Utilization of Small Commercial Grade Nickel Cadmium (NiCd) Cells in Low Earth Orbit (LEO) Applications

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The Defense Advanced Research Projects Agency (DARPA) has sponsored the Advanced Space Technology Program (ASTP) to enhance the cost-effectiveness and responsiveness of military space systems. One of the major themes of this program is the development of highly capable small satellites, generally referred to as "LightSats," which can perform selected defense missions at relatively low cost. A key element of the programmatic approach is the utilization of commercial grade parts and practices where practical, as opposed to the much more conservative aerospace grade parts. ASTP has incorporated commercial grade batteries into its first generation LightSats; however, an attempt has been made to study the trade-offs and design considerations to optimally employ these batteries on small satellites.

For certain applications, particularly for small relatively inexpensive satellites, commercial grade cells may be a viable alternative to aerospace cells. Differences between aerospace and commercial grade cells range from physical construction and technology incorporated, to the level of quality control in manufacturing. These differences are reflected in both greater cost and increased lead time for the aerospace cells. Our research and experience suggest that certain manufacturing technologies are preferable when considering commercial cells for space applications. Once the cell type is chosen, candidate cells must be thoroughly screened to insure survival and acceptable performance in the space environment. To insure optimal performance, cells should be rigorously matched in electrical characteristics when forming batteries. Test procedures should be tailored to fit the application in order to yield the best performance in a specific physical, electrical, and operational environment. An acceptance test plan for screening and matching cells is discussed.

The present paper is the first in a series of reports which will document the approach, results, and lessons learned from ASTP's commercial battery studies.

INTRODUCTION

The Defense Advanced Research Projects Agency (DARPA) has initiated a number of space technology development efforts over the past several years. These multi-faceted and interrelated projects are organized under DARPA's Advanced Space Technology Program, or ASTP. The major thrust in DARPA's space efforts is the development of the key enabling technologies that will enhance the capabilities, performance, accessibility, and survivability of military space systems, while simultaneously minimizing their cost, size, weight and power consumption. One of the initiatives which ASTP has sponsored is an effort in small satellites, known as the LightSat Initiative, which is comprised of near-term demonstrations of "off-the-shelf" technology satellites for direct support to tactical forces, as well as advanced technology development efforts to achieve much greater military utility in the future.

There are a number of key cost and schedule reduction elements in DARPA's efforts to make LightSats affordable and responsive. Quite obviously, reducing the size and weight of a satellite so that it may be launched on a small, less expensive booster is an important term in the cost-reduction equation.

One of the important experiments which ASTP is performing is the utilization of commercial practices and commercial grade parts in military LightSats where practical, as opposed to the more conservative aerospace grade parts or MIL-STD components. The key to this programmatic approach for cost and schedule reduction is that the increase in risk of premature system failure or degradation must be consistent with the overall mission cost, mission level of criticality and required lifetime. Prudent use of commercial grade parts can drastically reduce satellite cost and accelerate development, within acceptable levels of increased risk.

Other cost reduction strategies include modular designs, leveraging off learning curve advantages, and economies of scale in cases where operational requirements called for LightSats to be "mass" produced to achieve proliferated deployments. Use of concurrent engineering could also be a cost saver, and incorporating Total Quality Management (TQM) will help reduce costs by continually emphasizing product and process improvement at all levels.

As part of its study of streamlined development approaches for small satellites, the ASTP has incorporated commercial grade batteries into its first generation LightSats. (Throughout this paper, the term cell will refer to a basic electrochemical device capable of storing electrical energy. A battery consists of one or more cells [1].) An attempt has been made to study the trade-offs and design considerations to optimally employ these batteries on small satellites. The present paper is the first in a series of reports which will document the approach, results, and lessons learned from the ASTP commercial battery studies.

This paper will focus on the commercial batteries currently flying in the first two DARPA LightSats. Commercial grade flight batteries for a future DARPA mission are currently being evaluated and tested, and will be discussed in a future paper.

The batteries built for the first mission were composed of 15 cells wired in series, with redundant stacks in each of the two satellites. Although other size commercial cells are built with similar technology, the procedures and results stated herein are specifically reported for Nickel Cadmium (NiCd) 4 amp-hour "D" cells.

