A First-Principles-Based Dynamic Model for the International Space Station Battery Packs

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Tom Hartley wishes to acknowledge NASA Glenn Research Center for their continued support of battery modeling via NASA Grants NCC 3-820 and NCC 3-998.
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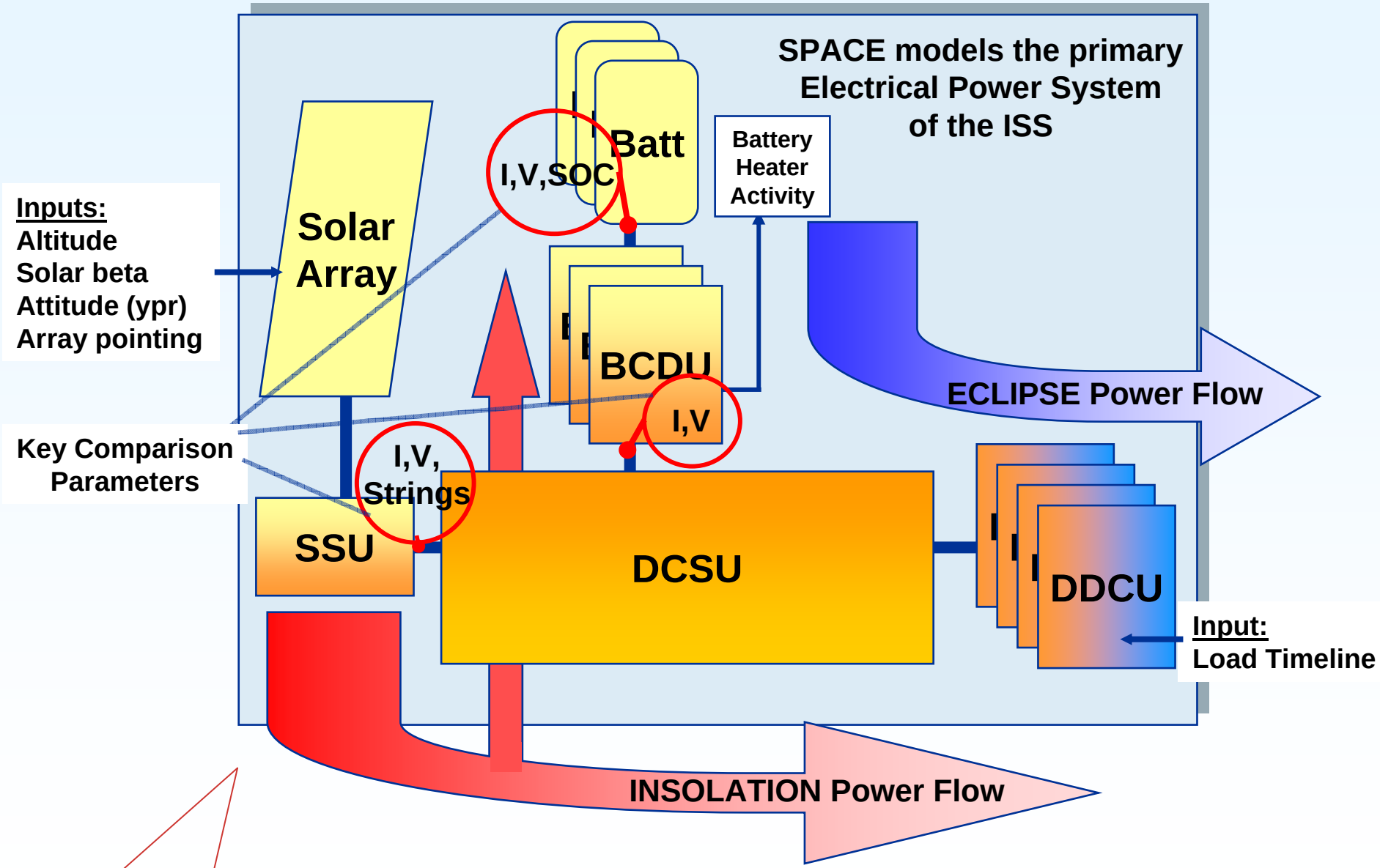
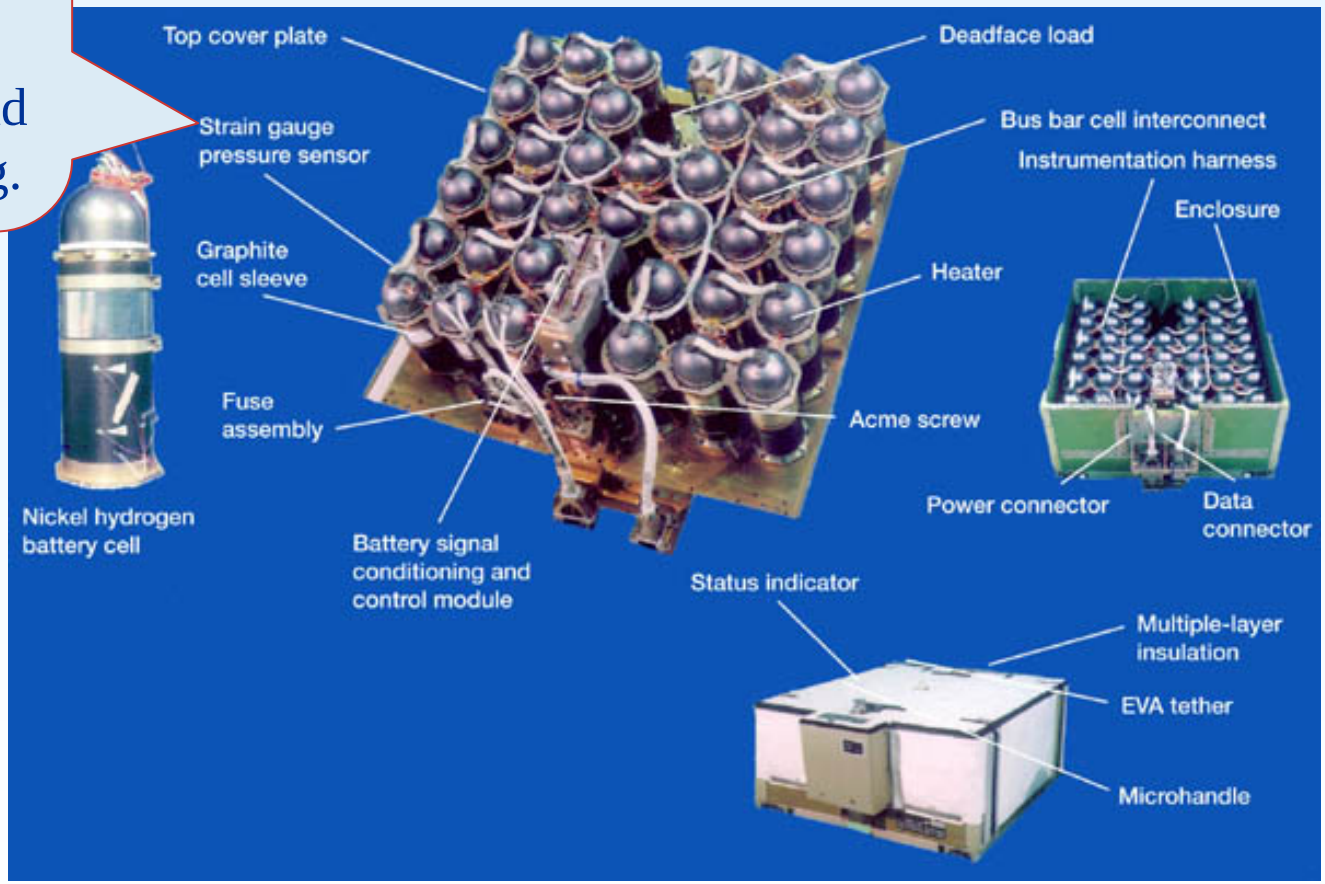
Space Station EPS



ISS ORU

Pressure sensors used to indicate SOC.
Concerns about pressure drift lead to reconditioning.

