ADVANCED NICKEL-CADMIUM BATTERIES FOR GEOSYNCHRONOUS SPACECRAFT

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A nickel-cadmium battery has been developed that can be operated at 80% depth of discharge in excess of 10 (possibly 15) years in a geosynchronous orbit application, and has about a 30% weight savings per spacecraft over state-of-the-art nickel-cadmium batteries when used with a 1000 watts eclipse load. The approach used in the development was to replace nylon separators with inert polymer impregnated zirconia, use electrochemically deposited plates in place of conventional chemically precipitated ones, and use an additive to extend negative plate lifetime. The design has undergone extensive testing using both engineering and protoflight cell configurations.

HUGHES GEOSYNCHRONOUS BATTERY BACKGROUND

The Nickel-Cadmium Evolution

Since the late 1960s the design of nickel-cadmium battery cells used by Hughes, for its geosynchronous spacecraft, has undergone a series of evolutionary developments. Each of these generations of battery cells, starting with Generation 1 in 1968 through today's Generation 4, has a number of major cell design factors which show a continued progression toward optimum values that have enhanced performance and reliability with concomitant improvements in useable energy density. The design factors selected for each new generation have been built on the data base collected from laboratory life tests, as well as continued observation of actual in-orbit performance of a large number of spacecraft over the years. Table 1 shows a summary of some of the more important nickel-cadmium cell design features for the four generations of cells utilized by Hughes over the past 18 years. In addition, Figures 1-3 show graphical representations, by generation, of the values for some of these parameters. These graphs clearly show the evolutionary trends of these parametric changes which supported the improved performance from those early satellite days. These parametric values, incidentally, are intended to be nominal in nature and are in implementation represented by a range of values about the nominal. The various generations of nickel-cadmium cells were flown or will be flown on the programs listed below. Not all programs and applications are listed, but representative ones are shown, along with the approximate calendar period for the design and applications activities.

- oGeneration 1 Ni-Cd Cells--ANIK A, INTELSAT 4--1968-1972
- oGeneration 2 Ni-Cd Cells--WESTAR 1-3, INTELSAT 4A, PALAPA, COMSTAR--1973-1977

oGeneration 3 Ni-Cd Cells--GOES, LEASAT, HS376 Series--1978-Present

oNickel-Hydrogen Cells--Military Applications, HS-393 Series, Future--1979-Present

oGeneration 4 Ni-Cd Cells--Future HS-376, Low Power DBS and Special Applications--1987-Future

Generation 4 Nickel-Cadmium Cells

Since nickel-hydrogen technology became available for flight applications soon after the third generation of nickel-cadmium cells, as noted in the timeline data above, why develop a fourth generation nickel-cadmium cell? A number of system-level trade studies had shown that a high performance nickel-cadmium cell would continue to show favorable weight and cost advantages over nickel-hydrogen cells when used in low power or small satellite applications. A nickel-cadmium cell which could equal nickel-hydrogen performance for 10 year synchronous missions, i.e., operate at or near 80% depth-of-discharge (DOD), would show such advantages at power levels below 1500 watts (W).

A further study was made in 1982 to determine the best approach to providing an aerospace-quality sealed nickel-cadmium cell. It was decided that incorporation of some nickel-hydrogen technology could benefit the performance of a new generation nickel-cadmium cell. Specific areas for improvement would focus on the positive electrode and the separators. An internally funded program was initiated to develop the new nickel-cadmium cell design that would meet the goals of 10-15 years in geosynchronous orbit at 80% DOD.

DEVELOPMENT OF GENERATION 4 NICKEL-CADMIUM CELLS

Initial Evaluations with Nickel-Hydrogen Type Separators

In our initial investigations with nickel-hydrogen cells we found that a yttria-stabilized zirconia cloth made by the Zircar Corporation was well suited to the alkaline and oxidizing environments within the cell, but some difficulty was encountered in handling the brittle material. In order to alleviate the handling problem, as well as reduce direct flow of oxygen through the highly porous material from the positive to negative plate, techniques were developed to impregnate this Zircar material (ref. 1) with polymers compatible with the harsh cell environment. Although one of these polymers had a tendency to poison catalytic activity of the hydrogen electrode, it appeared to function quite well in a nickel-cadmium cell(ref. 2). Encouraged by these results, we began a series of electrochemical and physical measurements on the separators and constructed Ni-Cd engineering (boilerplate) and protoflight cells to further evaluate lifetimes in both low earth orbit (LEO) and geosynchronous orbit (GEO) regimes. These tests were performed at our Malibu Research Laboratories (HRL) and Space and Communications Group (S&CG) test facilities.

Accelerated Testing Techniques

In order to evaluate our new separator materials (as well as other components and additives), in a timely manner, it was necessary to devise accelerated cycle life tests which could closely simulate real time battery performance in orbit. This was especially true for the higher GEO orbits since only 1000 cycles are accumulated over a ten year period in real time. Even in the lower 90 minute orbits, if cycling occurs at a low DOD, one may wait three to four years to observe a cell failure under real time conditions. As the results below will show, this time can be reduced by at least 50%, with reasonable confidence in the data, by using an accelerated test. Other results will show that an extraordinarily large number of cycles at a high rate will not guarantee long lifetime in a GEO situation.

In order to simulate real time GEO conditions as accurately as possible we used three different accelerated testing techniques. One of these techniques was a four-day cycle regime (Regime I) which included a 16-cycle period. It has been described previously (ref. 3). This regime was applied to all boilerplate cell testing and to some flight type cells. The regime included cycles of various DODs in 10% steps: 10, 20, 30, ..., 70, 80, 80, 70, ..., 20, 10% DOD, respectively. A charge/discharge ratio of 1.2 at a temperature of 10 to 15 deg. C. was used. A nine minute trickle charge at 0.02C rate followed the recharge at the 0.1C rate. Discharge was at the 0.5C rate. Test cells were reconditioned typically every third eclipse period by discharging them at the 0.5C rate for one hour followed by discharge across a 10 ohm resistor for 77 hours then constant current charge at 0.1C for 18 hours. This technique was extremely valuable in evaluating GEO cycling capability of a boilerplate cell with new additive and negative electrode components. If the cell would not perform under this cycling regime, it would not perform under real time conditions.

Another accelerated regime (Regime II) used in this study was that in which only the solstice period is accelerated by an elevated temperature. The eclipse portion of the regime was performed using 46 day real time GEO cycling at 10 deg. C. The accelerated continuous sunlight period consisted of trickle charge at C/36 for 21.25 days at 50 deg. C. Test cells were reconditioned after each eclipse season as described in reference 3. This test regime was probably more severe than a real time regime since state-of-the-art cells, which had lasted over 10 years in a real time test regime, lasted only ten seasons in this one.

In order to compare our data to that of accelerated testing being performed on our flight programs, a third GEO regime (Regime III) was used. This regime was similar to Regime II except that temperature was not elevated during the continuous sunlight (solstice) period. Time between eclipse seasons was 14 days with C/60 trickle charge. Reconditioning was performed prior to each eclipse season.

In our initial LEO testing of boilerplate cells in an accelerated regime, a cycle regime (Regime IV) was used which allowed us to perform testing in about one-half the time normally used to perform testing for a 90 minute orbit (ref. 2).

