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NiCd CELL RELIABILITY IN THE MISSION ENVIRONMENT

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INTRODUCTION

This paper summarizes an effort by Gates Aerospace Batteries (GAB) and the Reliability Analysis Center (RAC) to analyze survivability data for both General Electric and GAB NiCd cells utilized in various spacecraft. For simplicity sake, all mission environments are described as either LEO or GEO. "Extreme value statistical methods" are applied to this database because of the longevity of the numerous missions while encountering relatively few failures. Every attempt has been made to include all known instances of cell-induced-failures of the battery and to exclude battery-induced-failures of the cell. While this distinction may be somewhat limited due to availability of in-flight data, we have accepted the learned opinion of the specific customer contacts to ensure integrity of the common databases.

This paper advances the preliminary analysis reported upon at the 1991 NASA Battery Workshop. That prior analysis was concerned with an estimated 278 million cell-hours of operation encompassing 183 satellites. That paper also cited "no reported failures to date" [see Reference 1]. This analysis reports on 428 million cell hours of operation encompassing 212 satellites. This analysis also reports on seven "cell-induced-failures."

MISSION ENVIRONMENT

Several assumptions have been made concerning both the mission environment and the overall population of cells by which the numbers of cell-hours or cell-cycles are estimated. First for simplicity sake, all mission environments are described as either LEO (predominantly rapid and repetitive cycling) or GEO (predominantly long periods of overcharge followed by brief duty cycles). Generally Polar Orbits are incorporated into the LEO analysis, and Highly Elliptical orbits are incorporated into the GEO analysis. LEO is considered to experience sixteen cycles per day. Second, the analysis assumes twenty-two cells per battery and two batteries per satellite.

The third area of assumption becomes more an area of definition and discrimination. Defining the words *failure, termination,* and *deterioration* can lead to both endless discussion and endless dissension. For purposes of this analysis, *failures* is defined as: outright failure or termination of a cell and/or a battery. Deterioration is defined as: expected performance had deteriorated or degraded to the point that the original mission intention has been significantly limited or compromised either by manifestation of immediate performance deterioration or the limiting of expected life. Discriminating between cell-induced battery failures and battery-induced cell failures encounters the same discussion and dissension. Both definition and discrimination are hampered by different levels of telemetry sophistication for receiving in-flight performance data. This analysis unilaterally accepts both definition and discrimination as proffered by the responsible technical personnel.

It should also be noted that the analysis is being performed at the complete satellite battery level and not the individual cell level, since this is the level for which the data was collected.

MISSION PERFORMANCE

Table 1 contains the detail and arithmetical summary of the 212 satellites reported in this analysis. Details include cell capacity rating, mission environment, launch date and years of operation. Neither customer, program or reason for satellite termination is identified in this listing. Note that four specific indicators of operational life were used since this information was extracted from several sources. They are final or total years of operation, data as of December 1987, data as of January 1991, and data as of April 1992. Total LEI Mission Years reported are 331.7 years; total GEO Mission Years reported are 777.9 years. Note that specific failure data is not included in Table 1.

MISSION SUMMARY

The last page of Table 1 provides the total Mission Summary, the LEO Mission Summary, and the GEO Mission Summary. For 212 spacecraft analyzed, 1109.5 Total Mission Years have accumulated. This equivalent 428 million cell-hours is considerably greater than the 278 million cell-hours reported on last year [Reference 1]. In addition, the previous report did not differentiate between the various mission environments.

For the LEO Mission Environment, 74 spacecraft or satellites were analyzed. Accumulated are 332 Total Mission Years or 85 million Total Cell-Cycles. For the GEO Mission Environment, 138 spacecraft or satellites were analyzed. Accumulated are 778 Total Mission Years or 300 million Total Cell-Hours.

As previously stated, cell-induced failures are not cited or summarized in Table 1. Neither will these failures be tabulated separately due to their sensitive nature. In brief summary, one "long term" GEO has occurred, and six LEO failures have occurred ranging from approximately four thousand to thirty-two thousand cycles. Again note that a cell-induced performance failure does not necessarily imply a mission termination.

