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Handbook for Handling and Storage of Nickel-Cadmium Batteries: Lessons Learned

Floyd E. Ford
Gopalakrishna M. Rao
Thomas Y. Yi

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Floyd E. Ford
Swales & Associates
Beltsville, Maryland

Gopalakrishna M. Rao
Thomas Y. Yi
Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics and
Space Administration

Scientific and Technical
Information Branch

PREFACE

During the past decade the need for ground handling and storage requirements for nickel-cadmium (NiCd) flight batteries has been recognized. This recognition has been evident from the development of formal project documentation of handling and storage plans for several Goddard Space Flight Center (GSFC) projects: International Ultra-violet Explorer (IUE), Solar Maxiumum Mission (SMM), Landsat (Land Satellite), Earth Resource Budget Satellite (ERBS), Cosmic Background Explorer (COBE), Gamma Ray Observatory (GRO), Tracking and Data Relay Satellite System (TDRSS), etc. These plans focused on "what" should be done to minimize degradation of flight batteries during preflight activities but provided no insight into "why" the various procedures and restrictions were necessary. Additionally, the degradation modes being circumvented or minimized were not well documented or well understood by the personnel outside the battery community.

In recognition of these factors, one of the tasks in the Secondary Battery Technology Program, under the auspices of the NASA Aerospace Battery Steering Committee and funded by Code Q, NASA Headquarters, was to prepare a NASA document which provided uniform guidelines for the handling and storage of conventional[1] NiCd flight batteries. A further objective of this document is to provide the reader with an understanding of the rationale for each guideline along with data supporting the rationale. Finally, in the course of developing the handbook, the design and evolution history of the aerospace NiCd cell for GSFC Flight Programs was a natural by-product of this effort. Consequently, the appendix of this document provides "lessons learned" as experienced over 30 years experience in the design, testing, and flight applications of aerospace NiCd batteries.

The authors would like to acknowledge the invaluable support and assistance of the members of the aerospace battery community, especially the consultation with Messrs. George Morrow, David Baer, and Dr. Gerald Halpert who provided unpublished NiCd battery test data and donated their time and expertise to its interpretation. We wish to also acknowledge the members of the NASA Aerospace Battery Steering Committee, who provided an excellent review and critique of the document. Thanks, also, to Ralph Sullivan and Harry Culver for their review of the final draft.

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[1] Throughout this text, the term NiCd refers to conventional NiCd cells that have been used since the beginning of the space program. When reference is made to the more recently developed Super or Advanced NiCd technology, it will be so designated.

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LIST OF ACRONYMS AND ABBREVIATIONS

Ah	Ampere Hour
APL	Applied Physics Laboratory
ATS	Applications Technology Satellite
C	Rated capacity (nameplate capacity)
°C	degree Centigrade
CMC	Carboxy-Methyl-Cellulose
COBE	Cosmic Background Explorer
dm	decimeter
DOD	Depth of discharge
DPA	Destructive Physical Analysis
EOC	End of charge
EOD	End of discharge
EPI	Eagle Picher Industries
ERBS	Earth Resource Budget Satellite
gm	grams
GE	General Electric
GEO	Geosynchronous-Earth orbit
GEP	Gates Energy Products
GIDEP	Government Industry Data Exchange Program
GOES	Geostationary Operational Environment Satellite
GRO	Gamma Ray Observatory
GSFC	Goddard Space Flight Center
HCl	Hydrochloric acid
HCMM	Heat Capacity Mapping Mission
INCO	International Nickel Company
I&T	Integration and Test
IUE	International Ultraviolet Explorer
KOH	Potassium Hydroxide
Landsat	Land Satellite
LEO	Low-Earth orbit
LOFTI	Low-Frequency Trans-Ionospheric Satellite
MCD	Manufacturing Control Document
ml	Maximum loft, describing the surface condition of the Pellon 2505 separator material
MMS	Multimission Modular Spacecraft
MPS	Modular Power System
NASA	National Aeronautics and Space Administration
NHB	NASA Handbook
NiCd	Nickel-Cadmium
NOAA	National Oceanic and Atmospheric Administration
NSWC	Naval Surface Warfare Center, (Crane, Indiana)
NWSC	Naval Weapons Support Center, (Crane, Indiana)
OAO	Orbiting Astronomical Observatory
OSO	Orbiting Solar Observatory
pH	A measure of acidity
PQ	General Electric's process of adding cadmium to the positive plate
psi	Pounds per square inch
psia	Pounds per square inch absolute
psig	Pounds per square inch gauge
QA	Quality assurance
RTOP	Research and Technology Objective and Plan
SAFT	Societe Accumulateur Fixe Traction
SAGE	Stratospheric Aerosol and Gas Experiment

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

SAS	Small Astronomy Satellite
Seasat	Sea Satellite
SMM	Solar Maximum Mission
SMS	Small Meteorological Satellite
STP	Standard Temperature and Pressure
T	temperature
t	time
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TIROS	Television Infrared Observing Satellite
V/T	Temperature-compensated voltage limit for charge control
Wh	Watt hour

INTRODUCTION

The handling and storage guidelines presented herein have evolved from nearly three decades of experience with aerospace sealed nickel-cadmium (NiCd) cells and batteries by power system and battery subsystem engineers who have been involved with programs from conceptual design to mission complete testing. The accepted practice during the early days of space flight was to install flight batteries during spacecraft integration where they would remain throughout the life of the satellite. It was not unusual for flight batteries to be in place for 18 months prior to launch. The early spacecraft designs had no provisions for monitoring battery parameters during ground testing except those available through telemetry when the spacecraft was powered up. Today's accepted practice of "reconditioning" batteries within a few days of launch was not known, nor were there any design provisions for accomplishing the reconditioning. The earliest documented effects of NiCd battery deterioration from extended exposure to spacecraft integration and test (I&T) activity was in the late 1960s on the second Orbiting Astronautical Observatory (OAO-A2) spacecraft. During spacecraft thermal vacuum test, the voltage of all three OAO batteries exceeded the specification limit during low temperature (0°C) testing. Subsequent analysis revealed manufacturing problems which compounded the results of the batteries' exposure to extended periods of spacecraft integration. It was from that experience that members of the aerospace battery community became aware of the need for strict NiCd cell-manufacturing control specifications and flight battery handling and storage requirements.

This handbook is concerned with 'conventional' NiCd batteries and cells fabricated with nylon separators and chemically impregnated plates. Batteries of this type have been manufactured since the early 1960s. Although they are still in use today, there were significant changes in the NiCd cell-manufacturing processes and in their subsequent performance in the late 1980s. These changes and their causes are documented in this handbook. However, most of the performance data in this handbook are applicable to cells made prior to this transition, those used in the first 25 years of the U.S. space program. This performance may <u>not</u> be obtained from conventional NiCd cells of recent manufacture (those made since the mid-1980s). Also, the handbook does <u>not</u> address newer technology cells such as the Hughes Super[2] NiCd or its 'Advanced' derivatives.

This handbook provides guidelines for the handling and storage of NiCd flight batteries. The intent is to establish uniform NASA-wide guidelines that all flight programs can use as a basis for developing project-unique handling and storage procedures. It should serve as a guide for project managers and design engineers during the early phase of spacecraft design to ensure that appropriate design features are incorporated into the spacecraft to allow for the implementation of prudent handling

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[2] Trademark of Hughes Aircraft Company.

and storage procedures for NiCd flight batteries. In the latter phase of the satellite manufacturing, including integration and testing (I&T), the I&T launch personnel can consult the handbook for proper handling of the NiCd batteries.

The guidelines are not requirements, but recommendations based on many years of experience with ground and in-flight handling of batteries. The overall goal is to minimize the deterioration and irreversible effects of improper handling of NiCd flight batteries on flight performance. A secondary goal is to provide the reader with an understanding, in nonanalytical terms, of the degradation mechanisms of NiCd cells and how these mechanisms are effected by improper ground handling of flight hardware.

"A NICKEL-CADMIUM CELL PRIMER" section of this document provides the reader with a brief introduction to NiCd cells. The effects of the environment on NiCd batteries is discussed in the "THE ENVIRONMENT AND NICKEL-CADMIUM BATTERIES SECTION" section, and the "BATTERY HANDLING AND STORAGE GUIDELINES" section contains 12 guidelines for battery handling and storage with supporting rationale for each guideline. The "APPENDIX" of this document provides a synopsis of NiCd cell design and evolution over 30 years of space flight on Goddard Space Flight Center (GSFC) satellites, along with a chronological review of key events that influenced the design of NiCd cells being flown today. A comprehensive treatment of hermetically sealed-cell NiCd theory and battery application data is provided in Ref. 1.

A NICKEL-CADMIUM CELL PRIMER

The basic components of a NiCd cell are the positive plates, the negative plates, separator, and electrolyte. The majority of aerospace cells flown on U.S. satellites have been made using the Societe Accumulateur Fixe Traction (SAFT) process. The plate fabrication process starts with a roll (spiral) of perforated nickel-plated steel sheet that serves as the current collector (also called the substrate). The steel sheet is unwound and passed through a wet nickel slurry and sintered in a high-temperature furnace to produce a high-porosity (>80%) nickel plaque. Several spirals are stacked on a "post" and placed in a tank in which the high-porosity plaque is chemically impregnated with nickel nitrate to form the positive plates and with cadmium nitrate to form the negative plates. Impregnation is done with a vacuum process and usually requires several cycles to obtain the desired loading levels in the plaques. The amount of loading (material pickup) is determined by weight increase, which is usually specified in units of grams per square decimeter (gm/dm^2). The weight of the active material is directly related to the ampere hour (Ah) capacity of the plate.

The impregnation is followed by a chemical conversion of the nickel nitrate to form nickel hydroxide in an alkaline solution to fabricate the positive plates. Similarly, the cadmium nitrate is converted to cadmium hydroxide in an alkaline solution to make negative plates. This is accomplished with an electric current as the plaque material is passed through large tanks containing the alkaline solution. Several wash cycles are used to remove contaminants prior to cutting the spiral into plates.

The second most common plate-manufacturing method uses a nickel mesh or screen for the substrate. The manufacturer uses a dry powder sintering process. This technique uses a mold to hold the screen (substrate) dry powder while running through a sintering furnace. This process is less automated than the SAFT process and does not lend itself to high volume automated production. Impregnation is done in small batches using processes similar to those described above.

The sealed prismatic NiCd cell is constructed of positive plates (nickel electrodes), negative plates (cadmium electrodes) and a separator material that is interleaved with the plates and serves to insulate the positive plate from the negative plate and retain the electrolyte. The plates are connected to the respective cell terminals, which are attached to a cell cover and inserted in a steel case and welded shut. The electrolyte is normally 31% concentration of potassium hydroxide (KOH) and is added through the "fill tube," which is then fitted with a pressure gauge.

The testing of aerospace NiCd cells is conducted in three parts. The first series of tests is conducted on the cell components. These tests include chemical and/or physical analysis of the separator, electrolyte, and plates, and flooded plate test in temporary cells to ensure adequate capacity of the positive and negative plates. The second series of tests are those that the cell manufacturer conducts to demonstrate that the cells meet the manufacturer's requirements. The third series demonstrate that the cells meet the customer's requirements and provide the data for cell acceptance or buy off. In addition, the data from the customer's test usually provides the basis for matching cells (cell selection) that go into each flight battery. Provisions are included in the test and inspection processes for customer review and acceptance of test data and component analysis. The fill tubes are pinched off and welded closed (pressure gauges removed) when all cells complete the required tests.

To the project and program users, a cell (and battery) appears as a simple "two-terminal" device that one passes current through in one direction to store energy and in another direction to use the energy. To a battery technologist, the NiCd cell is a highly complex, interactive electrochemical device where the present and future performance is totally dependent on its past history. This history includes the attributes and characteristics of the raw materials, the processing of these materials into components, the assembly of these components into a sealed cell, and all testing, handling, and storage up to the specific test being conducted. Every NiCd cell has a finite life that is determined by its past history. Consequently, a cell or battery of cells should be classified as perishable and treated accordingly.

The ability to successfully manufacture an hermetically "sealed" NiCd cell is predicated on a delicate balance between the utilization of active material, the relative state of charge of the active material between the positive and negative plates at the time the cell is sealed, the amount of electrolyte placed in the cell at closure, the properties of the separator material, and the free volume allowed by the case design. The aerospace NiCd cell, which has no free or excess electrolyte, is referred to as an "electrolyte-starved" design.

The primary prerequisite for a sealed, electrolyte-starved cell to operate safely is that the positive plates be limiting on charge so that only oxygen is generated during overcharge. During charge, some of the current is utilized in the generation of oxygen gas, which is related to positive plate efficiency. In overcharge, all the current is used at the positive plate to produce oxygen gas. During both charge and overcharge, oxygen is recombined at the negative electrode. Therefore, the cell pressure will increase to a level that is dependent on the recombination rate of oxygen at the negative electrode, the rate of diffusion of the oxygen through the separator, the amount of electrolyte in the cell, and the cell free volume. The cell pressure at C[3]/10 overcharge rate at 20°C is typically in the range of 50 to 70 pounds per square inch gauge (psig).

The negative plates of a cell should contain approximately 50% more capacity than the positive electrode. Of this "excess" negative capacity, approximately 60% will remain uncharged when the positive plates are fully charged. This uncharged material is referred to as "overcharge protection" and is required to prevent the negative plates from becoming fully charged and generating hydrogen gas.

The remainder of the excess negative is in the charge state when the cell is completely discharged and is for overdischarge protection. This excess charged cadmium is referred to as precharge and serves two purposes. On discharge, when the cell voltage drops below 1 volt, the positive plates are limiting, thereby leaving charged cadmium material to react with any residual oxygen when the cell is completely discharged. Typical pressure in completely discharged cells is 3 to 5 pounds per square inch absolute (psia). A second reason for the positive plates to be limiting on discharge is to prevent the effects of negative capacity fading, which occurs during normal use, from causing a loss in cell capacity. While the reason for negative plates to fade is not fully understood, it is thought to be related to changes in crystal sizes of the cadmium species, which can exist in at least two states (gamma and beta).

From the above elementary principles of operation, years of manufacturing, destructive cell analysis, cell life testing, and flight experience, a fundamental set of requirements for cell manufacturing and construction has evolved. These include a "flooded" cell test on "temporary cells" to establish a lot acceptance for the minimum positive and negative plate capacity, and a minimum negative to positive capacity ratio of 1.5:1. The flooded test and subsequent washing also provides additional cleaning of the plates.

The importance of the excess negative material and the proper distribution (precharge and overcharge protection) of the excess in a sealed cell cannot be overstated. Of the two, ensuring that the overcharge protection is available for the life of the cell is the most important. Should the negative plates become fully charged, hydrogen (H_2) gas will be generated during overcharge, and there is no effective mechanism within the cell for the recombination of H_2 gas. If a cell is overdischarged (potential reversed) H_2 gas is generated at the positive electrode at the rate of 418 cubic centimeters per ampere hour at standard temperature and pressure (STP). Because of the limited

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[3] C is defined as the cells' rated Ah and is used to designate charge and discharge current rate.

free volume in a sealed cell, voltage reversal can quickly build up pressure and rupture the cell case or battery package.

The primary degradation mechanisms that cause failure of NiCd cells can be characterized as negative plate capacity fading, cadmium migration, positive plate expansion and deterioration, electrolyte redistribution, and separator breakdown. These degradation mechanisms are always present, with the rate being determined by the materials and manufacturing processes used in making the cell, the environment, and electrical condition of the cells. No mechanism is mutually exclusive of the others, and either one or all can determine the useful life of the cell. These are discussed in considerable detail in the appendix.

THE ENVIRONMENT AND NICKEL-CADMIUM BATTERIES

The performance degradation of flight batteries can be readily measured in terms of decreased discharge voltage, capacity loss, and increased overcharge voltage. The rate of degradation of these parameters is dependent on the specific application and the environment. And it can be correlated to changes in or degradation of the positive plates, negative plates, separator, and electrolyte. Degradation such as separator breakdown, cadmium migration and positive plate expansion are irreversible. Changes such as electrolyte redistribution and cadmium crystal size are reversible through tests and processes described herein. The purpose of ground handling and storage procedures is to minimize any irreversible degradation and to counter reversible changes that affect on-orbit performance of flight batteries.

It is generally accepted that the rate of an electrochemical reaction in a NiCd cell doubles for every 10°C rise in temperature. Years of testing performed for NASA at the U.S. Naval Surface Warfare Center (NSWC) at Crane, Indiana, have characterized the effects of temperature on performance and cycle life of NiCd cells manufactured during the sixties and seventies (Refs. 2, 3, and 3A). Figure 1 is a composite of data from these NSWC life cycle tests and GSFC flight experience. It illustrates the improvement in battery life when operating at 0°C vs. 20°C in low earth orbit. The life capability depicted in the figure is indicative of the performance of NiCd cells manufactured by General Electric (GE) and Gulton during the 1960s and '70s. It is not necessarily representative of cells manufactured since the early 1980s, so these data are not intended to be used for cells and/or battery designs from current vendors. The generally accepted temperature for optimum battery performance is 5°C. This temperature reflects a compromise between the extreme cold (< -5°C) temperature effects on plate charge acceptance and the higher temperature effects on plate charge efficiency and nylon separator degradation. Errors in thermal design for batteries should always favor the lower operating temperature.

All cell components are affected by elevated temperature. The most readily observed effect is the decrease in charge efficiency, which is evident as a decrease in storable capacity (Ref. 3) that becomes significant above 20°C. The decrease in charge efficiency as temperature increases is generally attributed to the positive electrode. Various additives (Ref. 4) have been used (cobalt, cadmium, lithium, etc.) in attempts to increase the charge efficiency at elevated temperatures with various degrees of success.

