Use of Electrical/Thermal Cell Model for Mars Express Battery Health Assessment

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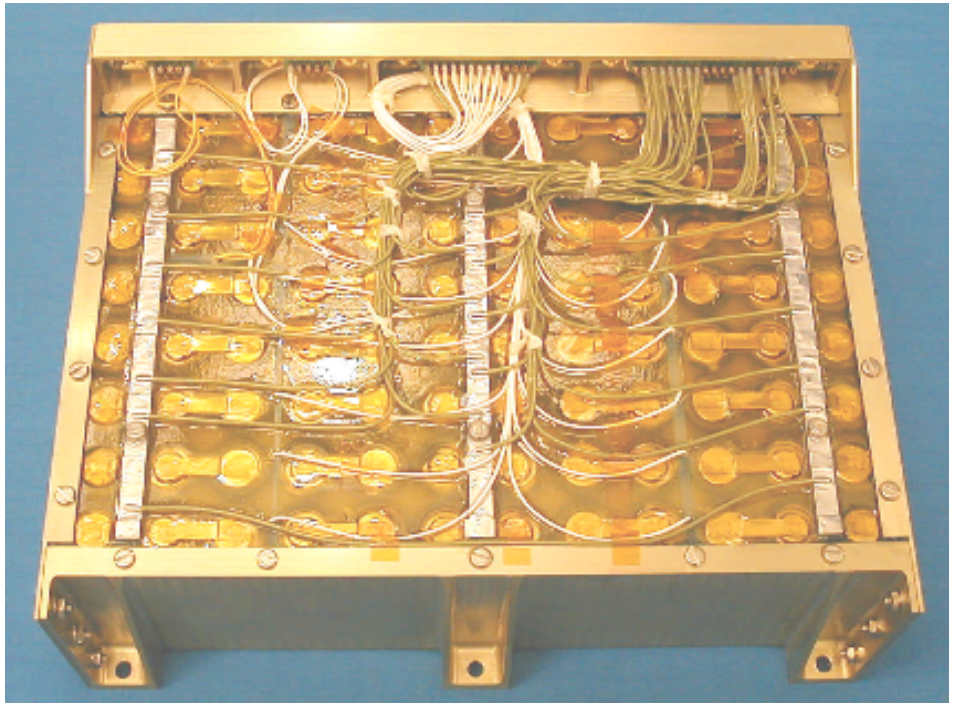
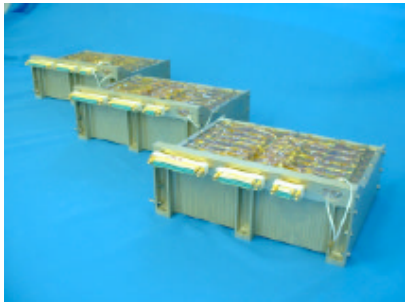
Overview

- *Part 1: Mars Express battery design and ground life tests*
- *Part 2: Adapting BOL Electrical/Thermal model to aged cells*
- *Part 3: Application of model to ground test*
- *Part 4: Application to Mars Express Flight Data*

Mars Express Batteries

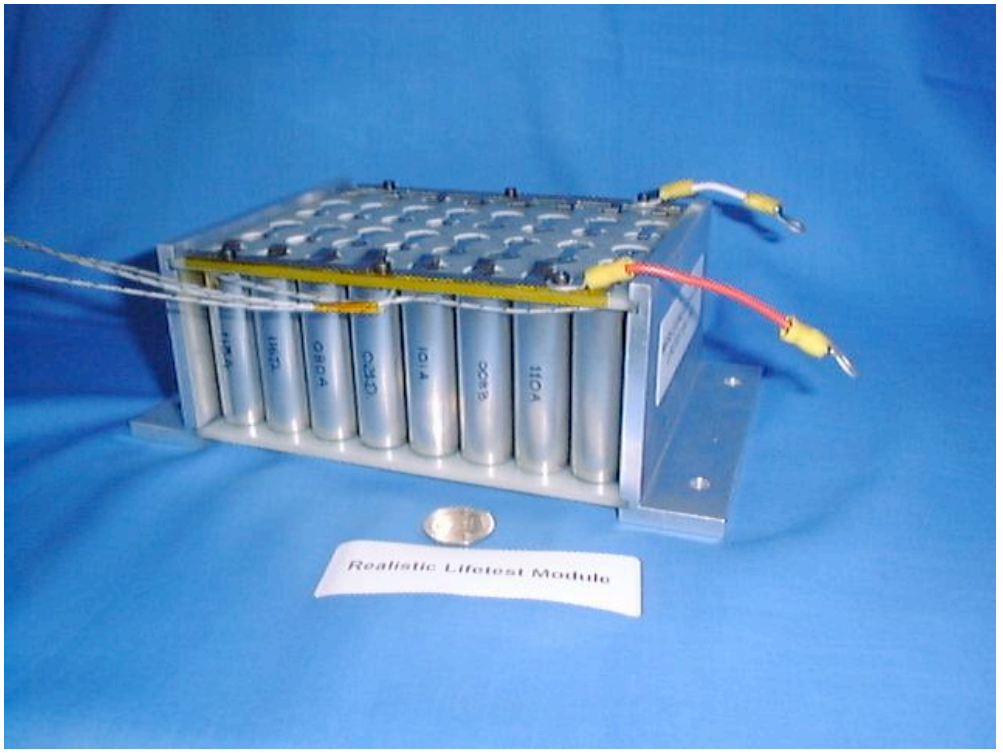




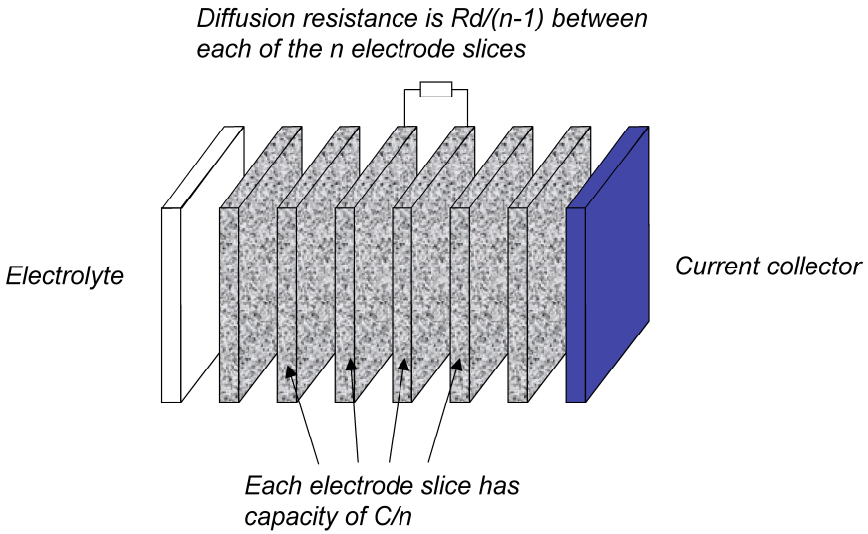
- *The spacecraft has 3 518 Wh 6s16p batteries made by ABSL using Sony 18650HC cells*
- *Each has mass of 4.7 kg (specific energy 110 Wh/kg)*
- *Each battery is charged/discharged via a separate BCDR but BCDRs are controlled to share current equally between batteries*

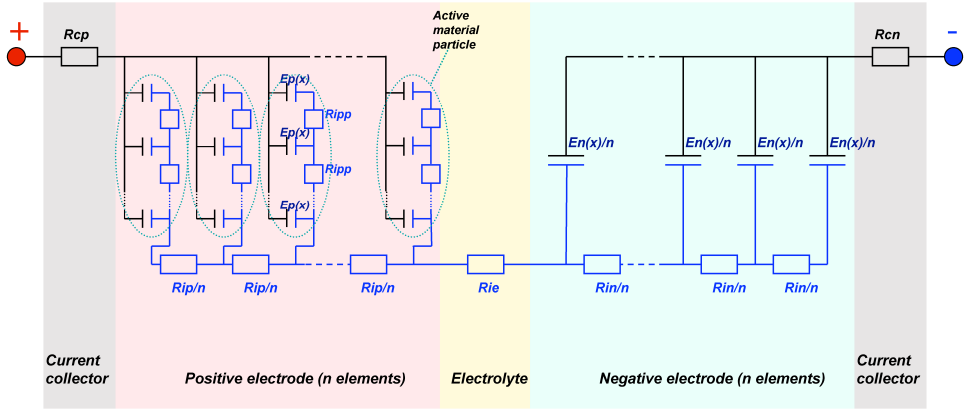
MEX Real-time Life-test at ABSL - hardware

- *Test Milestones:*
  - *Test start : 5-Dec-99*
  - *1st Martian Year End: 3-Jan-02*
  - *2nd Martian Year End: 14-Nov-05*
- *Test item:*
  - *12Ah test module, 6s-8p*
  - *Individual cell voltage monitoring*
  - *Same voltage, 1/2 capacity of flight battery*
  - *Same batch of cells as flight battery*
  - *Same flight standard screening and matching (capacity, impedance)*
- *Test temperature:*
  - *20 deg C (max I/F temp)*



Part 2: ESTEC BOL Cell Model





- *Model predicts voltage and heat dissipation of a lithium ion cell under any given current/power/temperature profile.*
- *Model parameters are measurable experimentally (all except individual electrode EMF on sealed cells)*
- *The model takes into account:*
  - *Electrode EMF versus state of charge*
  - *Thermoneutral potential*
  - *Internal resistance*
  - *Diffusion resistance*
  - *EMF Hysteresis*

Details in "Electrical/Thermal Model Of a Sony 18650HC Li-Ion Cell", G. J. Dudley, J. De Roche, F. Tonicello, C. Thwaite, ESPC Stresa, Italy May 2005

ESTEC Model Parameters

BOL Model is based on following information, implemented as look-up tables:

1) *Positive electrode EMF as function of state of charge*
2) *Negative electrode EMF as function of state of charge*
3) *Thermoneutral potential as function of state of charge*
4) *EMF hysteresis as function of state of charge (temperature-independent)*
5) *Hysteresis Ah "time-constant" as function of state of charge (temperature-independent)*
6) *Ionic-electronic resistance as function of temperature (SOC-independent)*
7) *Diffusion resistance as function of temperature (SOC-independent)*

