

MCR-85-641 ✓

FINAL REPORT
FOR
NICKEL CADMIUM BATTERY EXPERT SYSTEM
NAS8-35922

DEVELOPED FOR
NASA/MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

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NOVEMBER 1986

(NASA-CR-179031) NICKEL CADMIUM BATTERY
EXPERT SYSTEM Final Report (Martin Marietta
Aerospace) 39 p CSCL 10C

N87-20471

G3/33 Unclass
45234

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GLOSSARY

AHI	- ampere hours in
AHO	- ampere hours out
BPRC	- battery protection and reconditioning circuits
CCC	- charge current controllers
DOD	- depth of discharge
EOC	- end of charge
EOD	- end of discharge
EOF	- end of file
EPS	- electrical power system
HST	- Hubble Space Telescope
MMDA	- Martin Marietta Denver Aerospace
MSFC	- Marshall Space Flight Center
NICBES	- Nickel-Cadmium Battery Expert System
SOW	- Statement of Work
SPA	- solar panel array

SECTION 1.0 PURPOSE

This Final Report details the work done under Contract Number: NAS8-35922, for NASA Marshall Flight Space Center (MSFC). It includes the modeling and implementation of a prototype diagnostic expert system for Nickel-Cadmium Battery Health Management, as well as recommendations for future enhancements.

SECTION 2.0 PROBLEM

This section details the problems found in Nickel-Cadmium Battery Management. The areas of difficulty are compounded by large amounts of data and a lack of consistency, except at a general level, between battery performance tests.

2.1 Hubble Space Telescope Battery Testbed Background.

NASA and MSFC are involved in the development of autonomous systems for spacecraft. The Electrical Power System (EPS) has been identified in several studies and by the Advanced Technology Advisory Committee as a leading candidate for implementing advanced automation approaches such as knowledge based and expert systems. The Hubble Space Telescope (HST) EPS Testbed provides an opportunity to take a significant step toward autonomous operation of an EPS for spacecraft.

Power for the HST comes from a system of 20 Solar Panel Arrays (SPA's) and six 23-cell Nickel-Cadmium batteries. The HST EPS is simulated by a Testbed at MSFC. Each battery has two power supplies associated with it, divided into a single-SPA and a dual-SPA. A seventh dual-SPA brings power directly into the bus distribution system. These 13 power supplies simulate the 20 SPA's. Figure 1 is a schematic diagram for the testbed.

The testbed at MSFC was built to simulate the HST EPS as closely as practical. There are 6 Charge Current Controllers (CCC) that control the operation of various relays that disconnect when a temperature dependent voltage level is reached, and connect SPAs to the batteries. Each CCC controls 3 SPAs; a K2 relay controls one SPA and a K1 relay controls two SPAs. Thus only two power supplies are needed per battery. The 13th power supply simulates the two SPAs that are connected directly to the diode bus.

The batteries are diode isolated from each other. There are two batteries connected to each of three diode busses. The diode busses then feed three independently controllable load banks. As on the flight HST, each battery can be switched to a reconditioning load and its associated SPAs can be switched to one of the other two diode busses.

The batteries are mounted three each on two aluminum plates in a single temperature chamber. Each plate has a heater element that can control the battery temperature up to 10 degrees Celsius above the chamber ambient temperature.

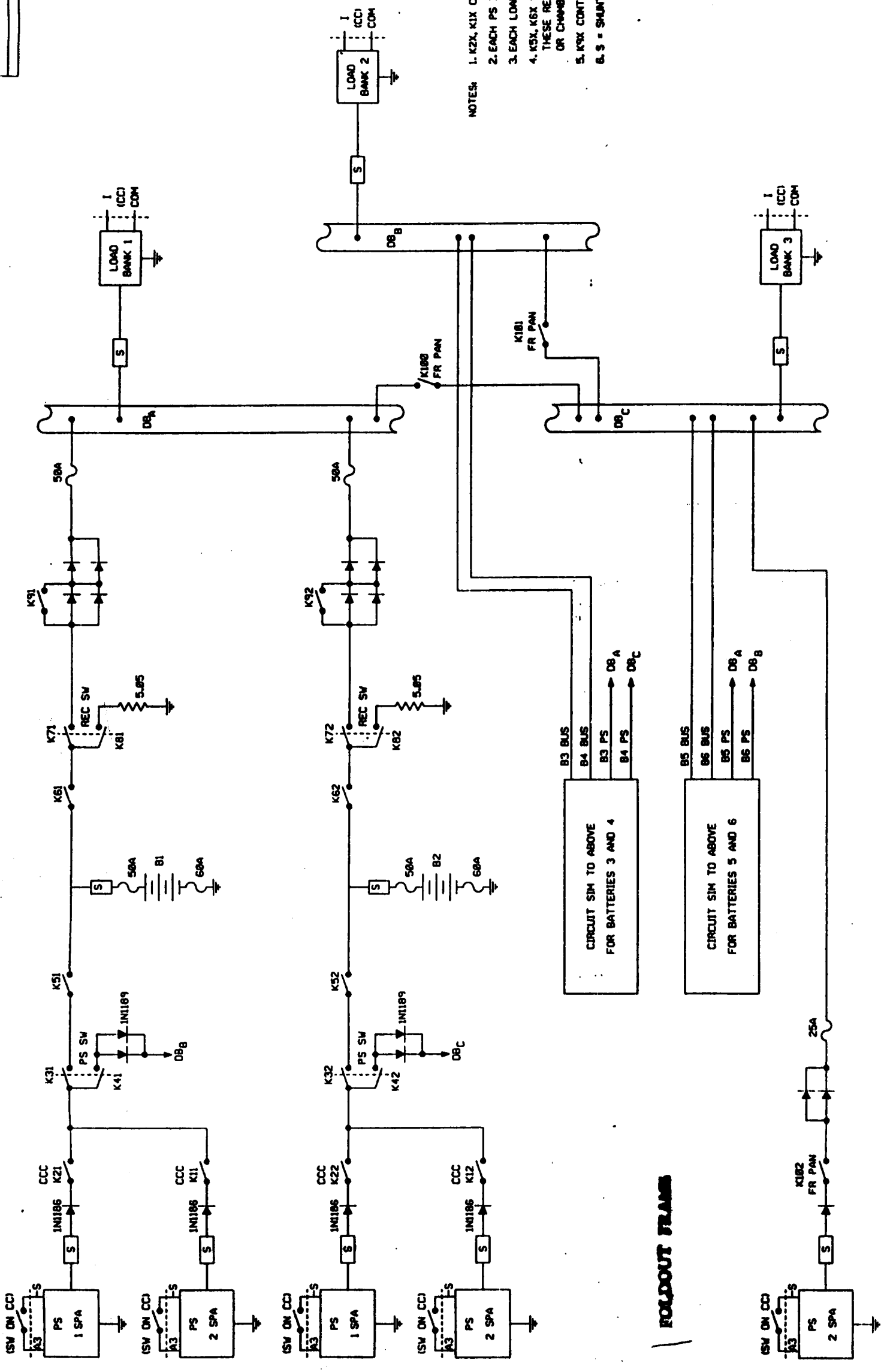
Also incorporated in the testbed is a microprocessor controller that was built and programmed at MSFC. This control computer (CC) controls; the temperature of the batteries, the load banks in either a

REV	DATE	BY	APP
1			
2			
3			
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6			
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9			
10			

2 FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

- NOTES:
1. K2X, K1X CONTROLLED BY CCC (SEE SEPERATE SCHEMATIC)
 2. EACH PS INDIVIDUALLY CONTROLLED (ON/OFF) BY CC (CONTROL COMPUTER)
 3. EACH LOAD BANK PROGRAMMED BY CC
 4. K5X, K6X SET AND RESET BY FRONT PANEL CKT (SEE SEP SCHEM)
 5. THESE RELAYS OPEN IF DOAS FAILS, CC FAILS, +15 FAILS, OR CHAMBER FAILS NOT (SEE TIME-OUT CKT SCHEMATIC).
 6. S = SHUNT



constant current or constant power mode, the over voltage diode trip point, and, using sensed CCC relay operation it controls the 13 power supplies in much the same fashion as the HST DF224 flight computer controls the SPA trim relays for a step to trickle charge. It also can maintain a trickle charge on the batteries.

