iridium Everywhere

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

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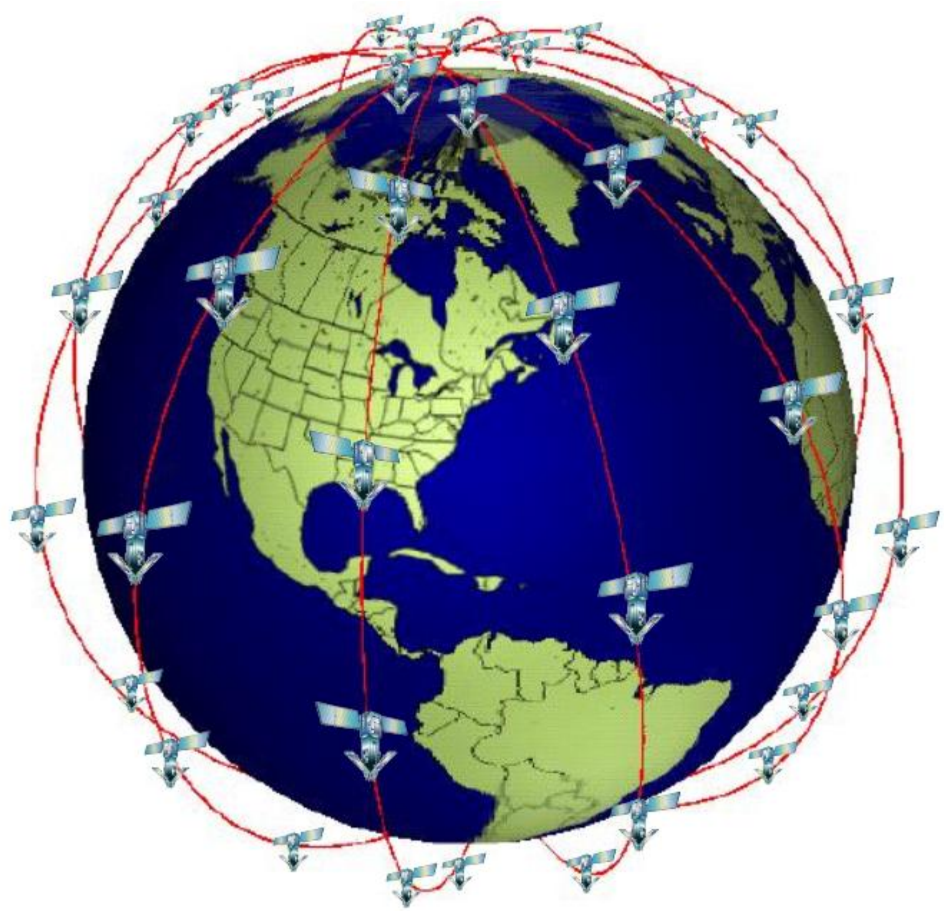
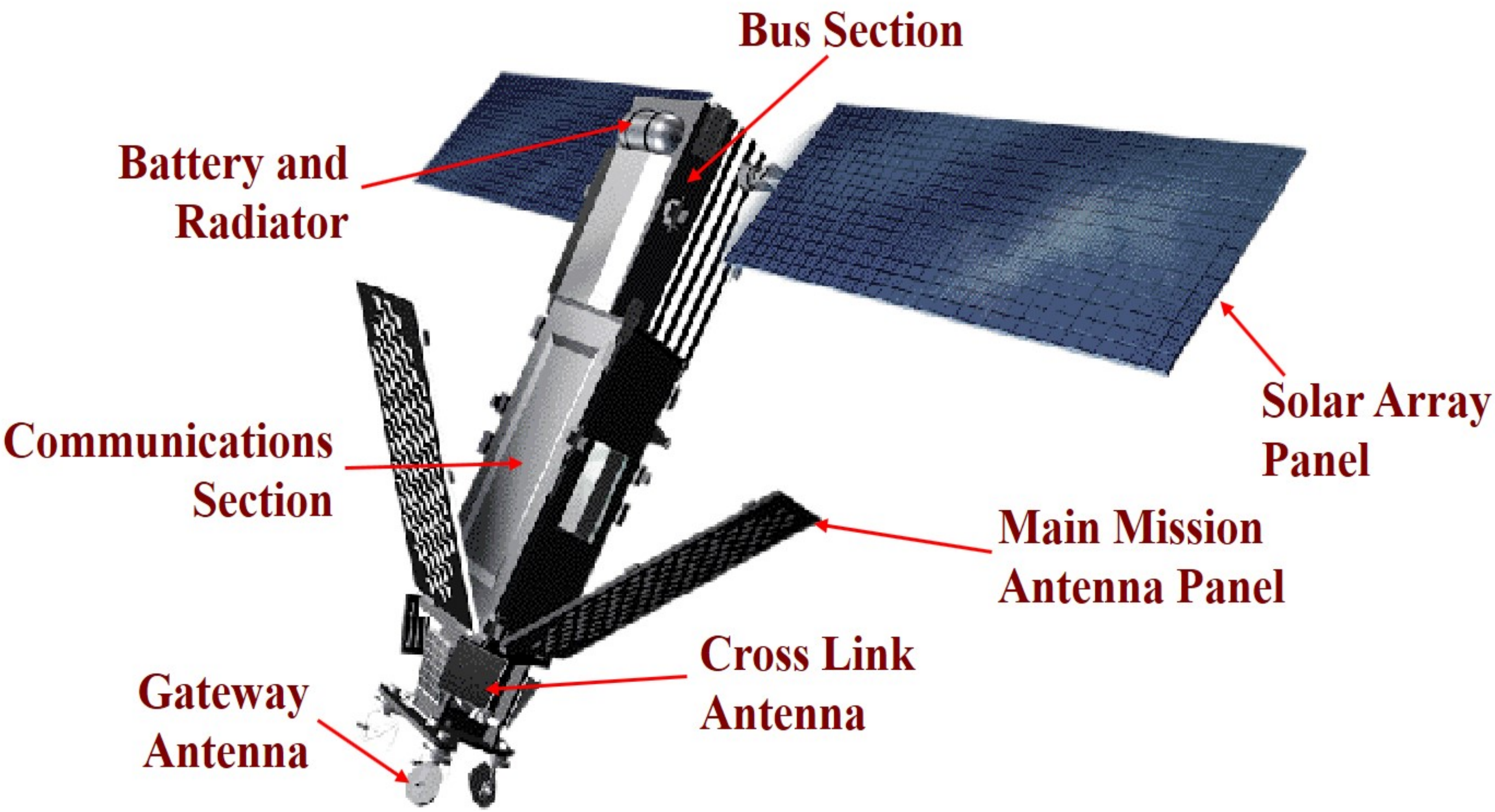
IRIDIUM SATELLITE – 21+ YEARS AND COUNTING

- IRIDIUM is a 66-satellite telecommunications constellation comprised of 6 planes of 11 satellites 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)
- 95 satellites launched, most between May 1997 and December 1998
  - Final 7 satellites launched in 2002, after batteries had been stored for ~3.5 years

