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THE 1996 NASA AEROSPACE BATTERY WORKSHOP

THE IN-ORBIT PERFORMANCE OF BATTERIES ON THE SKYNET 4 SPACECRAFT FLEET: A NICKEL-CADMIUM SUCCESS STORY.

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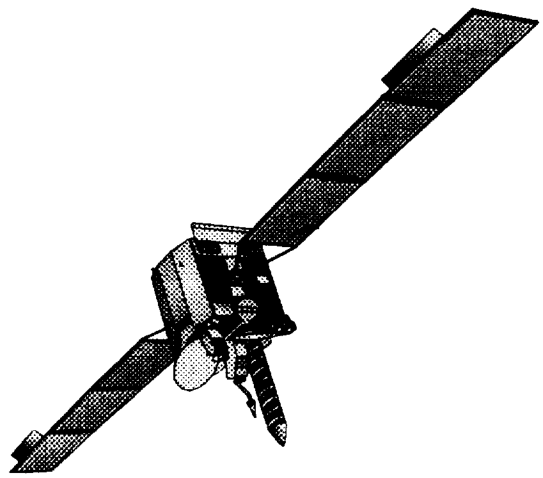
Abstract.

The SKYNET 4 constellation consists of three spacecraft which were launched between December 1988 and August 1990. The spacecraft are three-axis stabilized geostationary earth-orbiting military communications satellites with a design life of seven years on station. With the mission objective achieved all the batteries continue to give excellent performance.

This paper presents a review of the history of the six batteries from cell procurement to the end of their design life and beyond. Differences in operational strategies are discussed and the lifetime trends in performance are analyzed. The combination of procurement acceptance criteria and the on-station battery management strategy utilized are presented as the prime factors in achieving completely successful battery performance throughout the mission.

SPACECRAFT IN ORBIT VIEW



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Introduction.

The SKYNET 4 series of three military communications satellites provide flexible tactical communications for maritime and land forces and strategic communications. They were designed, built, integrated and tested by British Aerospace Space Systems Limited (now part of Matra Marconi Space UK Limited). The spacecraft platform was derived from the platform used by the European Space Agency's (ESA) successful ECS and MARECS satellites. These are three-axis stabilized geostationary satellites which provide wide coverage. A view of one of these spacecraft as it would appear in orbit is given in the figure above.

CELL AND BATTERY STANDARDS

PARAMETER	NASA	ESA	MMS
Maximum Temperature / °C	35	30	35
Maximum Pressure / psig	80	Not Specified	60
Maximum DoD / %	70	80	50
Maximum cell volts / V	1.55	1.56	1.56
Design Life / years	8	13	7
Capacity Dispersion / %	5	3	3

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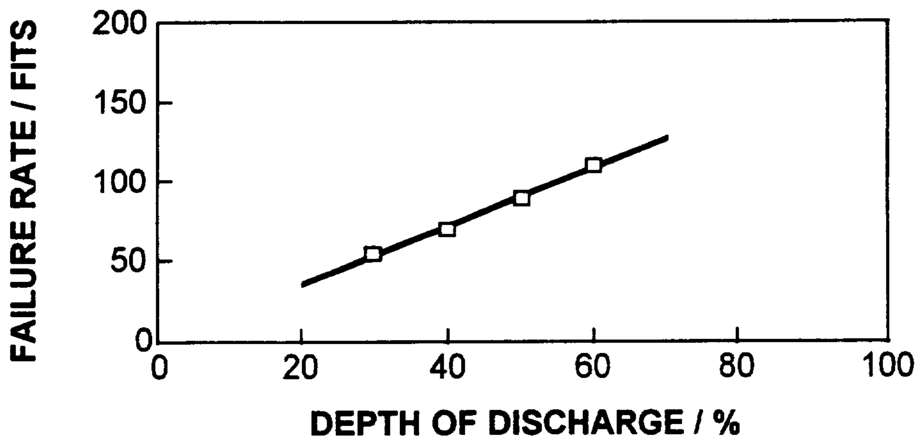
Battery Definition.