This testbed development work was performed by several people at MSFC. John R. Bush was responsible for the HST breadboard and controller. John A. Pajak was responsible for the data system and the associated wiring. Rober E. Kapustka was responsible for the battery protection and recontinuing circuits (BPRC). John R. Lanier is the team leader of EPS Systems Team which has responsibility for this testbed.

2.2. Nickel Cadmium Batteries.

Nickel-Cadmium batteries are appropriate energy storage media for a wide range of applications. They exhibit a combination of high capacity, long life and low maintenance requirements. There is, however, much that is unknown about the behavior of these batteries, in terms of design, manufacture, and operating characteristics. Even persons who have been working with these batteries for over 15 years, say that there is no such thing as a battery expert. Reference 1 documents a number of long-standing problems in this domain. APPENDIX A provides an overview of the Nickel Cadmium Battery domain. The EPS requires constant monitoring for fault detection. A system which could predict anomalies by relaying battery status and battery trend information along with explanations as to why a particular battery is exhibiting such behavior would be extremely beneficial. Corrective measures could then be performed to deter the expected fault(s). Although total automation is the desired final result, a prototype phase can demonstrate that such expectations are realistic.

2.3 Excessive Data

Extensive sensor data can be gained from batteries and battery testbeds sufficient to analyze their behavior. Data on cell pressure, voltage, battery current, temperature, solar assemblies and bus current are gathered from the HST testbed. As the system is operated over months or years, accumulations of this data fill hundreds of computer tapes and great heaps of printout paper. Information is hard to glean from the endless lists of numbers. Interested personnel hand-plot data on graph paper to determine battery behavior. Unfortunately, other useful information is lost due to the overwhelming amount of work required to sift it from the numbers.

There is no reason not to automate some of this information gathering. Computers are very good at plotting values, finding averages, keeping running sums, and generally extracting desired information from vast quantities of data. This kind of assistance will help human analysts do their job better.

SECTION 3.0 OBJECTIVES

The major objective is to demonstrate the applicability of AI methodologies for the automation of energy storage management, in this case, Nickel-Cadmium Batteries. With the HST EPS Testbed as the application domain, an expert system was to be developed which incorporates the physical characterization of the EPS, in particular, the Nickel-Cadmium Batteries, as well as the human's operational knowledge. The expert system will return not only fault diagnostics but also status and advice along with justifications and explanations in the form of decision support. The requirements for the next phase are developed by the use of rapid prototyping. This demonstration prototype is the first of many steps toward a truly automated reasoning system.

SECTION 4.0 APPROACH

To meet the objectives described above requires several steps. First we needed to consider an adequate computing environment for a first prototype. It was then necessary to decide upon one programming language which could efficiently monitor the telemetry stream and another one which could not only provide a structure for the data but also for the human's "rules" for Nickel-Cadmium Battery management. An expert system approach was taken. This involved the knowledge acquisition necessary to characterize the problems intrinsic to energy storage management and the design of a viable model which employed the gathered knowledge along with mathematical operations to build status and trend analysis. Finally, we implemented a prototype, the Nickel-Cadmium Battery Expert System (NICBES), which meets the functional and efficiency requirements of the end users, the engineers.

4.1 Computer Environment.

The IBM-PC AT was selected as the programming media. Its availability, its memory and speed, and its support of various programming languages as well as graphics capabilities, make it adequate for this first stage of prototyping.

4.2 Data Handling Language.

'C' is an excellent data manipulation language. It is both efficient and fast, an essential qualification for real time data handling. Such a language was needed to monitor the telemetry stream, to process the telemetry, and to write the output to data files. MICROSOFT C was chosen due to its compatibility with the IBM-PC AT.

4.3 Logic Programming Language.

PROLOG, named for PROgramming in LOGic, is a computer programming language that is used for solving problems that involve objects and the relationships between them. PROLOG programs are made up of a set of statements, called clauses, that are either facts or rules. A fact expresses something that is considered to be true. A rule, on the other hand, expresses how new facts may be inferred from known ones. For example, given the rule

"If a battery cell has a hard short, then its voltage is zero."
and the fact

"Cell 16 of Battery 5 has nonzero voltage."
we can infer that Cell 16 does not have a hard short.

PROLOG is designed so that it can draw conclusions from a set of facts and rules. It allows the programmer to concentrate on the logic of the problem, rather than on the flow of control as in a "standard" procedural language such as Fortran or Pascal.

The natural independence of the facts and the rules allows great flexibility in a program written in PROLOG. Facts and rules reside together, with the only difference in syntax being the incorporation of an if then structure, and variables in the rules. A PROLOG program is run interactively by queries from the user, and in response to such a query, the rule that is called may make queries of its own upon the rules and facts it needs to answer the question. The PROLOG interpreter answers "yes" if it can satisfy your question, and "no" if it cannot.

The mathematical theory underlying PROLOG encompasses the model that underlies relational databases, relational calculus. Thus, PROLOG is useful for information management applications. PROLOG is widely used in natural language systems and representation of knowledge in expert systems.

Although PROLOG is not meant to be a "number-crunching" language, PROLOG implementations such as ARITY PROLOG, used in the NICBES program, support a number of arithmetical operations, as well as string manipulations and very simple graphical primitive operations. An excellent introduction to PROLOG is given in the Clocksin and Mellish book, "Programming in PROLOG" (Reference 2).

Another important aspect of PROLOG is the ease of development that it provides. Each predicate (simple function) can be tested individually as it is written. They can then be linked together in modules (functions) and retested. Changes can be made quickly for both the simple predicates and for the larger groupings. The English-like context also makes it easily understandable and in some cases, self-documenting. These methods are ideal for the rapid prototyping of systems such as NICBES.

4.4 Expert Systems.

As put in the book "BUILDING EXPERT SYSTEMS" (Reference 3), "The area of expert systems investigates methods and techniques for constructing man-machine systems with special problem-solving expertise." Expertise involves not only the facts in a particular field, but heuristics for problem solving. These are rules of thumb, hints, strategies, special methods that aid human experts in solving problems - drawn from both common sense and experience.

The definition above specifies a "man-machine system" rather than a computer program. There is good reason for this since almost all expert systems run interactively, answering the user's questions, or asking for more information, or exploring a line of reasoning. Most are able to give justifications for their decisions.

Expert systems are often termed knowledge based because of the central importance of the knowledge rather than any formal reasoning process. Most of the difficult and interesting problems do not have algorithmic solutions. In addition, formal reasoning does not have means for representing knowledge, using multiple levels of abstraction, or controlling complex processes.

Knowledge is a scarce resource, usually transferred from a human expert to an apprentice, often over years of time. Transferring it to a program is an even more difficult task, but the results can be reproduced many times to enable many people to use it or to learn from it. An important side effect of the knowledge engineering required to build an expert system is the quantification and refinement of the domain knowledge. This has often been useful to human experts and trainees, apart from its use in the program since in some cases the requisite knowledge has never before been written down in one place.

Battery testbed fault diagnosis and battery status advising are natural applications of expert system technology. The nature of the knowledge in this field is highly heuristic, based upon intuition and years of experience. Logical operations in battery behavior diagnosis cannot readily be reduced to algorithms. The human interface for diagnosis and consultation fits the interactive nature of the expert system, answering questions and giving advice. For these reasons, NICBES, an expert system, was developed to aid humans in this field.

4.5 Knowledge Engineering

NICBES was developed by a standard method for expert systems. The knowledge engineer researched the subject of Nickel-Cadmium Batteries and their management through an extensive literature search. Upon feeling comfortable with the terminology and general theory of batteries, discussions were held with personnel at MSFC who have specific knowledge of the batteries and the testbed, and with the project manager who developed the goals of the system.

SECTION 5.0 IMPLEMENTATION

Upon identifying the critical parameters of the Nickel-Cadmium Batteries, their casual relationships and the heuristics used by human experts as energy storage management guidelines, the knowledge engineers were ready to design and implement a Battery Model. The design incorporates the representation of both the necessary data and the knowledge of the experts. As previously stated, it was very important to also make the system easy to use as well as understandable.

