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Retiring Undefeated: Iridium Nickel-Hydrogen Satellite Batteries (1997-2018)

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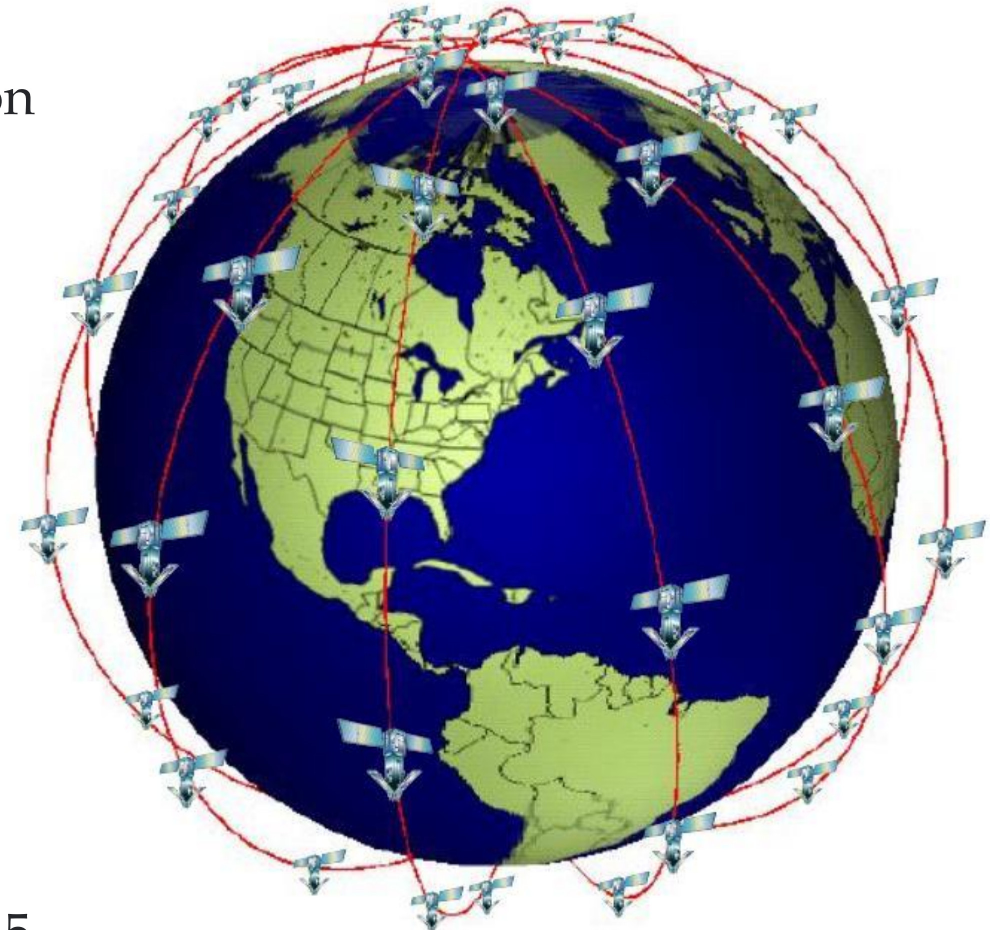
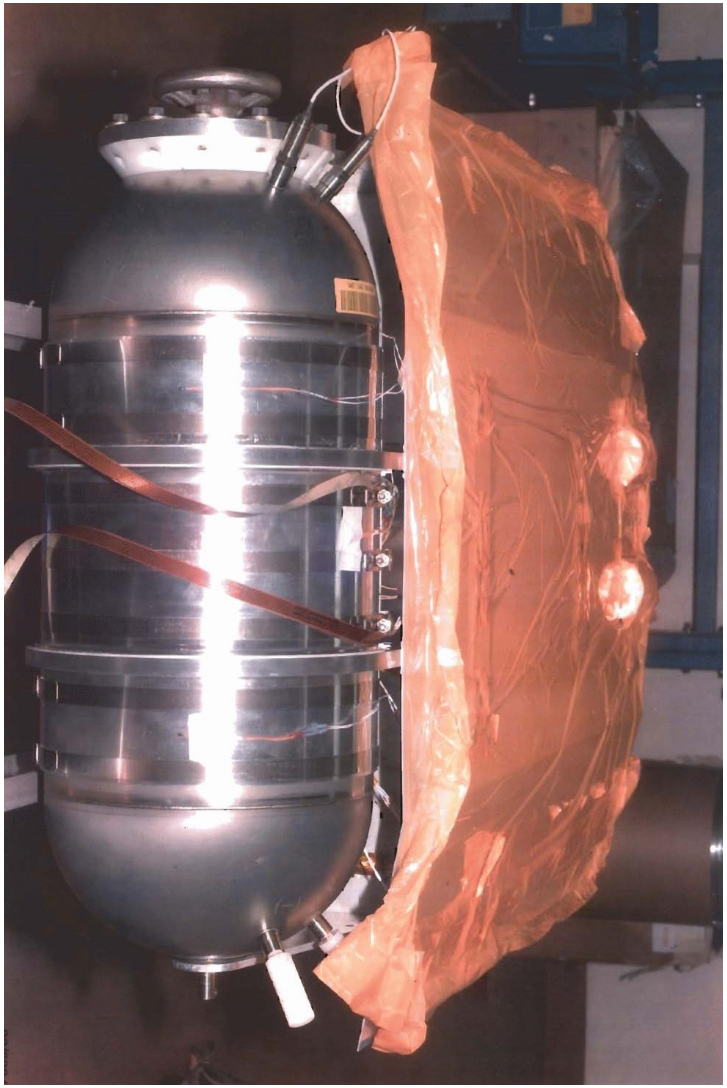
IRIDIUM SATELLITE – 21+ YEARS AND COUNTING

- IRIDIUM is a 66-satellite telecommunications constellation comprised of 6 planes of 11 satellites (or "SVs") each
  - 780 km altitude
  - 86.4 degree inclination
  - 100.48 minute orbital period
  - Beta season ~260 days
  - Dry mass: ~550 kg for Block1 (NEXT SVs ~685 kg)
- 88 satellites launched between May 1997 and December 1998, and a final 7 in 2002, after batteries had been stored for ~3.5 years



