NICKEL-CADMIUM BATTERY OPERATION MANAGEMENT OPTIMIZATION USING ROBUST DESIGN

JULIAN O. BLOSIU
FRANK DELIGIANNIS
SALVADOR DI STEFANO

JET PROPULSION LABORATORY/
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

Optimization of Battery Operation Management Using Robust Design

Julian O. Blosiu, Frank Deligiannis, Salvador Di Stefano

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

In recent years following several spacecraft battery anomalies, it was determined that managing the operational factors of NASA flight NiCd rechargeable battery was very important in order to maintain space flight battery nominal performance. The optimization of existing flight battery operational performance was viewed as something new for a Taguchi Methods application. Nevertheless, for this experiment, a modified L16 orthogonal array was selected with five operational factors at four levels. Each experiment run consisted of sixty charge-discharge cycling at the selected operational levels. The designed experiment of the 1.16 partial factorial performance lasted nine weeks. A full factorial would have lasted over eleven years. Also, the continuation trial proved to indicate over 96% improvement of nominal battery performance as compared to the performance at the initial best-thought operational levels. The cost savings was estimated at over 400°/0, while experimentation time saving was estimated at over 300°/o.

1. INTRODUCTION

Nickel cadmium rechargeable batteries are currently used for an entire class of NASA observatory spacecraft including GRO, UARS, EUVE and TOPEX/Poseidon. Optimum levels of on-board spacecraft battery operation performance were determined to extend the life of these batteries and thus the life of NASA spacecraft. in recent years, several spacecraft NiCd battery anomalies occurred that drastically affected spacecraft life. This prompted NASA to call upon JPL to initiate studies and analysis in order to establish an operation management protocol for these batteries.

The evaluation, qualification and operation management of secondary batteries for NASA space vehicles is an involved and very lengthy process. There are many variables and levels of each variable which affect the overall reliability and performance of batteries. Rechargeable battery performance evaluation requires tens or even hundreds of cycles, Testing for the performance effects of these parameters could be a never ending task.

II. BACKGROUND AND OBJECTIVES

NASA was’ concerned about the performance of the existing on-board batteries. The challenge faced was to design a protocol for battery operation process for life performance optimization in the shortest time possible with minimum cost while significantly improving battery performance. At first, since this was not viewed as a classical product or manufacturing process design optimization, no relation was seen to Dr. Genichi Toguchi’s Methods of Robust Design. Nevertheless, at a closer look, it became obvious that the optimization of an operation process, in this case a rechargeable battery operation, is no different than optimizing any process.

A team of battery experts was formed at JPL to perform a study of battery operation optimization using the old methods.

Based on practical experience, it was determined that controlling the recharge fraction of flight batteries in operation was important to maintain nominal performance. “The recharge fraction is one of the parameters used to determine battery overcharge. The recharge fraction is normally derived on an orbit basis and there are several operating factors that influence it. The factors influencing the recharge fraction are:

1. Charge current during peak power tracking (Peak charge current)
2. Battery depth-of-discharge
3. Operating temperature
4. Orbit duration
5. V/T level of charging

Best thought experiments were performed where. the above five factors were set at estimated levels. After over a year, a best thought battery operation performance was established. Figure 1 describes the cell voltage divergence profile optimization using the old method.

After analyzing the battery performance of Figure 1, it was soon realized that the best thought battery operation management was far from an ideal functional performance as shown in Figure 2. A more quantifiable experimentation and analysis for further battery operation optimization was needed.

III PARAMETER DESIGN EXPERIMENTAL APPROACH

In performing battery operation management optimization in the past, JPL has used the classical approach to experimentation which is to modify one parameter and keep the rest of the parameters fixed. Most often, this old method requires considerable time and resources in order to attain an acceptable performance.

