FAILURE MODES EXPERIENCED ON SPACECRAFT NiCd BATTERIES

Sidney Gross
Boeing Aerospace Company
Seattle, Washington 98115

ABSTRACT

A review has been made of failures and irregularities experienced on nickel cadmium batteries for 31 spacecraft. Only rarely did batteries fail completely. In many cases, poorly performing batteries were compensated for by a reduction in loads or by continuing to operate in spite of out-of-voltage conditions. Low discharge voltage was the most common problem observed in flight spacecraft (42%). Spacecraft batteries are often designed to protect against cell shorts, but cell or battery shorts accounted for only 16% of the failures. Other causes of problems were high charge voltage (16%), battery problems caused by other elements of the spacecraft (10%), and open circuit failures (6%). Problems of miscellaneous or unknown causes occurred in 10% of the cases.

INTRODUCTION

Information on battery problems can be useful in guiding research to improve battery technology. Problems that are serious or reoccur are the obvious ones to concentrate on. Observed problems can be caused by more than one phenomenon, however. It is the function of research programs to define these wearout and failure phenomena, to learn about their causes, and to attempt improvements. A survey was made, therefore, to document observed problems on spacecraft, with the scope limited to U.S. spacecraft. The survey was also limited to the information that could be obtained in a relatively short period of time.

A survey of problems on spacecraft nickel cadmium batteries cannot easily be a thorough or highly accurate undertaking. Up to December 31, 1975, a total of 725 U.S. satellites were placed in Earth orbit, posing an immense task for an accurate survey. The task is made even more difficult by the fact that only seldom are spacecraft performance and problems documented.

The approach taken in this survey was to rely primarily on the knowledge of battery specialists within the industry. Operating problems, especially major ones, are significant events that are not easily forgotten. There are important difficulties in this approach, however, including faulty or incomplete memory, transfer or relocation of cognizant personnel, poor communication between spacecraft users and battery specialists, and unwillingness to be candid. Only rarely can information be obtained on classified spacecraft.

RESULTS

Spacecraft having identified failures or irregularities with nickel cadmium batteries are listed in Table 1. Not included are those spacecraft where battery problems occurred but were caused by another subsystem or power system element. For example, the NRL 160 series spacecraft had serious thermal problems with the batteries, and the ATM Skylab module lost some batteries temporarily due to stuck relays.

Table 1 includes thirteen spacecraft which have experienced discharge voltage degradation. There are very likely many more such instances which have not been listed, for that kind of behavior is common and is a major shortcoming in nickel cadmium technology.

Descriptions of identified battery problems are given in Table 2. Quantitative information was used when available, but in some cases only qualitative information was available. No attempt was made to eliminate from this listing those occasions when problems occurred after the design lifetime had been passed, for that information can also be useful.

For convenience, battery problems have been coded on Table 2 into categories from 1 to 6. Table 3 identifies the codes and lists the number of occasions each type of problem was experienced. Low discharge voltage was the most common problem, followed by shorts and high charge voltage.

CONCLUSIONS

Nearly all the kinds of nickel cadmium battery problems seen during laboratory testing also have been observed in spacecraft. Most of the problems have been degradation displayed as low discharge voltage; only rarely have batteries failed completely. In many cases, poorly performing batteries have been countered by a reduction in loads, compromising on requirements to avoid undervoltage conditions.

There have been enough problems that it is clear that nickel cadmium battery technology needs improvement. Spacecraft experience is thus in agreement with laboratory experience, which also suggests improvement is desirable. The need for improvement is further emphasized when it is considered that greater reliability, longer life, and deeper depths of discharge are desired for many future spacecraft.

Table 1. SPACECRAFT WITH IDENTIFIED NICKEL CADMIUM BATTERY PROBLEMS

SPACECRAFT	ORBIT	LAUNCH	BATTERY	REFERENCES
Transit 4A	Near Earth	June 29, 1961	34 cells, Sonotone 4 AH	1
Navigation Satellite 1B	Near Earth	April 1960	?	2
OAO-1	Near Earth	April 1966	22 cells, Gulton 20 AH, 2 batteries + 1 standby battery	3, 4
OAO-2	Near Earth	December 1968	Some cells with auxiliary electrodes	3, 4
OAO-3	Near Earth	August 1972	Some cells with auxiliary electrodes	3, 4
SAS-A	Near Earth	December 1970	8 (?) cells, Gulton 6 AH	5
SAS-B	Near Earth	November 1972	8 cells, G.E. 6 AH, teflonated negatives	5, 6, 7, 8
SAS-C	Near Earth	May 1975	12 cells, Gulton 9 AH	5, 6, 7, 8
Intelsat 3 (Five S/C)	Geosynchronous	December 1968 to April 1970	22 cells, Gulton 12 AH	9, 10, 11
Intelsat 4, F-2	Geosynchronous	January 1971	25 cells, 15 AH, LiOH in KOH, no Ag in neg.	9, 11, 12
Intelsat 4A	Geosynchronous	January 1971?	25 cells, 24 AH, Ag in neg.	9, 11
Unspecified	---	---	---	---
Classified	Geosynchronous	---	---	10, 12
72-1	Near Earth	October 1972	18 cells, G.E. 15 AH	14
Landsat-1	Near Earth	July 1972	23 cells, G.E. 6 AH, 8 batteries	15
SMS-1	Geosynchronous	May 1974	20 cells, E.P. 3 AH, 2 batteries	16, 17
TETR-2	Near Earth	November 1968	?	4
171	Near Earth	December 1971	22 cells, Sonotone 5 AH, polypropylene, 2 batteries	18