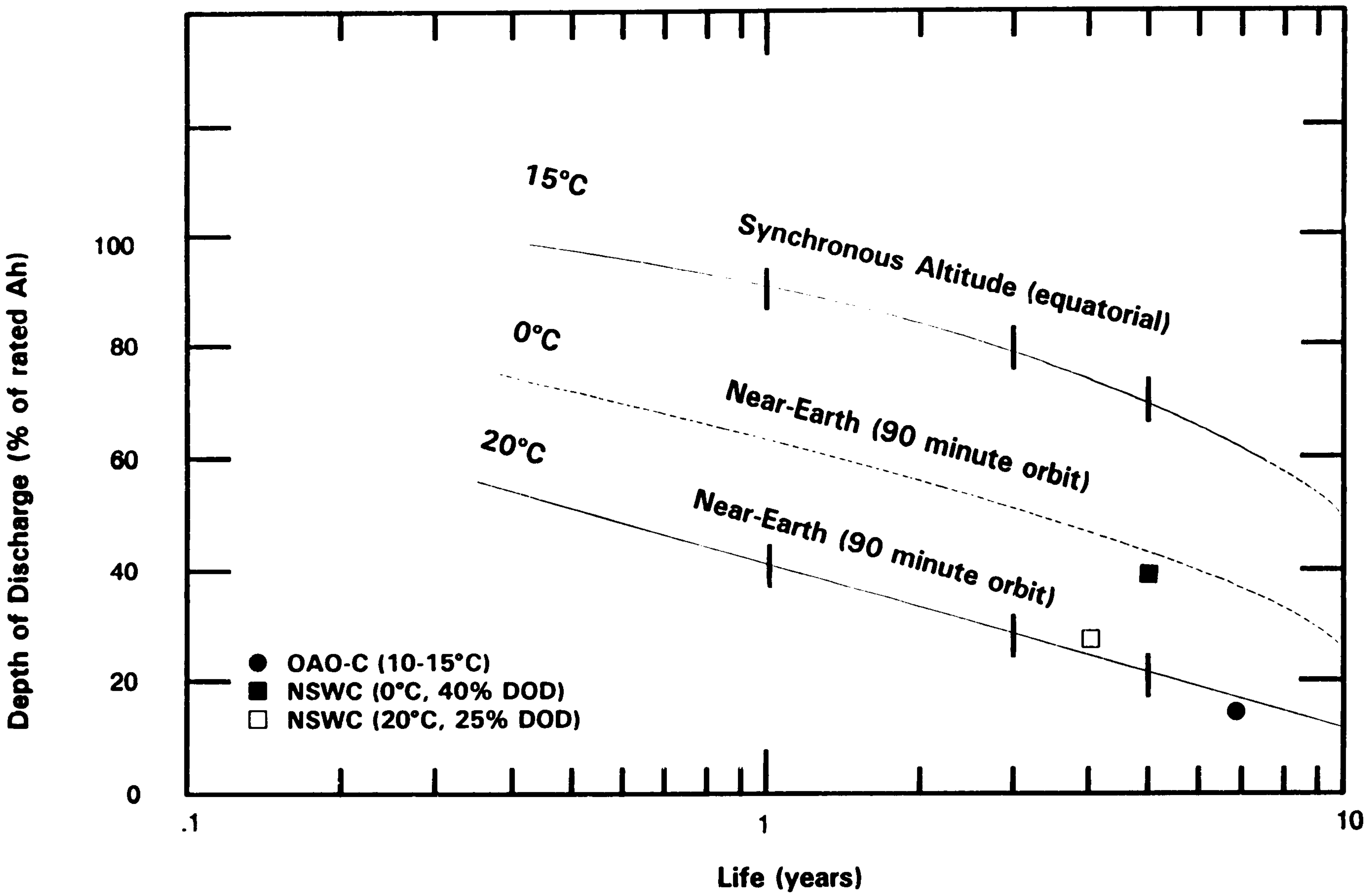

Figure 1. Life of conventional NiCd cells manufactured in the '60s and '70s based on NSWC life test data and GSFC flight experience. These data are not intended to be used for cell and/or battery designs from current vendors.

The stability of the nylon separator material is significantly affected by temperature (Ref. 1). The rate of nylon hydrolysis in 31% KOH solution increases by a factor of 3 for each 10°C increase in temperature. Work by Lim (Ref. 5) suggests a process by which the nylon hydrolysis products react with the charged positive plates, which indirectly increases the relative state of charge of the negative plates, thereby using up negative overcharge protection as the nylon separator breaks down.

Calculations by Lim showed the overcharge protection initially designed into a General Electric (GE) cell would be consumed when a 10 weight-percent of the separator had been hydrolyzed and indicated that a 10% weight loss should occur at 25°C in about 7 years. At 15°C this time is projected at 20 years. Scott (Ref. 1) presented rationale for why the time-versus-temperature relationship for separator deterioration should apply during discharge and/or shorted storage, as well as during orbital cycling. This work shows that the way to control nylon separator deterioration is to both store and operate cells at low temperature. Destructive physical analysis (DPA) of cells that had been cycled for several years at low temperature (0°C) and high depth of discharge (DOD) showed the separator, while deteriorated, was not the contributing failure mode (Ref. 6).

Of all the NiCd cell failure mechanisms, the degradation of the cadmium plate is the least understood. The environment is known to cause profound changes in the negative plate crystal morphology (Ref. 7). The growth of large crystals is one of the most important factors in negative plate capacity fading and contributes to the conversion of the cadmium material (active to inactive) with cycling. The change in crystal morphology is also thought to cause the generation and persistence of the cadmiate ion that is responsible for cadmium migration.

In general, conditions that promote the formation of small crystals in the negative plates are good, and those that promote large crystals are bad. Some conditions known to promote the formation of large crystals include open circuit stand, low discharge rates, and high temperature. Conversely, conditions that promote small crystals are prolonged low charge rates, high discharge rates, and low temperature (Ref. 7). It should be especially noted that large cadmium crystals formed from very low discharge rates (open circuit being the lowest possible rate) at elevated temperature are difficult to reduce during subsequent charges. The knowledge of how the environment influences negative crystal structure is a key factor in the development of handling and storage guidelines.

Other factors influencing cadmium migration are the mechanical compression introduced into the plate stack during cell assembly, compression used in the fabrication of most batteries, and expansion of positive plates with cycling. A well-designed cell will have a minimum interelectrode spacing (maintained by the separator) of 0.007 inches when inserted into the cell container. Chemically impregnated positive plates expand with use, and, as a consequence, the electrolyte is squeezed from the separator. With increased cycle life, the surfaces of the cadmium plates dissolve and appear to slowly precipitate on the separator. This mode of separator degradation should be given special consideration in cell design for batteries where compression force will be used to restrain the cells.

The temperature of a battery is usually measured on the surface of a specific cell or on the battery frame not representative of the internal temperature of the cells. Depending on the mode of battery operation and the surrounding environment, the internal cell temperature within a plate stack could be 8° to 10°C hotter than that being measured. Consequently, when the measuring sensor is reading 20°C, the cells' internal temperature could be as high as 30°C.

The effect of temperature gradients between cells in a battery on near-term performance is evident as voltage divergence between cells. Under extreme conditions, the voltage divergence could cause thermal runaway when voltage-limiting charge control is used. The degradation effects of temperature are so cumulative over the entire life of a cell that after several years in orbit, significant deviations in performance can be expected between batteries that operate at different temperatures or among cells within a battery that has a large temperature gradient. The cumulative effect is manifested in the warmer cells or battery exhibiting earlier degradation of capacity, "softening[4]" of the charge voltage, and internal shorting of cells (Ref. 8). The thermal design for the battery should limit the temperature gradient to 3°C maximum among cells within a battery and 5°C maximum between batteries.

The battery temperature is directly related to battery heat generation. On discharge, the reaction is exothermic where the heat dissipation is approximately 16% of the power being delivered at the battery terminals. Charging a battery is endothermic until near full charge when the reaction becomes exothermic and remains so throughout overcharge. The heat generated during overcharge is the product of the battery voltage and current. The higher the temperature, the earlier the reaction becomes exothermic; e.g., at 20°C, the reaction becomes exothermic at approximately 80% of full charge, whereas at 0°C the reaction becomes exothermic at approximately 95% of full charge.

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[4] "Softening" of the charge voltage is an observed phenomenon where a cell's voltage, as a function of state of charge, diminishes with cycle life.

A fully charged NiCd cell will have an open circuit voltage approximately 1.30 volts after several hours on open circuit stand. During charge, a cell's voltage is a function of state of charge, charge rate, and temperature. Similarly, the discharge voltage is dependent on the state of charge, discharge rate, temperature. Neither the open circuit voltage nor any charge or discharge voltage is a reliable indicator of state of charge. NiCd cells are capable of accepting high charge rates (up to 2 C), as long as the cell's voltage does not exceed the H_2 evolution potential and/or as long as the cell is not in overcharge. Conversely, a NiCd cell can produce exceptionally high discharge currents (10 to 50 C), limited only by the internal resistance, which is 2 to 3 milliohms. The constraining factor for both charge and discharge is the internal cell temperature.

The most distinguishing voltage characteristic of a NiCd cell is that when the cell is nearing full charge, the cell voltage peaks and then decreases with continuing charge. This is called "rollover" and is more pronounced at lower temperatures.

The NiCd cell charge voltage has a negative temperature coefficient of approximately -2.3 millivolts per degree C. This negative temperature coefficient, along with other variables that affect cell voltage, makes the use of a single temperature-compensated voltage (V/T) limit for charge control very unforgiving.

For purposes of orbital operations, the efficiency of a NiCd cell is usually expressed as "Recharge Ratio" (Ah in/Ah out). This is the inverse of cell efficiency and should always be greater than one for sustained operations. Figure 2 illustrates the recommended charge-to-discharge ratio for low-Earth orbit (LEO) applications. The data were derived from years of cell tests and have been verified on numerous flight programs. The two curves are intended to bracket the acceptable recharge, with the upper limit being driven by limited thermal dissipation and the lower limit being that necessary to prevent capacity loss. The implications of operating above about 15 C is evident. Since synchronous orbit applications usually have low charge rates (C/10 to C/30), the recharge would be approximately 10% higher than those for low-Earth orbit (LEO) missions.

To achieve the desired recharge ratio under widely varying conditions (load variations, Sun angles, eclipse times, cell type, etc.), a family of temperature-compensated voltage (V/T) limits have been developed by the GSFC for battery charging. These are illustrated in Figure 3. These V/T levels have a heritage to the OAO-A2 satellite launched in 1968. The wide dynamic range of recharge ratios that can result from the V/T levels is shown in Figure 4 for 25% DOD. The upper curve illustrates a case of excessive overcharge and the resulting divergence in parallel battery performance under this excessive overcharge condition. Increasing the DOD or decreasing the charge rate would result in the lower recharge ratios. Conversely, decreasing the DOD and increasing the charge rate would cause the recharge ratios to increase. V/T level 8 was selected to provide a "safe" operating voltage below the H_2 evolution voltage of cells and should be used with caution. V/T levels 1 and 2 were chosen to control the charging of a 22-cell battery with one shorted cell.

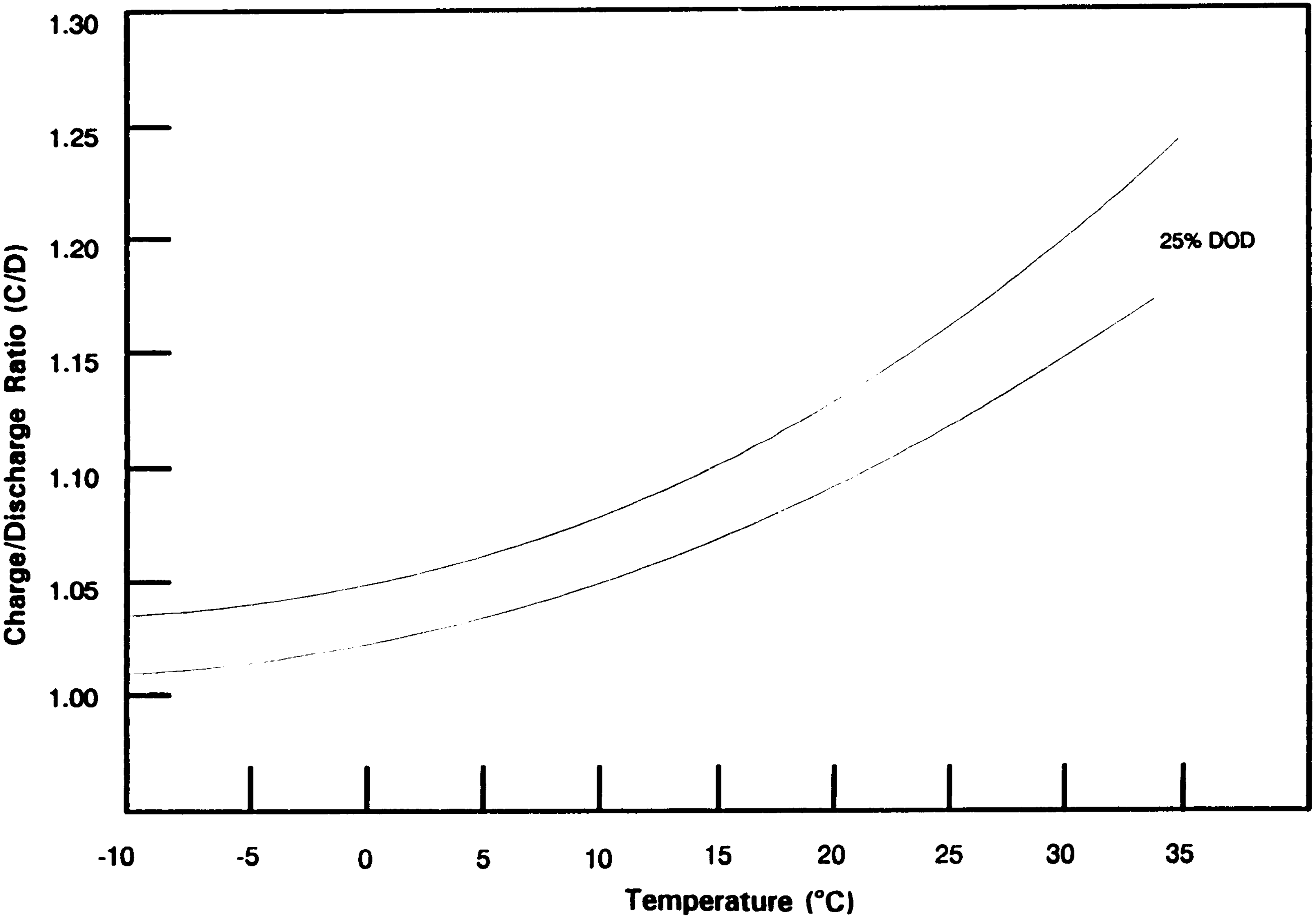

Figure 2. Recommended charge/discharge ratio vs. temperature.

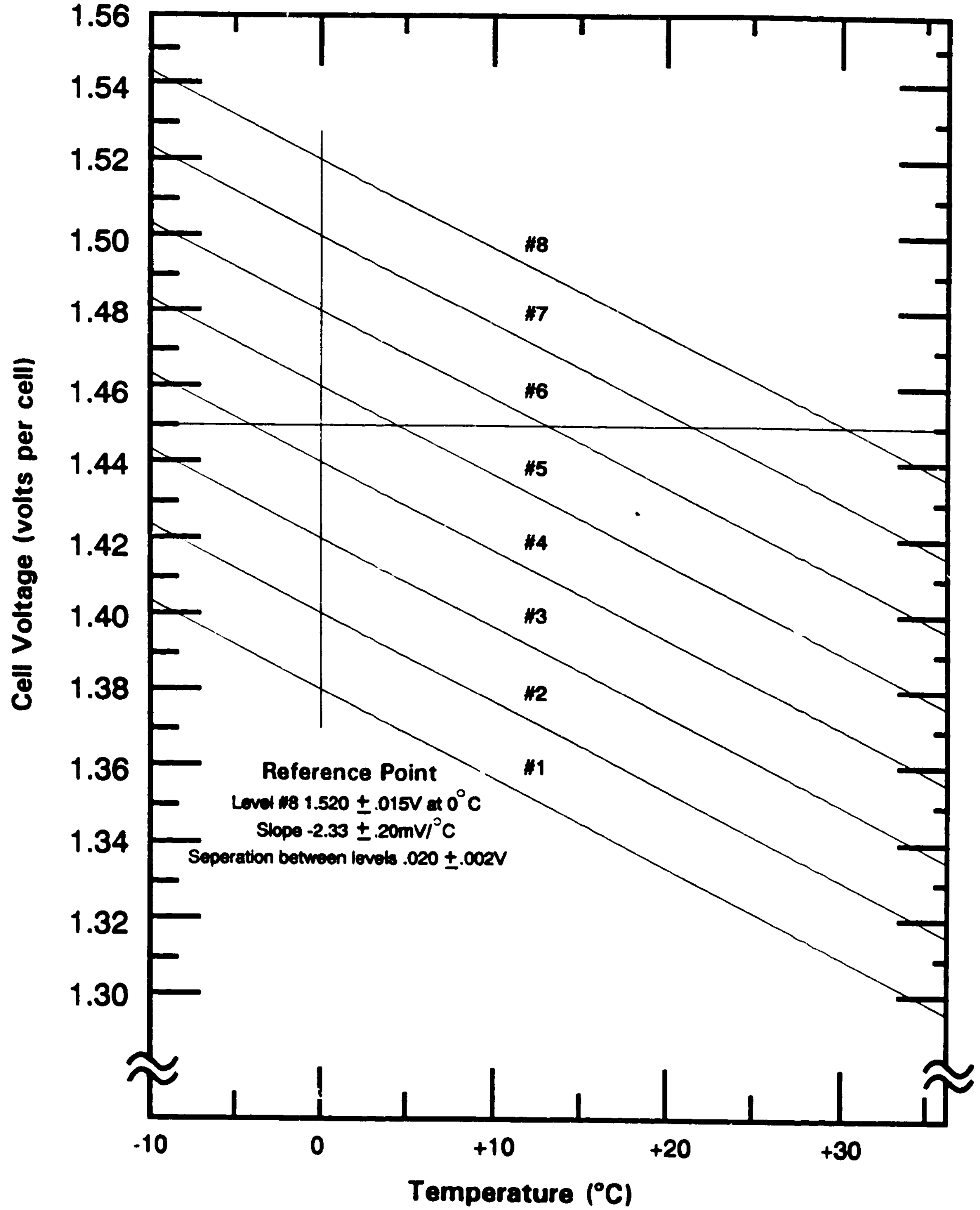

Figure 3. Voltage temperature characteristics for multilevel NiCd battery charging.