IRIDIUM SATELLITE BATTERIES

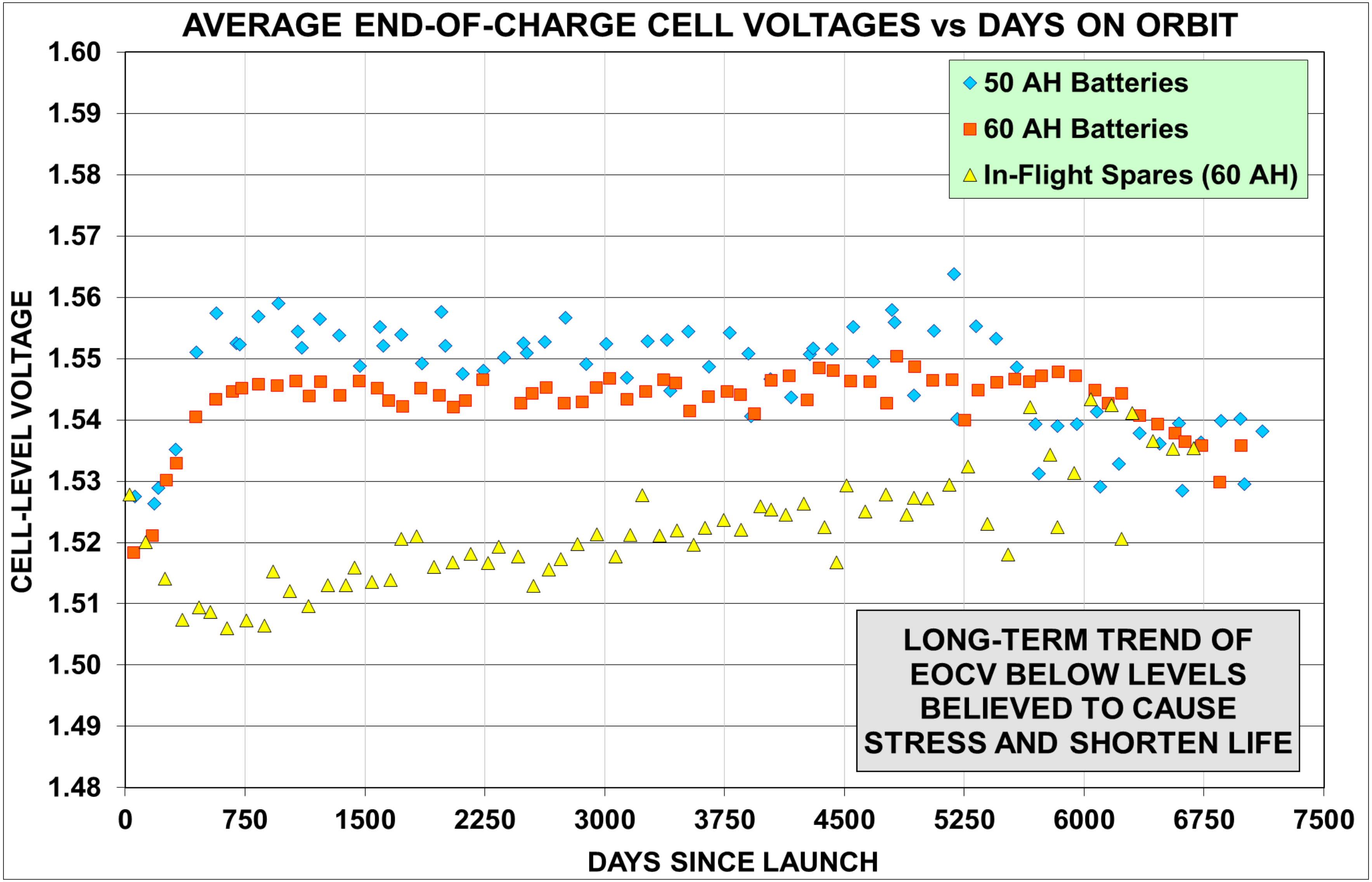
- Each satellite contained one Eagle-Picher Single Pressure Vessel (SPV) Nickel-Hydrogen battery
  - 22 cells, each with its own Electrolyte Containment System (ECS)
  - 31% KOH
  - Hydrogen Precharge
  - Battery weight ~67 lbs. (50 A-h) or ~80 lbs. (60 A-h)
- 20 space satellites contained a 50 A-h battery (First four launches) and 75 contained a 60 A-h battery
- As of April 1, these batteries – through their various lifetimes – accumulated > 1500 YEARS (>13.2 million hours) of failure-free performance



BATTERY CHARGE CONTROL

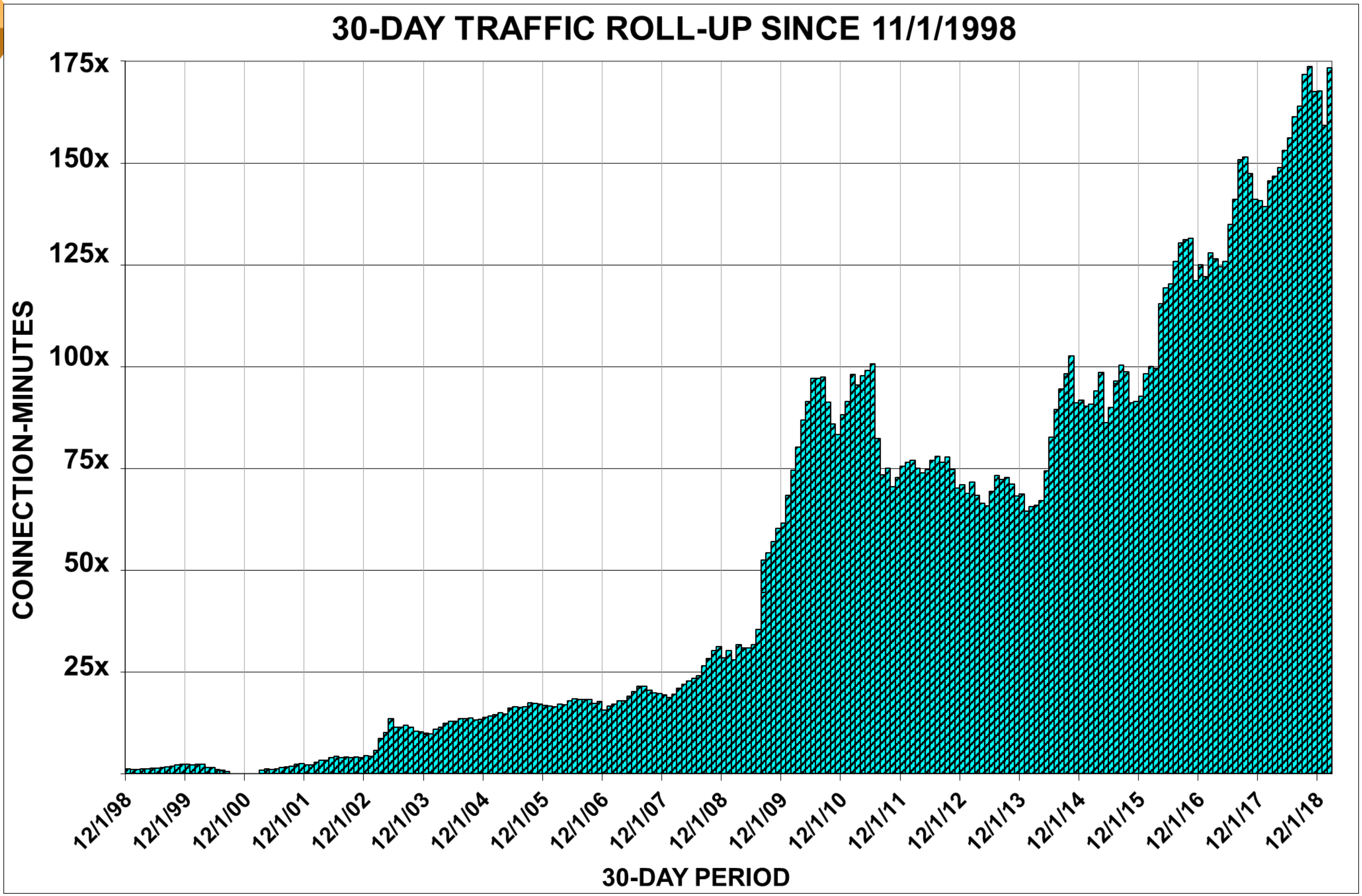
- Charge to a battery-unique pressure each orbit, normalizing the reading to its 0 deg. C equivalent via Charles' Gas Law
- Each battery's target pressure is 85% of the full-charge pressure as measured in the 10 Deg. C capacity test performed at the battery vendor (and as also normalized to 0 Deg. C)
- Other methods of charge control were available and occasionally employed, but pressure-based control was considered the most reliable and therefore was used almost exclusively
  - EOCV, Recharge Ratio, Charge Efficiency ("slope"), and Overtemperature were also available for voting combinations with pressure and each other
- Energy balance achieved on a daily basis; NOT orbit-by-orbit, so batteries <u>may</u> not be recharged completely every orbit
- End-of-charge voltage unconstrained
- Increased for about the first 500 days and then settled out