Table 1. (Continued)

SPACECRAFT	ORBIT	LAUNCH	BATTERY	REFERENCES
172	Near Earth	December 1971	Battery used cylindrical F cells	19
173	Near Earth	December 1971	Battery used cylindrical F cells	19
174	Near Earth	December 1971	Battery used cylindrical F cells	19
CTS	Geosynchronous	January 1976	24 cells, G.E. 5 AH, polypropylele, 2 batteries	20
ATS-6	Synchronous	May 1974	19 cells, Gulton 15 AH, 2 batteries	21
ITOS	Near Earth	January 1970	12 AH, ?	22
VELA 1	Near Earth	October 1963	Gulton 6 AH, 2 batteries	23
VELA 2	Near Earth	October 1963	Gulton 6 AH, 2 batteries	23
DODGE 1	Near Earth	July 1967	Battery used cylindrical F cells	24, 25

Table 2. FAILURES AND IRREGULARITIES IN SPACECRAFT NICKEL CADMIUM BATTERY APPLICATIONS

SPACECRAFT	FAILURE OR IRREGULARITY	CODE
Transit 4A	After five years of satisfactory operation, the battery was unable to support the mission. Cause of failure is unknown.	6
Navigation Satellite 1B	This battery contained a thermostat to turn off battery charging if temperature became too high. The thermostat setting drifted to a lower value with time, eventually reaching the normal battery temperature. As a result, the battery charger system was permanently disconnected.	5
OAO-1	The OAO-1 had sequential charging between three batteries. The sequencer failed, causing the charger to stay on only one of the batteries. Since there was no override or disable possible, the battery got very hot, approximately 150^{O}F. As a result, the system had to be turned off. This failure was caused entirely by the charge controller.	5
OAO-2	The OAO-B and -C had a number of commandable temperature-biased voltage levels for charge, plus an alternate end of charge signal from an oxygen sensing auxiliary electrode. After three years, the auxiliary electrode gave erroneous signals, but the cause is not known. No compromise to the battery has occurred.	6
OAO-3	Though the spacecraft was designed for only six months operation, the spacecraft still continues to be used after 4½ years. As a result, low battery voltage problems are occurring. When the spacecrafts voltage limit of 1.18 V/cell is reached, the battery goes into a protective mode. A second level voltage limit of 1.12 V/cell is also used, and this limit too is exceeded at times.	1
SAS-A	Excess solar array power on this spacecraft is shunted using a transistor switching circuit. Thermal cycling of the transistors caused them to eventually fail open, putting the full excess array current on the battery. After one year of high temperature and high voltage, the battery failed. This failure was caused by failed electronics.	5

Table 2. (Continued)

SPACECRAFT	FAILURE OR IRREGULARITY	CODE
SAS-B	This spacecraft operated in an equatorial orbit, resulting in repetitive battery cycling at 22% DOD; the charge was temperature-biased voltage limit with 4 a max and a trickle rate of C/20. Battery voltage deteriorated with time, and within six months the voltage was below 1.1 V/cell. Reconditioning was tried but had only a temporary helpful effect. Increasing charge by removal of the coulometer did not help. Lowering temperature by restraint of spacecraft attitude helped a little. Though the spacecraft eventually failed due to a converter failure, such poor battery performance so early in its life may justifiably be viewed as a battery failure.	1
SAS-C	This spacecraft operated in an equatorial orbit, similar to SAS-B, resulting in repetitive battery cycling at 22% DOD; the charge was temperature-biased voltage limit with a 6 a max and a trickle rate of C/80. Battery voltage deteriorated with time, and within five months the voltage was below 1.1 V/cell. Reconditioning was tried but had only a temporary effect. Increasing charge by removal of the coulometer did not help. Lowering temperature by restraint of spacecraft attitude helped a little. The spacecraft is still functioning, but the reduced capability imposes operation limitations on the spacecraft. Such poor battery performance so early in its life may be viewed as a battery failure.	1
Intelsat 3	The Intelsat 3 series of five spacecraft had battery problems. Battery voltage during charge increased with operational life, causing early trip to trickle charge. As a result, the battery could not be fully charged and so there was a loss in capacity and inability to supply the load. In some flights, loads had to be reduced after about two years operation to make the spacecraft survive. The battery problem was determined to be due to the lack of enough overcharge protection and the use of wetting agent in the separator. The negative/positive ratio was only about 1.3. A more flexible charge control system would possibly have lengthened battery life.	1