A detailed description of the power subsystem and the battery design philosophy was given at last year's workshop [1], where spacecraft A of the SKYNET series was the focus of attention. Spacecraft B has identical batteries to spacecraft A, even having cells from the same manufacturing lots (each spacecraft had one battery built from Gates 35AB03 lot 6 cells and the other from lot 7). Spacecraft C had batteries made from cells of lot 8, which gave similar test results to the earlier lots except during the early cell level tests, when marginally lower capacities, particularly at 0°C, were recorded.

The procurement specification for the batteries was based on a combination of American [2] and European [3] standards which are compared in the above table. The maximum depth of discharge of 70% or 80% was not adopted as a result of system reliability considerations.

Ni-Cd BATTERY CELL FAILURE RATES



SOURCE: ESA STANDARD PSS-01-302 ISSUE 1

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Available data at the time of the design of these spacecraft showed that cell failure rates, measured in Failure unITS (FITS), increased with depth of discharge [4], as illustrated in the above graph. Furthermore, following the work of Dawson [5], it was decided not to use cell by-pass electronics but to use the mass saving to offset the use of a larger capacity battery. Reliability analysis set the maximum failure rate for a cell at 89 FITS and consequently the design maximum depth of discharge was set to 50%.

BATTERY MANAGEMENT STRATEGY

1. The average battery temperatures are strictly maintained below 15°C.

2. Overcharge is limited in eclipse by having a k-factor goal of 105%.

3. Overcharge is limited in the hotter solstice by having trickle-charge enabled for only 50% of the time.

4. The depth of discharge is well within the design limit of 50%, with all spacecraft in the range 32-40% as they reach the latter part of their design life.

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Battery Management Strategy.

The primary objectives were to keep the battery temperatures below 15°C throughout the mission, which has led to toggling trickle charge on and off during the solstices for the battery on the sun facing side of the spacecraft, and minimizing overcharge. The same battery management strategy is applied to all three spacecraft with two important exceptions: spacecraft A has a lower end of charge voltage limit set to terminate main charge when the recharge ratio (k-factor) is of the order of 90% and spacecraft B's batteries are only reconditioned once per year.

BATTERY CURRENTS AND RATES

PARAMETER	Current / A	C/	C_{der}/	Rate Limits
Main Charge	1.85 ± 5%	18.9	14.2	$C/10^{*} > I_{mc} > C/20$
Trickle Charge	0.3 ± 10%	116.7	87.5	$C/70 > I_{tc} > C/200$
Discharge	10.5 ± 10%	3.3	2.5	$I_d < C/2^{*}$

*Cell Manufacturer's limit

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The secondary objective in the battery management strategy was to minimise cell current density. Although the cells had a nameplate capacity of 35 Ah the manufacturer recommended the use of a derated capacity, defining C_{der} as the capacity of the cell when discharged for one hour at a maximum current density of 20 mA cm^{-2}, in the calculation of maximum charge and discharge rates [6]. As the Gates 35AB03 cell had a positive plate total area of 1324 cm^2 this gave a derated capacity of 26.5 Ah. The above table gives the charge, discharge, and trickle charge ranges seen in orbit and compares both the rates based on nameplate capacity and on derated capacity with the limits given in the Power Standard [3]. In all cases it can be seen that the spacecraft are operating with comfortable margins on their design limits.

CHARGE TERMINATION CRITERIA

1. End of charge voltage trip level is reached.
2. Rate of temperature rise exceeds 1°C in 15 minutes.
3. The charge input exceeds 1.05 times the charge withdrawn during the preceding eclipse.
4. Average temperature of either battery reaches 15°C.
5. Battery upper temperature limit, as indicated by any thermistor, is reached.