5.1 Nickel-Cadmium Battery Characterization.

General statements can be made about Nickel-Cadmium batteries. The most important factors affecting their performance, ignoring design and manufacture, include ambient temperature, depth of discharge (DOD) and charging scheme. It has been observed that occasional changes in such operating parameters can be of marked benefit in the life cycle of the cell.

As the batteries go through a great number of charge - discharge cycles, aging takes place, due largely to electrolyte migration, separator deterioration, hydrogen generation because of overcharging, and memory effect. This last condition results from utilization of only a small part of the battery's capacity over a number of charge - discharge cycles, causing a change in the crystalline structure of the metals on the plates. Reconditioning is done by draining a battery completely and holding it at a low potential for a period of time, then recharging the battery. This rebuilds a finer crystalline structure and restores much of the battery's capacity. Reconditioning is a strain on the battery and should not be undertaken lightly. However, it is a valuable tool in enhancing battery capacity. Eventually, deterioration of the battery goes too far and reconditioning can no longer restore usefulness.

During the draining procedure of reconditioning, a weak cell can undergo reversal, causing permanent damage. The BPRC prevents this occurrence. BPRCs protect each cell of the batteries.

During battery operation cell voltages tend to diverge, migrating into groups of strong cells and weak cells. As cells get weaker they do not carry their share of the load which then must be taken up by the stronger cells. The need for reconditioning is indicated by a high divergence, a low EOD voltage and particularly by both conditions together. A low EOC voltage, particularly if accompanied by a low recharge ratio (ampere hours in divided by ampere hours out), usually indicates that the battery is being insufficiently charged.

When a Nickel-Cadmium battery is overcharged hydrogen gas is generated, causing a sharp increase in cell pressure. The hydrogen generation is an irreversible chemical reaction. Since the hydrogen is not recombined it is possible that a cell may rupture due to an accumulation of gas. Another problem due to overcharging is heat production, and causing an increase in the intake of current, causing more heat production leading to thermal runaway and battery self-destruction. Care must be taken so that overcharging does not occur, usually by shutting off power when a certain cell voltage is reached. After main charge is shut off, the battery remains on trickle charge for the rest of the charging cycle, a non-destructive "topping off" of the charge.

Decisions to recondition, change the charging scheme or adjust workload are presently made by rule of thumb and intuition gained from years of experience. Battery management remains a difficult subject. Further details are available in APPENDIX A, Life Cycle Performance Characteristics of Nickel-Cadmium Batteries.

5.2 Knowledge Acquisition.

Discussions with the HST EPS project manager revealed that, in addition to the fault diagnosis and battery status responsibilities of the proposed expert system, an important goal was a user interface that was informative and easy to use for the users and other interested observers.

In question and answer sessions with Mr. Bush, the operation of the testbed was explained so that this knowledge could be incorporated into the program. The functionality of each part of the system was explained along with the malfunctions that could occur, and their probable causes. Mr. Bush decided upon the alarms that would be sent by the system and diagnosed their probable causes.

Mr. George volunteered to serve as the battery "expert" despite his disclaimer of the term. The theory and practice of battery management were discussed in great detail. The relative importance of various battery parameters was discussed, along with their relationship with battery management and expected useful life. The proper use of reconditioning was emphasized as a powerful tool that requires caution in its application. As stated above, reconditioning causes a strain on the battery and should be undertaken only when necessary to restore capacity. The knowledge engineer also determined the kind of information that was needed to aid in proper battery management and how best to display that information for maximum utility.

Following the knowledge engineering discussion a revised plan for NICBES was developed which incorporated suggestions of the NASA personnel. Then the expert system was coded in PROLOG and extensively tested to assure proper behavior. A systems programmer wrote the programs for the interface and file handler portion of the system. Faults and failure behavior for the testbed and batteries were simulated by "doctored" data files, as well as induced and simulated faults in data transmitted from the testbed.

5.3 NICBES Design.

NICBES was designed as a two-part system. The first portion was needed to read telemetry output from the DEC LSI-11 and then to condense this data into current and historical data files which satisfy the input demands of the Expert System. The Expert System then utilizes the pre-processed HST EPS Testbed data to perform Fault Diagnosis, Battery Status and Advice. These functions are supplemented by a Decision Support Module which provides summary output information in the form of graphs. Since the IBM-PC AT does not support multi-tasking, the Data-Handler and the Expert System have to be executed independently. This is time consuming and inconvenient but no immediate alternatives have been found at this time. Therefore, the operator must first run the Data-Handler until enough data is processed to build the data files required by the Expert System. The Expert System can then be run after which the Data-Handler is reinitiated to generate the next set of data files. Figure 2 provides an overview of the major functional components of the design.

NICBES FUNCTIONAL DIAGRAM

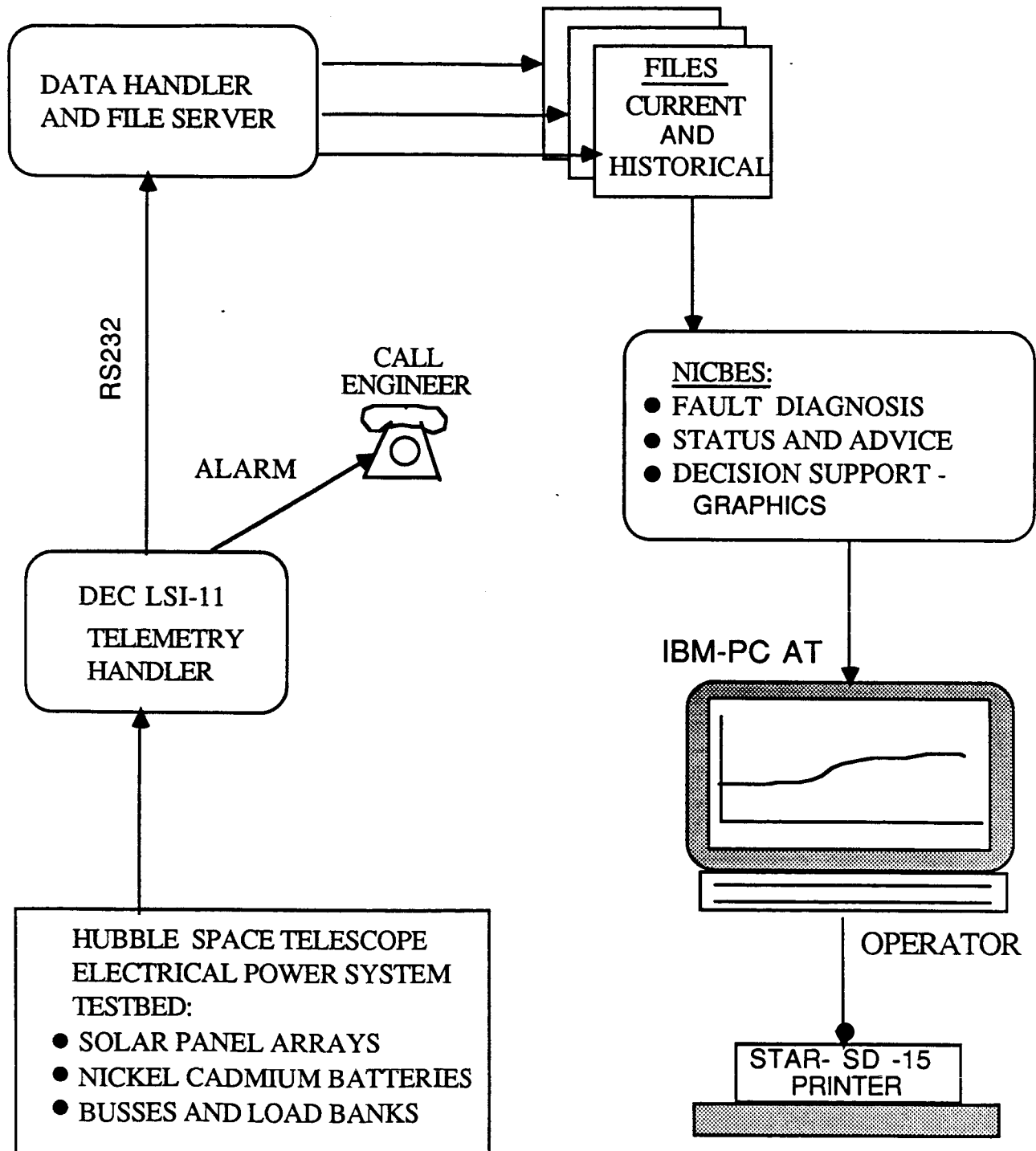


FIGURE 2

A central theme through out the knowledge engineering talks was the use of the computer as an informational tool. As mentioned in Section 2.3 excessive amounts of data were produced. Extraction of useful information from the data is time-consuming at best. More could be learned about the operation of both the testbed and the batteries with better decision support on the part of the expert system. For this reason, the user interface and decision support system was accorded a position of importance in the development. A set of twelve plots was chosen, based upon discussions with NASA personnel, for their maximum utility to the concerned parties. A fairly limited graphic environment on the IBM-PC AT resulted in a simple graphic style, but one which conveys the needed information.