Table 2. (Continued)

SPACECRAFT	FAILURE OR IRREGULARITY	CODE
Intelsat 4 F-2	After six years of the required seven years operation, one of the seven Intelsat 4 spacecraft went below the 1.15 V/cell limit, and loads had to be reduced. A voltage limit of 1.1 V/cell would probably have been a more realistic requirement, but it is unlikely that even this would have fully avoided the voltage problems. The spacecraft appears to have met its contractual load requirements in spite of this problem.	1
Intelsat 4A	Discharge voltage on one of the two spacecraft is within requirements, but with relatively little margin to spare. This fact, plus the fact that negative limited cells have been observed in ground tests, reduces confidence in the future performance of this battery.	1
Unspecified Spacecraft	Information on this unclassified spacecraft and its battery behavior are not publicly available. It has had low battery voltage anomalies, however.	1
Classified Spacecraft	A sudden open circuit occured on one of three batteries in a spacecraft. This was diagnosed as probably the opening of an intercell connector, caused by mechanical stress during cycling.	4
72-1	The design requirement for this was two years. After approximately three years, a short developed across one cell in each of two batteries. For a short while, there were two cells shorted on one of the batteries, but one of those two shorts opened. The battery and their charge control system were able to function properly in spite of these anomalies. This spacecraft has been working all right for five years.	3
Landsat-1	Eight batteries are parallel in this spacecraft. One of the batteries failed due to low discharge voltage and has been disconnected. Additional information on cause of failure is not available.	1
SMS-1	High voltage, in excess of 1.52 V/cell were reached during charge following discharge to 60% DOD. This problem was not observed during accelerated ground testing of a similar battery.	2

Table 2. (Continued)

SPACECRAFT	FAILURE OR IRREGULARITY	CODE
TETR	A flight failure on this spacecraft occurred when the case of one cell apparently shorted to the battery frame. Cell case and frame were separated by mylar. It is believed that constant pressure on the mylar eventually caused breakthrough. An internal cell short could also have caused this problem.	3
171	After 4.3 years trouble-free operation, one of two active batteries suddenly open circuited. It could not be determined whether the problem was with a cell, a solder joint, or a connector. One of two spare batteries was subsequently switched on to take the place of the failed battery and performed all right.	4
172, 173, 174	After a number of years operation, the batteries exhibited an increase in charge voltage and a decrease in discharge voltage. Spacecraft operation was unaffected, however.	1, 2
CTS	After two eclipse seasons on this geosynchronous spacecraft, battery voltage and capacity dropped below 1.15 V/cell at 50% DOD and capacity dropped to 70% of its initial value. Two reconditioning cycles gave a temporary improvement on ground tests. Ground test cells were found to be dry when opened.	1
ATS-6 (formerly called ATS-F)	Though the spacecraft design requirement was for two years, it has completed three years service. Voltage at 50% DOD point has degraded to 1.13 V/cell, and capacity has dropped to 12.4 AH from an initial value believed to be from 16 to 18 AH. End of charge battery voltage has been increasing with time, giving problems obtaining a full charge, since only one charge voltage level is used in the charger.	1, 2
ITOS	After several successful flights with this series of spacecraft, a problem of high charge current developed at high temperature, giving charge currents of about C/5 or C/6. This problem is believed to have been primarily a charger problem, and on subsequent spacecraft the voltage-temperature curve was lowered. Changes in battery characteristics probably also have contributed to this problem, however.	6

Table 2. (Continued)

SPACECRAFT	FAILURE OR IRREGULARITY	CODE
VELA 1	Within six months of spacecraft operation, several cells shorted in the battery. This is believed caused by silver used in the ceramic seal braze migrating across the ceramic.	3
VELA 2	Within six months of spacecraft operation, several cells shorted in the battery. This is believed caused by silver used in the ceramic seal braze migrating across the ceramic.	3
DODGE 1	After operating approximately 3½ years, a flight malfunction occurred which is believed to have been due to one cell shorting in the battery.	3

Table 3. CODE FOR BATTERY PROBLEMS

CODE	PROBLEM	NUMBER OF EVENTS	PERCENTAGE
1	Discharge voltage low	13	42%
2	Charge voltage high	5	16%
3	Short, cell or battery	5	16%
4	Open, cell, battery or circuit	2	6%
5	Problem not caused by cell performance	3	10%
6	Miscellaneous or unknown cause	3	10%

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