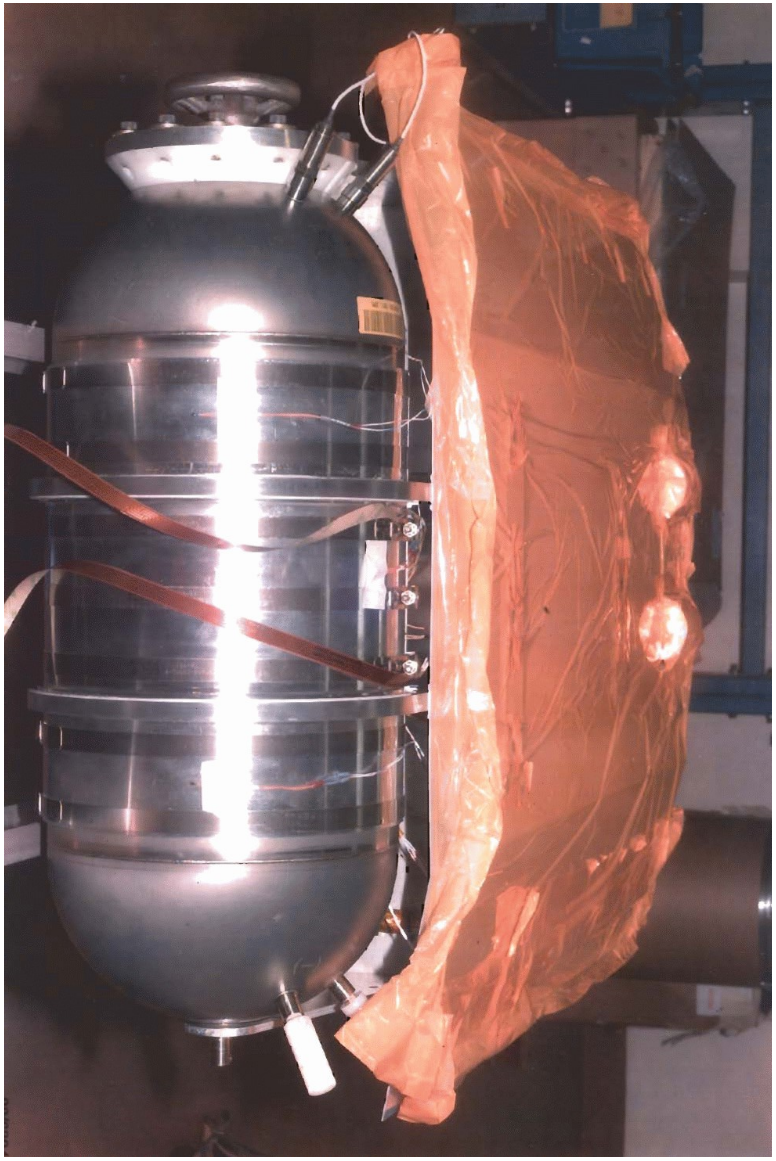


MAJOR ELEMENTS OF THE IRIDIUM BLOCK1 SATELLITE



IRIDIUM SATELLITE BATTERIES

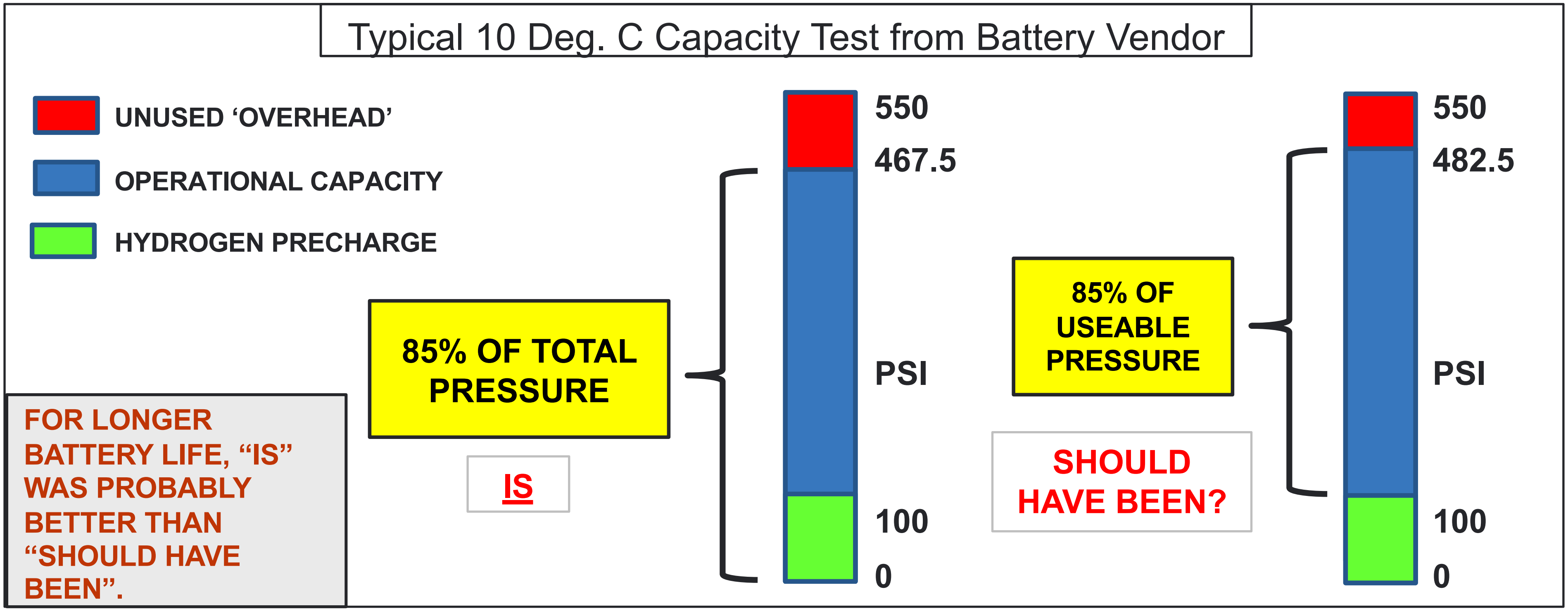
- Each space vehicle contained a single Eagle-Picher SPV Nickel-Hydrogen battery
    - Singe Pressure Vessel (SPV)
    - 22 cells, each with its own Electrolyte Containment System (ECS)
    - 31% KOH
    - Hydrogen Precharge
    - Battery weight ~67 lbs. (50 A-h) or ~80 lbs. (60 A-h)
- 20 space vehicles contained a 50 A-h battery (First four launches)
- 75 space vehicles contained a 60 A-h battery
- As of November 27, these batteries – through their various lifetimes – accumulated > 1500 YEARS (>13.1 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
  - Charge-off 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)
  - This methodology did not take into account the amount of hydrogen precharge (See figure on next page)
    - Hydrogen precharge wound up varying from 15 – 20% of the total pressure used in on-orbit charge control
      - ~464 PSI for 50 A-h batteries and ~553 PSI for 60 A-h batteries
  - Note that this presentation frequently switches between psi (vendor data) and Pascals (orbital telemetry)

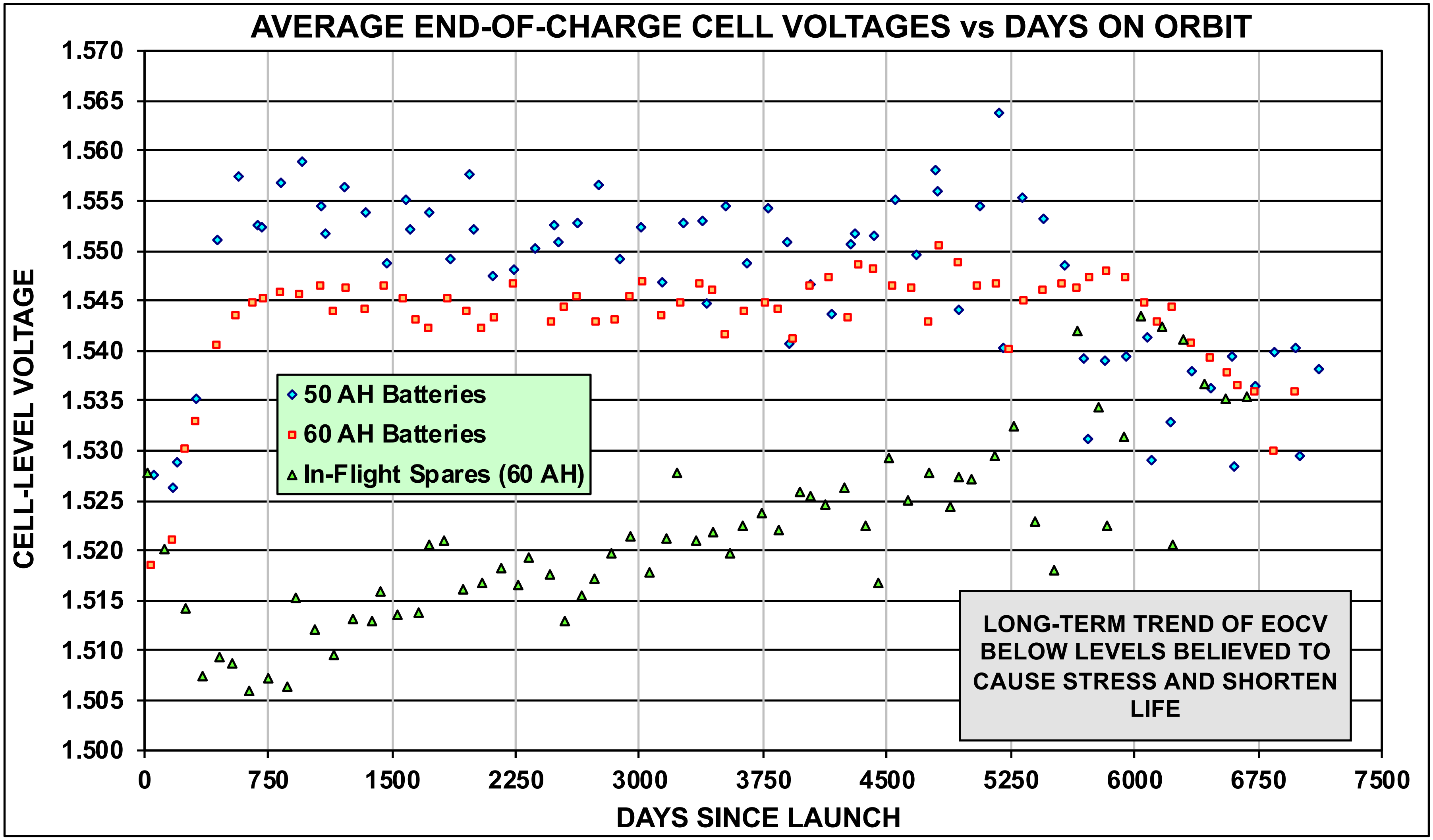
BATTERY CHARGE CONTROL – CONT'D



- 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 may not be recharged completely every orbit

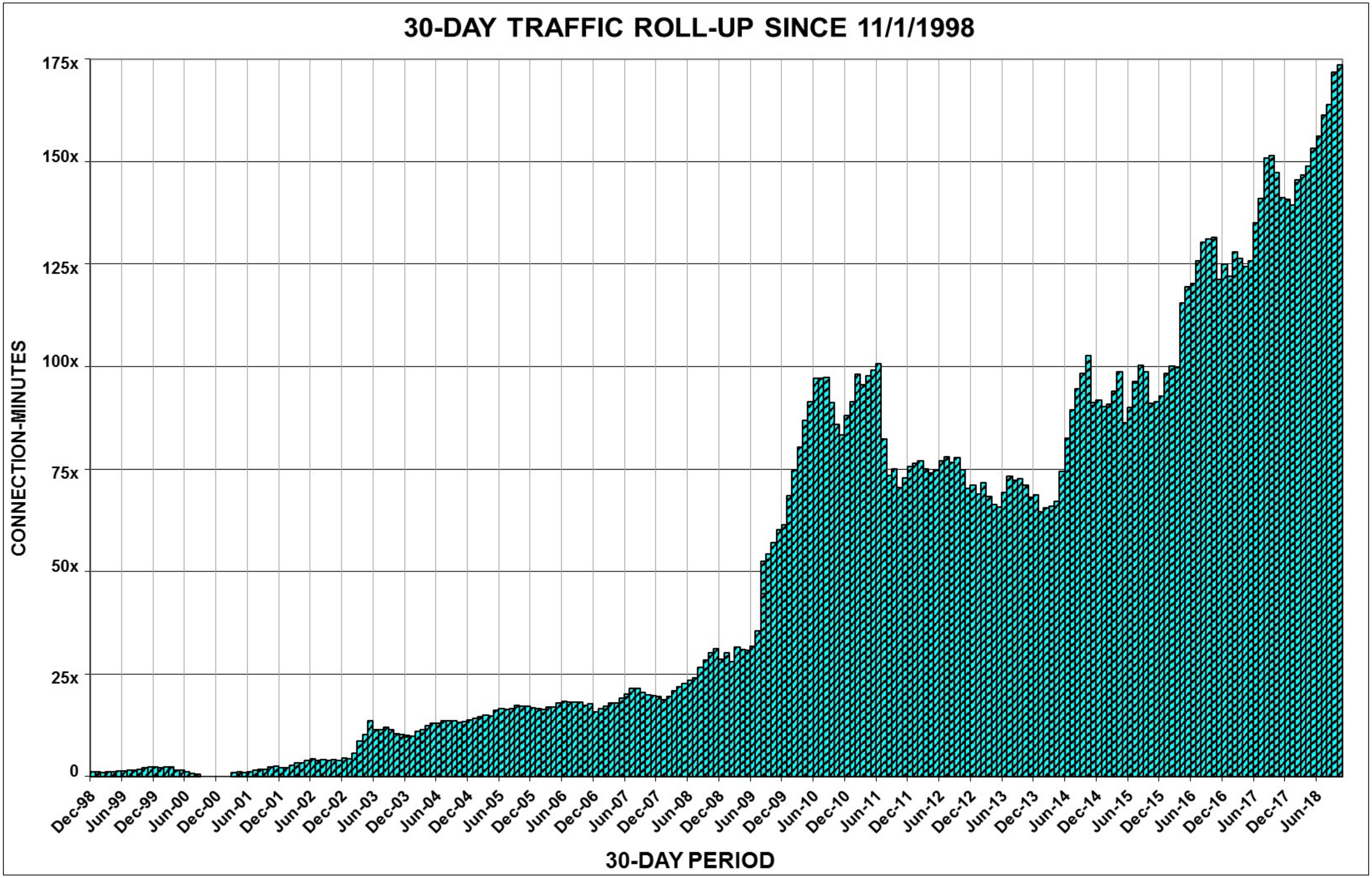
PRESSURE-BASED CONTROL EFFECT ON CHARGE VOLTAGE

- End-of-charge voltage unconstrained
- Increased for about the first 500 days and then settled out