S&CG Protoflight Design Cell Tests

The 12 ampere-hour (AH) cells used in this test were constructed using new electrochemically deposited (ED) electrodes and various separator combinations. Cells having Pellon 2505 nylon material were used as controls. Preliminary results of the tests have been described in an earlier publication (ref. 3). In summary, separators used in the test were polysufone impregnated Zircar (PS-Z), polybenzimadazole impregnated Zircar (PBI-Z), polybenzimadazole impregnated polypropylene (PBI-PP) and Pellon 2505. Two different test regimes were used to evaluate the above configurations, a real time test closely simulating possible flight conditions in GEO and Regime II. Cells were constructed as close to flight configuration as possible at the General Electric Battery Business Department, Gainesville, FL. Prior to being placed on cycle life testing, the cells were subjected to the Hughes standard flight acceptance tests.

Results of the life testing on the PBI-Z and PBI-PP configurations are illustrated in Figure 4. As reported earlier (ref. 3), cells with Pellon 2505 failed after 10 seasons in the accelerated test due to high charge voltages which resulted in hydrogen gassing. (The 50 deg. C. temperature acceleration was apparently too severe causing accelerated nylon hydrolysis which resulted in loss of overcharge protection.) The PS-Z cells were removed from test since they were slightly damaged during initial construction. Other details of the testing will be given later in this paper. Since results of this testing were accumulated over a long time period, they did not influence the course of this development program, initially, as did other results such as those from the LEO tests.

LEO Testing of Boiler Plate Cells

Prior to fabrication of the 12 AH flight cells described above, we had performed studies on a series of boilerplate Ni-Cd cells which contained the chemically stable, polymer reinforced, Zircar separators. In this case conventional electrodes having chemically deposited active material were used. An accelerated cycle life test (Regime IV) was carried out at various temperatures (25, 40 and 50 deg. C.) in a cycle regime similar to a LEO regime rather than a GEO regime (ref. 2). Cycle life (to 0.5V) of those cells containing polysulfone impregnated Zircar (PS-Z) is compared with that of aerospace Ni-Cd cells containing Pellon 2505 nylon separators (ref. 5) in Figure 5. These results showed that the cycle life of a nickel-cadmium cell is remarkably (roughly three times) improved with this new separator. Cycle life up to 43,000 cycles was observed at 25 deg. C. at 40% DOD. The results at various temperatures showed that Arrhenius activation energy for the cycle life was 11 kcal/mole as shown in Figure 6. These extremely encouraging results allowed us to initiate the development of the Generation 4 advanced Ni-Cd battery for GEO applications with an ambitious goal of over 10 years operation at 80% DOD operation.

Capacity Fading and Storage Problems

Although cells with the new separators and CD electrodes showed excellent cycle life in a LEO type regime, they showed a rapid capacity fading in GEO cycling (ref. 3). The cells usually failed within 10 eclipse periods in Regime I (80% DOD). This capacity fading was identified to be due to the

fading of cadmium electrode capacity at low rate (0.1 C) charging which is normally required on a GEO spacecraft. This fading was believed to be due to formation of large cadmium crystals during low rate charge (ref. 6).

In order to eliminate this problem, which is usually observed with low rate charging, a high rate pulse charging scheme (HGEO regime) was successfully developed (ref. 3). This scheme involves sequential charging of individual battery sub-packs one at a time at a 0.4 C rate or higher. Seven out of eight boiler plate cells in a test series completed over 120 eclipse periods of Regime I cycling using this method of charge. Failure was defined as end-of discharge-voltage (EODV) falling below 1.0 volt. This cycle life corresponds to a 20 year equivalent number of cycles in GEO indicating that not further improvement might be needed for the goal performance, if the HGEO charging could be implemented in the spacecraft. Spacecraft systems level studies indicated that a conventional low rate charging scheme would be more desireable due to weight and cost considerations. Therefore, our subsequent efforts were directed toward development of a cell design which did not depend on a HGEO charging regime.

In attempts to test a second series of protoflight cells in which CD negative electrodes and ED positive electrodes were present, we experienced a loss in capacity on storage which accompanied the capacity loss associated with low rate charging. This storage capacity loss was attributed to the ED positive electrode since it was not observed in cells with CD positive electrodes. This type of capacity loss was eliminated with a modification in the processing of the ED positive electrodes. Test results confirming a stable storage capacity are given later in the paper.

Investigation and Formulation of Permanent Solutions to Capacity Losses

In our search to find a solution to negative capacity fading other than HGEO charging, it became rather obvious that the first 12 AH protoflight cells which we had on test had not experienced capacity fading that was present in the boilerplate cells and the second series of protoflight cells. The 12 AH cells had the unique feature of ED negative electrodes. Thus an investigation into the capacity stability of ED cadmium electrode was initiated. At the same time an investigation into the various "expanders" that were used for cadmium electrodes was pursued. As test results below indicate, we were successful in finding an additive which serves as an expander, and were able to demonstrate that use of an ED cadmium electrode will eliminate capacity fading associated with low rate charging.

In the course of this study over 40 different design variations were evaluated using cycle Regime I. Our investigations included examination of: variation in active material impregnation procedure (CD or ED) and loading levels of both cadmium and nickel electrodes, various additives to the electrolyte or the cadmium electrode, variation of polymers for the impregnation of the zirconia separator, variations in electrode spacing, and variation of activation (or preconditioning) procedures.

EVALUATION AND TESTING

Storage Evaluation Tests/ Boilerplate Cells

Storage evaluation tests were performed on four different test cells using three different storage modes in sequence. The initial storage mode was

an open circuit storage at room ambient temperature (about 22 deg. C.) after discharging test cells to 0.5 V. at the C/2 rate from a fully charged state. The second storage mode was another open circuit storage at ambient temperature after shorting the cells across a 1.0 ohm resistor for 70 hours. The last storage mode was a shorted storage with a 1 ohm resistor across the terminals at ambient temperature after discharging the cells.

Results of the boilerplate cell storage tests are shown in Figure 7. The capacities of cells containing ED nickel electrodes showed no decrease during open storage up to 77 days, while a gradual minor decrease was observed during subsequent shorted storage for additional 160 days (Fig. 7A and 7B). The cells containing CD nickel electrodes showed a slight decrease after initial 18-day open circuit storage, but no further decrease was observed on additional storage in the same storage mode (Fig. 7C and 7D), while the capacity improved during the second mode of open circuit storage. This improved capacity did not decrease significantly during the subsequent shorted storage. Overall, no significant storage problem is expected with any of these designs. However, for a long term storage (ca. 100 days), an open circuit mode appears to be preferred for the advanced Ni-Cd cell which contains ED nickel electrodes.

Storage Evaluation Tests / Protoflight Cells

Results of this test are summarized in Table 2. Data support results from boilerplate cell tests and clearly indicate that shorted storage for periods less than 71 days does not result in capacity loss. We thus have eliminated the gross capacity fading which was present in earlier cell designs with ED plates.

Cycle Life Testing / Boilerplate Cells

In the course of arriving at our advanced design we have fabricated approximately 120 boilerplate test cells and performed accelerated cycle life tests on more than 100 cells. These tests were divided into seven different iterative series screening out less desirable designs in each iterative step. In the final test series design variables were narrowed down to the use of mostly polybenzimidazole impregnated zirconia (Zircar) separators (PBI-Z), a Hughes proprietary additive, and mostly ED electrodes. Some of these cells have been cycled over 190 eclipse periods in cycle Regime I at 80% DOD without a deterioration of their voltage performance as shown in Figure 8. This cycle life is equivalent to about 30 years of cycling in a GEO regime. We believe that these cells will have lifetimes of over 10 years or probably over 15 years at 80% DOD operation in GEO. The final recommended designs included a combination of ED nickel and cadmium electrodes, PBI-Z separators and an additive.