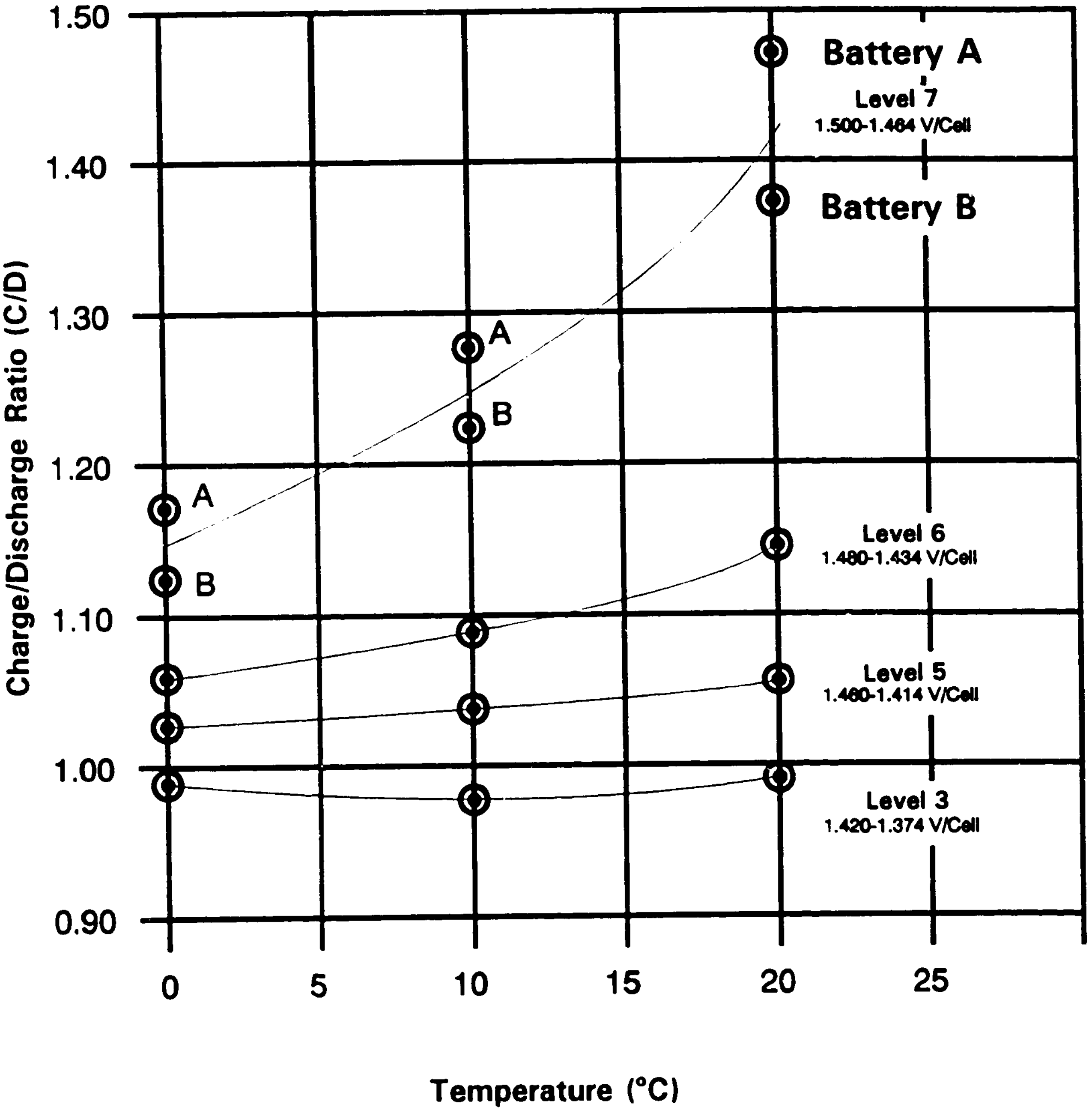

Figure 4. Charge/discharge ratio vs. temperature and charger levels for NiCd batteries A and B.

BATTERY HANDLING AND STORAGE GUIDELINES

NiCd batteries can be irreversibly degraded through improper use and handling. These guidelines are intended for use by battery engineers in developing a project-unique Battery Handling and Storage Requirements Document for conventional nickel-cadmium batteries. It is also intended to provide project personnel with insight and understanding of the degradation mechanisms of NiCd batteries. The rationale for each guideline is stated along with the degradation mechanism that the guideline is intended to minimize. The complexity of a NiCd cell electrochemistry precludes quantifying the precise relationship between the loss of in-orbit performance caused by degradation from a specific integration and test activity. Also, it is recognized that the need to verify overall systems and spacecraft integrity may, at times, conflict with a guideline. Nevertheless, the need for spacecraft-level verification must be balanced against the irreversible degradation that the flight batteries will experience. Implementing these guidelines will assure the greatest likelihood of optimum performance of the flight batteries throughout the mission.

Open Circuit Stand and Intermittent Use Is Very Detrimental to NiCd Batteries.

This statement forms the basis for all battery handling and storage requirements, i.e., the elimination of, to the extent practical, open circuit stands. A corollary to this declaration would be that a discharged battery with cells short-circuited and stored at cold temperature has a life that is limited by the rate of degradation of the separator material (which is very low at 0°C). The maximum time that a discharged and shorted battery can be stored and still provide several years' life in orbit has yet to be established. GSFC limits the wet storage life of a cell to 3 years from the cell activation to spacecraft launch. This restriction has, however, been waived for several spacecraft such as NOAA 8, 11, and 12, TDRS 3, 4, and 6, and EUVE upon a successful prelaunch DPA of a cell stored in an identical environment to the flight battery.

Experience has shown that the most damaging battery activity has been intermittent use in combination with open circuit stand. Whereas, the least damaging state has been cold temperature storage of a discharged battery with its cells short-circuited. Given the present lack of understanding of the degradation mechanisms associated with either of these conditions, we must rely upon practical experience to define those battery activities required to minimize flight battery degradation. The following guidelines constitute those activities and represent a composite of "lessons learned" from 30 years of ground handling and flight experience with NiCd cells (see APPENDIX).

GUIDELINE NO. 1

Flight batteries should not be subjected to extended spacecraft integration and test activities.

Rationale: The open circuit stand and intermittent use of NiCd batteries during extended (usually several months) spacecraft I&T have shown to significantly accelerate the degradation of batteries. Results from controlled tests have shown that after 6 months of this kind of use, cells exhibited permanent and irreversible changes. These changes were unlike anything observed on spacecraft batteries after several years of spacecraft flight operations. The degradation is observed initially as an increase in cell overcharge voltage at low temperatures, which is indicative of loss in overcharge protection. Also, I&T use promotes significant cadmium migration. Both of these are recognized as dominant wear-out mechanisms that determine battery life.

Special Considerations: The exception to this guideline should be rare and only when "identical" test batteries are inadequate to satisfy a system or spacecraft test objective. The risk of integrating the flight batteries at the launch site can be minimized with proper engineering and quality assurance provisions. The precedent for launch site integration of flight batteries was set by the GSFC on the OAO-A2 satellite in the late 1960s and has been followed by some of the most successful GSFC missions: OAO-C, SMM, ATS-F, OSO-I, TDRSS, IUE, Landsat, COBE, to name a few. The alternative of using flight batteries for I&T assures an early demise in performance and serious battery problems on orbit.

GUIDELINE NO. 2

Flight batteries should be maintained in a discharged and shorted condition and stored at cold temperatures when not required for "critical" spacecraft testing.

Rationale: The chemical and/or electrochemical activity in the discharged state is at a minimum. Lowering the temperature assures even less activity. The principal benefactor of the low temperature is the nylon separator material where the degradation rate is minimal. The optimum temperature for storage appears to be around 0°C.

Special Considerations: When a battery is placed in cold storage, it should be wrapped with an antistatic bag that is evacuated and sealed. This package, along with packets of desiccant, should then be placed in a second antistatic bag, which is also evacuated and sealed. Upon removing from cold storage, the packaged battery should be allowed to warm up to room temperature prior to opening the bags to preclude condensation on the battery during warm-up.

Note: A battery consists of individual cells connected in series, each of which has its own unique characteristics. Consequently, there exist only two states in which all cells are known to be at the same equilibrium -- all cells in overcharge or all cells completely discharged. Periodically, a battery must be taken to one of these states to remove cell imbalance and assure uniform performance. Of the two states, discharged with all cells shorted is preferred because it has low electrochemical activity.

GUIDELINE NO. 3

The use of flight batteries after an open circuit stand of 4 hours or longer should be initiated with a short (3 to 5 minutes) discharge prior to initiating battery charge. Typically the discharge is done with spacecraft load and in concert with the spacecraft ground power console.

Rationale: While the use of batteries for spacecraft integration is not recommended, this is a precautionary measure that should be implemented when the batteries are on the vehicle. This guideline is predicated on the equilibrium condition within cells after periods of open circuit stand. During normal cycling use, the battery is discharged, followed by a recharge and some overcharge. In this mode, there is always a partial pressure of oxygen (from the overcharge), with oxygen recombination occurring at the negative electrode. In a relatively short time on open circuit, the oxygen recombines and the internal cell pressure returns to a vacuum. Charging cells that are fully charged in the absence of oxygen creates an "unnatural" condition, since there is no oxygen available to react with the negative electrodes. Past experience has shown this technique to reduce the negative effects of open circuit stand on performance.

Special Considerations: Any time a discharge is initiated on a battery, precautions should be taken to ensure that cell reversal does not occur. Under most conditions, the battery protection designed into the spacecraft is adequate to prevent any harm during the discharge. Special attention should be given to the battery pack voltage or battery differential voltage, since this will provide an early indication of cell imbalance within a flight battery.

GUIDELINE NO. 4

During short periods when the battery is not needed to support spacecraft integration and test, it should be maintained on a low rate trickle charge.

Rationale: Trickle charge at low rates (C/60 to C/100) is preferred to open circuit stand for a battery. While there are degradation mechanisms associated with trickle charge, data from controlled tests indicate this mode to be much less detrimental than open circuit stand.

Special Considerations: The primary consideration for selecting the trickle charge rate is determined by the spacecraft thermal constraints. While in overcharge, all energy into the battery will be dissipated as heat, i.e., the overcharge current times the battery voltage equals the thermal dissipation in watts. Rates as low as C/100 have been found to be effective for maintaining the battery in a full state of charge at temperatures of 20°C and below. In no case should the battery be kept on charge if the spacecraft thermal subsystem cannot maintain the battery temperature below 25°C. See Guideline No. 5.

GUIDELINE NO. 5

The temperature of a battery during spacecraft integration and test should not exceed 25°C. If the battery temperature reaches 25° C, all electrical operations on the battery should be terminated. In no case should the battery temperature be allowed to exceed 30°C when being charged or discharged.

Rationale: The effect of elevated temperature on NiCd degradation and performance has received extensive treatment. It has been demonstrated that batteries operated around 5°C give optimum in-orbit performance. It is also known that exposure to elevated temperatures accelerates cadmium migration and separator breakdown. Separator breakdown depletes the overcharge protection in the cells. Since the rate of nylon separator degradation increases by a factor of 3 for every 10°C rise in temperature, strict adherence to this guideline is advised.

Special Considerations: Temperature measurements are made on the surface of specific cells or the battery frame and are not representative of the internal temperature of individual cells. Depending on the mode of battery operation, spacecraft environment, and the position of the cell within a battery package, the internal cell temperature can be 8° to 10°C hotter than that being measured on the cell or battery surface. Consequently, when the measuring sensor indicates a reading of 20°C, the actual internal temperature of a cell could be as high as 30°C. When the battery temperature is around 20°C, spacecraft operating modes resulting in high internal battery heat dissipation should be avoided.

GUIDELINE NO. 6

The design of flight batteries should include the following provisions for ground console interfacing with the battery while integrated in the spacecraft:

- *Signal lines for monitoring total battery voltage, charge and discharge currents, battery temperature, and individual cell voltages*
- *Capability to charge the battery from the ground test console*
- *Capability to discharge the battery from the ground test console*
- *Capability to place a resistor across each cell*
- *Capability to place shorting plug across each cell*
- *Capability to provide adequate thermal control*

Rationale: The state of health of the battery must be monitored at critical points during spacecraft integration and test. The ability to discharge, charge, trickle charge, and recondition without powering up the spacecraft or removing the battery from the spacecraft allows monitoring and maintenance of battery health with minimum impact on spacecraft schedule.

Special Considerations: All external interfaces through the battery test connector should be provided with appropriate fuses, resistors, and interlocks to ensure that failures in the harness, battery test console, and related equipment do not damage the battery or spacecraft.

GUIDELINE NO. 7

A battery stored discharged and shorted for a period greater than 14 days should be activated with a "conditioning cycle" prior to placing it in use. The conditioning cycle (20°C) is defined as follows:

1. *C/20 charge for 40 hours (+/- 4 hours).*
2. *C/2 discharge to first cell at 1.0 volt.*
3. *Discharge each cell with 1 ohm resistor to less than 0.03 volts*[6]*. Short each cell for minimum of 4 hours.*
4. *C/10 charge for 16 hours (+/- 1 hour).*
5. *Repeat steps 2 and 3 above.*
6. *C/10 charge for 16 hours (± 1 hour). (See note for Guideline No. 9)*

Rationale: The low charge-rate for electrical activation after extended storage has proven to be the most effective way of preparing a battery for use. At the higher rates, some users have observed high cell voltages (> 1.5 volts) during the initial charging. While such performance may be peculiar to a specific cell design or history, the C/20 "activation" charge is standard in the industry. The low-rate overcharge, which occurs after approximately 30 hours of charging at the C/20 rate, allows for an extended period of oxygen recombination at the negative electrode, which is thought to enhance the development of small crystals on the negative electrodes. The C/2 discharges provide a calibration against prestorage battery capacity measurements.

Special Considerations: Active cooling is usually required to ensure that the battery temperature does not exceed the 20°C limit. During discharge, the heat generated is approximately 16% of the power being delivered at the battery terminals. Charging a battery is an endothermic reaction until overcharge is reached, at which time the reaction is exothermic where all power into the battery is dissipated as heat.

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[5] The criteria were 0.1 volts per cell until the mid-1970s. Since then, there has been a gradual change to 0.03 volts.

GUIDELINE NO. 8

Batteries should not stand on open circuit for more than 7 days without being charged. Charging should be initiated only after implementing Guideline No. 3.

Rationale: The concern being addressed is the "self-discharge," which occurs when cells are on open circuit, and the effects of this low-rate discharge on the formation of large cadmium crystals. Controlled tests have shown capacity loss of just under 1% per day at 23°C and about 1.5% at 35°C (Ref. 9). The self-discharge rate of each cell may not be identical, consequently after extended periods of open circuit, there can be an appreciable capacity loss and capacity divergence between cells in a battery. The recommended way to remedy this divergence is to discharge the battery as described in Guideline No. 3 and trickle charge for several hours to bring all cells into balance with overcharge.

Special Considerations: See Guidelines No. 2 and 4.

GUIDELINE NO. 9

A battery should be "reconditioned" if it has been on open circuit, subjected to intermittent use, i.e., open circuit, trickle charge, occasional discharge, etc., for a period of 30 days. Reconditioning is effected by performing the following sequence at 20°C:

1. *Discharge at C/2 constant current rate to first cell at 1.0 volt.*
2. *Drain each cell with 1 ohm resistor to less than 0.03 volts*[6].
3. *Short each cell for a minimum of 4 hrs.*
4. *Recharge battery at C/20 constant current rate for 40 hrs ± 4 hrs (see note below).*

Rationale: Exercising the active material by periodic discharge of each cell followed by a low rate charge helps retard permanent change in crystal structure of the cadmium electrodes and forces electrolyte redistributions within the cell. The less frequent the reconditioning cycles, the less effective it is in restoring the discharge voltage of a battery. Thirty days is chosen as a balance between the cumulative effects of reconditioning discharges on battery degradation and the extended periods without periodic discharges.

Special Considerations: Care should be taken to ensure that the battery temperature does not exceed 25°C. The V/T level 7 (Figure 3) should not be exceeded during recharge. See Guideline No. 5 for other considerations.

Note: The recharge method following the 1 ohm let down is not critical if the cells have not been discharged and shorted for extended periods. After a few hours (4 to 8) at the C/20 rate, charging at high rates is acceptable. If the battery is integrated into the spacecraft, final charging can be accomplished with the spacecraft battery charger.

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[6] The criteria were "for 16 hours or to less than 0.1 volts per cell" until the mid-1970s. Since then, there has been a gradual change in the requirement for GSFC spacecraft to "less than 0.03 volts per cell."

GUIDELINE NO. 10

Flight batteries should be reconditioned as part of the spacecraft prelaunch checkout (expendable launch vehicle) or as part of the final preparation for spacecraft integration into the Shuttle cargo bay. Upon completion of the reconditioning, flight batteries should be kept on low-rate trickle charge until launch. See Guideline No. 9 for definition of the reconditioning sequence.

Rationale: The importance of proper preparation of a battery for on-orbit use cannot be underestimated. The reconditioning cycle restores the battery discharge voltage to "like new" condition by enhancing the formation of small cadmium crystals and electrolyte redistribution. A complete discharge establishes capacity balance for all cells within a battery. The low-rate trickle ensures that the battery is maintained at full state of charge for launch.