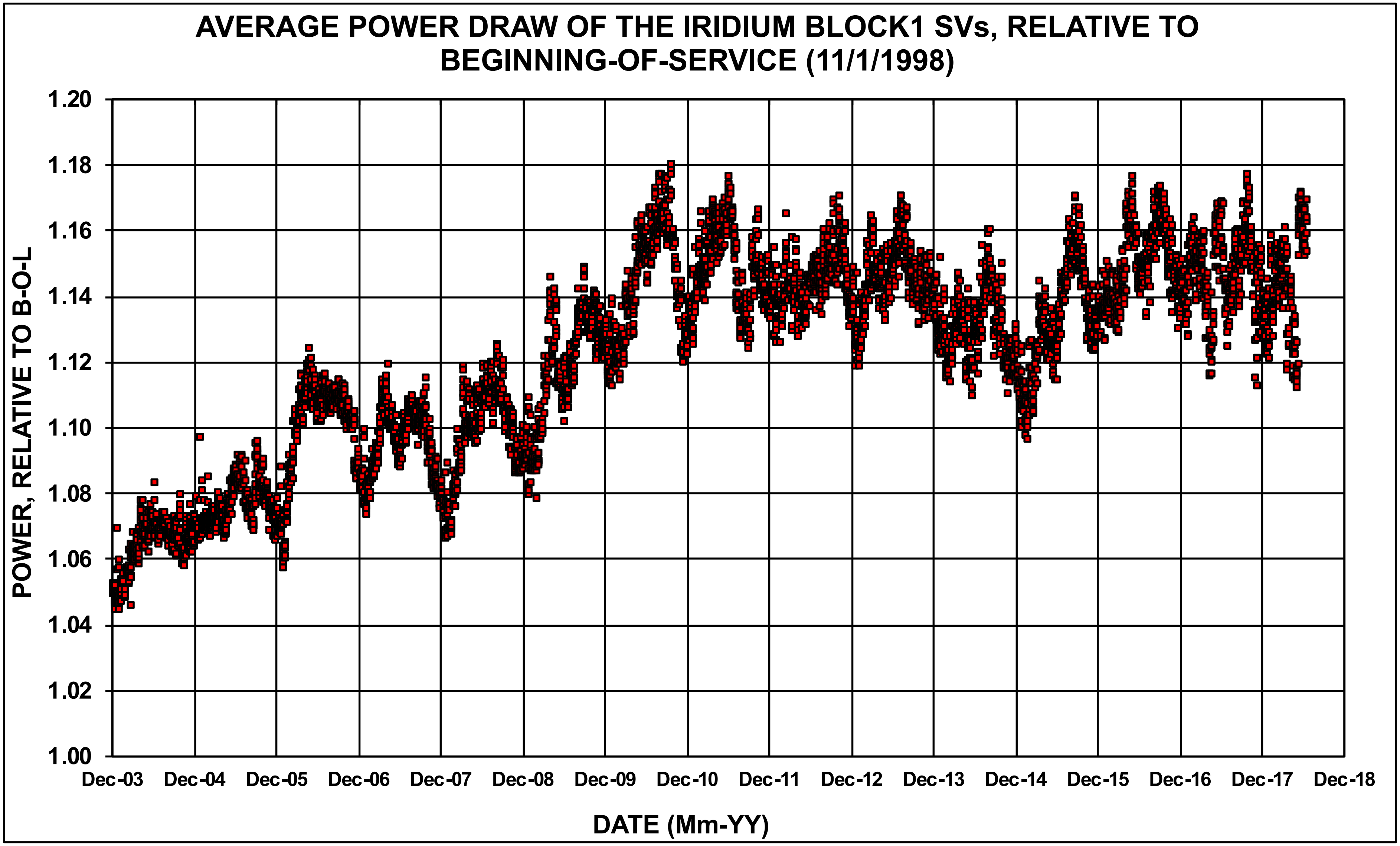


BATTERY DEPTH-OF-DISCHARGE / SV POWER CONSUMPTION

- Almost all satellites in history have experienced decreased electrical consumption with on-orbit life, and a concurrent decrease in battery DOD, mainly due to:
  - Failure of scientific instruments
  - Failure of spacecraft Bus equipment
    - Tape Recorders
    - Transponders
    - Reaction Wheels
  - Curtailing of operations due to budget constraints or the age of the spacecraft
- Iridium satellites – however - INCREASED consumption
- While scattered equipment failures have occurred, spacecraft load increased steadily for the first 12 years
  - On a handful (see following figures), load increased right up to the point that Iridium-NEXT satellites began to be substituted into the constellation
  - Equally true, as expected, for battery DOD
- Iridium traffic is > 65 times as much as it was 20 years ago



30-DAY TRAFFIC ROLL-UP SINCE 11/1/1998
175x
150x
125x
100x
75x
50x
25x
0
CONNECTION-MINUTES
Dec-98
Jun-99
Dec-99
Jun-00
Dec-00
Jun-01
Dec-01
Jun-02
Dec-02
Jun-03
Dec-03
Jun-04
Dec-04
Jun-05
Dec-05
Jun-06
Dec-06
Jun-07
Dec-07
Jun-08
Dec-08
Jun-09
Dec-09
Jun-10
Dec-10
Jun-11
Dec-11
Jun-12
Dec-12
Jun-13
Dec-13
Jun-14
Dec-14
Jun-15
Dec-15
Jun-16
Dec-16
Jun-17
Dec-17
Jun-18
30-DAY PERIOD