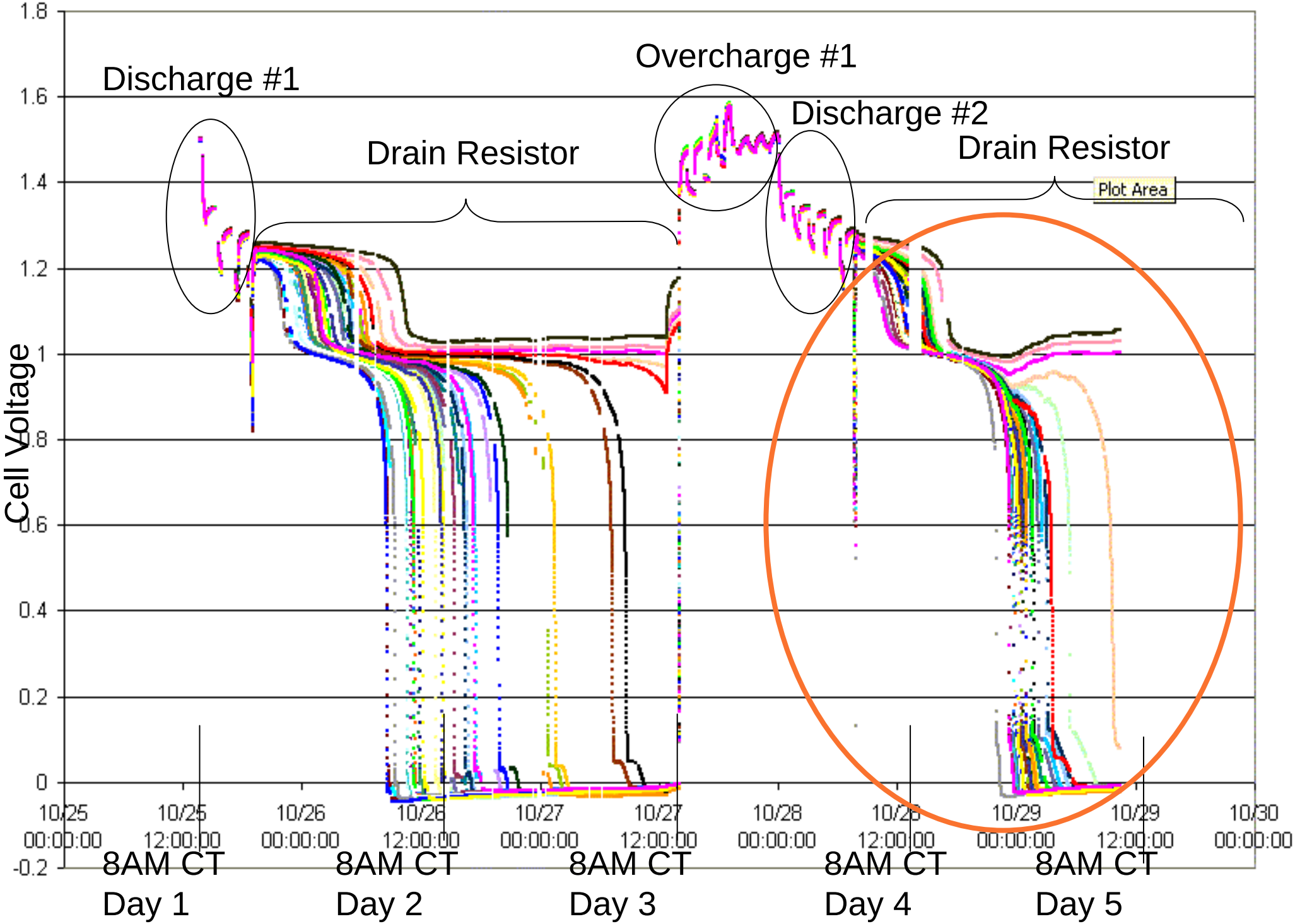


http://www.grc.nasa.gov/WWW/RT1999/5000/5420miller.html

10/29/2004

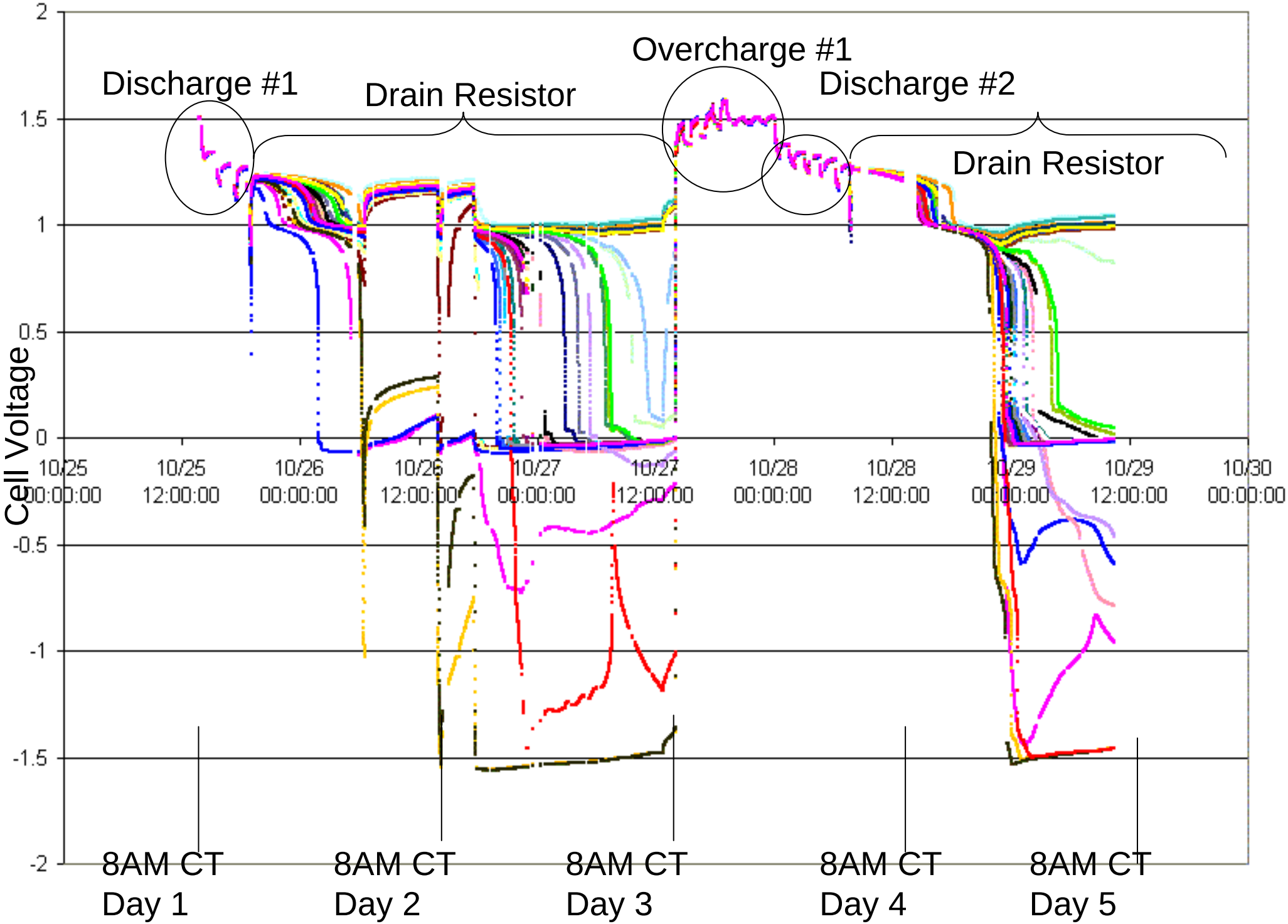
4B2 ORU A Cell Voltages

Matthew Scudder

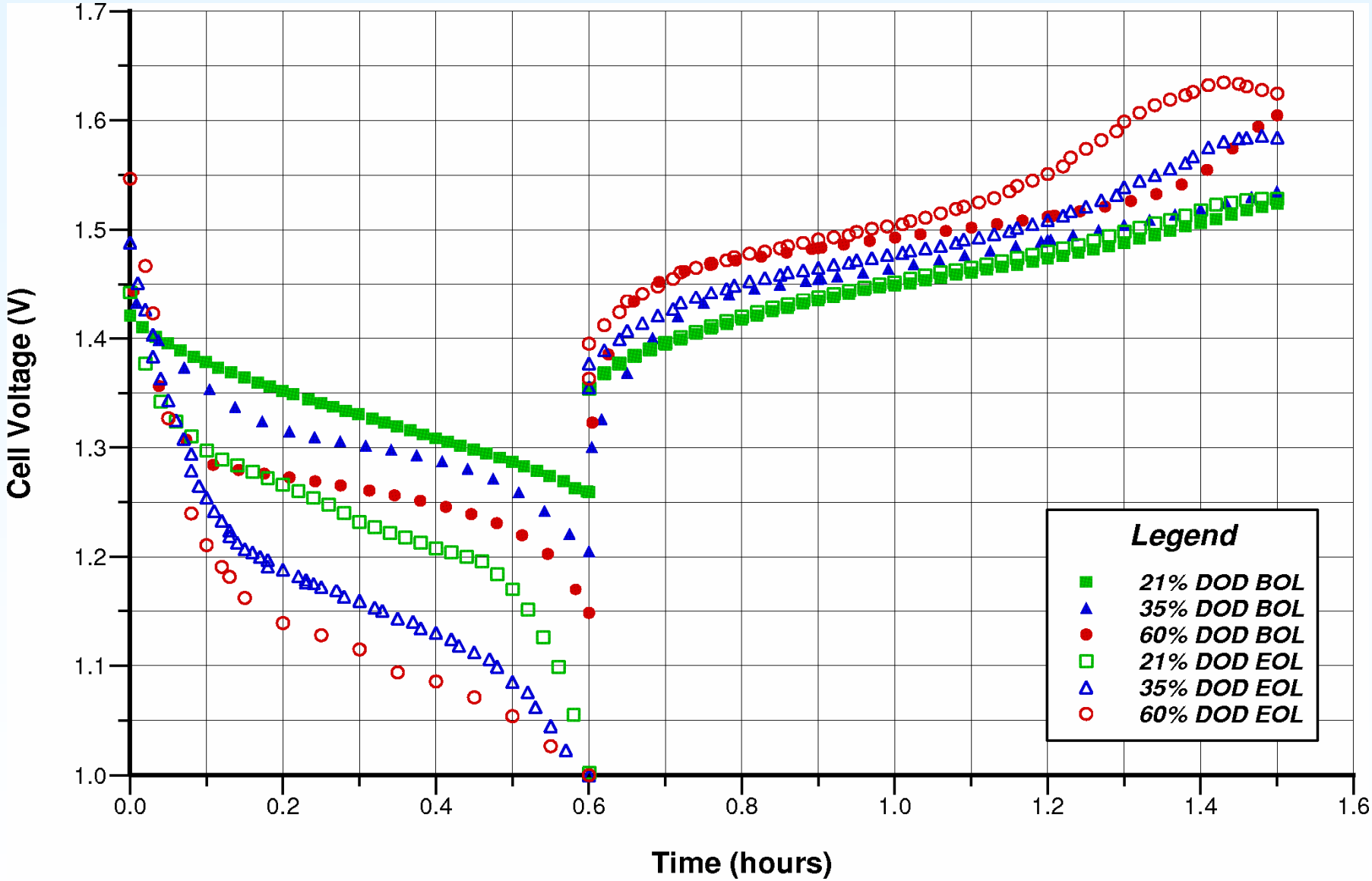


10/29/2004

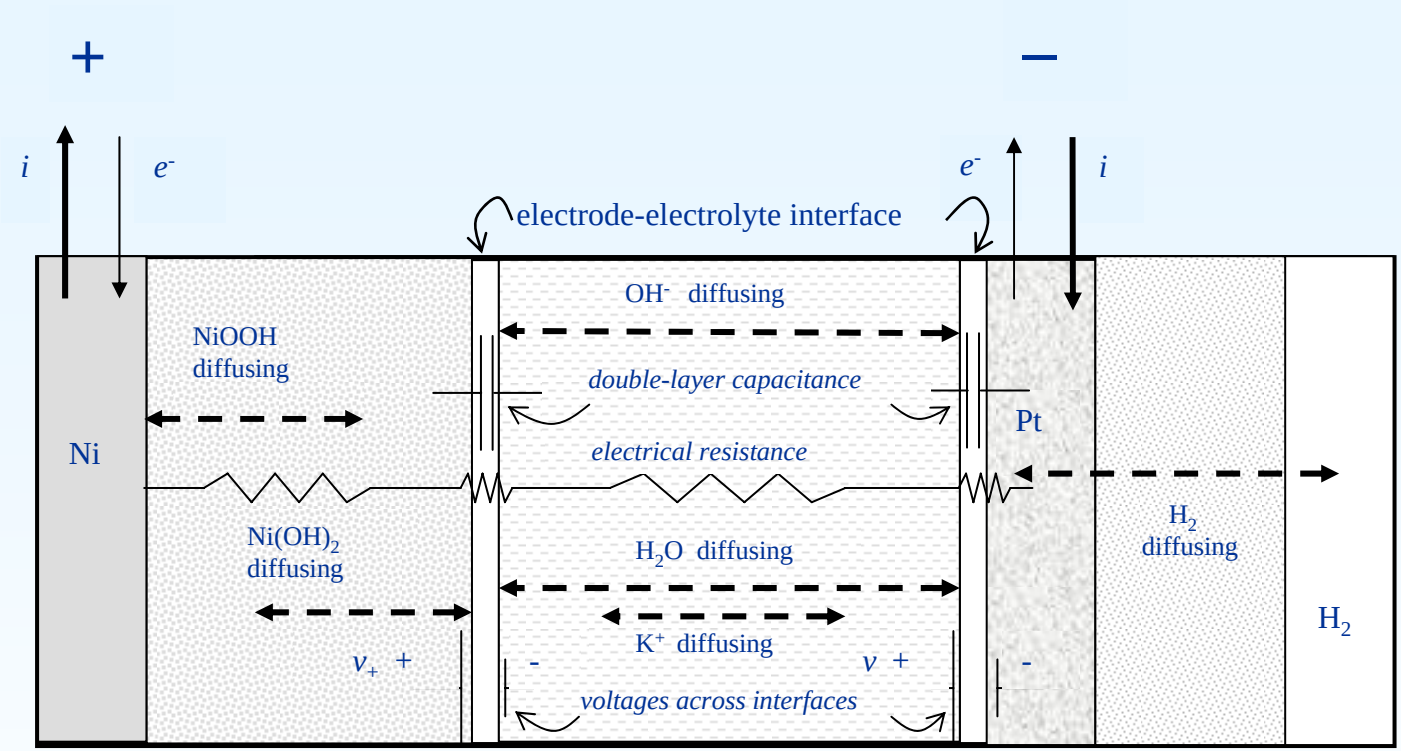
4B2 ORU B Cell Voltages



Empirical Loral Model



Overview of NiH2 Electrochemistry

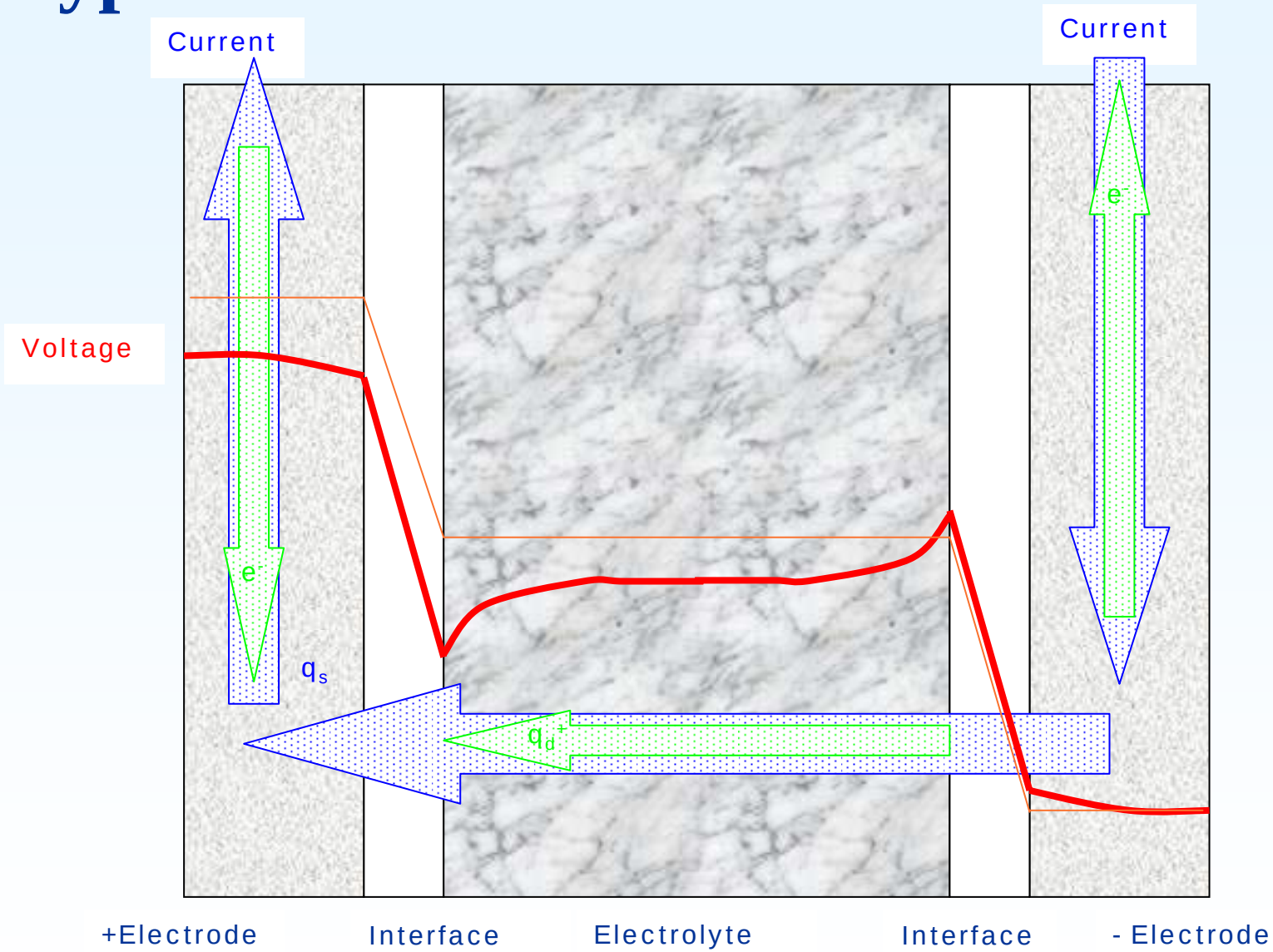


Normal charge-discharge operation of a nickel-hydrogen cell:

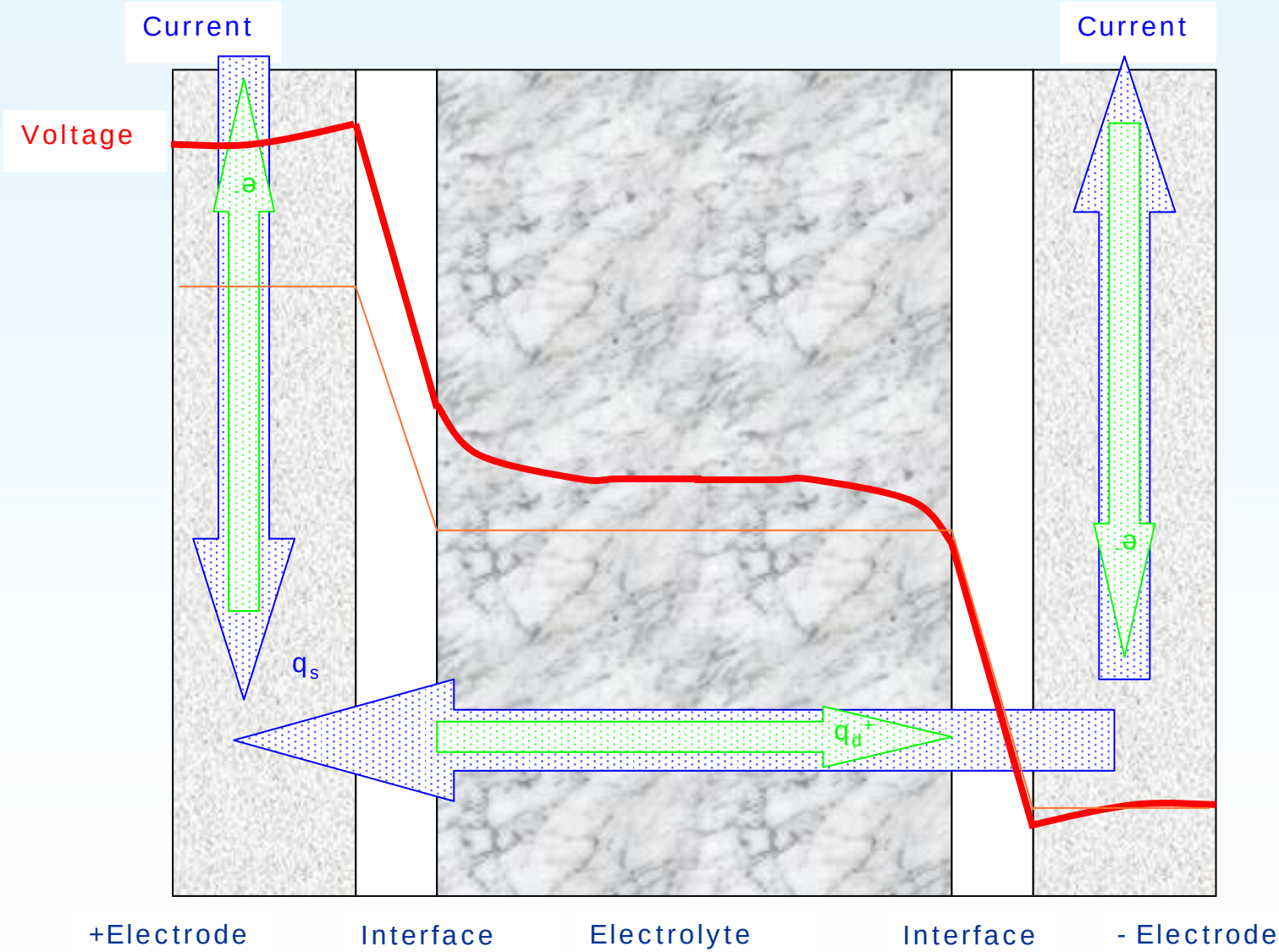
positive nickel electrode: $NiOOH + H_2O + e- \underset{charge}{\overset{discharge}{\rightleftarrows}} Ni(OH)_2 + OH-$

negative hydrogen electrode: $\frac{1}{2} H_2 + OH- \underset{charge}{\overset{discharge}{\rightleftarrows}} H_2O + e-$.

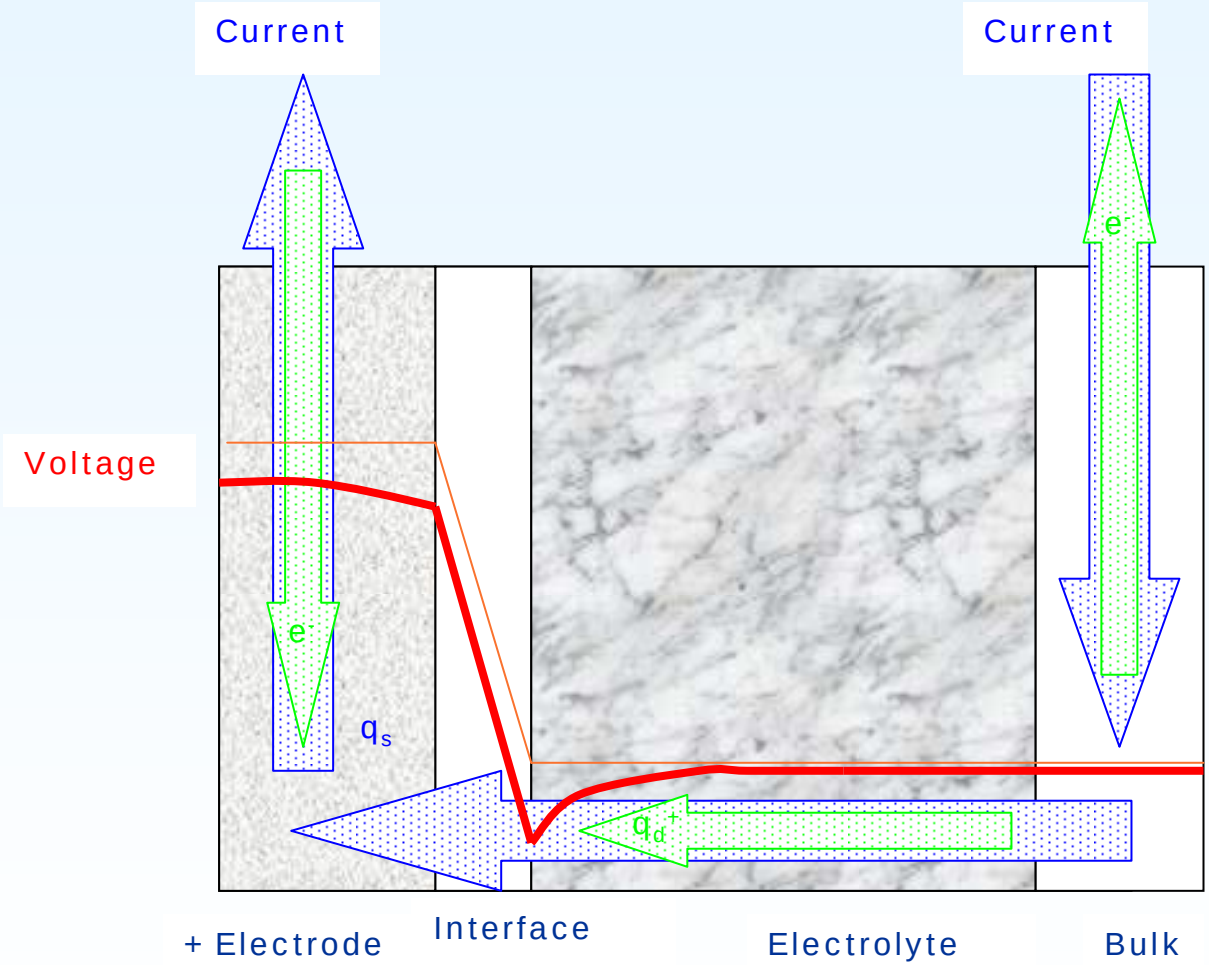
A Typical Electrochemical Cell - Discharging



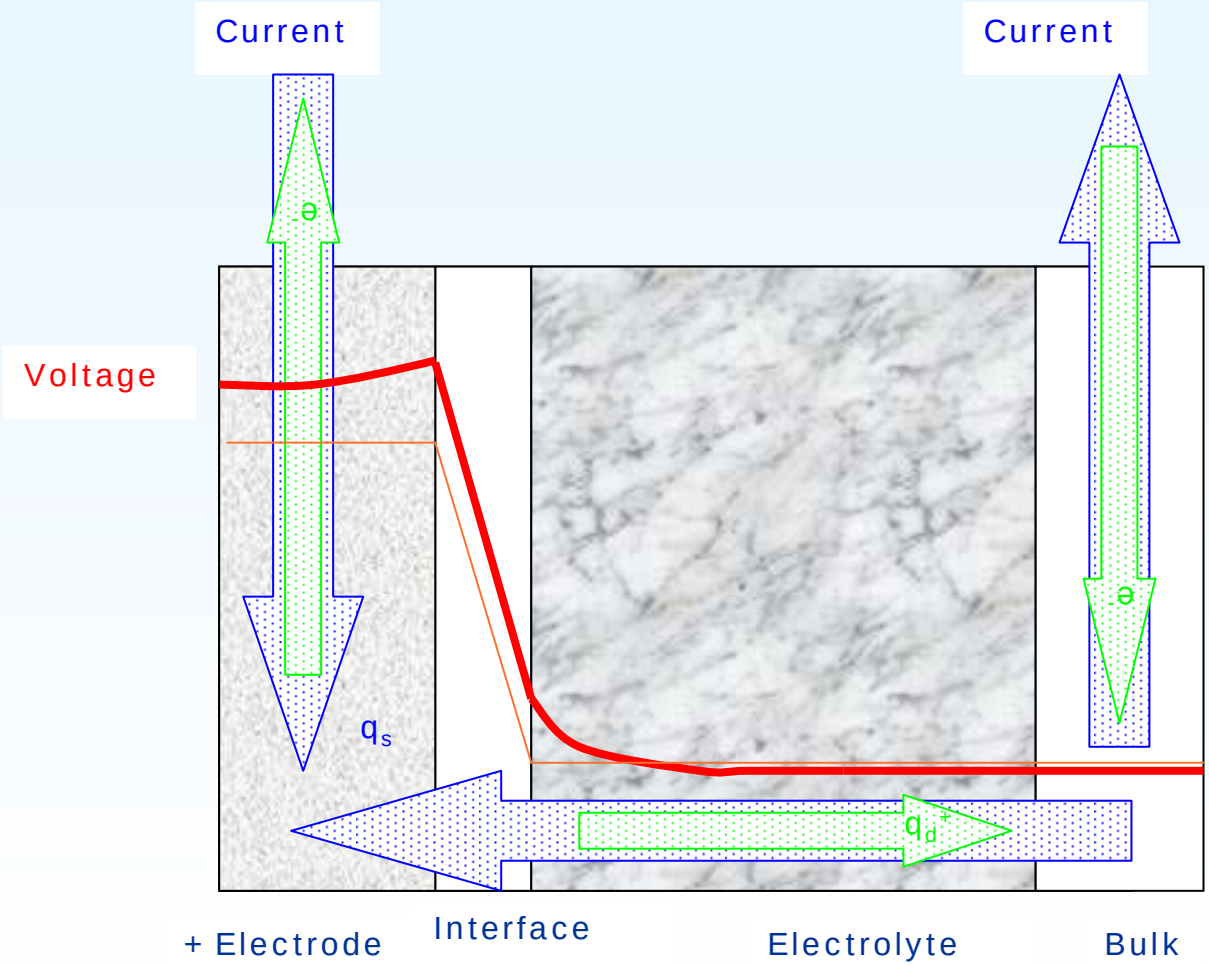
A Typical Electrochemical Cell - Charging



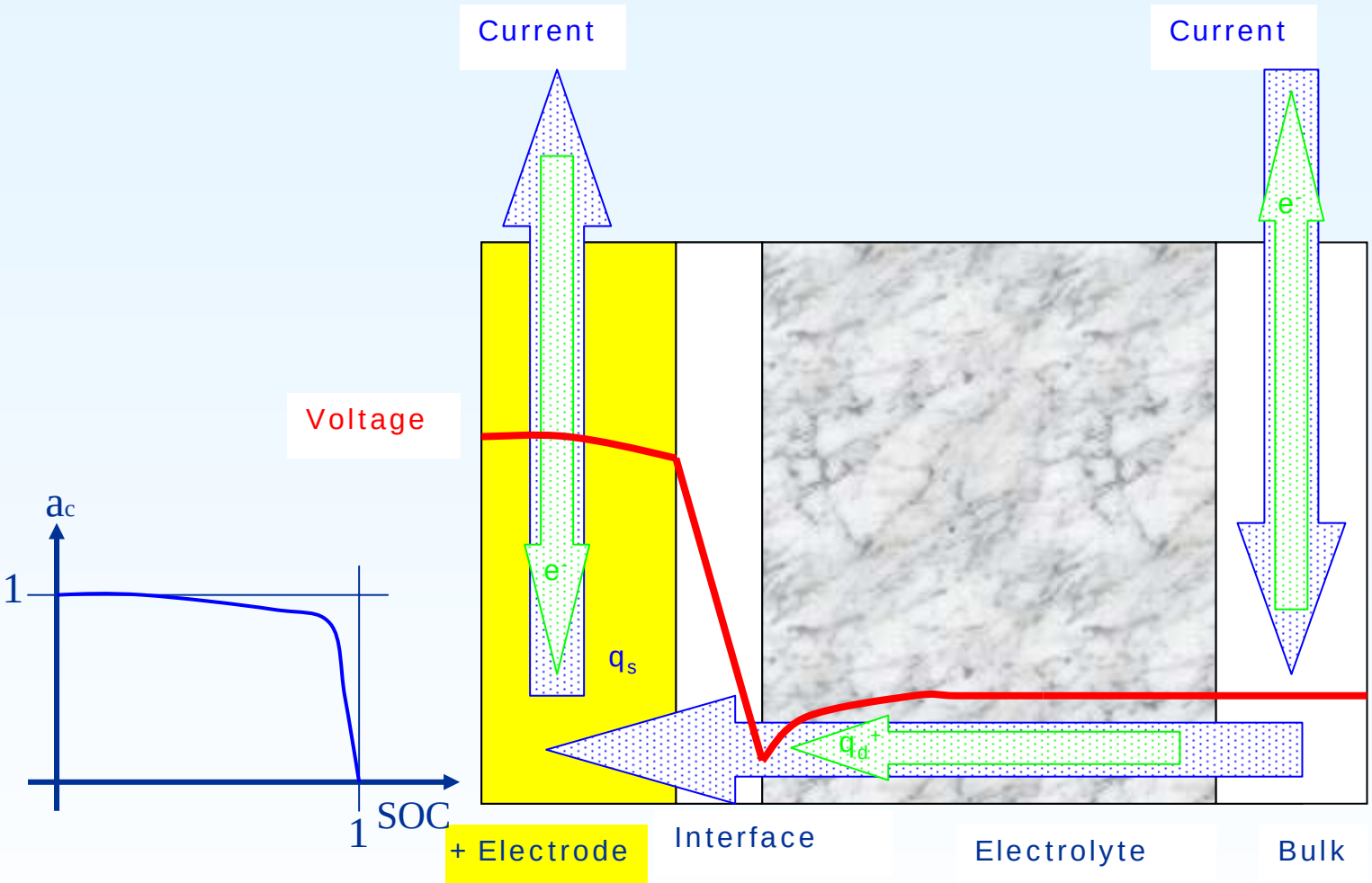
A Simpified Electrochemical Cell - Discharging