Effectiveness or stability of the additive has been demonstrated after four calendar years of continuous cycling. Results are shown in Figure 9. Although it is not a demonstration in a real time regime, it is an extremely encouraging indication for the long term effectiveness of the additive. In addition, no harmful effect of this additive for long life has been identified.

Cycle Life Testing / Protoflight Cells

Over the past eight years some 45 flight configuration (protoflight) cells with various separators, electrode and additive combinations have been cycle life tested in order to verify boilerplate cell tests which are described above. We have described preliminary results of 12 AH first iteration cells in a previous publication (ref. 3) and have summarized the results in Figure 4. Test conditions were described earlier in this paper. Results of this testing have been quite encouraging, but it has taken some time to accumulate the data.

Shortly after placing the 12 AH cells on test, a second 20 AH design iteration, containing CD cadmium electrodes, was purchased from the same vendor and subjected to the same tests as the 12 AH cells. The cells exhibited a voltage decrease to below 1.0 V per cell after a couple of seasons (80% DOD max.) of cycling in Regime II. Shortly after obtaining these results we began the extensive testing with various boilerplate combinations.

After our boilerplate cell tests had indicated that the CD cadmium electrode had a tendency to fade in capacity at GEO charge rates in the absence of an additive at 80% DOD, it was decided that a third iteration of flight configuration cells should be fabricated and tested in order to verify the boilerplate cell test results. Some 30 of these cells were purchased from one vendor and another 10 from a second vendor and placed on test using GEO Regimes I and III. Control cells without additive and with CD cadmium electrodes were included in the group. Results to date have been quite encouraging with more than 25 years equivalent of cycling in Regime I and over 5 years equivalent in Regime III to date. Some typical voltage at maximum DOD versus eclipse season plots are shown in Figure 10.

Tear Down Analyses

Tear down analyses were carried out on both Ni-Cd boilerplate cells, which were heavily cycled in an accelerated LEO type regime, and 12 AH protoflight cells, which had undergone 9 seasons of real time GEO cycling.

Results of the analyses on GEO cells are summarized in Table 3. Original plate thicknesses were 0.029+/-0.001 inches. Specified capacities were 12 AH and initial negative/positive ratios were set at 1.7. These results show amazingly little swelling of the electrodes, good capacity and remarkably little cadmium migration.

Analyses on the LEO boilerplate cells consisted of visual inspection, microscopic and SEM studies of cycled electrodes, measurements of electrode thicknesses, flooded electrode capacities, BET surface area, and pore distribution by mercury intrusion porosimetry.

Results of some of these analyses are summarized in Table 4. The CD(chemically deposited or chemically precipitated) electrodes from cells 31 and 32 expanded several times more than those of ED electrodes from other cells indicating an advantage of ED electrodes over CD electrodes. General morphology of electrodes under SEM was similar in nature to those described earlier (ref. 7). The predominant mode of failure in this LEO test was the gradual capacity degradation of the nickel electrode and development of shorts

by cadmium migration. Although the separator dryout looked severe, it did not appear to be the direct cause of cycle failure. We believe that there is sufficient amount of micropores in the zirconia separator for retaining the electrolyte and providing the minimum required conductivity across the separator for cell operation.

ESTABLISHMENT OF FINAL DESIGN FOR FLIGHT QUALIFICATION

A fourth design iteration has recently been implemented which is simply an optimized version of the best performing design from the third iteration. Cells of the fourth iteration design are just now beginning characterization and environmental testing. This design will be used on our next flight in place of conventional nickel-cadmium cells. Figure 11 shows how batteries using this new cell design will compare to conventional ones in terms of power versus weight.

CONCLUSIONS AND SUMMARY

The decision to initiate a program for the improvement of nickel-cadmium cell performance to levels similar to nickel-hydrogen cells was a difficult one. There was no evidence at that time that such an effort was even feasible or that the performance objectives were achievable with even moderate risk. Further, considerable industry-wide effort and resources were being spent on nickel-hydrogen technology, the new generation aerospace battery, with very little attention paid to nickel-cadmium technology improvement. However, our studies continued to show that considerable cost and weight benefits could be derived from nickel-cadmium cells that performed as well as nickel-hydrogen cells, when such cells were used in low power, generally below 1500 watts, low earth orbit and synchronous orbit applications.

A four year development effort was initiated, with a team from the Hughes Space and Communications Group and the Hughes Research Laboratory. The program has progressed to the point where several candidate designs have been assembled to Hughes specifications into flight configuration, flight quality cells at Gates Energy Products (fomerly General Electric in Gainesville, Florida) and are awaiting the start of final characterization/qualification testing in readiness for their first flight program application in the near-future. This milestone is the culmination of an extensive and detailed design/development/test program which probably surpasses any previously implemented for aerospace nickel-cadmium cells.

The program is continuing, extending the cycle and calendar life data base. Eight years of real time testing on protoflight and boilerplate cells at 60-80% DOD has now been achieved. Over 4000 80% DOD accelerated GEO cycles on boilerplate cells have been recorded to date. Other data has shown that this advanced cell design, even in several variations, exceeds the cycle life of conventional aerospace nickel-cadmium cells by threefold. In all test programs, at any DOD, temperature, and cycle test regime, over any calendar period, the advanced design always demonstrated three times the cycle life of state-of-the-art nickel-cadmium cells. One group of test cells has exceeded 43,000 accelerated cycles at 40% DOD at room temperature with no failures. Other life test cell groups have exceeded 2000 geosynchronous simulated cycles (accelerated calendar time) at 80% DOD at 10 deg. C.

Significant component improvements to achieve such performance in this advanced design include the non-degradable impregnated zirconia separator, electrochemically impregnated nickel and cadmium electrodes, modified interelectorde spacing and plate compression, and an additive which prevents the formation of large cadmium crystals on the negative electrode. Test data has shown that cadmium migration in this cell is reduced by a factor of 5 to 10 below that of conventional cells.

In conclusion, the advanced nickel-cadmium cell should easily make a 10 year, and likely 15 years, mission in geosynchronous orbit operating at 80% DOD, based on the data generated thus far.

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TABLE 1. Ni-Cd CELL DESIGN SUMMARY

PARAMETER	GENERATION			
	1	2	3	4
POSITIVE PLATE LOADING, gm/dm 2	14	12	10	9
NEGATIVE PLATE LOADING, gm/dm 2	16	14	12	12
POSITIVE PLATE THICKNESS, IN.	0.028	0.028	0.024	0.028
INTERELECTRODE SPACE, IN.	0.004	0.006	0.007	HUGHES PROPRIETARY
TERMINAL INSULATOR	CERAMASEAL	GE	GE	GE
FILL TUBE JOINT	TIG WELD	Ni-Au BRAZE	Ni-Au BRAZE	Ni-Au BRAZE
SEPARATOR	PELLON 2505	PELLON 2505	PELLON 2505	PBI-Z
ELECTROLYTE CENTRATION, % KOH	34	31	31	31
FILL LEVEL, cc/Ah	2.5	3	4	4.5
CASE CONSTRUCTION	WELDED SEAMS	1 PIECE	1 PIECE	1 PIECE, CORRUG .