It should be noted that the procedures contained in this paper are not the only method to screen and match commercial grade cells. The Amateur Satellite Company (AMSAT) has experience in this area, and they follow a special (proprietary) procedure. The procedures contained in this paper are also specifically tailored for the intended mission and environmental conditions:

- Orbit altitude: 400 nautical miles
- Orbit inclination: 90°
- Temperature limits: -10°C to +40°C
- Design maximum depth of discharge (DOD): 10%

If the mission differs from that stated above, the battery screening and matching procedures would need to be examined for validity, and modified in a fashion consistent with the particular conditions of a given mission.

AEROSPACE/COMMERCIAL CELL DIFFERENCES

The manufacturing differences between aerospace and commercial cells are substantial. In addition to the basic design of the cell, the differences also include the quality of screening and testing. It should be noted that the differences summarized for illustration in this section are those indicated by one company which manufactures both commercial and aerospace cells [2]. These differences may or may not be valid for other manufacturers. See Figure 1 for a summary table of the manufacturer's differences between aerospace and commercial grade cells.

Configuration

Physically, the commercial cell bears no resemblance to the aerospace cell. The commercial cells are essentially a set of long parallel plates rolled concentrically and inserted into a cylindrical case. The aerospace cells include several sets of rectangular plates stacked side by side. The final package is a rectangular box, the dimensions of which are determined by the capacity.

Closure

The commercial cell uses a crimp seal with a plastic layer. Over time and after numerous thermal cycles, the seal will degrade, allowing leaking and the loss of electrolyte. The aerospace cells use a metal to ceramic configuration which results in a true hermetic seal with little or no degradation over time or thermal cycles.

Termination

Different methods are used to terminate the cell at the positive and negative electrodes. Some commercial cells use a pressure contact or crimp. The aerospace cells and certain commercial cells contain welded contacts.

Venting

The commercial cells have a pressure relief valve which vents the cell when internal cell pressure exceeds a certain value. The vents in most commercial cells are designed to be resealable; however, it is uncertain that the vent would function as designed in the vacuum of space. The aerospace cells use no vent. If excess pressure builds inside the cell, the walls will bulge if not constrained, but will not leak. The cell walls are designed to be strong enough to withstand this pressure, minimizing the burst potential.

Plate Stress Test

As part of the quality screening done on aerospace cells, the individual plates undergo a stress test. This test exercises the plate with high rates of charge and discharge. Plates that show evidence of flaking or do not meet established standards are discarded. No such test is performed with the commercial cells.

Electro-Capacity Test

The Electro-Capacity Test (ECT) is performed on the aerospace plates to verify specified capacity levels and to verify the Negative/Positive (N/P) ratio. The test also acts in the cleaning process to remove residual nitrates and carbonates. No such test is performed on the commercial cells.

Plate Inspection

Each plate destined for an aerospace cell undergoes rigorous individual inspection for imperfections that may lead to premature failures during use. This procedure includes close visual inspection for edge burrs and sorting the plates by weight to attain consistency between cells. Burrs are a concern because the plate separation is only .008-.010 inches. As the separator material degrades over time and cycles, burrs can lead to a shorted cell. A quick visual inspection is done on the commercial cells.

Chemical Analysis

The aerospace cells undergo a chemical analysis to verify precharge setting, overcharge negative protection, and to check for impurities that may lead to a premature chemical breakdown in the electrolyte. The commercial cells undergo no such test.

ITEM	COMMERCIAL NiCd	AEROSPACE NiCd
CONFIGURATION	Wound, Cylindrical Cells	Parallel Plate, Rectangular Cells
CAPACITY	0.5 - 6.0 Amp-Hours	2.0 - 50.0 Amp-Hours
CLOSURE	Crimped Seal w/ Plastic Layer	Ceramic to Metal (True Hermetic Seal)
TERMINATION	Pressure Contact or Welded	Welded
MATERIAL QUALITY CONTROL	Minimal	Extensive
CHEMICAL ANALYSIS	None	Plate and System Level
ELECTROLYTE FILL	Fixed Volume of Electrolyte for Each Cell	Adjusted to Establish Cell Performance
VENTING	Pressure Relief Valve - Vents Hydrogen and Oxygen	None
TESTING	30 - 60 Minutes	Extensive 3-6 Months

Figure 1. Summary of manufacturing differences between commercial grade and aerospace cells.

Current/Voltage/Pressure Testing

The aerospace cells undergo extensive cycling tests at various temperatures and charge/discharge rates to verify characteristics and performance. Current, voltage and pressure measurements are recorded. Cells which do not perform to specifications are readjusted, and if still out of spec, a thorough analysis is made with corrective action. This extensive testing takes 4-12 weeks. The commercial cells undergo a quick-screening voltage and current test that lasts from 30-60 minutes.