A Simplified Electrochemical Cell - Charging



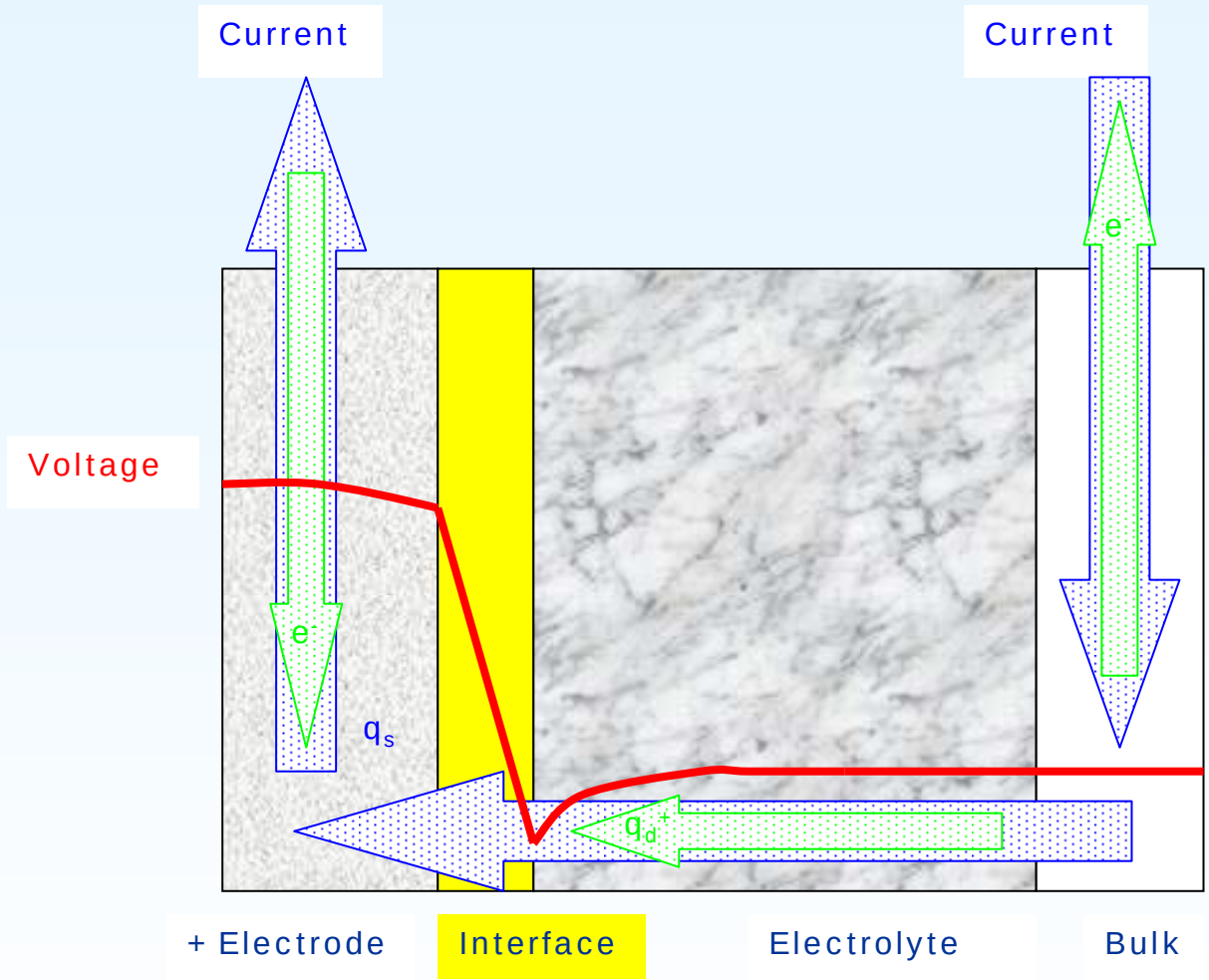
Stored Charge Model



stored material with self-discharge and charge acceptance:

$$\frac{dq_s(t)}{dt} = -a_c(q_s)\,i(t) - \frac{1}{R_{sd}}\,q_s(t)$$

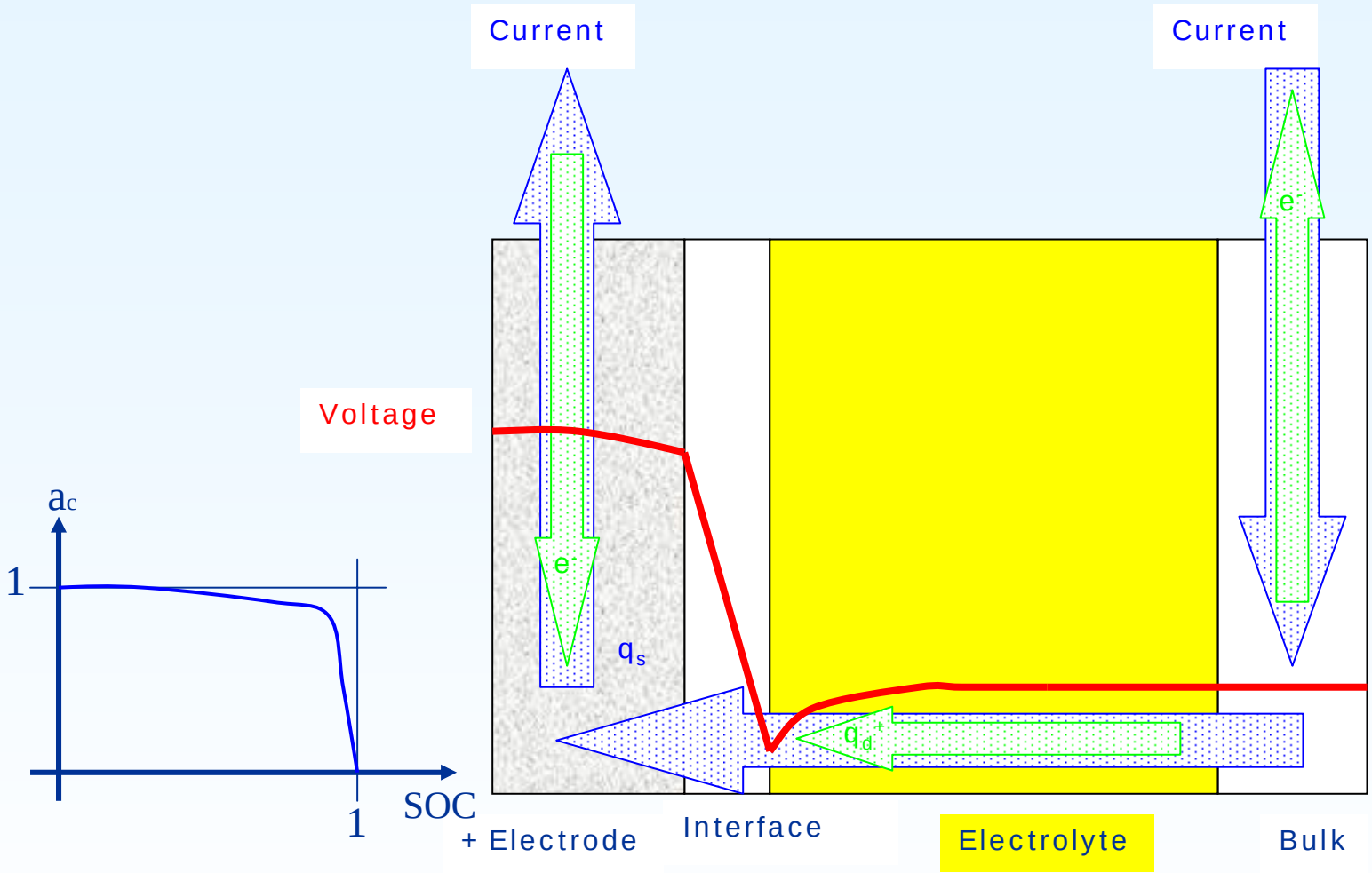
Electrode-Electrolyte Interface Model



$$i(t) = k_0\left(q_s^a(t)e^{(F/RT)(1-\alpha)(v(t)-v_0)} - q_d^b(t)e^{(F/RT)(-\alpha)(v(t)-v_0)}\right)$$

$$v(t) \cong k_1 + k_2\ln\left(1+k_s\left|i\right|\right)\mathrm{sgn}(i) + k_3\ln(q_d) + k_4\ln(1-q_s) + \cdots$$

Diffusing Charge Model



$$\frac{dq_d(t)}{dt} = k_{dr} q_{bulk} - k_{dr} q_d(t) - k_d\, a_c(q_s) i(t)$$

Essentialized Model Overview

Terminal behavior: **current into the battery is +*i***,
the terminal voltage is +*v*,

stored material with self-discharge:

$$\frac{dq_s(t)}{dt} = a_c(q_s)\,i(t) - \frac{1}{R_{sd}}\,q_s(t)$$

assumes one dominant electrode, one major diffusion process, and approximate electrode kinetics

diffusing material:

$$\frac{dq_d(t)}{dt} = k_{dr}\,q_{bulk} - k_{dr}\,q_d(t) + k_d\,a_c(q_s)\,i(t)$$

electrode-equation:

$$v(q_s, q_d, i) = k_1 + k_2 \ln\left(1 + k_s\,|\,i\,|\right)\mathrm{sgn}(i) + k_3 \ln(q_d) + k_4 \ln(1 - q_s) + \cdots.$$

Best Modified Model of 4B2

Terminal behavior: **current into the battery is +*i***,
the terminal voltage is +*v*,

Stored material with self-discharge:

$$\frac{dq_s(t)}{dt} = i(t) - 0.008 q_s(t),$$

Diffusing material:

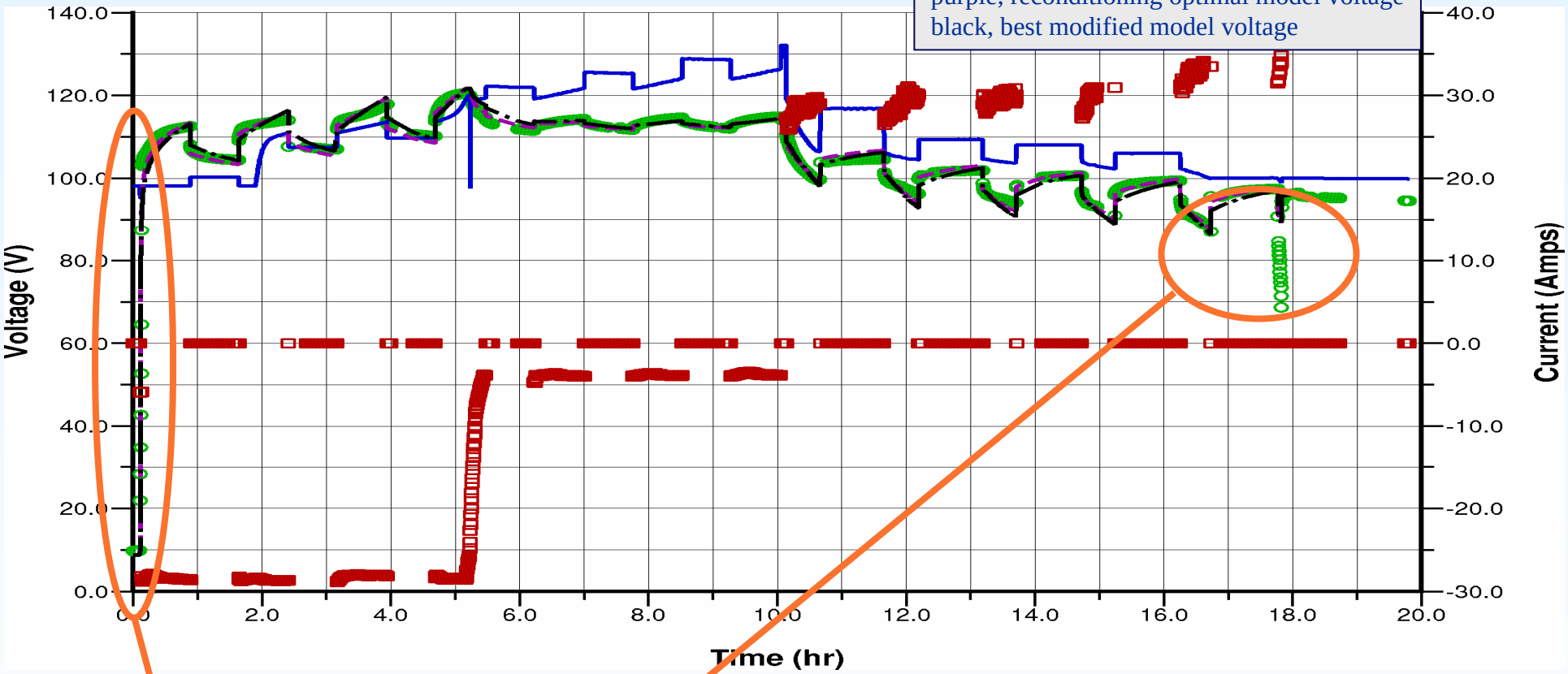
$$\frac{dq_d(t)}{dt} = i(t) - 1.1\, q_d(t),$$

