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Nickel-Cadmium Battery Technology Advancements for Geosynchronous Orbit Spacecraft

Richard H. Sparks*
TRW Defense and Space Systems Group, Redondo Beach, Calif.

The general desire to increase battery service lifetimes to 10-12 years in geosynchronous orbit is providing strong encouragement for nickel-cadmium battery development along several promising lines of investigation. An important aspect of this work involves meeting continuing demands for improvements in the usable specific energy and energy density of battery systems. The desired extensions of battery lifetime reflect the requirement to increase the return on investment in spacecraft systems. The improvement goals in battery mass and volume characteristics anticipate opportunities in the Shuttle era for larger spacecraft with advanced payloads operating at higher power levels. The paper presents a description of some recent investigations, a summary of the results achieved to date, and an identification of future areas of work that may yield further improvements in nickel-cadmium battery capability and performance.

Introduction

PERFORMANCE of the nickel-cadmium battery system in geosynchronous orbit spacecraft has been acceptable for most three-year applications. Some spacecraft have operated without notable battery problems for well over five years. When problems have occurred, they usually have been due to 1) the development of high charging voltages which cause the charge controls to overly restrict battery recharge, and 2) several instances of shorted and/or degraded cells. Severe problems with poor voltage regulation have been reported; however, these effects have been reduced through the use of shallow (approximately 1.0 V per cell) reconditioning discharges.

New work directed toward improving the capability and performance of the nickel-cadmium battery system has been in progress since 1970. The major areas of investigation are:

1) Evaluation of the deep discharge reconditioning (DDR) technique in which batteries are discharged to near zero volts per battery.

2) Comparative studies of the effect of temperature and depth-of-discharge on cycle life performance with and without DDR.

3) Evaluation of new developments in battery cell materials and manufacturing processes that promise to extend service life and improve specific energy.

4) Development of a lightweight long-life battery that uses advanced nickel-cadmium cell technology.

5) Definition of guidelines for the conduct of low-cost cell and battery ground-storage and preflight logistics operations.

The paper summarizes the results of these efforts in detail.

Development of Reconditioning Methods

It has been known for many years that shallow or soft reconditioning procedures provide some temporary relief from the effects of long term repetitive cycling. To better understand the advantages and limitations of this technique when it is used with batteries operated at 50-85% depth-of-discharge, comparative tests of batteries with shallow discharge reconditioning (SDR), deep discharge reconditioning (DDR), and without reconditioning were conducted.[1,2] Investigations have shown that there is no discharge-related wear-out mode for at least 20 years of equivalent orbital cycle service† in the geosynchronous orbit if DDR is used. Stable discharge voltage regulation results at 75% depth-of-discharge were demonstrated by accelerated life tests as shown in Fig. 1. By comparison, the results obtained using SDR and no reconditioning are not satisfactory for long service life as shown in Fig. 1.

The test program being conducted operates two batteries containing 24 Ah cells of standard construction. The average operating temperature is 9°C, varying from 7°C minimum on charge to 21°C maximum at end-of-discharge. The deep discharge reconditioning method consists of a low rate discharge of the entire battery through a resistor sized to discharge 0.4 A at 1.0 V per cell average. The DDR discharge lasts for three to five days. Alternately, shallow reconditioning discharge is performed in two ways: 1) discharge at normal load rates to 1.0 V per cell average battery voltage followed by a 40-h discharge rate to 0.9 V per cell average; or 2) discharge at a 40-h discharge rate to 0.9 V per cell average battery voltage. Charge rates used for these tests varied between the 12-h rate and the 20-h rate.

A second series of tests[1] has demonstrated that cycling 50-Ah cells to an 85% maximum depth-of-discharge using simulated geosynchronous orbit loads is practical throughout seven years of equivalent orbital cycle service operation with 1) DDR, and 2) maintenance of average battery temperatures below 20°C during eclipse operations and in-orbit (continuous sunlight seasons) storage. Results of these tests (Fig. 2) show that deep discharge reconditioning maintains stable battery voltage performance whereas the voltage of batteries operated without reconditioning degrades very rapidly when operated near 20°C; satisfactory operation at 0°C cell temperature does not depend as much upon deep discharge reconditioning (Fig. 2).