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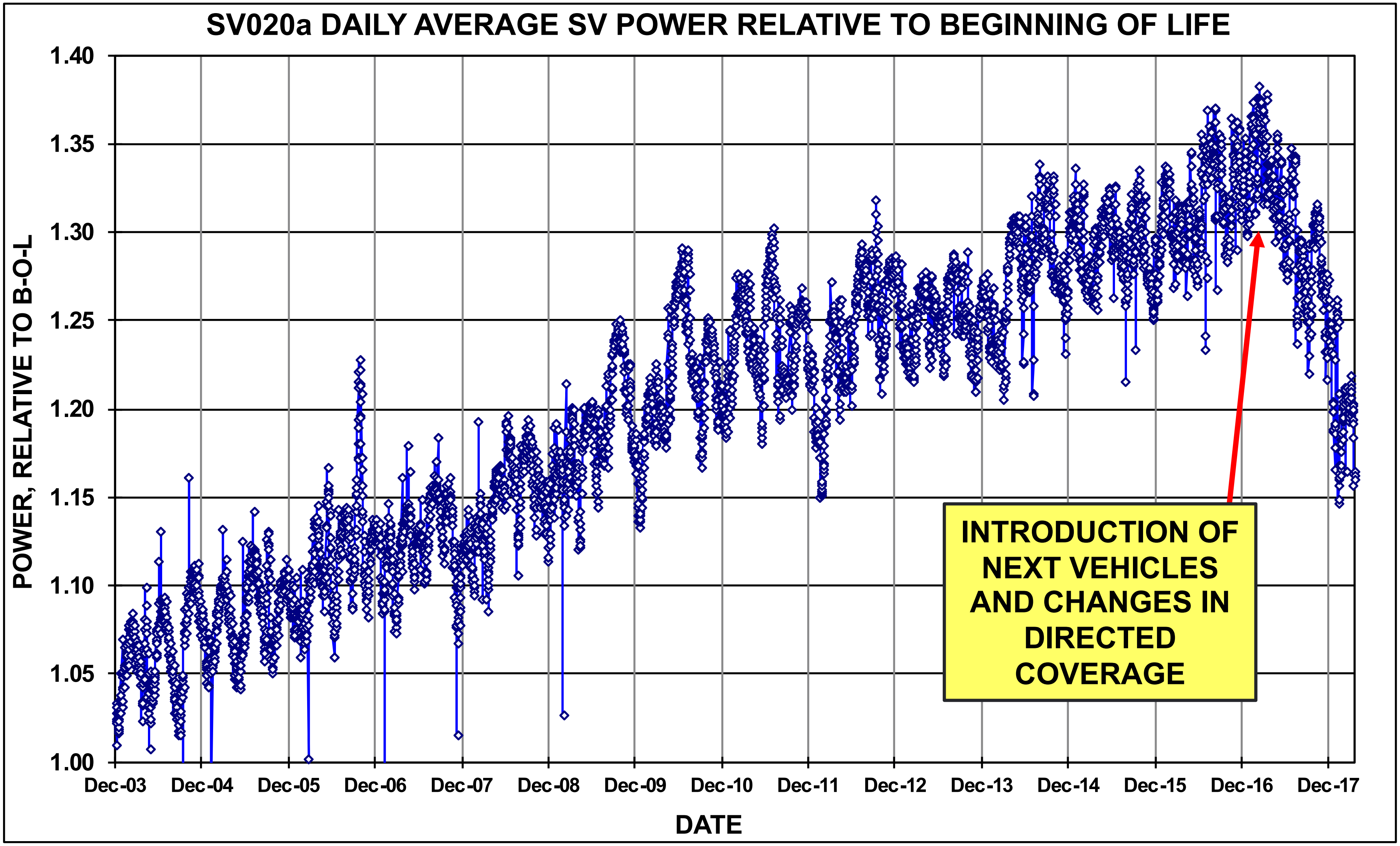
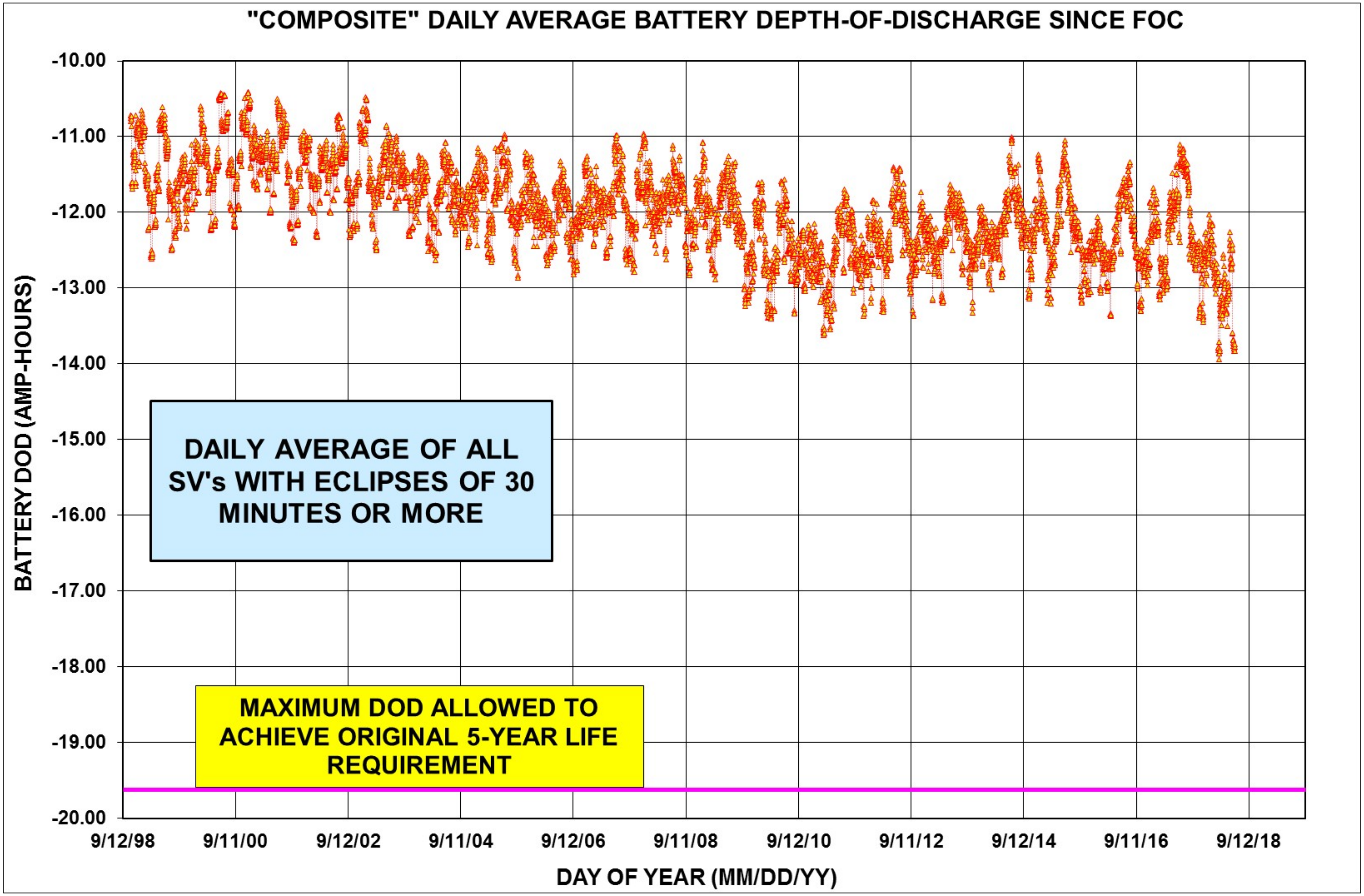
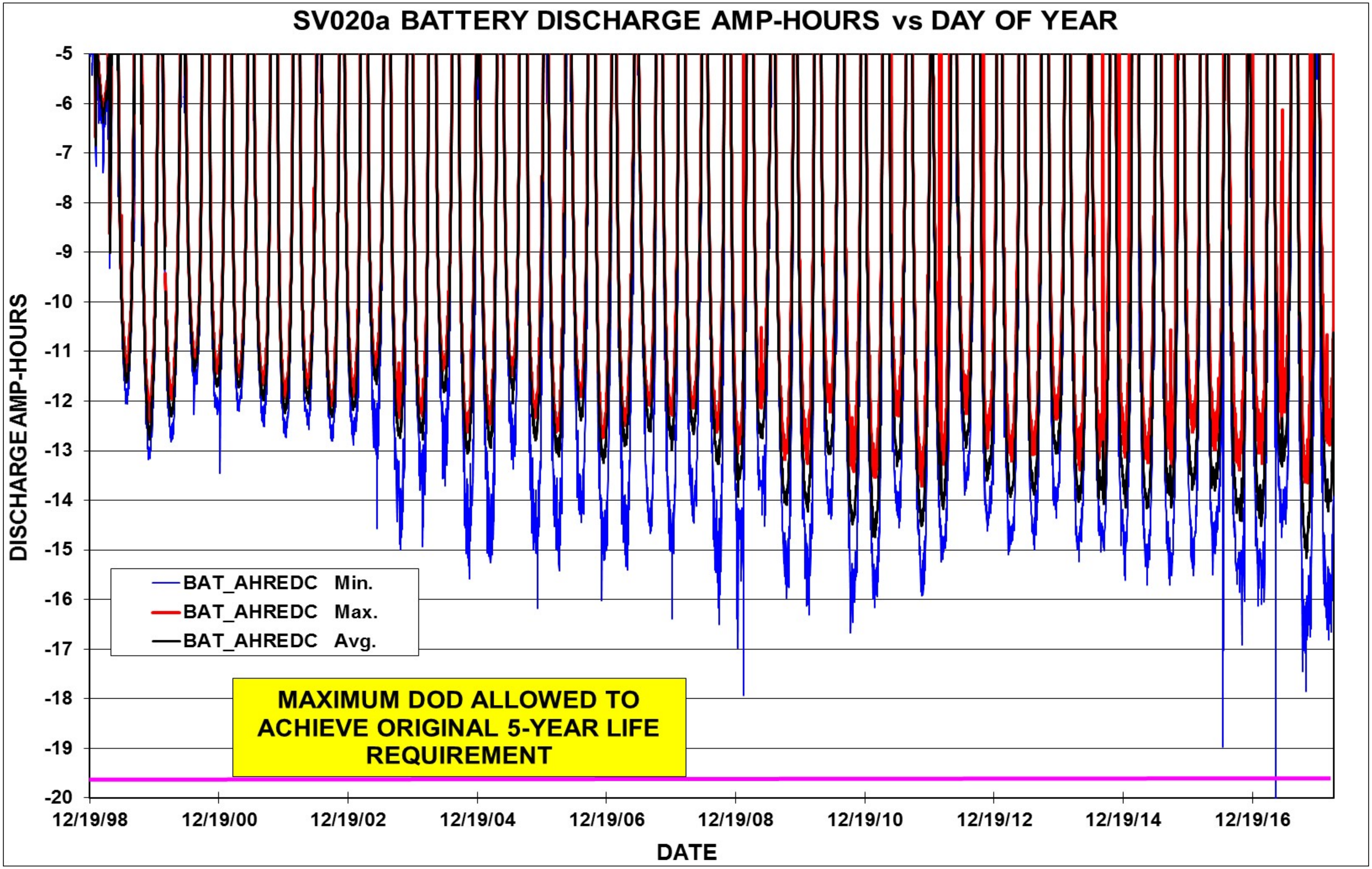
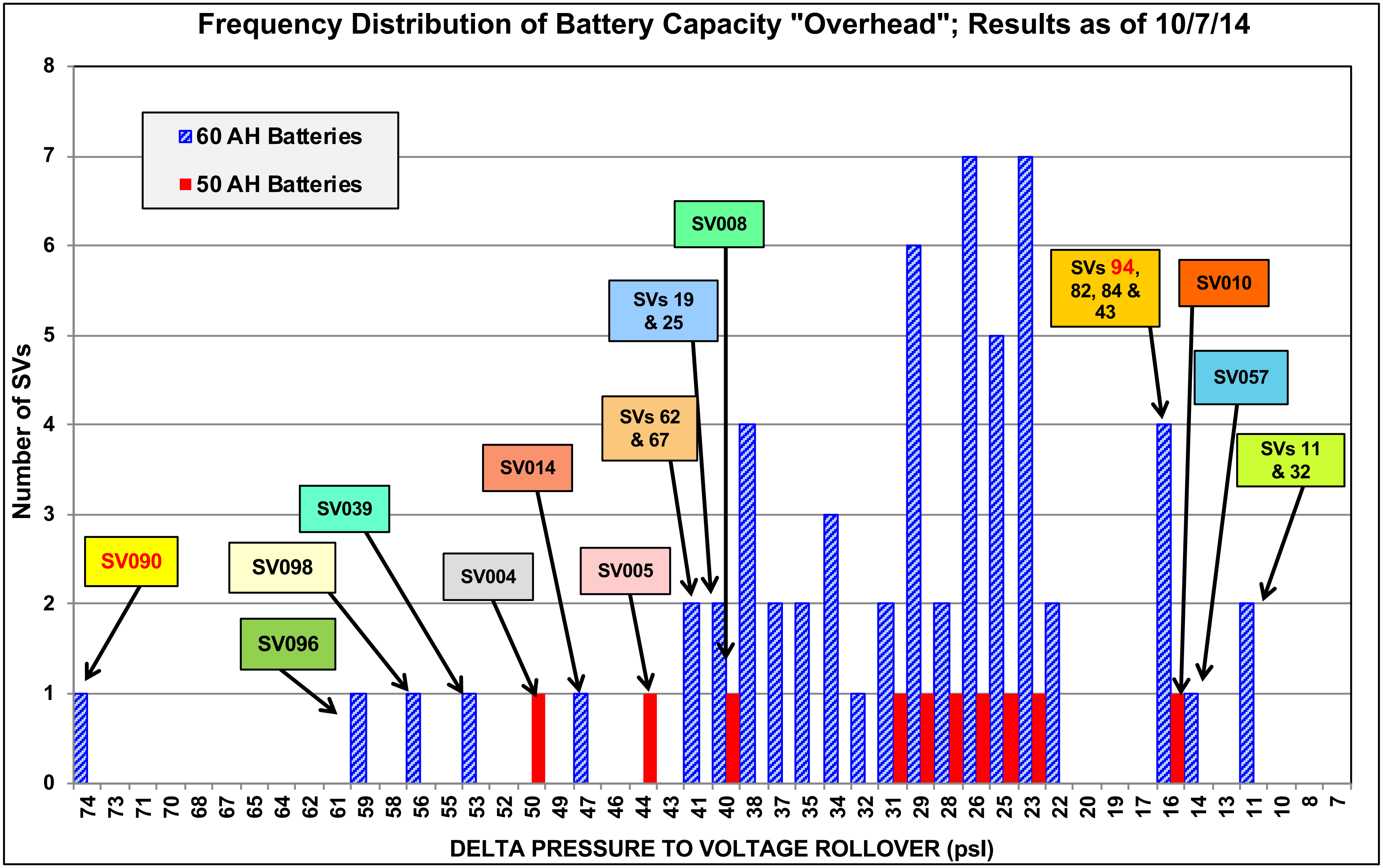