The Status and Advice System of NICBES also uses these plots to support its statements about battery status and the generated advice. The natural syntax of PROLOG as a query language was used to good effect in the question and answer organization of the interface. This meant the avoidance of a great deal of the work that would have been required to develop this program in a procedural language, where often the management of user queries and replies takes up the largest portion of the code.

SECTION 6.0 RESULTS

An expert system prototype has been developed for the Nickel-Cadmium Battery Health Management process. It provides not only Fault Diagnosis, but also gives the engineer concise information on the battery's status, advice on what corrective measures can be taken for found battery problems, and supports its conclusions with an extensive set of graphics. Eventually this system can be expanded to give detailed maintenance procedures which may be performed by engineers or which can themselves be done automatically and thereby remove the engineer from the loop. Before this can happen, the Expert System's rules and reasoning must be validated to insure that all possible events are covered and that the conclusions reached are accurate. This can only be done by running the Expert System over a lengthy period of time with a Nickel-Cadmium Battery "expert" providing evaluations of the system and adding any additional rules or data which are deemed necessary for completeness.

This section details the results of implementing the NICBES prototype. The Data-Handler and each module of the Expert System are detailed.

6.1 Data-Handler.

The Data-Handler's responsibilities include reading the telemetry, processing it and writing the condensed data to files which the Expert System can access.

Telemetry is sent from the DEC LSI-11 to the IBM-PC AT over a RS232, in six-second bursts, once every 60 seconds. Table 1 below details the information contained in the telemetry.

TABLE 1 - TESTBED TELEMETRY

Start of Telemetry Burst

A

Header Information (Integer)

year
 day of year - 198X
 hour - 0 to 24
 minute - 0 to 60
 second - 0 to 60
 orbit - Positive Integer
 phase - 0 for discharge, 1 for charge
 day minute (minute in charge) - 0 to 70
 night minute (minute in discharge) - 0 to 37

Battery Information (for each of 6 batteries)

battery number Integer 1 - 6
 cell voltage 23 Reals -2 to +2 volts
 cell pressure 23 Integers 0 to 150 psi
 battery voltage Real 0 to 40 volts
 battery current Real -30 to +25 amps
 negative for discharge phase
 positive for charge phase

BPRC current

Real 0 to 5 amps

temperature sensors 6 Reals -15 to 30 (degrees C)

battery reconditioning

Integer 0 for no, 1 for yes

Miscellaneous Information

Solar Array current

13 Reals 0 to 20 amps

Bus Voltage

3 Reals 0 to 40 volts

Bus current

3 Reals 0 to 90 amps

The Data-Handler, a program written in MICROSOFT C, continuously monitors the telemetry data-stream. This program puts the data it processes into list formatted files so that the Expert System can easily analyze it. Many of the files are in the form of a circular buffer, with data from the last 12 orbits. Each file is described in APPENDIX B. Each of the Data files has 6 rows of data, one for each battery. In many of the Data files there are 12 columns, one for each orbit, listed chronologically. The Current files are written every minute with only the required information for fault diagnosis.

This seems like a great deal of data to be stored in the system, but the telemetry sends 370 values per minute, thus 35,520 values per orbit of 96 minutes, 532,800 per day. Data and functions of data stored in the files were carefully chosen for maximum information density. Important values from the last 12 orbits are kept in files from the 426,240 values sent. The choice of 12 orbits was made based upon discussions with Mr. George, who said that 10 or 12 orbits would be enough for decision-making in most cases. Considering the cost to the system of keeping much larger amounts of data, this number was readily accepted.

The Data-Handler continues to process telemetry for 12 or more orbits until the operator shuts down the system. The exception is when a fault is detected. At this time the entire set of data files is written and the system exits to make way for the Expert System fault diagnosis.

6.2 Expert System.

The Expert System performs several functions. These include fault diagnosis, battery status and advice, plus decision support. It is programmed in ARITY PROLOG and operates on the data files output by the Data-Handler. When PROLOG is called, the necessary data files and function files are consulted and the Expert System is initiated. A Flow Diagram is given in Figure 3.

6.2.1 User Interface.

The Expert System is menu driven, that is, user selections to various menus determine which system module will be activated. The exception to this is the fault diagnosis which is run automatically when the fault flag has been set to one. Figure 4 displays the Menu Flow Diagram. The user can view any portion of the Expert System and select any battery. The NICBES USER'S MANUAL describes the menus and their choices. Guidance is given on which choices will give the engineer the most information. Hardcopy of any screen report or graph is available by using screen print commands.

6.2.2 Fault Diagnosis.

This module diagnoses the cause of the alarm, and determines the malfunctions in the batteries or other testbed components. In some cases, more than one cause is possible. All relevant explanations are printed on the screen. As mentioned above, NICBES is alerted by the Data-Handler when an alarm rings. The Expert System is called to diagnose the possible causes of the problems. Table 2 shows the alarms.

