The Long-Term Performance of Small-cell Batteries Without Cell-Balancing Electronics

C. Pearson, C. Thwaite, D. Curzon (AEA Technology)
G. Rao (NASA/GSFC)

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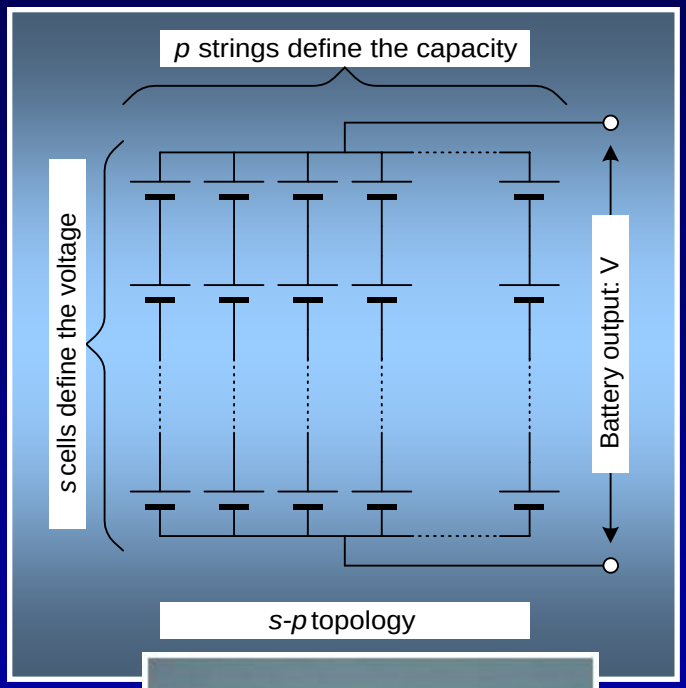
Background: AEA Small Cell Approach



- Standard Sony 18650 commercial cells
- Space Qualified
- Ensure continued uniformity
  - Lot Acceptance Test (LAT)
  - Screen cells
  - Match cells
- No cell balancing

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Background: Cell Uniformity History

- Tests ~8 yrs ago showed Sony HC do not imbalance
- AEA developed a theory (ESPC 2002)
  - Self-discharge (SD) decreases with state-of-charge (SOC)
  - Cells diverge to a state of dynamic equilibrium
  - Equilibrium spread depends on cell SD uniformity
- Balancing model verified against test data
- Short-term measures of SD difficult in Sony cells
  - Very small values, depends on technique
- Long-term evidence supports lower SD at low SD
- Battery testing best proof of performance
  - Typically mission specific tests

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Selected Test Data: Old Data

- GEO Standard Test
  - Commenced October 1998
- AEA - 6s2p modules
- Fixed 60% depth-of-discharge (DOD)
- 0°C, 20°C, 40°C
- 0.12C charge and taper to 25.2V
- 0.5C discharge
- 3 years pre-test storage: 50%SOC, 20°C
- Unmatched cells

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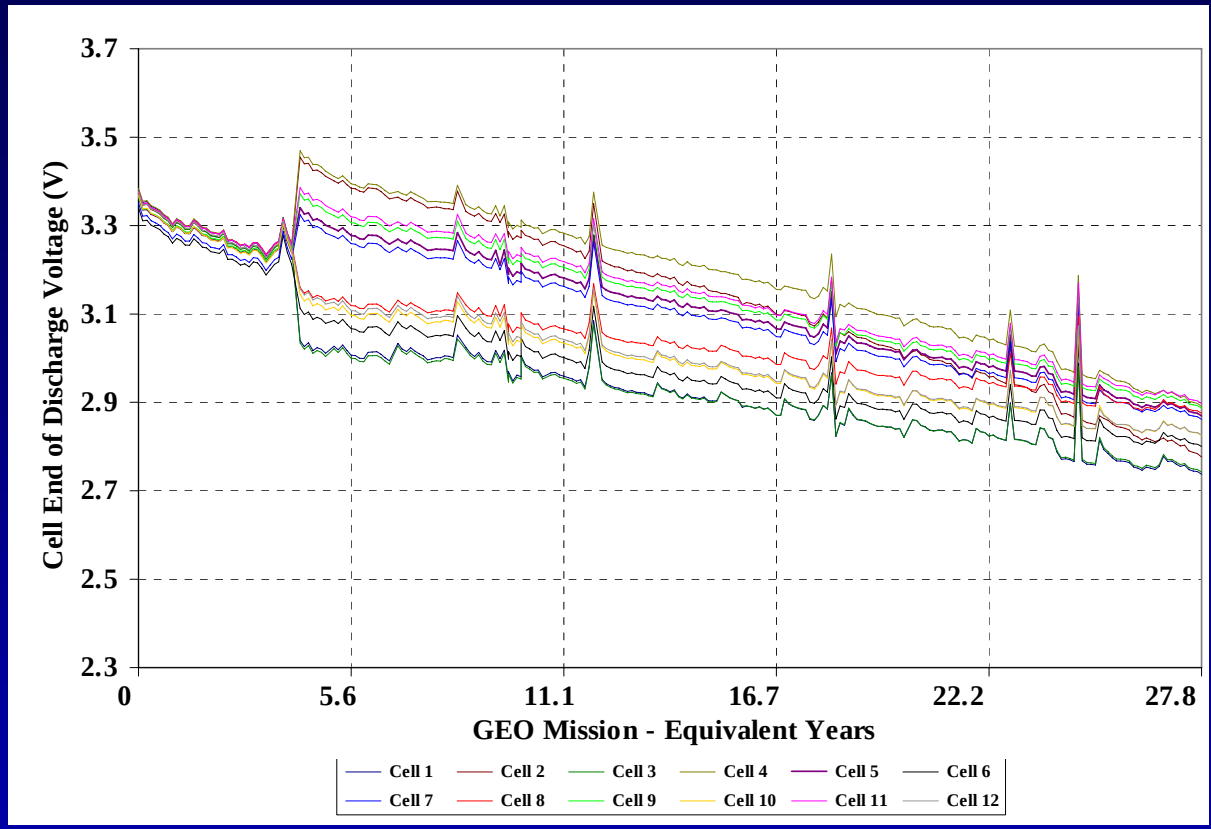
GEO Standard 20°C End-of-Discharge (EOD) Voltages



- 20°C Battery shorted after 350 cycles
- Despite battery abuse, cells remain uniform for further 2000 cycles