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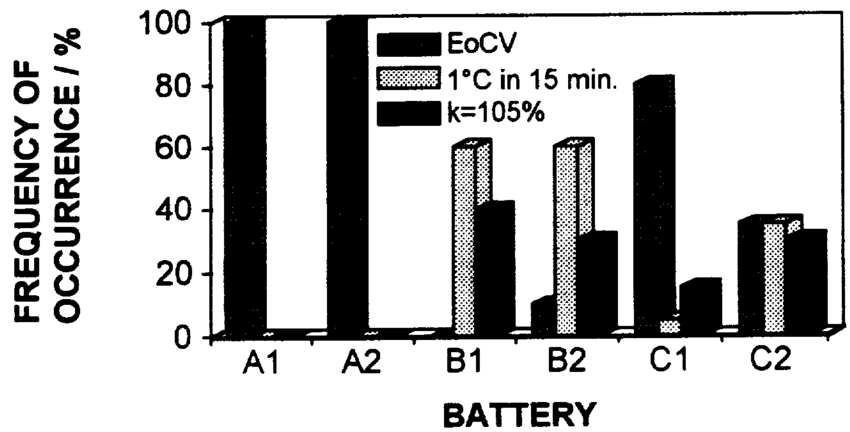
Charge Termination.

Of the above charge termination criteria, numbers 1 and 5 are automatic and the remainder are manual by ground intervention. Automatic termination is preferred as the operator workload associated with the manual enabling and termination of main charge is significantly reduced, as is the real-time data analysis required to determine the manual termination criteria. Following the success of the strategy of setting a lower end of charge voltage limit on spacecraft A to ensure automatic charge termination, albeit with a lower than recommended recharge ratio, this strategy was adopted for all three spacecraft prior to the Autumn 1996 eclipse season.

The thermal limits, criteria 4 and 5, are only expected to be reached in abnormal circumstances. To date, only termination by criteria 1, 2, or 3 have been experienced.

CHARGE TERMINATION



SPRING 1995 ECLIPSE SEASON

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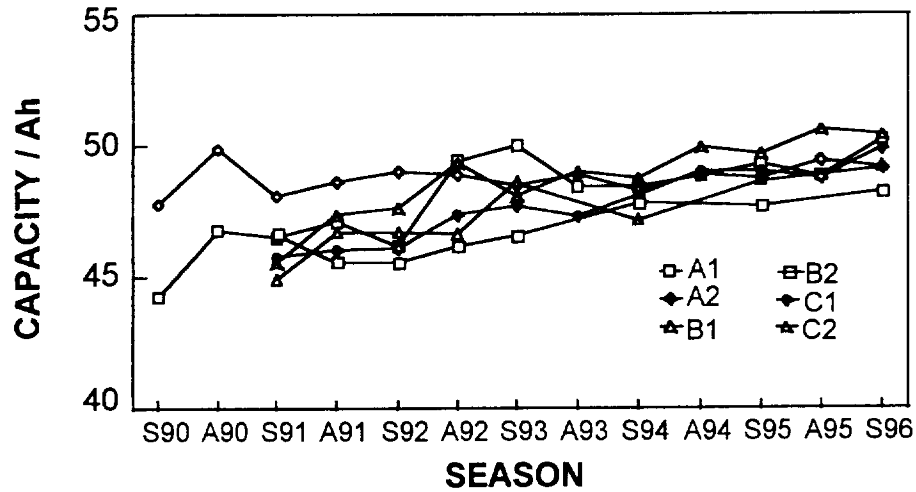
The above chart gives the frequencies of occurrence of the three charge termination criteria encountered during the Spring 1995 eclipse season. The low end-of-charge voltage (EoCV) on spacecraft A at 41.4 V ensures this criteria is always reached first. Although this results in a k-factor of ~90%, the fairly high trickle charge rate of the order of C/100 ensures the batteries are fully charged each season. Among the other batteries there is a fairly even distribution of charge termination criteria.