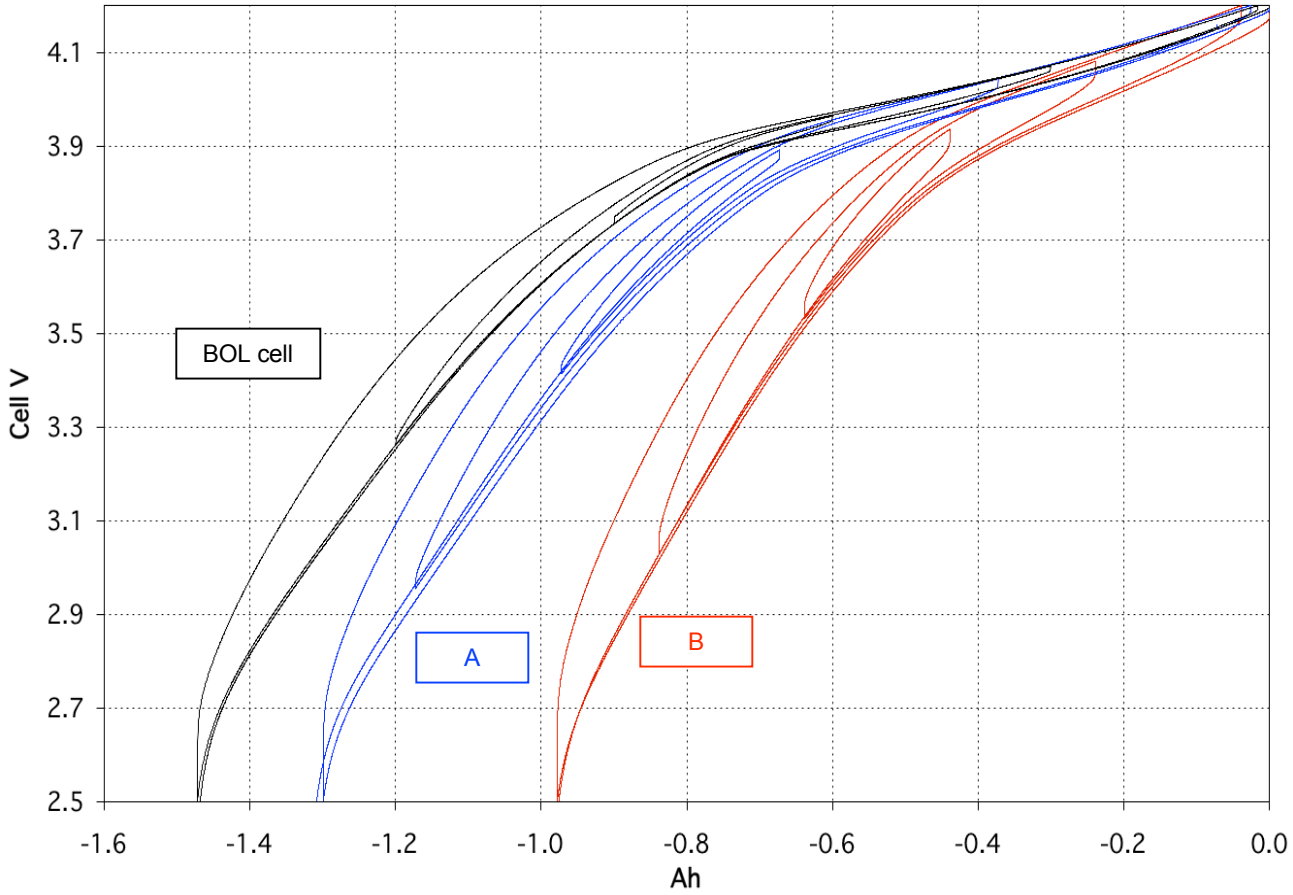
Note: Self-discharge rate can be neglected

Model parameters for aged cells

- *Can the BOL model be used for cycled/aged cells?*
- *We know that:*
  - *Available cell capacity reduces*
  - *Internal resistance increases*
  - *Diffusion resistance increases (e.g. slower voltage relaxation after current switch-off)*
- *But are there new effects that have to be taken into account?*

- *To try to answer this question, one aged cell, denoted A, and one very aged cell, denoted B, have been characterised in detail at 20 deg.C:*
  - *C/50 to C/5 constant current cycles*
  - *Step-discharge and step-charge cycles*
  - *Temperature - dependence not yet investigated*

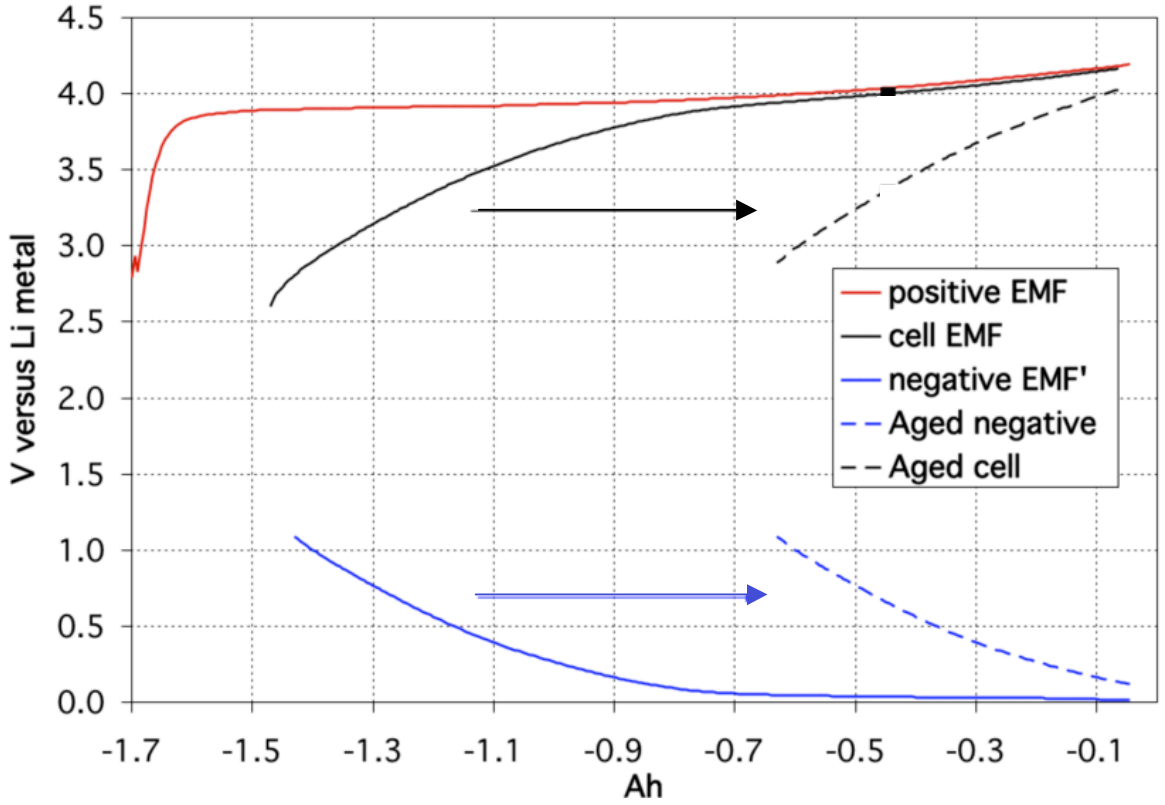
Aged cells versus BOL cells - C/50 cycles



Comparison of C/50 cycles of aged cells with BOL cell

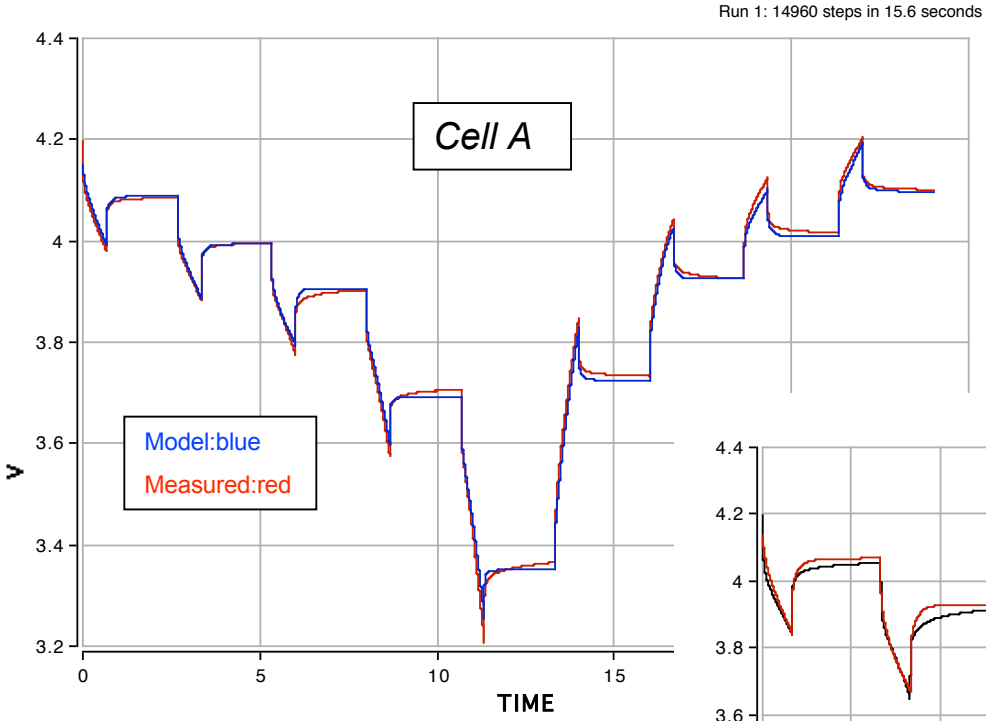
- *C/50 cycles to determine:*
  - *Electrode capacities*
  - *Hysteresis parameters*
- *Conclusions:*
  - *Capacity loss*
  - *Hysteresis not much changed*
  - *Shorter high SOC 'shoulder' suggests **negative electrode SOC loss**, especially for cell B.*

Electrode relative SOC changes with ageing

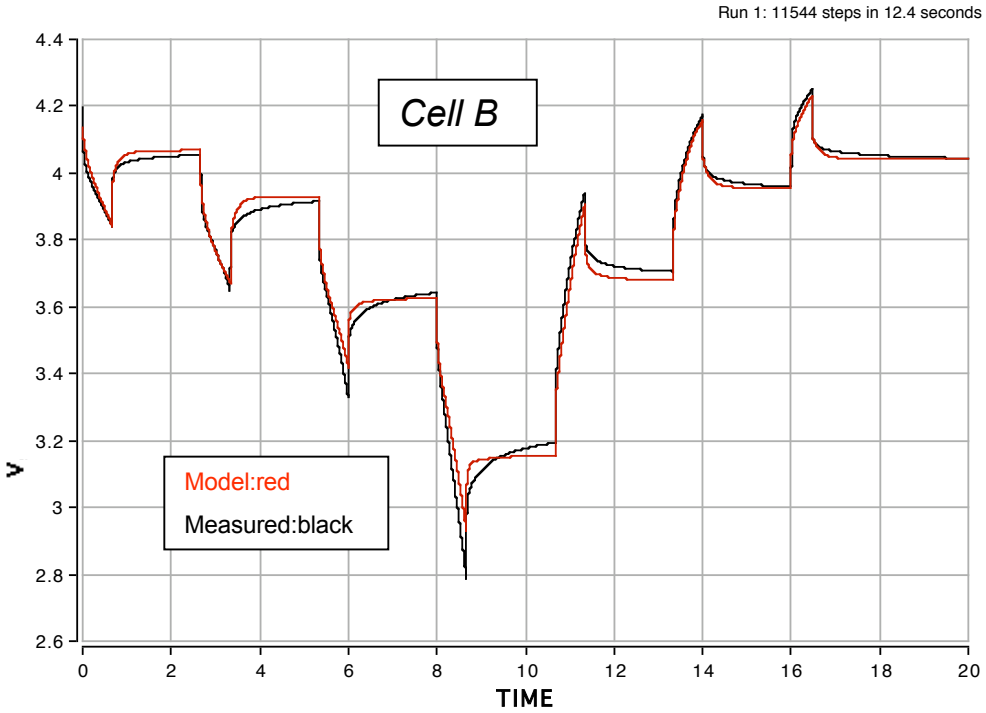


- *During cycling, the negative electrode continues to react with the electrolyte increasing thickness of the SEI.*
- *This increases the internal resistance*
- *It must also result in the negative electrode continuing to loose SOC compared to the positive*