EXPERT SYSTEM FLOW DIAGRAM

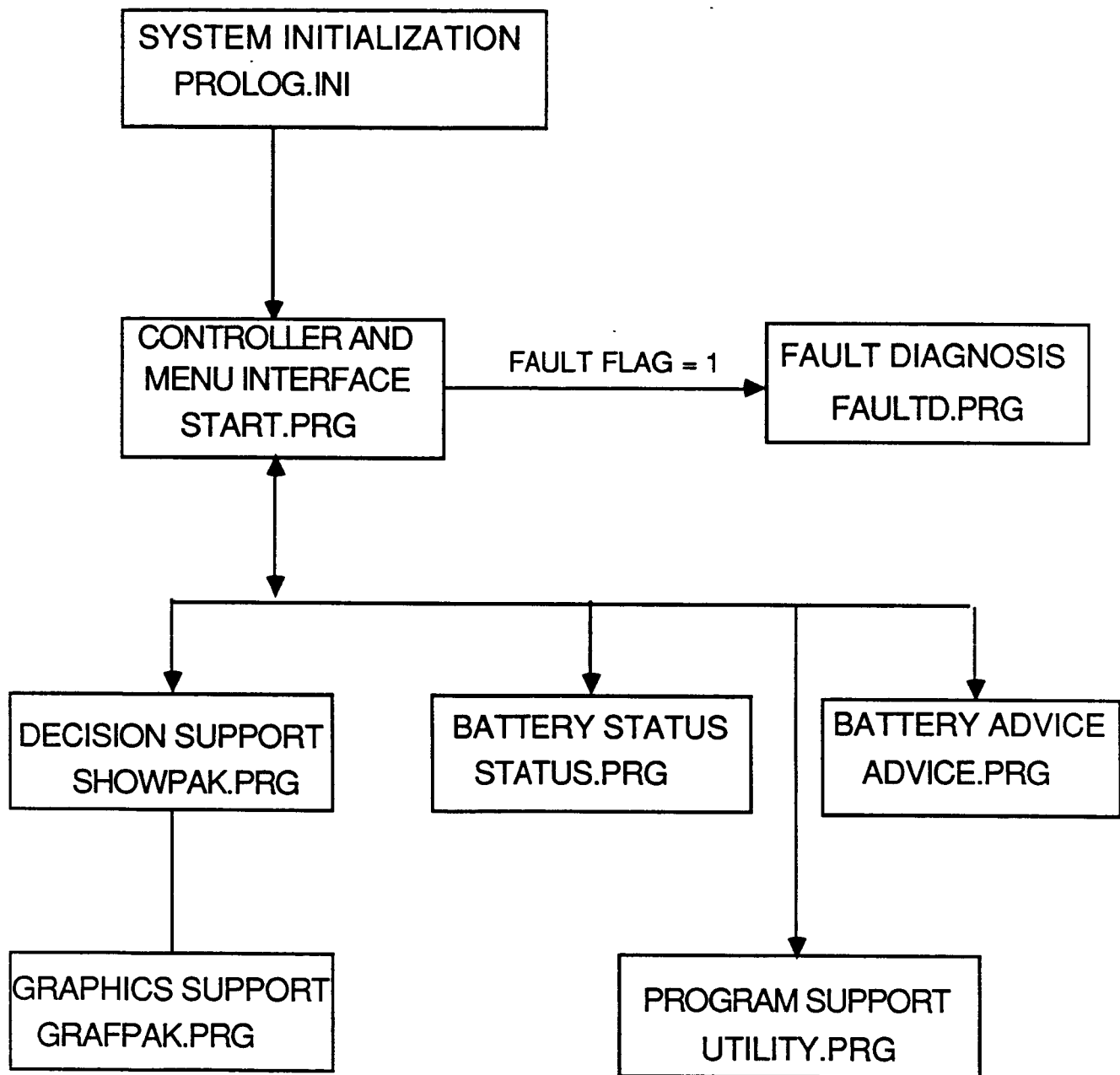


FIGURE 3

NICBES MENU FLOW DIAGRAM

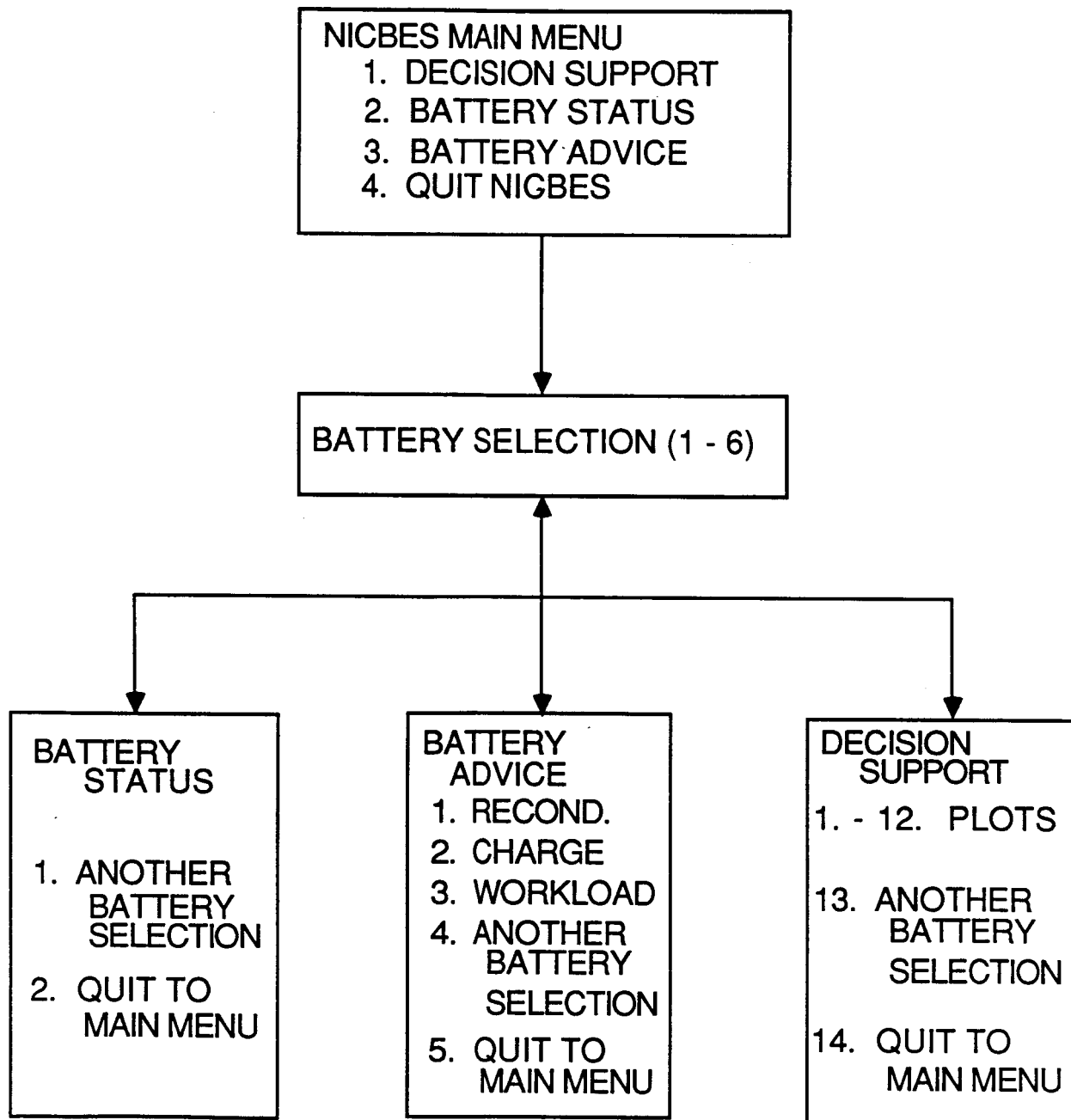


FIGURE 4

TABLE 2 -- TESTBED ALARMS

1. Power Supplies
 - a. SPA current < 5 amps during first 5 minutes of charge phase.
 - b. SPA current > = 8 amps for 1-SPAs (1,3,5,7,9,11).
SPA current > = 16 amps for 2-SPAs (2,4,6,8,10,12,13).
 - c. SPA current > 5 amps during discharge phase.
2. Batteries
 - a. Cell voltage <= 0 volts for any cell in any battery.
 - b. Cell voltage > 1.55 volts for any cell in any battery.
3. Load Banks
 - a. Sum of 3 bus currents > 99 amps.
 - b. Load < 5 amps on any single bus during discharge phase.
4. Temperature
 - a. Average of the 6 temperature sensors > 25 C or < -10 C.
5. Communication
 - a. Missing 3 consecutive telemetry bursts.

The Expert System will analyze the cause of any of these failures. Some of the failures may have more than one possible cause, in which case all relevant hypotheses will be displayed for the use of the engineer. By analysis of recent telemetry the most likely cause can often be deduced and this information will also be available. Diagnoses and supporting information will be printed on the screen automatically without specific human request.

6.2.3 Battery Status.

The Status portion of the Expert System checks the selected battery for reconditioning, temperature, workload, charging scheme and divergence. A message is written to the screen as each check is performed, followed by a statement of "no problem" or adverse conditions found. The user may request the status of any of the six batteries in the testbed. NICBES will consult the appropriate files, and return an answer based upon the information found there. Where appropriate, graphs from the Decision Support System will be used to support these answers. Advice may also be sought on whether the battery is due for reconditioning, a change in workload, or a change in charging scheme. Status first checks to see if the selected battery is being reconditioned. If so, Status stops as the data may be misleading. Otherwise, four procedures are called to check selected battery performance. Averages (battery data averaged over 12 orbits) are used for the status analysis. Table 3 details the conditions checked and what the implications are:

TABLE 3 -- NICBES STATUS ANALYSIS

<u>CONDITION</u>	<u>STATUS</u>
Temperature check (Data files 8 and 9)	
Temperature average over last orbit > 0 and over last 12 orbits < 0	=> Cold
Temperature average over last orbit > 11 and over last 12 orbits > 10	=> Hot or possible overcharging
Temperature average over last orbit > 11 and over last 12 orbits < 10	=> Possible overcharging
Workload Check (Data files 1 and 13)	
AHO average over last 12 orbits < 3. (3.0 Ampere-hours)	=> Underwork
AHO average over last 12 orbits > 14. (14.0 Ampere-hours)	=> Overwork
Charging Check (Data files 2 and 3)	
Recharge ratio average < 1.02 and average high-charge voltage < 32.5V	=> Insufficient Charge
High-charge voltage > 33.8V	=> Possible Overcharge
Divergence Check (Data file 4)	
Divergence average > .8V between high and low cells	=> High divergence
High cell minus average greater than average minus low cells + 1	=> Too many cells at low values

6.2.4 Battery Advice.

The Advice portion of the Expert System goes into further detail than the Status section on three subjects; whether a battery needs reconditioning, change in charging scheme or change in workload. The battery parameters used for trend analysis are given in Table 4, below.