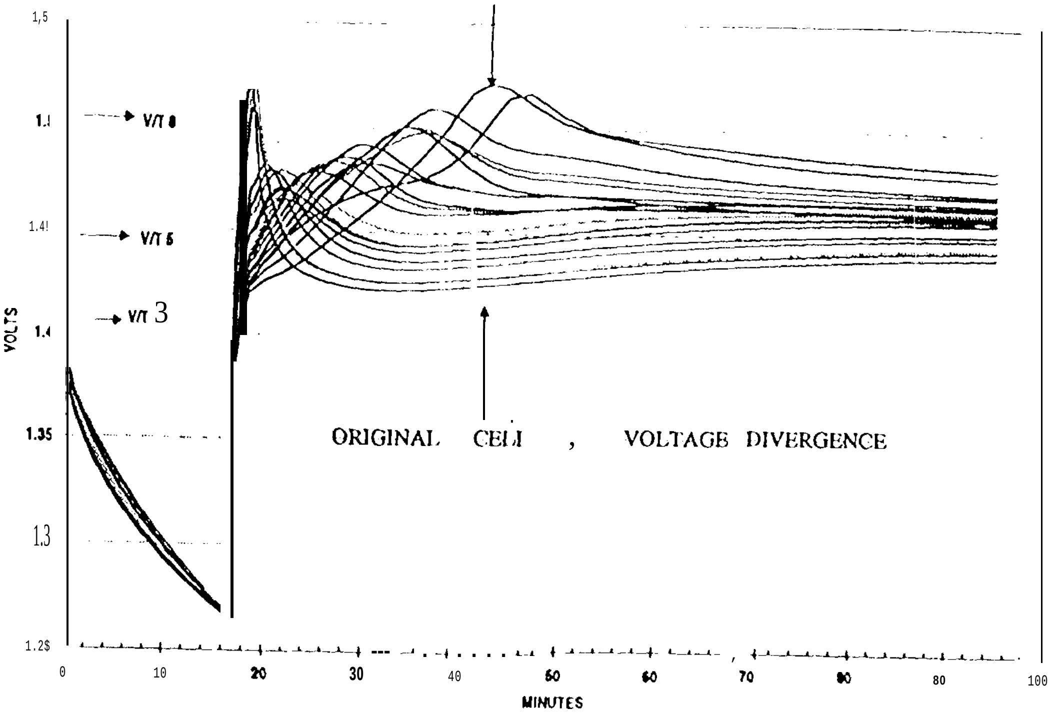


Figure 1. Voltage profile prior to applying Robust Design

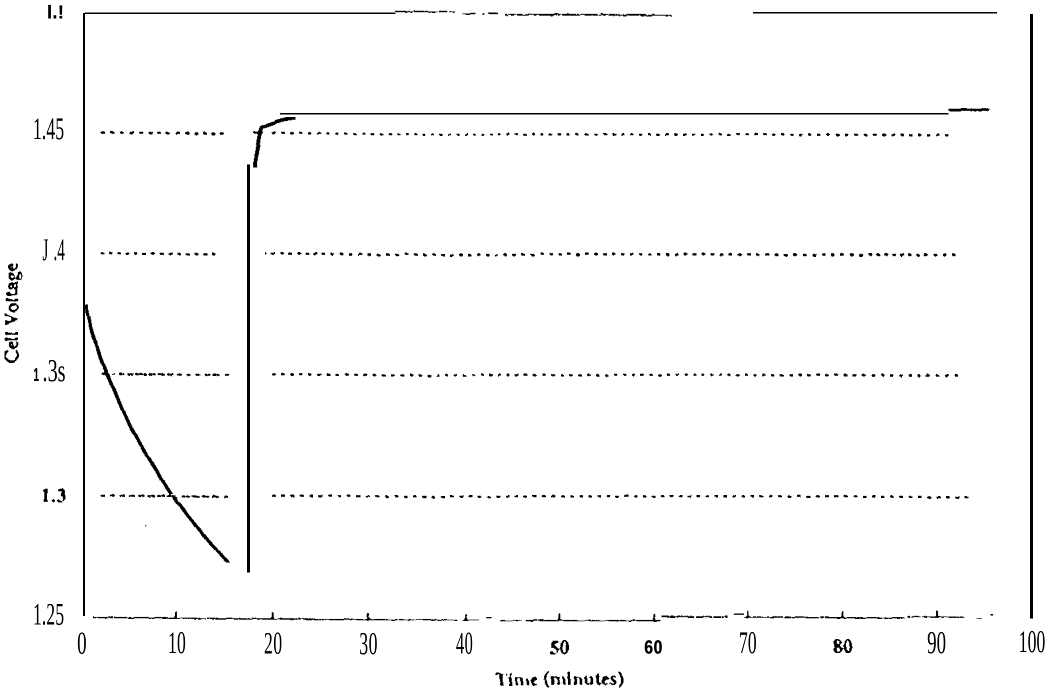


Figure 2, Ideal Voltage Profile

For these reasons, designed experimentation was considered next. Each of the five previously considered factors was selected to perform at four different levels as listed below.