Pre-Acceptance Test Plan (Pre-ATP)

Aerospace cells undergo 3 weeks of pre-acceptance tests. The normal procedure includes adjusting the amount of electrolyte, performing extended overcharge tests to determine the stability of the cell, and electrical cycling. Commercial cells undergo no such testing; a fixed amount of electrolyte is added to each cell.

Acceptance Test Plan (ATP)

The aerospace cells undergo 4-12 weeks of customer specified acceptance tests. The required tests vary between orders, but typical testing includes:

- cycling at 3 or 4 temperatures
- extended overcharge testing
- high rate discharge tests
- impedance test
- open circuit stand

Commercial cells are shipped without these tests.

CRITERIA FOR CELL SELECTION (Commercial Grade Vs. Aerospace Cells)

A commercial NiCd may be the cell of choice based on programmatic and system design considerations. The mission requirements for performance and lifetime and the acceptable risk will be the overriding factors in deciding whether a commercial grade cell may be appropriate for the application. Additional factors are program schedule, cost, and other system design considerations. See Figure 2 for a summary of differences between aerospace and commercial grade cells over these parameters.

Failure Mode

A consideration in choosing the cell is assessing the risk associated with most likely failure modes. The most likely failure mode of an aerospace cell is a short circuit caused by degradation of separator material which allows contact of the plates [2]. In a series battery, a short circuited cell will result in reduced performance (lower voltage output) from the battery. The most likely failure mode of a commercial grade cell is an open circuit [2]. This condition could be caused by the degradation of the crimp seal allowing the electrolyte to evaporate or by internal pressure causing venting of the cell. An open circuit in a series cell will cause failure of the entire battery.

Expected On-Orbit Lifetime

The lifetime of aerospace cells is a minimum of 3 to 4 years for a satellite in low earth orbit and operating at a 25% DOD [2]. Commercial cells have very little available data to base lifetime estimates on under these conditions. As reported in the AMSAT Journal, commercial cells have existed in space applications for periods in excess of eight years. (It should be noted that this data is not specific to the D size cells, matching procedure, or stated mission contained herein.) Screening and matching commercial cells greatly increases the probability that the cells will achieve long life on orbit. The performance of the cells flown in the DARPA missions will be tracked in order to provide data points regarding the expected lifetime of commercial grade cells.

Lead Time

The lead time associated with parts can make one option preferable to another in a program that places emphasis on fast-paced design, development and implementation. The lead time associated with aerospace cells is typically 45-50 weeks. On a fast paced technology program, that lead time can approach the length of the development effort. (It is possible that an aerospace cell manufacturer would consider a reduced lead time if some test procedures were shortened or eliminated. Careful consideration would be required to devise an abbreviated test regime. At this time, this approach has not yet been thoroughly explored.) The lead time associated with a commercial grade cell is significantly less than its aerospace counterpart. The time to procure cells should not exceed 2 weeks (based on the availability of cells) and the procedure for screening and matching employed in this study lasted 6 weeks. The total lead time for screened and matched batteries utilizing commercial cells is therefore approximately 8 weeks. This reflects a 9-10 month time savings that can be achieved through the use of commercial grade cells.

Cost

Cost is frequently considered as a driver in the choice of cell. As one might expect, the added quality screening and testing of the aerospace cells significantly increases the cost over the off-the-shelf commercial cells. Aerospace cells in the 4-12 amp-hour range cost between $2,500 and $3,500 per cell. The cost of commercial off-the-shelf cells is between $5 and $15 per cell. However, when the cost of screening and matching the commercial cell is added, the cost differential is significantly reduced. The direct material cost of the commercial grade cells included in our study is about $7.50-$9.80 per cell. The total cost of a commercial grade cell after the screening and matching procedure is estimated to be approximately $1300 per cell (based on a lot of 120 cells) for the first lot and $800 per cell for every additional lot of the same size. (The setup cost for implementing an automated charge/discharge monitoring system is incurred only once.) It should be noted that these costs are calculated based on experimental work performed in a laboratory environment and do not reflect benefits from a learning curve. Cost is also based on production of small quantities and does not incorporate economies of scale. When these figures are compared with the $2,500-$3,500 cost for an aerospace cell, commercial grade cells have a distinct cost advantage. However, 120 cells are processed to yield 60 flight cells; the rest are discarded. When the cell cost is calculated on a per-flight-cell basis, this doubles the cost to $2600 per-flight-cell initially and $1600 per-flight-cell thereafter. Additionally since one string of aerospace cells is required for reliable operation while redundancy is employed in the application of commercial grade cells, there is relatively little cost savings from the commercial grade cells. Cost of the cell should be commensurate with total launch cost (including the vehicle and range support) and the mission risk.