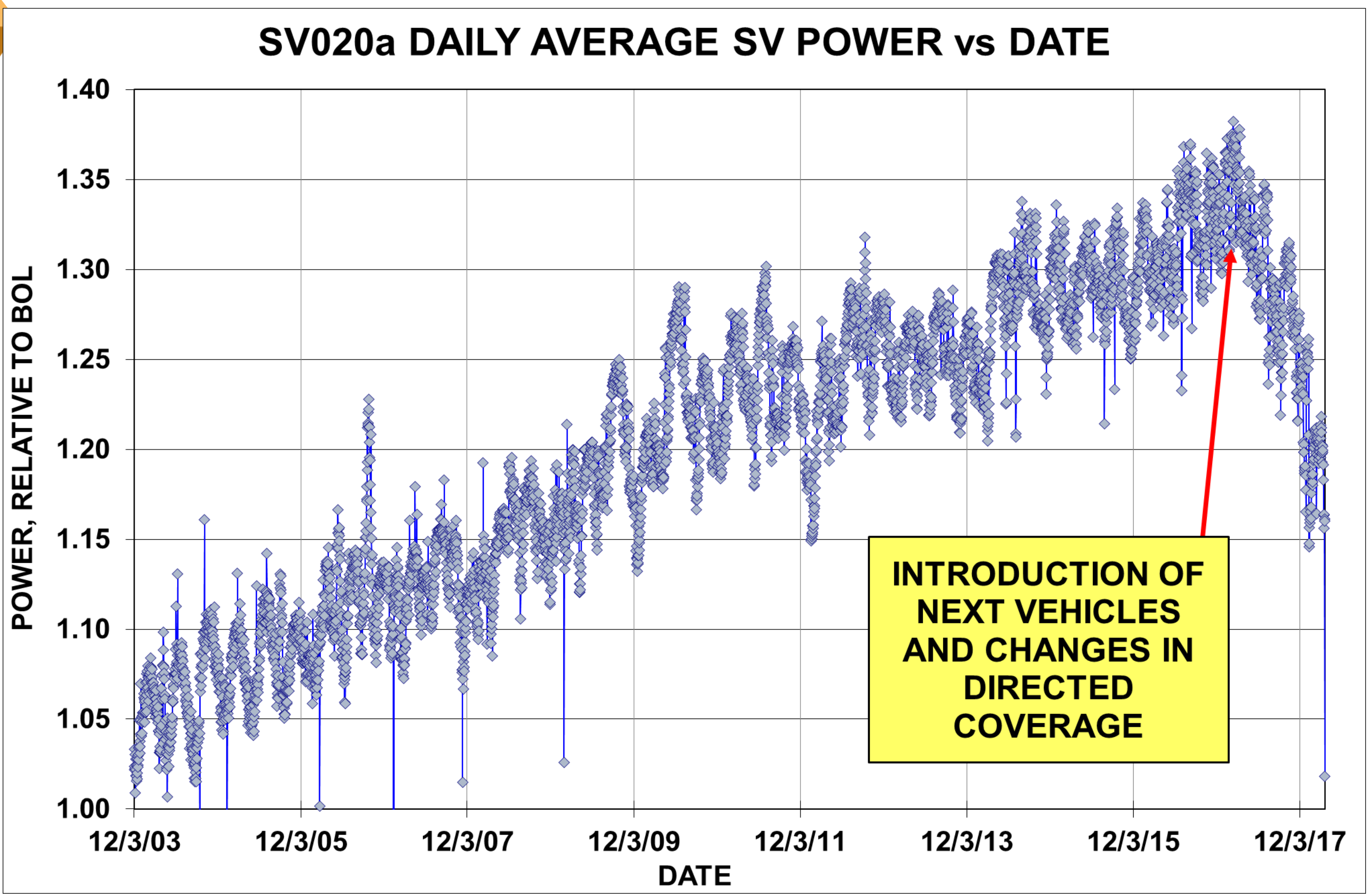
PRESSURE-BASED CONTROL EFFECT ON CHARGE VOLTAGE

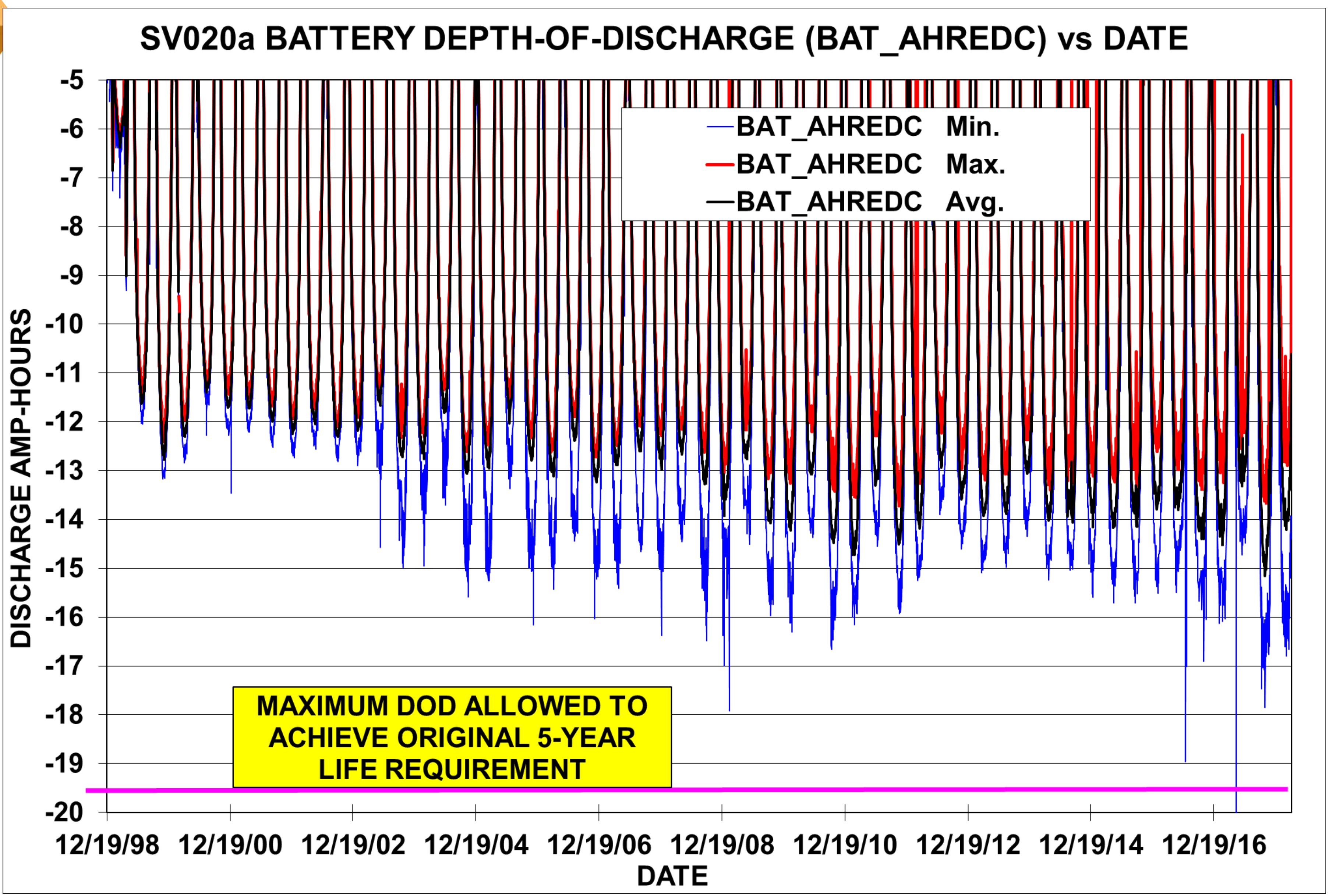


BATTERY DEPTH-OF-DISCHARGE / SV POWER CONSUMPTION

- Almost all satellites in history have experienced decreased electrical consumption with on-orbit life, and a concurrent decrease in battery DOD, mainly due to equipment failures of one kind or another
  - Budgetary constraints may also limit satellite loading with age
- Iridium satellites – however - INCREASED consumption
- While scattered equipment failures have occurred, spacecraft load increased steadily by about 15% for the first 12 years (1998 – 2010)
  - On some satellites, the load increased right up to the point that the new Iridium-NEXT satellites began to be substituted into the constellation