BATTERY RECONDITIONING CAPACITIES



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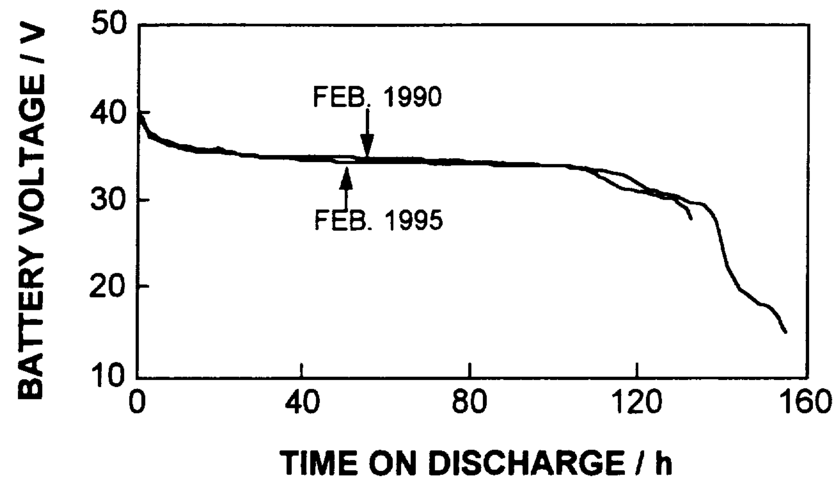
In-Orbit Performance.

1. Reconditioning.

The reconditioning cycle also serves as a battery health check. This consists of discharging the battery through a 102.5 Ω resistor until the first cell falls below 400 mV or until all cells are below 600 mV. Although it may be preferable to terminate the discharge for example when the first cell reaches 100 mV, ground station availability and "down-time" have to be taken into account. Allowing for a maximum down-time of thirty minutes, the 400 mV limit is considered a safe voltage level where a further thirty minutes of discharge would not lead to reversal.

The above figure shows the returned capacity during this cycle each time it has been performed. The 35AB03 cells used in the SKYNET batteries had a positive plate loading of 12.65 ± 0.6 g dm^{-2} of active material. This gives a theoretical capacity of 48.4 Ah on average. The gentle increase in capacity with time is considered normal and is attributed to the corrosion of the nickel substrate of the cathodes. In all cases the rate of increase in capacity is less than 1 ampère-hour per year.

DISCHARGE CURVES FOR BATTERY A1 DURING RECONDITIONING



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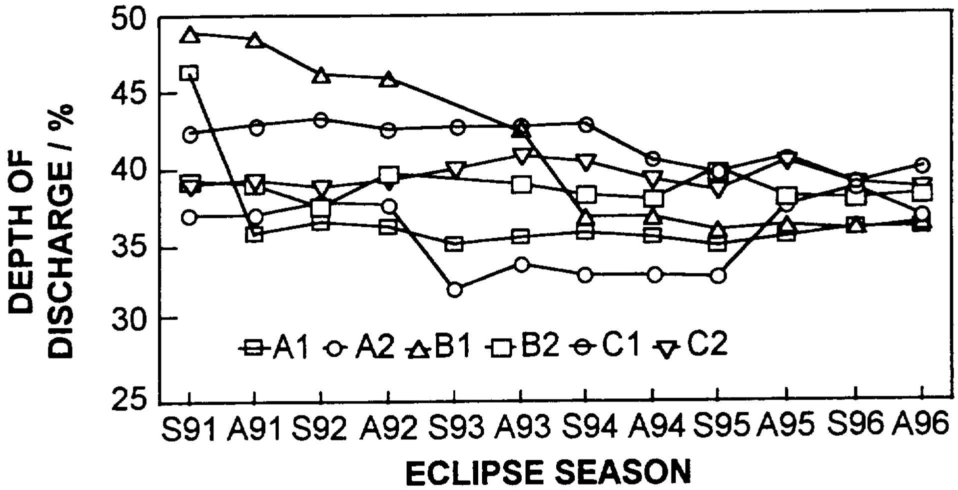
The batteries are reconditioned prior to each eclipse season, except in the case of spacecraft B which has annual reconditioning. Examination of the reconditioning discharge profile provides information on the health of the batteries. The above diagram compares the discharge profiles for spacecraft A battery 1 from 1990 with that from 1995. A second voltage plateau is evident immediately before the termination of discharge, indicating that the cells are limited by the positive electrodes. The depression of the 1995 curve by approximately 100 mV implies the internal resistance of the battery has increased by 7% over the five year period. This can be attributed to the normal electrolyte redistribution during lifetime.

