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Historical performance of nickel/cadmium and nickel/metal hydride geosynchronous-orbit packs and determination of voltage/temperature levels for advanced nickel/cadmium designs

Harlan Lewis [a,*], Warren Hwang [b], Michelle Manzo [c]

[a] *NAVSEA Crane, 300 Highway 361, Code 609, B2949, Crane, IN 47522, USA*
[b] *Energy Technology Department, The Aerospace Corporation, MS M2/275, P.O. Box 92957, Los Angeles, CA 90009-2957, USA*
[c] *NASA-Glenn Research Center, Attn: 5420, MS 309-1, Cleveland, OH 44135, USA*

Abstract

This paper will review the performances of nickel/cadmium and nickel/hydrogen Geocentric Earth Orbital (GEO) satellite battery packs which have been evaluated at NAVSEA Crane for the Air Force and NASA-Glenn. The nickel/cadmium data will deal, in part, with the attempts to find space-qualified substitutes for the disappearance of Pellon 2505 as a separation material. The nickel/hydrogen data will illustrate the development of this chemistry as a substitute for nickel/cadmium batteries.

Keywords: Applications/earth satellites; Nickel/cadmium batteries; Nickel/metal hydride; Batteries

1. Background

Since 1989, NAVSEA Crane has been evaluating nickel/cadmium (Ni/Cd) and nickel/hydrogen (NiH) cell packs in accelerated GEO life cycling for several Air Force and NASA-Glenn programs [1]. This report will examine the cycle life performance data obtained for 12 Ni/Cd and 5 NiH packs, at several temperatures and depths of discharge, and for several design parameters. Where possible, performance comparisons will be made. However, in most cases, single designs were evaluated with parameters that do not permit comparative analysis, so the data are presented chiefly for performance information.

2. Introduction

In a real time synchronous orbit, the velocity of a satellite and its distance from the earth are adjusted such that one revolution of the satellite matches one rotation of the earth.

The earth's shadow cone changes relative to the satellite's plane of orbit (see Fig. 1), so every 180 days the satellite enters an eclipse season. This season lasts approximately 40 days, after which the remaining 140 days are in continuous sunlight. At the beginning of an eclipse season the satellite first moves through the outer area of the earth's shadow cone. Each day of the eclipse season it progresses through a different section of the shadow cone until it has completely traversed the cone at the end of the season. The satellite's time within the shadow cone thus varies from day to day within the eclipse season beginning with a minimum, progressing to a maximum, and returning to a minimum. In most of our Ni/Cd testing, the following procedure was utilized to accelerate the GEO cycling:

(a) The period simulating continuous sunlight was reduced from 140 to 14 days, while the cells were continuously charged at *C*/100 (trickle).
(b) The period simulating the eclipse was set at 42 days (which is actually a function of the orbital altitude).
(c) All cells were discharged for 12 min the first day of the eclipse season; the discharge time was increased by 3–4 min per day for 20 days to a maximum of 72 min. This maximum discharge was then held for 4 days (20th–23rd day of eclipse).
(d) The discharge time was then decreased by 3–4 min per day for days 24–42 to complete the synchronous-orbit period.
(e) Fourteen days would then elapse on trickle until the beginning of the next shadow period. Thus the

* Corresponding author.
E-mail address: lewis_h@crane.navy.mil (H. Lewis).

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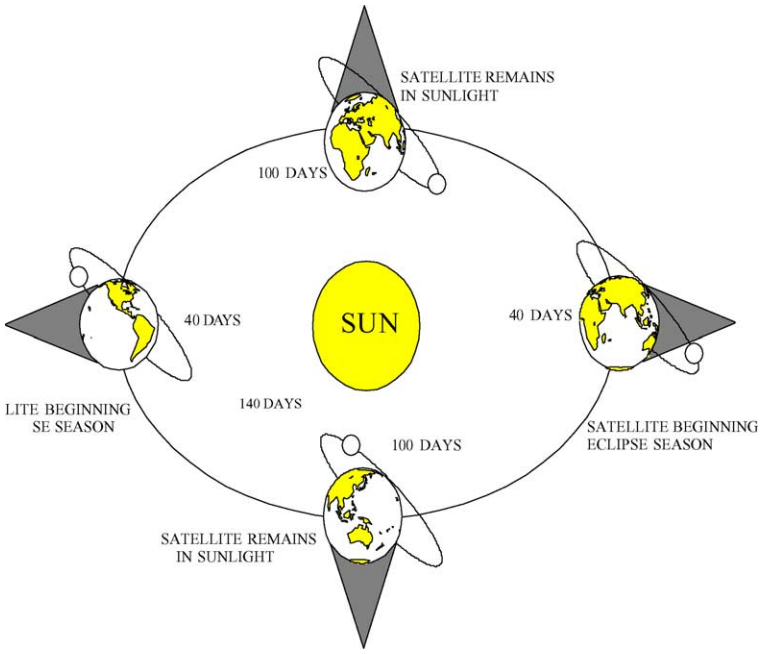

Fig. 1. GEO orbit configuration.

interval between each shadow beginning was 56 days.

3. Test results for nickel/cadmium packs

The individual pack descriptions are contained in Table 1, organized by the end-of-testing date.

In the following text, DOD is depth-of-discharge, EoDV is end-of-discharge voltage, EoCV is end-of-charge voltage, and SOS is start of shadow.

3.1. Packs 6250 A–D (Gates Aerospace Battery Co., formerly GE Battery Co.)

These were designed as a performance comparison for Pellon 2505 and 2536 separations.

At 0 °C, the pack performances (6250 A & B) for Pellon 2505 and 2536 are illustrated in Fig. 2.