Aged cells - step-cycles



C/5 step cycles to determine internal resistance and diffusion resistance parameter values



Evidence for new slow relaxation process not present in BOL cells

Parameters for aged and BOL cells

- *Found that these cells can be modeled with reasonable fidelity (not quite as good as BOL cells) without changing any of the look-up table data*
- *Only necessary to specify the parameters in red in the table below, relative to the value for a BOL cell:*

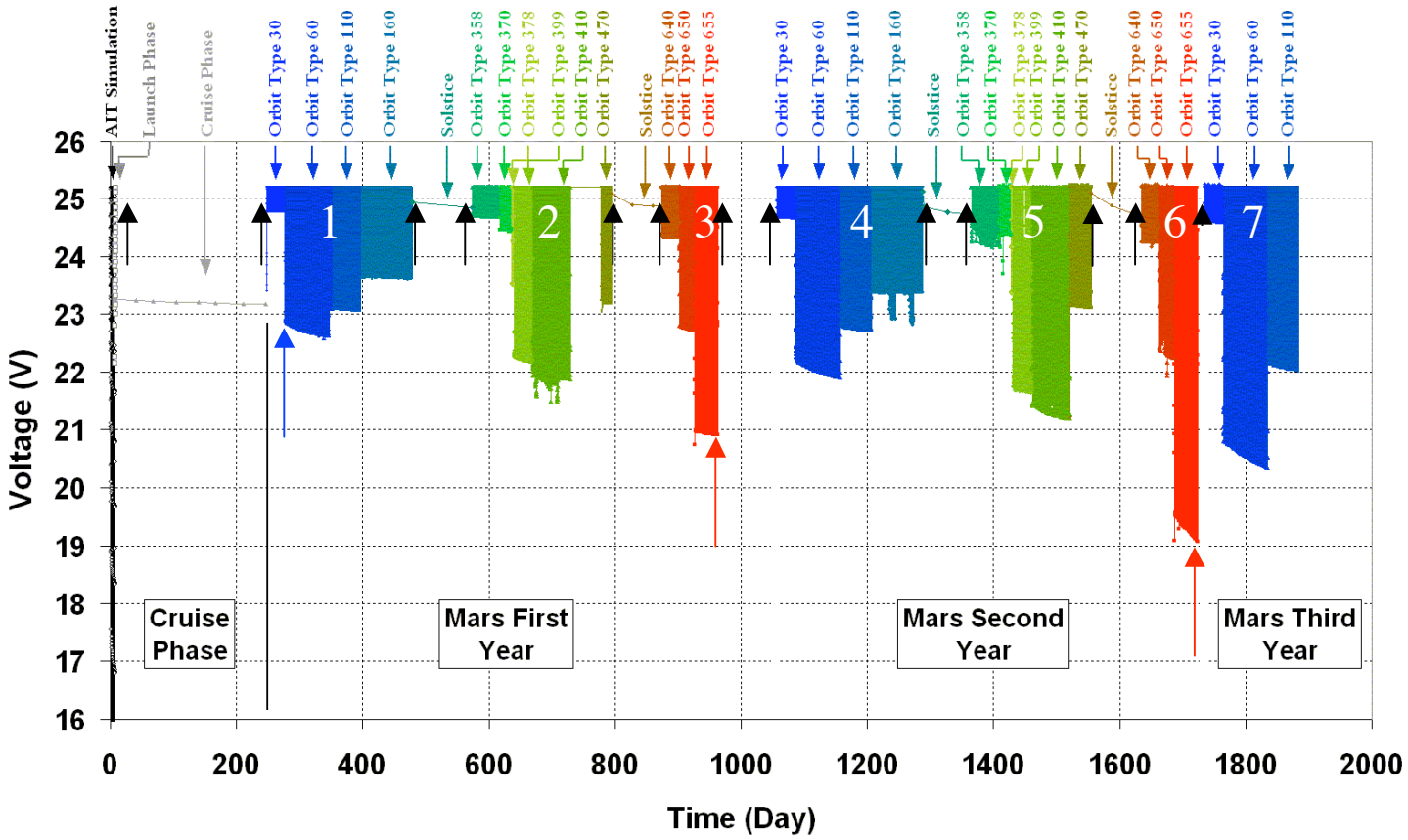
Parameter / Cell	BOL cell	Cell A	Cell B
Internal resistance	1	2.0	3.5
Diffusion resistance	1	1.7	5
Positive electrode capacity	1	0.87	0.64
Negative electrode capacity	1	0.93	0.79
Positive - Negative SOC at 4.2 V (Ah)	0	-0.08	-0.20
Hysteresis amplitude	1	1	1.5
Available negative capacity (Ah)	1.47	1.315	0.985

Note: Self-discharge currents of all cells measured during C/50 cycles < 60 µA (test equipment limit)

Parameters for aged cells - conclusions

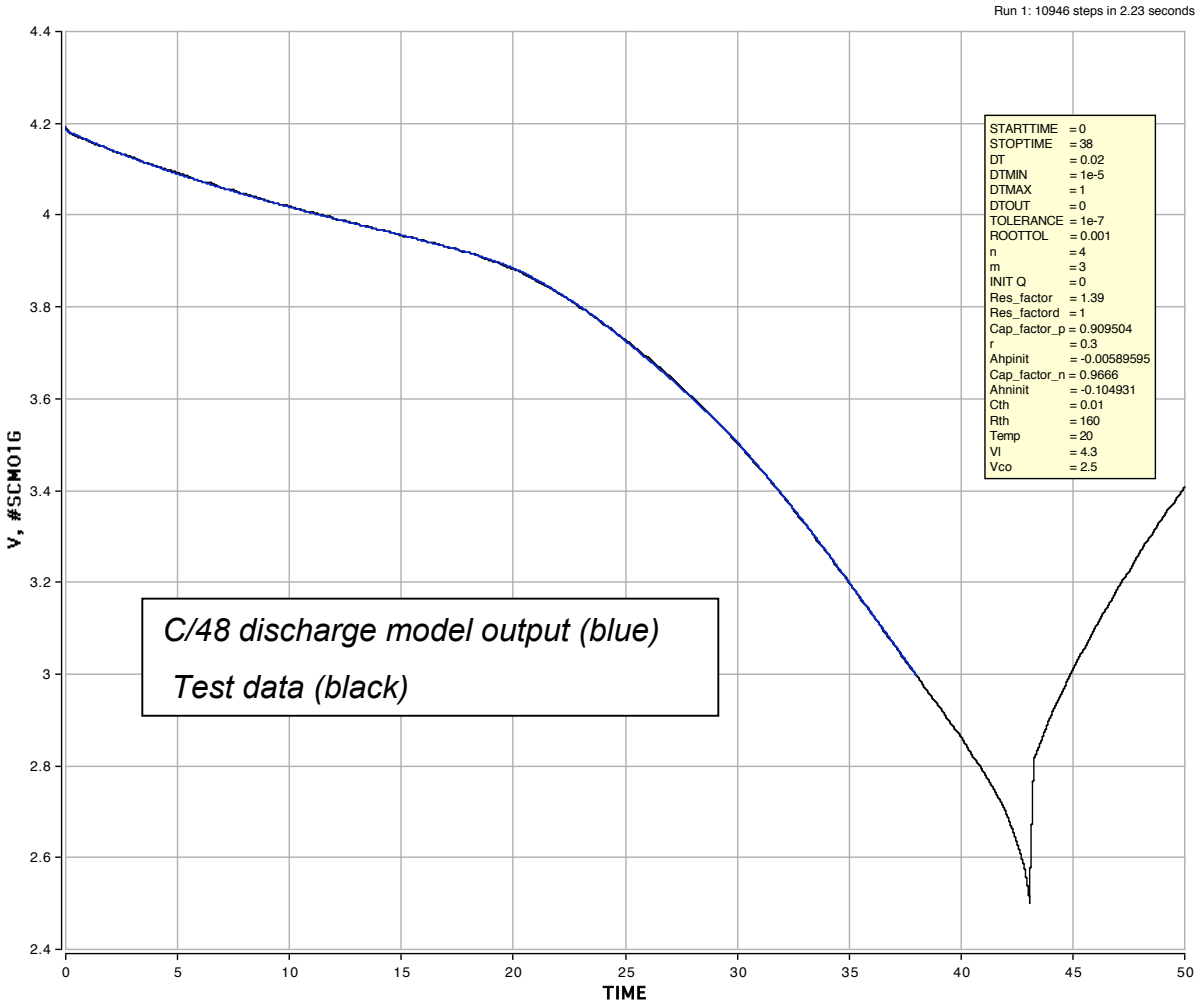
- *With ONLY 5 parameters changed, aged cells can be modeled i.e:*
  - *No change of lookup tables required*
  - *Thermal model appears to remain valid (though not yet thoroughly verified)*
- *Hysteresis change only needed for extremely aged cells*
- *The above seems reasonable for ageing due to mechanical effects (e.g. isolation of active material) which would not be expected to influence parameters that are intrinsic properties of the electrode active materials or electrolyte.*
- *The temperature-dependence of resistance parameters may change due to chemical effects (growth of SEI and other layers on positive electrode particles). This has not yet been investigated.*

MEX Real-time Life-test at ABSL - profile



- *C/48 capacity cycles shown with black arrows*
- *Analysed orbit 655 type cycles shown with red arrows; orbit 60 type cycle with blue arrow*