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*Manager, Department of Power Control and Distribution Engineering, Space Systems Division.

†Equivalent orbital cycle service in this paper means real time eclipse discharges normally encountered in geosynchronous orbit; demonstrated capability using accelerated life tests where acceleration has been achieved by eliminating continuous sunlight season trickle charging.

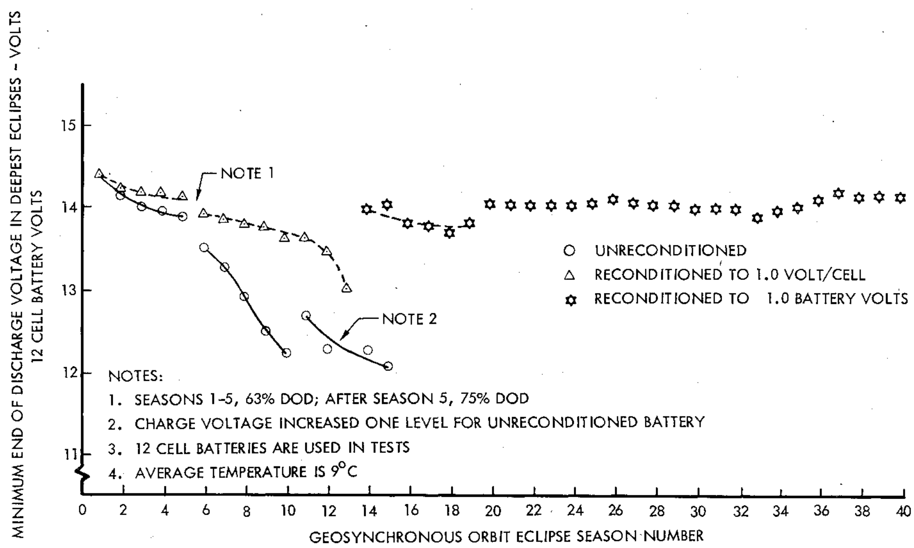

Fig. 1 24-Ah nickle-cadmium battery accelerated life test minimum discharge voltage in deepest eclipses.

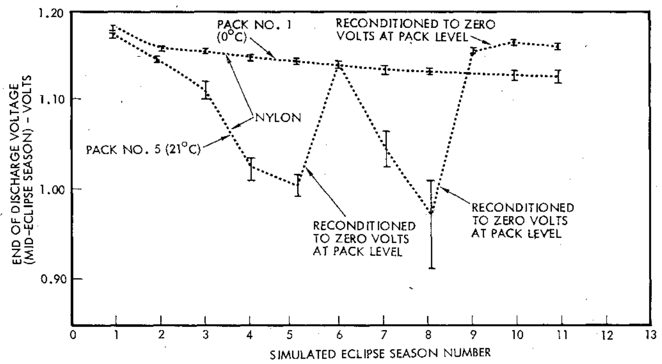

Fig. 2 50-Ah cell pack accelerated life test performance at 80-85% depth-of-discharge.

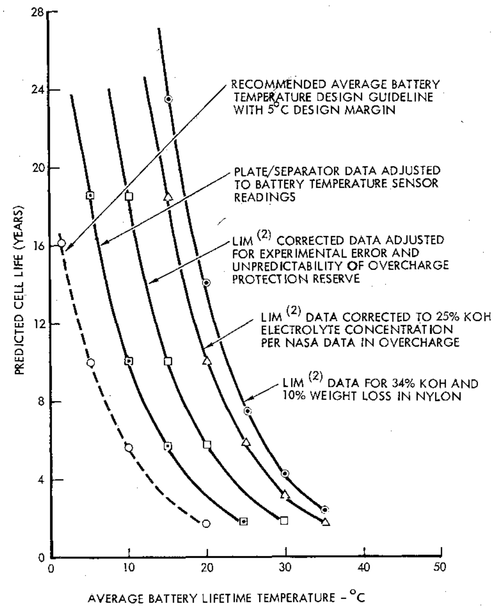

Fig. 3 Cell life vs temperature for geosynchronous orbit applications.