The plot is annotated to show actual pack performance and testing anomalies. It is observed that the 2536 separation pack "B" exhibited a lower peak shadow EoDV in the last nine orbits, and began to fail at shadow #28. In cycle #30,

Table 1
Nickel/cadmium and nickel/hydrogen GEO Packs

Pack ID	Manufacturer	Final shadow and (#)	GEO cycles	Temperature (°C)	Ah	Maximum % DOD	# Cells	Notes on separation
Nickel cadmium packs								
6250A	Gates	16 September 1991 (31)	1032–1493	0	50	75	5	Pellon 2505
6250B	Gates	26 August 1991 (30)	1032–1450	0	50	75	5	Pellon 2536
6250C	Gates	9 July 1991 (29)	1032–1418	20	50	75	10	Pellon 2505
6250D	Gates	10 July 1991 (29)	1032–1428	20	50	75	10	Pellon 2536
0251B	EPT	7 December 1992 (1)	135	5	50	75	9	Super Ni/Cd
6224S	SAFT	14 February 1994 (30)	1355	20	24	80	5	VOS-A
6335B	Gates	1 July 1994 (NA)	2093	20	35	41	10	GPS-Magnum
6240S	SAFT	1 November 1995 (40)	1686	20	40	80	4	VOS-A
0211E	EPT	4 November 1997 (4)	271	10	21	80	5	Magnum
6211S	SAFT	6 April 1999 (25)	1376–2753	10	50	80	5	VOS-A
0211H	EPT	13 December 2000 (31)	1686	10	21	80	5	Super Ni/Cd
6211R	Sanyo	23 February 2001 (40)	2750–4997	10	35	80	5	
Nickel hydrogen packs								
3007L	EPT	30 September 2000 (23)	1371	10	45	75	6	CPV cells
3487A	EPT	25 August 2000 (NA)	133–2838	0	40	75–60	5	Asbestos separation
3487B	EPT	20 January 1996 (NA)	367	0	40	75	8	"B" separation
3487Z	EPT	3 September 1996 (NA)	1168	0	40	75	10	Zircar separation
3487C	EPT	Current	3850	10	40	65	10	Zircar separation

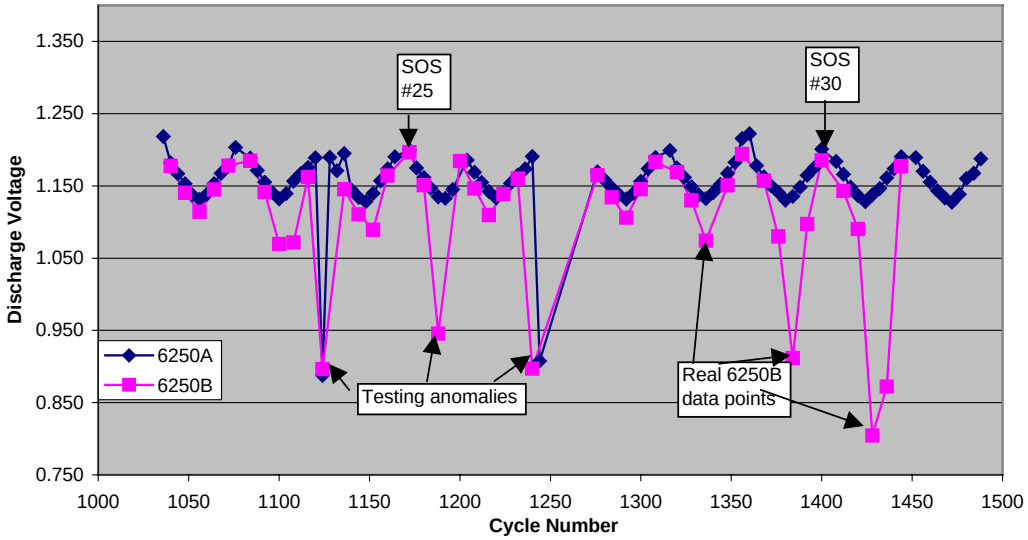

Fig. 2. NiCd Pellon 2505 (6250A) vs. 2536 (6250B) at 0 °C.

only 3/5 cells were still on test, and two of those had peak shadow EoDV's <1.00 V. In pack "A" all five cells were ≅1.13 V EoD during the 4 days of maximum shadow.

At 20 °C (Fig. 3), the trend downward in the "D" pack data (2536 cells) is also marked in the last three full cycles. At cycle #29 in the "D" pack, all 10 cells were at <1.00 V EoD during the 4 days of maximum shadow, with 5/10 <0.95 V EoD. In the "C" pack, only 2/10 cells were slightly below 1.00 V EoD, with the other eight >1.03 V EoD.

3.2. Pack 6224S

These five 24 Ah SAFT cells were placed on test in July 1989. A total of 30 accelerated GEO orbits were obtained, and no cells failed the cycling requirements. The last eleven 42-day orbits are plotted in Fig. 4. The pack was discontinued at cycle 1355 at the request of the sponsor. At that time, the EoD deep shadow voltages were essentially constant, orbit-to-orbit, and the pack was performing well.

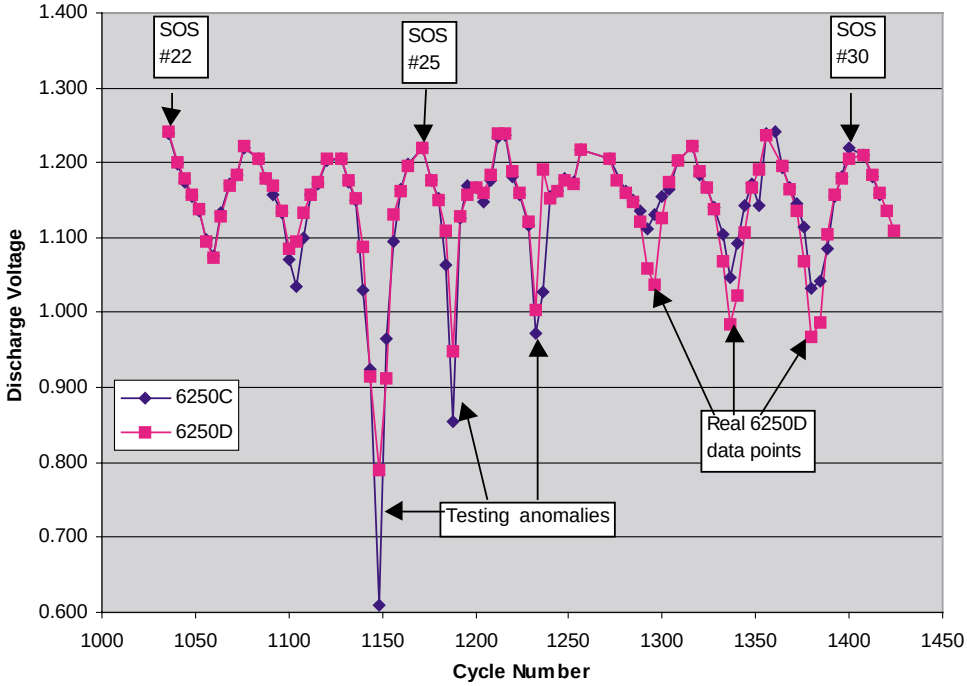

Fig. 3. NiCd Pellon 2505 (6250C) vs. 2536 (6250D) at 20 °C.