TABLE 2. ADVANCED Ni-Cd PROTOFLIGHT CELL STORAGE MODE TEST RESULTS[a]

CELL DESIGNATION, 1 CELL EACH[b]	INITIAL CAPACITY	74 DAY OC[a]	ADDITIONAL 26 DAYS OC	ADDITIONAL 49 DAYS SHORTED	ADDITIONAL 71 DAYS SHORTED
ED (+)/PBI-Z/ED (−)	21.08	21.43	21.32	21.12	21.45
CD (+)/PBI-Z/CD (−)	23.46	23.71	23.47	23.44	23.65

a - CAPACITIES MEASURED BY 0.1C CHARGE FOR 18 HOURS WITH DISCHARGE AT 0.5C RATE (10.0 A) AFTER CONDITIONING CYCLE OF C/20 CHARGE FOR 40 HR FOLLOWED BY C/2 DISCHARGE TO 1.0 V. ALL CAPACITIES MEASURED TO 1.0 V

b - ED (−) = ELECTROCHEMICALLY DEPOSITED, POSITIVE
PBI-Z = POLYBENZIMADAZOLE IMPREGNATED ZIRCAR, SEPARATOR
ED (−) = ELECTROCHEMICALLY DEPOSITED, NEGATIVE
CD = CHEMICALLY DEPOSITED

TABLE 3. ANALYSIS SUMMARY FOR 12 AH CELLS (AFTER 9 REAL TIME SEASONS)

GE PART NO.	ECO1	ECO2	ECO4	ECO5
FILL DATE	21 NOV 78	21 NOV 78	21 NOV 78	21 NOV 78
SEPARATOR	POLYPROPYLENE/ PBI	ZIRCAR/ PBI	POLYPROPYLENE/ PBI	ZIRCAR/ PBI
POS THICKNESS (AVERAGE), IN.	0.032	0.031	0.31	0.031
FLOODED CAP				
POSITIVE, AH	16.30	16.50	16.59	15.59
NEGATIVE, AH	22.80	21.50	24.30	22.00
Cd/Sep, G	0.0016	0.0032	0.0022	0.0026
Cd IN, G/CELL*	0.021	0.042	0.029	0.033

* - 0.1 GM TO 0.4 GM/CELL SEEN IN MARISAT CELL TESTS

TABLE 4. TEARDOWN ANALYSES DATA OF HEAVILY CYCLED NI-Cd BOILER PLATE CELL IN AN ACCELERATED LEO TYPE CYLCE REGIME

CELL NO.	CELL TYPE	NO. OF CYCLES	CYCLING CONDITIONS % DOD/°C	Ni ELECTR EXPANSION, %	FLOODED CAPACITY*, Ah
31	CD/Z-PS/CD≠	43,113^{V}	40/25	36.4	1.27 (2.18)
32	CD/Z-PS/CD	43,113^{V}	40/25	42.7	1.18 (2.18)
42	ED/Z-PS/CD	8,276^{V}	60/40	6.7	1.45 (1.69)
43	ED/Z-PS/CD	5,838^{S}	60/40	7.1	1.78 (1.69)
44	ED/Z-PBI/CD	5,051^{S}	60/40	5.2	1.87 (1.69)
45	ED/Z-PBI/CD	5,139^{S}	60/40	7.1	1.72 (1.69)
46	ED/Z-PS/CD	9,447^{V}	80/25	6.0	1.41 (1.69
47	ED/Z-PBI/CD	6,255^{S}	80/25	3.6	1.65 (1.69)

*: VALUES IN PARENTHESES ARE RATED CAPACITY OF THE ELECTRODE IN Ah
v: CYCLE FAILURE BY A GRADUAL VOLTAGE DROP TO BELOW 0.5 V
s: FAILURE BY AN ABRUPT VOLTAGE DROP DURING CYCLING PROBABLY DUE TO AN INTERNAL SHORT FORMATION
≠ Z-PS= POLYSULFONE INPREGNATED ,SEPARATOR
Z-PBI= PBI-Z
SEE TABLE 2 FOR OTHER DESIGNATIONS