  - Battery DOD increased in a similar manner for most
- Iridium traffic is 61 times as much as it was 17 years ago


30-DAY TRAFFIC ROLL-UP SINCE 11/1/1998
CONNECTION-MINUTES
175x
150x
125x
100x
75x
50x
25x
12/1/98
12/1/99
12/1/00
12/1/01
12/1/02
12/1/03
12/1/04
12/1/05
12/1/06
12/1/07
12/1/08
12/1/09
12/1/10
12/1/11
12/1/12
12/1/13
12/1/14
12/1/15
12/1/16
12/1/17
12/1/18
30-DAY PERIOD

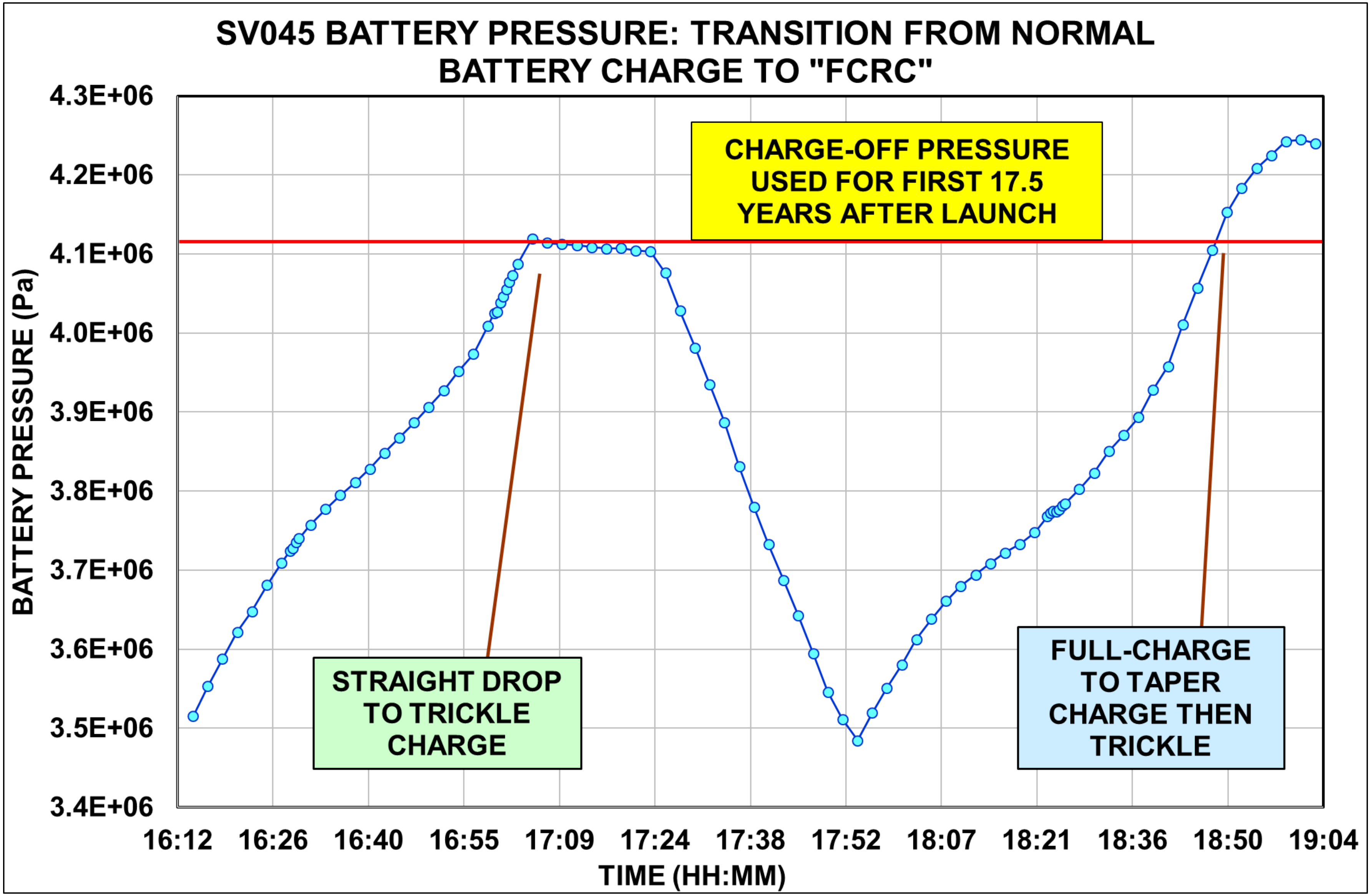

SV020a DAILY AVERAGE SV POWER vs DATE
POWER, RELATIVE TO BOL
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
12/3/03
12/3/05
12/3/07
12/3/09
12/3/11
12/3/13
12/3/15
12/3/17
DATE
INTRODUCTION OF NEXT VEHICLES AND CHANGES IN DIRECTED COVERAGE