FACTORS	LEVELS 1	2	3	4
1. Peak Charge Current (A):	10	20	30	40
2. DOD (%):	5	10	15	25
3. Temperature (°C):	0	5	10	15
4. Orbit Duration (rein):	90	100	110	120
5. V/T level:	2	3	4	5

in this particular case, a full factorial with five factors at four levels would have required 1024 experiments. Since each experiment is needed to be performed at the given levels for 60 cycles (approximately four days), a total of 4096 days or 11.2 years of experimentation would have been required, had this approach been taken, It was very obvious that it was not very cost effective for NASA to allow for over 11 years of experimentation to obtain the data and establish the optimum operation performance of these batteries.

Novel battery management techniques had to be implemented to quickly recover space flight battery performance. For this reason a NASA battery testbed was established to systematically evaluate various battery management techniques.

This was the time when Taguchi Methods of Robust Design were first considered in order to improve battery life by optimizing battery operation process. To quickly determine which of the above factors needed to be operated at what levels and to influence the battery recharge fraction the most, fractional factorial techniques were considered.

The proposed test articles were three existing 22-cell Nickel-Cadnliun~ batteries available at JPL. Two batteries were approximately nine years old and had been used on the GRO and TOPEX/Poseidon missions as "test and integration" batteries. The third battery was assembled with cells from four different manufacturing lots after the cells were cycled for several hundred cycles. Thus, there was plenty product to product noise.

IV. EXPERIMENT LAYOUT, RESULTS AND ANALYSIS

In setting up the Taguchi designed experiment, the 5 above described factors each at four levels were studied. A modified 1.16 orthogonal array was selected for this experiment which allowed evaluation of the 5 factors at 4 levels each. With each experiment performed 60 times, the total duration of this experiment was reduced from the initial 11.2 years to only 10 weeks.

Even though a significant signal factor was identified, due to time and cost constraints, a static robust design was performed. The macro modeling or P-diagram approach is described in Figure 3.