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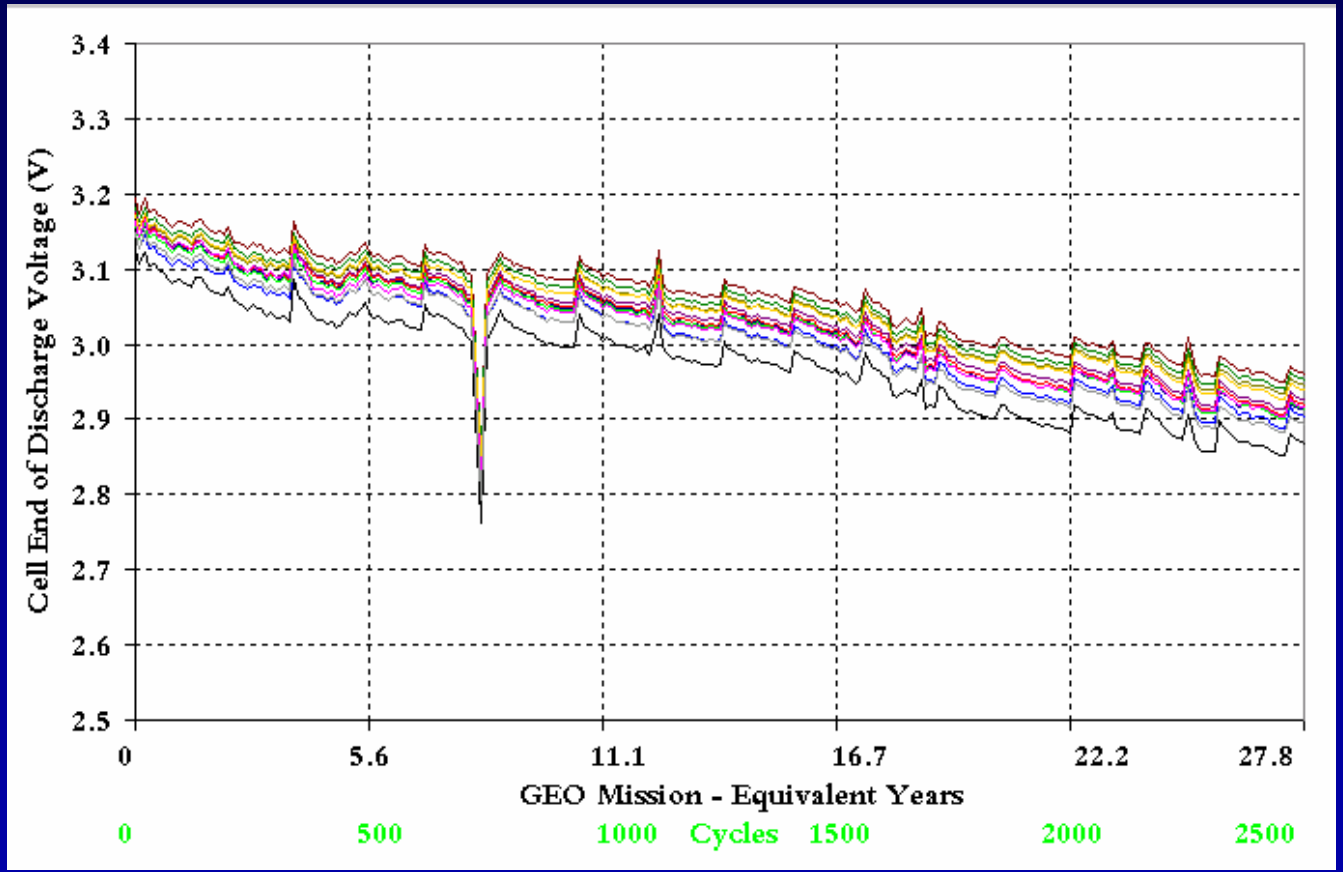
GEO Standard 0°C EOD Voltages



- 0, 40°C tests showed uniform cell performance

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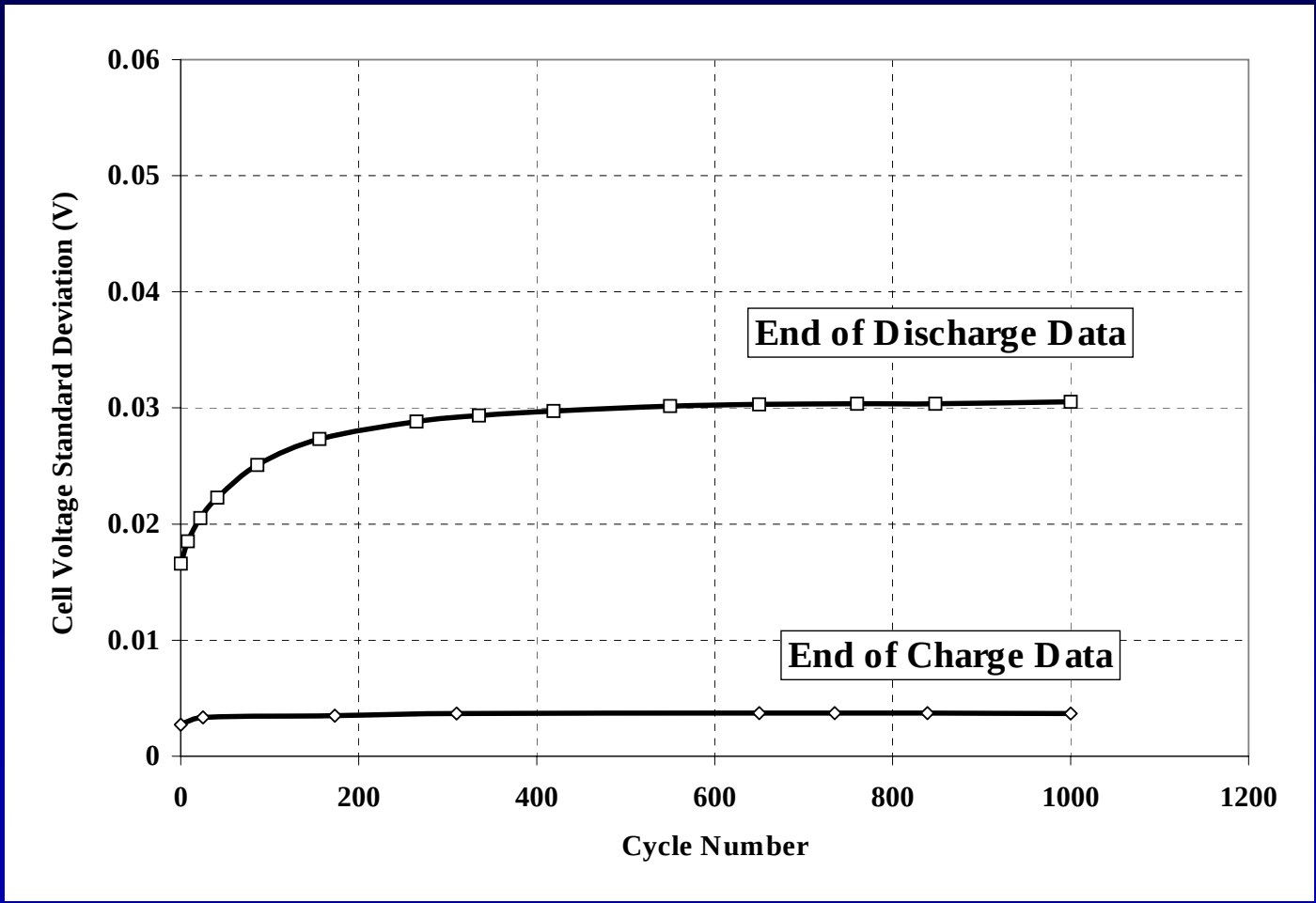
Selected Test Data: Old Data (cont'd)