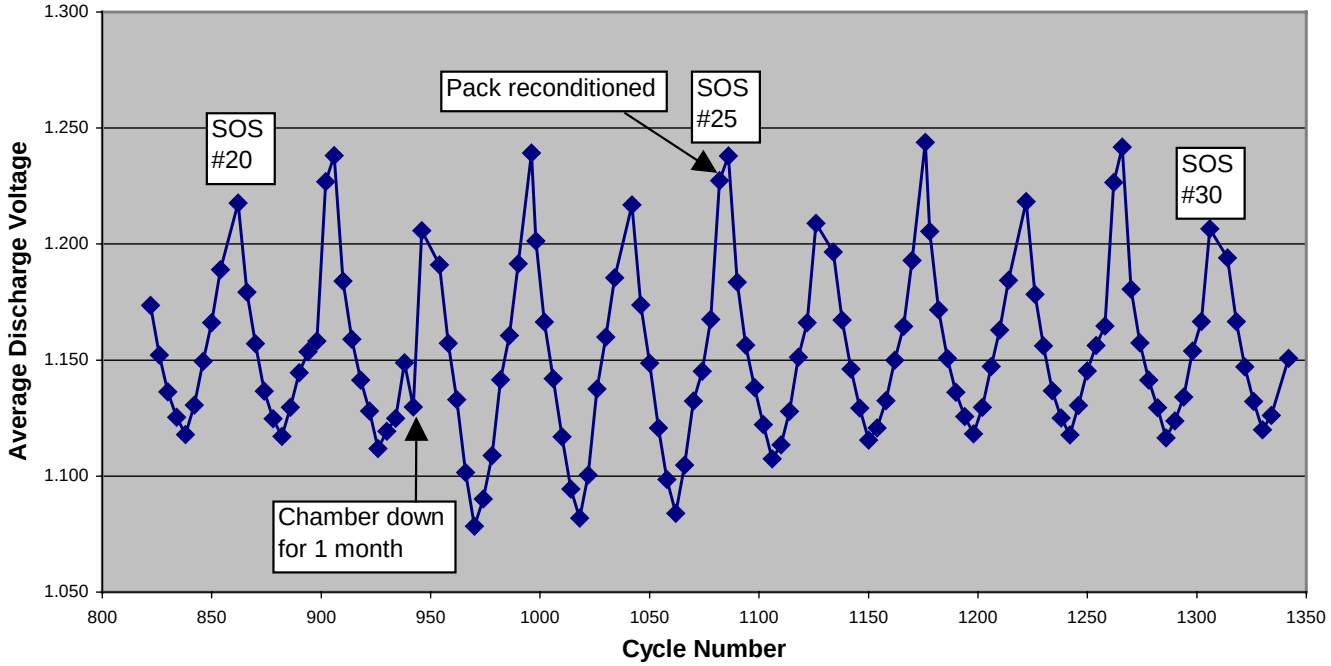

Fig. 4. 6224S SAFT VOS-A design.

3.3. Pack 6240S

These four 40 h SAFT cells were identical to 6224S except for the Ah rating, and were cycled identically. The pack completed 39 GEO orbits before being discontinued, but in the last seven orbits, the pack performance began to deteriorate noticeably, as shown in Fig. 5. The average EoDV plot shows a marked decline in the last orbits. In SOS #39, at 1744 cycles, cell #3 went negative during the 14th shadow day and cell #2 dropped below 1.00 V EoD, so testing was discontinued.

3.4. Pack 6335B

This pack of ten 35 Ah cells from Gates was cycled differently from preceding packs. Each season consisted of 102 eclipses of 55.2 min eclipse duration and 568.8 min sun duration for a 10.4 h total. No solstice or complete sun period was simulated. The testing was designed to repeatedly put the pack through the most strenuous part of the shadow period in a compressed schedule to give required data prior to a satellite launch. The test duration was set for 2496 cycles, with 102 deep discharges each

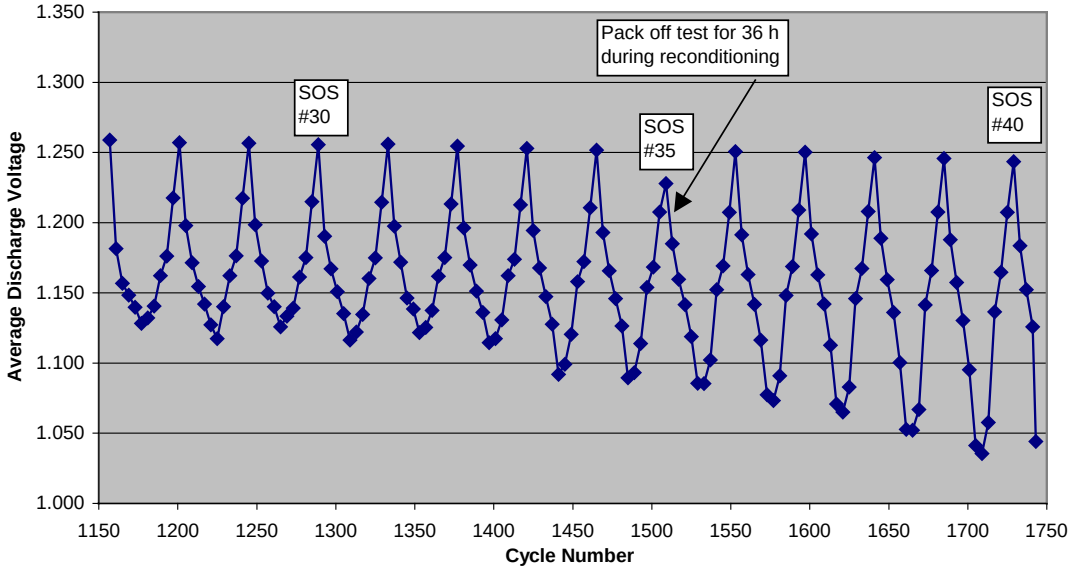

Fig. 5. 6240S SAFT VOS-A design.