MAXIMUM DEPTH OF DISCHARGE DURING ECLIPSE



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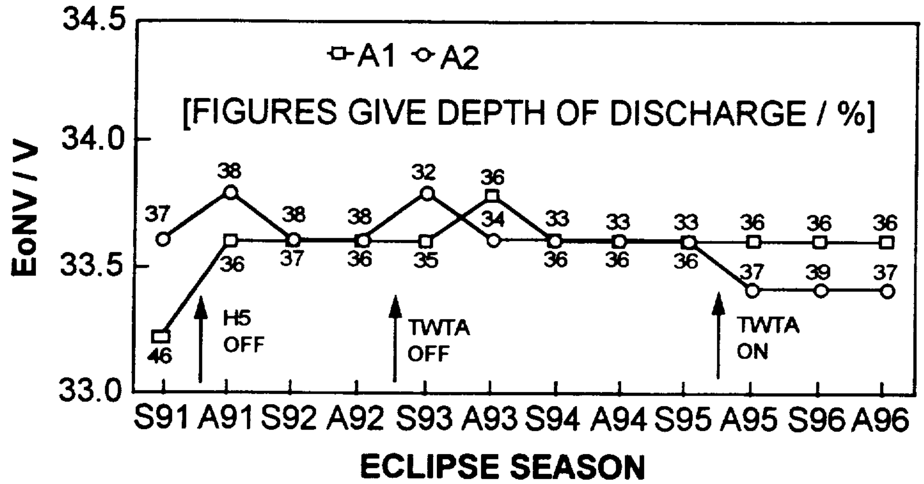
2. Eclipse Performance.

As operational demands vary the depth of discharge each battery experiences also varies from season to season, as may be seen in the above figure. The solar absorbency of the secondary surface mirrors increases with time as deposits condense from the out-gassing spacecraft, causing the spacecraft temperature to rise. Midway through the life of the spacecraft this temperature rise is compensated for by the permanent disabling of a 50 W general level heater, thereby reducing the load on battery one of each spacecraft in later years. To enable comparisons of battery voltages to be made differences in depths of discharge must be taken into account. However, from the above figure it can be seen that all six batteries have converged and are operating in the range 38 ± 2 % depth of discharge.

END OF NIGHT VOLTAGES - SPACECRAFT A



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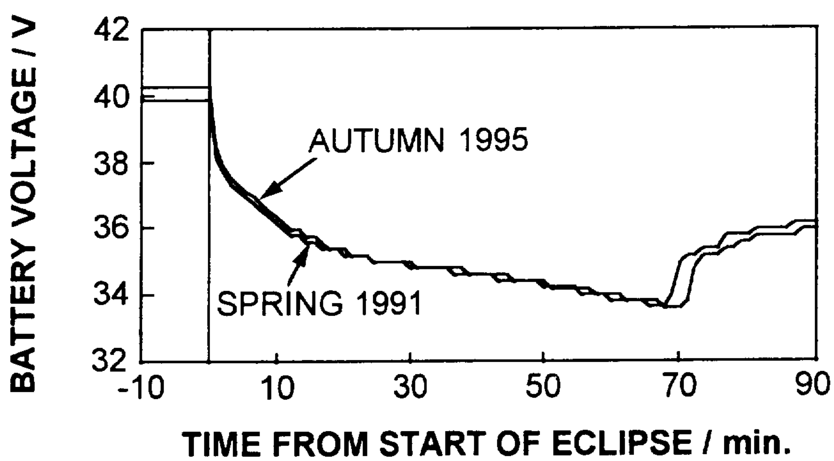
2.1 Spacecraft A.