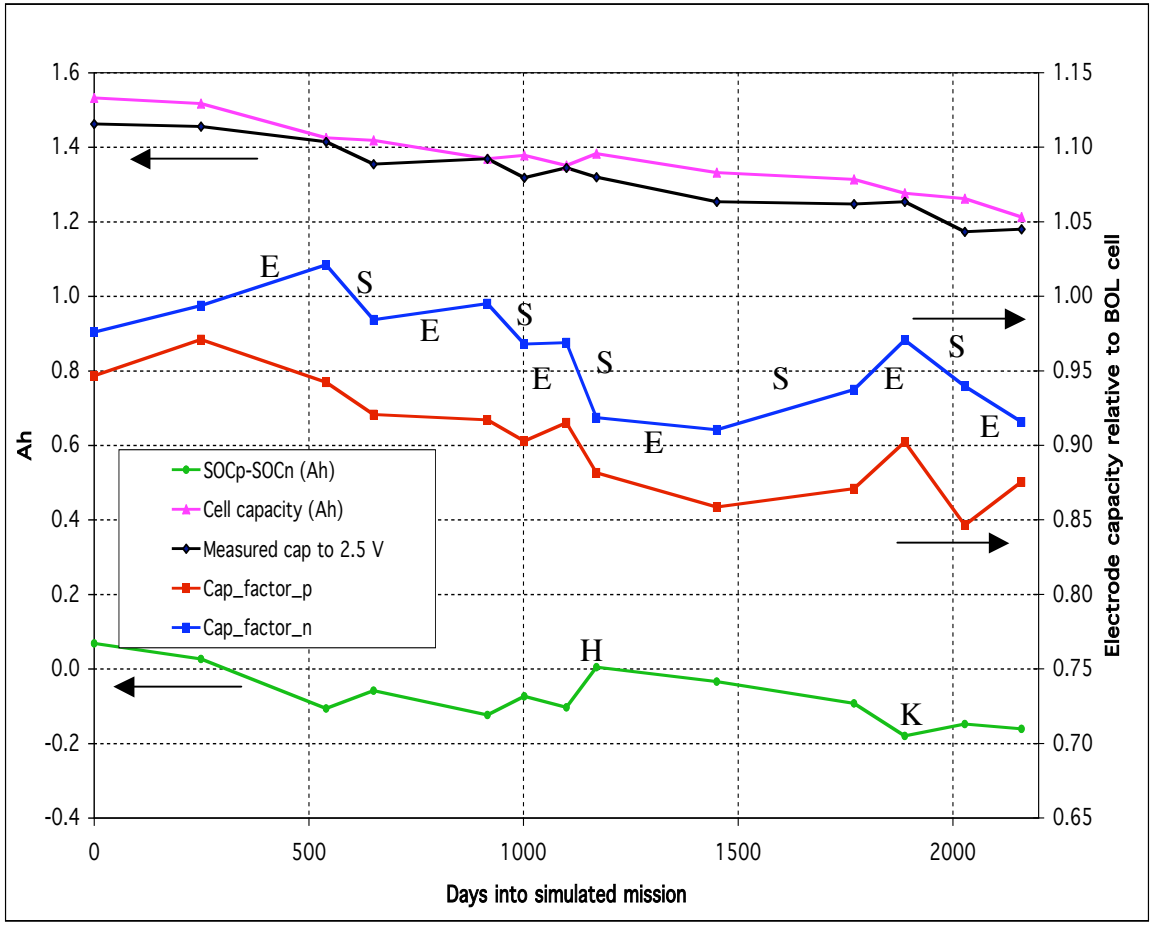
Model fit to MEX life test data - C/48



- *Ran cell model (scaled to battery size) for C/48 discharge*
- *Used multi-parameter curve-fitting procedure* to find values of parameters which give best agreement between battery voltage predicted by model and actual battery voltage data from test for each of the 13 data sets*
- *RMS voltage errors between 1.5 & 3 mV*

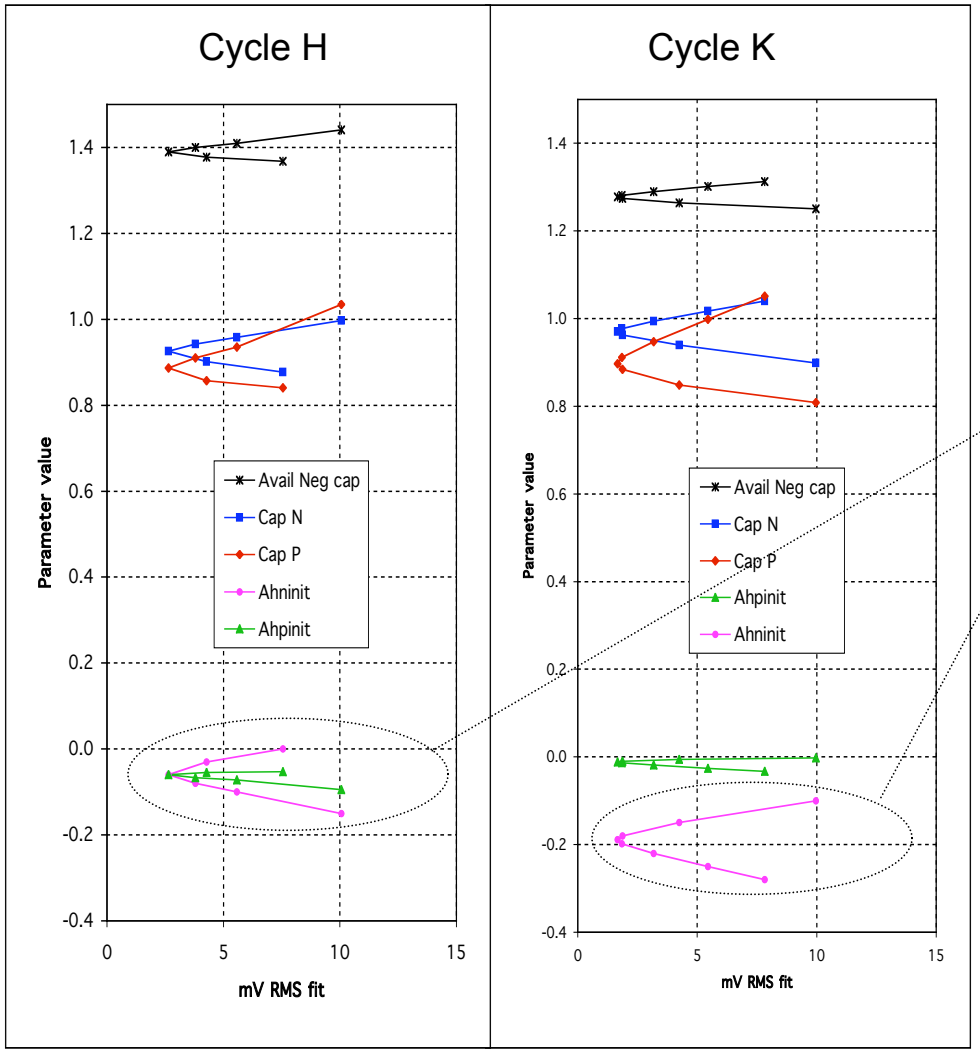
** Using multi-parameter curve-fit function in Berkeley-Madonna software*

Model fit to MEX life test data - C/48



- *Cell is negative electrode -limited*
- *During solstices:*
  - *Apparent decrease in negative electrode capacity almost offset by **increase in state of charge****
- *During eclipse seasons:*
  - *Apparent increase in negative electrode capacity offset by decrease in state of charge*
- *Data for points "H" and "K" are covered in more detail later*
- **Not consistent with SEI growth explanation alone*

C/48 data - sensitivity analysis



- *Are the changes in SOC difference between electrodes in different cycles real or noise?*
- *For cycles "H" and "K" imposed 6 different values of starting negative state of charge (Ahninit) and optimised other parameters for each choice*
- *Results suggest that changes are real*

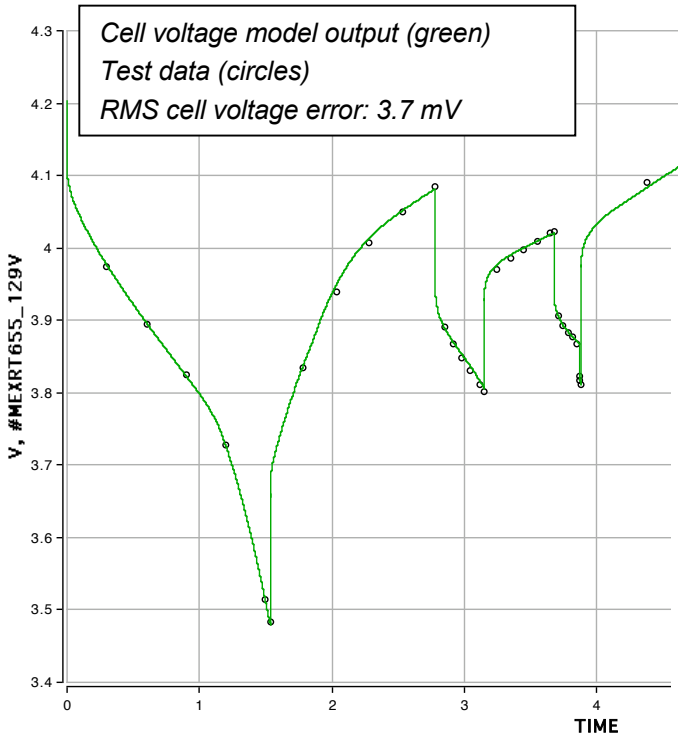
Model fit to MEX life test data - orbit 655

- *Run cell model using orbit (type 655) power profile as input*
- *Empirically select battery thermal R - C parameters in model to give observed temperature variation*
- *Curve-fit parameters for each of the 2 data sets. Results:*

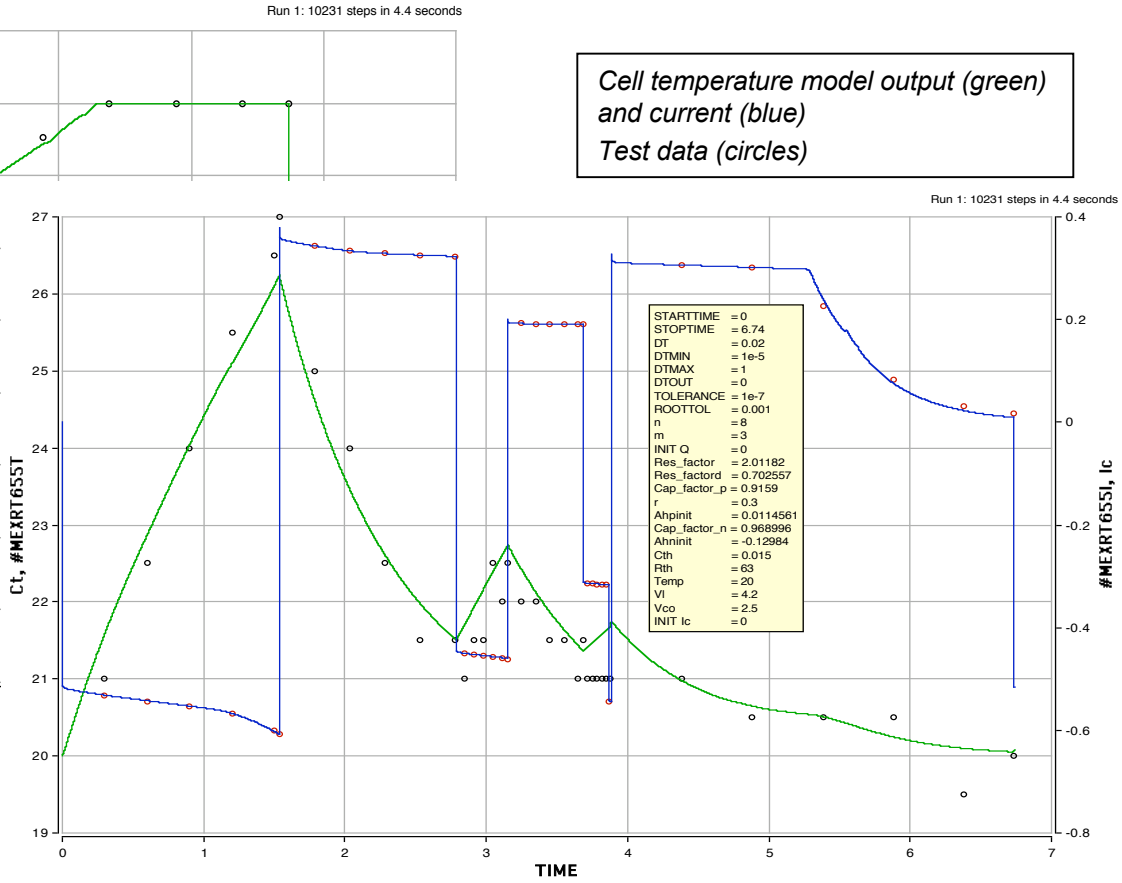
Parameter / Cell	*BOL cell*	*Eclipse cycle type 60 season 3*	*Eclipse cycle type 655 season 3*	*Eclipse cycle type 655 season 6*
Internal resistance	*1*	*1.33*	*2.00*	*2.26*
Diffusion resistance	*1*	*0.61*	*0.71*	*0.82*
Positive electrode capacity	*1*	*0.97*	*0.90*	*0.88*
Negative electrode capacity	*1*	*0.99*	*0.97*	*0.92*
Positive -Negative SOC (Ah)	*0*	*0.07*	*-0.15*	*-0.21*
Available negative capacity (Ah)	*1.47*	*1.46*	*1.30*	*1.16*
Number of cycles	*<50*	*125*	*1811*	*5425*
Hysteresis amplitude	*1*	*1 (assumed)*	*1 (assumed)*	*1 (assumed)*