Special Considerations: A variation of this guideline is to ship the flight batteries to the launch site discharged and each cell shorted. Following postshipment inspection and conditioning (Guideline 7), the battery should be discharged, cells shorted, and placed in cold storage until required for launch. Within approximately one week of launch, remove cell shorts and charge battery (per Guideline No. 9). Perform brief discharge (a minimum of 15 minutes) using spacecraft loads to verify load sharing and integrity of discharge paths. Perform recharge using spacecraft charger. Maintain battery on trickle charge until launch. Caution should be exercised to preclude battery temperature exceeding 25°C. See note for Guideline No. 9.

GUIDELINE NO. 11

Flight batteries should be discharged and cells shorted during shipment. Batteries should be packaged to exclude humidity, and the shipping container should be equipped with temperature indicators to provide assurances that flight batteries do not exceed 30°C.

Rationale: A NiCd battery can deliver very high currents (over 100 C) if shorted. If a short occurred inadvertently during shipping, such high currents would create a safety hazard for surrounding equipment and would destroy the battery because of the excessive heat generated. Temperature indicators will ensure that the battery is not exposed to temperatures that would damage or destroy the separator material.

Special Considerations: This guideline is the preferred mode of shipping batteries as discrete components. Under certain conditions, it may be advantageous to ship the flight batteries integrated into the spacecraft. When shipped with the spacecraft, the spacecraft shipping container usually provides humidity and temperature control. Even when shipped with the spacecraft, the batteries should be discharged and cells shorted for reasons cited above.

GUIDELINE NO. 12

A log book shall be maintained on each flight battery, starting with the first electrical activation after battery assembly through spacecraft launch. Each log book shall identify the project, battery serial number, and each cell serial number. Chronological (date and time) entries for all test sequences, summary of observations, identification of related computer-stored records, malfunctions, name of responsible test personnel, and references to test procedures controlling the event shall be recorded.

Rationale: A NiCd battery is perishable. Its ability to complete mission life is directly related to ground use and handling. Historical performance is required to ascertain the flightworthiness of the battery at launch time. The observations and recordings of key parameters over the history of the battery are necessary to provide trend data, which may indicate battery premature degradation.

APPENDIX

NICKEL-CADMIUM CELL DESIGN AND EVOLUTION

Nickel-cadmium (NiCd) cell designs flown on space missions are as varied as each mission objective. The manufacturing sources of NiCd cells flown on U.S. satellites include Sonotone Corporation, Gould National Battery, Gulton Industries, Eagle Picher Industries (EPI), and Gates Energy Products (GEP) - formerly General Electric (GE). Of these manufacturers, only GEP and EPI are currently manufacturing aerospace NiCd cells using chemically impregnated plates. Each manufacturer offers a variety of design iterations of a baseline cell design. This includes special treatments, additives, and special processing techniques.

This section of the handbook provides a review of the evolution of cell designs using chemically impregnated plates over the past 30 years.[7] The material in this section utilizes published information, unpublished data obtained from the files of the GSFC Space Power Applications Branch, and discussions with key U.S. aerospace battery specialists. In addition, this section makes extensive use of material published in Refs. 10 and 11, which were the earliest attempts to understand cell-design parameters and the interaction of these parameters on performance. Since the data from more than 30 years of testing and spaceflight experience with NiCd batteries is so extensive, this document contains only brief synopses of information important to understanding the design evolution of NiCd cells used in space applications.

CELL FLIGHT HERITAGE

The first aerospace NiCd batteries were flown on Explorer VI, launched in August 1959, and were manufactured by Sonotone Corporation. The batteries were made from cylindrical cells with a "paper" separator and operated at approximately 2% DOD in a 720-minute orbit. The Sonotone type "F" cell was used through Explorer XXII (launched 10/64) and on Television Infrared Observing Satellite (TIROS) I (4/60) through TIROS X (7/65). The design life of these missions was from 3 to 6 months, with a battery DOD from 2% to 5%. The earliest use of Pellon separators in aerospace batteries was on the Low-Frequency Trans-Ionospheric Satellite (LOFTI)-1 satellite, launched by the Naval Research Laboratory in February 1961. The LOFTI battery was made with Sonotone 3.5 (Ah) cylindrical cells. Batteries manufactured by Gould, using a Pellon separator, were used on Telstar I and II (launched 7/62 and 5/63, respectively). Records indicate this cell design was also used on Syncom I, II, and III launched 2/63, 7/63, and 8/64, respectively. For reference, Table A1 provides a

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[7] The relatively new technology NiCd cells made with electrochemically impregnated plates and chemically stable separators are not within the scope of this handbook.

summary of most of the battery designs discussed in this handbook.

In April 1962, Gulton Industries introduced prismatic 6.0-Ah batteries with cells constructed using Pellon separators that were flown on Ariel I. There is documentation that a polypropylene-type separator was used by Sonotone for batteries flown on Alouette, which was launched September 1962, and subsequently used in cells for Nimbus I, launched August 1964. In May 1966, General Electric 4.5-Ah cylindrical cells were first flown on Nimbus II and also used a Pellon separator. By the mid-1960s, the majority of NASA satellites were using Gulton- or GE-manufactured cells containing Pellon separator material. Both manufacturers relied on plate-manufacturing technology, also pioneered by SAFT (Bordeaux, France).

In the early 1960s, the commercial market for rechargeable NiCd cells began to grow, and General Electric responded by building a manufacturing plant in Gainesville, Florida, for making commercial NiCd cells. The initial plate-making process was licensed from SAFT. Gulton Industries purchased plates directly from SAFT. The Gainesville plant provided GE with the flexibility to experiment with various plate designs and implement special treatments and processes. By the mid-1970s, GE had taken the lead from Gulton in manufacturing aerospace cells. With the exception of EPI cells used on several missions discussed herein, GE cells have flown on all of the GSFC satellites using conventional NiCd batteries since the mid-1970s.

The principal user of NiCd cells and batteries made by EPI was Lockheed Aircraft, which used the batteries for classified military programs. One of NASA's earliest uses of the EPI NiCd cell was on Skylab (Orbiting Workshop). The early versions of the EPI cells used by Lockheed and also flown on Skylab were not truly hermetically sealed, since each cell had a pressure-relief device that allowed the cell to vent gas if overpressure occurred. A similar version of the EPI Skylab cell was flown on the Seasat mission which failed after 6 months because of an electrical short in the power system unrelated to the battery. The Skylab batteries were manufactured by EPI for the prime contractor, McDonnell Douglas Corporation, and Lockheed was the prime for Seasat.

In 1970, the GSFC awarded a contract to Ford Aerospace to build the Small Meteorological Satellite (SMS) to be flown at synchronous altitude using two batteries constructed with EPI 3.0 Ah NiCd cells. The cells for this program were the first effort by EPI to manufacture a hermetically sealed flight cell for a synchronous orbit satellite and the GSFC's first use of EPI cells (Ref. 12).

A cell-development program was initiated at EPI to determine the design parameters to be used in constructing the flight cells. The cell-design activity was based on the knowledge already gained from the GSFC-sponsored process variable study

Table A1. NiCd Batteries Used on GSFC Spacecraft (Selected List)

Spacecraft	Launch Date(s)	Orbit (kmXkm) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
LOFTI-1	2/61		3.5 Ah Cyl.		Sonotone
Explorer VI	8/59		F Cell ** Cyl.	14 Cell	Sonotone
Explorer XXII (S-66)	10/10/64	LEO, 106 m, 1075X887, 79.7°	F Cell ** Cyl.	23 Cell	Sonotone
Ariel I	4/26/62	LEO, 95.9 m, 770X361, 53.8°	6Ah Prismatic	2 10 cell	Gulton (1st Pris.)
Telstar I	7/62	LEO, 157.7 m, 5642X944, 44.8°	5 Ah Cyl.	1 19 cell	Bell Labs/ Gould
Telstar II	5/7/63	LEO, 225 m, 10,800X971, 42.7°	5 Ah Cyl.	1 19 cell	Bell Labs/ Gould
Alouette I	9/29/62	LEO, 105 m, 80.4°	5 Ah Cyl.	6 12 cell	Sonotone
Syncom I II III	2/14/63 7/26/63 8/19/64	GEO, 33.5° GEO, 38.6° GEO, 6°	6 Ah	2 22 cell	Gould (Same as above)
Nimbus I	8/18/64	LEO, 94.4 m, 602X387, 98.7°	4.5 Ah prismatic	7 23	RCA-Astro/ Sonotone
Nimbus II	5/15/66	LEO, 108 m, 1182X1096, 100.4°	4.5 Ah prismatic	8	RCA-Astro/ Sonotone
OAO-A1 OAO-A2 OAO-3	Apr 66 12/7/68 8/21/72	LEO, 100 m, 750X750, 35° (nominal)	20 Ah prismatic	3 22 cell	Grumman/Gulton
OSO-I	3/7/62	LEO, 95.2 m 595X553, 32.8°	12 Ah	2	Ball Bros.

Table A1. NiCd Batteries Used on GSFC Spacecraft (Selected List)

Spacecraft	Launch Date(s)	Orbit (kmXkm) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
SAS-A SAS-B	12/12/70 11/16/72	LEO, 96 m, 3.0° LEO, 95 m, 1.9° (550X550 nominal)	6 Ah	1 8 cell	APL/Gulton APL/GE
ATS-F (6)	5/30/74	GEO, m 1-6°	15 Ah	2 19 cell	Fairchild /Gulton
TIROS-1 2 3 4	4/1/60 11/60 6/61 2/62	LEO, 99 m, 738X689, 48.3° . . .	F Cell ** Cyl.	3 21 cell	GE-Astro/ Sonotone
TIROS-5 6 7 8	6/62 9/62 6/63 12/63	LEO, m, 955X591, 58.1°	F Cell ** Cyl.	3 21 cell	GE-Astro/ Sonotone
TIROS-9 10	1/65 7/2/65	LEO, 119 m, 2581X705, 96.3° LEO, 100 m, 835X741, 98.6°	F Cell ** Cyl.	3 21 cell	GE-Astro/ Sonotone
NOAA-1, (ITOS-A) 2 3 4 5	12/11/70 10/72 11/73 11/74 7/76	LEO, 115 m, 1472X1492, 101.9°	6 Ah	2 23 cell	RCA Astro/G.E.
NOAA-A NOAA-6, . . 11	6/79 . . Sep 88	LEO, 115 m, 1472X1492, 101.9°	26.5 Ah	2 17 cell	RCA Astro/G.E.

Table A1. NiCd Batteries Used on GSFC Spacecraft (Selected List)

Spacecraft	Launch Date(s)	Orbit (kmXkm) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
Landsat-4 5 D	7/16/82 3/84 7/82	LEO, 98.6 m, 7070X683, 98°	50 Ah	3 22 cell	MDESC/GAB
COBE	11/89	LEO, 900X900, , Sun Synchronous	20 Ah	2 22 cell	MDESC/GAB
SMS-1 (A) 2 (B)	5/17/74 2/6/75	GEO, 21.8 h, 1.8° GEO, 23.9 h, 0.1°	3 Ah	2 20 cell	Ford/EPI
GOES-1, SMS-C 2 3	10/75 6/77 6/78	GEO, 24.05 h, 1.0°	3 Ah	2 20 cell	Ford/EPI
GOES-C	8/80	GEO, 24.05 h, 1.0°	6 Ah	2 27 cell	Hughes/GE
GOES- . . 10		GEO, 24.05 h, 1.0°	12 Ah	28 cell	Loral/GAB
IUE	1/26/78	HEO, 23.9 h, 45469X25722, 28.6°	6 Ah	2 17 cell	GSFC/GE
SMM	Feb 80	LEO	20 Ah	3 22 cell	MDESC/GE
TDRS-A . . D (4)	4/83 . . 3/13/89	GEO	40 Ah	3 24	TRW/GE
HCMM (AEM-A)	4/26/78	LEO, 96.7 m, 646X558, 97.6°	9 Ah	1 21 cell	Boeing/EPI

Table A1. NiCd Batteries Used on GSFC Spacecraft (Selected List)

Spacecraft	Launch Date(s)	Orbit (kmXkm) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
SAGE	2/18/79	LEO, 96.7 m, 661X548, 54.9°	9 Ah	1 21 cell	Boeing/EPI
GRO	4/5/91	LEO, m 445X459, 28.5°	50 Ah	6 * 22 cell	MDESC/GAB
UARS	Sep 91	LEO, m 600X600, 57°	50Ah	3 * 22 cell	MDESC/GAB
EUVE		LEO, m 528X528, 28.5°		50 Ah	MDESC/GAB
TOPEX	Aug 92	LEO, m 1336X1336, 66° (Frozen Orbit)	50Ah	3 * 22 cell	
ERBS	Oct 84	LEO, m 610X610, 57°	50 Ah	2 22 cell	MDESC/GAB

* Consists of one or more Modular Power Systems (MPS). Each MPS contains three (3) 50 Ah, NiCd batteries.

** Sonotone's cylindrical F cell was typically rated at 5 Ah.

with EPI. Results from the cell development were used as the basis for manufacturing flight cells. However, the results obtained from tests of eight flight lots indicated considerable variation in cell performance within a lot and from lot to lot.

Batteries from these lots were subsequently flown on SMS-1, SMS-2, GOES-1, GOES-2, and GOES-3 from 1974 through 1978. The early flight performance of these batteries was acceptable; however, as the batteries aged, they required considerable "pampering" by the ground controllers during charging to keep the battery voltages within safe limits.

The spacecraft bus proposed by Boeing for the Heat Capacity Mapping Mission (HCMM) and the Stratospheric Aerosol and Gas Experiment (SAGE) was similar to that used on the S-3 military satellite. In fact, EPI indicated that the 9.0 Ah battery design was identical to that flown on the S-3 satellite (Ref. 13). The design life for both HCMM and SAGE was 1 year.

Within 6 months of the HCMM launch in April 1978, the battery began to exhibit symptoms of premature degradation, i.e., "softening" of the charge voltage and loss of discharge voltage and capacity. Over the next several months, all evidence indicated that several cells had intermittent "soft" shorts. Through considerable efforts on the part of ground controllers, the HCMM spacecraft continued to operate in a degraded mode until September 1980, when it was turned off.

The battery on the SAGE spacecraft, launched February 1979, exhibited similar symptoms of degradation after only 2 months in orbit. This battery had been used for 6 months in I&T on the HCMM spacecraft and was flown on SAGE, since the SAGE flight lot had exhibited significant degradation in only 6 months of ground test. In 4 months, the SAGE battery capacity was down from 9 Ah to just over 1 Ah. Even with severe battery degradation, operational modes were modified, and the SAGE spacecraft acquired 82% of mission events. To date, no other GSFC spacecraft has flown conventional NiCd cells or batteries manufactured by EPI.

The lessons learned from the above experiences with EPI cells were that plate- and cell-manufacturing processes are somewhat of an "art," as well as a science. Also, short-term (cell and battery acceptance) testing is no indication of long-term in-flight performance. Results from these two programs made it absolutely clear that the key to successful flight operation of NiCd batteries must start with stringent control of the raw materials and the processing of these materials at every step in the manufacturing process. The life and successful operations of NiCd batteries for a mission is already determined by the time the cells are finally sealed with electrolyte. Thereafter, the user can alter or accelerate the cell's degradation mechanisms by improper handling and use of the battery. However, the user cannot remedy basic manufacturing defects made into the sealed cell by testing.

The conventional NiCd cell design used in today's batteries has gone through many design iterations over the past three decades. An extensive treatment of NiCd cell theory, manufacturing techniques, testing, and applications is provided in the publication, Sealed-Cell Nickel-Cadmium Battery Applications Manual (Ref. 1). This applications manual is recommended reading for all battery engineers and technicians.

THE FIRST DECADE (1960 1969)

The first 10 years of the space program can be characterized as an intense learning period by the manufacturers and users of NiCd cells. Most of the processes and procedures used to make NiCd cells were considered proprietary by the manufacturer. A product was produced to the manufacturer's specification, and the users expended a lot of effort trying to understand why the product did or did not perform for a given mission. The experiences were mostly trial-and-error by the manufacturers and users. Each was struggling to understand a product that was short on theoretical understanding and long on manufacturing problems revealed by a new high-performance application for the technology. One tended to learn as much from mistakes as from successes.

During the initial years of the space program, the cylindrical cell was used extensively. The cell consisted of two plates and used "jelly roll construction" with the separator sandwiched between the plates. The rolled plates were inserted into a cylinder with one terminal isolated by a glass-to-metal seal. The cell case was used for the second terminal. A variety of separator material was used, depending on the manufacturer. Since the plates had to be "rolled" into a spiral configuration, they were usually very thin and developed cracks as the roll was made. Commercially available NiCd cells used in numerous low-performance applications still use this construction technique. One of the principal disadvantages of the cylindrical cells was the lack of reliability. Shorts in cells were not uncommon, which made them undesirable for space applications. Since cylindrical cells were pressure containers, the battery package was usually relatively light.

The introduction of prismatic cells in 1962 formed the basis of what has become the primary method of construction for all aerospace NiCd cells manufactured today. The prismatic cell has undergone many changes in both physical construction and plate design; however, the basic material such as stainless steel cases and nickel-plated substrate for the plates with ceramic-to-metal seals has been used consistently for almost 30 years. Early case wall thicknesses were typically 0.022 to 0.029 inches. Cell cases today range from 0.012 to 0.019 inches. The thinner case walls offered less rigidity to the compression forces usually required in battery construction; consequently, a substantial part of the compression load may be transmitted to the plate and separator-stack reducing interelectrode spacing. Cells made during the 1960s were usually manufactured with plates that were a cut-down version of 20 Ah plates. Consequently, cells smaller than 20 Ah were made with plates, in which the bottom and side edges had been sheared. This created conditions for cells to short, since the plate edges tended to flake off from handling during manufacture and also during use. This led to the requirement to "coin" all plate edges.