- QM lifetest for STRV Geo Transition Orbit (GTO) mission
- No cell matching
- 6s2p battery
- 20°C
- 44% DOD
- Charge at C/9 to 24V (4V per cell)
- Discharge at C/5
- 250 cycles per month, test lasted 4 months

STRV Lifetest: Cell Uniformity



- Strong evidence of self-balancing mechanism

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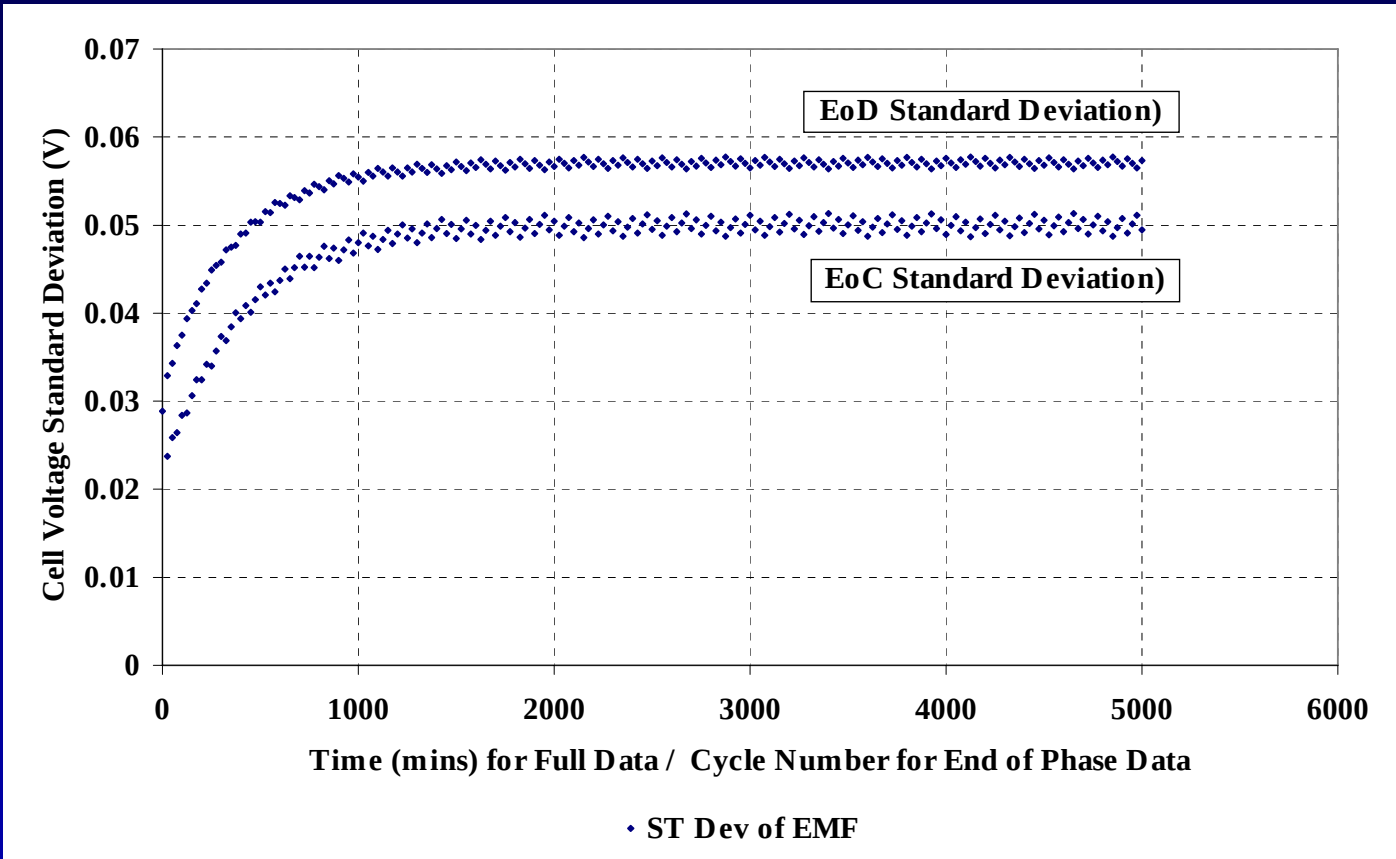
STRV: Cell Uniformity Prediction



- Characteristic self-balancing correctly predicted
- Conservative standard deviation predictions

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Selected Test Data: Ongoing

- Mars Express (MEX) Realistic Lifetest (RL)
- Milestones
  - Test started on Dec 5, 1999
  - Mars Cruise ended on Aug 16, 2000
  - 1st Martian year end on Jun 6, 2002
  - 2nd Martian year end on Mar 10, 2004
- Hardware Description:
  - 12Ah test module, 6s-8p
  - Individual cell voltage monitoring
  - Same voltage, 1/4 capacity of flight battery
  - Same batch of cells as flight battery
- Test temperature:
  - 20°C (max interface temp)