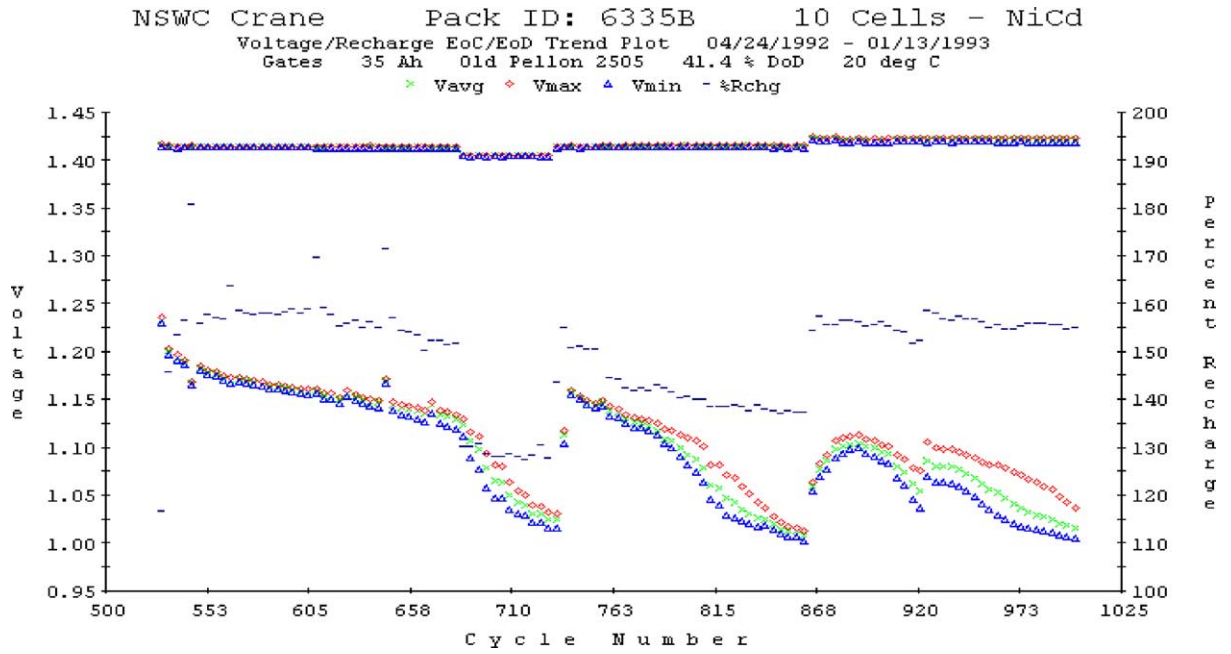

Fig. 6. 6335B repetitive maximum discharges.

"season" of ≈45 days, followed by a reconditioning and then a repeat of the 102 discharges. However, only 2093 cycles were completed, when testing was discontinued per sponsor instructions. The discharge rate was a constant 0.4*C* and 15.2–15.4 Ah were removed. The recharge was set at a *C*/12 rate for 10 min and then *C*/16.5 for 9.5 h, achieving a recharge of ∼190%. In the last orbit, the average EoDV was 1.161 V with no cell <1.16 V. The discharge data for several typical cycles are plotted in Fig. 6.

3.5. Pack 6211R

The five 5 Ah Sanyo cells in this pack were initially part of a VT study, so the GEO cycling began at cycle 2750. The GEO cycling was established to verify the cell integrity in an accelerated orbit study, and the pack completed 40 shadow periods. In the last simulated orbit, cell #5 fell below 1.00 V EoD and the average for the other four was 1.01 V, in the deepest shadow days. The last 14 orbital shadow periods are plotted in Fig. 7.

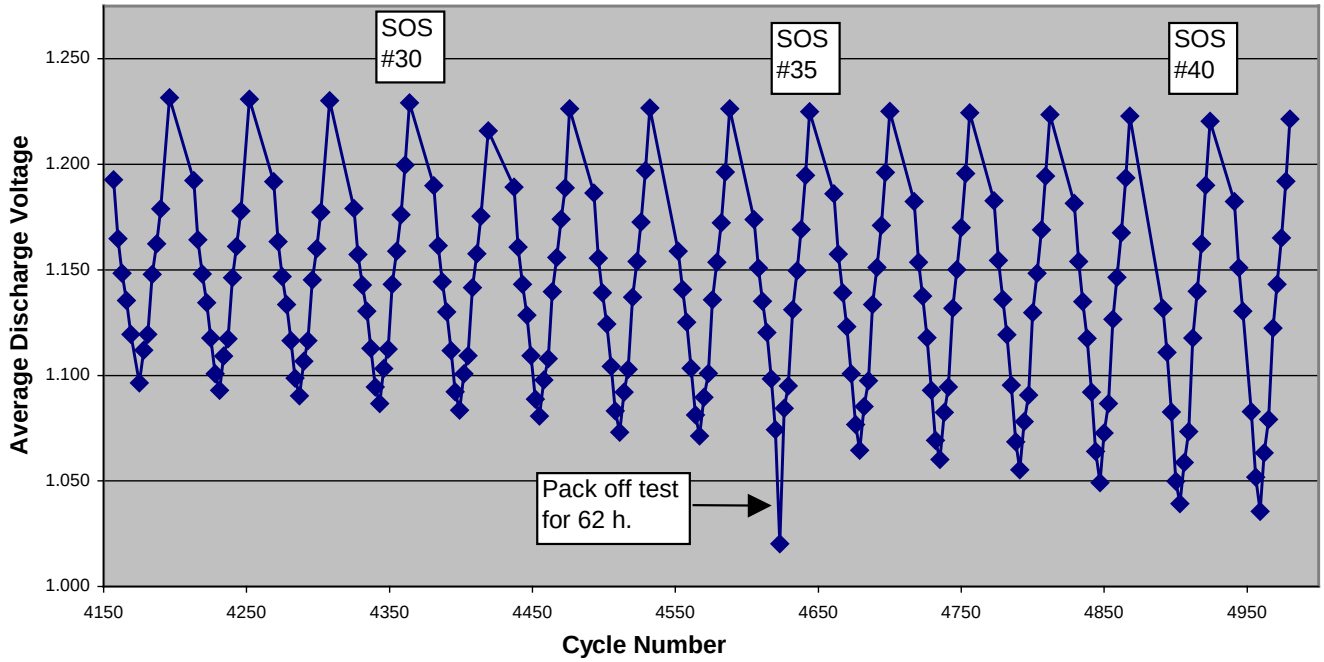

Fig. 7. 6211R, last 14 shadow periods.