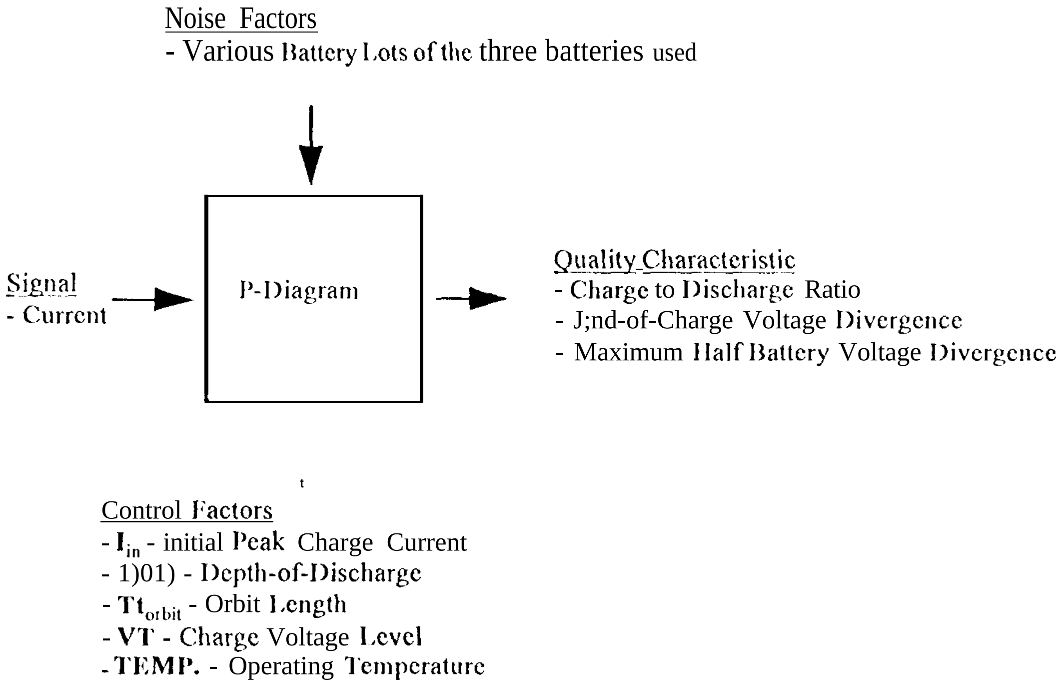
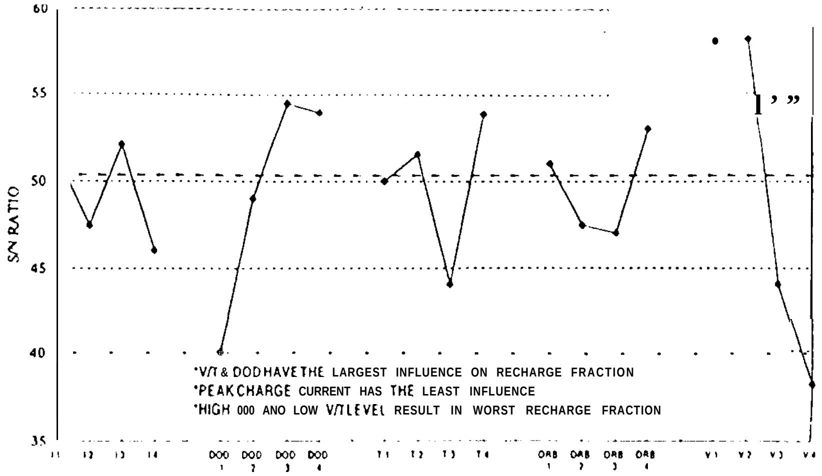


Figure 3. NiCd Battery P-diagram

The setup of the experimentation and output measurement is described in Figure 4. The A, B and C in Fig. 4 are the three batteries under experimentation. It is worth mentioning that six outputs measurements or quality functions ranked in order of importance were recorded (see Figure 4). ANOVA-TM Professional software package was used to analyze the data, Signal-to-Noise analysis was performed for "Nominal the Best" signal evaluation. Sensitivity analysis was performed for all six measurements and response graphs are shown here for only three: Recharge Fraction; End of Charge Divergence and; Max Half Battery Divergence (See Figure 5,6, and 7).