Coining is the process of stamping the sinter, increasing its density and thereby strengthening the plate edges. Even when coining of all edges is required, there is considerable variation in the degree or depth of the coined area. The only known drawback of coining is the slight loss of active area (less than 1%) that results in a penalty in specific energy density (watt-hours per lb), since the area of active material is reduced (Ref. 16). The increase in cell reliability far outweighs the relatively small loss in active material area. Plate coining dies, for the most popular cell sizes are currently available and routinely used by the manufacturers.

The effects of quantity and concentration of electrolyte on NiCd performance were not well-understood during the early 1960s. The reader is reminded that the operation of a sealed NiCd cell relies on a degree of electrolyte starvation (see Section 2). Consequently, there has always been a debate on what constitutes a sufficient amount of electrolyte. The aerospace cell produced during the 1960s generally contained concentrations of 31% to 34% and had a minimum of 3 cubic centimeters (cc) of KOH per rated Ah. It was only during the late 1960s, that the users began to understand that the life performance of cells was extremely sensitive to the amount of electrolyte placed in a new cell. All evidence (Ref. 1) indicates that the NiCd cell is relatively insensitive to concentration of KOH in the range of 22% to 38%.

The cells manufactured during the 1960s, (Ref. 17) tended to have thick positive plates (0.032 inches), thin negative plates (0.026 inches), and were "unsized" by the manufacturer. The thick plates were directed at high-energy density, since the ratio of active material to sinter and substrate was less. Loading[8] for the negative plate (2542 gm/dm^3) was significantly higher than the positive (2130 gm/dm^3). It should be noted that most space applications for this cell design were in the range of 5% to 12% DOD in low-Earth orbit; consequently, the discharge and charge rates were relatively low. Cells manufactured with plates of this design typically produced negative to positive ratios of 1.2 to 1.4. The only published data found for positive plate thickening or expansion for this plate design (Ref. 18) shows about the same percentage increase as cells manufactured more recently.

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[8] Loading refers to the grams of $Cd(OH)_2$ for negative plates and grams of $Ni (OH)_2$ for positive plates.

"Sizing" is the process by which plates are all brought within thickness specification by a stamping machine that ensures that plate thickness does not exceed a specified maximum. The sizing operation is unique to the GE process and is intended to ensure uniform plate thickness. Electron microscope images of plates show that severe compacting or crushing of plate surfaces occurs on some plates. Some loss in utilization of active material results from this process.

The earliest aerospace cells used glass-to-metal seals with several physical geometries being applied. Throughout the 1960s, leaks from these seals proved to be a frequent failure mode. For this reason, almost all cells used a single seal terminal with the second terminal being the cell case. In 1969, a nickel-braze seal, manufactured by General Electric Tube Division, was evaluated and placed on life test. This seal proved to be ultra-reliable and seals of this design heritage are currently used today. The availability of reliable seals allowed the use of dual seals on each cell to isolate the cell case. The dual seal design, along with an inert case liner, eliminated another potential failure mechanism at the battery level if a cell case shorted to another cell case or battery frame.

The use of additives or treatments to enhance characteristics of aerospace cells had become widespread by the late 1960s. The General Electric Co. offered a variety of treatments or additives in an attempt to customize a cell design to a specific application. One of the earliest additives used was carboxy-methyl-cellulose (CMC) added to the binder for the nickel slurry. The specific reason for the use of CMC by different manufacturers is not fully understood and has never been documented; however, cells with CMC appear to have a higher charge voltage than cells without it. There was some evidence to cause suspicion that CMC also increases the carbonate content of cells.

All manufacturers experimented with cobalt as an additive to the nickel electrode. The effect of cobalt as an additive is summarized by Scott (Ref. 1). The use of cobalt additive improves the charge acceptance of the nickel electrode at elevated temperatures, i.e., above 25°C with a corresponding increase in capacity to 1.0 volt. It is noted, however, that while the added cobalt increases initial specific capacity, it may not increase specific energy delivered to a constant power load. From numerous studies, it appears that levels of approximately 10% are optimum for high-temperature applications. Below 25°C, no obvious improvements are evident with this additive. Life tests by NSWC, Crane, have shown no clear advantage or disadvantage with regard to cell life (Ref. 18A).

A plate treatment referred to as PQ treatment was introduced for the positive electrode, by General Electric, in approximately 1969. The treatment consisted of incorporating a small percentage of cadmium material to the active material of positive plates.

It was believed by the manufacturer to provide a temporary protection against the effects of cell reversal. Another advantage cited was to improve charge acceptance or plate utilization of the positive plate at elevated temperatures. As will be discussed later, none of these advantages were proven with extended life tests.

A process by which the negative plates were coated with Teflon was introduced in cells made by General Electric, for the Small Astronomer Satellite (SAS-B), in 1969. Cells manufactured with Teflon-coated negatives generally could accept more KOH (for the same overcharge pressures) than cells without Teflon. This was attributed to the enhanced oxygen recombination at the negative electrode because of the Teflon. Claims stated in patents for the Teflon-coated electrodes included the retardation of cadmium migration. The use of Teflon by GE appears to have been an outgrowth of work done under contract to the GSFC to develop oxygen-sensing and recombination electrodes for NiCd cells (Ref. 19).

The very early method used for battery charging was usually constant current. This was possible since the DOD was typically less than 10% in low-Earth orbit LEO applications. However, as system demands increased, and a better understanding of the NiCd capability was realized, greater DOD was used. This required higher charge rates to recharge the battery each orbit. Higher charge rates created the need for a more precise charge control to minimize battery heat dissipation in overcharge. A number of charge-control methods were investigated and flown in satellite applications. These methods included electronic ampere-hour meter, third electrode (oxygen-sensitive electrode inside cell), cadmium-cadmium coulometer, and temperature-compensated voltage limit control. While each of these methods had merit in a given application, the method that proved most effective and flexible for LEO missions was a family of voltage-temperature V/T limits.

The loss of the first Orbiting Astronomical Observatory (OAO) satellite, in 1966, because of battery failure, after several weeks in orbit, placed new emphasis on the charge control of NiCd batteries. The OAO-A1 failure was attributed to "thermal runaway" between the batteries and charging system. The charging of the 3 batteries after each eclipse was done sequentially, i.e., one battery was charged to a predetermined voltage point, at which time the charger sequenced to the next battery and charged it to the voltage set point. The failure occurred when one battery did not reach the voltage set-point and continued to be charged at a very high-rate. The excessive overcharge caused the temperature of the three batteries (shared common radiator) to rise, which further decreased the battery voltage. The mismatch between the negative temperature coefficient of the battery voltage and the temperature-compensated voltage set point of the charger did not allow the charger to sequence to the next battery.

The battery charging system for subsequent OAO missions was completely redesigned. The new system used eight commandable temperature-compensated voltage levels for charging the three batteries in parallel (Ref. 20). After each eclipse, the batteries were charged until the selected voltage was reached, at which point the charge current was forced to "taper" to maintain the voltage limit at the battery terminals. The voltage limit was selected to provide a recharge ratio appropriate for the particular set of operating conditions (temperature, DOD, solar array output, etc.). The V/T levels were set to match the temperature-coefficient of the battery voltage.

The lesson learned from the OAO experience was that use of a charge-control technique that depends on defining a battery voltage set point near or in overcharge is not reliable. The very high charge currents available with the sequential charge method further compounded the selection of the voltage switch point, which tends to be unstable. The voltage limit current taper method causes the current to start tapering around 60% to 80% recharge of the previous discharge capacity instead of the 95% to 100% recharge used by the switch-method of control. With the taper mode, a voltage level is selected for battery recharge to coincide with the end of each sunlight period.

The work performed in the redesign of the OAO system, and the resulting operating success of two subsequent missions, had significant influence on the design of charge-control systems for all GSFC satellites. Most temperature-compensated multivoltage level systems used today have a heritage to those developed for the OAO-A2 spacecraft. There are systems flying today that still use voltage as a switch-point for charge control. However, these systems usually switch from a moderate charge rate (C/4 to C/8) to a low (C/10 to C/15) charge rate, prior to reaching full recharge. Final charging is completed in the low-rate mode. The flexibility of this system to respond to widely varying conditions (solar array output, load changes, etc.) is very limited without ground intervention.

The OAO program provided another lesson learned that had a profound affect on all future cell manufacturing. During the A2 spacecraft thermal vacuum test, the voltage on all three batteries at low temperature exceeded the specification limit. An investigation revealed that some cells in each battery had no overcharge protection remaining in the cell. After several reviews with the manufacturer, it was determined that the flooded plate capacities were not adequately measured and the method used to adjust the relative state-of-charge of the negative plates in the cell was not done in a manner that lent itself to quantification of the results. New plate-processing procedures (Ref. 20) were implemented, and the controlled oxygen-venting technique for setting precharge came into being. The flight batteries manufactured using the new processes operated over 8 years in orbit when the A2 spacecraft was turned off.

During the same time that the OAO cells were being built, several users received cells with Pellon 2505 ml (maximum loft) separator material, which contained a "wetting agent." The wetting agent was desirable in separators for commercial cells because of the fast wet time needed in a high-volume commercial manufacturing line (Ref. 21). Cells with separators using a wetting agent exhibited similar symptoms as cells with no overcharge protection, i.e., high voltage in overcharge -- especially at low temperature. From this experience, a number of screening tests (organic and inorganic content, wettability, strength, porosity, etc.) were devised that set the standards still being used today to determine the acceptability of nylon separator material.

By the end of the 1960s, cells failing because of seal leaks, shorts, impurities, and poor workmanship had all but disappeared. With these problems eliminated, the user began to make great strides into understanding wear-out mechanisms, which determine the operating life of NiCd cells.

The first decade of flight applications of NiCd cells evolved the NASA Interim Model Specification (Ref. 22) that was published in April 1969. It became the benchmark for specifications used in the GSFC procurement of all batteries for space flight using conventional NiCd cells. Subsequently, GSFC engineers developed several "procurement" versions of the model specification that were used during the early 1970s.

The first GSFC Battery Workshop was held in November 1969. The workshop originated out of an ad hoc meeting the previous year among a small group of users to discuss problems with Gulton Industries cells. This workshop provided a forum in which users and manufacturers met to discuss and debate the theoretical and practical aspects of NiCd cell manufacturing and the sharing of test and flight experiences. The workshop became the single and most important forum for Government, aerospace industry, and battery-manufacturing personnel to collaborate on numerous common items of interest. A new era of direct user-involvement with the manufacturers in the development of aerospace NiCd cells was initiated.

THE SECOND DECADE (1970-1979)

While the first decade may be characterized as one of experimentation to improve cell design, the second decade is best characterized as one of optimizing the design from a better understanding of the complex interactions of the manufacturing processes on cell life. Government-funded activity, initiated during the late 1960s, to understand the manufacturing processes and characterize these processes with the goal of optimizing initial- and life-performance of aerospace cells continued into the 1970s. Results of this effort began to provide the manufacturers and users with a broad knowledge base of materials, processes, and testing required to assure highly-reliable aerospace cells.

In 1974, a specification (Ref. 23) for NiCd cells was developed that established a uniform set of requirements for all the GSFC projects to implement with the prime contractor in procurement of flight batteries. This specification was the "third generation" of the Interim Model Specification. It established detailed stepwise processes, maximum and minimum requirements and traceability of all materials and components, more frequent and higher levels of sampling and inspection, delivery of material samples, destructive tests and analyses on cells to verify effectiveness of a process, standardized acceptance testing, and delivery of a complete data package. Another very important provision of this specification was that it established formal customer "buy-off" review of data at critical points in the manufacturing process. The ability to develop better specifications, although improving the product, does not in itself assure success.

Another factor that must be recognized was the continuing demand by the users to improve the specific energy density of NiCd batteries. The need to place larger and larger payloads into space continued to place a premium on component weight. Since the batteries constitute the largest component by weight of a spacecraft power system, there was constant pressure to reduce battery weight. Consequently, the users continued to pressure the manufacturer to improve cell energy density. This was sometimes, mistakenly, done through specifications rather than technology improvements.

In a competitive environment, there was no option but for a manufacturer to respond to high-performance specifications by "tweaking" the plate loading (active material) towards the high side of his specification to meet the requirement. Such parameters as plate pore-volume, level of KOH, interelectrode spacing, and separator compression were usually compromised as a result of the user's misguided push towards higher energy density. In extreme cases, the manufacturer would not coin all edges of the plates in order to gain the use of this small area. The increased loading usually resulted in an increase in initial capacity; however, complications invariably were experienced with the cells during the manufacturer's and/or user's acceptance test. These complications usually were in the form of cell overpressures, cell overvoltage at low temperature, and/or erratic-capacity performance.

The out-of-specification condition usually required a "rework" of some, or a complete lot of, cells to bring parameters within specifications. Cell rework constituted a variety of options the manufacturer might choose (with discretion) to bring the out-of-performance parameter within specification. Examples include readjusting the precharge, changing the amount of KOH, flushing finished cells with hot KOH, cutting open the cell to replace the separator, etc. As a result, many cell lots were "engineered" through acceptance testing, making each lot unique to some peculiarity of a variable in the process. The acceptance of reworked cells was done based on acceptance test-data with little insight into the impact on life-performance over a 5- or 10-year space mission. Attempts by the user to limit or control unauthorized reworks led to additional requirements in the next procurement specification.

It became apparent that the life-limitation of NiCd cells, for most space missions, was caused in-part by the lack of understanding of the complexity and interaction of the manufacturing variables. It became equally clear that attempts by the users to improve specific energy density through more stringent specifications were driving the cell manufacturers to make compromises in their processes that were not in the best interest of long-life aerospace cells. Perhaps the most disturbing part was the inability to predict life-performance of a current production lot based on previous extensive life test, since the variables in the manufacturing process and reworks made each lot unique. It should be understood that life tests are conducted by the user after the cells have been accepted.

In early 1970, the GSFC awarded a contract to EPI to conduct a cell design and process variable study (Ref. 24). The purpose of this study was to understand some of the complex interactions of the manufacturing process on cell performance, and to define manufacturing-tolerance on the processes that would provide a high user-confidence that the cell being manufactured would yield predictable life performance. A secondary objective was to establish EPI as an alternate source of NiCd cells for the GSFC satellites. The cells from this development effort were to be hermetically-sealed (no pressure relief) to prevent any possible contamination of the satellite and its payload.

During the 2-year process study, EPI performed a number of parametric studies. These included the variations associated with the sintering of plaques from dry powder, impregnation of plaques, loading level of plaques, reduction of impurities such as carbonate and nitrate, additional formation cycles, electrolyte levels in cells, and setting precharge. The results of this study indicated that the manufacturing process could be controlled and reproduced. EPI offered the potential of becoming a supplier, with a small and dedicated aerospace production line, ideally suited for aerospace users. Unfortunately, cells delivered from this program were found to have defective plate-to-tab welds that resulted in high impedance. Consequently, no life tests were performed.

Upon being awarded a contract for the SMS and GOES satellites in December 1970, Ford Aerospace initiated a cell-development program with EPI. The development program was to determine the design-parameters to be used in manufacturing flight-cells. The cell-design activity was based on the knowledge already gained from the GSFC-sponsored process variable study and evaluated electrolyte levels, plate-loading levels, and extra formation-cycles on the plate, prior to cell assembly (Ref. 12). Three groups of development cells were used to evaluate electrolyte level, loading levels, and the effects of a flooded cell-formation cycle. Additionally, some cells were constructed with different levels of precharge.

It should be noted that EPI's method for setting precharge consisted of cycling and overcharging the flooded-cell, while the cell was vented to the atmosphere. This was followed by a "power" discharge of the negative using the cell case as the counter electrode. This technique was not ideal, since the actual state-of-charge of the negative could not be ascertained to any degree of certainty. Also, for current to pass between the negative plates and cell case implied a relatively low-resistance cell liner. When the precharge adjustment was completed, the excess electrolyte was "dumped" out by inverting the cell. Throughout this sequence, the cell was exposed to the atmosphere, since the fill tube was open.

The results of the cell-development program showed the following:

- Acceptable positive plate loadings were in the range of 11.6 to 13.3 gm/dm^2.
- High-rate formation cycles enhanced the active material utilization.
- Electrolyte fill levels of 12.6cc (4.2cc/Ah) to 13.3cc (4.4cc/Ah)[9] of electrolyte were acceptable.
- Using low-rate power discharge usually resulted in more precharge than calculated.

A total of nine cell lots were manufactured for the SMS and GOES satellites. The production revealed that a wide range in plate loadings resulted from the EPI process, a large variation in precharge resulted from the "power" discharge method, and electrolyte fill levels were very sensitive to plate loadings. It is noted that electrolyte fill levels are relative only within a manufacturer's product line; i.e., 3cc/Ah for EPI cells is not comparable with 3cc/Ah for GE cells because of different manufacturing techniques.

Each cell lot had its own peculiarity in performance, with no two lots of cells being identical. Typical test anomalies included high pressure during overcharge, high-cell voltage on overcharge, wide variation in capacity at elevated temperatures and two lots having internal-weld defects. The defective welds were of the same generic problem found in the process-variable cells described above. The defective plate-to-tab welds were caused by the use of different metals without changing the weld schedule.

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[9] Electrolyte fill level (cc/Ah) is calculated using the manufacturer-rated capacity for the cell design.

During tests at the battery level, initial high-cell charge voltages were observed following shorted storage periods for two lots. Cell voltages at the start of charging ranged from 1.4 to 1.6 volts for a C/20 charge rate and would decrease with time on charge and cycling. Similar anomalous performance was observed following 1-ohm discharge of individual cells. This was one of the earliest observances of this unusual characteristic. Additionally, some batteries exhibited increase in overcharge-voltage after being stored 2 years in a discharged and shorted condition (0° to 5°C storage).

The initial on-orbit performance of these batteries was within acceptable standards; however, as the batteries aged, higher voltage was observed in overcharge, which required considerable attention from the ground controllers. The acceptable performance may, in part, have been attributed to the benign environment the batteries experienced in the synchronous orbit applications.