TABLE 4 - NICBES TREND ANALYSIS PARAMETERS

<u>Reconditioning</u>	<u>Charging Scheme</u>	<u>Workload</u>
EOD batt voltage	in-charge high voltage	EOD batt
voltage		
in-charge high voltage	recharge ratio	EOD cell
diverge		
recharge ratio	temperature	Avg AHO
EOD cell divergence	Avg in-charge cell diverge	
in-charge cell divergence	Avg EOD cell pressure	
	Avg EOC cell pressure	

Divergence is simply computed by taking the differences between corresponding values of two lists as high-voltage cells and low-voltage cells.

Trends are calculated by using two simple mathematical functions given below:

$$1. \frac{n-1}{2} \sum_{i=1}^n X(i)$$

$$2. \sum_{i=1}^n i * X(i)$$

where $i \leq 1$ to 12 orbits and $X(i)$ are the associated parameters.

The first function weights all parameter values for a battery equally, while the second function weights the recent parameter values more heavily. For a list of constant values, the two functions are equal. The difference between the two weighting functions is taken and then compared to hand crafted deviation factors to determine the trends. The deviation factors were derived from the stacks of orbital data received from MSFC. Trends are expressed as none, slightly up, up, strongly up, slightly down, down and strongly down. These are displayed in Table 5. The trends of several variables make up the cases for evaluation. The conditions which are checked and their implications have been detailed in Appendix C, Advice Analysis.

TABLE 5 - NICBES TRENDS AND DEVIATIONS

STRONGLY DOWN	DOWN	SLIGHTLY DOWN	NONE	SLIGHTLY UP	UP	STONGLY UP
-----!-----!-----!-----!-----!-----!-----						
-3 DEV	-2 DEV	-1 DEV	0	1 DEV	2 DEV	3 DEV

Messages are printed to the screen detailing which of the three choices is being examined and what the trends are for a particular battery. Given the condition, corrective action is recommended as reconditioning the battery, changing the workload or changing the charging scheme along with an explanation. Support for these decisions can be gotten by viewing the plots detailed in the next section.

6.2.5 DECISION SUPPORT SYSTEM

The display of information in a useful form is an important part of this system. The following 12 displays listed in Table 6, were chosen as being the most valuable. Other suggested displays which involved keeping data for hundreds of orbits were rejected as being beyond the scope of a small system such as this.

Rather than using EOC voltage as the high value, it was suggested by Mr. George that more information about battery behavior can be obtained by using the high cell voltage during the charge cycle. This is done by comparing incoming values to the highest value so far, throughout the charge cycle of an orbit. Battery voltage and lowest cell voltage at the time of maximum high cell voltage is also important information for battery analysis. The Data-Handler handles the collection of this data.

TABLE 6 -- NICBES GRAPHIC DISPLAYS

1. Plot of EOD battery voltage for last 12 orbits.
2. Plot of high cell voltage during charge for last 12 orbits.
3. Plot of recharge ratio for last 12 orbits.
4. Plot of high cell voltages, low cell voltages and average cell voltages at EOD for last 12 orbits.
5. Plot of high cell voltages, low cell voltages and the average cell voltages, taken at high-charge, for last 12 orbits.
6. Plot of cell voltages at EOD for the last orbit.
7. Plot of cell voltages, taken at high-charge, for last orbit.
8. Plot of average battery temperatures for latest orbit, taken at 2 minute intervals.
9. Plot of average battery temperature for last 12 orbits.
10. Plot of EOC and EOD cell pressures during latest orbit.
11. Plot of time on trickle charge for last 12 orbits.
12. Plot of battery current during reconditioning, at 2 minute intervals, for the last reconditioning.

Operators may request a hard copy of the dialogue or plots whenever desired. Further development of this portion of the system with other plots which can be added upon request of the system operators, will be relatively easy due to the development of the graphical primitive operations. A file containing the needed information must be created, then the existing functions can be called using that file and the other appropriate parameters of high and low values, scale and captions.

Based upon information from the Decision Support System, the operator may answer a number of questions about the cause of unusual behavior, such as:

- why high divergence?
- why temperature rise?
- why cell failed?
- why EOD voltage low?

Simple answers are given by the system, based on its diagnosis of information found in the data files. The functionality of this portion of the system is based upon discussions with Mr. Bush and Mr. George of MSFC.

Plots were chosen rather than graphs due to the implementation of the system on an IBM-PC AT. The resolution of the screen is not such as to provide an accurate graph. Changes may easily be made in the scaling of each plot, by the programmer, if a finer differentiation of values is needed. At present, this is not under operator control, due to the limitations in the resolution of the screen graphics. If the expert system is later moved to a high-resolution system (see Section 7.2.2), finer resolution of data would be possible.

SECTION 7.0 RECOMMENDATIONS

In the course of working on NICBES, several rather exciting enhancement ideas came to mind. A survey of similar AI applications also brought to light many creative but useful techniques and methodologies. Presented below are several concepts that would make NICBES a far more powerful and effective system.

7.1 STATISTICAL PREDICTION OF BATTERY LIFE

The first, and quite practical, enhancement is to incorporate a statistical prediction of battery life. A paper by Hafen and Corbett, "Nickel-Cadmium Cell Cycle Life Prediction Equation for Low Earth Orbit", (Reference 4) appearing in the 1981 IECEC proceedings, details a method for using linear regression to fit parameters into an equation for predicting battery life.

$$\text{Cycle of Mth failure} = a * \left(\frac{2M-1}{2N}\right)^b * (\text{DOD})^c * \exp\left(\frac{d}{T(\text{deg K})}\right)$$

where N = total number of cells

M = failure number (Mth cell failed)

DOD is in % (note--we'll have to derive an approximation to this)

T = temperature in degrees Kelvin

a,b,c,d are regression coefficients

It is important to derive the regression coefficients from data which is specific to the battery type in question. The coefficients will vary considerably between batteries of different manufacturers, different designs, and to some extent even between one lot number and another. The operating regime of the battery also has an influence upon the regression coefficients. Calculation of cycle life using arithmetical averages for temperature and DOD give incorrect results since cycle life is nonlinear with both temperature and DOD. A method is given in Hafen and Corbett to combine cycle lives from a variety of operating points.

A more general statistical model using the Weibull distribution has been described in the paper by Lurie and Steen, "Reliability Modeling of High Voltage Batteries", (Reference 5) appearing in the 1982 IECEC proceedings. The distribution of the two-parameter Weibull is in the form

$$R(t) = \exp \left(-n \left\{ \frac{t}{a} \right\}^b \right)$$

where a and b are parameters of the distribution, and t is time. The parameters must be found specific to the battery-type and charging scheme, and will change after a hard short or reconditioning. The parameter n is the number of cells in the battery, here 23 for the HST. Replacing t by (t - v) will give a three-parameter Weibull, where v is the location parameter. Unless v is known to be close to zero, using the two-parameter Weibull (where v = 0) runs the risk that the scale and shape of the curve will be in great error. The Weibull is often used to model failure probabilities of a compound system such as a battery of cells. It is very sensitive to correctness of the parameters, since an extremely wide variety of curves can be obtained.

Although the Weibull model bears investigation, we believe that the linear regression method given above will give a more accurate estimate, since it incorporates temperature and DOD, while the Weibull depends only upon time.

To incorporate statistical prediction, a determination must first be made of the most appropriate type of equation, then the parameters must be determined by regression analysis of appropriate data from battery operation. Once the equation is derived, it could be used for predictions under various proposed operating schemes. This capability would be incorporated under the Status and Advice system of NICBES.

7.2 Migrating NICBES to a More Powerful Environment.

In order to more fully extend the diagnostic and predictive power of NICBES, and to make the user interface more productive, it will be necessary to port the expert system to a environment which supports a fuller complement of features, both hardware and software. There are four broad areas of enhancement which would improve not only the power of the system but also the ease of user interaction as well.

