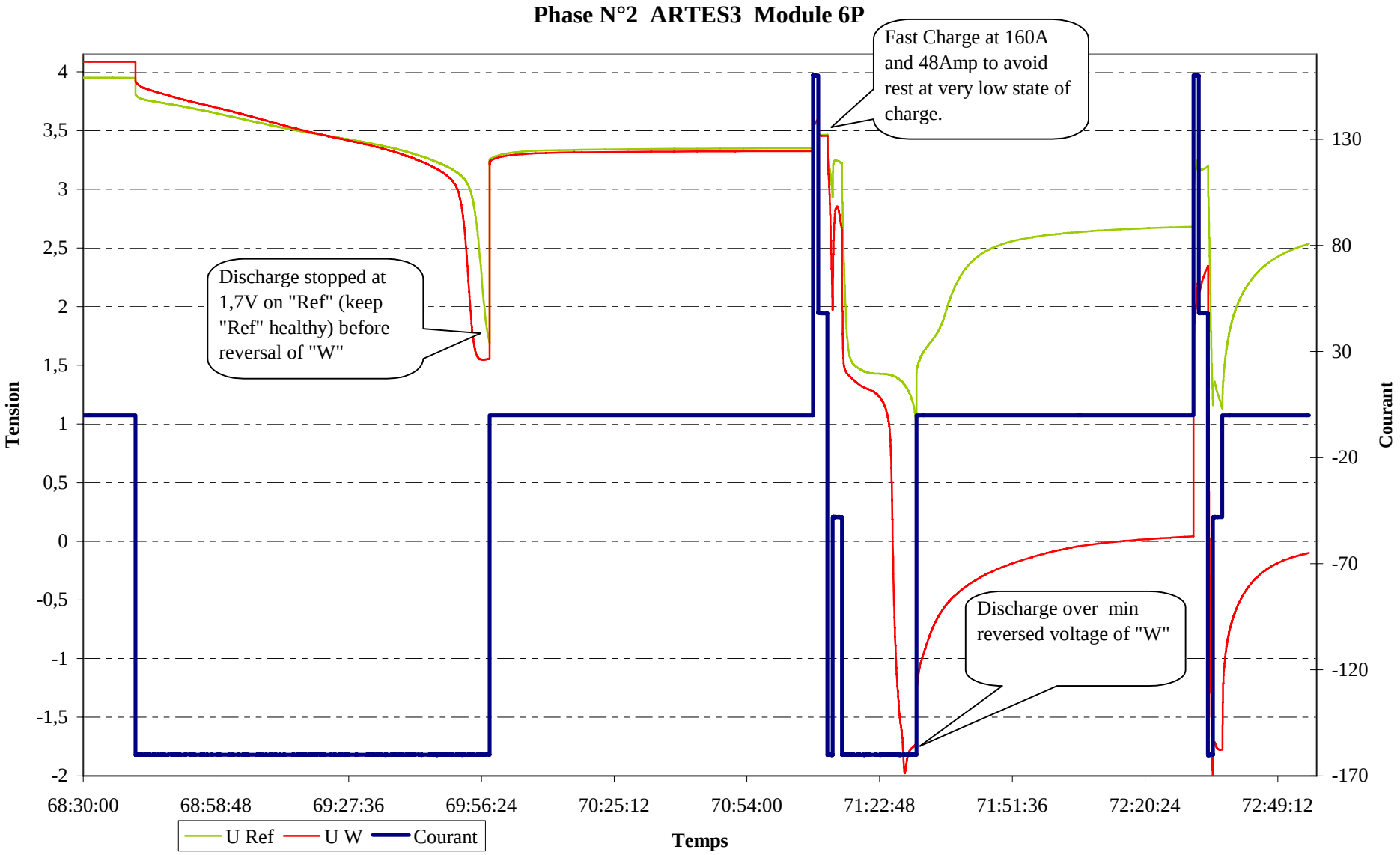


Prediction		
Module	Ref	W
57,13min disch (cycle 15) (Ah)	-50,8	-50,8
status (Ah)	7,6	-12,0
Charge status (%)	9,6	-31,0
DOD (%)	90,4	131,0
predicted OCV (V)	3,38	> reserve, shorted