The above figure gives the end of night voltages for spacecraft A for the peak eclipse each season. The numbers at each point indicate the depth of discharge of the battery at that eclipse. The battery voltage is measured on the spacecraft using an eight-bit analogue-to-digital converter to cover the voltage range 0-50 V, giving a resolution of 1 bit equals 194 mV. Battery 1 has had a constant peak eclipse depth of discharge after the general level heater H5 was turned off in June 1991, while battery two's depth of discharge fell by 4% during the period that one of its travelling wave tube amplifiers (TWTA) was switched off.

From the graph it can be seen that battery 2 had a depth of discharge of 37% in Spring 1991 and in the Autumn of 1995. During this period the battery voltage has decreased by 1-2 telemetry bits (~200 - 400 mV). As most of the spacecraft heaters are on bus 1 (heaters are resistive loads) and the payload is mostly on bus 2 (the payload is essentially a constant power load) this may explain the small difference in the above curves. While care must be taken with data with such limited resolution, it does appear that the battery with resistive loads is not degrading as much as the battery with constant power loads.

SPACECRAFT A BATTERY 2 VOLTAGE PROFILES DURING ECLIPSE



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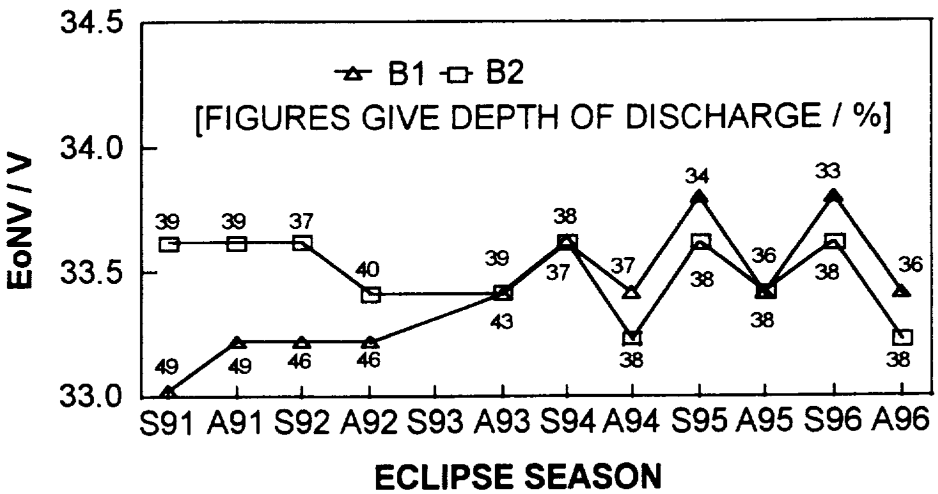
The above curves show the discharge voltage profiles during the Spring 1991 and Autumn 1995 seasons. The later curve shows a higher steady state voltage on trickle charge and a lower end-of-night voltage, though in both cases these differences correspond to one telemetry bit.

END OF NIGHT VOLTAGES - SPACECRAFT B



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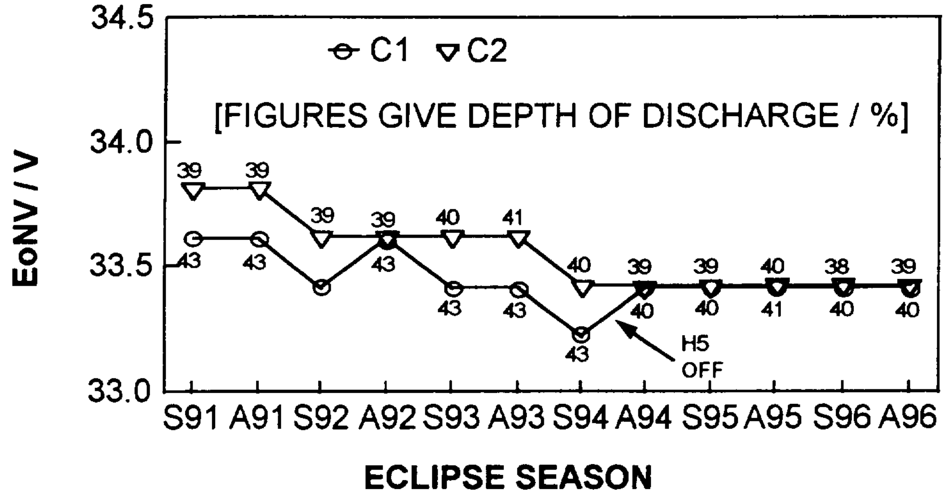
2.2 Spacecraft B.