Low-Temperature Operation

A picture has begun to emerge from the above testing, from data presented by Lim[3] on nylon separator degradation, and from in-orbit performance results which shows the importance of temperature on the service life and performance of nickel-cadmium batteries. The life tests performed at less than 10°C average temperature have demonstrated closely balanced performance and no failures from up to 20 years equivalent geosynchronous orbit cycling service operations. Analysis of spacecraft flight data has shown that the most prevalent wear-out mode for nickel-cadmium batteries is high voltage on charge—a strong indication that cell overcharge protection has degraded. This wear-out mode is observed approximately as predicted by Lim's work (see Fig. 3).

High charge voltage cannot be effectively countered by any known operational technique including deep discharge reconditioning. Based on the data observed to date, long-life spacecraft requiring ten or more years of battery operations can only be made successful if average battery temperatures are kept below 10°C. If this criterion is maintained and deep discharge reconditioning is used, nickel-cadmium battery utilization and life can be improved significantly over present guidelines for design used for most of the current communication spacecraft systems as shown in Fig. 4.

New Battery Cell Developments

Several new cell developments are being studied for the improvement of nickel-cadmium cell life and stored energy utilization. The most significant of these which yield good results for geosynchronous orbit applications are:

1) Electrochemically impregnated positive electrodes have been built and tested in cells. These electrodes do not swell as fast or as much as the standard chemically impregnated electrodes used in present flight cells. Testing at 70% depth-of-discharge has thus far demonstrated the stability of the electrodes and has shown improved electrolyte management within the cells.

2) Reduced loading of positive electrodes has been developed and tested[4] with good performance. Voltage degradation performance has not improved using these electrodes; however, capacity performance has been maintained and increased electrolyte quantity is provided in the cells.

These new developments are directed toward achieving a ten-year spacecraft life with 65-75% utilization of total stored battery energy.

Development of Lightweight Long-Life Battery

The need to reduce battery system weight to maximize communication system payloads remains as a high-priority objective, even with Shuttle launch capabilities. The geosynchronous orbit spacecraft weight is still limited to 2265 kg (5000 lbs) with approximately 225 kg (500 lbs) (Table 1)

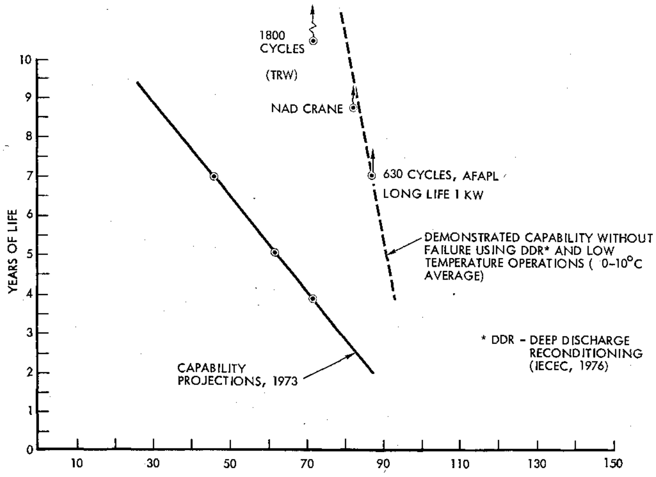

Fig. 4 Battery life capability of nickel-cadmium battery in geosynchronous orbit applications.