SV020a BATTERY DEPTH-OF-DISCHARGE (BAT_AHREDC) vs DATE
DISCHARGE AMP-HOURS
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
BAT_AHREDC Min.
BAT_AHREDC Max.
BAT_AHREDC Avg.
MAXIMUM DOD ALLOWED TO ACHIEVE ORIGINAL 5-YEAR LIFE REQUIREMENT
12/19/98
12/19/00
12/19/02
12/19/04
12/19/06
12/19/08
12/19/10
12/19/12
12/19/14
12/19/16
DATE

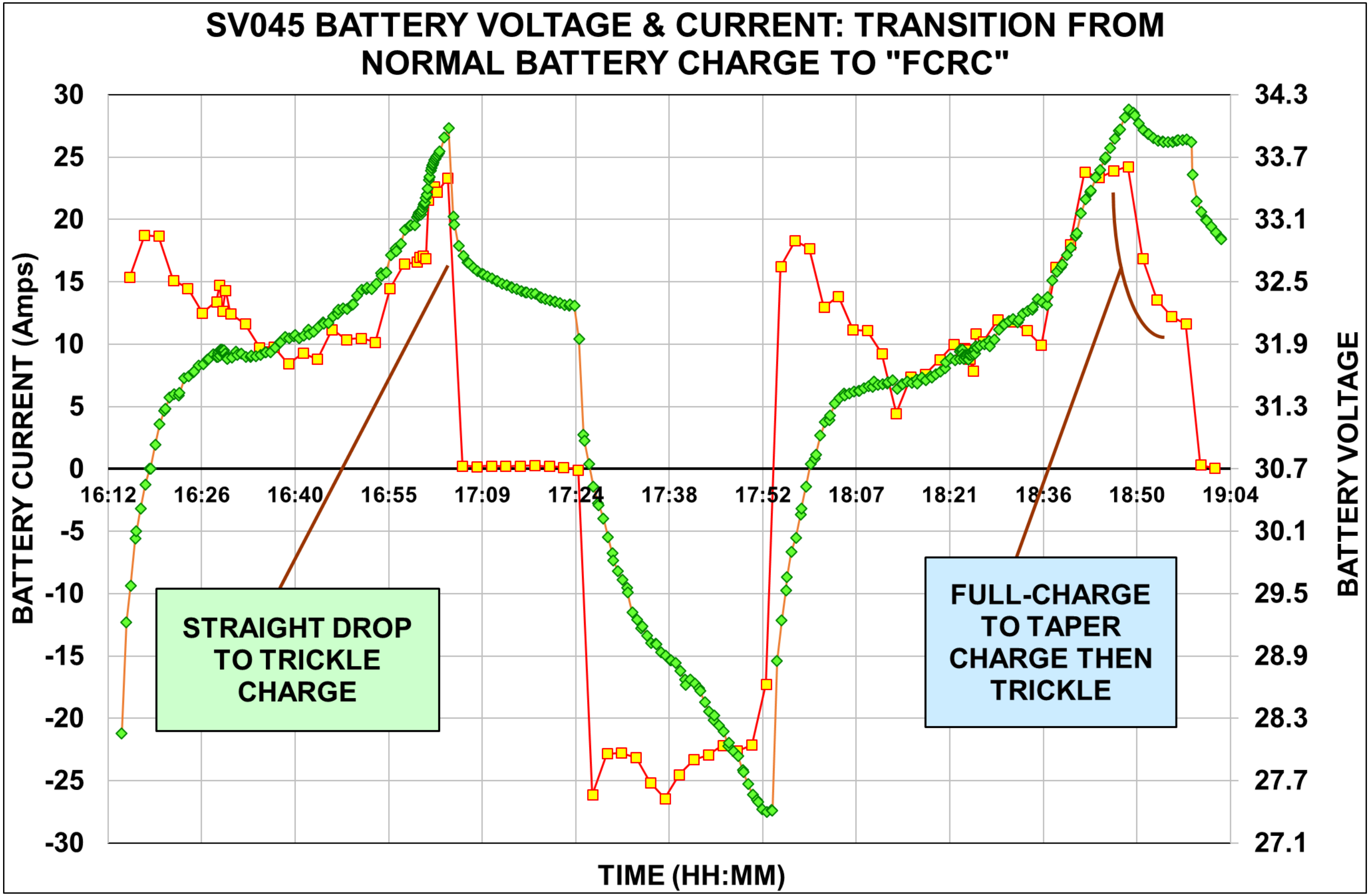
INCREASING USAGE OF THE BATTERIES

- Beginning in 2013, we began running tests to measure how much we could drive up the state-of-charge without adding too much stress
  - Charge up to voltage rollover and/or temperature rise
- Reasons for raising the state-of-charge on select batteries:
  - Allow for greater reserve for contingency operations
  - Allows for greater battery DOD (which was already occurring year-over-year) without having to move Undercharge Fault limits
  - Counteract sagging instantaneous (i.e. during Transmit time slots) battery/Bus voltages when subjected to load currents near end-of-eclipse of 2 – 2.5C (100 – 140 amps)
    - This was a special concern for 50 amp-hour batteries, which were both older and had higher internal impedance
- Once a safe higher pressure was derived, charge normally to the old pressure target, then taper-charge to the new higher pressure target
  - Termed “Full-Charge, Reduced Current”, or FCRC