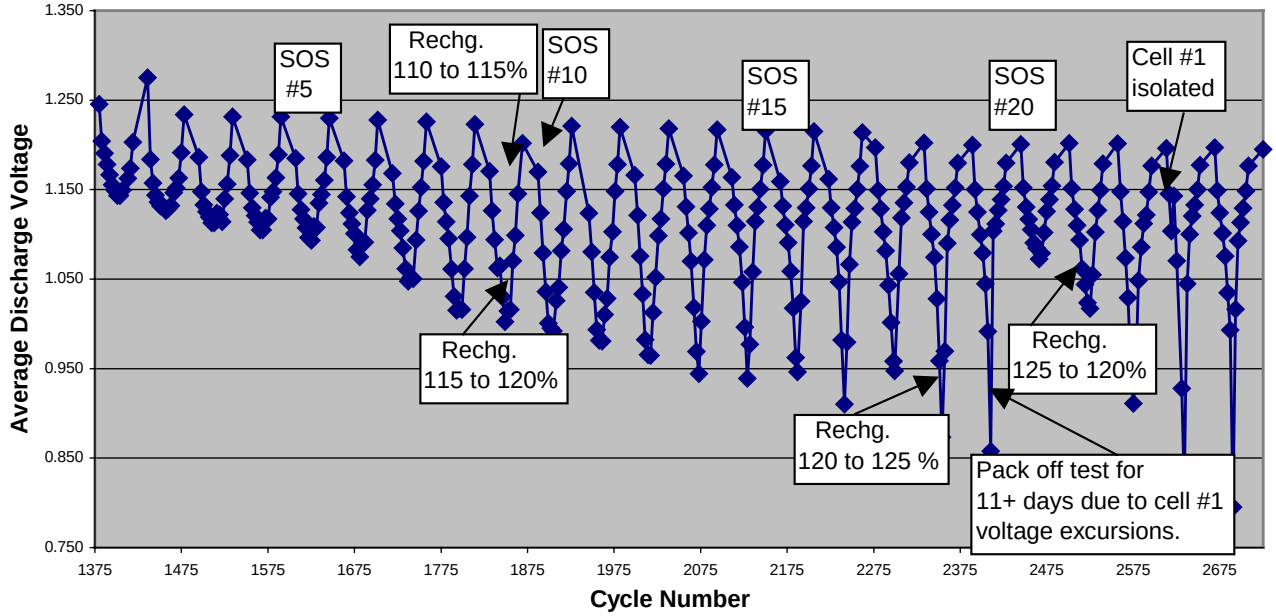

Fig. 8. 6211S SAFT VOS-A design.

3.6. Pack 6211S

A SAFT 50 Ah pack which was also part of a VT curve generation study during its first 1379 cycles, began its GEO accelerated orbital study at cycle 1380, in December 1997 and then cycled identically to 6211R. On shadow #23 (Fig. 8), one cell was removed for failure, and the pack was discontinued at shadow #25 because only one of the remaining four cells had a deep shadow EoDV >1.00 V.

3.7. Pack 0211H

This pack contained five 21 Ah super Ni/Cd cells and cycled for 30 shadow orbits, beginning in January 1996, without a cell failure. It exhibited a curious behavior, in that the deepest shadow EoDV's increased slightly after SOS #20 (Fig. 9).

However, during shadow #31, two cells went above a failure set point of 1.485 V during charge. The pack was left off for 22 days and then returned to cycling, but on the

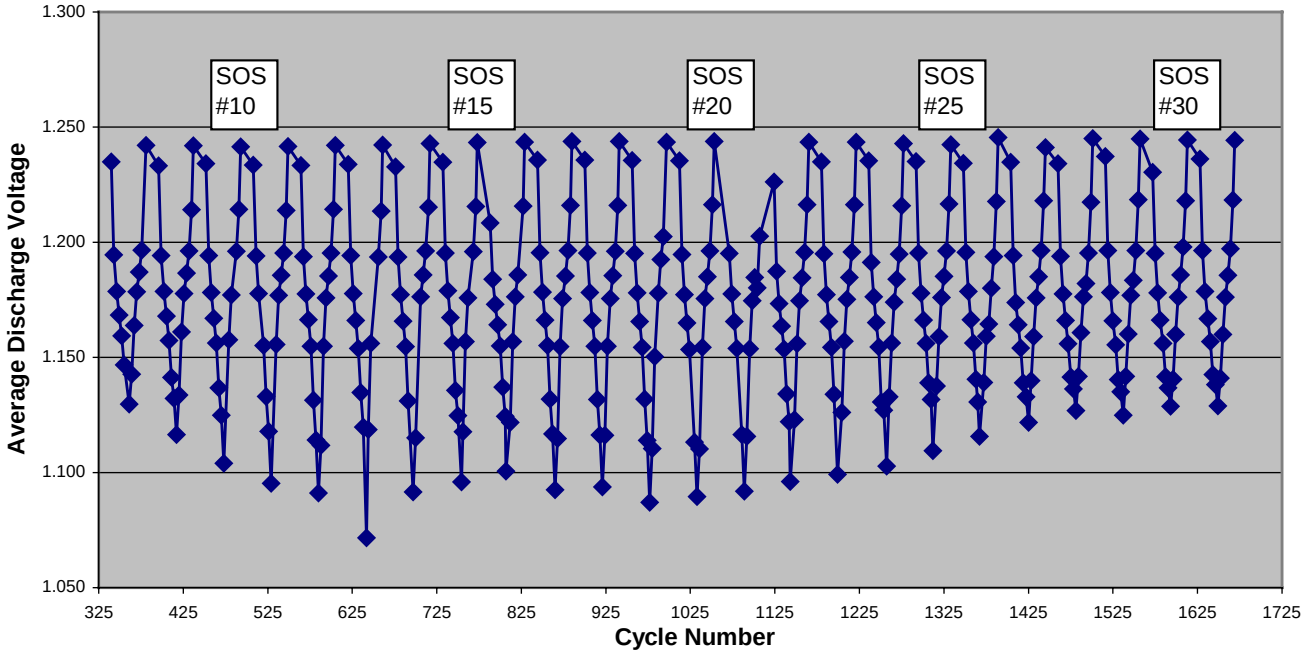

Fig. 9. 0211H super NiCd pack.