VARIABLE SETTINGS						AVERAGES																	
						CHARGE TO DISCHARGE AMPERE-HOUR RATIO			END OF CHARGE CURRENT (AMPERES)			END OF CHARGE RANGE OF CELL VOLTAGES (MV)			MAXIMUM RANGE OF CELL VOLTAGES (MV)			END OF CHARGE HALF-BATTERY DELTA (MV)			MAXIMUM HALF-BATTERY VOLTAGE DELTA (MV)		
EXPERIMENT	TEMPERATURE (DEGREES C)	ORBIT DURATION (MINUTES)	DOD BASED ON 150AH NAMEPLATE	INRUSH CURRENT	MAXIMUM VOLTS PER CELL	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
11	0	100	15%	90	1.46	1.01	1.02	1.02	0.8	0.7	0.7	13.8	45.6	15.6	28.1	50.9	24.2	-4.3	4.6	-1.1	19.8	39.7	24.9
16	0	110	25%	120	1.42	1.00	1.00	1.01	2.7	2.7	1.8	2.7	5.1	17.4	21.9	28.5	18.0	-2.9	0.1	-3.8	13.0	10.5	11.1
6	0	120	10%	60	1.44	1.02	1.02	1.03	0.6	0.6	0.4	13.3	29.3	12.9	34.8	50.0	32.1	-25.9	23.4	3.0	90.9	29.0	37.1
1	0	90	5%	30	1.4	[illegible]	1.01	1.01	0.4	0.4	0.3	12.4	2 .4	13.5	37.6	52.5	20.3	-25.0	15.5	0.2	73.7	26.1	32.9
5	5	110	5%	60	1.45	1.08	1.08	1.16	0.4	0.4	0.4	46.7	74.	24.3	132.9	136.5	41.0	-96.1	50.5	-6.0	327.6	66.6	5.7
12	5	90	25%	90	1.43	.00	1.00	1.01	6.0	6.0	3.8	4.3	9.8	23.	30.9	27.3	23.4	31.4	31.4	31.4	21.4	15.9	12.8
15	5	120	15%	120	1.39	1.01	1.01	1.01	1.1	1.1	0.6	2.3	6.1	7.6	36.3	39.6	24.5	-2.4	4.7	3.3	15.2	13.0	19.9
2	5	100	10%	30	1.41	1.01	1.01	1.01	1.2	1.2	0.6	5.2	11.3	11.5	27.0	38.2	28.5	-9.0	9.6	3.3	15.5	1.2	38.2
8	10	100	25%	60	1.38	0.98	0.98	0.99	5.2	5.2	5.3	3.4	3.9	5.5	6.6	7.5	29.5	-5.6	-1.1	6.2	4.2	3.2	20.1
9	10	120	5%	90	1.4	1.06	1.05	1.05	0.4	0.4	0.2	4.7	5.1	14.3	38.7	40.9	33.6	1.7	1.0	-1.6	23.6	16.4	54.5
14	10	90	10%	120	1.44	1.05	1.05	1.11	1.2	1.2	0.9	29.3	50.6	22.6	56.1	67.5	34.9	-44.7	35.7	-7.0	111.7	44.4	45.0
3	10	110	15%	30	1.42	1.01	1.01	1.03	1.8	1.8	0.9	14.3	21.3	17.4	19.9	26.5	22.4	-20.4	12.0	-0.8	39.5	12.0	35.4
4	15	120	25%	30	1.425	0.99	0.99	0.99	9.1	9.1	9.8	8.0	5.8	21.2	15.0	15.7	23.9	-1.5	-2.2	1.8	4.1	4.7	18.2
7	15	90	15%	60	1.385	1.01	[illegible]	[illegible]	1.9	1.9	1.7	3.7	3.3	5.6	21.9	28.7	20.7	2.2	1.4	3.2	4.2	4.2	20.9
10	15	110	10%	90	1.365	1.01	1.01	1.01	0.7	0.7	0.5	2.6	2.4	2.9	26.9	26.	23.1	0.1	0.7	2.2	0.2	4.6	25.2
13	15	100	5%	120	1.405	1.07	1.07	1.10	0.8	0.8	0.5	2.7	3.8	16.6	39.0	38.6	36.0	4.7	-4.5	-0.9	19.7	24.1	63.0
VER.1	5	120	25%	90	1.410	1.00	1.00	1.01	2.8	2.6	1.5	2.1	8.4	10.9	25.1	23.1	25.5	-4.3	4.8	0.3	-45.9	-13.9	12.7
VER.2	5	120	25%	90	1.410	1.00	1.00	1.01	3.0	3.0	1.6	3.0	5.2	11.6	29.2	25.3	21.5	-1.3	1.5	-2.1	-48.0	-14.0	22.9
VER.3	15	120	25%	90	1.410	1.0	1.02	1.03	2.6	2.6	1.5	4.5	8.2	14.0	26.4	23.6	21.5	-1.9	3.5	-1.3	-48.1	-8.7	34.4
UARS, REF.1	3	95	20%	102	1.460	1.02	[illegible]	1.04	2.4	2.3	1.5	21.0	36.6	10.4	39.0	57.3	41.0	-35.8	35.7	8.3	-72.0	47.8	48.4
UARS, REF.2	3	95	10%	102	1.460	.03	1.04	1.09	1.0	.0	0.8	33.3	40.7	14.9	89.3	98.4	31.7	-37.6	9.3	2.7	63.7	85.2	3.7
VER.4	15	120	25%	90	1.385	.0	1.0	.01	2.1	2.1	.7	.5	2.2	10.4	14.0	12.1	20.9	0.3	1.1	-0.6	-26.2	-9.9	18.0