SV020a DAILY AVERAGE SV POWER RELATIVE TO BEGINNING OF LIFE
POWER, RELATIVE TO B-O-L
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
Dec-03
Dec-04
Dec-05
Dec-06
Dec-07
Dec-08
Dec-09
Dec-10
Dec-11
Dec-12
Dec-13
Dec-14
Dec-15
Dec-16
Dec-17
DATE
INTRODUCTION OF NEXT VEHICLES AND CHANGES IN DIRECTED COVERAGE


"COMPOSITE" DAILY AVERAGE BATTERY DEPTH-OF-DISCHARGE SINCE FOC
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
-17.00
-18.00
-19.00
-20.00
BATTERY DOD (AMP-HOURS)
DAILY AVERAGE OF ALL SV's WITH ECLIPSES OF 30 MINUTES OR MORE
MAXIMUM DOD ALLOWED TO ACHIEVE ORIGINAL 5-YEAR LIFE REQUIREMENT
9/12/98
9/11/00
9/12/02
9/11/04
9/12/06
9/11/08
9/12/10
9/11/12
9/12/14
9/11/16
9/12/18
DAY OF YEAR (MM/DD/YY)


SV020a BATTERY DISCHARGE AMP-HOURS vs DAY OF YEAR
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 unused capacity was 'above' the long-used full-charge/end-of-charge pressure
  - Determined by charging to the point that voltage appears to roll over (and battery temperatures begin to rise), indicating true full-charge / beginning of overcharge
- Reasons for determining the 'overhead' battery capacity:
  - Could be used to raise the state-of-charge in some batteries
    - Allows 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
- It should be noted that at the beginning-of-life, these batteries had as much as 80 psi of unused 'overhead' capacity
  - Confirmed in accidental overcharge of one battery (SV062) ~4 months after launch
    - Voltage rollover and excessive battery heating observed when charge-off pressure exceeded by 78 psi


Frequency Distribution of Battery Capacity "Overhead"; Results as of 10/7/14
60 AH Batteries
50 AH Batteries
Number of SVs
DELTA PRESSURE TO VOLTAGE ROLLOVER (psi)
0
1
2
3
4
5
6
7
8
74 73 71 70 68 67 65 64 62 61 59 58 56 55 53 52 50 49 47 46 44 43 41 40 38 37 35 34 32 31 29 28 26 25 23 22 20 19 17 16 14 13 11 10 8 7
SV090
SV098
SV096
SV039
SV004
SV014
SV005
SVs 62 & 67
SVs 19 & 25
SV008
SVs 94, 82, 84 & 43
SV010
SV057
SVs 11 & 32

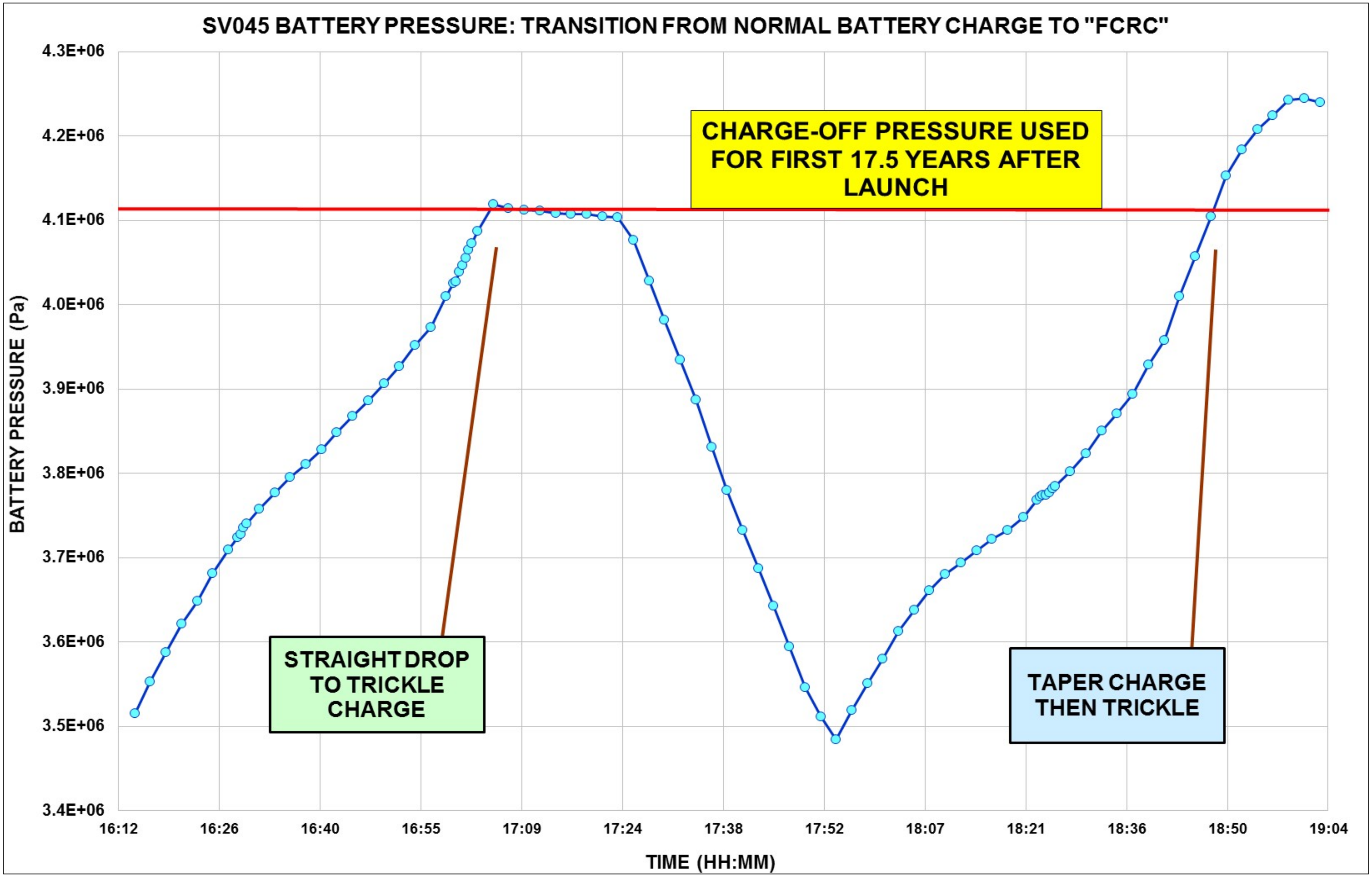
OUTLIERS FROM 'OVERHEAD CAPACITY' TESTING

- For batteries on SV090 and above
  - 5 of the 7 experienced a significant decrease in Hydrogen pre-charge (average ~ 37 psi) while in storage for ~3.5 years, and 6 of the 7 were also found to require a lower end-of-charge pressure (average ~25 psi)
- Non-linearities evolved over time in the gain ("slope") characteristic of some of the pressure transducers (and/or in the amplifying circuit)
  - SVs 43 and 57
- Drift in the Offset characteristic of some of the pressure transducers (and/or in the amplifying circuit)
  - SVs 10, 83 & 84
    - SV010's EOCP pressure had to be reduced by ~30 psi TWICE in order to alleviated rising EOCV, Recharge Ratios and battery temperature gradients
    - Battery pressure as a method of control had to be abandoned for much of the life of SVs 83 and 84
- SV090 was a spare vehicle that orbited for over 16 years but was never used in Service and thus had the least (by far) amount of wear on its battery