MEX life test data - orbit 655 eclipse season 3

Cell voltage model output (green)
Test data (circles)
RMS cell voltage error: 3.7 mV



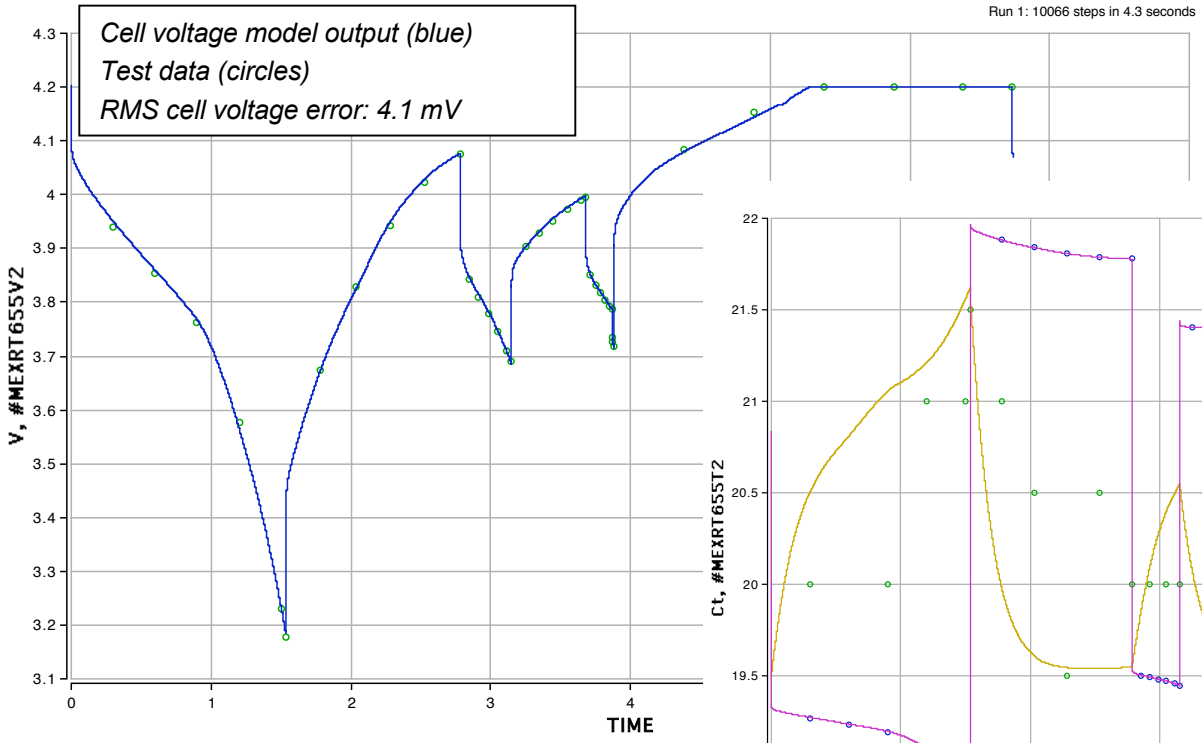
Cell temperature model output (green) and current (blue)
Test data (circles)



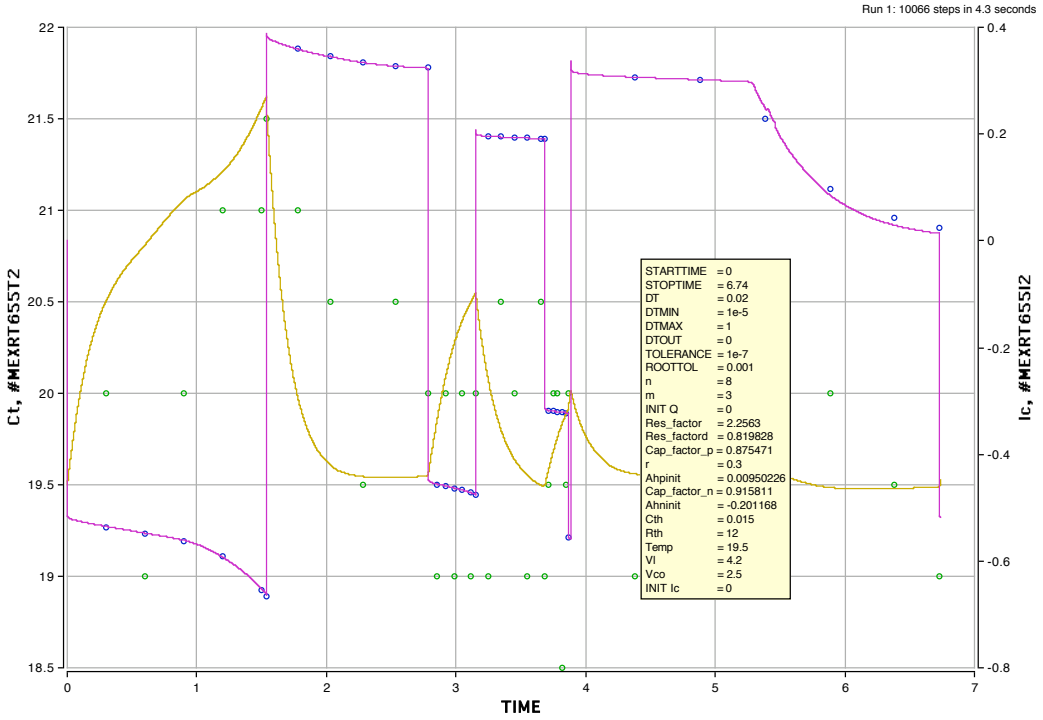
- *56% DoD. Very encouraging fits with model*
- *Temperature data well reproduced (temperature test data has 0.5 deg. C resolution)*
- *Taper-charge current in good agreement with test data*

MEX life test data - orbit 655 eclipse season 6

Cell voltage model output (blue)
Test data (circles)
RMS cell voltage error: 4.1 mV



Cell temperature model output (buff) and current (mauve)
Test data (circles)



- *58% DoD*
- *Again good fit possible with model*

MEX life test data - conclusions

- *From this very limited analysis:*

- *Good news:*
  - *Sets of model parameters have been found that simultaneously give good fit both to eclipse cycle (high-rate) and C/48 discharge data from immediately after the respective eclipse season*
  - *Further evidence that the model can be used for cycled cells*

- *Disappointing news:*
  - *Parameter fit for orbit 665 does not always find best fit nor parameters very close to those expected from C/48 data.*
  - *However, in such cases, imposing electrode capacity data from C/48 fit leads to an improvement in fit.*
  - *There appears to be several combinations of parameters which give nearly as good fits as the best.*
  - *Expected lower internal resistance and higher diffusion resistance - reason for obtained parameters is not clear.*

- *Conclusion: It is not easy to extract correct model parameters from limited DoD cycle data alone*

Part 4: Application of model to flight data

- *Unlike previously used battery technologies, reconditioning is not required with Li-Ion. Whilst this is an advantage it does mean that it is usually not possible to determine capacity of on-board Li-Ion batteries*

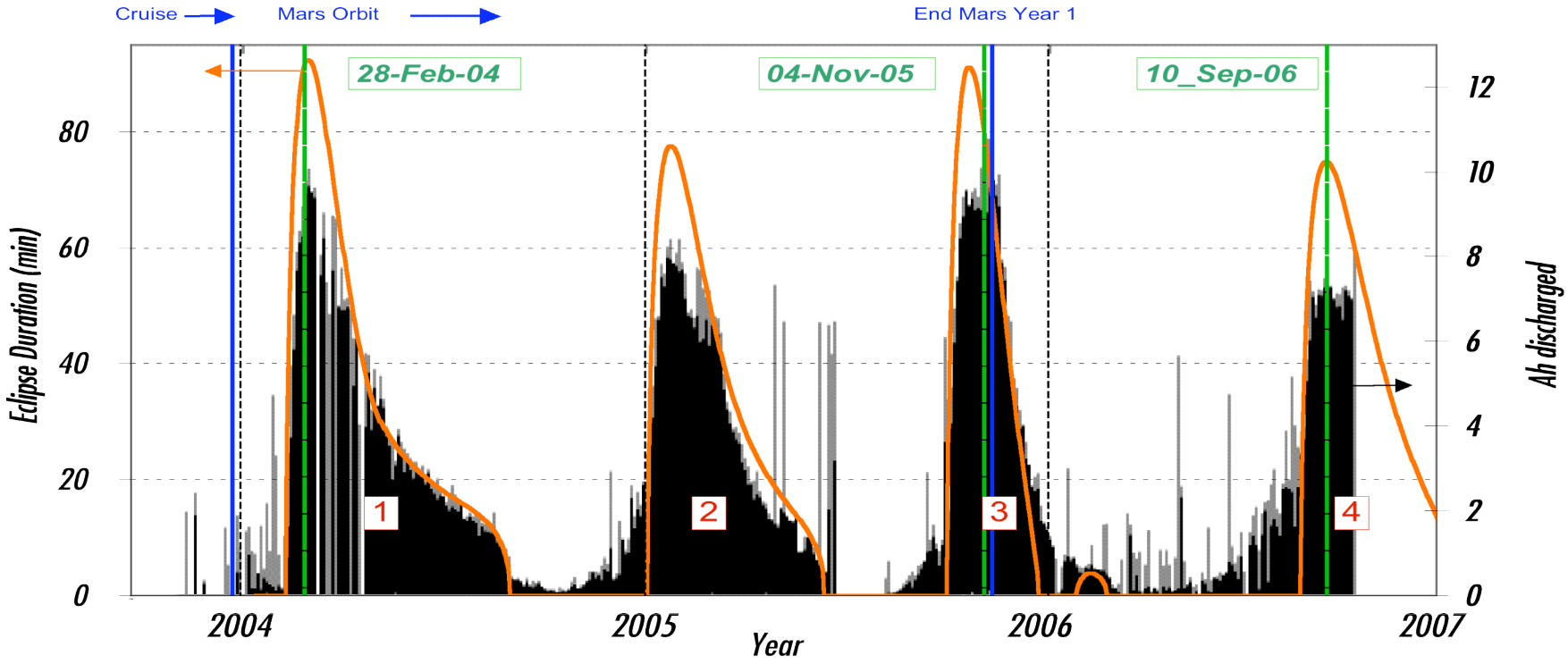
- *All that is available is telemetry data of battery voltage, current and temperature under highly variable load / charge rate.*