Figure 4. Experiment setup and output measurements



•V/T & DOD HAVE THE LARGEST INFLUENCE ON RECHARGE FRACTION
•PEAK CHARGE CURRENT HAS THE LEAST INFLUENCE
•HIGH 000 ANO LOW V/T LEVEL RESULT IN WORST RECHARGE FRACTION

Figure S. Signal to Noise Ratio for Recharge Fraction

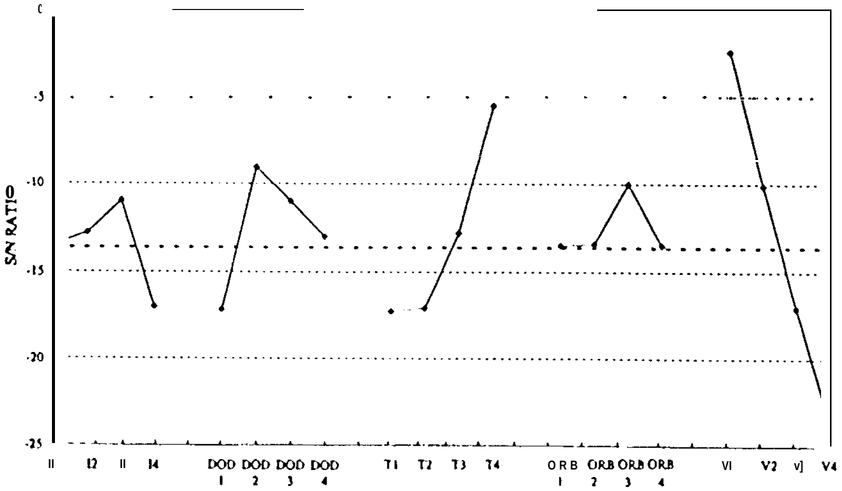
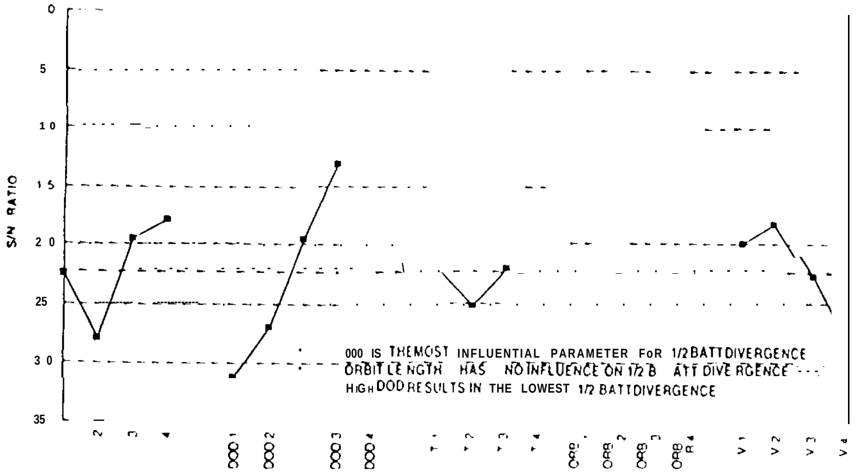


Figure 6. Signal to Noise Ratio for End-of-Charge Divergence



000 IS THE MOST INFLUENTIAL PARAMETER FOR 1/2 BATT DIVERGENCE
ORBIT LENGTH HAS NO INFLUENCE ON 1/2 BATT DIVERGENCE
HIGH DOD RESULTS IN THE LOWEST 1/2 BATT DIVERGENCE

Figure 7. Signal to Noise Ratio for Max 1/2 Battery Divergence

V. CONFIRMATION

The operation optimization was performed against the first quality characteristic "recharge fraction" with the other five factors being used only to influence the factor level selection for process average prediction. Cost was not considered in selecting the factor levels.