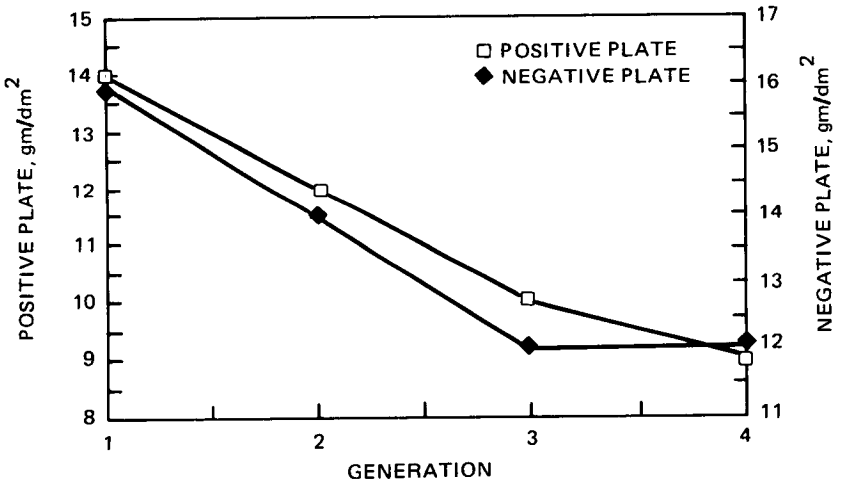

FIGURE 1. PLATE LOADING EVOLUTION Ni-Cd CELLS

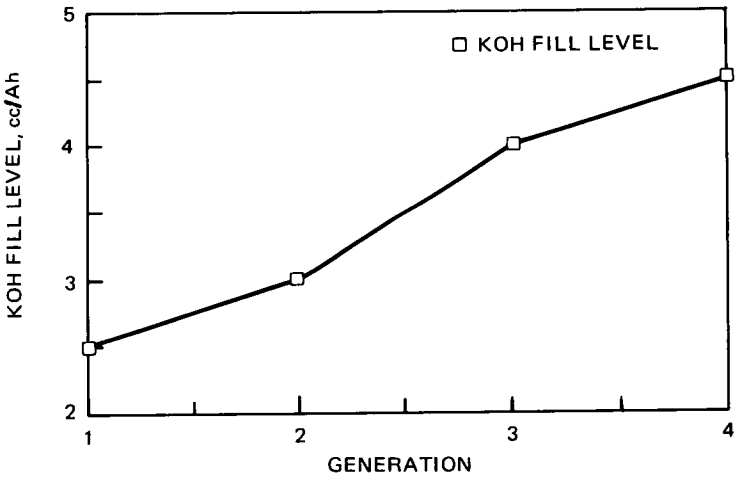

FIGURE 2. ELECTROLYTE FILL LEVEL EVOLUTION

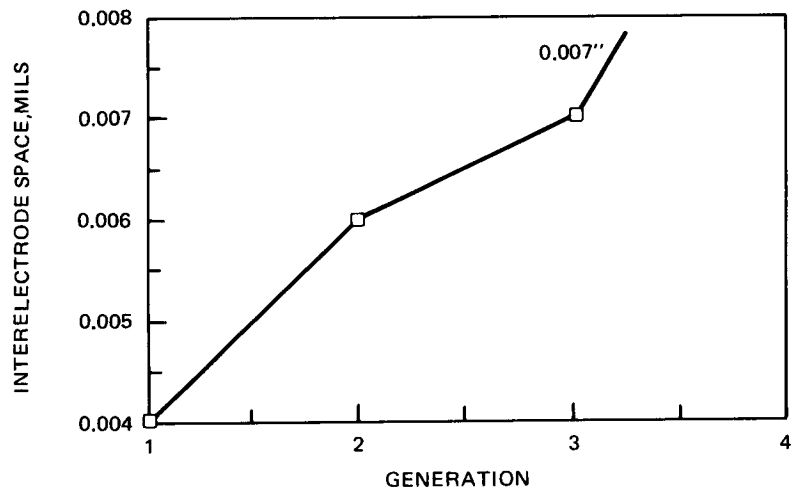

FIGURE 3. EVOLUTION OF INTERELECTRODE SPACING

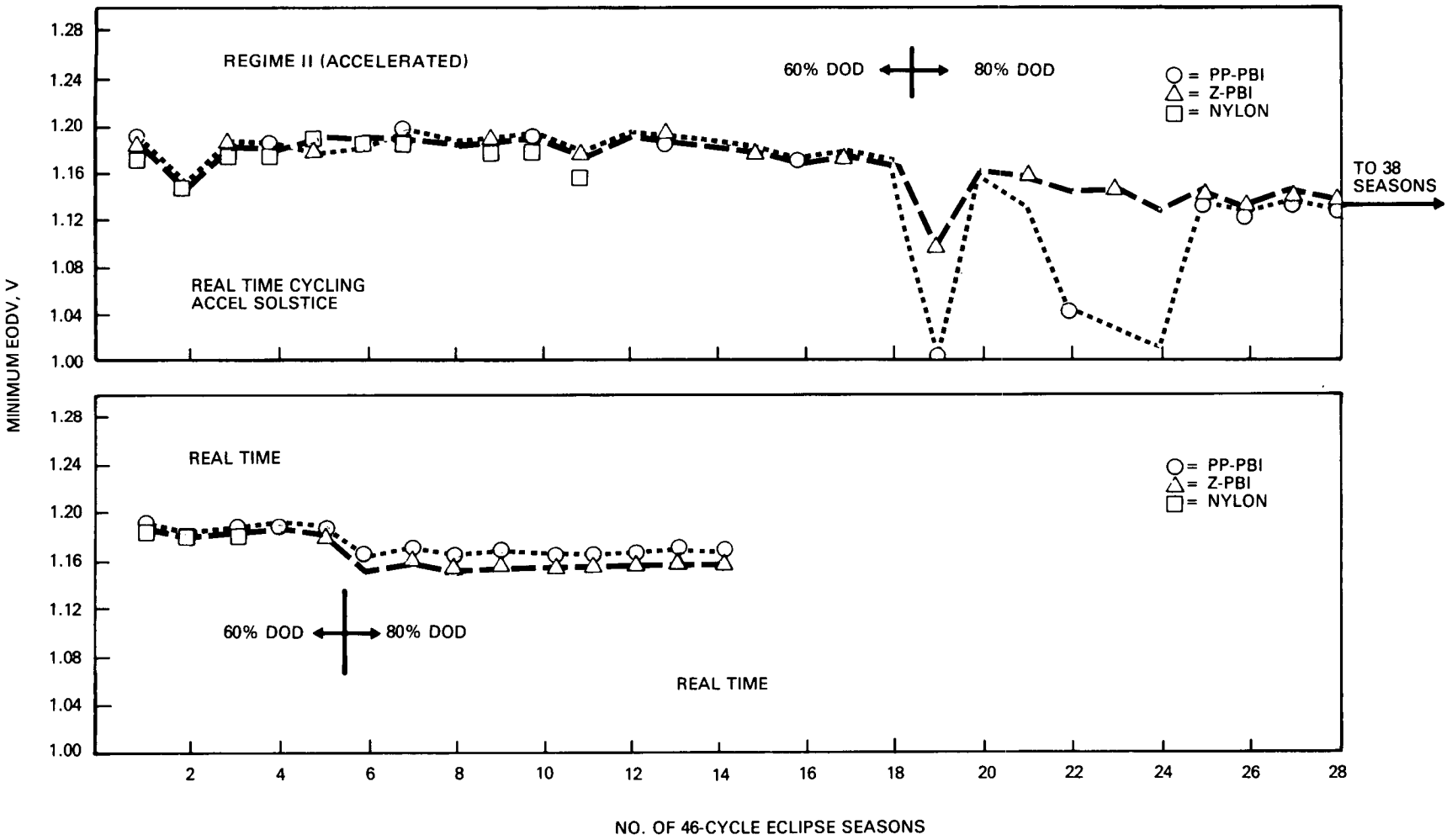

FIGURE 4. PERFORMANCE OF 12 AH PROTOFLIGHT CELLS IN REAL TIME AND ACCELERATED GEO REGIMES

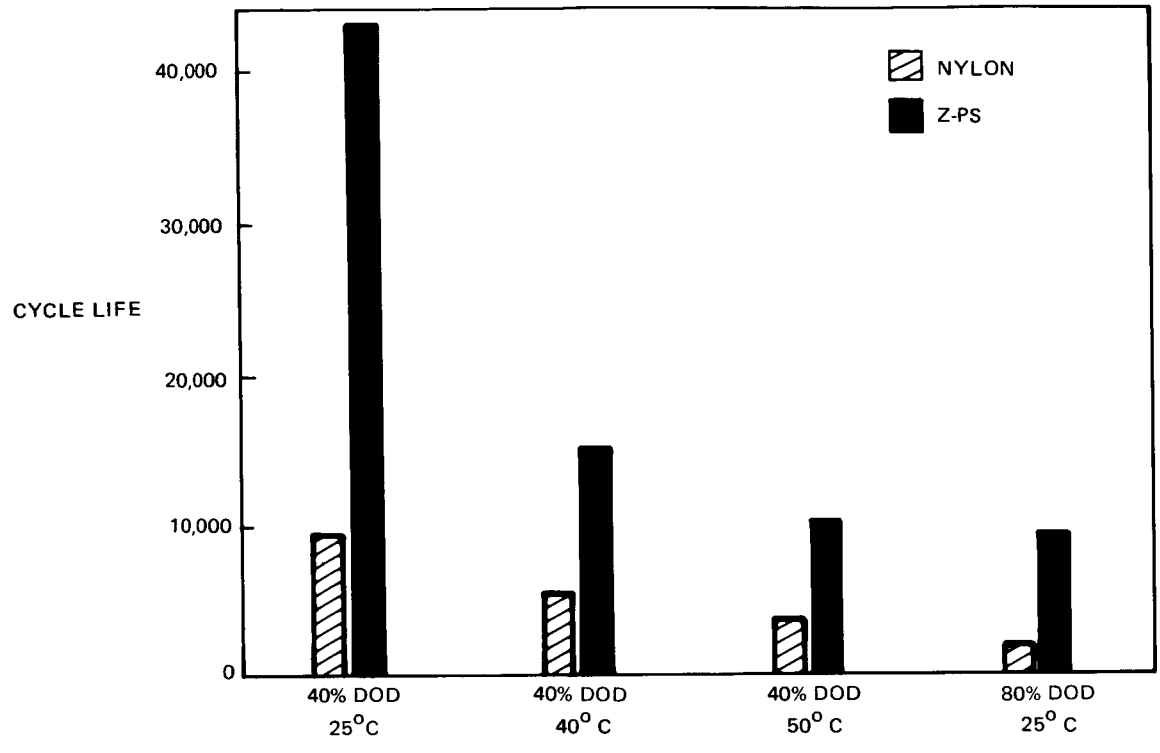

FIGURE 5. CYCLE LIFE COMPARISON OF Ni-Cd CELLS CONTAINING Z-PS SEPARATORS WITH CELLS CONTAINING NYLON SEPARATORS

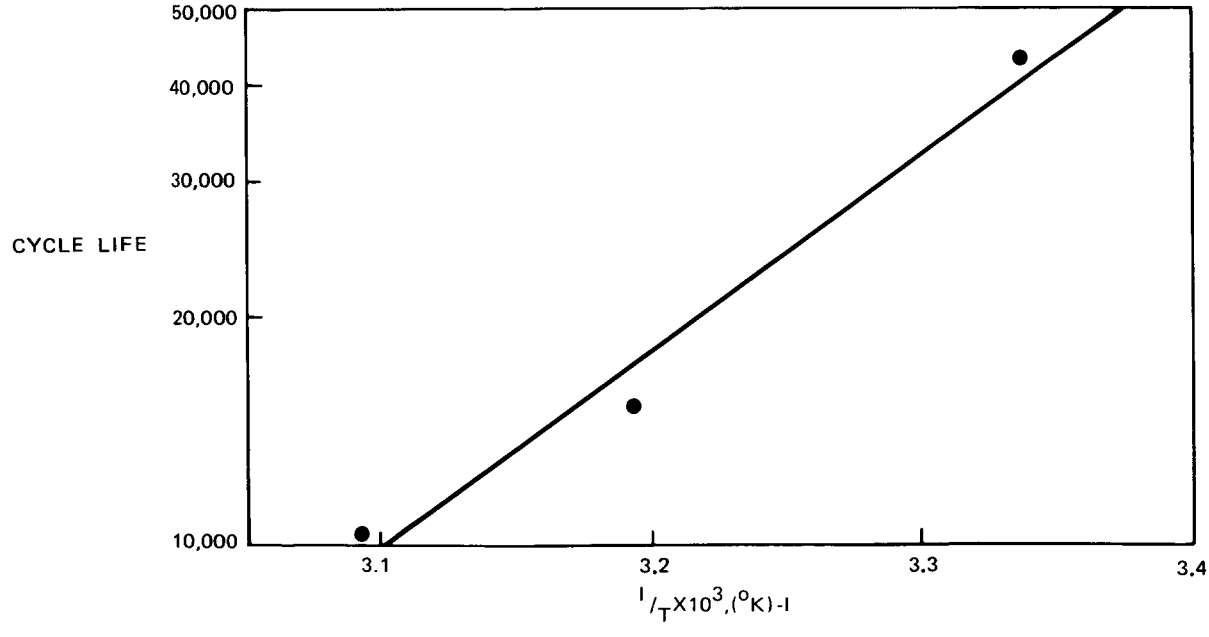

FIGURE 6. CYCLE LIFE OF Ni-Cd CELLS CONTAING Z-PS SEPARATORS AT 40% DOD VS 1/T

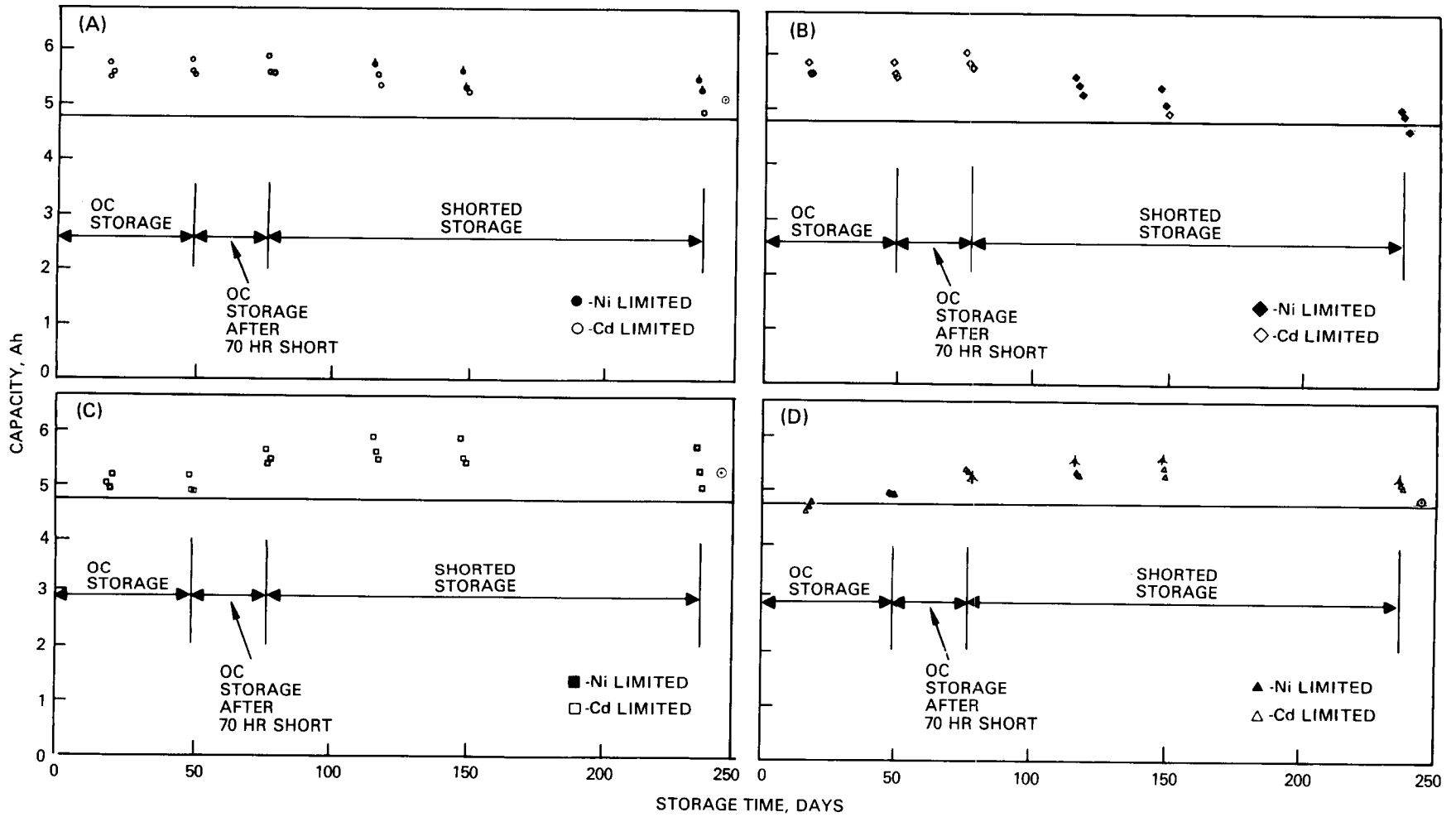

FIGURE 7. CAPACITY OF TEST CELLS VS STORAGE TIME AT VARIOUS STORAGE MODES. ALL CAPACITIES WERE MEASURED BY C/2 RATE DISCHARGE TO 1.0 V. A. A BOILER PLATE CELL CONTAINING ED NICKEL AND ED CADMIUM ELECTRODES WITHOUT THE ADDITIVE. B. SIMILAR CELL TO A WITH THE ADDITIVE. C. A BOILER PLATE CELL CONTAINING CD NICKEL AND ED CADMIUM ELECTRODES WITHOUT THE ADDITIVE. D. A BOILER PLATE CELL CONTAINING CD NICKEL AND CD CADMIUM ELECTRODES WITH THE ADDITIVE. FILLED SYMBOLS REPRESENT NICKEL ELECTRODE LIMITED CAPACITY AND OPEN CYMBOLS REPRESENT CADMIUM ELECTRODE LIMITED CAPACITY. THE LAST CAPACITY VALUE REPRESENTED BY A CIRCLE WITH A DOT INSIDE WAS MEASURED AFTER C/20 RATE CHARGE FOR 40 H.