FCRC – WHAT IT LOOKS LIKE IN PRACTICE



FCRC – WHAT IT LOOKS LIKE IN PRACTICE #2



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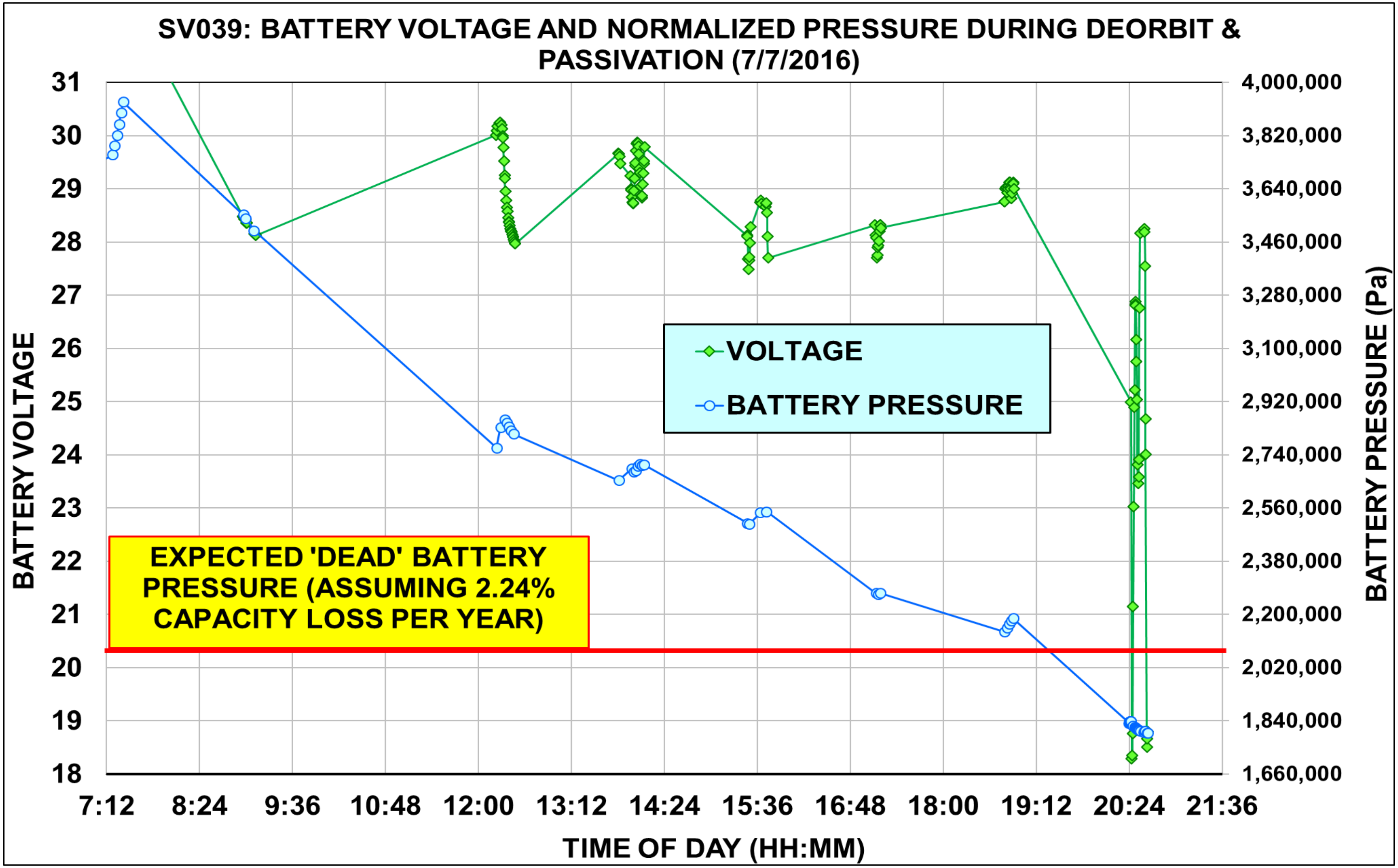
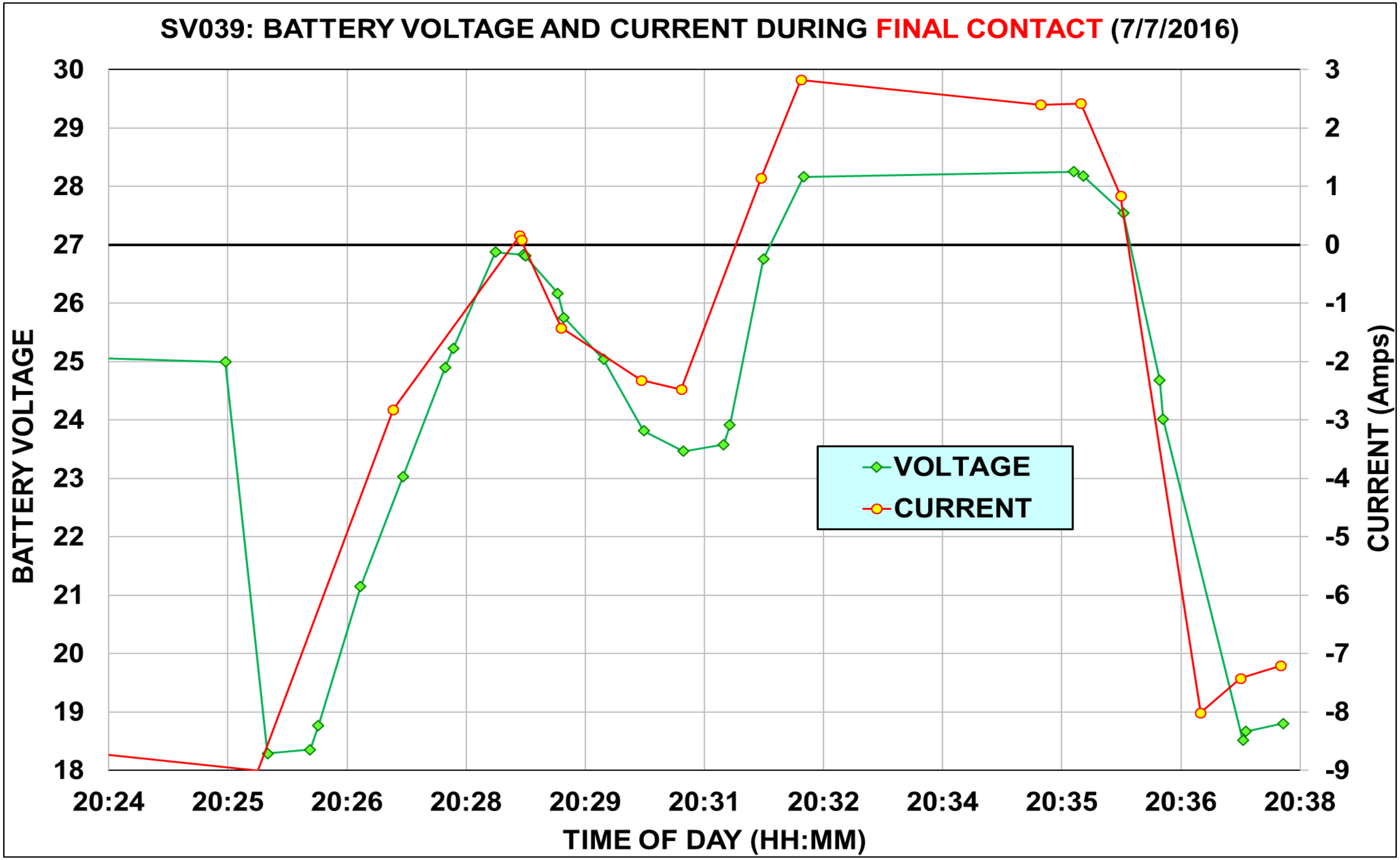
DEORBIT END-OF-LIFE BATTERY CAPACITY MEASUREMENT

- With the launch of Iridium NEXT satellites beginning in January 2017, older Block1 satellites could be replaced and deorbited
- Part of the deorbit process is to 'passivate' the satellite by orienting the solar arrays to increase atmospheric drag, which also makes it 'power negative' and the battery begins its final discharge.
  - Aided by disconnecting all or most of the solar array strings from the Bus in an attempt to 'tweak' the discharge rate
- We wanted to see if we could get some measure of the battery's end-of-life capacity from this process, despite these complicating factors:
    - As little as one pass (if that) per orbit (every ~97 minutes) of anywhere from 2.5 to 6.5 minutes duration
    - Battery discharging 10 – 13 amp-hours between contacts and could easily die between ground passes
    - Satellite likely begins tumbling before battery is depleted
    - Secondary Link contacts only: low bandwidth and not an 'omni' antenna