Suggested parameters selection for best performance confirmation was as follows:

PARAMETERS	VERIFICATION CONDITIONS
Peak charge (Amp)	30
DOD (%)	25
Temperature (°C)	5
Orbit Duration (min)	120
VT/Level	3

The projected S/N process average was 73.643 dB. The mean was T= 54.083 dB, thus with a delta increase of 19.56 dB. Verification Comparison Data is shown in Figure 8:

	C/D			EOC DIV.			MAX 1/2 BATT. DIV.		
BATT. #	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
INITIAL	1.03	1.04	1.09	-37.60	9.30	2.70	63.70	85.20	65.20
VER. 1	1.00	1.00	1.01	-4.30	4.80	0.30	-45.90	-13.90	12.70
VER. 2	1.00	1.00	1.01	-1.30	1.50	-2.10	-48.00	-14.00	22.90

Figure 8. Verification Comparison Data

Figure 9 describes the voltage divergence profile after applying Robust Design. Comparing the profiles of Figure 1 and Figure 9 graphical representation, before and after using Robust Design, the performance improvement was quite remarkable and was evaluated at over 96°/0 improvement. This performance more than confirmed the projected improvement.

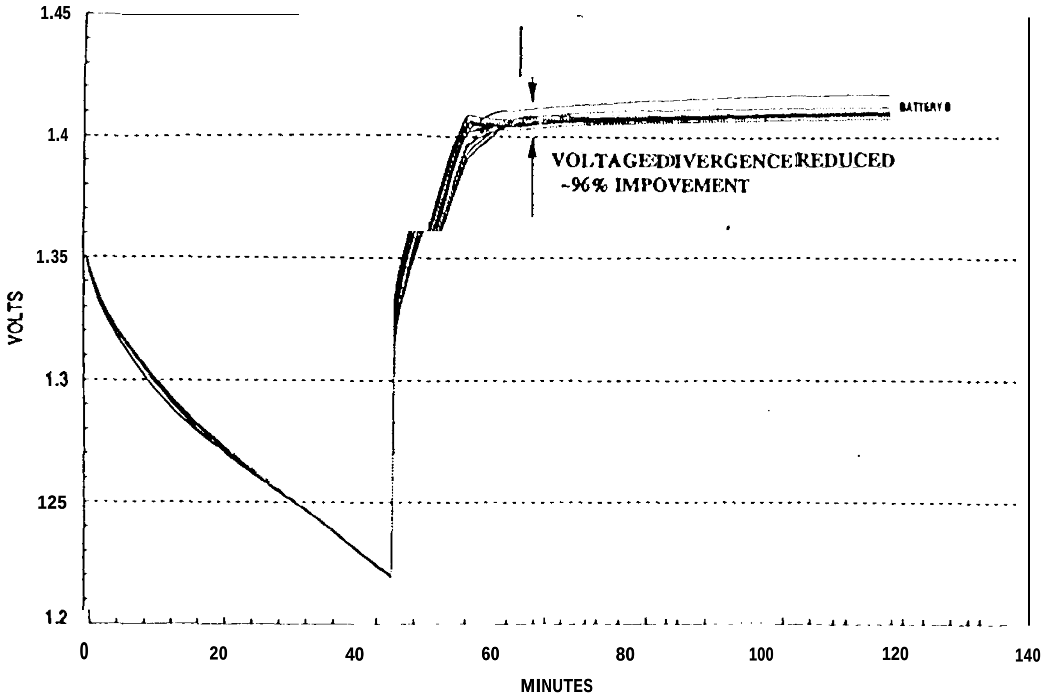


Figure 9. Voltage Profile After Applying Robust Design

VI. CONCLUSIONS

The excellent results of the application of Taguchi Methods of Robust Design has already assisted the power subsystem and battery analysts experts in determining the appropriate protocol for flight NiCd battery operation management for various current and future missions.

Results obtained using the old way of performing battery operation management were compared to the results obtained using Robust Design. By applying Taguchi Methods, it was estimated that a cost savings of over 400% was obtained as well as over 300% experimentation time reduction, while improving battery voltage performance over 960A.

This innovative application of Taguchi's Robust Design is viewed as a new technology of applying this modern engineering design optimization technique to the operational optimization of existing space flight battery in order to improve battery life nominal performance and thus extend spacecraft life.

With the results obtain from this static robust design implementation, currently a dynamic robust design is implemented using the Depth-Of-Discharge (DOD) and Temperature as signal factors.