The second flight application of EPI cells, for a GSFC satellite, resulted when Boeing Aerospace was selected as the prime contractor for the HCMM and SAGE spacecraft. The spacecraft bus proposed by Boeing for the HCMM and SAGE was very similar to the S-3 satellite built for a military program. In fact, EPI claimed the 9.0-Ah battery design was identical to that flown on the S-3 satellite. The design life for HCMM and SAGE was 1 year, and the battery design had performed for 3 years on the S-3 mission (Ref. 13).

The flight cells were manufactured by EPI to meet the "intent" of the GSFC NiCd cell specifications. However, in actual practice, most of the exceptions taken to the specification by EPI were granted. This was based on the argument that the cells for the S-3 program had a design and performance heritage and that changes should not be made to the process. Two cell lots were manufactured, one for each satellite battery. Cells from both lots were placed on life test by NSWC, Crane.

Five months (2,100 orbits) after the launch (April 1978), the HCMM battery began to exhibit symptoms of premature degradation, i.e., "softening" of the charge voltage and loss of discharge voltage and capacity. This was first manifested as an unexplained increase in battery temperature. Reducing the voltage charge level was only partially effective, and by orbit 3,811, a spacecraft undervoltage occurred. Efforts to increase battery recharge resulted in battery temperature increasing with little or no effect on battery end-of-eclipse voltage. By this time, the trend had become well-established; i.e., the battery discharge voltage was steadily decreasing, while battery temperature continued to increase.

Over the next several months, all evidence indicated that several cells had intermittent "soft" shorts, which is a phenomena in which a cell will have a significantly reduced voltage on charge and discharge for extended cycles, and then recover. This characteristic is not uncommon on cells near the end of their useful cycle life. Through considerable efforts on the part of ground controllers, the HCMM spacecraft continued to operate in a degraded mode until September 1980, when it was turned off. Mission end-of-life tests (Ref. 14) revealed battery capacity to 16 volts (21 cells) at 1.1 Ah.

In parallel with the HCMM operations, the SAGE spacecraft was being prepared for launch. Cells from the flight lot of the SAGE battery on test at the GSFC had exhibited severe capacity loss, premature degradation of charge voltage, and severe loss of capacity on open-circuit stand after only 6 months of test. Based on this early degradation in performance of cells from the SAGE flight lot, the decision was made to fly the HCMM I&T battery, which was from a different cell lot. This battery had been used to support approximately 6 months of spacecraft testing and subsequently, passed additional acceptance-test criteria. Also, when the decision was made, the HCMM flight battery and cells on life test by NSWC, Crane, were performing satisfactorily.

The launch of the SAGE spacecraft occurred in February 1979 with the HCMM I&T battery. After approximately 800 orbits, the battery began to show signs of premature degradation. In just over 2,100 orbits, the battery could no longer support the planned mission. The degradation was similar to that observed on the HCMM spacecraft.

Analysis of cells from both lots revealed very high-carbonate content, considerable evidence of cadmium migration, thickening on both positive and negative plates, and wide variation in efficiency (55% to 76%) of the negative plates. The early demise of the flight batteries was consistent with the theory of carbonate effect on performance, i.e., lower discharge voltage, increased charge voltage, and decreased charge acceptance (Ref. 15). Analyses by other investigators had shown that the presence of carbonate significantly enhances cadmium migration and the solubility of cadmium species.

During the investigation, it was revealed that a design change had been made in the fabrication of each battery pack. To meet the outgassing requirement, Boeing requested that EPI replace the fiberglass material used to wrap each cell with Teflon 3M-63 tape. Additionally, the mechanical assembly of each seven-cell pack had no control on the amount of pressure applied when torquing up the end plates. The build instructions required the jigged-assembly to be tightened to the stop. There was no limit on amount of pressure applied to the cell case when the pack was fabricated.

The HCMM and SAGE battery anomalies were not consistent with the performance of the HCMM life-test cells at NSWC, Crane. The test cells did not indicate the rapid and severe degradation exhibited by the flight batteries. After 2 years of cycling, these test cells had a capacity from 7.5 to 9.5 Ah. A tear-down analysis showed that these cells had more cadmium migration than expected, but the capacity was not reduced as experienced on orbit. Similarly, the NSWC test cells showed occasional increase in recharge ratio but unlike the two satellite batteries, this could be controlled by reducing the battery charger voltage.

The only known difference between the life-test cells and the flight batteries was the mechanical assembly and the thermal dissipation capability. The test packs at NSWC, Crane, were assembled with large 1/4-inch aluminum fins between each cell, with each cell being contained with 10 to 14 inch-pounds torque applied to the tie rods holding the aluminum plates. As indicated previously, there was no limit on the cell compression for the two flight batteries. Cell failure caused by excessive mechanical compression is the only mechanism that is consistent with observed symptoms and the NSWC test results. Current practices usually limit the cell compression to less than 50 pounds per square inch (psi) on flight batteries.

Given the failure mechanisms of the NiCd cell, one could easily postulate a condition in which excessive compression on cells would result in premature failure. An HCMM spacecraft anomaly on July 13, 1978, was thought to be caused by a large surge current in the spacecraft ground loop. A probable cause of this was thought to be a breakdown between one or more cell cases and the battery frame. Tests on cells at NSWC, Crane, where the cell case of the fifth cell in a pack was shorted to ground produced a current in excess of 100 amperes and 217 psia in 2.4 minutes. It was subsequently revealed that the plate stack liner was of Pellon material, not the nonconductive liner required by the GSFC specification. Tests of cells with a nonconductive liner had previously shown very low currents under similar conditions.

By the early 1970s, GE offered aerospace cells with a variety of additives and/or treatments. These included a "PQ" positive plate, negative plates with silver treatment, negative plates with Teflon treatment, electrolyte with lithium additive, and a carbonate-reduction process (Ref. 10). The use of a specific treatment or additive was sometimes done without consultation with the users. As a result, cells with additives or treatments began to show up in flight hardware. Only if there was a cell failure, test anomaly, or a chemical analysis, did the user become aware of what was in a given lot of cells.

In 1973, Goddard initiated a program with General Electric to evaluate the effects of reduced loading of active material on cell performance. The objective was to produce a prototype design for the International Ultraviolet Explorer (IUE) mission, which was critical on weight and design life at synchronous altitude. The underlying theory was that lighter loaded plates would allow more KOH, decrease positive plate expansion, both of which would minimize separator drying and cadmium migration over the life of the cell. This program was directed at optimizing the cell design for maximum DOD utilization over the mission life. The test results were documented in the NSWC annual reports, such as references 1A and 2.

The initial effects of reduced plate loading of approximately 10% allowed the KOH fill level of 4cc per rated Ah, whereas previously, the same cell design could only accommodate 3cc per rated Ah. The reduction in loading of the positive and negative plates had no significant effect on final cell capacity; in fact, a significant improvement in capacity performance at 35°C (Ref. 25) was observed. The 10% reduction was on the lower limit of the manufacturer's specification. To date, batteries with this cell design have provided over 14 years of life at 60% DOD in geosynchronous-Earth orbit (GEO) on the IUE spacecraft (Ref. 8).

The initial success of the above program led to a cooperative effort with GE to evaluate a number of cell designs and/or treatments that GE had previously offered or currently offered the users of aerospace cells. The program started in 1978, and ran over a period of 8 years, when it was concluded with destructive analysis of cells from each test condition. There is extensive documentation (Refs. 10, 11, 17, 18, and 26) summarizing the scope and salient findings of this work. A brief overview of data found in these references is provided herein, since the results are very germane to understanding the design heritage and evolution of the NiCd aerospace cell.

The nine design variables were chosen in consultation with G. Rampel of General Electric and were deemed to be the most important designs used prior to 1975. While many of these variables had been tested and evaluated by others over the years, there had not been a systematic approach to compare the relative merits of each design. A brief description for each design is provided to illustrate the design heritage of the NiCd cell.

Group 1 - Control

- Pack 3D
- Represented the aerospace cell design as of 1978
- Loadings on the light side of GE specifications
- Positives had cadmium treatment (PQ)
- Used Pellon 2505 ml nylon separator
- Plates received decarbonation treatment
- Test ended May 1983 after 23,467 cycles

Group 2 - Teflon-Treated Negatives

- Pack 3E
- Same as Control except negatives treated with Teflon level II
- Sightly more KOH than Control group
- Test ended May 1982 after 17,759 cycles

Group 3 - Silver-Treated Negatives

- Pack 3F
- Identical to Control except negatives treated with silver
- Slightly more KOH than Control group
- Test ended May 1982 after 17,781 cycles

Group 4 - Light Loading

- Pack 3G
- From same impregnation batch as Control group but with less active material (loading) pickup
- No Silver or Teflon Treatment
- Approximately 5cc of KOH more than Control group
- Test ended May 1982 after 17,854 cycles

Group 5 - No Cadmium Treatment (PQ) of Positive Plates

- Pack 3H
- Identical to Control group except no PQ treatment
- Test ended May 1983 after 23,281 cycles

Group 6 - Polypropylene Separator

- Pack 3I
- Identical to Control group except use of polypropylene separator
- Test ended May 1982 after 17,671 cycles

(Note: All other groups used Pellon 2505 ml separator.)

Group 7 - AK Old Cell Process

- Pack 3J
- Plates manufactured to specifications used during mid-1960s
- Plates not sized
- Negatives not depleted during flooded cell test
- No treatments or decarbonation
- No precharge adjustments made after cell assembly
- Test ended May 1983 after 23,334 cycles

Group 8 - AK Present Cell Processing

- Pack 3K
- Plate lot identical to Group 7
- Cells processed using same aerospace procedures as Control group
- Test ended May 1982 after 17,299 cycles

Group 9 - Electrochemically Impregnated Positives

- Pack 3L
- Positives were electrochemically impregnated
- All other designs identical to Control group
- Test ended May 1982 after 14,826 cycles

(Note: This was an early attempt by GE to use this new process.)

On new cells, the negative-flooded plate utilization showed a linear decrease with loading over the range of 1800 to 2500 gm/dm^3. Positive plate utilization in flooded cells appeared independent of loading over the range of 1850 to 2150 gm/dm^3, while the final (sealed) cell utilization decreased significantly with loadings above 2100 gm/dm^3. This data confirmed early observations that high plate loading compromised the performance of cells.

The groups of 12-Ah-rated cells were subjected to the GSFC standard acceptance test and placed in a low-Earth orbit cycling regime with the following parameters:

Temperature	20°C
Depth of Discharge	40% of rated capacity
Orbit Period	90 minutes (30 Discharge/60 Charge)
Charge Current	9.6 amps current limit to voltage limit (1.453 V/cell typical)
Discharge Current	9.6 amperes

During the 17,000 cycles (> 3 years) completed by cells in groups 2, 3, 4, 6, and 8, and over 23,000 (> 4 years) completed by cells in groups 1, 5, and 7, a periodic capacity test and cell-destructive tests were conducted to measure rate of degradation with cycle life.

After extensive analysis of data (Refs. 11 and 18), the conclusions provided in Reference 10 were as follows:

> "It is clear that cells manufactured with the fewest plate additives and treatments performed best (no PQ and Control). The worst performance among the present designs came from groups with the most additives and treatments (teflon and silver). Also, electrochemical impregnation proved itself to be a viable alternative and, perhaps because of its characteristics, a preferred manufacturing process for nickel-cadmium aerospace cells."

This test illustrated in a very conclusive manner, that for the GE NiCd cell design, the "unadulterated" (no additives or treatments) NiCd cell provides the best life performance for aerospace applications. Several observations are noteworthy. The group without cadmium treatment had the lowest capacity loss (15% vs. 35% for Control) at the end of three years and the highest end-of-discharge (EOD) voltage (typically 1.14 vs. 1.05 for Control) of all test groups. The next best EOD voltage was the AK Old Cell Process Group at 1.12 V/cell. One could easily surmise from this that the cadmium treatment contributes to both capacity and voltage degradation. Cells with no treatment placed on life test by the GSFC at the NSWC, Crane, during the 1960s confirm this conclusion.

The conclusions from the design-variable test program points out that the design of the aerospace NiCd cell is generally optimized to meet initial performance requirements. This is evident in the fact that some treatments/additives generally enhance specific performance parameters (capacity, pressure, voltage) during the manufacturer's and customer's acceptance tests. However, as the design-variable program has demonstrated, these treatments/ additives do not contribute to long cycle life. The lessons learned from this program are that the best aerospace cell design for long cycle life has high utilization of the active material (by limiting plate loading), contains a generous amount of KOH (approx. 4cc/Ah), and has no additive or treatment.

While considerable work was being directed at understanding the manufacturing effects on life performance, the user made significant progress in gaining insight into the operational aspect of NiCd batteries in space applications. This included the design of an effective charge-control system for batteries, characterizing the thermal properties of cells and understanding the voltage degradation phenomena associated with long-term repetitive cycling. The eight-level, temperature-compensated voltages used for charge control in the modular power system (MPS)(shown in Figure 3), were a further refinement of the system developed for the OAO program.

The eight levels were chosen to provide battery overcharge control under a wide range of orbital conditions, i.e., load variations, array outputs, vehicle altitude, inclination, etc. The lowest voltage level provided charge control of batteries being charged in parallel with one battery containing a shorted cell (Ref. 27). The MPS also incorporated three commandable constant-current charge rates to be used for trickle charging the batteries. This feature was added primarily to accommodate the use of the MPS in geosynchronous missions. The effectiveness of the multilevel voltage-charging system has been proven on numerous spacecraft (OAO-A2, OAO-C, OSO-I, SMM, ERBS, TIROS, Landsat-4 and 5, etc.). These missions have a combined cumulative space operating time estimated to be in excess of 50 years.

Much has been written on the subject of battery voltage degradation with cycle life. By the mid-1960s, the phrase "memory effect" had been coined to describe the phenomena associated with the loss of battery capacity to a predefined voltage. It had been well established that the EOD voltage of NiCd cells decreases with cycling, as is shown in Figure A1. This figure summarizes cycle tests done on GE 20 Ah NICd cells for the OAO program and illustrates the decrease in discharge voltage as a function of cycle life (Ref. 29 and 29A). It shows the primary degradation to be the development of a so-called "second plateau" in the discharge voltage level. The occurrence of this second plateau occurs sooner with increased life (cycles). For example, on new batteries, over 90% of the capacity can be obtained on a discharge to 1.2 volts per cell. After 6 months of cycling (~3000 cycles) at a moderate DOD, the amount of capacity to 1.2 volts may be less than 50% of that obtained on an uncycled battery. The selection of the proper system undervoltage had become more critical with increasing DOD and life demands imposed by new missions.

Significant progress (Ref. 28) was made in characterizing the "memory effect." What emerged was an understanding of the relationship between the voltage degradation and cell-capacity degradation when cycling at moderate (15% to 25%) DOD. During the early life of a cell, the amount of capacity available to 1.0 volt does not change appreciably with cycles; in fact in many cases (Ref. 29), the capacity to 1.0 volt per cell will show a slight increase during early cycling, as is shown in Figure A1. This is attributed to positive plate changes and KOH redistribution within the cell. What does change with cycling is the available capacity to any given voltage above 1.0 volt. The "memory effect" was shown to be a redistribution of voltage per unit time of discharge. With cycling, a "second-plateau" voltage develops where the amount of capacity available above 1.1 volts per cell decreases, while the amount of capacity below 1.1 volts per cell increases. The mid-voltage range (inflection point) of the upper and lower plateau is approximately 1.15 volts. The rate of change of the inflection point is dependent on cell design, temperature, DOD, number of cycles, and other parameters not fully understood.

The above discussion addresses changes observed during "early" life where permanent wear-out mechanisms are not readily apparent. During this time, the discharge voltage can be restored by "reconditioning" the cell. For the purpose of this discussion, reconditioning is the process in which a cell is discharged to 1 volt per cell, further discharged by a resistive load (.5 to 1 ohm), followed by a short for 4 to 8 hours. Charging is done using a low (C/20)-to-moderate (C/10) charge rate. During the early life of cells, reconditioning is very effective in restoring the available capacity above 1.2 volts. Life-test data indicate that as cell wear-out mechanisms become more predominant, reconditioning is less and less effective. In fact, from the NSWC, Crane, test program, one could surmise that deep discharges on cells after several thousand cycles may lead to cell shorts. This is based on observations that as cells age with cycling, the incidence of cell shorting during periodic capacity checks increases.