7.2.1. Multi-tasking.

Personal computers, even those as powerful as IBM-PC/AT, do not give the type of support for multi-tasking which would serve to greatly improve the utility of NICBES. In its current implementation, the data acquisition module of NICBES must be interrupted in order to invoke the expert system module. Thus, it is certain that the data files stored on the AT will contain gaps; a more serious consideration is that faults which occur while the expert system module is invoked will not be detected or analyzed, without resorting to patching in data from the LSI. Porting the data handler and expert system to an environment which supports multi-tasking would allow the data handler to operate continuously and the expert system to be invoked without loss of data. The ideal configuration would be one in which the data handler detected anomalous values, invoked the expert system module with the proper information to load the appropriate data, and then continued to process data while the expert system diagnosed and analyzed the input information.

7.2.2. Windows, Menus and Mouse.

The current NICBES system interface is of two types; interactive menus and textual information which are constructed with the standard Arity PROLOG output predicates, and plots and graphs which are constructed through the use of calls to Arity screen-handling predicates, which in turn reference standard IBM screen-handling utilities. This necessarily limits the speed and effectiveness of the user interface and the precision of the graphical output. Use of an environment which supports high-resolution graphic monitors, multi-window interfaces and mixed-mode input (e.g. mouse, text, graphic manipulation) will allow a far greater ease of user interaction and far more revealing system output.

7.2.3. Object-oriented Paradigm.

A powerful method of knowledge representation is the object-oriented paradigm. In this framework, knowledge can be represented as a combination of components and their attributes, relationships between components, and methods (procedural functions) which operate on the components and relationships. For example, a battery could be represented as an object which stands in the "has-a" relation to other objects representing individual cells. As data is input to the system, the cell objects are instantiated, and anomalous attribute values would trigger methods which would in turn instantiate "fault" objects. All objects could be tied to graphical representations which would be continuously updated on the output display.

The object-oriented paradigm lends itself to an easily maintained, easily understood logical system which can be readily adapted to changing situations and applications. If configurations are changed, or system parameters modified, the expert system can be quickly updated to reflect the new environment with a minimum of programming expertise and effort. Interfaces can also be modified rapidly by simply altering the graphical object associated with a given logical object. Although object-oriented shells have been implemented on the class of equipment on which NICBES is currently installed, their performance on such machines will undoubtedly prove unsatisfactory, and their development environments are neither efficient nor straightforward.

7.2.4. Extending the Chronological Scope of NICBES.

Personnel directly involved with the HST EPS testbed have indicated that analysis of Nickel-cadmium life-cycle characteristics could best be served if data were gathered and interpreted over extended periods of time, such as 1000 orbits. The memory limitations of AT class hardware make it impossible to load enough data into working storage to effectively deal with data of this quantity. Even if enough data could be loaded into working memory, or virtual paging techniques implemented, the processing time would be extreme, even more so because the expert system and the data handler must function as independent processes. More powerful environments which support working memories in the four to sixteen megabyte range, compared to the PC-DOS 640 kilobyte limit, would make this goal possible.

7.2.5. Graphics-driven Simulation and Modification.

Another valuable enhancement to NICBES would be the addition of a module which affords users the opportunity to dynamically interact with a graphic representation of the power system. The user could induce faults at various components and invoke the expert system to diagnose and analyze the simulated faults, including those of a type not usually encountered, thus exploring both the effectiveness, the accuracy and the reasoning capabilities of the system. Experimentation with parameter values would be facilitated, as well as the user's understanding of NICBES's behavior and logic. The ability to interactively indicate that the system's scope is deficient as well as specify exactly where new rules and data are needed will make it easier to accurately extend the capabilities of NICBES.

7.2.6 System Control and Fault Workaround.

An extremely valuable extension of the NICBES is to add the capability to respond to faults with fault correction or workarounds. This would require additional expert system modules that could plan actions and execute them. Additional interfaces to the hardware and new hardware controllers or "effectors" to carry out the actions planned by the expert control and fault correction modules would be needed. This task is a significant extension of the existing prototype. However, as system complexity, numbers, and distances to space platforms increase there is a concomitant need for increases in system autonomy afforded by this extension.

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APPENDIX A

Life Cycle Performance Characteristics

of

Nickel-Cadmium Batteries

1.0 The Life Cycle.

Nickel-Cadmium batteries are appropriate energy storage media for a wide range of applications. They exhibit a combination of high capacity, long life, and low maintenance requirements. Unfortunately, stringent tests (i.e. experiments with strictly controlled parameters) of life cycle performance characteristics have never been done; nonetheless, certain generalizations can be made.

1.1 Factors affecting performance.

The factors affecting performance of nickel-cadmium cells are varied. Ambient temperature affects both the capacity and the charging characteristics of ni-cad cells. Depth of discharge is the primary influence leading to the "memory effect". Charging regimes can have great affect on the subsequent performance of cells, and it is claimed that variety (i.e. frequent changes, within reason, of depth of discharge, temperature, charging regimes and other parameters) can be of marked benefit in the life cycle of the cells.

In this section, certain global and specific variables will be discussed which are of primary import on the life cycle characteristics of nickel-cadmium cells.

1.1.1 Age.

The age of a battery can be measured in two ways: chronologically and cyclically. Although the shelf life of a nickel-cadmium battery is not unlimited, deterioration is so slight, within reasonable time limits, that most applications can effectively disregard it as a factor. It is "cycle" age, the number of successive charge/discharge cycles that a battery or cell has undergone, which is of primary importance. The analogy can be made to a piece of mechanical equipment, which if properly stored, might last years unused, subject to whatever unavoidable oxidation might occur. When the machine is put into use, however, "wear and tear" endemic to the application begins to exert its influence, and the life expectancy of the machinery begins to decrease. So it is with electro-chemical cells, and thus "cycle" age is a far more indicative measurement of the life cycle characteristics of the battery.

Reconditioning (cf. below) is an effective procedure for rejuvenation of aging ni-cad cells, but its usefulness is limited. In recent tests of ni-cad batteries at MSFC, the batteries usually achieved 3000 cycles before notable performance deterioration occurred; after the first reconditioning, the battery exhibited "youthful" performance for approximately 1000 more cycles before critical performance faults became evident and reconditioning was recommended; subsequent reconditionings rendered the batteries rejuvenated for shorter and shorter periods. By the end of 8000 cycles, reconditioning was being performed every 200-300 cycles. Although the other factors affecting performance were not rigorously controlled, and consequently improvement of these figures might be anticipated if effectively enhancing charging, reconditioning and other procedures are developed, the point is clear: the life expectancy of nickel-cadmium cells is not unlimited, and performance deterioration is only to be expected with increasing "cycle" age.

1.1.2 Charging Regimes.

There are no standard charging regimes for nickel-cadmium batteries. Charging schemes are limited by power sources for input, and by sensor configurations for cut-off, but within these limits various schedules have been tried in applications and tests. Charging may be done with constant current or constant voltage sources; current or voltage may be stepped-down as the battery approaches a charged state; high or low (i.e. "trickle") charges have been tried. Limiting charge by recharge ratio or actual sensor readings of cell voltage and/or pressure may be applied. In short, no stringent tests seem to have been done in order to determine what charging regime may be most effective in prolonging the useful life of ni-cad cells.

An interesting, though unproven, suggestion by some experts is that the charge curve should as closely as possible approximate the discharge curve. Although this may be infeasible in some applications, where such fine adjustments to input current are awkward or too costly, a controlled test of such a scheme might prove extremely rewarding.

Far more important, at least in the short term, is the development of effective techniques for limiting input current so that destructive overcharging does not occur. Although many systems use a strict numerical ratio to balance input and output of current to the electro-chemical system, such a controlling factor must necessarily be set conservatively, since other variable factors, both global to the battery and local to particular cells, may influence the actual amount of potential and capacity regained by specific cells.