- *Problem is how to determine battery health?*

Application of model to flight data

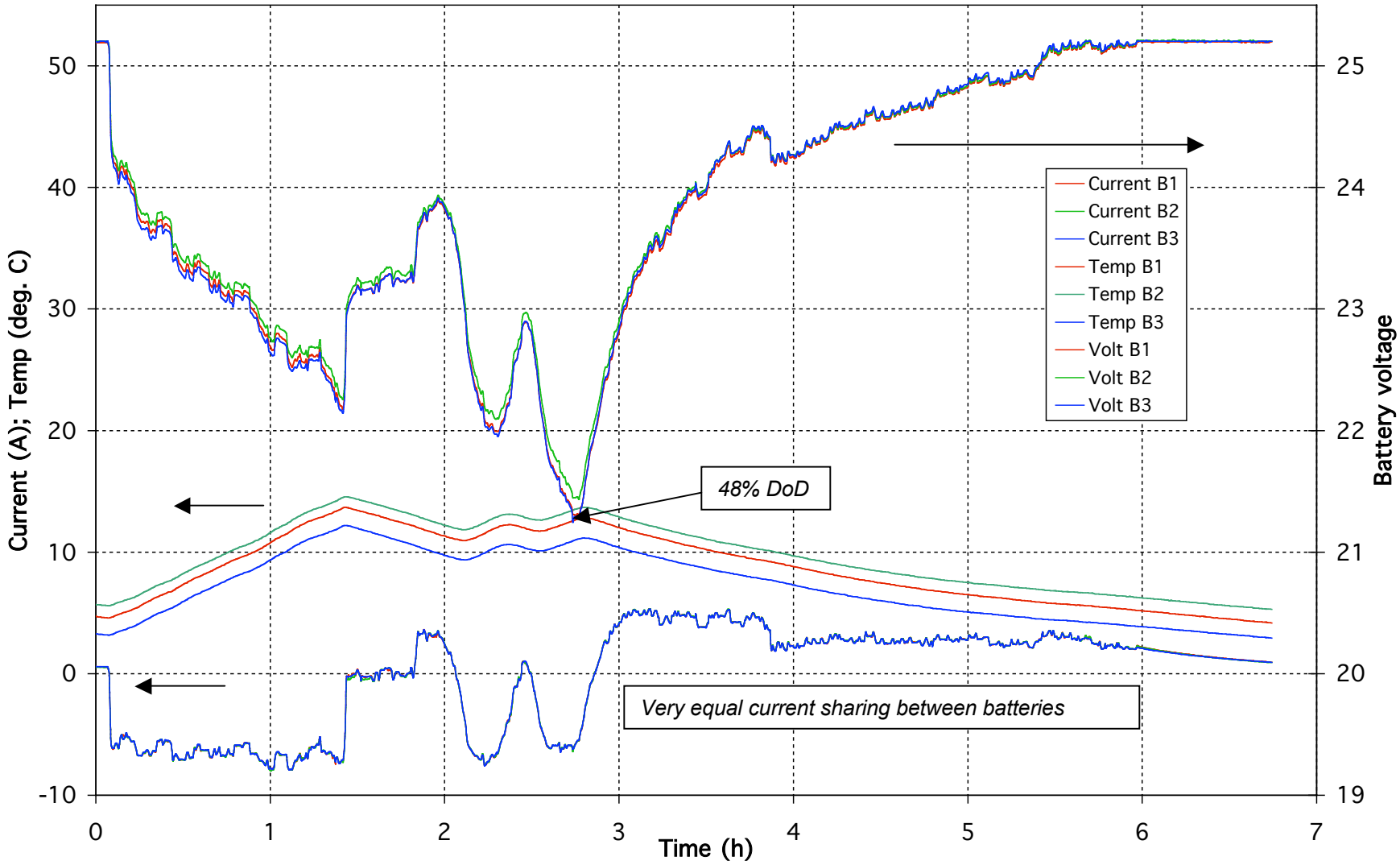
- *Approach tried with Mars Express similar to that used with test data:*
- *Run cell model (scaled to battery size) using current and temperature telemetry as input*
- *Use curve-fitting procedure to find values of parameters which give best agreement between battery voltage predicted by model and actual battery voltage telemetry*
- *Resulting values*
  - *Can be used to run model under any given current/power/temperature profile for short-term mission planning*
  - *Ideally should give some insight into (average) cell health*

Mars Express Eclipse Profile and Battery Usage

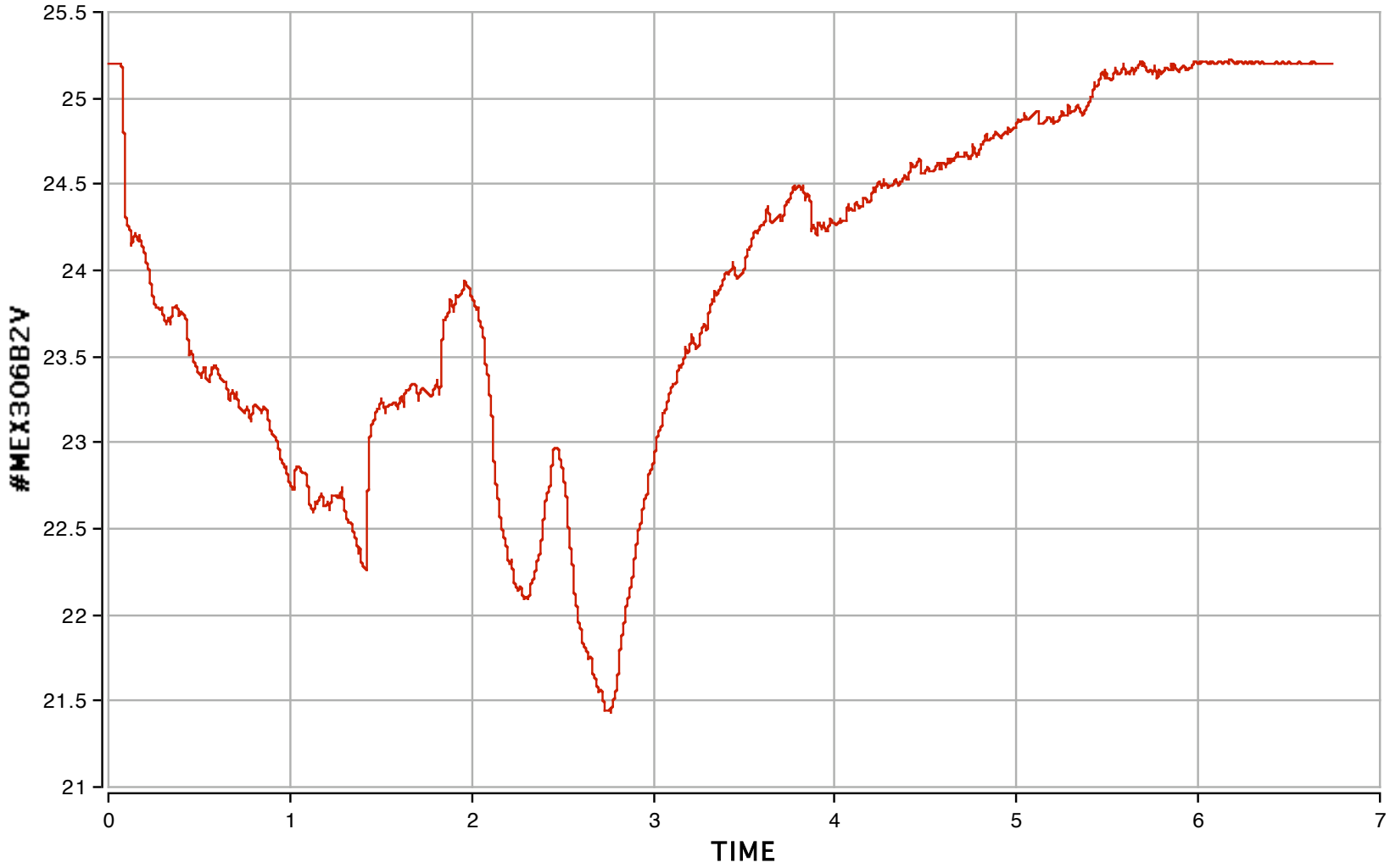


- *Launched June 2 2003. Mars orbit Dec 25 2003. Polar elliptical, period 6.7 h*
- *Martian year 687 Earth-days with 2 eclipse seasons*
- *Differences compared to ground test profile:*
  - *Batteries mostly charged during cruise phase*
  - *Eclipse profile different but representative (due to launch delay)*
  - *Batteries used also during solstice periods*
  - *Temperatures lower (-5 to +15 deg. C compared to 20 to 27)*

MEX eclipse season 3 (Sept 2005)

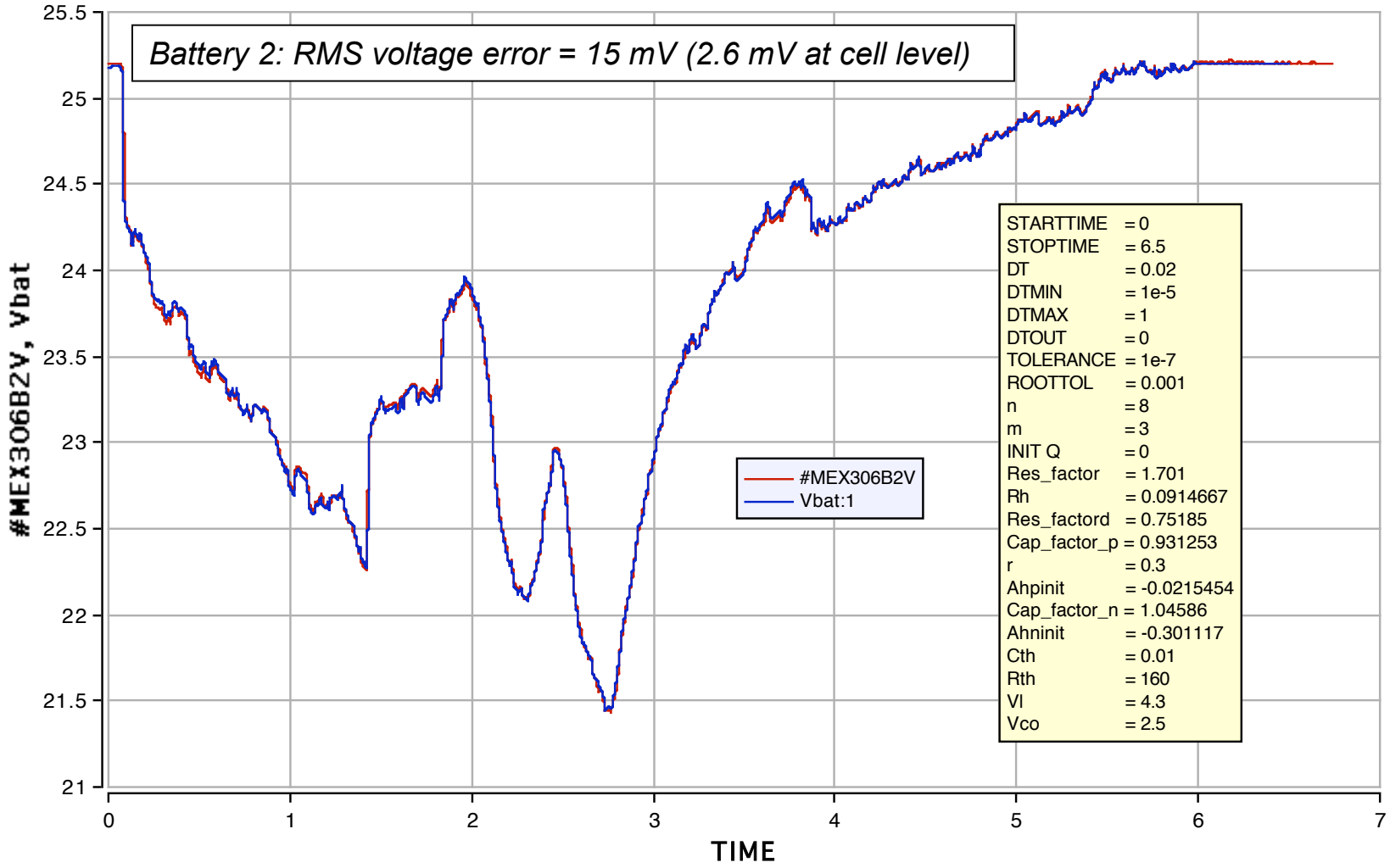


MEX eclipse season 3 (Sept 2005)