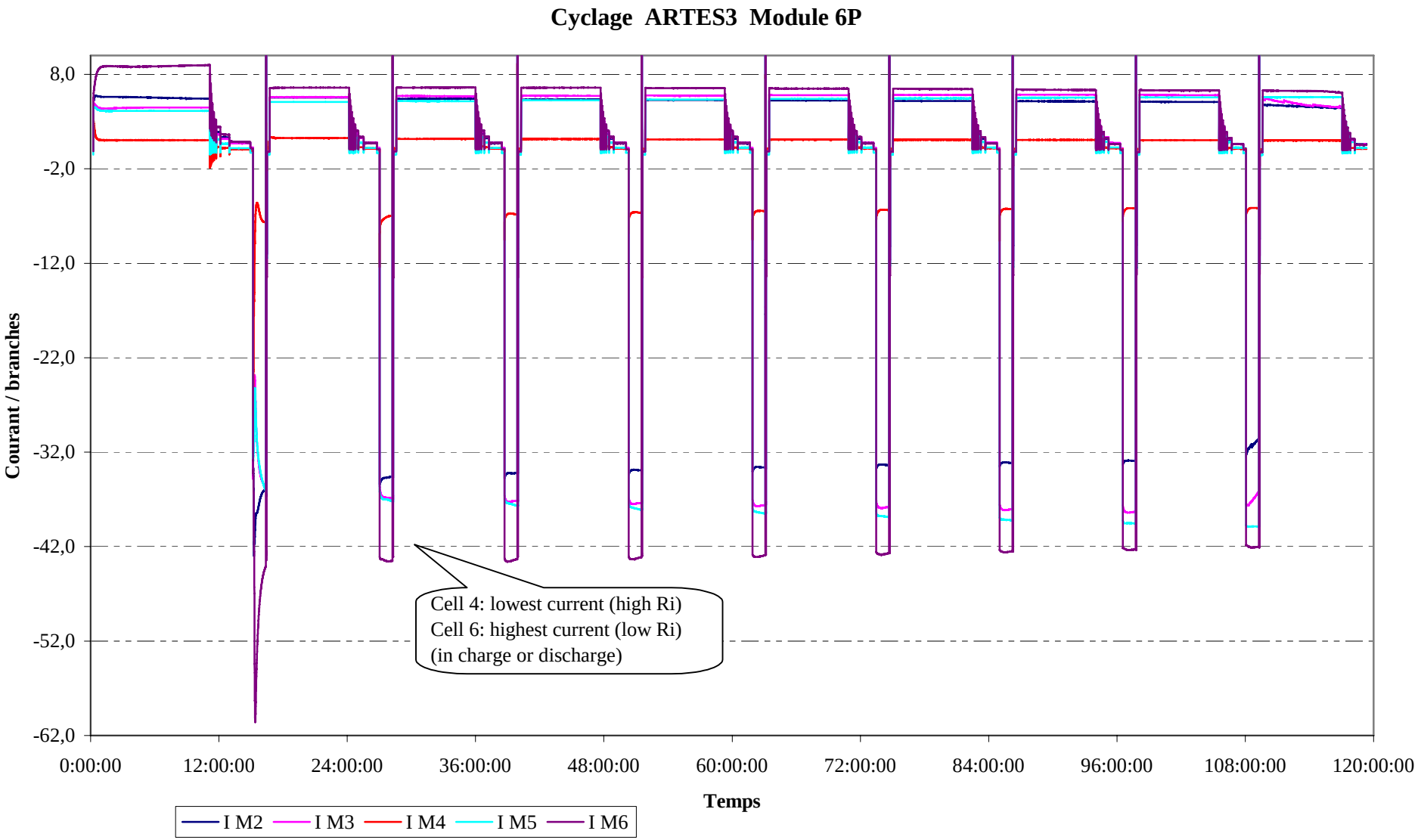
Model predictions



6P Module: reversal of 5P



6P Module: 5P Current distribution after short



CONCLUSION 1

- **Reversal Li-ion cell results in creating a stable, low resistance short circuit**
- **The cell short-circuit mechanism has been analyzed :**
  - Internal impedance varies with current
  - Thermal impact during short formation
  - All failure cases tested :open circuit at end of discharge, short circuit, leak current, structure leak…
  - Current dispersion within module.
- **Tests done validate the model.**
- **Additive tests to be done to take into account specific failure cases**

CONCLUSION 2

- **Thanks to the parallel mounting, even in case of cell open circuit and short-circuit, the <u>power supply is always on</u> (Vbat always higher than the requirements) without the recourse to by-pass.**

- **Eliminating the by-pass :**
  - increases battery reliability : cell reliability is higher than the by-pass one
  - saves weight even additive wiring impact due to current spread
  - saves cost
  - may induce battery thermal and management changes

Acknowledgements

- **Thanks to ESA for supporting this study in the frame of ARTES 3 Program**

END

Photos D.R.