Electrode-equation:

$$\begin{aligned} v(t) = {} & 110.2472 \\ & - 0.1800\,[0.5*(1+sign(i(t)))]i(t) - 0.1800\,[0.5*(1-sign(i(t)))]i(t)) \\ & + 4.0315\log(q_s(t)/77) + 508.1123[\exp(0.25 q_s(t)/77) - 1] \\ & - 1.8847 q_s(t) + 0.4700 q_d(t) \end{aligned}$$

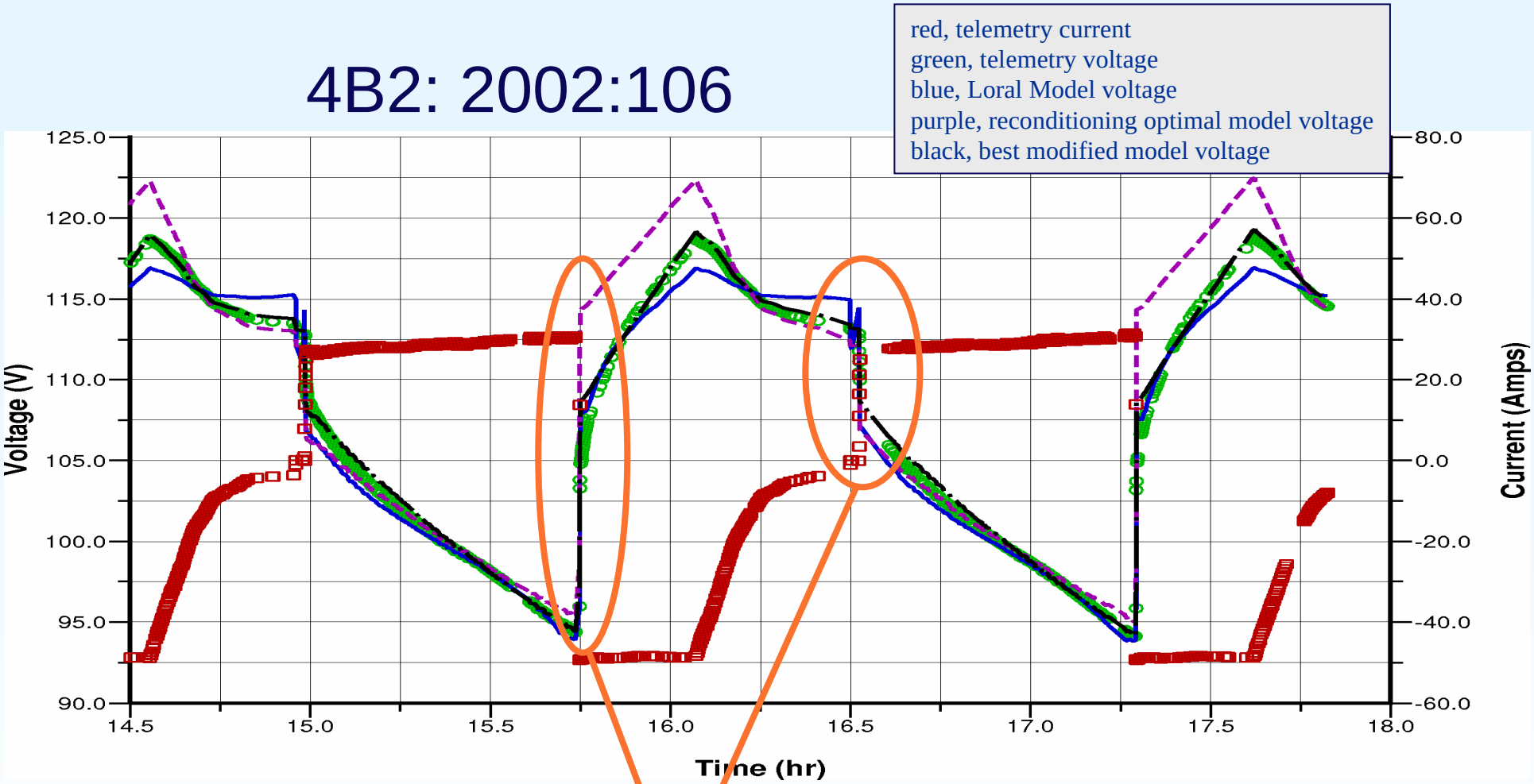
4B2: 2004:299

red, telemetry current
green, telemetry voltage
blue, Loral Model voltage
purple, reconditioning optimal model voltage
black, best modified model voltage



$$v(t) = 110.2472$$
$$- 0.1800\,[0.5*(1+sign(i(t)))]i(t) - 0.1800\,[0.5*(1-sign(i(t)))]i(t))$$
$$+4.0315\log(q_s(t)/77) + 508.1123[\exp(0.25q_s(t)/77)-1] - 1.8847q_s(t)$$
$$+0.4700q_d(t)$$

4B2: 2002:106



$$v(t) = 110.2472$$

$$- 0.1800\,[0.5*(1+sign(i(t)))]i(t) - 0.1800\,[0.5*(1-sign(i(t)))]i(t))$$

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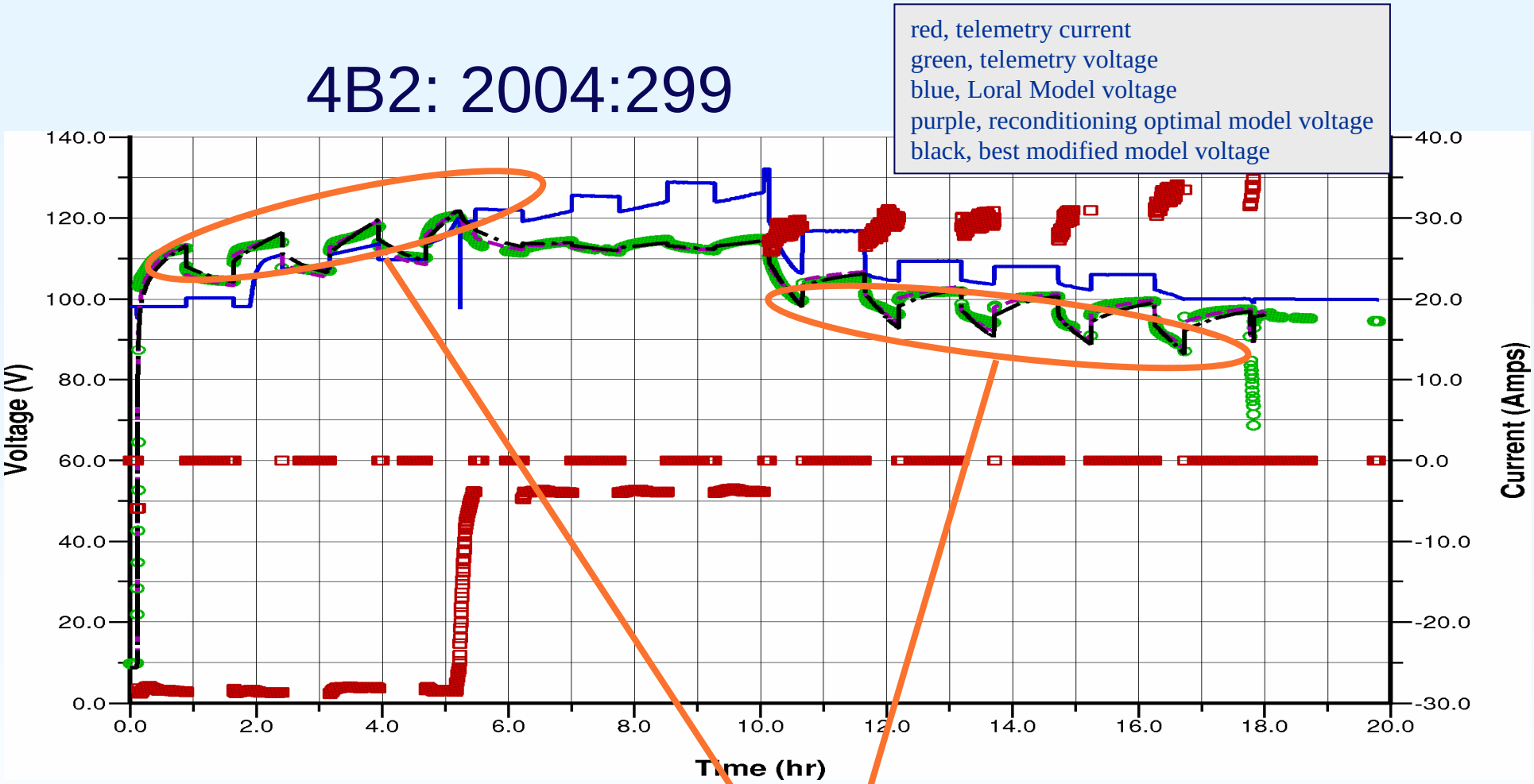
$$+0.4700q_d(t)$$

4B2: 2004:299



$$v(t) = 110.2472$$
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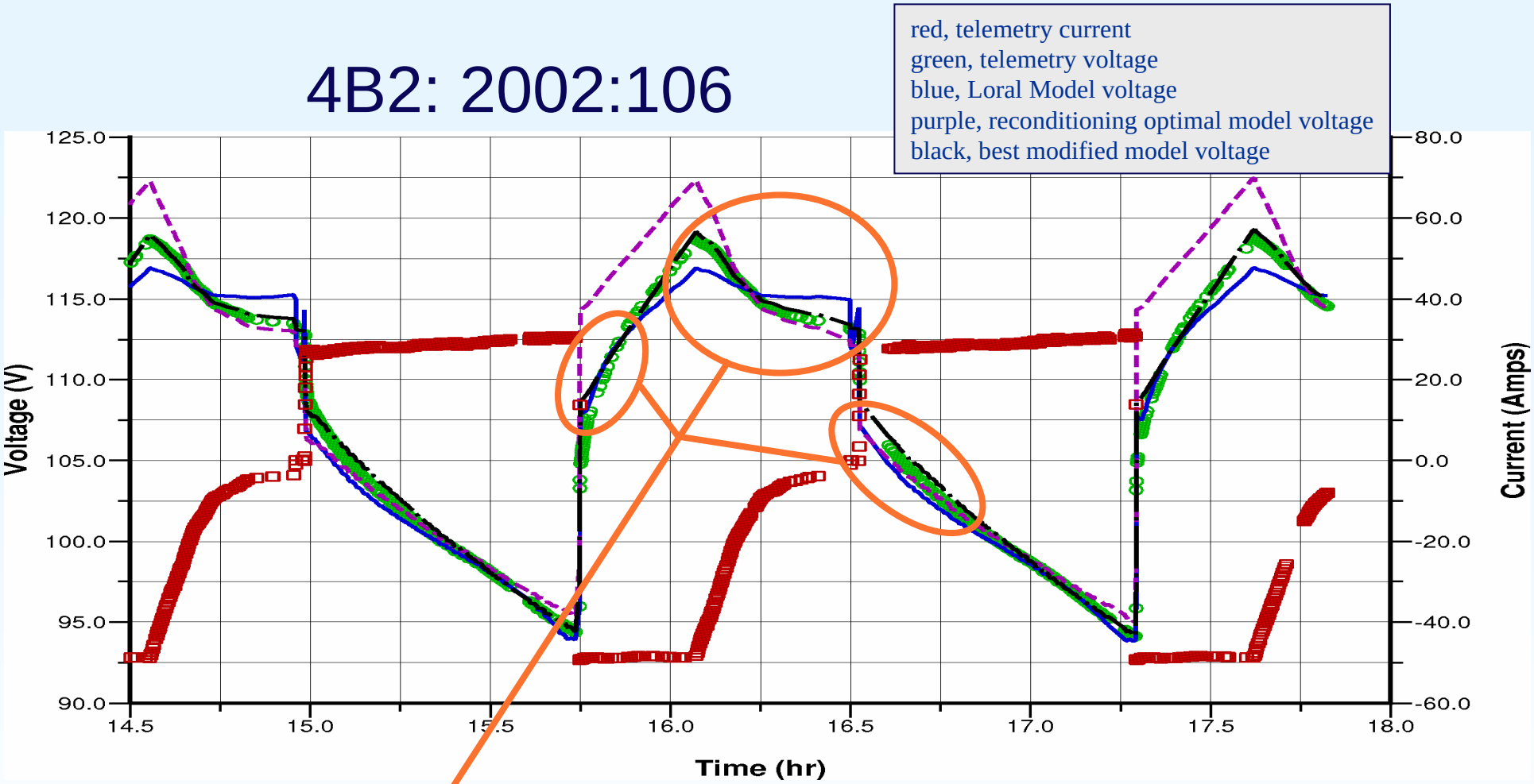
4B2: 2002:106