STATISTICAL ANALYSIS OF RELIABILITY DATA

A simple method of analyzing reliability data is to determine a failure rate by dividing the number of observed failures by the number of operating hours or cycles. The use of a failure rate inherently assumes that the rate of failures are occurring in a time independent random manner.

Since it is known that batteries typically exhibit wearout characteristics, or an increasing failure rate in time, a failure rate is too simplistic of a metric describing the reliability of the battery.

Weibull analysis is often used to quantify, from empirical time (or cycle) to failures data, the rate of occurrence of failure as a function of time. A complete Weibull analysis usually consists of plotting the cumulative percentage of failures against time on Weibull probability paper when a large percentage of the population has failed. This methodology, however, looses its usefulness when the population contains few or no failures. Since there have been a relatively small percentage of the population failing, alternative analysis methods were required.

The appropriate analysis methodology under these circumstances is the use of confidence limits in conjunction with the Weibull distribution. Nelson [Reference 2] has proposed such a methodology which will be used in this analysis. Background on the Weibull distribution and Nelson's methodology is given in the following paragraphs.

The probability density function f(t) of the Weibull time to failure distribution is;

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

where

α	=	characteristic life, time to 63% population failure
β	=	Weibull shape parameter
t	=	time

The reliability (probability of survival to a time t) is;

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

And the hazard rate h(t) (or instantaneous failure rate), given the part has survived until time t is;

$$h(t) = \left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1}$$

To estimate the value of the characteristic life in the Weibull distribution, the following maximum likelihood estimator is typically used;

$$\alpha = \left[\sum_{i=1}^{n} T_i^{\beta} \; / \; r \right]^{\frac{1}{\beta}}$$

where

T_i = Time to fail of the i^{th} part or survival time of the i^{th} part if it has not failed

r = Number of failures

n = Total population of parts

Since the database contains few failures, the characteristic life implied by this estimate is suspect. As stated previously, the appropriate analysis methodology to use under these conditions is to apply confidence limits to derive worst case reliability values. From this, lower bound estimates of lifetimes can be made within a given confidence level. To accomplish this, the Chi-square distribution can be utilized. The lower confidence limit for the Weibull distribution is:

$$\alpha = \left[\sum_{i=1}^{n} T_i^{\beta} \; / \; r \right]^{\frac{1}{\beta}} \left[2r \; / \; \chi^2 \,(C;\; 2r+2) \right]^{\frac{1}{\beta}}$$

where

χ^2 = the chi-square percentile at C% confidence and r failures

This value of characteristic life was then calculated for various values of betas and various confidence levels for both LEO and GEO. Table 1 summarizes the data used. The sum of the individual survival times raised to the power beta, as a function of beta, are as follows:

β	$\sum_{i=1} T_i^{\beta}$	
	LEO	GEO
1	331.9	777.9
2	2,911	6,220
3	38,182	57,977
4	624,847	588,803
5	11,472,255	6,357,012
6	2.236×10^8	7.215×10^7

The values of the Chi-square percentiles are given as follows:

C Confidence Level	Chi-Square Percentile	
	LEO (6 failures) 14 Degrees of Freedom	GEO (1 failures) 4 Degrees of Freedom
.25	10.17	1.923
.50	13.34	3.357
.75	17.12	5.385
.90	21.06	7.779
.95	23.68	9.488
.975	26.12	11.14
.990	29.14	13.68
.995	31.32	14.86
.999	36.12	18.47

The resulting lower limit characteristic life estimates as a function of confidence (C) and beta value are summarized in the following table for both LEO and GEO applications.