Physical Considerations

Physical aspects of the cell may be a design consideration in the choice of cell. The commercial grade cells differ from aerospace cells in shape, weight, and volume.

ATTRIBUTE	COMMERCIAL NiCd	AEROSPACE NiCd
FAILURE MODE	Open Circuit	Short Circuit
LIFETIME	No Data Available/Under Test Designed for Mission Duration Of 3 Years	3 Years (Minimum) in LEO
COST	\$7-\$10 per cell (off-the-shelf) \$1,600-\$2,600 per-flight-cell	\$2,500-\$3,500 per cell
LEAD TIME	8 Weeks	45-50 Weeks
SIZE	2.36 in. length by 1.26 in. diameter	2.5 (3 total) in. height by 2.1 in. width by 0.8 in. thickness
WEIGHT	132-157 grams/cell	212 grams/cell
VOLUME	3 in.^{3}/cell	5 in.^{3}/cell

Figure 2. Summary of Commercial Grade and Aerospace Cell Attributes.

Size: The cylindrical commercial grade cells average 2.36 inches in length and 1.27 inches in diameter. An equivalent capacity rectangular shaped aerospace cell has average dimensions of approximately 2.5 in. height (3 in. total height) x 2.1 in. width x 0.8 in. thickness.

Weight: The weight of a commercial grade cell ranges from 132-157 grams depending on the manufacturer. The aerospace cell is 43-70% heavier per cell at an average weight of approximately 225 grams. (Actual cell dimensions and weights will vary.) However, as a risk mitigation technique, redundancy has been employed in the utilization of commercial grade cells aboard the DARPA satellites. This need for redundancy cancels any potential weight advantage that could be provided by commercial grade cells. In fact, under these conditions, the aerospace cells actually afford a weight savings of 17-40%.

Volume: Volume occupied by the battery may or may not be a consideration in choosing a cell. The volume of a commercial grade D cell is roughly 3 in.^{3} as opposed to the approximately 5 in.^{3} occupied by an aerospace cell of the above dimensions. Greater efficiency can be achieved in packing a prismatic shape than a cylinder; the volume occupied by the battery, however, will depend on the design of the battery holder and the configuration of the cells as they are arranged in the stack. With the need for redundant stacks when using commercial grade cells, it appears that a battery of aerospace cells would actually occupy less volume.

COMMERCIAL CELL TECHNOLOGIES

Once the choice has been made to utilize a commercial grade NiCd for a space application, there are many options available on the market. Commercial grade cell technology has been investigated in support of this effort. The following section discusses lessons learned about the utilization of differing commercial grade cell technologies in the specified space application.

There is no fixed criterion for the selection of commercial NiCd cells. The intended application is the determining factor. If schedule is a driving force, the availability of necessary quantities of cells will also influence the selection. The cost of the commercial cell is not a consideration, as the cost of cell processing outweighs the material cost by more than 100 to 1.

Beyond mechanical criteria (formfactor, ruggedness, weight, length, diameter, etc.) there are at least three facets of commercial NiCd technology which enter into the selection decision. These are plate type, electrode termination, and separator material.

Plate Type

Pasted and sintered are the prevailing commercial plate technologies. A pasted plate has a film of the electrode material smeared on a thin substrate. A sintered plate is similar to a pasted plate except that it has undergone the additional manufacturing step of sintering (exposure to extreme heat). This sintered electrode is more uniform and porous than the pasted electrode. Since the plate actually supports the electrode active material, the availability of current carrying ions is increased due to the larger surface area associated with higher material porosity [1]. Combinations of these plate types are used within a cell for the positive and negative electrodes. The most common combination commercially available is sintered / pasted (positive and negative electrodes, respectively). The divergence from the more ideal sintered / sintered case is viewed as typical of commercial manufacturing where constant cost-to-performance trade-offs are necessary to survive in a competitive market. The sintered / sintered configuration is still commercially available and, based on existing information on NiCd technology, is the plate technology of choice. This is not to say that other plate configurations would not prove capable of performing in space, but the sintered / sintered cell will most probably provide superior performance.