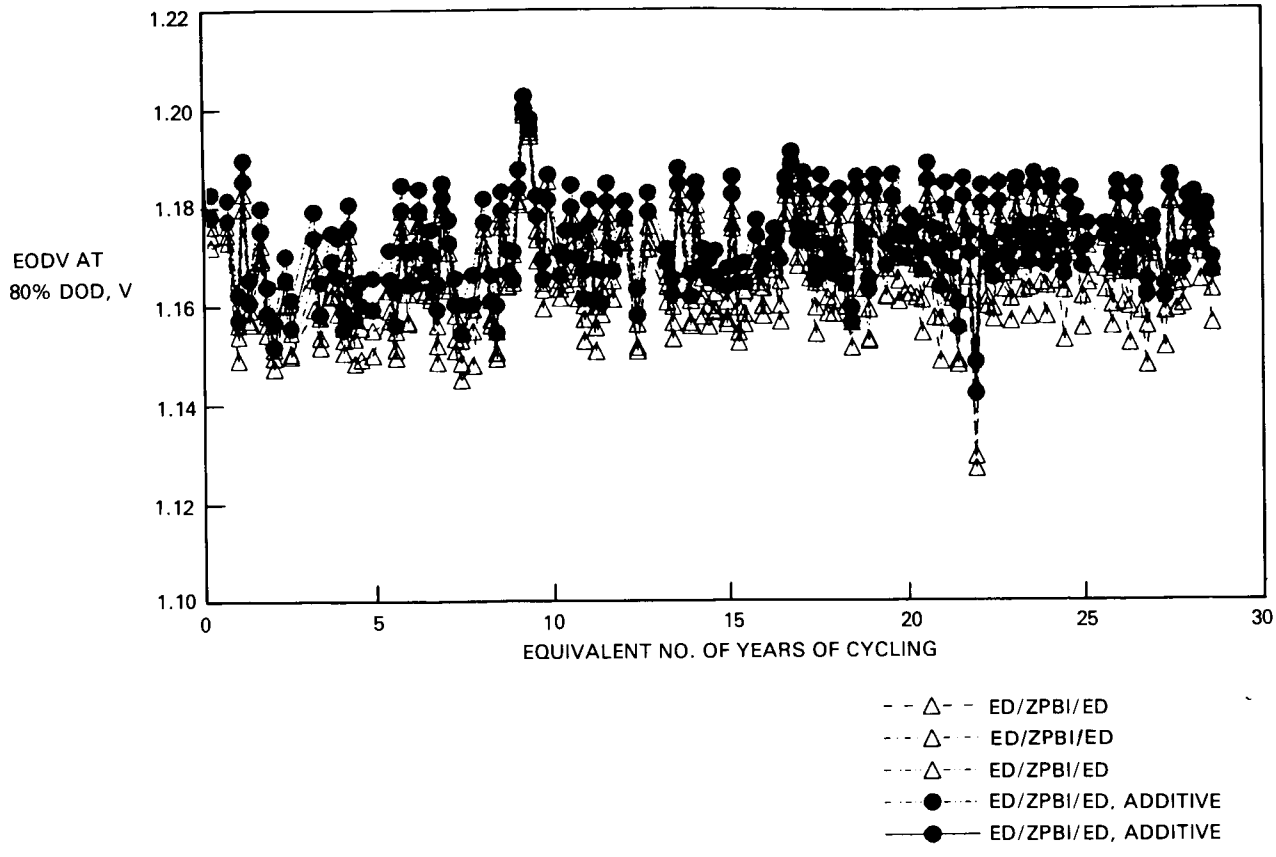

FIGURE 8. EODVs AT 80% DOD IN REGIME I VS CYCLE LIFE FOR THE ADVANCED Ni-Cd CELLS OF TWO DIFFERENT DESIGNS (FILLED CIRCLES AND OPEN TRIANGLES)