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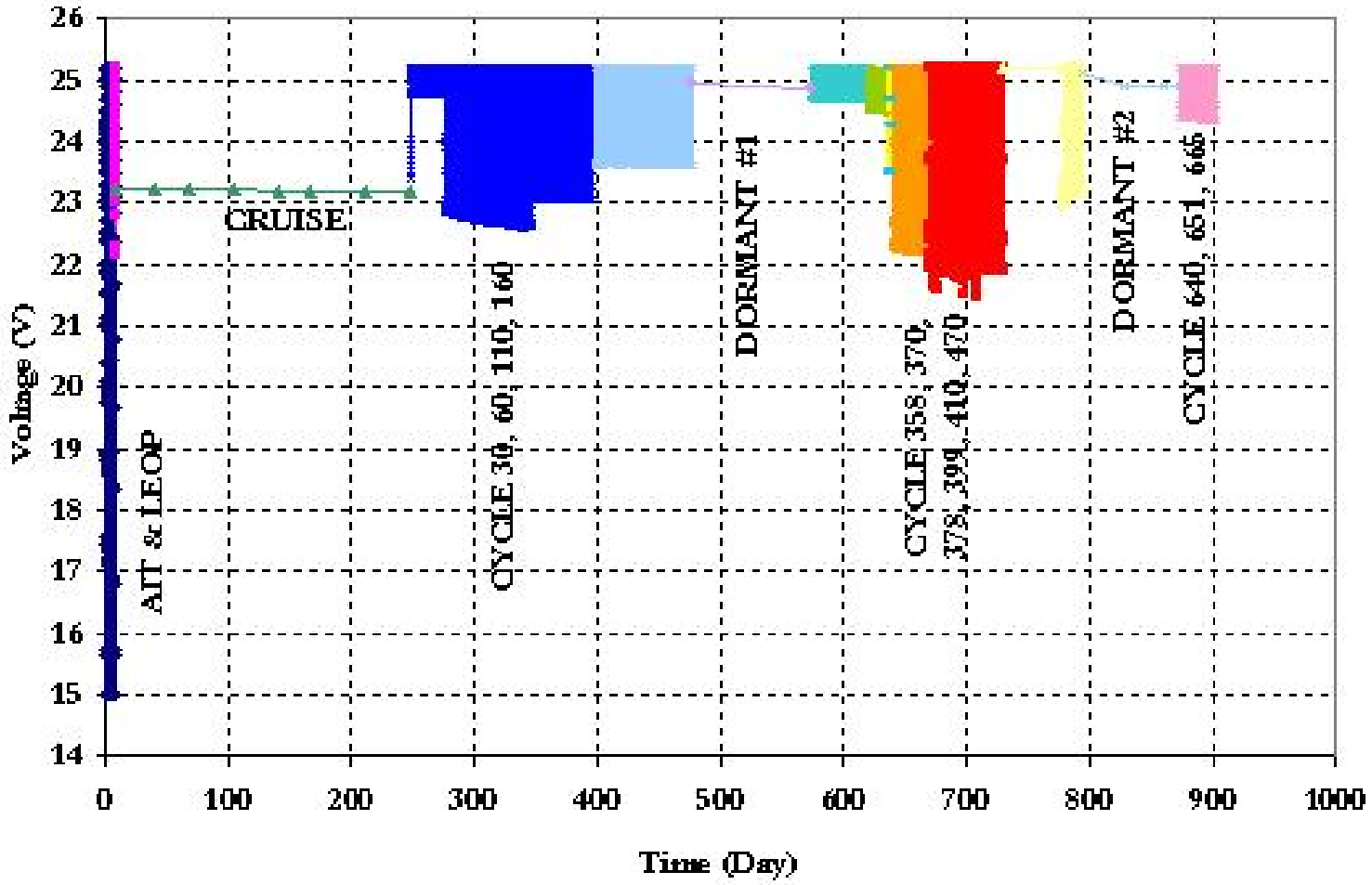
MEX Battery: Voltage



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MEX RL Test Profile: Summary

Cycle Type	Battery Discharge	Peak DOD	Primary Mission Cycles (One Mars Year)	Extended Mission Cycles (Two Mars Years)
Low Cycle	0 Wh < 25 Wh	2.5%	1800	4300
Standard Cycle	25 Wh < 100 Wh	10%	1990	3130
High Cycle	100 Wh < 250 Wh	24%	1000	1340
Extreme Cycle	250 Wh < 350 Wh	34%	240	510
Total number of Cycles			5030	8980

- Each orbit has up to 5 battery discharges
- Two periods each Martian-year with no eclipses