Electrode Termination

Electrode termination can be either pressed-fit or welded. The welded configuration provides better contact and less electrical resistance. Recent manufacturing cost reduction rationales have produced the newer pressed-fit method of terminating electrodes to the casing and cap (negative and positive case terminations respectively). Pressed-fit electrode terminations contribute up to an order of magnitude increase to cell impedance over the welded method. Plate type, electrode termination and separator material all contribute to cell internal impedance, but of these the major contributor is electrode termination. Low internal impedance is a desirable cell characteristic as it enables high-rate discharges, and constant discharge voltage [1]. Additionally, cells with lower internal impedance will have a tendency to display lower internal cell pressure during overcharge. This is important in the space environment due to the risk of failure resulting from venting.

Separator Material

Nylon and polypropylene are the dominant commercial NiCd cell separator materials. The separator is the dielectric insulator between the positive and negative electrodes which also retains some of the electrolyte. In a NiCd cell, the electrolyte is potassium hydroxide (KOH) in an aqueous solution [3]. The nylon separator is most commonly used in commercial off-the-shelf cells, and is designed for ambient operating temperatures between 10° and 40° C. The polypropylene separator is intended for applications up to 60° C. Nylon material is preferable for a space application when the predicted on-orbit thermal range is lower, because the nylon material has better wetting properties than the polypropylene. It also provides lower internal resistance and better capacity stability over the life of the cell [3]. If the cell must withstand higher temperatures over extended periods of time, then the provide better on-orbit performance than the nylon which will degrade over time and thermal cycles.

Since the evaluation of the applicability of commercial NiCd cells to aerospace environments is still in its infancy, it is prudent to use as much of existing NiCd technology as possible. Little, if any, commercial data is available on the use of commercial cells in space. The volumes of NASA and aerospace industry data on NiCd cells are predominantly of the older, more mature sintered and welded construction; however, the application should ultimately drive the selection.

PROCEDURE FOR SCREENING AND MATCHING COMMERCIAL GRADE NiCd CELLS FOR USE IN LIGHTSATS

Once the technology of commercial grade cell is chosen, cells should be subjected to a rigorous screening and matching procedure to insure that the optimum performance and lifetime is achieved from the batteries. Screening and matching procedures should be initiated with two to three times the amount of cells needed for flight to insure that a sufficient amount of cells pass the screening to afford the construction of tightly matched batteries. An acceptance test plan has been carried out which identifies cells which would not meet the vibration requirements and which could leak in the vacuum of space [4]. The test plan is designed to ensure that the accepted commercial grade NiCd cells are adequately sealed, do not display characteristics that could result in venting, and possess sufficient overcharge protection. Implementation of this plan also yields data which is used to determine the cell characteristics needed to construct matched batteries.

Deviations from the baseline test procedure were sometimes made during test when problems arose or schedule demanded expedition. These deviations and the rationale for making them are explained in the Discussion of Preliminary Findings section. The Cell Stabilization step in the listed procedure was deleted in actual practice for expediency in processing the cells. The rationale for the deletion of this step is that, although it is desirable to begin the screening and matching procedures with stabilized cell, the cells should become fully stabilized *during* the processing. The abbreviated test plan implemented in this study, which is approximately 6 weeks in duration, incorporates the minimum essential activities consistent with performance and lifetime expectations. The tailored procedures developed are the result of a cooperative effort involving the Aerospace Corporation, Tracor Technology Resources, Inc., Defense Systems Inc., DARPA, and Space Applications Corporation; they are based upon research performed at the Aerospace Corporation. Figure 3 summarizes the major steps of the acceptance test plan, and highlights the main objective of each step.

STEP	PURPOSE
Vibration Screening	To detect internal shorts.
Initial Charging	To begin electrochemically exercising the cell.
* Cell Stabilization	To fully form the positive and negative electrodes and distribute the electrolyte through the cell.
Room Temperature Capacity and Overcharge Determination	To determine if the cell has adequate overcharge protection and to provide cell matching data.
Charge Retention	To detect excessive cell self-discharge rates which would indicate internal short circuits or impurities.
0° Capacity and Overcharge Determination	To determine if the cell has adequate overcharge protection at low temperature and to provide cell matching data.
Vacuum Leak Test	To determine if the cell has adequate overcharge protection and is capable of surviving in the vacuum of space.
Impedance and Overcharge Determination	To provide cell matching data.
Final Leak Test	To determine if any cells have failed environmentally by either leaking or venting.
Cell Matching	To identify cells with similar electrical characteristics in order to be able to construct batteries that will provide the longest failure free performance on orbit.

* This step was deleted from the practiced test procedure with the understanding that stabilization will occur during the rest of the cycling.