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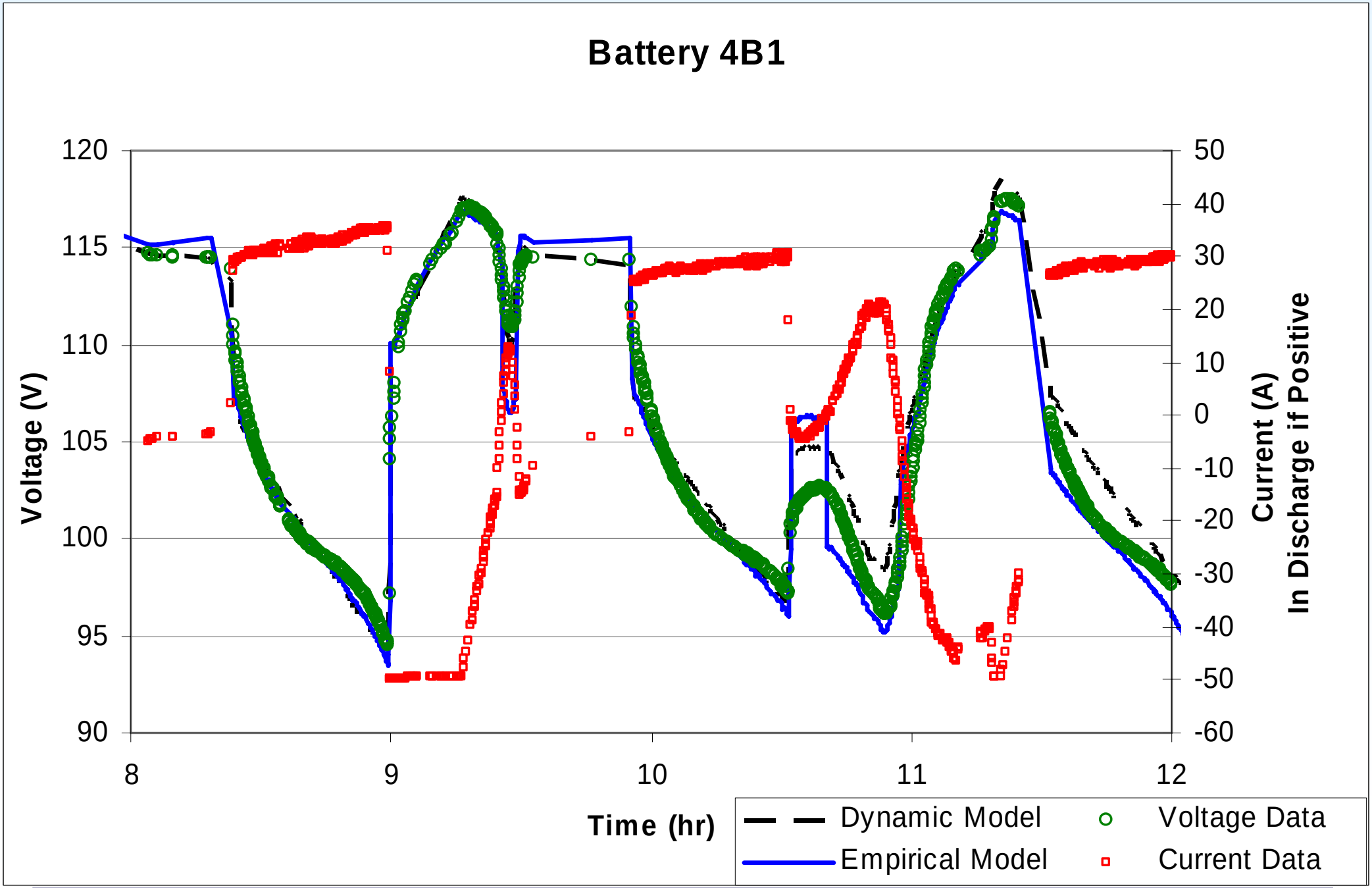
$$+4.0315\log(q_s(t)/77)+508.1123[\exp(0.25q_s(t)/77)-1]-1.8847q_s(t)$$
$$+0.4700q_d(t)$$

Summary

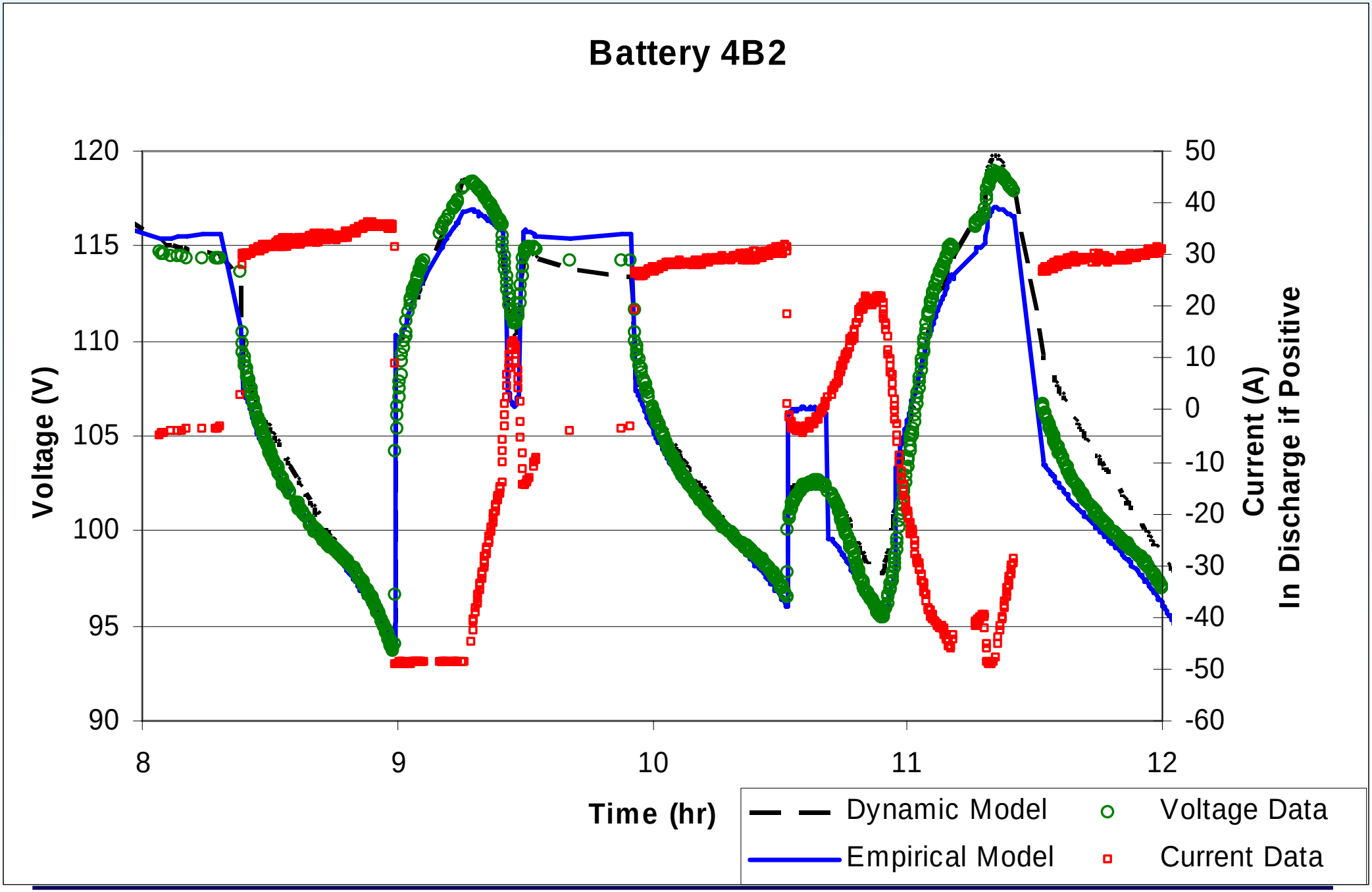
Event	Year	Day	Empirical Model RMS Error, Voltage Discharge	Empirical Model RMS Error, Voltage Charge	Empirical Model RMS Error, Voltage Total	First Principles, Optimized RMS Error, Voltage Discharge	First Principles, Optimized RMS Error, Voltage Charge	First Principles, Optimized RMS Error, Voltage Total	First Principles, Modified RMS Error, Voltage Discharge	First Principles, Modified RMS Error, Voltage Charge	First Principles, Modified RMS Error, Voltage Total
Flight 5A EVA#1, U.S. Lab install	2001	41	3.7	3.7	3.7	0.9	2.6	1.9	0.6	1.0	0.8
Flight 6A Shuttle undock	2001	119	3.1	3.4	3.3	1.4	4.8	3.8	1.3	2.0	1.8
Stage 6A BGAs Parked	2001	136	1.7	1.5	1.6	1.8	3.4	2.5	2.1	1.8	2.0
Flight 8A EVA#4	2002	106	0.6	1.8	1.3	0.9	3.1	2.4	0.5	0.7	0.6
Flight 8A Shuttle undock	2002	107	0.7	2.2	1.5	1.0	2.9	2.3	0.6	0.9	0.8
Stage 11A Xpop, loss of attitude cor	2003	78	0.9	1.3	1.1	1.4	2.6	2.3	1.0	1.1	1.1
SSU shunt test #1	2003	99	0.8	2.2	1.6	2.0	2.7	2.5	2.9	1.7	2.2
11P Vehicle Docking	2003	162	1.0	1.8	1.4	1.7	3.2	2.7	2.5	2.1	2.2
YvvZnadir, Xpop attitudes	2003	193	1.4	1.4	1.4	1.5	2.4	2.2	1.6	1.9	1.8
SSU shunt test #3	2004	90	0.9	2.0	1.5	1.2	2.7	2.2	1.1	1.2	1.2
SSU shunt test #4	2004	268	1.1	2.0	1.5	1.5	2.6	2.2	1.5	1.3	1.4
day before 4B2 reconditioning	2004	298	1.5	1.4	1.4	1.4	2.6	2.2	1.5	1.8	1.7
Return 4B2 to normal cycling	2004	306	2.6	3.3	2.9	2.4	2.9	2.7	2.8	2.0	2.3
	Averages		**1.5**	**2.2**	**1.9**	**1.5**	**3.0**	**2.4**	**1.5**	**1.5**	**1.5**
4B2 Reconditioning	2004	299	9.3	9.4	9.3	1.4	2.0	1.8	1.8	2.4	2.2

Event	Year	Day	Solar ß Angle (°)	Cycles	DOD	LF
Flight 5A EVA#1, U.S. Lab install	2001	41	24	15	12%	10%
Flight 6A Shuttle undock	2001	119	-33	12	12%	13%
Stage 6A BGAs Parked	2001	136	-1	15	21%	13%
Flight 8A EVA#4	2002	106	-8	6	23%	23%
Flight 8A Shuttle undock	2002	107	-12	8	24%	23%
Stage 11A Xpop, loss of attitude cor	2003	78	46	15	20%	32%
SSU shunt test #1	2003	99	-5	15	28%	33%
11P Vehicle Docking	2003	162	-7	15	22%	35%
YvvZnadir, Xpop attitudes	2003	193	40	15	19%	36%
SSU shunt test #3	2004	90	4	15	26%	42%
SSU shunt test #4	2004	268	8	15	19%	47%
day before 4B2 reconditioning	2004	298	-16	15	21%	48%
Return 4B2 to normal cycling	2004	306	17	9	14%	48%

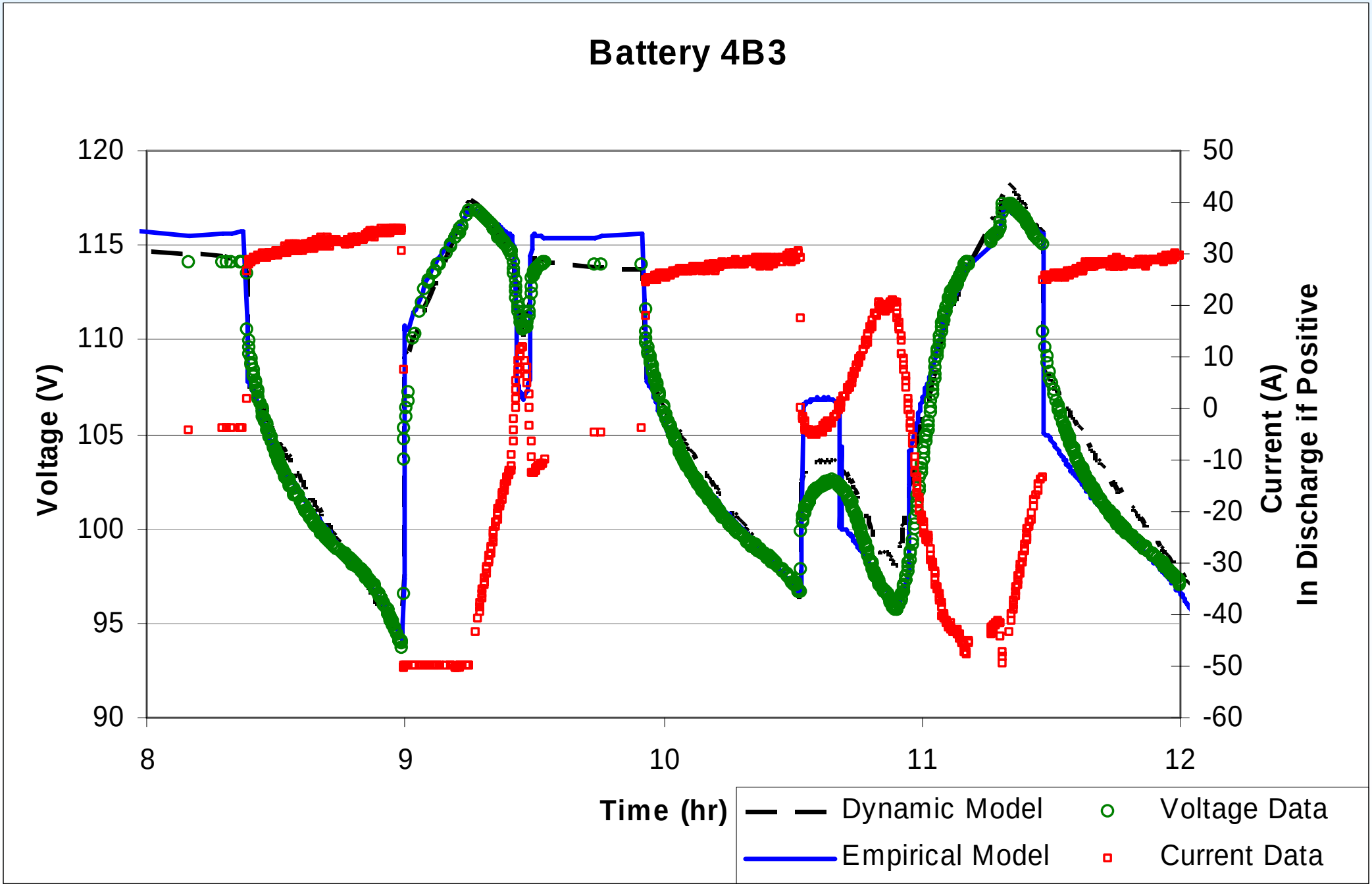
2003:162 (June 11)
Progress 11P Docks to ISS