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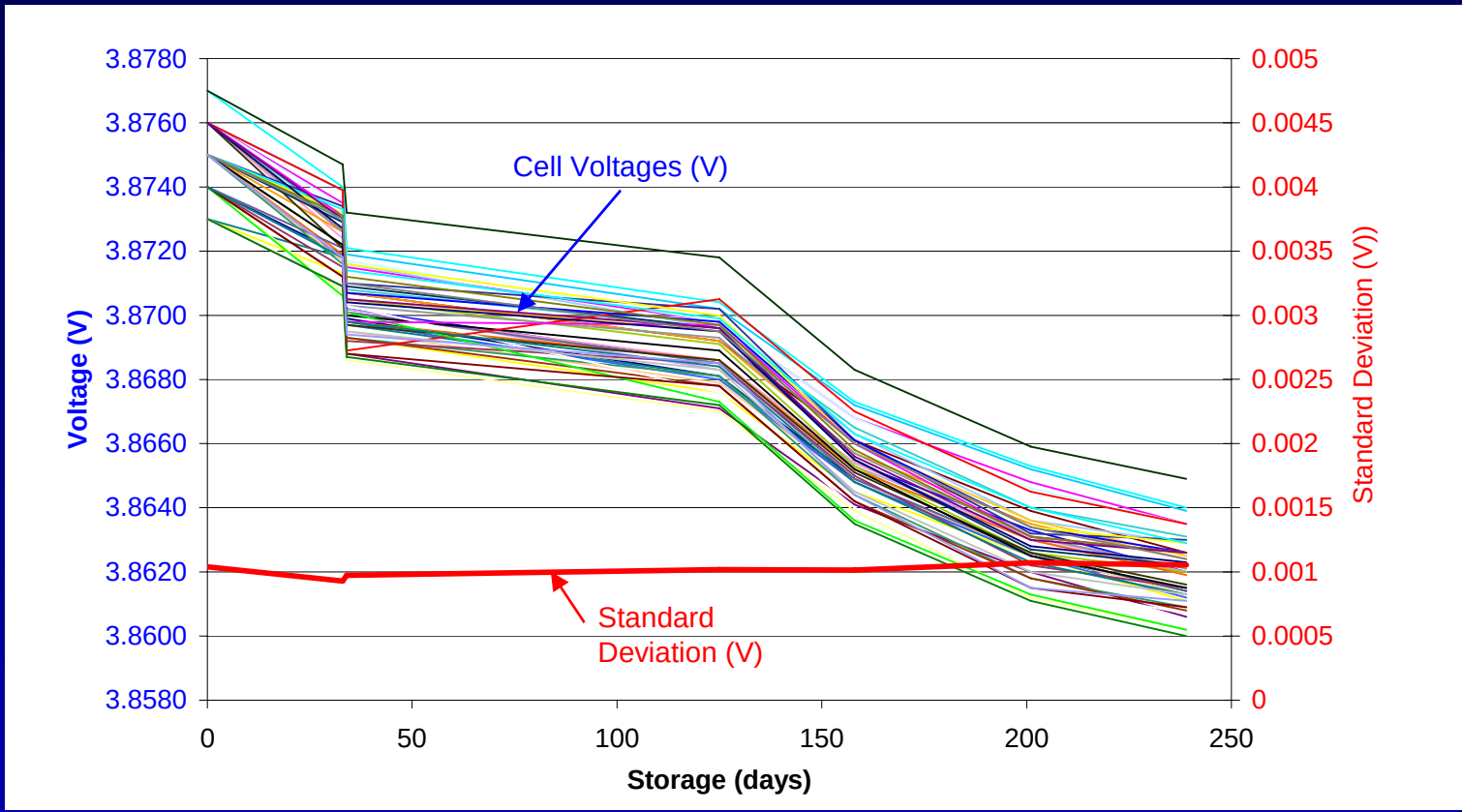
MEX Cell Uniformity: Storage Phase



- Cell voltage range ~5mV
- Cell voltage standard deviation ~1mV

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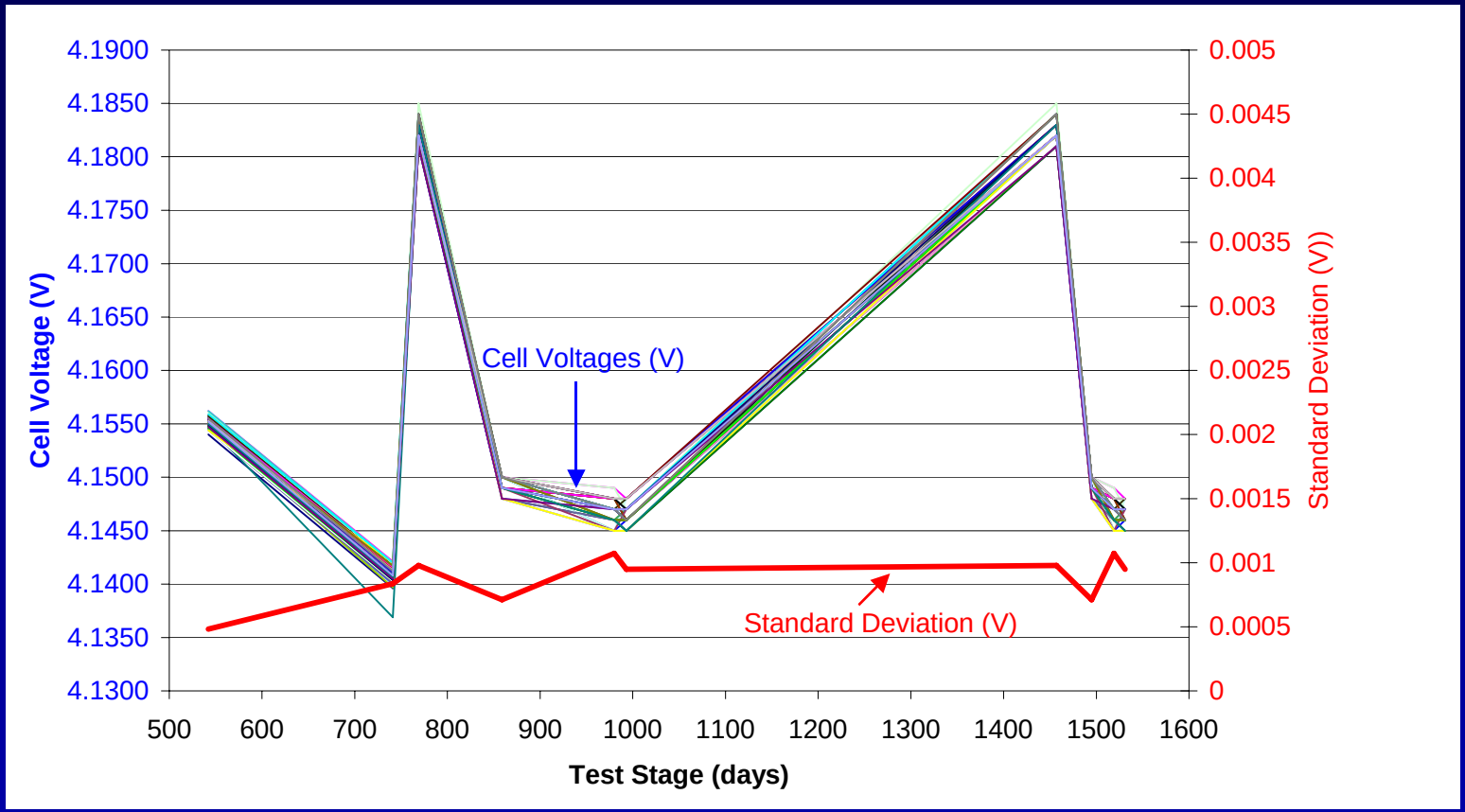
MEX Cell Uniformity: Martian Orbit