Figure 3. Steps for Screening and Matching Commercial Grade "D" Size NiCd Cells for use in LightSats.

DISCUSSION OF PRELIMINARY FINDINGS

This section will highlight some of the lessons learned in developing and implementing the procedures for cell selection, screening, and matching. Strengths and weaknesses observed in the different cell manufacturing technologies will be noted. The following convention will be used to describe cell technology:

- Test Item Positive Electrode / Negative Electrode, Positive Closure / Negative Closure (Separator Material)

The following types of cells have been included in this study:

- Type A Pasted / Pasted, Welded / Pressed-Fit (Polypropylene)
- Type B Pasted / Pasted, Welded / Pressed-Fit (Nylon)
- Type C Sintered / Pasted, Welded / Pressed-Fit (Nylon)

Types A and B Testing

The original choice of cell for the DARPA mission was Type A. The polypropylene separator is rated for performance in an extended high temperature environment (as it proves more durable at higher temperature) as opposed to the nylon separator (which provides greater wetting) used for standard temperature environments. Based on a refined thermal analysis, it was later decided to switch to the nylon separator because of lower predicted temperatures on the spacecraft. It was further decided that the redundant battery stacks offered an excellent low risk opportunity to run a space experiment using one stack each of the Type A and Type B cells on one of the satellites. Cell processing began with 90 Type B and 30 Type A cells in order to produce the proper mixture for flight (3 stacks of 15 Type B cells and 1 stack of 15 Type A cells). 120 cells (two times the amount of necessary flight cells) were cycled.

Based on cell behavior during both 0° C Capacity and Overcharge Determination and Vacuum Leak Testing, the Pasted / Pasted, Welded / Pressed-Fit cells were judged to be inadequate for this particular space application. These cells were found to exhibit behavior indicative of high internal impedance, to the degree that the cell voltage could reach limits where gas generation is possible in the cell. Due to the risk of cell venting leading to cell (and battery) failure on orbit, the cells were removed from test. (These results were independent of separator material.) Testing resumed with a different cell technology at the earliest possible opportunity.

Type C Testing

Type C cells were available in the necessary quantity and 120 cells were procured to begin cell testing immediately. A cell with this type of construction can be expected to possess a greater amount of overcharge protection than a cell with both positive and negative pasted electrodes. In the interest of time, Charge Retention was taken out of sequence and performed at the end. (By necessity, the test procedure was reduced to the critical elements; if a step was to be deleted, Charge Retention was judged to be the least critical.)

The cells began to display very high voltages (based on the predetermined maximum voltage limit) during 0° C Capacity and Overcharge Determination. Because the cells were not stabilized prior to the testing and based on the voltage characteristics listed by the manufacturer for these cells (which indicated a higher nominal voltage than that published for Type A and B cells), the maximum acceptable voltage was recalculated and maximum voltage limit increased accordingly. The cells were monitored carefully; none of the cells vented or leaked. The maximum voltage reached by the cells began to decrease with each successive cycle and eventually stabilized. Additionally, the shape of the charge curve validated that the cells contained adequate overcharge protection at low temperature. During Vacuum Leak Testing, these cells enjoyed a high success rate (based on the modified failure criteria).

With respect to matching, since the satellites use a temperature compensated voltage limited (VT) charge control and the DOD for the commercial grade NiCd cells is less than 10%, it is important to match the cells in the series battery with regard to the shape and magnitude of the current voltage charge curve. This matching greatly reduces the chance of overcharging and venting a "weak" cell in the battery, particularly below 0° C. Four battery stacks were matched and constructed for installation in the initial DARPA satellites.

CONCLUSIONS

This paper has reviewed the methodology which was developed to select, screen, and match commercial grade NiCd cells for application as flight batteries aboard DARPA's initial LightSats.

The major advantage of using commercial grade cells in a space application is the reduction in lead time. Utilization of commercial grade cells can save 8-10 months on a program where the emphasis is placed on fast design and development. Cost advantages will be marginal at best if these cells are to be appropriately screened, tested, and matched to reduce risk to an acceptable level for space missions.

The first set of DARPA satellites with commercial grade batteries have been on orbit for three months, and the power subsystems are performing nominally. During the life of the satellites, the performance of the commercial grade batteries on these satellites will be evaluated, and the results and lessons learned will continue to be reported in future papers. Continued work and documentation of prudent cost saving strategies - in power subsystems as well as in other subsystems - will help to realize the promise of making large and small satellites more cost-effective for defense, commercial, and scientific space missions.

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