2003:162 (June 11)
Progress 11P Docks to ISS



2003:162 (June 11)
Progress 11P Docks to ISS



2003:162 (June 11)
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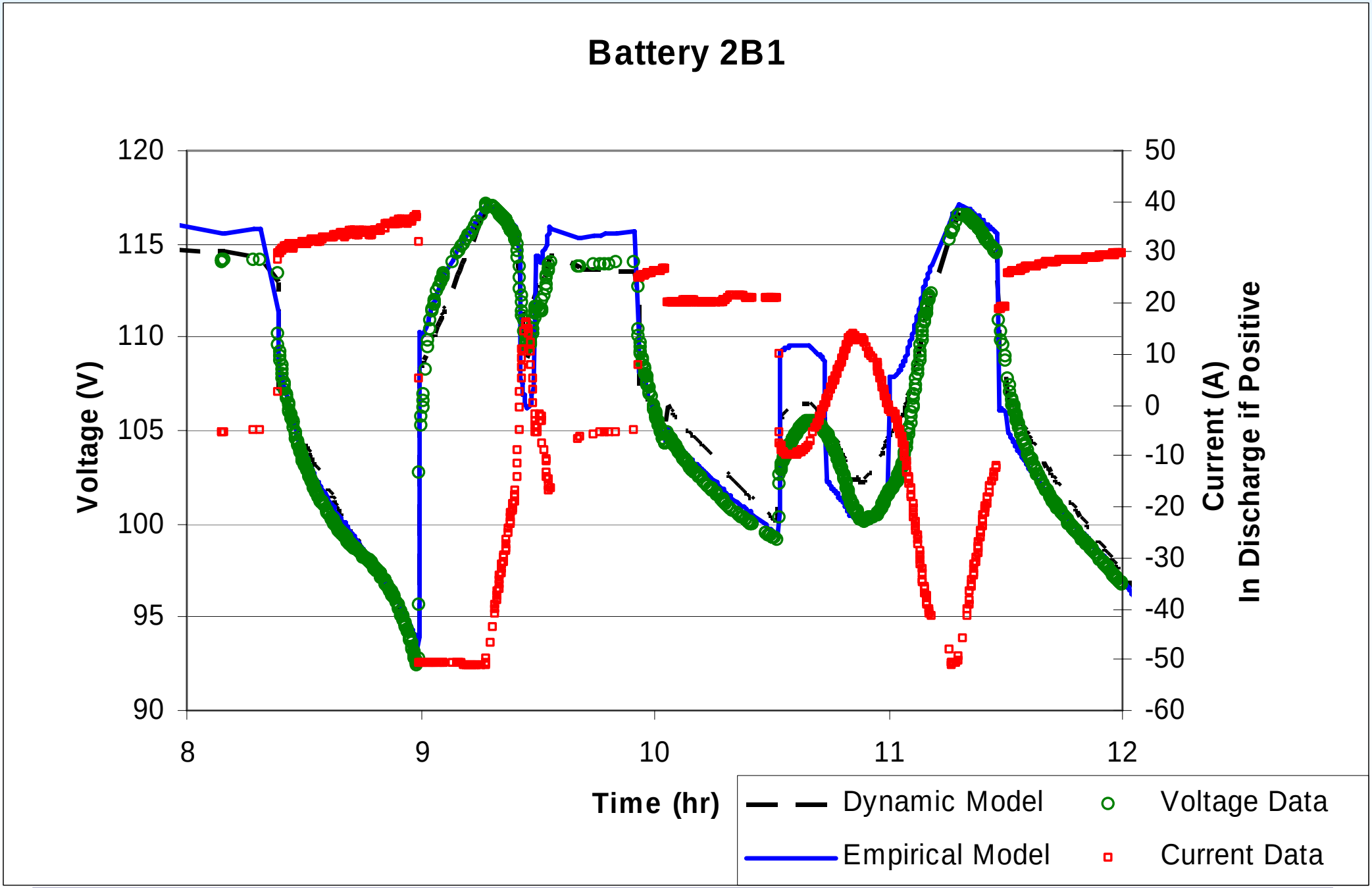
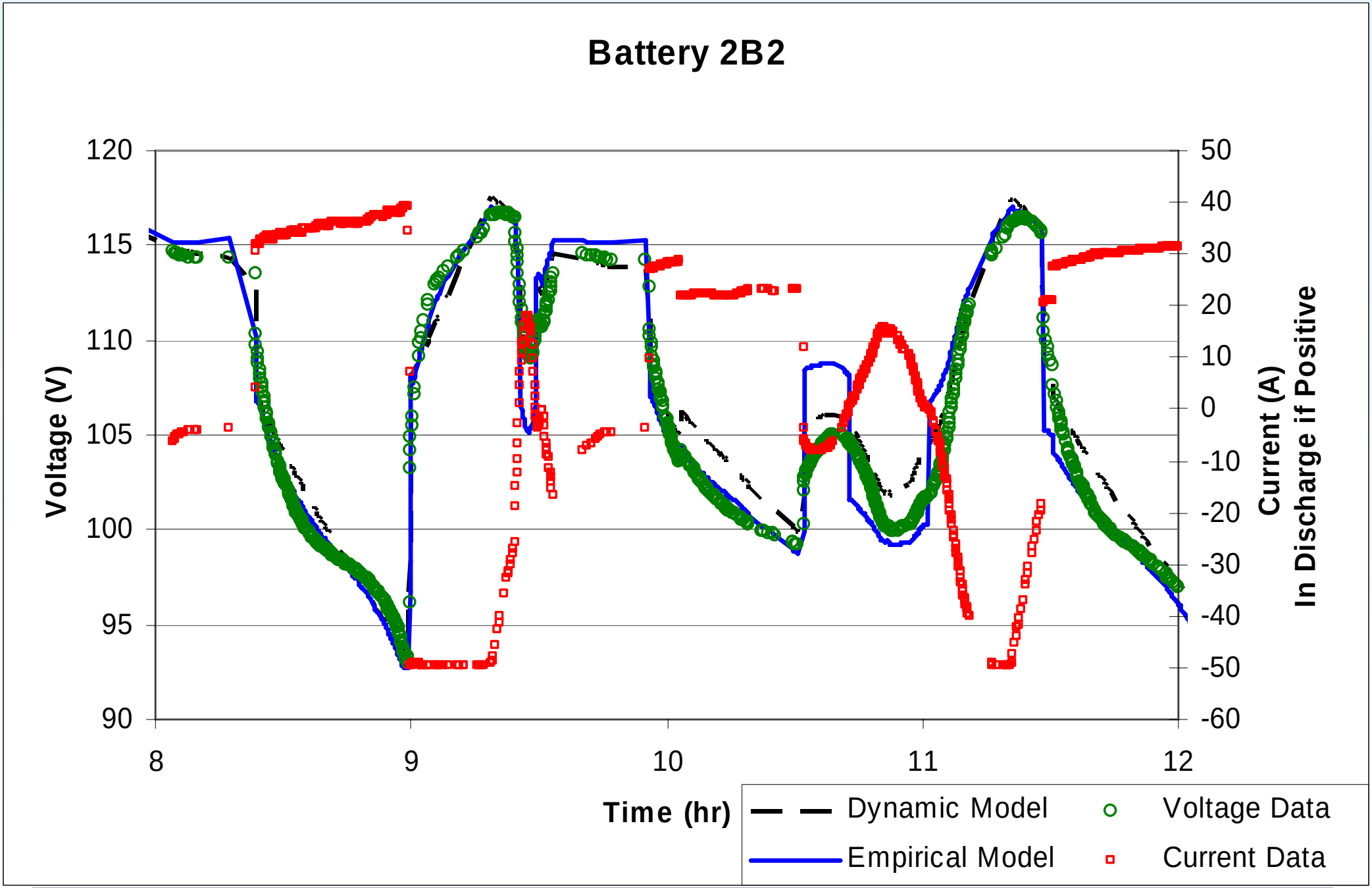
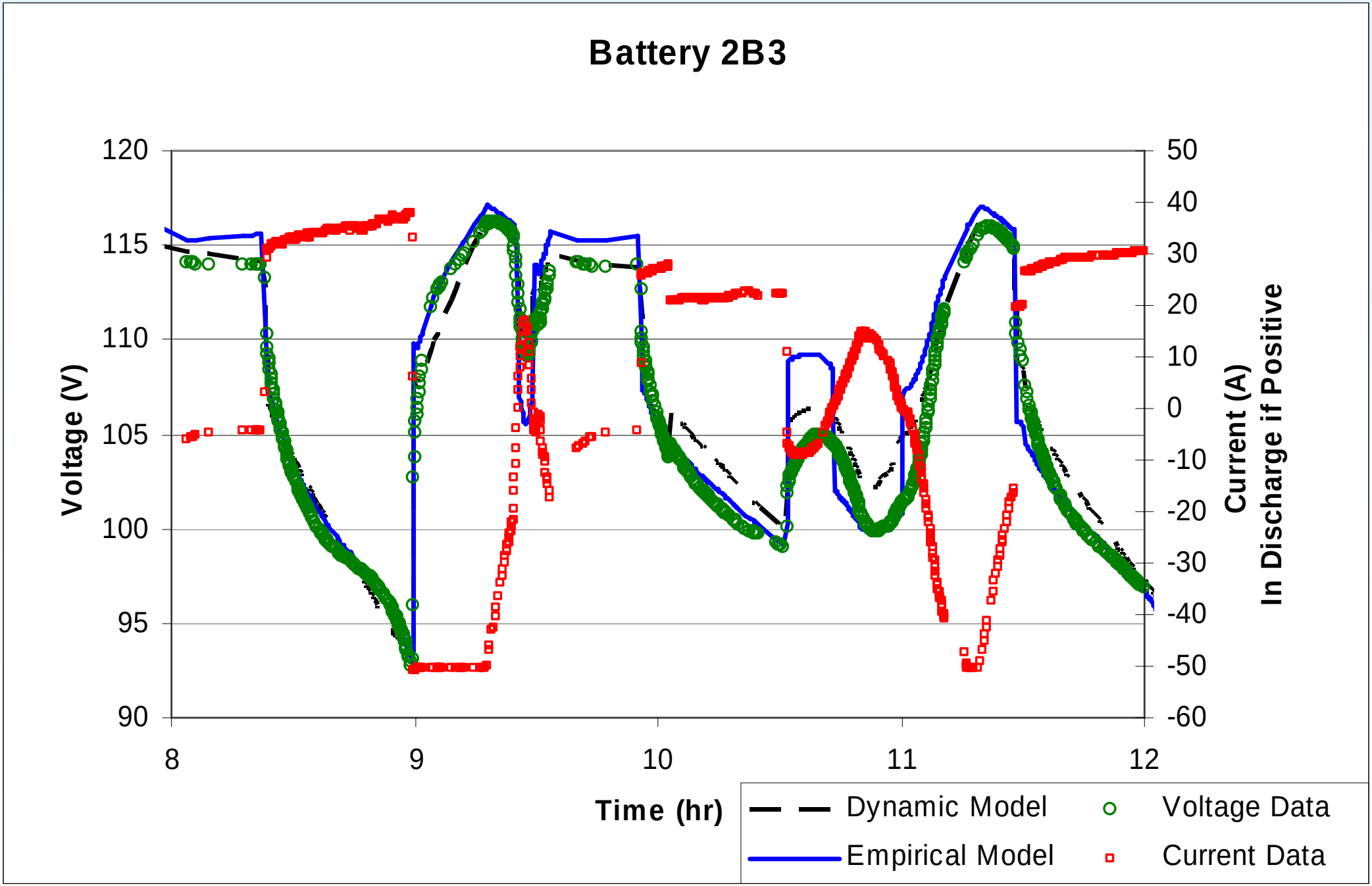