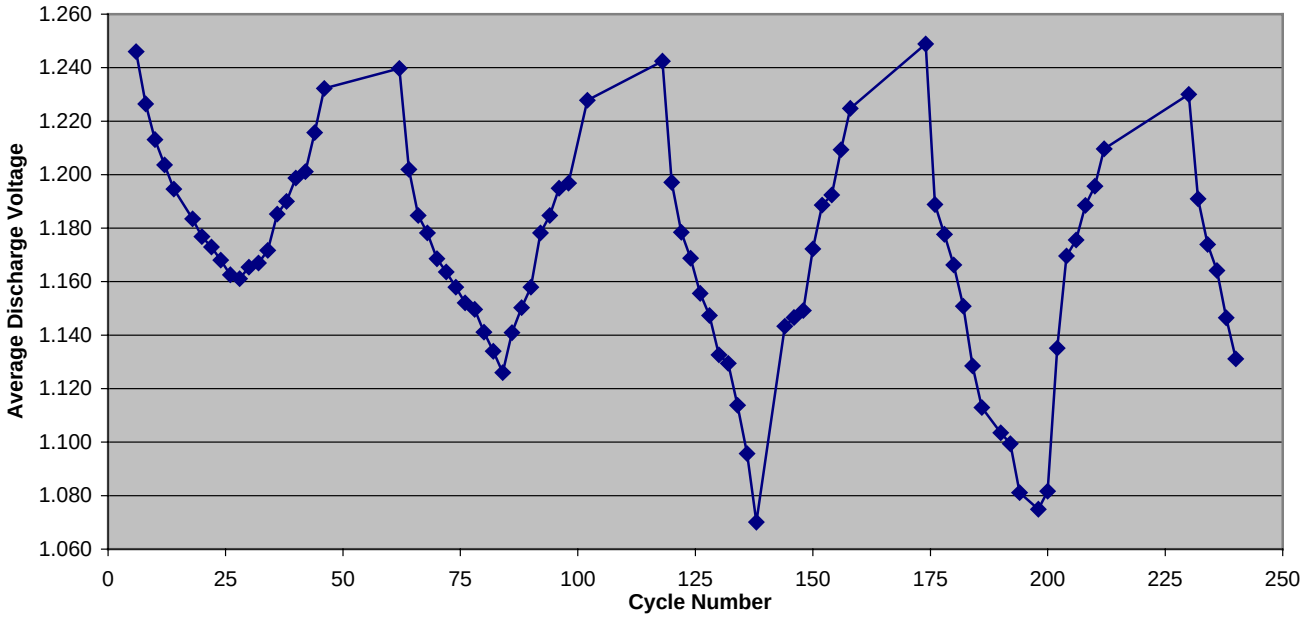

Fig. 10. 0211E, Magnum design.

next charge cycle the two cells again reached their upper limit, so the pack was discontinued. The data for 23 orbits are plotted in Fig. 9.

3.8. Pack 0211E

This pack contained five 21 Ah EPT Magnum-design cells. Testing began with the recharge set at 105%; by shadow #3, the cells had dropped below an EoDV of 1.00 at the point of deepest discharge. Over the next two shadows, the recharge was raised in 5% increments in an attempt to increase the EoDV. However, at shadow #5 the EoDV's were still below 1.00 at 120% recharge. The pack was reconditioned after shadow #5, but during shadow #6, when cycling approached the deepest DOD's, cell #'s 1 and 5 fell below 1.00 V again, so testing was discontinued. The data for the deepest discharge voltages are plotted in Fig. 10.

3.9. Pack 0251B

These nine 50 Ah super Ni/Cd cells at a maximum DOD of 75% at 5 °C. Problems developed immediately in the first shadow orbit, with the pack voltage exceeding the upper limit set point during the charge portion of each shadow cycle, and particularly cell #3 exhibited EoC readings >1.52 V. One shadow orbit was completed, then the pack was held on trickle charge for 3 months before being discontinued and returned to the sponsor.

4. Test results for nickel/hydrogen packs

Again, the individual pack descriptions are in Table 1. In the following text, IPV is an individual pressure vessel design and CPV is a common pressure vessel design. In this testing, except for pack 3007L, programs similar to pack 6335B were utilized, for an acceleration factor of 2.4×, based on 12 years of projected satellite life. The simulation used the most strenuous 4-day part of the shadow period for a projection of satellite battery life.

4.1. Pack 3007L

Contained six 45 Ah CPV cells which completed 1371 GEO cycles before being converted to an LEO test regime. The pack was tested in an accelerated GEO manner, simulating a mid-altitude orbit just like the Ni/Cd packs in the last section, with a 42-day shadow period followed by a 14-day solstice. In Fig. 11, it is noted that the average EoDV for the deepest shadow discharges for the first 10 orbits decreased rather markedly, continuing into the 14th shadow.

At the completion of this orbital period, the pack was on trickle charge for 61 days. At cycle 847 the pack was discharged three times at a 28.1 A rate to 75% DOD, recharged at a high rate to 110%, then placed on a 14-day trickle before being returned to GEO cycling at cycle 869. However, the EoDV for the deepest shadow resumed deterioration after the 15th orbit. The pack completed 23 shadow periods, during the last of which the average deepest shadow EoDV = 1.415 V with a six cell range from 1.370 to 1.679 V. At that point it was converted to an LEO orbit, at the sponsor's request, and completed 2200 LEO orbits before being removed from test.

The next three packs were part of a separator material study.

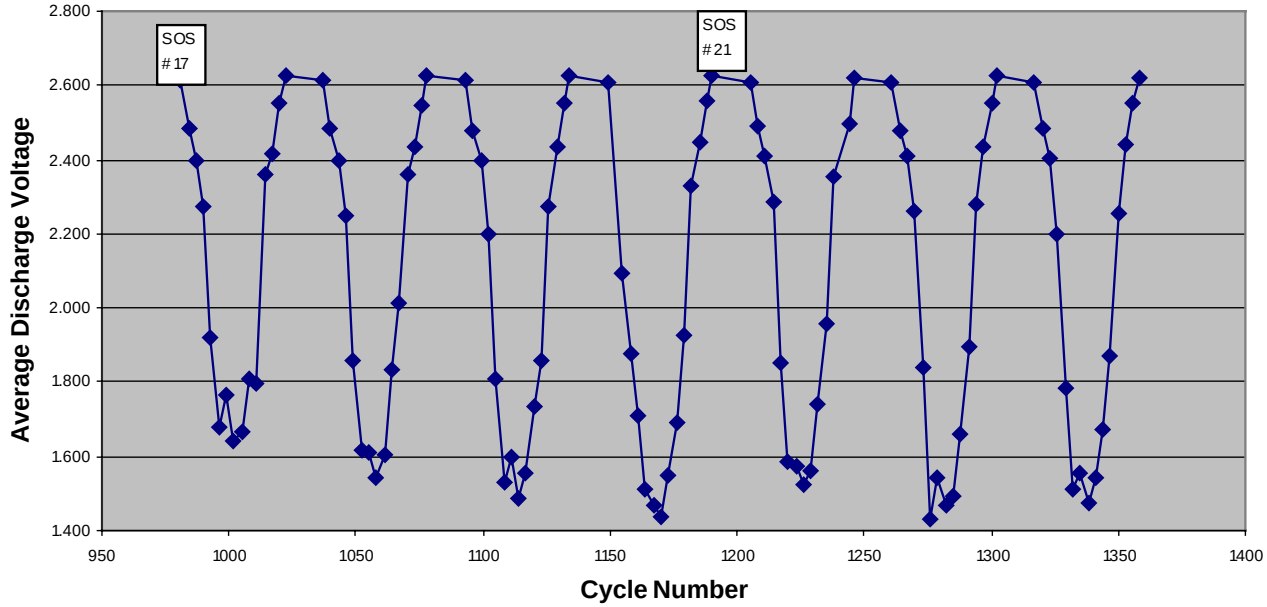

Fig. 11. 3007L, CPV cells—last seven shadows.