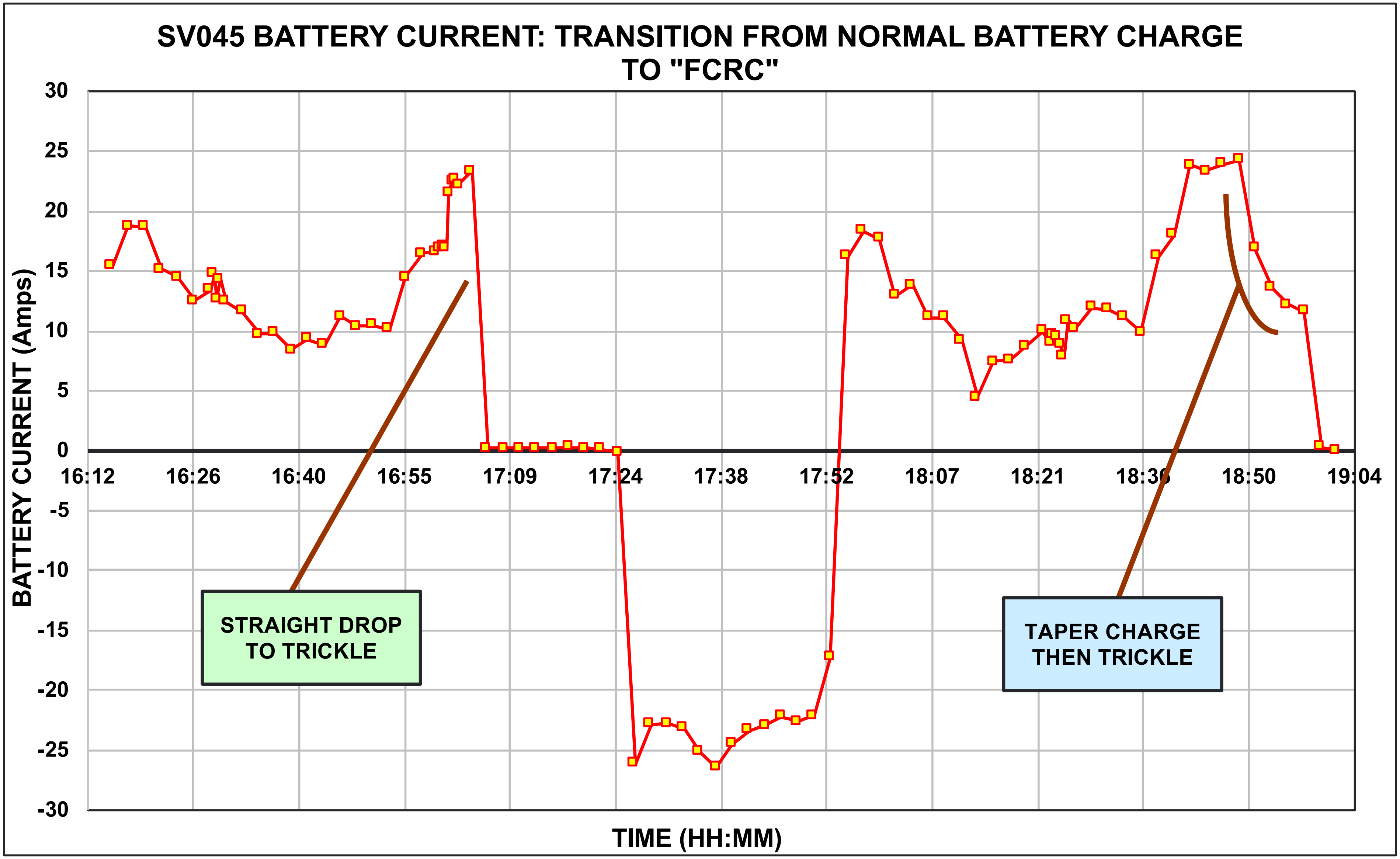
MAKING USE OF 'OVERHEAD CAPACITY'

- Before the characterization testing was complete across the constellation, the results began to be applied and charge-off pressure was increased on certain SVs to address operational issues:
  1. Sagging battery voltage (<22 volts) at end-of-eclipse due to ever-increasing discharge currents
  2. Proximity to Undercharge Fault Limits (pressure, voltage, amp-hours)
  3. Operational battery capacity margin (i.e. amp-hours needed in worst-case for Attitude Recovery & SafeMode)
- Only employed when eclipses are approaching 32 minutes in duration (later expanded to include eclipse periods from 30 minutes and up)
- The charge-off pressure was typically increased operational capacity between 0.7 and 2.6 amp-hours (depending on the SV), with an average of ~1.5 amp-hours
- We termed our method "FCRC", for Full-Charge (at) Reduced Current and it was used on a total of 57 satellites
- The method tapers the charge current after the battery passes through the older, established charge-off pressure on its way to the new one, limiting battery voltage excursions to unhealthful levels

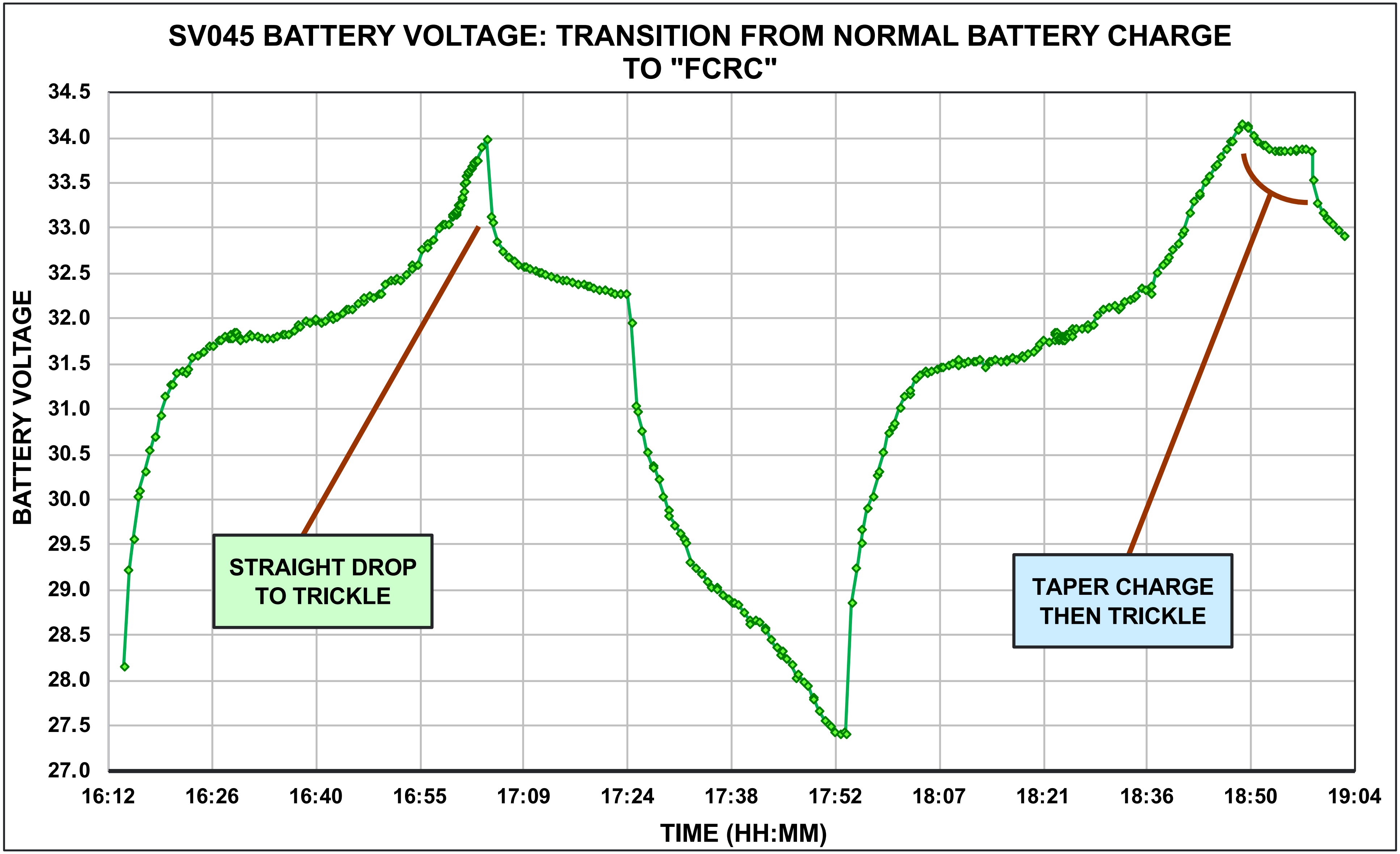
FCRC – WHAT IT LOOKS LIKE IN PRACTICE #1