Table 1 Shuttle/IUS geosynchronous launch, typical power subsystem weight allocation for a 2265 kg (5000-lb) spacecraft

Component	Weight, kg(lb)
Solar array	91(200)
Battery	136(300)
Power control assembly	11(25)
Power conversion	18(40)
Harness	68(150)
	324(715) = 14% of total spacecraft weight

NOTES: 30-V system; 1.5 kW system in 1977; redundant battery energy storage system.

allocated to the battery and solar array power source. To meet this requirement, a significant improvement is needed in both battery system utilization and in specific energy of the battery system itself.

A project designed to provide both increased stored energy utilization and improved specific energy for the battery system has been in process for four years.[5] Cells with usable specific energies of 51 Wh/kg (23 Wh/lb) have been constructed and successfully cycled using accelerated tests for the equivalent of ten years in geosynchronous orbit at 70% depth-of-discharge. Lightweight cell and battery packaging developments have progressed rapidly with recent qualification of a battery assembly (Fig. 5) achieving 46 Wh/kg (21 Wh/lb) at 100% of measured capacity. These batteries used electrochemically impregnated positive electrodes to improve electrolyte management and active material utilization within the cells.

Guidelines for Storage and Handling

A large amount of data show that the prelaunch history of nickel-cadmium batteries strongly influences later flight performance and life. Accordingly, tightly controlled storage and handling practices have been developed and implemented. The objectives of these practices are to preserve cell overcharge protection, minimize separator degradation, and to maintain the stability of the negative electrode morphology. The standard practices are as follows:

1) Long-term storage at low temperature, preferably at or below 0°C, is required.

2) Open-circuit storage over five days is prohibited.

3) Charging following open-circuit stand periods of more than 2 h without prior shallow discharges is avoided whenever possible.

4) Trickle charging at elevated temperatures above 23°C is avoided whenever possible.

5) Short discharges without fully recharging and exposure to intermittent spacecraft integration tests are avoided under all circumstances.

6) Activated shelf life prior to launch is minimized, within economical guidelines, by application of a coordinated spacecraft system logistics plan.

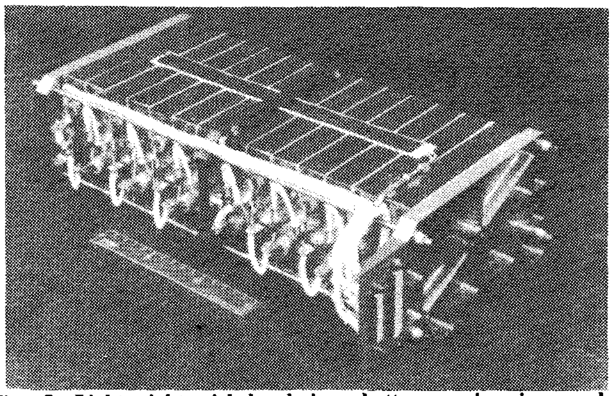

Fig. 5 Lightweight nickel-cadmium battery engineering model: weight = 14.6 kg (32.17 lb), specific energy = 27.6 Wh/kg, 75% depth-of-discharge (rated).

In addition to the above guidelines, advanced in-orbit operational planning is also utilized to minimize stress and to extend service life prior to wear-out. Key in-orbit procedures that are useful for standby operations include:

1) Shorted storage of redundant batteries during continuous sunlight periods reduces battery temperature and separator degradation.

2) Low-rate trickle charging at less than the 100-h charging rate, reduces temperature and maintains battery capacity. Low-rate trickle charging also reduces stress in the cells when overcharge protection is degraded.

By applying these guidelines, improved battery service has been achieved with good performance in geosynchronous orbit spacecraft for over seven years.