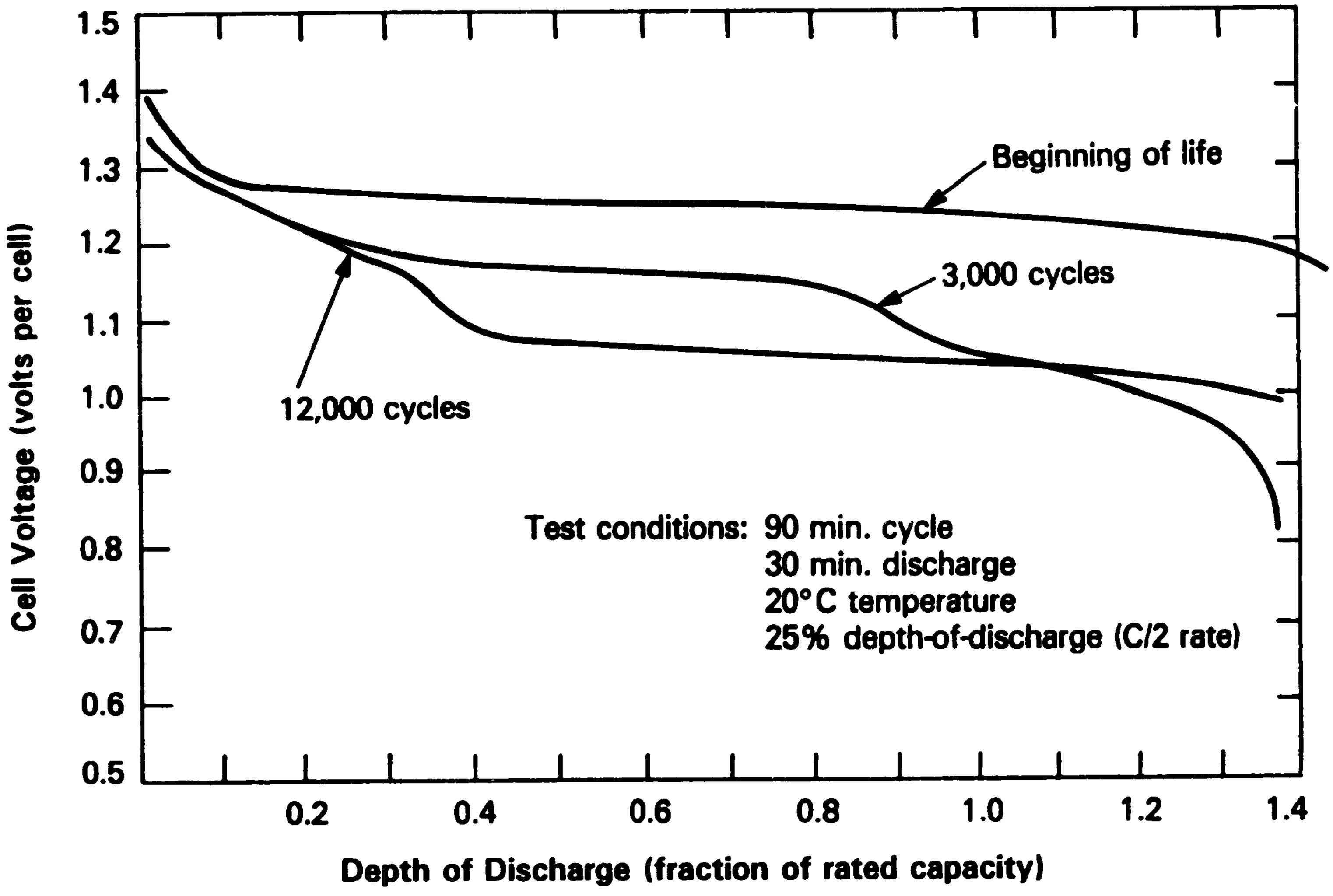

Figure A1. Discharge voltage of GE 20-Ah NiCd Cells vs. cycle life.

[Ref. private communication, D. Baer. Taken from life-cycle data on OAO 2 cells as described in References 28 (1971) and 29 (1972).]

A very important aspect to understand is that the amount of energy obtained at any given time in a cell's life is the same; i.e., you get the same amount of energy on discharge from a cell exhibiting the "second plateau" as you get on a discharge subsequent to the reconditioning cycle, as is illustrated qualitatively in Figure A1. This indicates that while the energy storage capability of a cell degrades with life, at any point in the life of a cell, the storable energy is constant.

With the understanding of how batteries degrade, designs were incorporated into power subsystems that provided maximum flexibility in battery utilization over the life of a mission. Battery undervoltage settings were made commandable and adjusted downward as the battery aged during the mission. More sophisticated techniques used the differential voltage between groups of cells within a battery, or partitioned the battery in cell groups (typically 5), and detected low voltage on each group. When properly implemented, these techniques provided for maximum system safety from cell reversal during deep discharges while allowing maximum battery capacity utilization over the life of a mission. Implementation of the commandable undervoltage, along with the ability to prevent cell reversal, negated the need for on-orbit reconditioning to maintain battery-discharge voltage on these early systems.

By the mid-1970s, the NSWC, Crane, test facility, under the sponsorship of NASA, Navy, and Air Force, had been testing both primary and secondary batteries for over 15 years. NASA's part of the test program was focused on aerospace-type batteries, with over 90% of the effort directed towards NiCd life test. By the mid-1970s, a considerable database had accumulated on life capability of a wide variety of NiCd cells under a wide range of operating conditions. Because of the multiplicity of manufacturers and the design and processing variables, the task of predicting battery life was still an art. In spite of the complexities, depth of discharge (DOD) as a function of lifetime for both LEO and synchronous missions was derived (Figure 1) and became part of the requirement for several GSFC early missions (Ref. 30).

Another significant outgrowth from this period was the awareness and understanding of how NiCd batteries degrade during ground handling and/or storage. Most spacecraft programs would purchase cells, fabricate a flight and flight spare battery, and use the flight battery throughout the spacecraft-integration period, which could be up to 2 years. The storage conditions for batteries, when not on the spacecraft, varied among the users. Most often, batteries were discharged prior to storage, but there were no consistent practices on conditions (temperature, humidity, cells shorted, etc.) once discharged. The "wet life" (point at which cells are activated with KOH) was ill-defined and mostly judgmental on the part of battery manufacturers and users. The long-term effects of storage and spacecraft-integration environment were not understood.

A prerequisite to discussing the effects of storage and spacecraft-integration effects on flight batteries is to review the life determining wear-out mechanisms of NiCd cells. The dominate mechanisms are positive-plate expansion, cadmium migration, separator drying, and loss of overcharge protection. The order listed does not imply order of precedence, since the mechanism that is most prevalent is dependent on the environment and use factor, and the mechanisms are not mutually exclusive from one another. Consequently, environments or uses that promote or accelerate these mechanisms are considered detrimental to the mission life of flight batteries.

From several spacecraft-integration experiences, during the late 1960s, it became apparent that modes of battery operation as experienced during several months of spacecraft integration and test activity were detrimental and resulted in irreversible changes in cell parameters. Even after only a few months of integration activity, cell characteristics showed symptoms of those expected after several thousands of orbits in space.

There had been numerous attempts to quantify the various effects of storage modes on cell degradation. One test that proved to be very enlightening was initiated in 1971 (Ref. 31). This consisted of four packs of cells at room temperature: The first was discharged and shorted; the second was discharged to 1.0 volt per cell and left open circuit; the third was placed on C/40 trickle charge; and the fourth, simulated a spacecraft-integration and test activity, which consisted of intermittent use (random charge or discharge), followed by periods on open circuit. Every 6 months, each pack was subjected to a series of tests to measure change in performance from that obtained on the prestorage test (Ref. 32).

The results obtained were very dramatic. After 6 months, the "integration pack" failed the 0°C overcharge test because of cell overvoltage and high pressure. The discharged-and-open circuit pack failed the test at the 30-month point, the trickle-charge pack failed the test at 42 months, and the discharged-shorted pack passed the test after 60 months, at which time the test program was terminated. The 0°C overcharge test is an indication of the overcharge protection remaining in the cell and is predicated on the fact that negative plate utilization decreases with temperature, while positive plate utilization is near maximum.

Destructive analysis of cells showed extensive cadmium migration on the integration pack after only 18 months. Cells from the other packs showed only minor cadmium migration after the same period. Capacity degradation followed the same trend; i.e., the integration pack showed the worst loss, while the discharged pack showed the least. The amount of electrolyte found in the separator of the integration pack was approximately 80% of that found in the discharged-shorted pack, while the trickle-charge cell separator contained only 50%.

The results of 5 years of tests were suppo ed by findings of other investigators during this period (Ref. 32A). The deleterious effects of spacecraft-integration activity on flight batteries was very conclusive. From this, battery and power system designers developed a high-sensitivity to the proper handling and storage of flight batteries. Once Project Managers were apprised of the risk, test batteries were purchased to support the spacecraft integration, and flight batteries were kept in storage until a few months before launch. The superb life-performance obtained on the batteries for OAO-C, IUE, SMM, Landsat-4 and 5, and ERBS satellites, to a large extent, can be attributed to the care taken to minimize ground handling and spacecraft-integration tests on the flight batteries. Also, the cells for these batteries were representative of the best manufacturing expertise available at that time.

In 1976, NASA initiated a program to develop a standard spacecraft bus concept, which became known as the Multimission Modular Spacecraft (MMS). The design of the MMS required a modular power system to provide an orbital average power from .4 to 1.2 kilowatts maximum, with a peak for 10 minutes up to 3.0 kw day or night (Ref. 30). This MMS design had to accommodate a wide variety of payloads in orbits, from low inclination to polar orbit and from low-Earth to synchronous altitudes. The MMS/MPS requirements dictated a varying energy storage compliment to satisfy the wide range of power and redundancy requirements. Two battery designs were selected as meeting all MPS and MMS requirements. One design used 20-Ah cells and the other used 50-Ah cells. The MPS could accommodate up to three 20-Ah or 50-Ah batteries.

In concert with the MPS development, a program to develop and qualify several manufacturers for the Standard 20- and 50-Ah cells was initiated. In the initial program phase, four manufacturers (GE, EPI, Gulton, and Yardney Electric) were selected to manufacture cells for the qualification and life-test program. The philosophy for the cell procurement was for each manufacturer to build cells to the same specification (Ref. 23), but first to develop a Manufacturing Control Document (MCD) that would be approved and controlled by the GSFC. All subsequent cell procurements for MMS missions would be manufactured to the same MCD. The intent was to establish a known manufacturing baseline for the 20- and 50-Ah cell that would assure consistency and repeatability in performance for all future missions.

The use of an MCD was not new. The difference was that NASA had joint sign-off authority on all changes to the MCD; whereas previously, the manufacturer could (and frequently did) make necessary changes, as long as the cell passed the customers' acceptance test. Company proprietary documents applicable to the MCD were also referenced. This included the manufacturers' acceptance test, as well as the GSFC acceptance test. It is noted that a manufacturer's acceptance test was generally conducted before running the customer's test. It was during the manufacturer's acceptance test that most cell "rework" occurred.

The end result of this effort was that General Electric was the only manufacturer whose cells had successfully completed all qualification tests. The initial phase of the standard cell program proved highly successful and met all the MMS objectives, as evidenced in the excellent performance of the three 20-Ah batteries flown on the Solar Maximum Mission (Ref. 33). The first procurement of the Standard 50-Ah cells for the Landsat-D mission proved equally successful.

The decade of the 1970s renewed the confidence of users that a NiCd cell could be manufactured with a high-degree of uniformity, reliability, and predictability. It also reemphasized the void in understanding the complexity of the cells' chemical, physical, and electrochemical processes; the sensitivity of cell performance to materials and processes; and that specifications and MCDs do not always ensure a successful product. By the end of the 1970s, the impact of the declining research and development funding for NiCd technology programs began to be evident. The manufacturer became less willing to maintain a "dedicated" aerospace production facility for a low-volume, high-quality market in a production environment driven by commercial volume. By the end of the 1970s, old problems began to cause new concerns within the aerospace battery community.

THE THIRD DECADE (1980-1989)

By the beginning of the third decade, most GSFC missions used GE cells for aerospace NiCd batteries because of the success of the standard battery program and the poor performance of batteries manufactured for the HCMM, SAGE, and GOES missions. It is estimated that by 1980, GE was supplying NiCd cells to more than 80% of the aerospace market that used less than 3% of their commercial plate-manufacturing capacity.

In 1980, a new process was initiated in which positive plaques were subjected to a hot gas-passivation process. Cells manufactured for most customers not using the NASA Standard Cell were made with this new process. Since the GSFC would not approve this change to the Standard Cell MCD, this new step was not incorporated into the standard cell. However, some GSFC projects were procuring cells with MCDs controlled by the prime contractor, and cells with passivated plates were used for several of GSFC's satellites (TDRS, GOES, and TIROS/NOAA). The ramifications of process changes are not always evident to the customer until long after the batteries are in service in space.

Starting with the passivation of nickel plaques, other changes were made by GE during the next several years. As a result of these changes, GE shut down the plate-making plant for 3 months in the fall of 1984, to investigate a number of problems that users were experiencing with cells and batteries in the field. A highlight of some of these changes is provided to give the reader insight into the variability in cell manufacturing and the sensitivity of NiCd cells to this variability (Ref. 34). The items listed may not represent all changes made but are felt to be representative of key events over the period.

- June '82: CMC binder for nickel slurry changed.
- September '82: INCO nickel powder-processing source changed.
- September '83: Sinter temperature increased.
- September' 84: Plant shut down for 3 months to resolve problems.
- October '84: Furnace belt speed reduced.
- December '84: Installed larger slurry mixer for positive plates.
- January '85: Installed larger slurry mixer for negative plaques.
- April '85: CMC binder changed back to that originally used.
- June '88: High shear slurry used for positive-plate slurry mixture.
- September '88: High shear slurry used for negative-plate slurry mixture.

In May 1982, an early sign of process changes surfaced during a plate "buy off" review for cells to be used on the ERB satellite. The plates were supposed to be identical to the previous four lots of 50-Ah plates made for the Landsat program using the Standard Cell MCD. However, it was subsequently revealed that these plates were made to an unauthorized plate process. Agreement was reached between all parties to make new plates. In August 1982, the Government was notified that one lot of plates from two new plate lots had been made to an unauthorized process. In this case, there were sufficient plates in the one acceptable lot to satisfy the contract requirements for required cell quantity.

In November 1982, a meeting between personnel from the GSFC and GE was held to discuss a number of steps that GE was taking to improve the NiCd cell design and to define a program to requalify cells with improved features. The main topics of discussion were the new anticorrosion (passivation) plate treatment and a further reduction in positive plate-loading levels. From tests described previously, it has been demonstrated that cells made with a positive plate loading of 12.5 ± 0.5 gm/dm^2 (Ref. 26) had reduced plate expansion and blistering while operated in a typical aerospace regime. From this meeting came an understanding that no cell design changes, new plate-manufacturing processes, or plate/cell treatments would be implemented on GSFC programs until the GSFC had been given an opportunity to requalify the cell. It was further agreed that the processes used to manufacture the NASA Standard 20-Ah and 50-Ah cell would remain available until requalification was complete (Ref. 34A).

In January 1983, cells made with the acceptable plate lot failed the voltage and pressure requirements during the low-temperature (0°C) overcharge requirements. Subsequent to a retest, rework of cells by reducing the precharge and adjusting the quantity of electrolyte was initially rejected, since substantive data and the failure mechanism had not yet been explained.

The Teflon film on the cadmium plates was then found to be approximately 50% less than that used for previous lots. After considerable dialogue, it was agreed to allow the electrolyte adjustment, but not the precharge adjustment since there was no known precedent for the latter. The electrolyte adjustment reduced the level down to the range of 3cc/Ah; whereas, earlier standard cell lots had ranged from 3.3 to 3.6cc/Ah. Other notable differences about these cells were that the negative-plate loadings were at the very high end (13.09 gm/dm^2) of the specification; plate weights were on the high side of the specification; and the negative-plate porosity was less than 50%, the lowest of all lots produced for the standard 50-Ah cell.

The removal of electrolyte corrected the high-pressure problem but the high voltage was made worse, since the cells exceeded the voltage requirement at room temperature. A case for the precharge adjustment was made by showing that these cells, when in overcharge, had approximately 73% of the total negative capacity charged, as compared with approximately 64% for the Landsat-D cells. It was found that precharge reworks were routinely made on cells manufactured between 1975 and 1983, which included standard 50-Ah cells made for the Landsat-D satellite (Refs. 35, 36, 37).

The final outcome was that new cells were built and flown on ERBS. The replacement of cells became the critical path in the program's schedule. The experience with the production of cells for ERBS batteries vividly illustrates the impact that manufacturing process changes usually have on a flight program. For various reasons, not all of which were fully understood, three plate lots were rejected prior to obtaining cells acceptable for flight. In this case, a schedule with a large slack ultimately became the critical path.

After the ERBS review with GE, the GSFC met with users to discuss the scope of cell problems on other space programs. The consensus of this meeting indicated that problems found during the manufacture of cells for ERBS were not unique. One user had rejected nine posts of plates in 1 year. The observations cited by users included more reworks, reduction in electrolyte, lower plate porosity, larger lot-to-lot variations, and higher end-of-charge voltage. The general consensus was that most of the quality issues came about with cells made after 1979.

While the exact reasons for passivation of the positive plaques is not documented in the literature, one source (Ref. 38) believed the changes were made to reduce the corrosion of the plaque during impregnation. Such corrosion weakens the sinter and reduces the yield of acceptable plate lots from the plate stress test (used to screen plate lots). Passivation of the positive plaques would then be expected to reduce the corrosion and result in stronger plaques and a higher yield. It has long been recognized that the degree of corrosion of sintered plaques during impregnation is very sensitive to pH value, temperature, and other variables related to the impregnation solution. It is possible that the passivation process was implemented as a "fix" for the inability to control corrosion during the impregnation process.

NiCd cells made with passivated plaques resulted in reduced life to approximately 1 to 2 years in a LEO application. They were observed to have reduced KOH fill level, flaking of plate material, and inability to attain and maintain charge. There was no obvious advantage for the users to allow the passivation process to be used. The remedy to plaque corrosion should be in the stringent control of the process that causes the corrosion. As had been demonstrated on numerous occasions during the 1960s and '70s, the reduction in the amount of KOH in a cell decreases plate utilization and compromises life.

Although the test results from the design-variable cells had clearly demonstrated the relative merits of the various GE cell designs, concerns were expressed about cells manufactured for the TIROS spacecraft in which the passivation treatment was used on the plates. The final electrolyte quantity for one lot of the TIROS cells was approximately 2.8cc/Ah. Based on previous manufacturing and life-test data, the compromise of electrolyte in these cells, caused by the passivation process, was of serious concern (Ref. 38A).

During the 1983-84 time frame, a problem with cell-test anomalies, which was caused by the negative-plates, was reported by users. An analysis revealed that failed cells had early and excessive cadmium migration, a loss of overcharge protection, and cadmium residue in the cell container. Initially, the problem was attributed to the change in the processing of nickel powder. The new nickel powder resulted in low density and pore size within plaques, caused by furnace-temperature profile and belt speed. Extensive material research was performed before the change was made. No differences were reported between plates made with the old and the new powder. Since the powder was assumed to be identical, no changes were made to the sintering parameters. In the Fall of 1984, GE shut down the plant to investigate the problem. Analysis of cells, made since the shutdown, did not show any evidence of the negative-plate problem (Ref. 38).