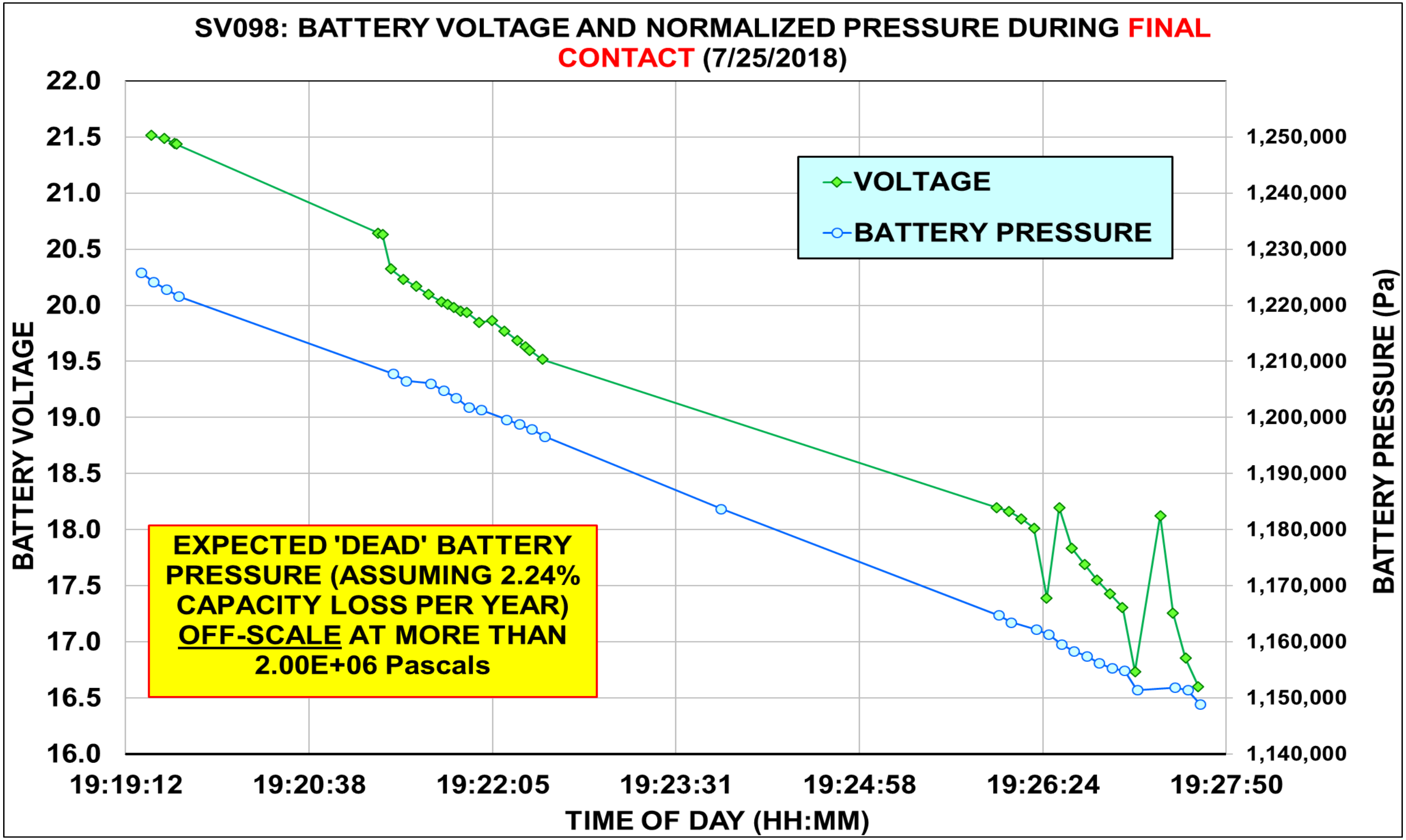
WHAT'S AN END-OF-LIFE CAPACITY MEASUREMENT LOOK LIKE?

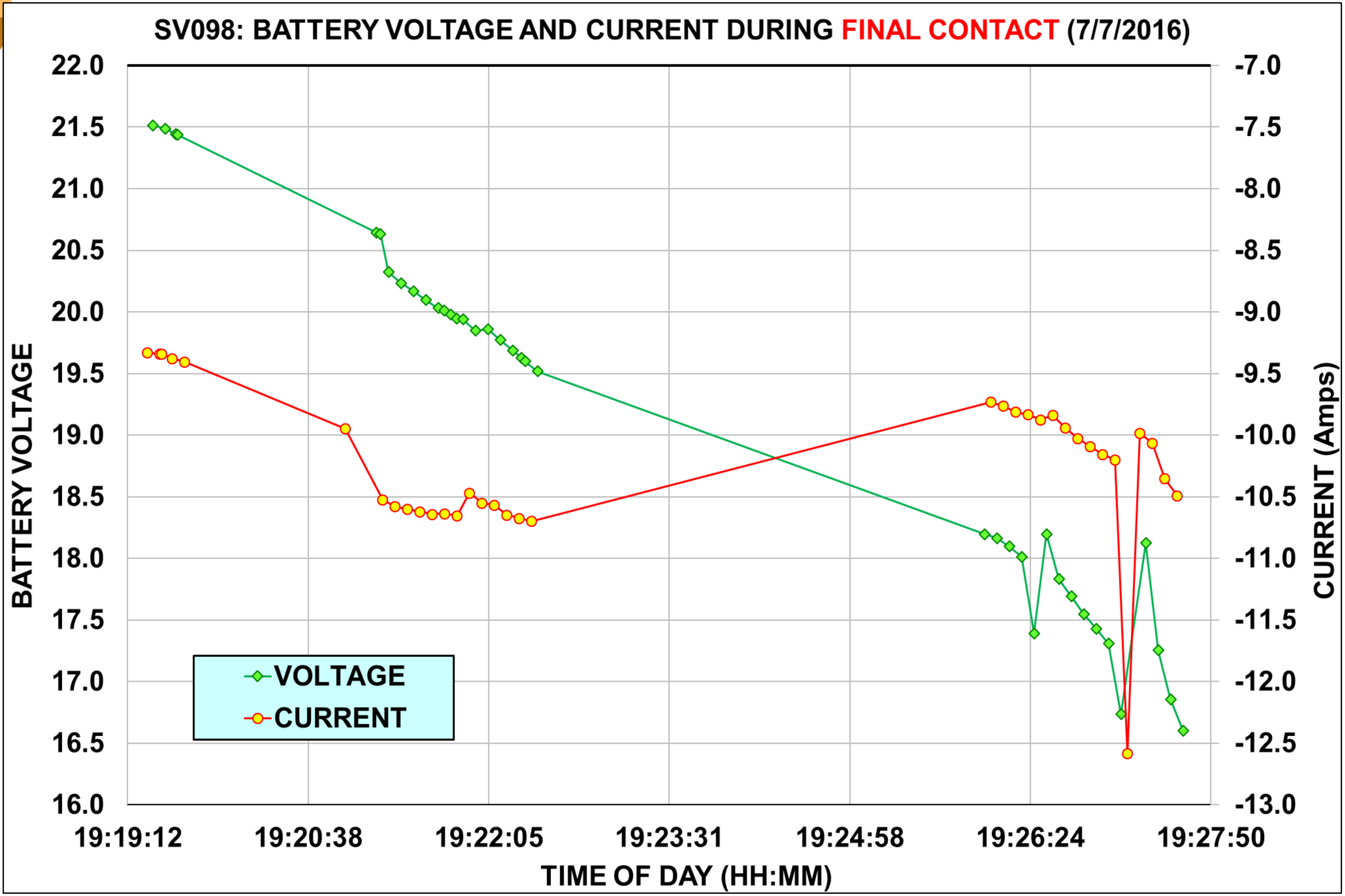


A BATTERY ON ITS '2ND-PLATEAU' VOLTAGE IS ALSO ON ITS 'LAST LEGS'