FCRC – WHAT IT LOOKS LIKE IN PRACTICE #2



FCRC – WHAT IT LOOKS LIKE IN PRACTICE #3



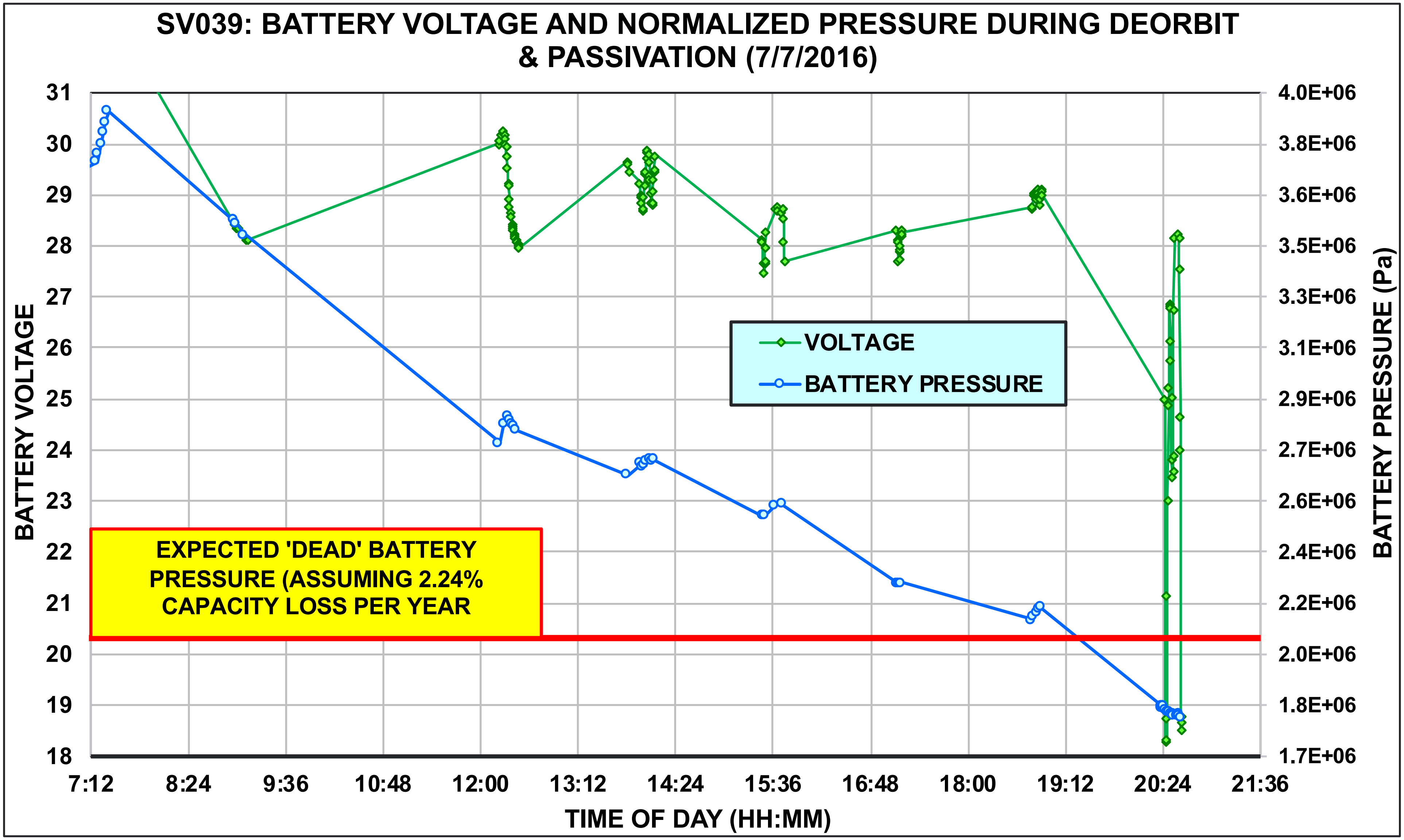
DEORBIT END-OF-LIFE BATTERY CAPACITY MEASUREMENT

- 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. Additional steps can accelerate the vehicle's demise (after propellant has been exhausted and/or vented first):
  - Inhibit battery charging
  - Disable Fault responses (so the satellite doesn't "bail itself out")
  - Disconnect the solar array from the Bus (or portions of it) to set the discharge rate
- We wanted to see if we could measure the battery's end-of-life capacity as part of this process, particularly from the final contact with the satellite
  - Difficult for several reasons:
    - Secondary Link means low bandwidth and no stored telemetry
    - As little as one pass (if that) per orbit of anywhere from 1 to 6 minutes duration
    - Once the SV is passivated, the battery is depleting between 11 and 13 amp-hours between contacts (or about 1/3 the expected EOL capacity) and could easily die before we see it again
    - SV almost certainly tumbling before battery is depleted

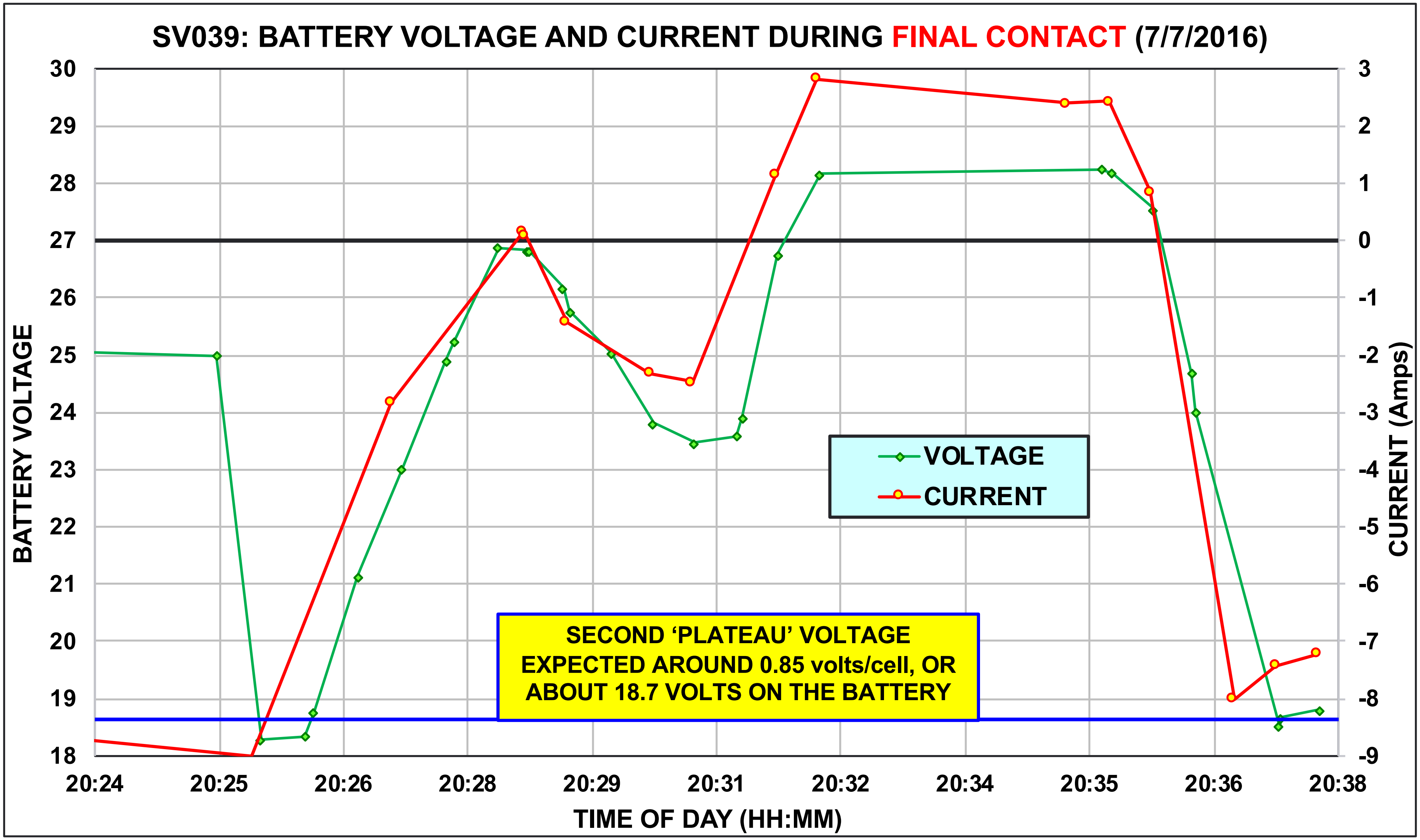
EXPECTATIONS FOR CAPACITY LOSS / RESULTS

- Hubble Space Telescope (HST) On-orbit battery reconditioning data* seemed to give a good model for long-term Nickel-Hydrogen battery degradation
  - *"Hubble Space Telescope Battery Capacity Update" by Roger Hollandsworth & Jon Armantrout of Lockheed Martin Space Systems Company & Gopalakrishna Rao of NASA-Goddard Space Flight Center, as presented to the 2007 NASA Battery Workshop
- From these published results we derived an average capacity degradation rate of 2.24% per year
  - Note that we started using this statistic in 2010 to set our Undercharge Limits in light of such capacity loss
- Despite the handicaps of our proposed data collection, we were able to obtain very usable results for 25 of 51 satellites deorbited as of November 23, 2018.
- By and large, the Iridium/EPI SPV battery fared better than Hubble's perceived 2.24% capacity loss per year
  - Average to-date has been 1.52%
- One of the largest outliers in our results was again SV090, which had its Hydrogen precharge 'move' during storage
  - Also the least-used and therefore least worn-out battery in the entire constellation – and therefore, not surprisingly, exhibited the least amount of capacity loss.

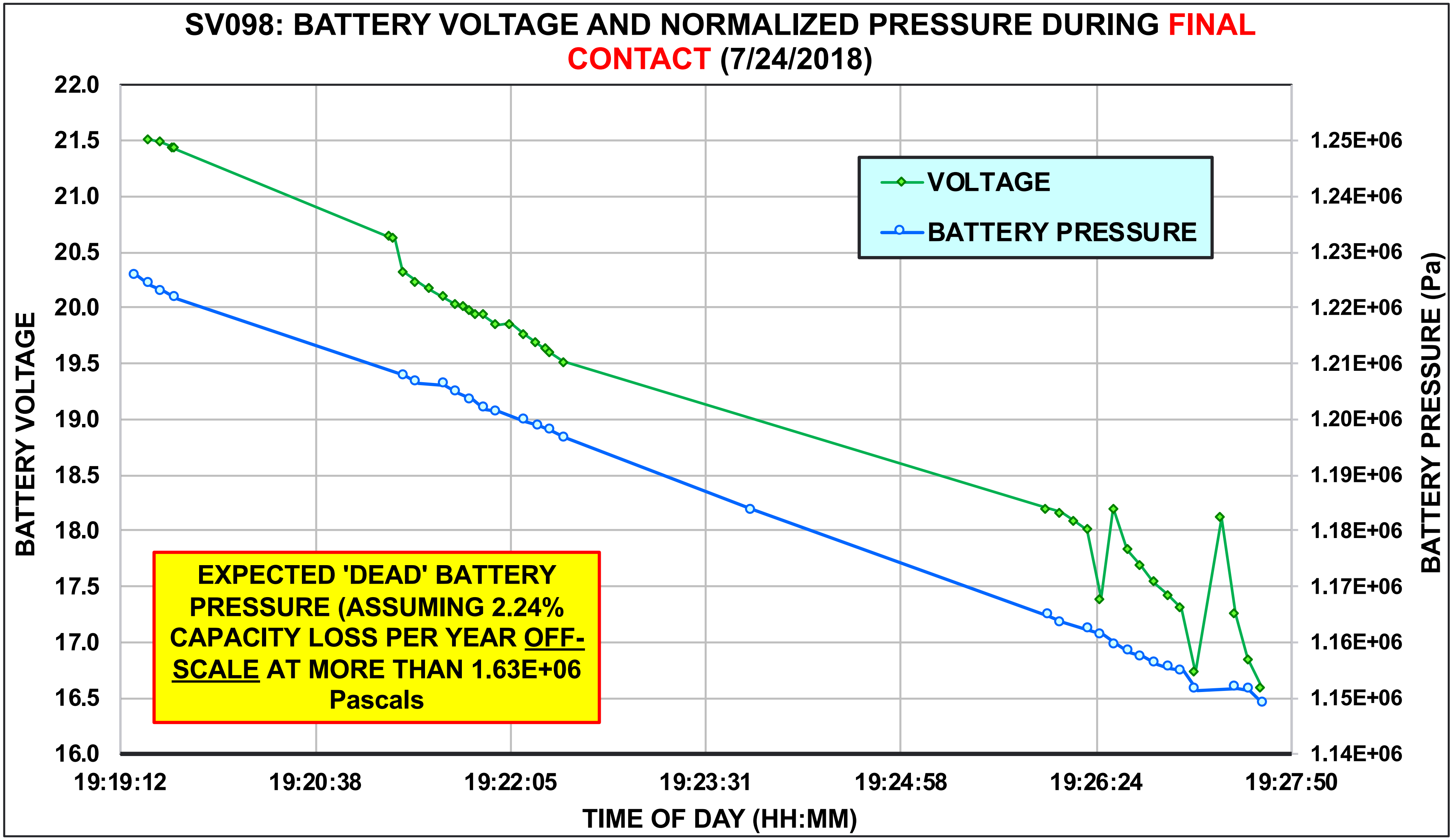
WHAT'S AN END-OF-LIFE CAPACITY MEASUREMENT LOOK LIKE?