α FOR LEO APPLICATIONS

β	C								
	.25	.50	.75	.90	.95	.975	.990	.995	.999
1	65.3	49.8	38.8	31.5	28.0	25.4	22.8	21.2	18.4
2	23.9	20.9	18.4	16.6	15.7	14.9	14.1	13.6	12.7
3	19.6	17.9	16.5	15.4	14.8	14.3	13.8	13.5	12.8
4	18.7	17.5	16.4	15.6	15.2	14.8	14.4	14.1	13.6
5	18.6	17.7	16.8	16.1	15.7	15.4	15.1	14.9	14.5
6	18.8	17.9	17.2	16.6	16.3	16.1	15.8	15.6	15.2

α FOR GEO APPLICATIONS

β	C								
	.25	.50	.75	.90	.95	.975	.990	.995	.999
1	809	463	289	200	164	139	117	105	84
2	80.4	60.9	48.1	40.0	36.2	33.4	30.6	28.9	25.9
3	39.2	32.6	27.8	24.6	23.0	21.8	20.6	19.8	18.4
4	28.0	24.3	21.6	19.7	18.8	18.0	17.2	16.8	15.9
5	23.1	20.7	18.8	17.5	16.8	16.2	15.7	15.4	14.7
6	20.5	18.7	17.3	16.3	15.7	15.3	14.9	14.7	14.1

As an example, if a beta value of 4 is assumed, one can be 90% confident that the characteristic life for LEO applications is a minimum of 15.6 years.

If it is desired to calculate the time (t) to the P percentile failure of the population, the following can be used;

$$t = \alpha\left[-\ln\left(1-\frac{P}{100}\right)\right]^{\frac{1}{\beta}}$$

If the characteristic life is the lower confidence limit as tabulated previously, the time to P percent failure will also be the lower confidence limit. For example, using the characteristic life of 15.6 years for beta = 4 and 90% confidence, the worst case time (at 90% confidence) to reach 1% failure is;

$$t = 15.6\left[-\ln\left(1 - \frac{1}{100}\right)\right]^{\frac{1}{4}} = 4.94 \text{ years}$$

In this example, there is 90% confidence that the time to 1% failure will be greater than 4.94 years.

DISCUSSION ON LONGEVITY OF LEO MISSIONS

Let us assume that five years in LEO environment (29,200 cycles) is a typical mission life time requirement. Then several superlatives can be shown. First, 24 of the 74 LEO missions analyzed were operated beyond that benchmark including one mission for 22 years. Second, testing of a four-cell pack of 26.5 Amp-Hour cells has recently achieved 11.7 years (68,110 cycles) in a LEO test regime. This cell pack (Pack No. 0026G) is currently under test at Crane-NSWC at 10°C and 20% DOD.

SUMMARY AND RECOMMENDATIONS

This database contains substantial updating and upgrading from our previous report. The previous report cited 183 satellites operating for 278 million cell-hours and "no reported failures." This report contains 212 satellites operating for 428 million cell-hours and seven reported failures. We continue to use the extreme value statistical methods of Wayne Nelson as the most viable analysis technique due to relatively few failures.

Predictions of the Characteristic Life and times to percentile failures based upon assumed β values has shown a small decrease in the "predicted life" due to the observance of failures. However, these estimates appear more realistic because any failure improves the estimation of Confidence Intervals; and because the total base of survivability increased 54%.