4.2. Pack 3487A

This pack contained five 40 Ah IPV cells with asbestos separation. The pack began GEO orbits at cycle 133 with a maximum DOD of 75% every cycle for 102 days, followed by 5.2 A recharge for 7.04 h total at 0 °C. During this first 102-day period, on cycles 188 and 189, cell #1 dropped to 0.949 V EoD, so the recharge was raised from 108 to 114–117% for cycles 189–204, then to 122% for cycles 205–234, the end of the first 102-day period. The pack was reconditioned and the recharge time was increased to 11.06 h with 126% recharge, and then from cycle 274–343, it was 152–160%. The third 102-day period ended the initial evaluation cycling, and for the next four periods, the average EoDV decreased steadily (Fig. 12). Midway through the seventh period, the DOD was decreased to 60%, where

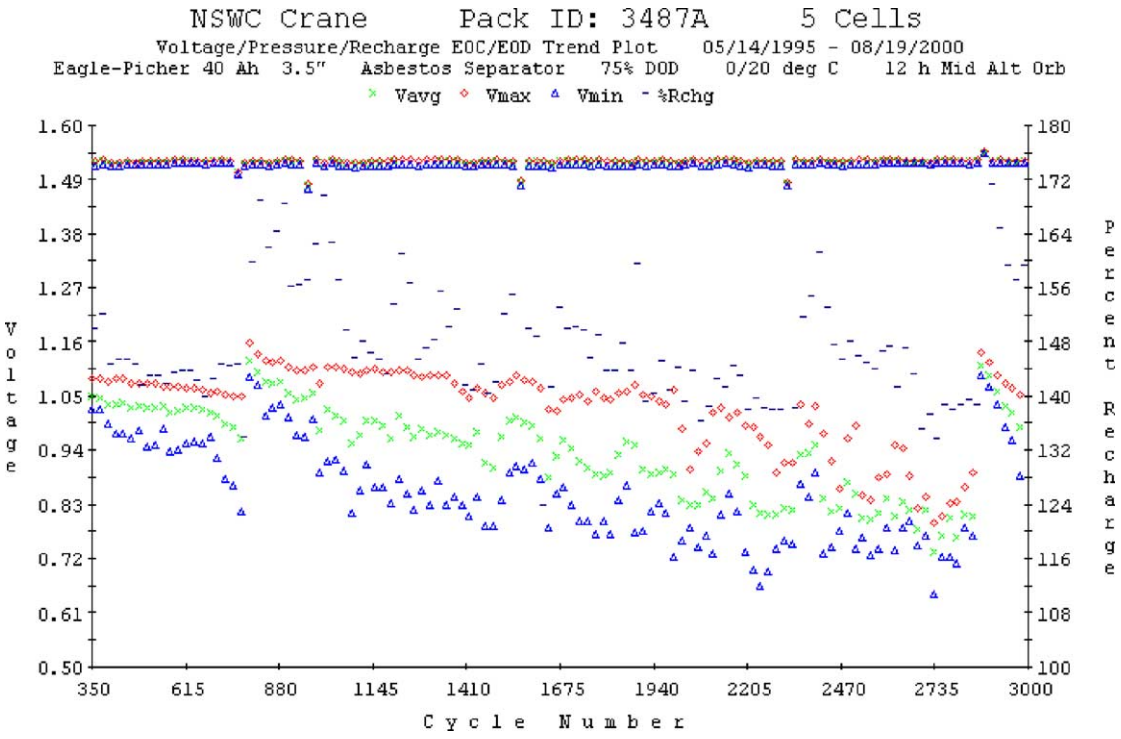

Fig. 12. 3487A, asbestos separation.

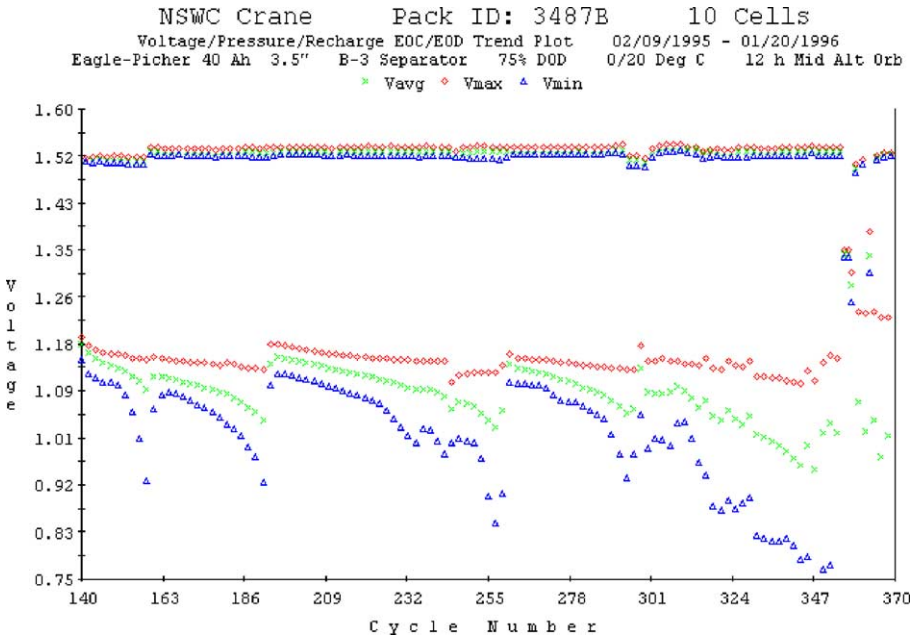

Fig. 13. 3487B, proprietary separation.

it remained for the rest of the twenty-six 102-day periods with 56 min discharge, 11.06 h recharge. The pack was reconditioned after every 102-day period with a 21-day, 0.63 A charge. The EoDV's continued to decline, and at cycle 2708 the avg. EoDV = 0.808 V, so a full pack reconditioning occurred at cycles 2709–2711, with the cycling restarted at cycle 2718. In the last period, only three of the original five cells were still on test.