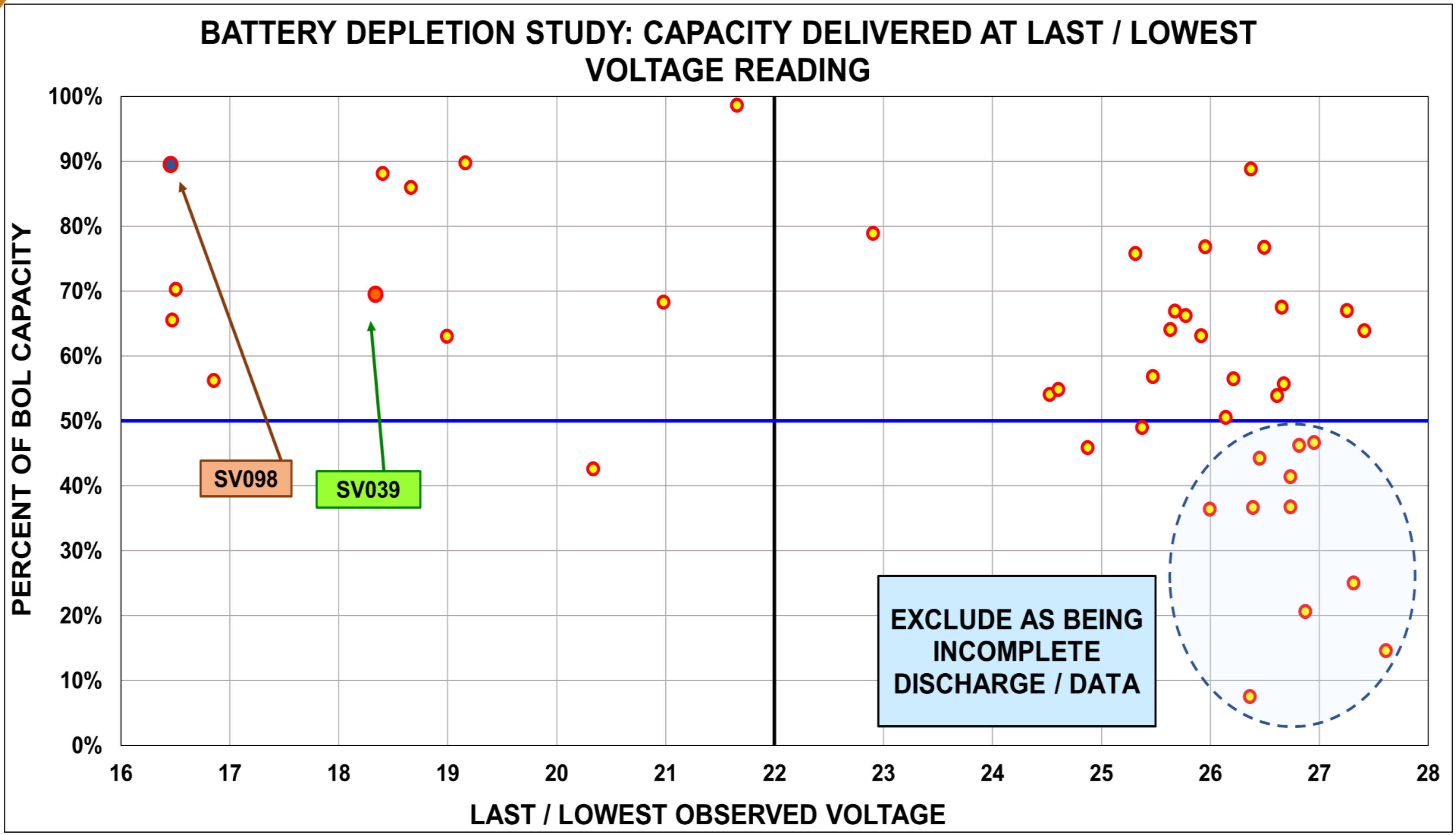
WHAT'S AN END-OF-LIFE CAPACITY MEASUREMENT LOOK LIKE? ANOTHER EXAMPLE




SV098: BATTERY VOLTAGE AND CURRENT DURING FINAL CONTACT (7/7/2016)
BATTERY VOLTAGE
CURRENT (Amps)
TIME OF DAY (HH:MM)
22.0
21.5
21.0
20.5
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
16.0
-7.0
-7.5
-8.0
-8.5
-9.0
-9.5
-10.0
-10.5
-11.0
-11.5
-12.0
-12.5
-13.0
19:19:12
19:20:38
19:22:05
19:23:31
19:24:58
19:26:24
19:27:50
VOLTAGE
CURRENT

EXPECTATIONS FOR CAPACITY LOSS / RESULTS

- Hubble Space Telescope (HST) On-orbit battery reconditioning data, as presented at the 2007 NASA Battery Workshop, seemed to give a good model for long-term Nickel-Hydrogen battery degradation
- From these published results we derived an average capacity degradation rate of 2.24% per year, or ~44.5% after 20 years
- Despite the handicaps, we were able to obtain very usable results for 33 of 59 satellites deorbited between July 7, 2016 and March 14, 2019.
- Usable results defined as any below 25.5 volts and/or at least 50% BOL capacity observed.
- By and large, the Iridium/EPI SPV battery seemed to fare better than Hubble's perceived 2.24% capacity loss per year
  - Average to-date has been 1.65% per year on-orbit
  - Not sure how much of the 2nd-plateau capacity was included in HST calculations


BATTERY DEPLETION STUDY: CAPACITY DELIVERED AT LAST / LOWEST VOLTAGE READING
PERCENT OF BOL CAPACITY
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
16
17
18
19
20
21
22
23
24
25
26
27
28
LAST / LOWEST OBSERVED VOLTAGE
SV098
SV039
EXCLUDE AS BEING INCOMPLETE DISCHARGE / DATA

CONCLUSIONS

- Iridium closely followed LMSC's instructions for battery management except as dictated by circumstances
- Iridium closely monitored battery performance using some thirty-odd telemetry mnemonics, another dozen derived relationships – on a variety of time-scales – yielding over 4,000 trend plots
- Iridium obtained up to 4X the required Mission life of 5 years
- Great thanks are owed to LMSC for a disciplined approach to battery management and to Eagle-Picher – Joplin for a tremendous product.
- And a great ***Thank You*** to all my colleagues that provided their analysis, their support, their attention to detail over the years.

Douglas Hafen – Electrical Power Subsystem Engineer

Joseph Allard – Manager, Service Team

Craig Vogler – Manager, Space Systems Team

Kenneth Rock – Space Vehicle Lead Platform Engineer

Thomas Guffey – Chief Engineer

James Sedler – Attitude Determination System Engineer

Jake Leaskey – Platform Software Engineer

Audrey Puderbaugh – Attitude & Orbital Control / Propulsion Engineer