TABLE 1:GAB NiCd PERFORMANCE IN MISSION ENVIRONMENT

STATUS AS OF JULY, 1992

( ) FINAL
unmarked as of 4/92

* as of 12/87
**as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
4	LEO	66/02	(1.25)	1.3	
4	LEO	66/02	(4.5)	4.5	
4	LEO	66/10	(2.0)	2.0	
4	LEO	66/12	(20)	20.0	
4	LEO	67/01	(0.9)	0.9	
4	LEO	67/03	(2.4)	2.4	
4	LEO	67/04	(2.8)	2.8	
12	LEO	67/04	[22.0]	22.0	
4	LEO	67/11	17.8*	17.8	
4	LEO	67/11	(2)	2.0	
4	LEO	68/08	(0.2)	0.2	
4	LEO	68/08	(0.9)	0.9	
4	LEO	68/12	(7.2)	7.2	
4	LEO	69/02	(4.8)	4.8	
6	LEO	69/04	(1.75)	1.8	
4	LEO	70/01	(1.4)	1.4	
4	LEO	70/12	(0.7)	0.7	
6	LEO	70/12	(0.8)	0.8	
15	GEO	71/01	14.6*		14.6
15	GEO	71/12	(11.5)		11.5
15	GEO	72/01	13.6*		13.6
15	GEO	72/06	14.0*		14.0
6	LEO	72/07	(5.75)	5.8	
6	LEO	72/10	(2.2)	2.2	
7	GEO	72/11	(10.6)		10.6
6	LEO	72/12	(7.25)	7.3	
7	GEO	73/04	(10.2)		10.2
15	GEO	73/08	(9.8)		9.8
6	LEO	73/11	(2.6)	2.6	
6	LEO	73/12	(5.0)	5.0	
7	GEO	74/04	(9.0)		9.0
7	GEO	74/10	[9.8]		9.8
24	GEO	74/11	10.8*		10.8
6	LEO	75/01	(5.0)	5.0	
7	GEO	75/05	[9.5]		9.5
24	GEO	75/05	10.2*		10.2
6	LEO	75/06	(4.5)	4.5	
12	LEO	75/06	[3.0]	3.0	
24	GEO	75/09	9.9*		9.9
6	LEO	75/10	(0.4)	0.4	
6	LEO	75/11	(5.6)	5.6	
6	LEO	75/?	(1.0)	1.0	
24	GEO	76/01	9.6*		9.6

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992 — ( ) FINAL, unmarked as of 4/92 — * as of 12/87, **as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
2	LEO	76/03	(4.0)	4.0	
2	LEO	76/03	(1.0)	1.0	
10	GEO	76/03	(3.0)		3.0
6	LEO	76/04	(3.0)	3.0	
24	GEO	76/05	[8.5]		8.5
7	GEO	76/07	[9.1]		9.1
24	GEO	76/07	9.1		9.1
7	GEO	77/03	8.4*		8.4
24	GEO	77/05	8.2*		8.2
6	GEO	77/06	(7)		7.0
6	LEO	77/08	[13]	13.0	
6	LEO	77/12	(3.0)	3.0	
6	GEO	78/01	7.7*		7.7
24	GEO	78/01	7.6*		7.6
15	GEO	78/02	(0.6)		0.6
24	GEO	78/02	14.2		14.2
6	LEO	78/03	(5.5)	5.5	
24	GEO	78/03	7.4*		7.4
4	GEO	78/04	(3.8)		3.8
7	GEO	78/05	7.2**		7.2
15	GEO	78/05	[6.0]		6.0
24	GEO	78/06	[7.2]		7.2
7	GEO	78/08	(0.3)		0.3
6	LEO	78/10	12.2**	12.2	
15	GEO	78/10	11.2**		11.2
15	GEO	78/11	12.2**		12.2
15	GEO	78/12	[2.8]		2.8
17	GEO	78/12	6.7*		6.7
7	GEO	79/08	6.0*		6.0
15	GEO	79/09	10.5		10.5
6	LEO	79/10	[10]	10.0	
15	GEO	80/02	(4.4)		4.4
24	LEO	80/02	[9.8]	9.8	
15	GEO	80/04	9.7**		9.7
6	LEO	80/05	(1.0)	1.0	
6	GEO	80/09	(2.8)		2.8
22	GEO	80/11	4.8*		4.8
35	GEO	80/12	11.3		11.3
24	GEO	81/02	(4.5)		4.5
6	GEO	81/05	(3.6)		3.6
12	GEO	81/05	8.6**		8.6
35	GEO	81/05	10.9		10.9
6	LEO	81/07	11.0	11.0	
5	GEO	81/08	4.0*		4.0