4.3. Pack 3487B

This pack contained eight 40 Ah cells with a proprietary separation designated B-3. GEO cycling was begun at 143 cycles with the same program as pack 3487 A, at 75% DOD. During the first 102-day period the pack went off test several times for low cell voltages on discharge, so the DOD was changed to 65% at cycle 194 (half-way through the

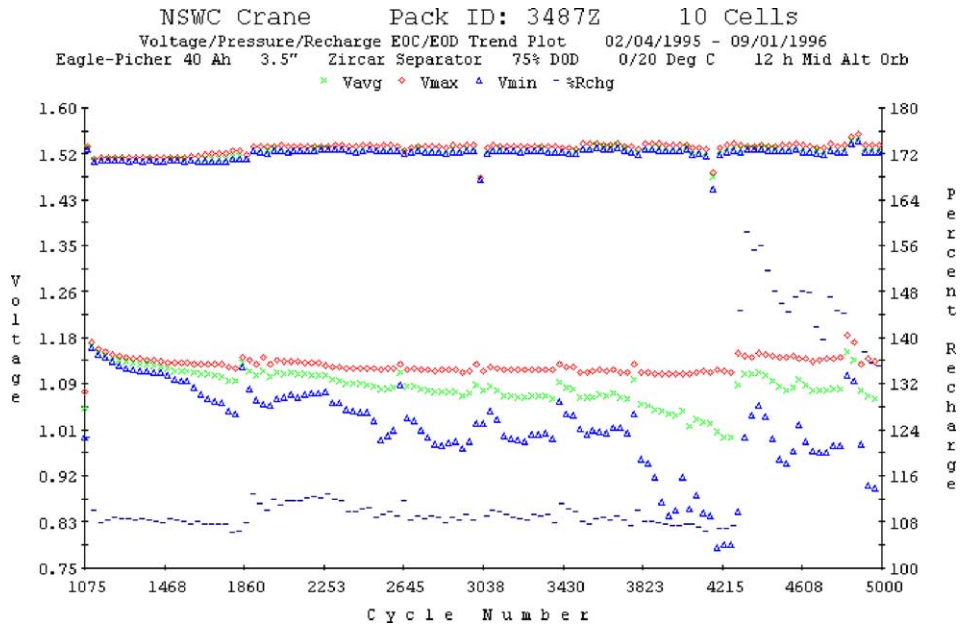

Fig. 14. 3487Z, Zircar separation.

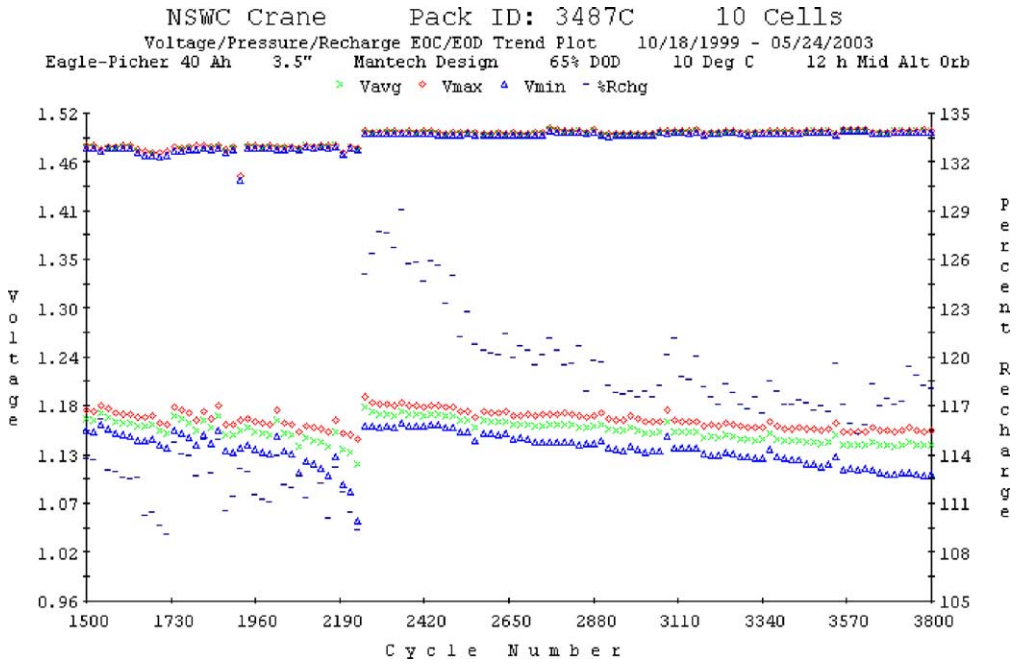

Fig. 15. 3487C, Mantech design.

first period). The pack continued to exhibit both high EoC and low EoD voltages on several cells, through the next two 102-day periods, with the EoDV of cell #6 falling to 0.200 V in cycle 352. The pack was discontinued, per sponsor's instructions, at the conclusion of the third period (Fig. 13).

4.4. Pack 3487Z

These ten 40 Ah IPV cells contained Zircar separation. The test program was the same as for 3487 A, and the first two 102-day conditioning cycles began at cycle 133. The pack completed ten 102-day periods but the EoDV's began to deteriorate seriously by the 7th period. The pack was reconditioned after the 8th 102-day period, but the cell voltages resumed a significant decline at EoD with cell #1 at a negative 0.122 V EOD in cycle 989. The pack was discontinued after the 10th period (Fig. 14).

4.5. Pack 3487C

This pack contains ten 40 Ah cells of a Mantech design. It is being cycled at 10 °C, rather than 0 °C like the previous three packs in the 3487-series, because it has a specific mission profile. The DOD is 65% and the period time is 92 days in a mid-altitude orbit (MAO). It began cycling in July 1997 and is in the 72nd day of the 41st MAO (30 June 2003). The only change to the cycling program occurred at cycle 2256, when the percent recharge was changed to ∼124 from ∼109%, by changing the 6.5 h trickle charge from 1.1 to 2.5 A, because cell #4 dropped below 1.00 V EoD. The current avg. EoDV is 1.14 V, over a spread of 1.11–1.16 V (Fig. 15).

5. Conclusions

(a) Pellon 2536 separation did not provide the orbital life of 2505.
(b) SAFT VOS-A (proprietary) appeared to provide the desired life performance.
(c) Pack 6335B, even though the test life was shortened, performed well.
(d) Sanyo pack 6211R held up well, in spite of the initial stress of VT testing, for 2700 cycles. However, the SAFT pack from the same VT study failed prior to expectations.
(e) Pack 0211H appeared to be performing well out to the 31st shadow, when two cells failed the EoCV criteria.
(f) In the NiH separation study, the "B" separation was a very poor performer, while the Zircar cell pack outperformed the asbestos.

Reference

[1] P.A. Malachesky, et al., Proceedings of the 25th Intersociety Energy Conversion Conference, August 1990.