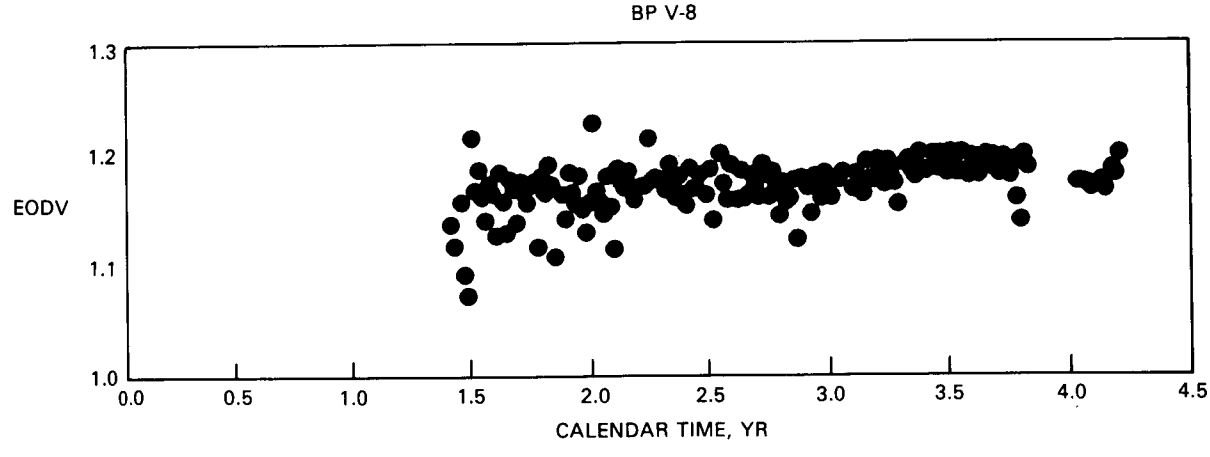

FIGURE 9. EODVs OF A TEST CELL WITH CD NICKEL AND CADMIUM ELECTRODES WITH THE ADDITIVE IN REGIME I VS CALENDAR TIME

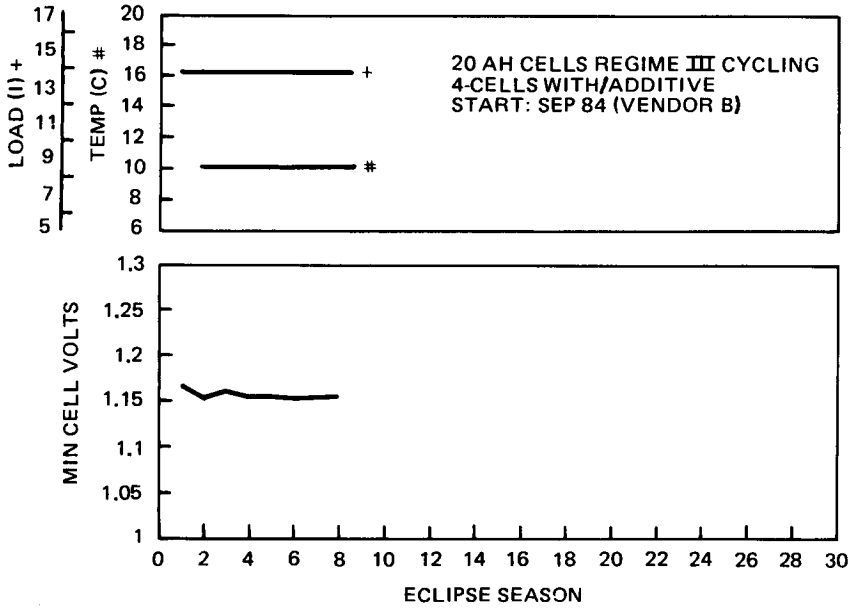

FIGURE 10A. ACCELERATED GEOCYCLE PERFORMANCE OF THIRD INTERATION PROTOFLIGHT CELLS

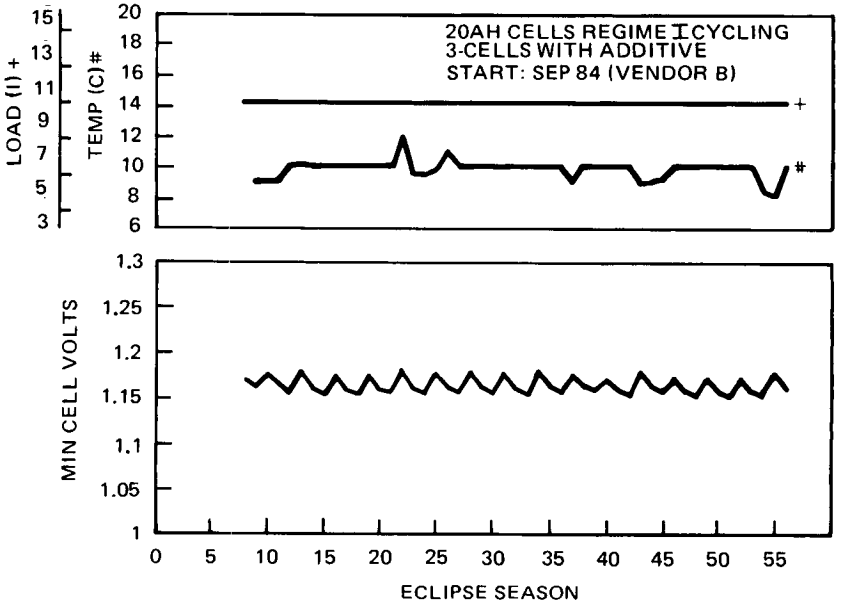

FIGURE 10B. ACCELERATED GEOCYCLE PERFORMANCE OF THIRD INTERATION PROTOFLIGHT CELLS

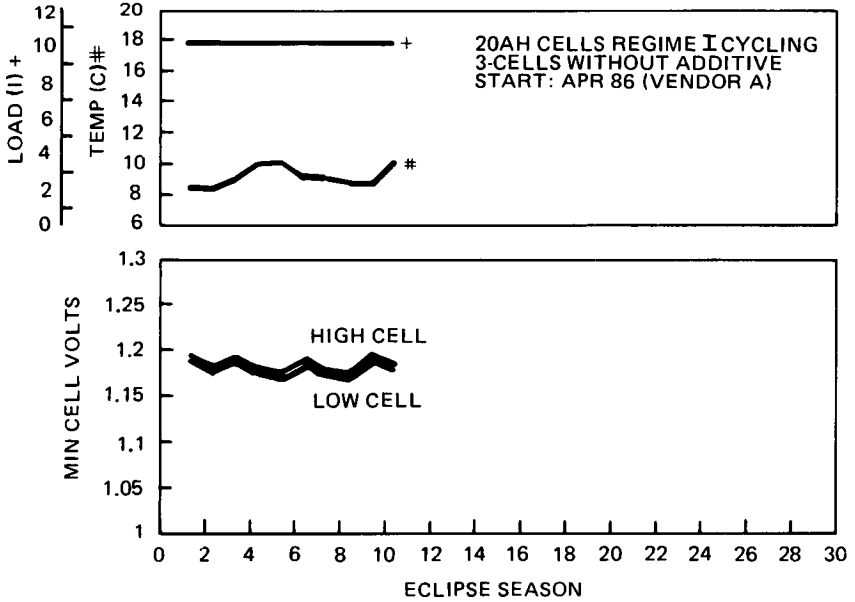

FIGURE 10C. ACCELERATED GEOCYCLE PERFORMANCE OF THIRD INTERATION PROTOFLIGHT CELLS

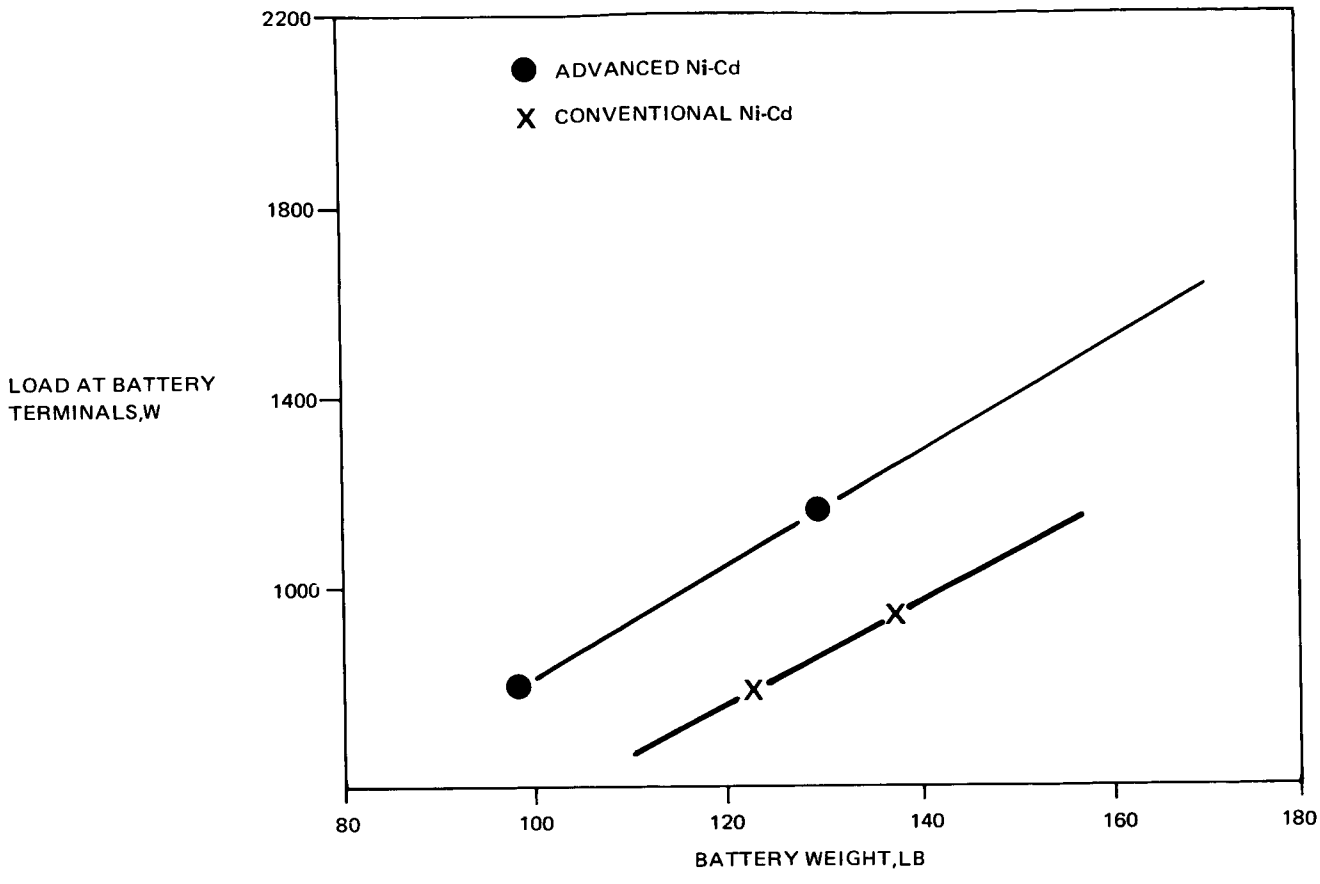

FIGURE 11. BATTERY WEIGHT VS SPACECRAFT POWER COMPARISON FOR ADVANCED AND CONVENTIONAL Ni-Cd