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992   ( ) FINAL   * as of 12/87
unmarked as of 4/92   **as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
22	GEO	81/09	4.1*		4.1
17	GEO	81/11	4 .0 *		4.0
35	GEO	81/12	10.4		10.4
17	GEO	82/01	3.85 *		3.9
17	GEO	82/02	10.2		10.2
24	LEO	82/02	0.8	0.8	
35	GEO	82/03	10.1		10.1
12	GEO	82/04	(.8)		0.8
17	GEO	82/06	9.9		9.9
50	LEO	82/07	8.5**	8.5	
17	GEO	82/08	9.7		9.7
35	GEO	82/09	9.6		9.6
24	GEO	82/10	9.5		9.5
35	GEO	82/10	9.5		9.5
17	GEO	82/11	2.8*		2.8
22	GEO	82/11	9.4		9.4
15	GEO	83/02	9.2		9.2
15	GEO	83/02	2.5*		2.5
30	LEO	83/03	9.1	9.1	
6	GEO	83/04	7.8 *		7.8
30	LEO	83/05	1.0	1.0	
12	LEO	83/06	4.2	4.2	
17	GEO	83/06	2.2*		2.2
24	GEO	83/06	8.8		8.8
24	GEO	83/06	8.8		8.8
6	LEO	83/07	9.0	9.0	
21	GEO	83/07	2.1*		2.1
12	GEO	83/08	8.6		8.6
12	GEO	83/08	4.0**		4.0
40	GEO	83/08	8.5		8.5
24	GEO	83/09	8.5		8.5
4	GEO	84/01	(1.6)		1.6
6	LEO	84/02	8.5	8.5	
50	LEO	84/03	6.8**	6.8	
12	LEO	84/04	5.5	5.5	
15	GEO	84/06	7.8		7.8
4	LEO	84/08	3.0**	3.0	
5	GEO	84/08	1.0*		1.0
21	GEO	84/08	1.0*		1.0
25	GEO	84/08	7.7		7.7
15	GEO	84/09	7.6		7.6
12	GEO	84/10	5.0		5.0
17	GEO	84/10	2.6*		2.6
50	LEO	84/10	6.2*	6.2	

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992 ( ) FINAL * as of 12/87

unmarked as of 4/92 **as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
15	GEO	84/11	.8*		0.8
17	GEO	84/11	7.6		7.6
25	GEO	84/11	7.6		7.6
24	GEO	85/02	7.2		7.2
35	GEO	85/02	[0.6]		0.6
24	GEO	85/03	2.5**		2.5
25	GEO	85/04	7.0		7.0
21	GEO	85/06	2.8**		2.8
21	GEO	85/06	0.2**		0.2
35	GEO	85/06	[4.5]		4.5
50	GEO	85/07	7.0		7.0
12	LEO	85/08	[6.0]	6.0	
25	GEO	85/08	6.7		6.7
27	GEO	85/08	6.7		6.7
15	GEO	85/10	6.5		6.5
35	GEO	85/10	6.5		6.5
4	GEO	86/02	[4.0]		4.0
24	GEO	86/03	6.9		6.9
6	LEO	86/09	5.8	5.8	
30	LEO	86/10	5.7	5.7	
12	LEO	86/11	3.1**	3.1	
35	GEO	86/12	6.3		6.3
6	GEO	87/02	5.2		5.2
30	LEO	87/06	4.8	4.8	
50	GEO	87/07	5.0		5.0
12	LEO	87/09	2.2**	2.2	
12	LEO	87/09	2.2**	2.2	
27	GEO	87/09	5.3		5.3
40	GEO	87/11	5.4		5.4
35	GEO	88/02	3.0**		3.0
6	GEO	88/03	(0.8)		0.8
30	LEO	88/03	4.1	4.1	
12	LEO	88/04	1.7	1.7	
12	LEO	88/06	1.5	1.5	
12	LEO	88/06	1.5	1.5	
24	LEO	88/07	4.0	4.0	
12	GEO	88/07	3.7		3.7
12	LEO	88/08	1.3**	1.3	
30	GEO	88/09	3.6	3.6	
40	GEO	88/09	3.5		3.5
35	GEO	88/12	3.3		3.3
35	GEO	89/02	3.1		3.1
40	GEO	89/03	3.0		3.0
30	GEO	89/05	2.9		2.9