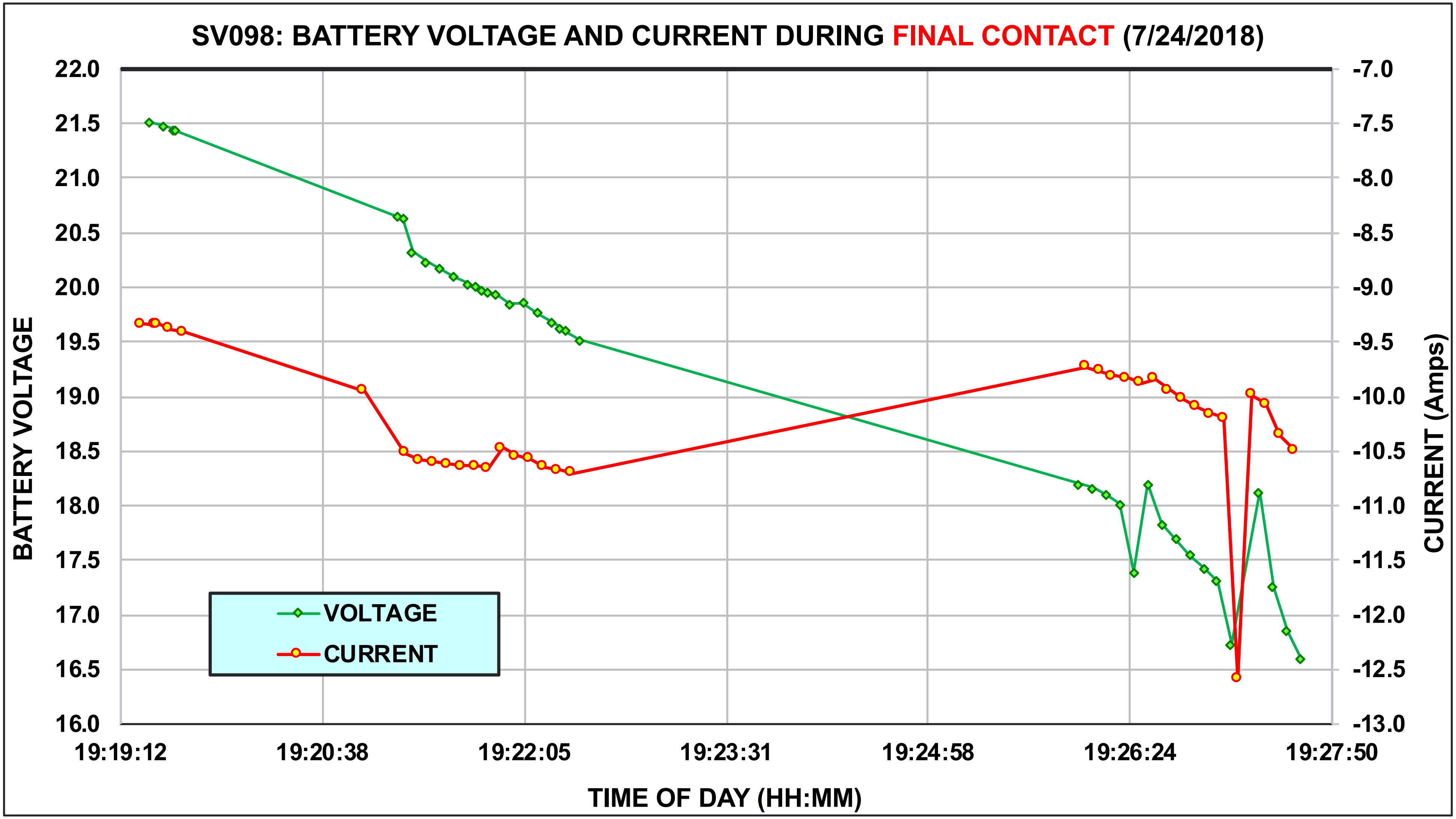


A BATTERY ON ITS '2ND-PLATEAU' VOLTAGE IS ALSO ON ITS LAST LEGS



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




SV098: BATTERY VOLTAGE AND CURRENT DURING FINAL CONTACT (7/24/2018)
BATTERY VOLTAGE
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
CURRENT (Amps)
-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
TIME OF DAY (HH:MM)
VOLTAGE
CURRENT

RESULTS OF END-OF-LIFE CAPACITY MEASUREMENTS

BOL CAPACITY	SVID	% LOSS PER YEAR	YEARS WITH TRAFFIC LOADING	LOWEST OBSERVED VOLTAGE
50	5	2.27	20.12	16.85
50	6	2.10	17.73	26.61
50	10	0.74*	20.79	26.37
50	12	1.33	20.33	20.98
50	13	2.58	19.92	20.33
50	15	2.17	19.19	25.46
50	18	2.47	19.26	24.87

*Pressure sensor known to be drifting in Offset throughout life

RESULTS OF END-OF-LIFE CAPACITY MEASUREMENTS – cont'd

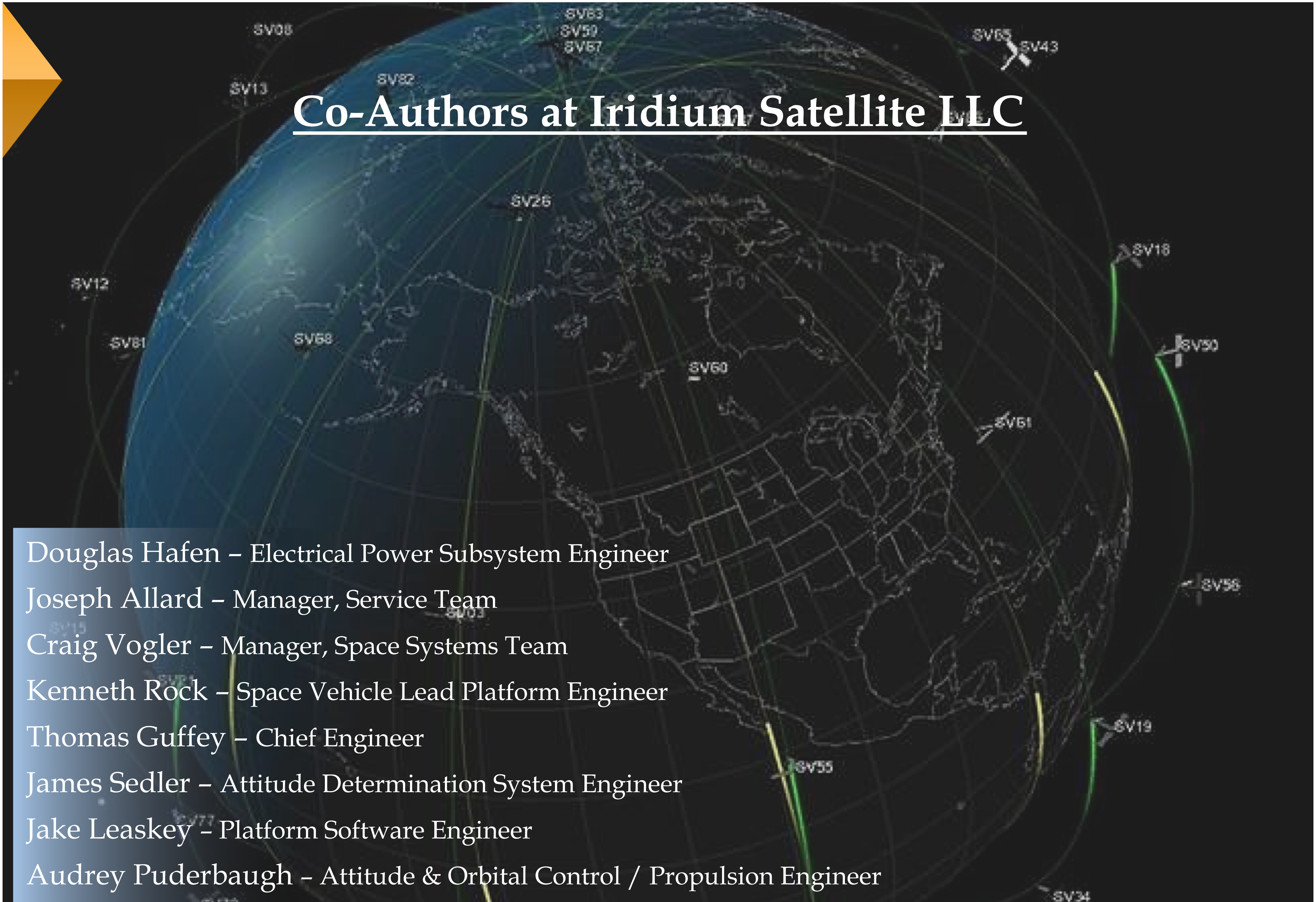
BOL CAPACITY	SVID	% LOSS/YEAR	YEARS WITH TRAFFIC LOADING	LOWEST OBSERVED VOLTAGE
60	11a	1.85	7.20	26.65
60	30	1.71	19.85	25.77
60	34	1.85	19.65	25.91
60	37	1.61	19.92	27.41
60	39	1.21	18.34	17.44
60	40	1.72	18.99	26.37
60	43	0.56	19.16	25.77
60	46	2.09	20.07	24.60
60	49	0.95	19.95	25.95
60	51	2.10	5.30	26.67
60	67	1.46	19.94	16.47
60	68	0.95	19.90	26.49
60	72	1.71	19.88	25.63
60	77	1.55	11.56	25.67
60	80	1.30	19.72	16.50
60	90	0.33	0	18.66
60	96	1.19	4.02	25.31
60	98	0.32	3.72	16.46

CONCLUSIONS

- Iridium closely followed LMSC's instructions for battery management except as dictated by circumstances (i.e. end-of-life considerations)
- 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 & co-authors as listed on the next page. They provided their analysis, their support, their attention to detail – and most of all:

THEIR FOREBEARANCE!

Co-Authors at Iridium Satellite LLC



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Audrey Puderbaugh – Attitude & Orbital Control / Propulsion Engineer

AH – THE GOOD LIFE……