New Developments for Future Spacecraft

The recent advances in nickel-cadmium battery technology have been paralleled by new and promising developments of nickel-hydrogen battery systems. A comparison of current and future battery system performance capabilities is shown in Table 2. The nickel-hydrogen system offers the best opportunity for future improvements in stored energy per unit mass and for longer life when compared to the nickel-cadmium system. However, the standard nickel-cadmium battery system requires only 25-35% of the standard nickel-hydrogen system volume and is easier to package into a simple thermal control system. Advanced nickel-hydrogen developments are expected to approach the volume utilization of standard nickle-cadmium batteries, but will occupy twice the volume of advanced nickel-cadmium batteries which are being developed in 1977/78.

Present geosynchronous orbit spacecraft are constrained in three important ways:

1) North-south panel areas that provide economical thermal control mounting areas for near 0°C operation are very limited.

2) Internal spacecraft volume is limited, particularly in regions of the spacecraft that can provide acceptable operating temperature regimes required for nickel-hydrogen batteries.

3) New spacecraft designs rely heavily on proven technology with an associated data base for the prediction of reliability and performance.

Table 2 Nickel-cadmium and nickel-hydrogen battery capability for geosynchronous orbit applications (50-Ah capability)

Capability parameter	Units	Standard nickel-cadmium	Lightweight nickel-cadmium	Nickel-hydrogen standard design	Nickel hydrogen advanced designs
Cell specific energy	Wh/kg	36	51	57	60
Cell energy density	Wh/cm^3	0.120	0.155	0.044	0.05-0.07
Battery assembly specific energy	Wh/kg	27	37	51	57
Battery assembly energy density	Wh/cm^3	0.031	0.054	0.012	0.028
Useable battery assembly specific energy	Wh/kg	20.4	27.7	40.8	45.6
Useable battery assembly energy density	Wh/cm^3	0.023	0.040	0.009	0.022
Battery system, useable specific energy	Wh/kg	15-18	19-23	28-33	33-37

These design constraints, along with the substantial improvements in nickel-cadmium battery stored energy utilization and life, are encouraging the continued use of nickel-cadmium batteries for at least the next decade in many existing geosynchronous orbit spacecraft.

With the evolution of new spacecraft designs tailored to provide greater low-temperature component mounting area, it appears that the nickel-hydrogen battery system will become the main stored energy system for new geosynchronous orbit spacecraft in the 1980's. The system will yield 1.5-2.0 times the usable specific energy of nickel-cadmium systems, thus making larger communications payloads feasible within the weight constraints identified in Table 1.

Conclusions

The useful life of nickel-cadmium batteries can be increased to over ten-years by careful control of prelaunch operations and by operating the batteries near a 0°C average temperature.

The use of deep discharge reconditioning (DDR) increases the capability of the nickel-cadmium battery to operate reliably with good voltage regulation up to 75-85% depth-of-discharge in the deepest eclipses encountered by geosynchronous orbit spacecraft.

Implementation of newly developed plate manufacturing processes is expected to improve nickel-cadmium battery performance and reliability for ten-year spacecraft systems.

Recently developed nickel-cadmium batteries will provide improvements in battery system usable specific energies from the present capability of 15 Wh/kg (7 Wh/lb) to 22 Wh/kg (10 Wh/lb). This improvement is based upon the use of 51 Wh/kg (23 Wh/lb) cells already being developed, 46 Wh/kg (21 Wh/lb) battery assemblies already environmentally qualified, and upon operation of the batteries at 70% maximum depth-of-discharge (based upon rated capacity) in the deepest eclipses. Allocation of 15% for redundancy and 15% for charge control and thermal control elements are included in the projection.

New developments involving the nickel-hydrogen battery system are very promising although the system is difficult to retrofit into existing spacecraft designs because it displaces two to three times the volume of present nickel-cadmium batteries. However, as new spacecraft designs are developed for use with the Shuttle/IUS launch system, volume will be less of a problem and the new configurations can be arranged to provide adequate mounting areas for the nickel-hydrogen batteries on north-south panels or on special radiators. Nickel-hydrogen systems are expected to replace nickel-cadmium batteries because of their lighter overall system weight, simplified operation, and potential for increased operating life.

Acknowledgments

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