2003:162 (June 11)
Progress 11P Docks to ISS



2003:162 (June 11)
Progress 11P Docks to ISS



Error Analysis for 4B1 Model

Event	Year	Day	Solar ß Angle (°)	Cycles	DOD	LF	Empirical Model RMS Error, Voltage Discharge	Empirical Model RMS Error, Voltage Charge	Empirical Model RMS Error, Voltage Total	First Principles, Modified RMS Error, Voltage Discharge	First Principles, Modified RMS Error, Voltage Charge	First Principles, Modified RMS Error, Voltage Total
Flight 5A EVA#1, U.S. Lab install	2001	41	24	16	12%	10%	3.7	4.1	3.9	1.6	2.1	1.9
Flight 6A Shuttle undock	2001	119	-33	3	12%	13%	3.1	3.9	3.6	1.1	1.7	1.4
Stage 6A BGAs Parked	2001	136	-1	7	21%	13%	2.0	1.5	1.8	1.2	1.5	1.3
Flight 8A EVA#4	2002	106	-8	6	23%	23%	0.7	1.7	1.1	0.8	0.9	0.8
Flight 8A Shuttle undock	2002	107	-12	9	24%	23%	0.8	2.3	1.5	0.9	1.0	0.9
Stage 11A Xpop, loss of attitude cor	2003	78	46	16	20%	32%	1.0	1.5	1.2	1.5	1.0	1.2
SSU shunt test #1	2003	99	-5	9	28%	33%	0.6	2.2	1.5	1.5	1.0	1.2
11P Vehicle Docking	2003	162	-7	5	22%	35%	1.1	1.7	1.4	1.5	1.1	1.3
YvvZnadir, Xpop attitudes	2003	193	40	9	19%	36%	1.3	1.8	1.6	1.2	0.7	0.9
SSU shunt test #3	2004	90	4	16	26%	42%	0.9	1.8	1.4	1.3	1.1	1.2
SSU shunt test #4	2004	268	8	16	19%	47%	1.0	2.5	1.8	1.7	1.3	1.5
day before 4B2 reconditioning	2004	298	-16	16	21%	48%	1.7	1.0	1.4	1.8	1.4	1.6
					AVERAGE		**1.5**	**2.2**	**1.8**	**1.3**	**1.2**	**1.3**
4B3 Reconditioning	2005	45			100%	48%				2.2	2.1	2.2

Error Analysis for 4B2 Model

Event	Year	Day	Solar ß Angle (°)	Cycles	DOD	LF	Empirical Model RMS Error, Voltage Discharge	Empirical Model RMS Error, Voltage Charge	Empirical Model RMS Error, Voltage Total	First Principles, Modified RMS Error, Voltage Discharge	First Principles, Modified RMS Error, Voltage Charge	First Principles, Modified RMS Error, Voltage Total
Flight 5A EVA#1, U.S. Lab install	2001	41	24	16	12%	10%	3.7	3.7	3.7	0.6	1.0	0.8
Flight 6A Shuttle undock	2001	119	-33	3	12%	13%	3.1	3.4	3.3	0.9	1.2	1.0
Stage 6A BGAs Parked	2001	136	-1	7	21%	13%	1.7	1.5	1.6	0.7	1.1	0.9
Flight 8A EVA#4	2002	106	-8	6	23%	23%	0.6	1.8	1.3	0.5	0.7	0.6
Flight 8A Shuttle undock	2002	107	-12	8	24%	23%	0.7	2.2	1.5	0.6	0.9	0.8
Stage 11A Xpop, loss of attitude cor	2003	78	46	16	20%	32%	0.9	1.3	1.1	1.0	1.1	1.1
SSU shunt test #1	2003	99	-5	9	28%	33%	0.8	2.2	1.6	1.3	0.8	1.0
11P Vehicle Docking	2003	162	-7	5	22%	35%	1.0	1.8	1.4	1.4	1.0	1.2
YvvZnadir, Xpop attitudes	2003	193	40	9	19%	36%	1.4	1.4	1.4	0.9	1.1	1.0
SSU shunt test #3	2004	90	4	16	26%	42%	0.9	2.0	1.5	1.1	1.2	1.2
SSU shunt test #4	2004	268	8	16	19%	47%	1.1	2.0	1.5	1.5	1.3	1.4
day before 4B2 reconditioning	2004	298	-16	16	21%	48%	1.5	1.4	1.4	1.5	1.8	1.7
					AVERAGE		**1.4**	**2.1**	**1.8**	**1.0**	**1.1**	**1.1**
4B2 Reconditioning	2004	299			100%	48%	9.3	9.4	9.3	1.8	2.4	2.2

Error Analysis for 4B3 Model

Event	Year	Day	Solar ß Angle (°)	Cycles	DOD	LF	Empirical Model RMS Error, Voltage Discharge	Empirical Model RMS Error, Voltage Charge	Empirical Model RMS Error, Voltage Total	First Principles, Modified RMS Error, Voltage Discharge	First Principles, Modified RMS Error, Voltage Charge	First Principles, Modified RMS Error, Voltage Total
Flight 5A EVA#1, U.S. Lab install	2001	41	24	16	12%	10%	2.9	4.7	3.9	1.5	1.8	1.7
Flight 6A Shuttle undock	2001	119	-33	3	12%	13%	2.5	4.5	3.8	1.5	1.8	1.6
Stage 6A BGAs Parked	2001	136	-1	7	21%	13%	1.3	2.3	1.8	1.0	1.4	1.2
Flight 8A EVA#4	2002	106	-8	6	23%	23%	0.8	2.3	1.5	0.6	0.7	0.6
Flight 8A Shuttle undock	2002	107	-12	8	24%	23%	0.8	2.7	1.7	0.7	1.0	0.9
Stage 11A Xpop, loss of attitude cor	2003	78	46	16	20%	32%	0.4	1.9	1.3	1.1	1.0	1.0
SSU shunt test #1	2003	99	-5	9	28%	33%	1.0	2.6	1.9	1.3	0.9	1.1
11P Vehicle Docking	2003	162	-7	5	22%	35%	0.7	2.3	1.5	1.2	0.9	1.1
YvvZnadir, Xpop attitudes	2003	193	40	9	19%	36%	0.8	2.2	1.7	1.2	0.7	0.9
SSU shunt test #3	2004	90	4	16	26%	42%	0.8	2.3	1.6	1.1	1.1	1.1
SSU shunt test #4	2004	268	8	16	19%	47%	0.6	2.9	1.9	1.8	1.1	1.4
day before 4B2 reconditioning	2004	298	-16	16	21%	48%	1.1	1.4	1.2	1.9	1.5	1.7
					AVERAGE		**1.1**	**2.7**	**2.0**	**1.2**	**1.2**	**1.2**
4B3 Reconditioning	2005	45			100%	48%	8.8	15.2	13.1	1.8	2.0	1.9

Error Analysis for 2B1 Model

Event	Year	Day	Solar ß Angle (°)	Cycles	DOD	LF	Empirical Model RMS Error, Voltage Discharge	Empirical Model RMS Error, Voltage Charge	Empirical Model RMS Error, Voltage Total	First Principles, Modified RMS Error, Voltage Discharge	First Principles, Modified RMS Error, Voltage Charge	First Principles, Modified RMS Error, Voltage Total
Flight 5A EVA#1, U.S. Lab install	2001	41	24	16	16%	10%	1.8	4.4		1.2	1.6	1.4
Flight 6A Shuttle undock	2001	119	-33	3	28%	13%	1.9	3.9		0.6	1.2	0.9
Stage 6A BGAs Parked	2001	136	-1	7	22%	13%	0.8	3.8		1.5	1.6	1.6
Flight 8A EVA#4	2002	106	-8	9	26%	23%	1.3	3.3		0.9	0.9	0.9
Flight 8A Shuttle undock	2002	107	-12	8	26%	23%	1.1	2.5		1.1	1.3	1.2
Stage 11A Xpop, loss of attitude cor	2003	78	46	16	16%	32%	0.6	2.9		1.5	1.1	1.2
SSU shunt test #1	2003	99	-5	9	35%	33%	2.3	3.5		1.6	1.1	1.3
11P Vehicle Docking	2003	162	-7	5	23%	35%	0.4	1.8		1.2	1.1	1.2
YvvZnadir, Xpop attitudes	2003	193	40	9	20%	36%	0.8	2.6		1.1	1.0	1.0
SSU shunt test #3	2004	90	4	16	27%	42%	1.3	2.7		1.3	1.5	1.4
SSU shunt test #4	2004	268	8	16	30%	47%	1.6	3.0		1.9	1.4	1.6
day before 4B2 reconditioning	2004	298	-16	16	26%	48%	0.8	2.2		1.8	1.8	1.8
					AVERAGE		**1.2**	**3.0**		**1.3**	**1.3**	**1.3**
2B1 Reconditioning	2005	290			100%	48%				5.2	4.9	5.0

Error Analysis for 2B2 Model

Event	Year	Day	Solar ß Angle (°)	Cycles	DOD	LF	Empirical Model RMS Error, Voltage Discharge	Empirical Model RMS Error, Voltage Charge	Empirical Model RMS Error, Voltage Total	First Principles, Modified RMS Error, Voltage Discharge	First Principles, Modified RMS Error, Voltage Charge	First Principles, Modified RMS Error, Voltage Total
Flight 5A EVA#1, U.S. Lab install	2001	41	24	16	16%	10%	2.7	3.9		1.5	1.6	1.5
Flight 6A Shuttle undock	2001	119	-33	3	28%	13%	1.2	2.9		0.7	0.8	0.8
Stage 6A BGAs Parked	2001	136	-1	7	22%	13%	1.5	2.1		1.6	1.4	1.6
Flight 8A EVA#4	2002	106	-8	9	26%	23%	0.8	2.7		1.2	0.8	1.0
Flight 8A Shuttle undock	2002	107	-12	8	26%	23%	0.7	2.0		1.2	1.2	1.2
Stage 11A Xpop, loss of attitude cor	2003	78	46	16	16%	32%	1.4	2.6		1.8	1.1	1.4
SSU shunt test #1	2003	99	-5	9	35%	33%	1.5	3.3		1.9	1.1	1.5
11P Vehicle Docking	2003	162	-7	5	23%	35%	1.5	1.7		1.4	1.2	1.3
YvvZnadir, Xpop attitudes	2003	193	40	9	20%	36%	1.2	1.3		1.3	0.8	1.0
SSU shunt test #3	2004	90	4	16	27%	42%	1.0	2.2		1.4	1.3	1.4
SSU shunt test #4	2004	268	8	16	30%	47%	0.9	2.6		2.2	1.4	1.8
day before 4B2 reconditioning	2004	298	-16	16	26%	48%	1.1	1.3		1.5	1.6	1.6
					AVERAGE		**1.3**	**2.4**		**1.5**	**1.2**	**1.3**
2B2 Reconditioning	2005	70			100%	48%				2.7	2.4	2.5

Error Analysis for 2B3 Model

Event	Year	Day	Solar ß Angle (°)	Cycles	DOD	LF	Empirical Model RMS Error, Voltage Discharge	Empirical Model RMS Error, Voltage Charge	Empirical Model RMS Error, Voltage Total	First Principles, Modified RMS Error, Voltage Discharge	First Principles, Modified RMS Error, Voltage Charge	First Principles, Modified RMS Error, Voltage Total
Flight 5A EVA#1, U.S. Lab install	2001	41	24	16	16%	10%	2.1	5.1		1.7	1.9	1.8
Flight 6A Shuttle undock	2001	119	-33	3	28%	13%	1.5	3.7		0.8	1.2	1.0
Stage 6A BGAs Parked	2001	136	-1	7	22%	13%	1.9	3.2		1.8	1.6	1.7
Flight 8A EVA#4	2002	106	-8	9	26%	23%	1.1	3.3		1.0	0.9	1.0
Flight 8A Shuttle undock	2002	107	-12	8	26%	23%	0.9	2.7		1.3	1.3	1.3
Stage 11A Xpop, loss of attitude cor	2003	78	46	16	16%	32%	0.8	3.2		1.6	1.1	1.3
SSU shunt test #1	2003	99	-5	9	35%	33%	1.9	3.8		1.5	1.2	1.3
11P Vehicle Docking	2003	162	-7	5	23%	35%	0.9	2.6		1.5	1.2	1.3
YvvZnadir, Xpop attitudes	2003	193	40	9	20%	36%	0.8	1.8		1.1	0.8	1.0
SSU shunt test #3	2004	90	4	16	27%	42%	1.2	2.8		1.3	1.4	1.3
SSU shunt test #4	2004	268	8	16	30%	47%	1.2	3.1		1.9	1.5	1.7
day before 4B2 reconditioning	2004	298	-16	16	26%	48%	0.8	2.1		1.4	1.8	1.6
						AVERAGE	**1.3**	**3.1**		**1.4**	**1.3**	**1.4**
2B3 Reconditioning	n/a	n/a										

Electrode Equation Parameters

		cee	Capacity	Cs(1)	Constant	Rd	Rc	Low end	High SOC	Qd	Qs
4B1		0.250	83	22.6	109	-0.25	-0.14	3.99	570	0.33	-1.93
4B2		0.250	77	1.0E-09	110	-0.18	-0.18	4.03	508	0.47	-1.88
4B3		0.250	81	1.0E-09	109	-0.21	-0.15	3.99	553	0.42	-1.93
2B1		0.250	80	6.0E-10	108	-0.21	-0.135	4.10	484	0.38	-1.70
2B2		0.250	80	6.0E-10	108	-0.21	-0.135	4.10	484	0.38	-1.70
2B3		0.250	80	n/a	108	-0.23	-0.115	4.10	484	0.38	-1.70

Electrode-equation 4B2:

$$v(t) = 110.2472$$
$$- 0.1800\,[0.5*(1+sign(i(t)))]i(t) - 0.1800\,[0.5*(1-sign(i(t)))]i(t))$$
$$+4.0315\log(q_s(t)/77)+508.1123[\exp(0.25q_s(t)/77)-1]$$
$$-1.8847q_s(t)+0.4700q_d(t)$$

Overview of today's discussion

We have presented a first principles model structure for modeling electrochemical systems.

Model parameter identification is based on a combination of nameplate information and input-output data.

Resulting models are predictive, and accurately represent the battery pack behavior over the life of the packs, before, during and after reconditioning.

Provides large and small perturbation responses.

Methodology has been applied to NiH2, NiMH, Li-ion, Pb-acid packs.

Aging effects can be numerically identified, or predicted (see next talk).