- EOC Voltages – range <5mV
- Cell voltage standard deviation ~1mV

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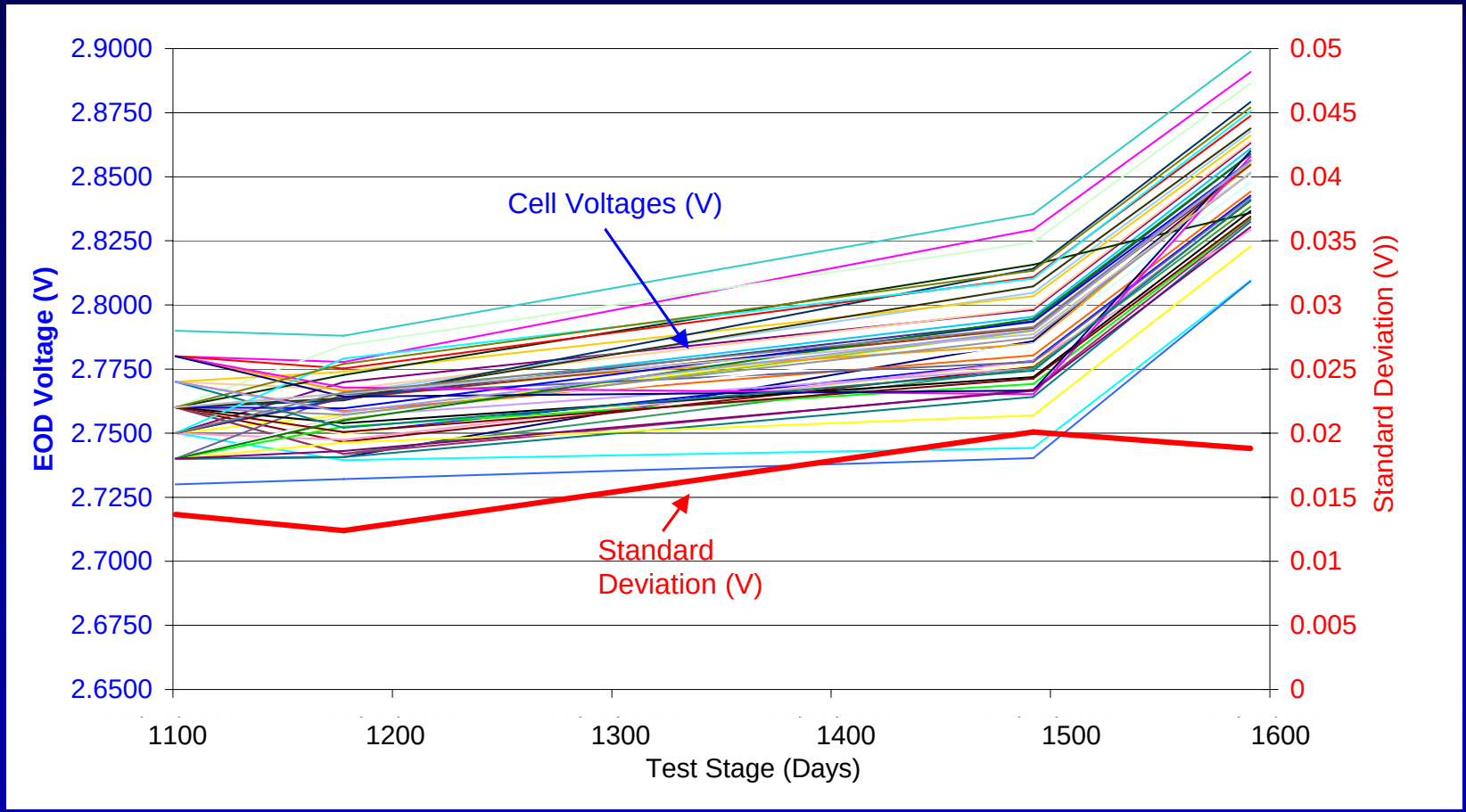
MEX Cell Uniformity: EOD Voltages



- Range <100mV, standard deviation ~20mV
- Uniformity maintained over 4 year test

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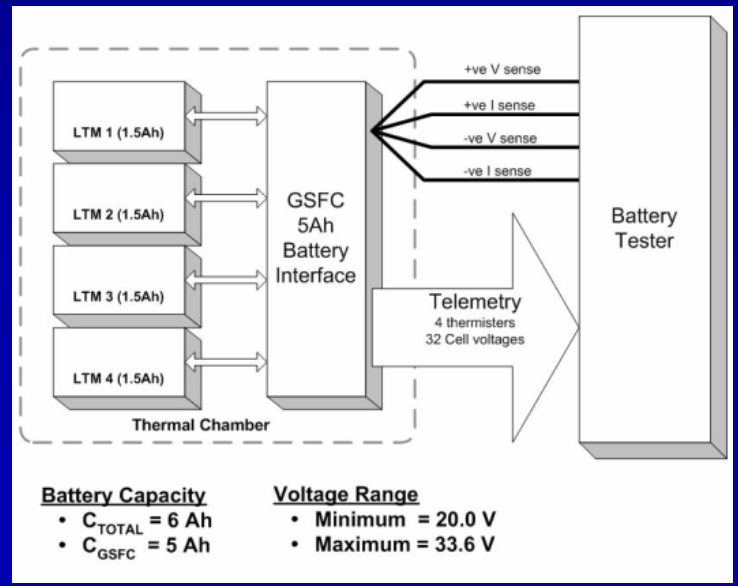
Selected Test Data: Ongoing (cont'd)

- NASA/GSFC LEO/GEO Test
- NASA/GSFC Funded, performed at AEA
- Mixed profile
  - LEO 30%DOD
  - GEO (up to 72%DOD) with solstice periods
- 8s4p battery (4x8s1p)
- Monitoring:
  - Individual cell voltage
  - Individual pack temperature
- Test Will Continue



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NASA/GSFC LEO/GEO Test

Stage	Orbit Type	Days	Stage	Orbit Type	Days
1	SCM (AEA 01 & GSFC 01)	2	16	GEO Eclipse cycles 42 days	42
2	Impedance measurement 01	3	17	SCM (GSFC 07)	1
3	LEO 30% DOD 450 Cycles	28			
4	SCM (AEA 02)	1			
5	LEO 30% DOD 450 Cycles	28			
6	SCM (AEA 03 & GSFC 02)	1	21	LEO 30% DOD 450 Cycles	28
7	GEO Eclipse cycles 42 days	42			
8	SCM (GSFC 03)	1			
9	GEO Solstice 140 days	140			
10	SCM (GSFC 04)	2			
11	Impedance measurement 02	1			
12	LEO 30% DOD 450 Cycles	28			
13	SCM (GSFC 05)	1	28	SCM (AEA 04 & GSFC 12)	2
14	LEO 30% DOD 450 Cycles	28	29	Impedance measurement 04	1
15	SCM (GSFC 06)	1		**TOTAL DAYS IN TEST**	**735**