A spacecraft is vulnerable during reconditioning when one of its batteries is fully discharged. As spacecraft B's batteries are only reconditioned once per year the effect of omitting reconditioning prior to an eclipse season can be evaluated. The option of being able to omit a reconditioning sequence may be desirable, particularly during a period of stress. The above curve shows the end-of-night voltages for the peak eclipse. Annual reconditioning, prior to the Spring eclipse season was introduced in 1994. The difference in battery voltage between the Spring and Autumn seasons is up to 400 mV. Surprisingly, the annual recondition seems more effective at restoring battery voltage than when half-yearly reconditioning was employed. However, no explanation for this phenomenon is offered.

Although battery one was more heavily discharged during the earlier part of its life, its end-of-night voltage in later life appears constant when the reconditioning effect is taken into account. Battery 2 has had a nearly constant depth of discharge throughout life with no evidence of voltage degradation.

END OF NIGHT VOLTAGES - SPACECRAFT C



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2.3 Spacecraft C.

This is the control spacecraft in the sense that the batteries are operated in accordance with established procedures. The loading on both batteries has been constant throughout life with the exception of the level heater H5 being turned off in August 1994. This gave a 3% reduction in depth of discharge. From the discharge profiles the battery voltage fall with depth of discharge, at the discharge rates used, can be determined. All spacecraft battery voltages fall within the range -65 ± 5 mV per percent depth of discharge. Thus although battery one's voltage appears to fall by one telemetry bit, when the lower depth of discharge is taken into account this is equivalent to two bits, the same as battery two.

These two batteries, while giving better than acceptable performance, are under performing the other four batteries. With hindsight this may not be surprising, as even in the cell vendor's data pack these cells were seen to have marginally lower capacities, and consequently these batteries are being worked "harder" in orbit.

SUMMARY

1. 10 387 776 cumulative cell hours in orbit with no failures.
2. Recharge ratio of 90% and a trickle charge rate of C/100 is sufficient to maintain the batteries fully charged.
3. Annual reconditioning is sufficient to fully restore battery performance.
4. The low-current, low-temperature (LILT) philosophy of battery management has resulted in better than expected battery performance over the design life.

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Summary.

The six batteries on these three spacecraft have to date (3rd December 1996) accumulated over 10 million cumulative cell hours with no failures and continue to perform with barely detectable signs of degradation. The cell and battery specifications developed by both ESA and NASA combined with an in-orbit battery management strategy based on low temperature, low current density and low depths of discharge have resulted in a spacecraft fleet whose batteries have exceeded all expectations. The LILT approach additionally results in a simplification of the battery operational procedures. Semi-autonomous eclipse operation is possible with a single voltage limit, as temperature compensation or VT curves are not needed with the constant current charging available from the dedicated solar array strings.

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References.

1. P. J. Johnson and N. R. Francis, Proc. 1995 NASA Aerospace Battery Workshop, NASA Conference Publication 3325, (1996), 175.

2. NASA Specification NHB8073.1, "NASA Specification for Manufacturing and Performance Requirements of NASA Standard Aerospace Nickel-Cadmium Cells",(1988).

3. "Power Standard", ESA Publication PSS-02-10 Vol. 1 Issue 1 (1992).

4. "Failure Rates for ESA Spacecraft and Associated Equipment", ESA Publication PSS-01-302 Issue 1 (1985).

5. T. Dawson, "Elimination of Battery Cell Bypass Electronics on FLTSATCOM", Paper 849002, Proc. IECEC '84, (1984), 72.

6. D. F. Schmidt, General Electric Company, Private Communication, (1986).