Perhaps the event that had the most significant impact on the NiCd aerospace cell, was Pellon Corporation's announcement in 1976 that the production of the Pellon 2505 ml separator-material would stop. The impact of Pellon's action was delayed significantly, because the battery manufacturers had large quantities of this material in stock. They used the time, prior to shutdown, to increase their reserves.

With few exceptions, Pellon 2505 ml had been used in every aerospace NiCd cell since the beginning of the space program. This material had been selected from a NASA/GSFC separator study with Gould National Battery Company in 1963. In this study, more than 30 separator materials were evaluated (Ref. 39). It should be pointed out that Pellon did not manufacture this material exclusively for battery use. They also produced the material for the garment industry. While Pellon engineers and marketing personnel worked with NASA, and the industry of the application of their products to aerospace batteries, battery-manufacturers were never the primary users of this material.

In 1982, with the supply of Pellon 2505 ml projected to last into the mid-1980s, GSFC proposed a program to the Chief Engineer's Office at NASA Headquarters to initiate a qualification program of new separator material for the NiCd aerospace cell. A Research and Technology Objective and Plan (RTOP) that required $120K, over a 4-year period, was submitted to NASA Headquarters. This RTOP provided for purchase of cells using the Standard MCD with new separator material and life test of these cells under identical conditions to those used on the Standard Battery Program for the MPS/MMS.

In September 1982, a meeting between NASA, Navy, and Air Force personnel was held, in which a joint program to meet the needs of other government users of NiCd aerospace cells was defined. The NASA part of this program was also submitted to NASA Headquarters, with the GSFC proposed as the NASA manager of the joint program. NASA Headquarters concluded that requalification of an item should be left to a specific project or program office, since most flight hardware was project-unique. Consequently, the separator requalification program was not funded. In the meantime, the supply of the Pellon 2505 ml was declining at a rate greater than initially projected because of the increased demand for the larger NiCd cells. As a consequence, each user and/or government agency proceeded on an independent course to find a suitable replacement for the Pellon 2505 ml separator.

In 1984, the GSFC obtained funding from NASA Headquarters to procure 50-Ah cells with a new separator material (Pellon 2536) and cells containing the Pellon 2505 ml for test and evaluation. Cells for this test program also included those manufactured with standard plates, passivated plates, and cells with reworked (increased and decreased) precharge. All packs were tested at

40% DOD in a 1.5-hour simulated orbit (Ref. 40). One group was tested at 20°C, and another group tested at 0°C.

A detailed review of the results is beyond the scope of this document; however, it can be stated that all cells exhibited inferior performance to previous GE cells (standard cells, design variable cells, and IUE prototype cells) under a similar test regime. After 6 months, the capacity to 1.0 volt per cell was down by 50% of precyling capacity. Even lowering the 20°C pack to 10°C after 6 months did not appreciably improve cell performance. The data indicated that the useful life of these cells would not exceed 2 years in satellite applications.

During the mid-to-late 1980s, other users were reporting anomalous test results similar to the results observed on the cells described above. In just over a year of cycling (approximately 6,000 cycles), users were experiencing anomalies in 10% to 40% of their cells under cycling regimes that previously had exceeded 15,000 to 20,000 cycles without anomalies (Ref. 38). Cells were exhibiting unusual voltage divergence. At least part of these anomalies were thought to be attributed to a batch of "old" Pellon 2505 ml material that had degraded while in storage for several years in an uncontrolled environment. In April 1988, GE sent a letter to customers identifying cell lots containing "bad" 2505 ml separator material.

Analysis indicated that this lot of separator material still contained zinc chloride ($ZnCl_2$), which is part of the nylon fiber chemical-bonding process used by the separator manufacturer. When the material was pulled from storage by the cell manufacturer for use, it failed the inorganic content test and was rewashed. After rewash, the material passed the inorganic test. Tests showed the rewashed separator to have a high rate of oxidation degradation (as much as 15 times what was expected) when placed in KOH. One theory for the degradation suggested that the nylon fiber was weakened by the formation of hydrochloric (HCL) acid during extended storage when the $ZnCl_2$ combined with moisture. Cells manufactured with this separator passed the manufacturer's and customer's acceptance tests, and it was only when cells failed during the user's life test, that the latent defect became evident.

This experience serves as a vivid illustration of problems confronting the users. To date, neither the manufacturers nor users have developed an infallible acceptance or screening test that eliminates "bad cells" or "bad cell lots" from getting into flight hardware. The only way of identifying cells with latent defects is by real-time life test. This usually takes several months to a few years.

By the mid-1980s, users were in a state of quandary, trying to unravel the complex and convoluted situation that had evolved from the plate-manufacturing changes, the "bad" separator material, and the introduction of Pellon 2536 material into flight hardware. Extensive problems surfaced on at least three separator (Pellon 2536) requalification programs. Cells were failing for reasons the users had not experienced since the 1960s. KOH fill levels for some cells had decreased to 2.5cc per ampere hour, which was well below the level of 3.0cc per ampere hour, typically found in cells made during the late 1960s.

Numerous problems with batteries on a number of NASA programs resulted in forming a NASA Aerospace Battery Steering Committee in 1985. This committee consisted of representatives from each NASA Center, the U.S. Government, and observers from Aerospace Corporation who represented the Air Force. The committee reported to NASA's Office of Chief Engineer. The committee held its first meeting in June 1985. The purpose of the committee was to facilitate communications of technical issues and to provide an independent means of battery-system review of NASA programs for NASA management (Ref. 40A).

The committee's initial work focused on reviewing the status of the cell- and battery-test program for a number of projects, and making recommendations about the suitability of the batteries for flight use. In concert with this activity, the committee made recommendations to NASA Headquarters on a wide range of program activity needed to resolve serious deficiencies in the aerospace battery community. Task groups were formed to study and recommend actions in such areas as uniform tests, acceptance-test quality, and future NiCd cell design. A group also evaluated the data from NSWC, Crane, and made recommendations concerning near-term design fixes, etc.

The findings of this NSWC, Crane, data group are noteworthy. A synopsis of these include the following: complete-pack failures occurred only with cells having new 2536 separator in combination with low-electrolyte fill (1.8 to 1.9cc/Ah); earliest failures occurred on cells with low-electrolyte fill, run at low-temperature (0°C), while cells tested at high temperature (20°C) lasted longer; all cells with low-electrolyte fill that were analyzed by DPA, had cadmium band and pinholes or burns at the top of the plates; cells with sufficient electrolyte and either old or new separator, performed excellently during cycling test; NiCd cells with new components did not perform as well as the best "vintage" NiCd cells, yielding about 1/3 to 1/2 the number of cycles, (Ref. 40B).

In 1987, the GE battery group was purchased by Gates Energy Products (GEP). In June 1988, the GSFC, in conjunction with Aerospace Corporation and McDonnell Douglas Corporation, issued a Government Industry Data Exchange Program (GIDEP) Alert on cells made by GEP. Plant reviews and other activities leading up to issuance of the Alert and subsequent reviews (Ref. 41) revealed numerous discrepancies in the GEP quality assurance procedures, which were subsequently corrected. The facility used to passivate plaques was singled out as having no process procedures, no instructions, no QA inspections, uncalibrated temperature meters, etc. It should be noted that this was the second Alert ever issued by NASA on a manufacturer of aerospace NiCd cells during the 30-plus years of the space program. At the time of the Alert, NASA had 12 satellite programs with batteries of questionable manufacturing history. One set of GRO batteries (MPS 2) was not affected, since it was determined that cells were made with "good" Pellon 2505 ml separator, and that plates were made during a time when no known problems existed.

At the November 1988 GSFC Workshop, GEP presented a summary of the management, engineering, and product assurance changes implemented to address the numerous problems being observed by users of its products. The management change was primarily in the change of Quality Control Engineering to a full Product Assurance Department that reported directly to the General Manager. From engineering analysis of cells, GEP confirmed the findings of the users as discussed previously. These were cells with loss of overcharge protection, cells with excessive cadmium migration, cells with separator sticking to negatives, and cells with poor separator strength.

The cell critical-design parameters introduced by GEP (Ref. 42) are presented here verbatim, since their findings are relevant to the theme of this section.

POSITIVE ELECTRODE:

Sinter strength important in reducing swelling.

Nickel attack (corrosion) needs to be controlled to provide strength and maintain porosity.

Loading levels need to be controlled to reduce swelling, reduce pore-blockage, reduce electrolyte redistribution.

NEGATIVE ELECTRODE:

Loading levels should be controlled to reduce cadmium migration:

Must maintain adequate -/+ (negative to positive) ratio, precharge and overcharge protection.

Critical in maintaining low-oxygen pressure during overcharge.

ELECTROLYTE MANAGEMENT:

Both positive and negative plate characteristics play a critical role in electrolyte management.

More critical with Pellon 2505 separator because of lower electrolyte retention characteristics, higher weight.

Indicates need to maximum plate porosity/pore volume, optimize loading levels.

Increase pore volume, optimized loading, g/cc void, improves utilization, reduces microscopic current density, reduces the effects of electrolyte redistribution.

Greater electrolyte levels enhance life characteristics.

Greater reserve for plate swelling.

Greater thermal conductivity - reduce heat build-up.

The summary presented by GEP is recognition of plate- and cell-design attributes that evolved from 25+ years of manufacturing and application work with NiCd aerospace cells. There have been numerous studies, spanning the previous two decades, on all these topics. Studies such as those with Tyco Labs, Eagle Picher Industries, General Electric, Gulton Industries, work at Wright-Paterson Air Force Base, and others too numerous to mention contain conclusions similar to those given at the 1988 Battery Workshop.

It is noteworthy to reexamine specific work performed by GE over the 3-decade period that is relevant to the findings presented above. Work performed for the GSFC on third electrode studies in the late 1960s identified variability in negative-plate characteristics. GE developed a negative-plate fade test that was used to "screen" negative-plate lots for acceptance to be used in aerospace cells (Ref. 19). This plate-lot qualification test was subsequently included in the NASA Standard Cell Specification. During the production of the first group of cells made to this specification, one negative-plate lot was rejected because it failed the test criteria. Some time later, GE recommended this test be deleted (Ref. 43), since it was not providing any useful data. For reasons unknown to the authors, this recommendation was accepted.

GE's work on the design-variable cells, as discussed herein, clearly established the interaction of plate loading, cell electrolyte levels, plate utilization and other cell-design variables, prior to 1980. By 1985, the long-term effects of all these variables were well known among the battery community (Ref. 26). Cells manufactured by GE for a separator-qualification program (Ref. 40), and delivered in February 1985, showed that cells containing passivated positives accepted less KOH than cells without. The same cells demonstrated the compounding of the electrolyte-starvation problem, by containing the new separator in cells with passivated-positive plates.

In July 1988, a combined Government/Industry Audit Team conducted an in-depth review of GEP's quality assurance program, and found over 50 discrepancies throughout the aerospace facility. A follow-up on this audit, in May 1989, found that GEP had made considerable progress, and approximately 70% of the previous audit findings were closed. The team was very complimentary of GEP's effort and initiative in addressing the Audit Team's concerns. A subsequent follow-up, by the Audit Team in May 1990, found that the GEP Electrode Operations had adequate procedures, facilities, equipment, and trained personnel to fully meet all program requirements. The Audit Team upgraded GEP from a conditional status to an approved supplier of aerospace cells (Ref. 44).

GEP's search for a suitable replacement for Pellon 2505 ml and 2536 identified two new candidates (Ref. 45). The two materials are designated as T64196 (2538) and T64150 and have physical and chemical properties similar to Pellon 2505 ml. Of note is the comparison of electrolyte retention of the new separator (2538) with the 2505 ml. The 2538 material retains 500% to 700% of electrolyte by weight, versus 800% in the 2505 ml material. This quality, along with "wet out time" (presently, no data on this), is generally accepted as the "figure of merit" for all separators to be compared.

Cells made with the new separator were subjected to 1000 cycles, after which GEP concluded that the 2538 was a viable option and proposed that this material be used for all new cell orders. GEP claims that when plate porosity is controlled above 30%, the use of 2536 separator is acceptable. The electrolyte fill levels for the GEP "lightweight" 50 Ah showed 123cc (2.46cc/Ah) for the 2536 material and 130cc (2.6cc/Ah) for the 2538 material. The relatively low levels of KOH in these cells are disturbing, since the database for predicting life is based on cells with electrolyte levels in excess of 3cc/Ah.

Another problem cited by GEP for the 2536 material was the lower compressibility, which made it unsuitable from a dimensional standpoint. It seems that after completed acceptance test, some cells made with this material would not meet thickness requirements. This was shown to be caused by positive-plate expansion during test - an accepted characteristic for chemically impregnated plates. The conclusion that this material is unacceptable, based on the above observations, deserves further discussion.

The issue of plate-stack compression and what constitutes an acceptable design has been debated throughout the 30 years of NiCd cell use. One only has to study the failure mechanisms of the NiCd cell and apply deductive reasoning to conclude that cell life is obviously decreased, with an increase in compression on the plate stack. The normal cell cycling wear-out process of the positive plates increasing in thickness, the drying of the separator (electrolyte redistribution), and the increasing solubility of the cadmium species (cadmium migration) creates a condition in which the cell-plate stack tends to grow into one homogeneous glob of material. Excessive mechanical compression on new cells can only accelerate this process. The only requirement for compression on the cells is the need to maintain mechanical integrity (plate tabs not cracking or breaking) during battery and spacecraft vibration tests. With the cell case thickness being used today, the compression force below 50 lbs/in^2 is more than adequate. Batteries using cells with very thin cases should employ means other than compression to restrain cell movement.

Further work to evaluate the effects of long-term storage was initiated in 1985. Cells purchased for the IUE program and stored at the GSFC for a period of 9 to 11 years at room temperature (discharged and shorted) were subjected to a repeat of the original acceptance test (Ref. 46) and then placed on life test. The test regimes included a LEO and synchronous orbit and a standard set of test conditions used on cells from this lot when they were new. After 4 years, testing of these packs was discontinued because of lack of funding. At the time the test was terminated, the pack on LEO cycling had completed 21,000 cycles, and the pack on GEO cycling had completed 42 shadow periods (Ref. 2).

There was no measurable difference in the lifetime between these cells, and those from the same cell lot tested several years earlier. This test provided one additional data point indicating that the cycle life of NiCd cells is not appreciably affected by wet storage life after 9 years, even at room temperature with the cells shorted. The results of this test on finished cells would seem to be in disagreement with Lim's analysis of separator tests, discussed in section 3. Lim concludes that all of the overcharge protection would be consumed in 7 years at 25°C because of hydrolysis of the separator. It is not clear why these results are different, but it should be remembered that the test conditions are very different.

The maximum acceptable wet storage time is still unknown and may be limited solely by the nylon separator stability. It is clear that cells of this design and manufacturing history have the potential to be stored for many years and still be acceptable for a space mission of several years.

The procurement of aerospace NiCd cells for all NASA programs was standardized with the release of NASA Handbook, NHB 8073.1, in June 1988 (Ref. 47). Most of the requirements in this handbook are traceable to the Interim Model Specification (Ref. 22) published in 1969, and have direct heritage to GSFC Specification 74-15000 used in the development of the NASA Standard 20- and 50-Ah cells.

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13. ABSTRACT *(Maximum 200 words)*

The handbook provides guidelines for the handling and storage of conventional NiCd flight batteries. The guidelines are based on many years of experience with ground and in-flight handling of batteries. The overall goal is to minimize the deterioration and irreversible effects of improper handling of NiCd flight batteries on flight performance. A secondary goal is to provide the reader with an understanding, in nonanalytical terms, of the degradation mechanisms of NiCd cells and how these mechanisms are affected by improper ground handling of flight hardware. Section 2 of this document provides the reader with a brief introduction to NiCd cells. The effects of the environment on NiCd batteries are discussed in Section 3, and Section 4 contains 12 guidelines for battery handling and storage with supporting rationale for each guideline. The appendix of this document provides a synopsis of NiCd cell design and evolution over 30 years of space flight on Goddard Space Flight Center (GSFC) satellites, along with a chronological review of key events that influenced the design of NiCd cells being flown today.

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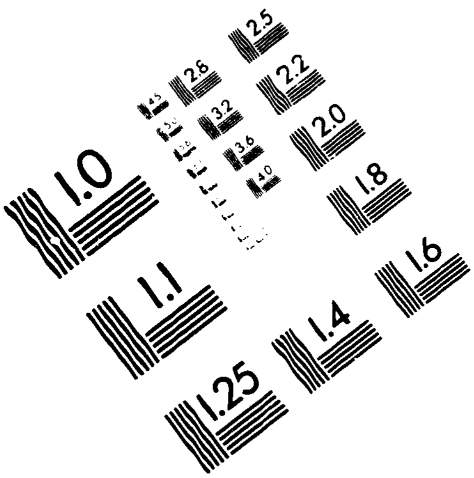

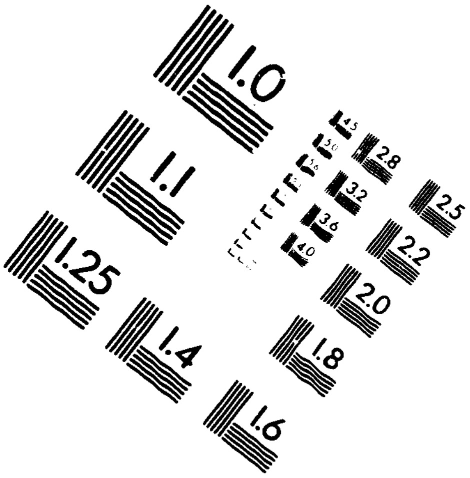


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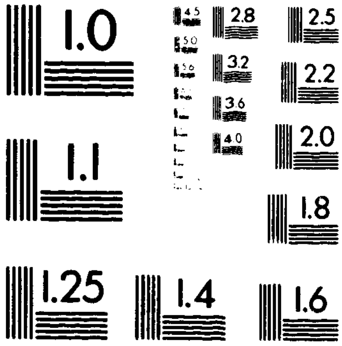
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