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992 — ( ) FINAL, unmarked as of 4/92 — * as of 12/87, ** as of 1/91

RATING A-H	MISSION	LAUNCH DATES	YEARS OF OPERATION	LEO YEARS	GEO YEARS
35	GEO	89/06	2.8		2.8
35	GEO	89/06	2.8		2.8
40	GEO	89/06	2.8		2.8
21	GEO	89/08	2.6		2.6
35	GEO	89/08	2.6		2.6
5	GEO	89/09	2.5		2.5
35	GEO	89/09	2.5		2.5
35	GEO	89/10	2.4		2.4
24	LEO	89/11	2.4	2.4	
35	GEO	89/12	2.3		2.3
35	GEO	89/12	2.3		2.3
35	GEO	90/01	2.1		2.1
10	LEO	90/02	2.1	2.1	
35	LEO	90/02	2.1	2.1	
35	GEO	90/03	2.0		2.0
18	GEO	90/06	1.8		1.8
15	LEO	90/07	1.7	1.7	
35	GEO	90/07	1.7		1.7
17	GEO	90/08	1.7		1.7
21	GEO	90/08	1.7		1.7
35	GEO	90/08	1.7		1.7
35	GEO	90/08	1.7		1.7
32	GEO	90/10	1.5		1.5
35	GEO	90/10	1.5		1.5
35	GEO	90/11	1.4		1.4
40	GEO	90/11	1.4		1.4
30	LEO	90/12	1.3	1.3	
35	GEO	91/01	1.2		1.2
32	GEO	91/03	1.1		1.1
50	LEO	91/04	1.0	1.0	
30	LEO	91/05	0.9	0.9	
35	GEO	91/07	0.8		0.8
17	GEO	91/08	0.7		0.8
40	GEO	91/08	0.7		0.7
50	LEO	91/09	0.6	0.6	
40	GEO	91/11	0.3		0.3
50	LEO	91/11	0.3	0.3	
TOTAL LEO MISSION YEARS				331.7	
TOTAL GEO MISSION YEARS					777.9

TABLE 1:Cont'd.

STATUS AS OF JULY, 1992

MISSION SUMMARY:	
TOTAL MISSION YEARS	1109.5
TOTAL MISSION DAYS	0.40 Million
TOTAL MISSION HOURS	9.72 Million
TOTAL BATTERY HOURS	19.44 Million
TOTAL CELL HOURS	427.65 Million
TOTAL SPACECRAFT ANALYZED	212
LEO MISSION SUMMARY:	
TOTAL MISSION YEARS	331.7
TOTAL MISSION DAYS	0.12 Million
TOTAL MISSION CYCLES	1.94 Million
TOTAL BATTERY CYCLES	3.87 Million
TOTAL CELL CYCLES	85.22 Million
TOTAL SPACECRAFT ANALYZED	74
GEO MISSION SUMMARY:	
TOTAL MISSION YEARS	777.9
TOTAL MISSION DAYS	0.28 Million
TOTAL MISSION HOURS	6.81 Million
TOTAL BATTERY HOURS	13.63 Million
TOTAL CELL HOURS	299.81 Million
TOTAL SPACECRAFT ANALYZED	138

This reporting format and analysis technique were the pathfinder for similar databases anticipated for the NiH2 and NiMH Product Lines. We find this format to be sufficiently stable and mature to apply to those product lines. Our expectations are to update on a bi-annual basis and report on the database every four to five years.

REFERENCES

[1] Denson, William K. and Klein, Glenn C., "Analysis of Nickel-Cadmium Battery Reliability Data Containing Zero Failures," Proceedings of the 1991 NASA Battery Workshop.

[2] Nelson, W., "Weibull Analysis of Reliability Data With Few or No Failures," Journal of Quality Technology, Vol. 17, No. 3, July 1985.