MEX eclipse season 3 (Sept 2005)

Run 1: 6334 steps in 2.62 seconds



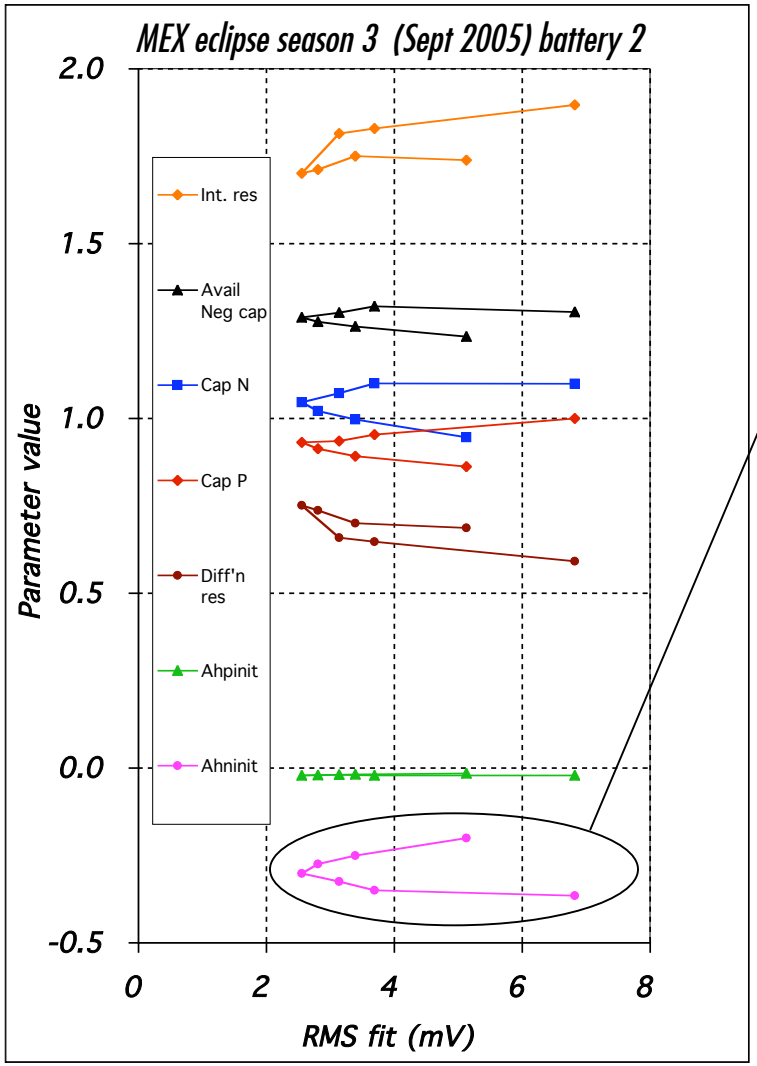
MEX eclipse season 3 telemetry analysis results

Parameter / Cell	BOL cell	Ground test (Eclipse cycle 655 season 3)	MEX Flight battery 1 season 3	MEX Flight battery 2 season 3	MEX Flight battery 3 season 3
Internal resistance	1	2.00	1.77 *	1.70 *	1.81 *
Diffusion resistance	1	0.71	0.74	0.75	0.72
Positive electrode capacity	1	0.90	0.93	0.93	0.94
Negative electrode capacity	1	0.97	1.04	1.05	1.04
Positive -Negative SOC (Ah)	0	-0.15	-0.28	-0.28	-0.28
Available negative capacity (Ah)	1.47	1.30	1.28	1.29	1.28
Model Voltage fit (Cell RMS mV)		3.7	2.7	2.6	3.7
Number of cycles	<50	1811	~ 2300	~ 2300	~ 2300
Average DoD (%)		28	~10	~10	~10

- *Parameters very similar for all 3 flight batteries*
- *As with the ground test internal resistance in high and diffusion resistance is low.*
- *Available negative capacity from model very similar (corresponds to 87% of BOL capacity)*

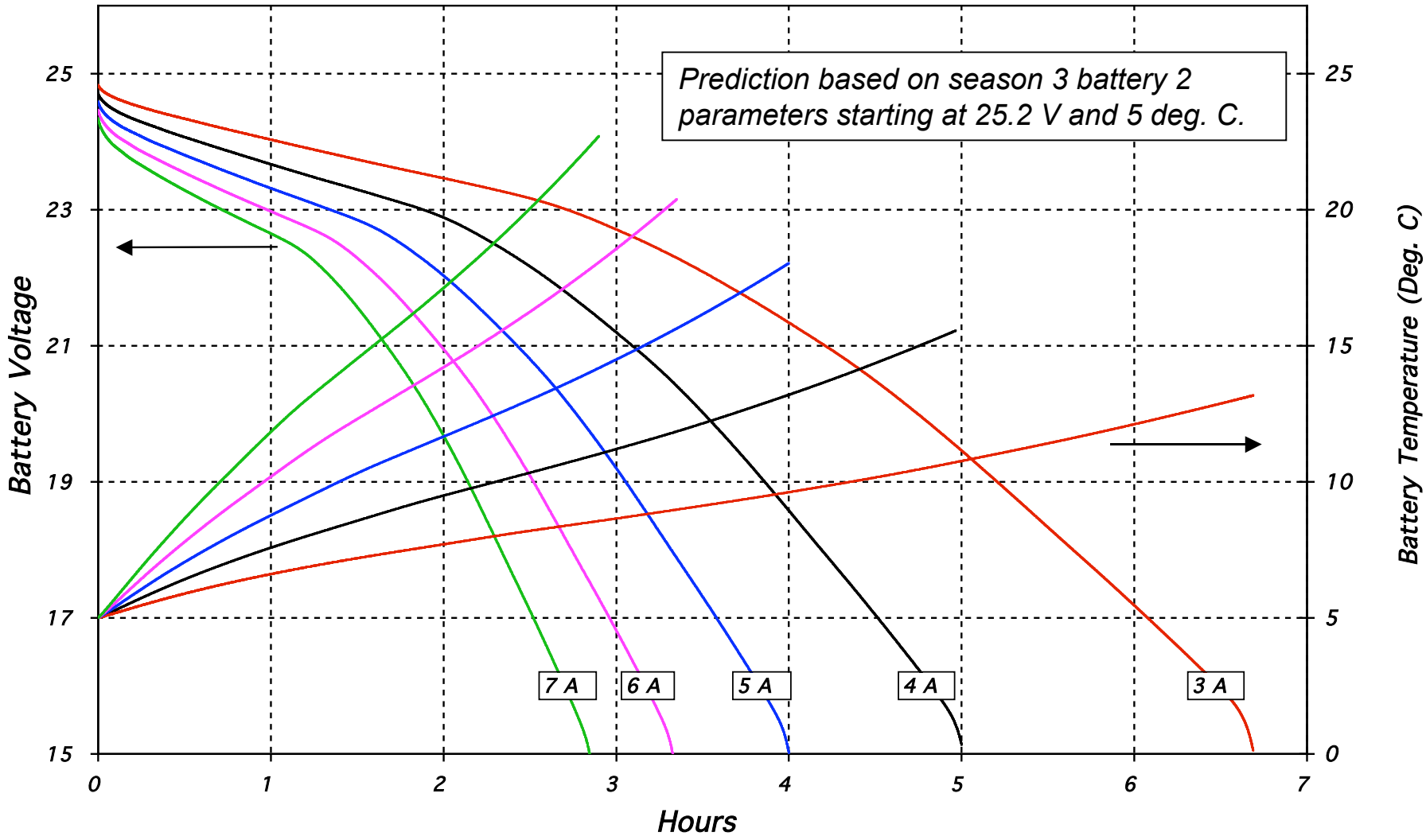
** 34.3 mohm harness resistance between battery and voltage measurement point taken into account*