	EoD	EoC
Max. Cells Dispersion	13 mV	5mV

	EoD	EoC
Max. Cells Dispersion	11 mV	5mV

	EoD	EoC
Max. Cells Dispersion	36 mV	5mV

Test presently ¾ through first GEO solstice period

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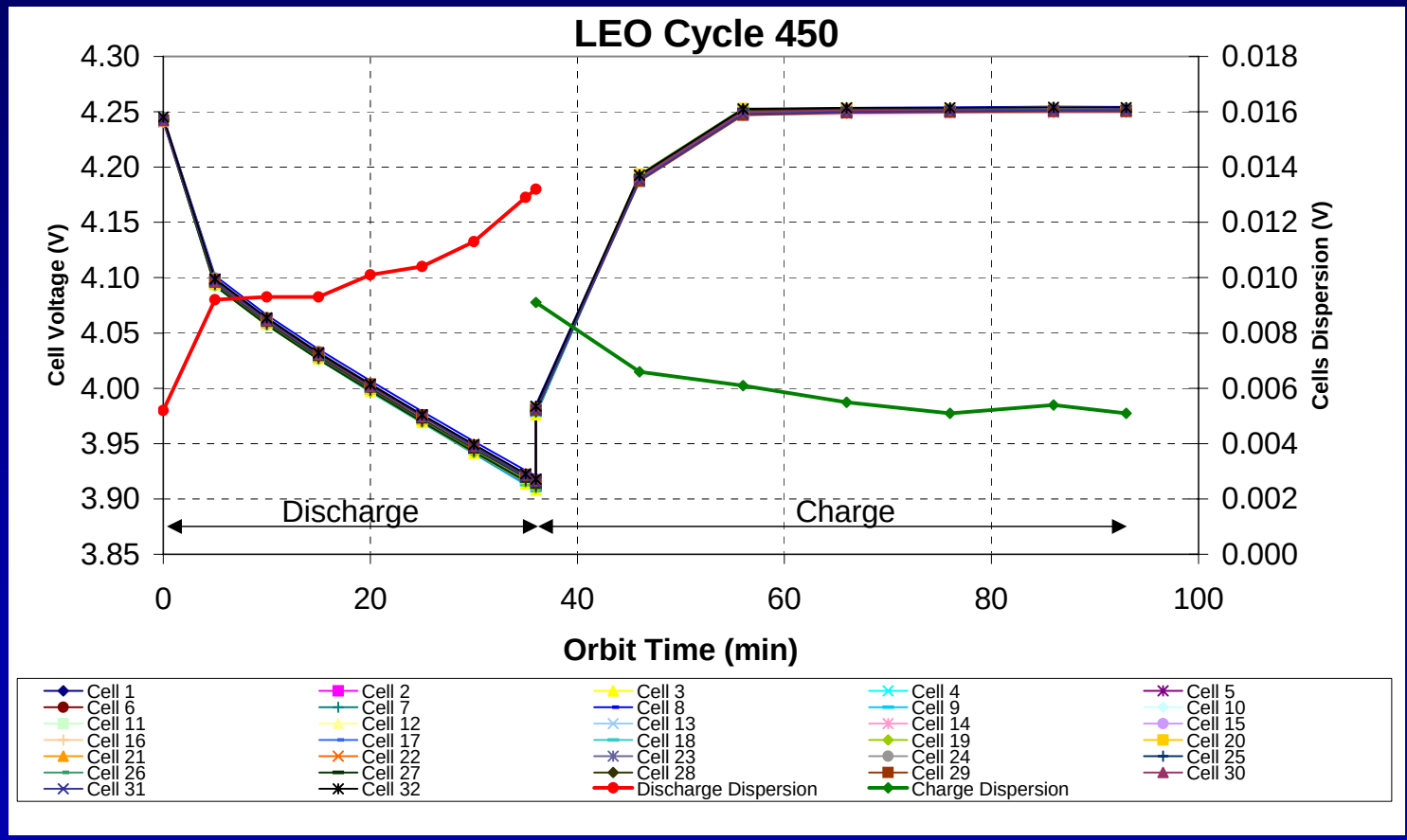
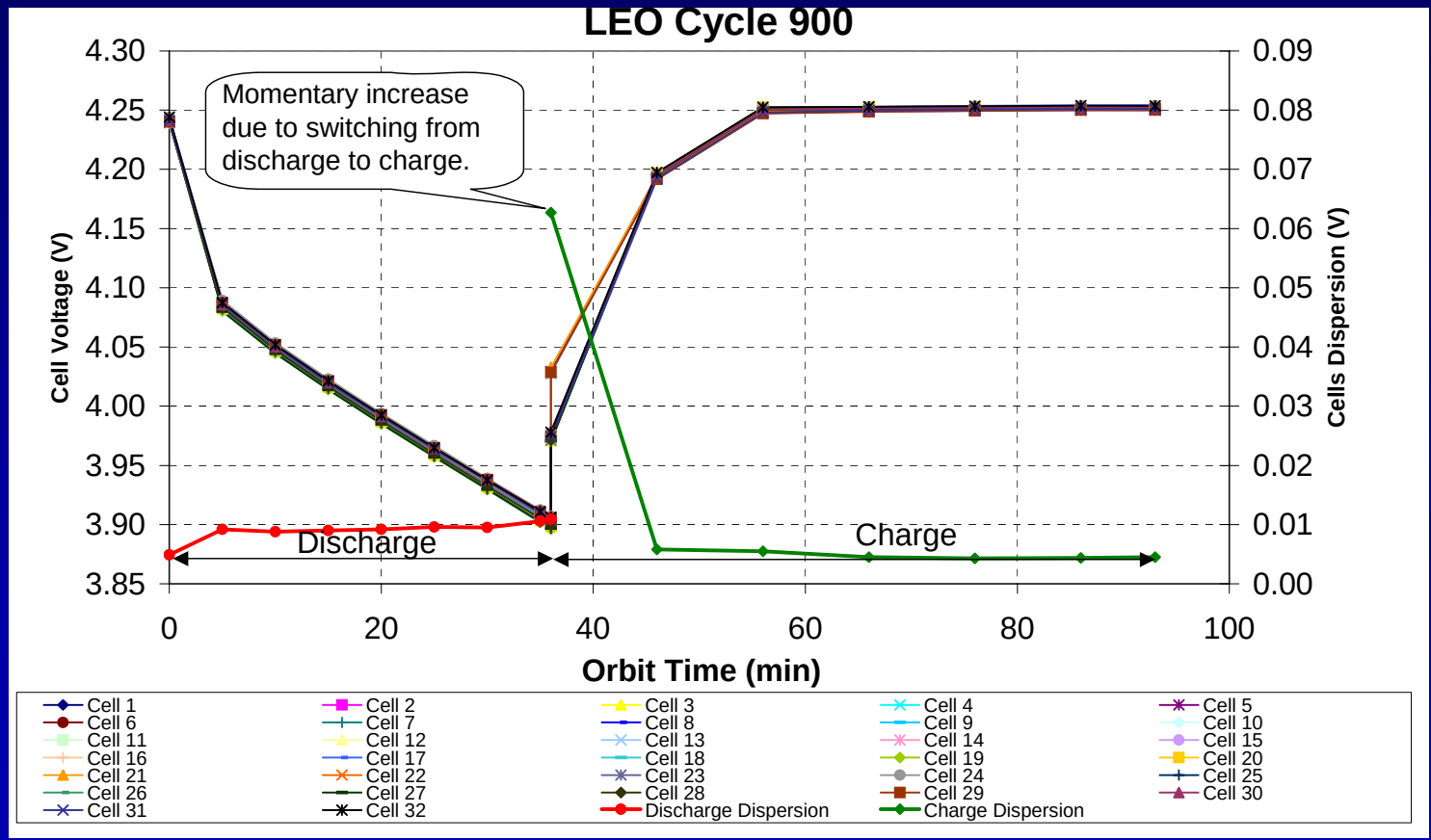
NASA/GSFC LEO/GEO Test: Dispersion - LEO 30% DoD Cycle 450

	EoD	EoC
Max. Cells Dispersion	13 mV	5mV



NASA/GSFC LEO/GEO Test: Dispersion - LEO 30% DoD Cycle 900

	EoD	EoC
Max. Cells Dispersion	11 mV	5mV



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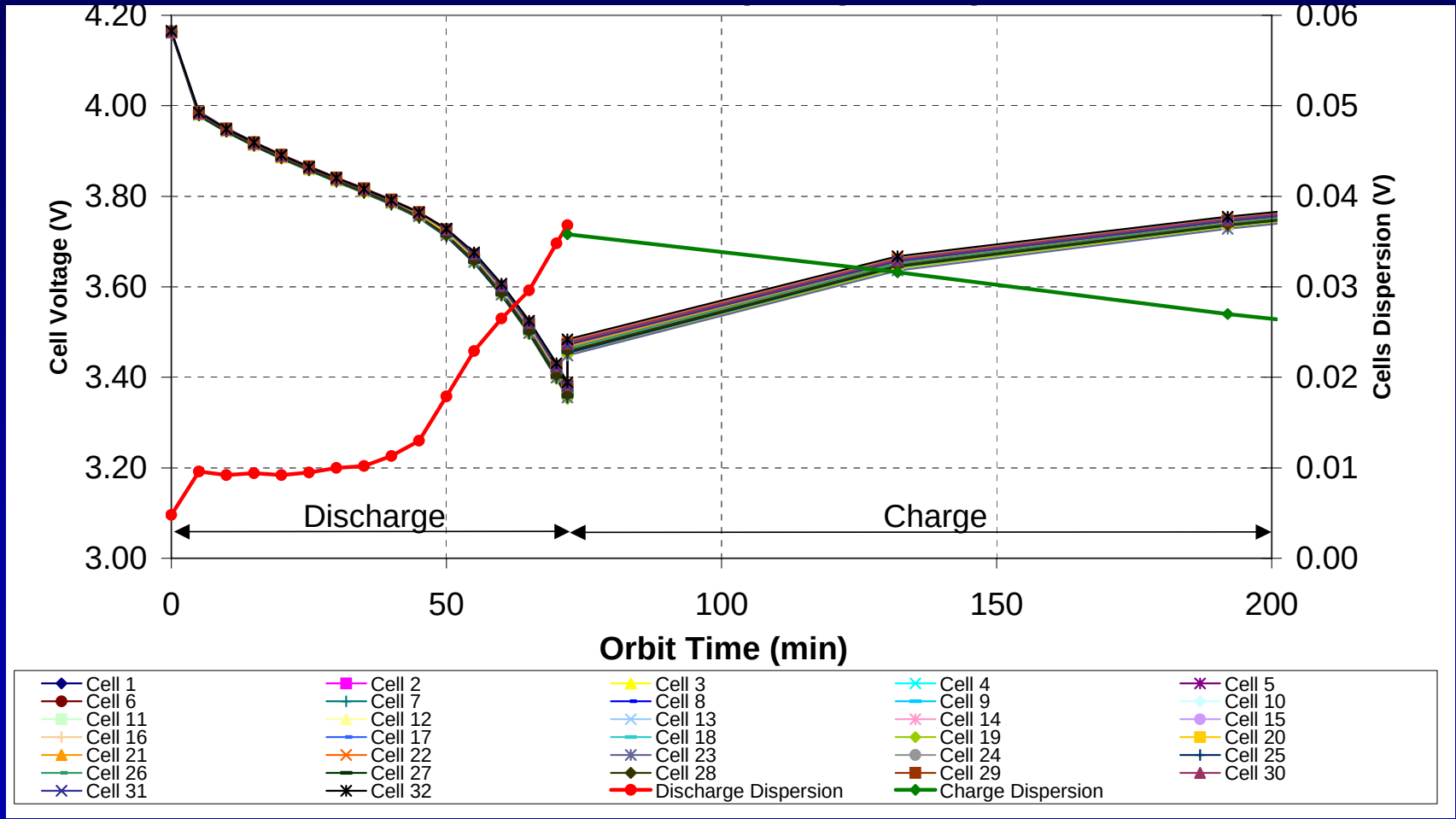
NASA/GSFC LEO/GEO Test: Dispersion - GEO, 72min Eclipse



Other Data

- Other customer funded tests
  - IAI LEO tests
  - Multiple mission specific lifetests
- PROBA
  - 3 years successful LEO operation
- MEX, 11 months in orbit
  - Didier Loche, ASTRIUM:

  "The MEX batteries are performing well with no anomalies and they are well matched. The measured capacity fade of 15%correlates with predictions and the MEX lifetest."
  - Test will continue

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Acknowledgements