MEX telemetry data analysis - sensitivity analysis

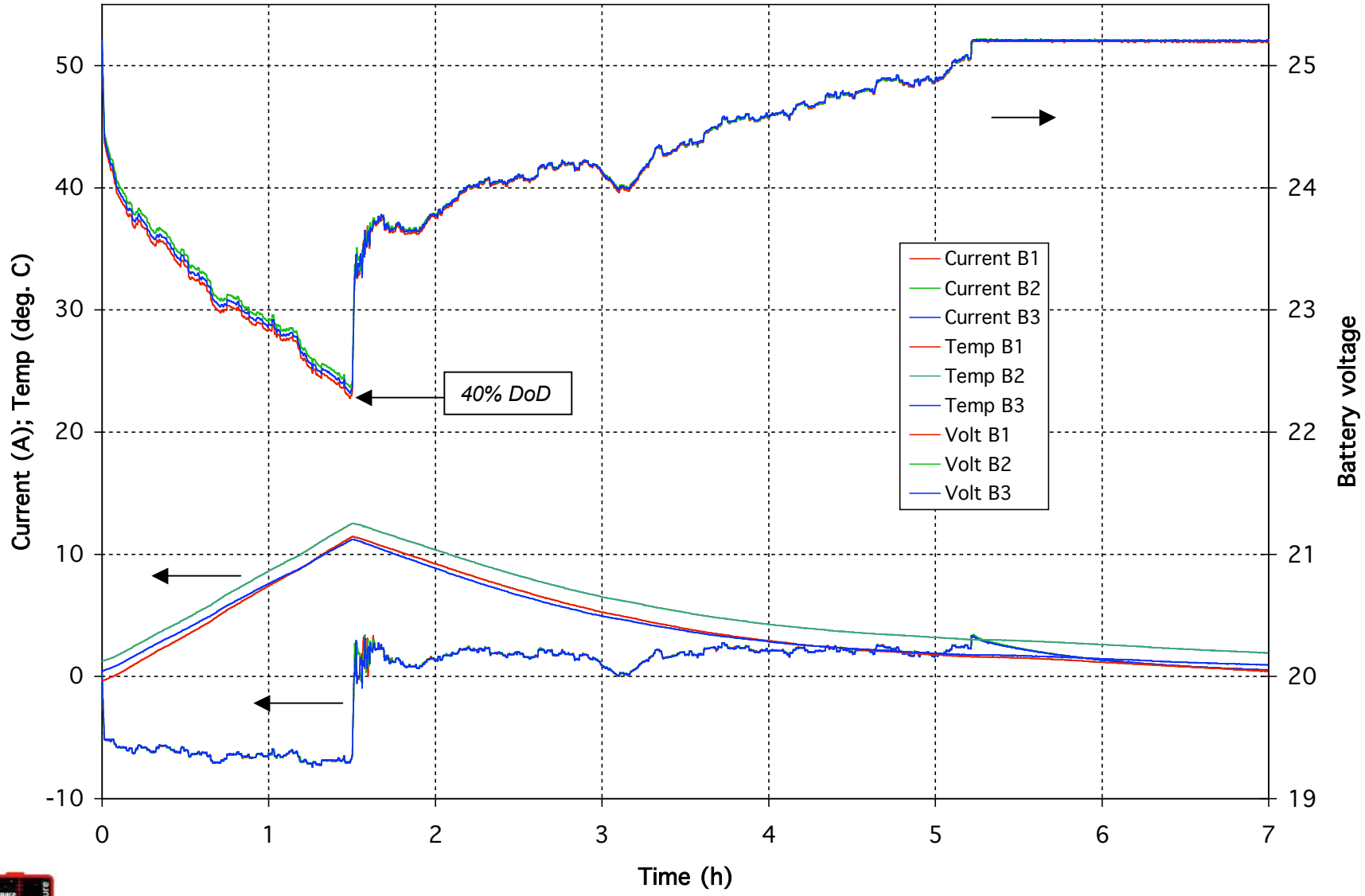


- *Imposed 6 different values of starting negative state of charge (Ahninit) and optimised other parameters for each choice*
- *Shows that parameters for positive electrode are much better defined than those of negative electrode*
- *This is because at high states of charge, cell EMF is mostly determined by positive electrode*
- *Available negative capacity (black) (= Cap N + Ahninit - Ahpinit) represents available cell capacity*
- *Estimate available capacity as 1.29 +/- 0.05 Ah/cell (i.e. 87 +/- 3 % BOL capacity)*

Short-term performance prediction

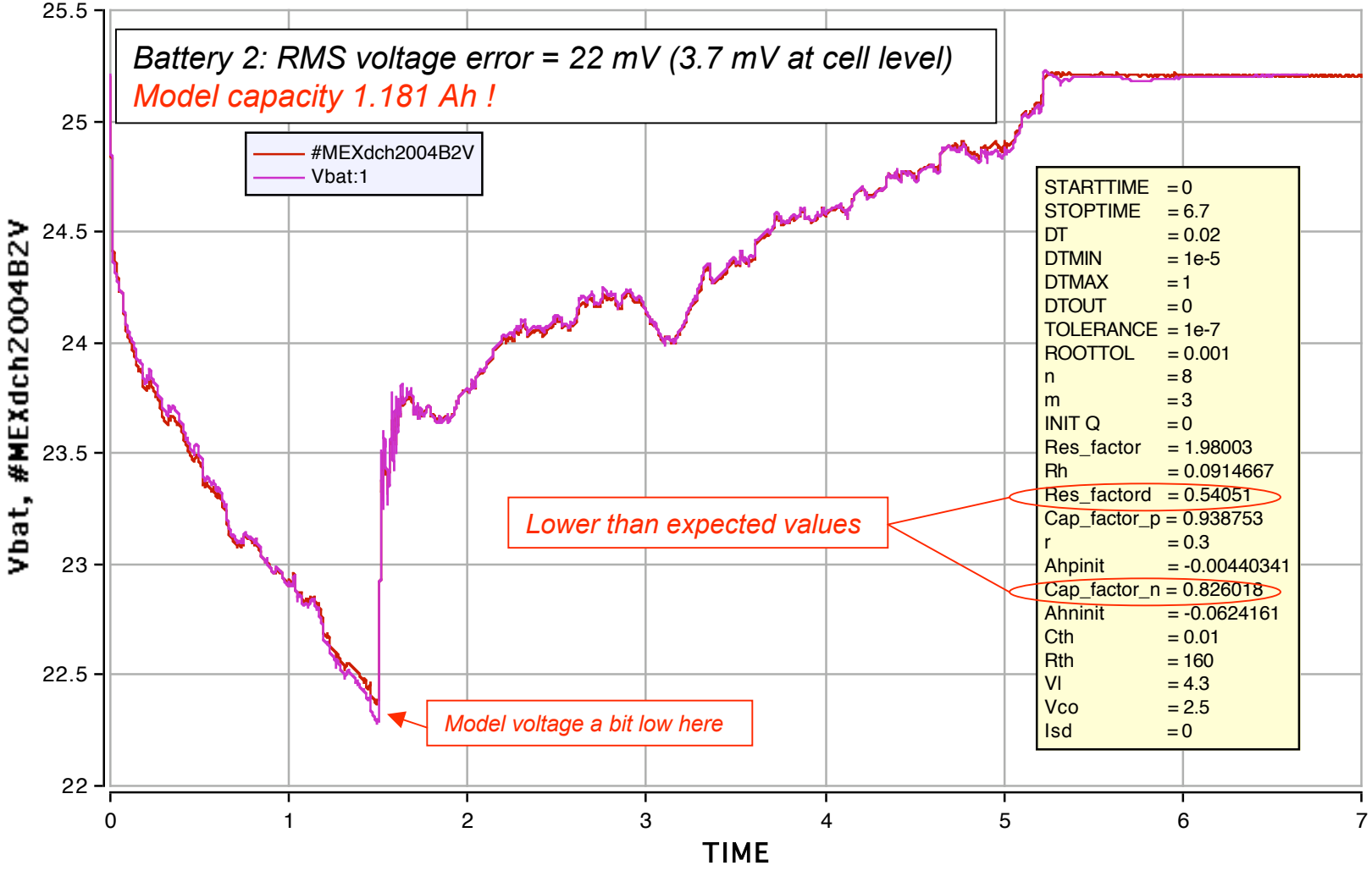


MEX Eclipse season 1 (Feb 2004)



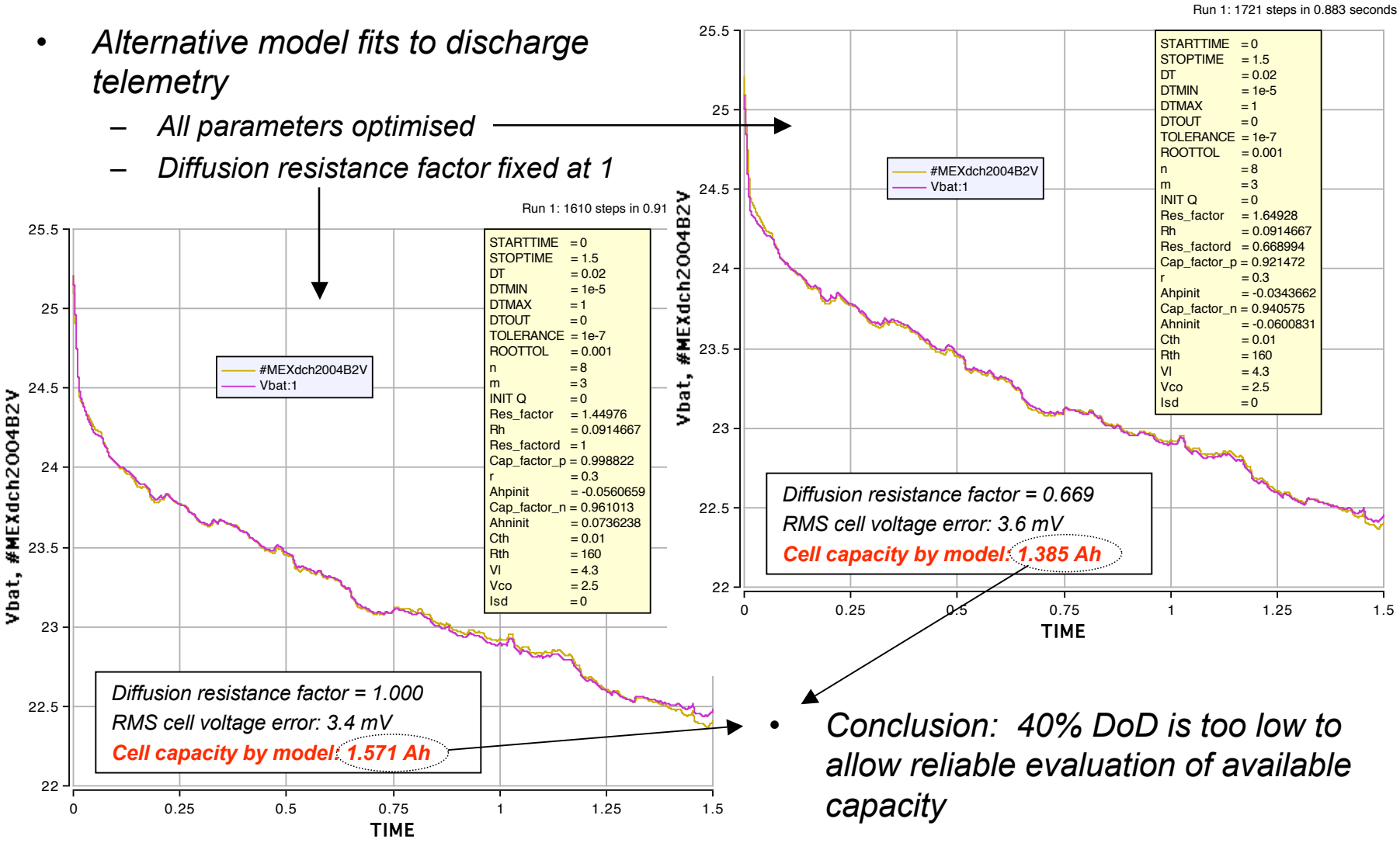
MEX Eclipse season 1 (Feb 2004)

Run 1: 7576 steps in 10.2 seconds



MEX Eclipse season 1 (Feb 2004)

- *Alternative model fits to discharge telemetry*
  - *All parameters optimised*
  - *Diffusion resistance factor fixed at 1*



- *Conclusion: 40% DoD is too low to allow reliable evaluation of available capacity*

Conclusions

- *The ESTEC electrical-thermal model for Sony 18650HC cells can accommodate aged cells by varying the values of 5 parameters.*
- *Despite a good fit to measured data (1.5 to 5 mV RMS at cell level), parameter values for the negative electrode are subject to large uncertainty for shallow cycles (< 45 % at BOL) because of the shape of the negative electrode EMF curve.*
- *Since cells are negative-limited, it follows that battery capacity can only be predicted with confidence from cycles with DOD > 45% at BOL. (decreasing as cells age).*
- *With the above constraint the performance of a flight battery can be predicted under any given current profile with moderate confidence.*
- *The Mars-Express batteries remain well-matched and showing a capacity loss of about 13% after the first Mars year, slightly more than the real time ground test battery.*
- *This is the first attempt at using the model this way and it is hoped to advance its usefulness and as well as understanding of the underlying parameters in the future.*

Acknowledgements

- *Rob Spurrett of ABSL and Michel Denis of ESOC are thanked for support for this paper and supply of the test and telemetry data respectively.*

- *Eric Ecale of Astrium EADS for MEX harness resistance calculation*

- *The ESBTC test lab team for managing the ESTEC tests used to develop the model.*