1.1.3 Depth of discharge.

Depth of discharge (DoD) is the per cent of cell capacity used in any one discharge cycle. For example, if the capacity of a battery is 50 ampere hours, and a 1 amp load is applied for five hours, the DoD is 10. Typically, operating a ni-cad battery at low (< .20) DoD values for many cycles will result in diminished capacity through the "memory effect" (cf. below). Where possible, it is advisable to vary the DoD,

either through increased loads or through regular omission of charging periods to avoid this effect. If the DoD is extremely high (| .80) for many consecutive cycles, the "memory effect" is not evident, but other deleterious results, such as plate or separator breakdown, may result. In short, the consensus seems to be that extremes in DoD should be avoided, and that DoD should be varied wherever possible. This is in line with the remark made above that variety, anthropomorphic as such a term might seem, is perhaps a worthwhile method of keeping a ni-cad cell "happy".

1.1.4 Reconditioning and the "Memory Effect".

When Ni-Cad cells are utilized at a small percentage of their actual capacity for long periods of time, the capacity of the cell diminishes, as if the cells become accustomed to low discharge rates and lose their ability to sustain greater total AHO. This is due to a change in the crystalline structure of the nickel and cadmium metals on the plates. This condition is known as the "memory effect" and is perhaps the greatest single detrimental factor in long-term battery performance, aside from actual internal physical breakdown (e.g. short) of a cell.

Reconditioning is a term broadly used to mean the procedure of draining a cell to its actual capacity limit, holding that cell at a low potential/low capacity level for a period of time, and then fully recharging the cell. This procedure cause realignment of the chemical structure of the nickel and cadmium plates, and depending on the number of previous cycles which the cell has undergone, can restore the actual capacity of the cell to a nearly "new" value. However, with increasing "cycle age", the restorative effect of reconditioning becomes more and more temporary, and reconditioning more frequently necessary.

One point of particular and critical importance is cell reversal when draining a battery in the reconditioning procedure. As weaker cells reach the lower limit of their capacity, there is a tendency for them to reverse polarity and try to regain power from stronger cells. Cell reversal at currents greater than 1 ampere can result in permanent damage to the reversed cell, and as such should be avoided especially. If the cell cannot be protected from such reversal, the load current on the battery must be kept at a low enough value to avoid damage. If one or more cells are particularly weak, this diminishment in load can make the reconditioning procedure extremely time-consuming. In the recent MSFC ni-cad battery test, five days were necessary to bring all cells down in the first reconditioning procedure; needless to say, cell reversal protection circuits were quickly installed, and the reconditioning time was reduced to a matter of hours.

1.1.5 Temperature.

Ni-Cad cells perform quite well at temperatures between 0° and 40° C. However, it is well to avoid sudden shifts in temperature, since they may adversely affect battery performance and make accurate evaluation of charging regimes and capacity values difficult. It is also

the case that internal faults within a cell, such as a short, may cause temporary rises in internal cell temperature, and that charging a cell also causes the internal cell temperature to rise. For this reason, it is advisable to have several temperature sensors on the battery, if it is not feasible to have one for each cell.

1.2 Measurements and Evaluation of Parameters.

1.2.1 Recharge Ratio (RR) and Efficiency (Eff).

RR is a derived measurement, equal to Ampere Hours In (AHI) divided by Ampere Hours Out (AHO); as used in some tests and applications, it serves as a limit on charging schedules and as an indication that battery reconditioning is necessary. In general, a RR of less than 1.04 would indicate that the battery is not being brought back to a fully charged state, and a RR of greater than 1.15 indicates that the battery cells are being overcharged. RR in the high end of the permissible range is a probable indication of diminishing capacity in the battery, although this judgement should only be made on the basis of examination of the current trend in RR, since short term fluctuations in RR may be due to idiosyncrasies of individual cells.

Eff is analogous to RR; it is equal to Watt Hours Out (WHO) divided by Watt Hours In (WHI). Ideally, a battery would be 100% efficient; this is, however, never the case. Eff measurements of less than 95% will usually be equivalent to a high RR, and indicate the same conditions.

1.2.2 Capacity.

Capacity is measured in ampere hours of current deliverable before voltage falls below some arbitrary threshold. Since the discharge curve of nickel-cadmium cells is relatively flat through the greater part of capacity, usable voltage levels are obtainable through up to roughly 90% of capacity. Most applications, however, use a very small percentage of available capacity, and thus detection of lessening capacity (due to "memory" effect) is rendered more difficult.

1.2.3 Individual Cell Measurements

By far the most useful measurements are End of Charge (EOC) and End of Discharge (EOD) voltage and pressure values for individual cells in the battery. Ideally, any test or application of Ni-Cad batteries should monitor voltage and pressure of each cell at both EOC and EOD. From these measurements, derived parameters such as voltage divergence (VD) (i.e. the difference in potential between the highest and lowest cell(s)) and average voltage, as well as destructive overcharging, can be quickly determined. The significance of these values will be discussed in section 2 below.

2.0 Determining the Status of the Battery through Parameter Values

2.1 Pressure

High EOC cell pressure: A high EOC cell pressure indicates that the cell is becoming fully charged. Care must be taken, however, that overcharging does not take place. As the nickel plate becomes fully charged, oxygen is released, resulting in a gradual rise in internal cell pressure; upon discharge, the oxygen will recombine, and cell pressure will drop. However, when the nickel plate reaches full charge, the cadmium plate will begin to rapidly release hydrogen, and a sharp increase in cell pressure will result. Hydrogen will not recombine upon discharge, and a decrease in cell performance will occur. Extreme overcharging may even result in a "ballooned" or ruptured cell.

For this reason it is recommended that cell charging be limited on an individual basis, using pressure and voltage sensors to indicate when a particular cell is fully charged. At that point, the cell should then be removed from the charging circuit. This is a safer, though more expensive, method than using RR as an indication of charging adequacy. In applications where replacement of damaged cells is dear or impossible, such a procedure may be greatly desirable.

High EOD cell pressure: High EOD cell pressure is usually the result of non-recombinant hydrogen generation during the charging cycle. As such, it serves as confirming evidence of suspected overcharging.

2.2 Voltage

In the following, the terms "high" and "low" with respect to voltage are used in purely relative senses. A "low" EOD voltage at one level of depth of discharge might be a very high one at deeper levels of discharge. Although there are ideal values for the EOC level of new cells which are fully charged, "cycle" age may mean that a slightly lower value for full charge is acceptable. Thus, the terms "high" and "low" must be evaluated in terms of the other affecting parameters.

A cell which exhibits high EOD and EOC voltages is a good cell, having a high potential at EOC and a strong capacity through discharge. Other combinations of high and low values, however, may be indicative of trouble.

Low EOD voltage is an indication of lessened capacity, and is probably due to the "memory effect". As capacity decreases, the same AHO load will result in lower and lower EOD voltages, since the ability of the the cell to maintain an acceptable voltage level is a direct function of its capacity. Reconditioning will usually achieve a rebound in cell capacity; if not, problems such as separator deterioration or plate breakdown may be suspected.

Extremely high EOC voltages will usually be accompanied by high internal pressure values; see section 2.1.

Low EOC voltages are usually the result of the memory effect; however, if all cells are displaying low EOC voltages, and the RR is low, it is probable that the cells are being insufficiently charged.

2.3 Voltage Divergence

Voltage divergence is the difference in the highest and lowest voltage values at a given point in time, usually EOD or EOC. Cells tend to group; the cell(s) with high voltage values at EOC usually continue to have them, and the cell(s) with low values usually remain low. Through time, the absolute value between high and low cell voltage increases, and cells tend to migrate from "average" values to either the high or low group. EOC voltage divergence is a usually higher than EOD voltage divergence, since stronger cells will "pick up" weaker cells under a load. EOC voltage divergence is a surer indicator of "memory effect", since, if battery charging is being limited by RR thresholds, cells which are losing capacity will be recharged less. Conversely, if charge is being limited through pressure and voltage readings, EOC divergence will be slight, but a rise in measured RR will indicate that certain cells are losing capacity. By monitoring the relative charge times of respective cells, low capacity cells can be identified.

Voltage divergence of greater than 150 mv at EOC indicates that the low cell(s) is losing capacity, since if a "healthy" cell has a EOC voltage of 1.5 volts, a voltage level of 1.35 in any cell will be an indication that that cell is near the end of the discharge curve and has very little remaining capacity.

2.4 Average Voltage

Average voltage values are of primary usefulness in conjunction with voltage divergence values to give an overall indication of the entire battery status. If the average voltage at EOC is at an acceptable level, while voltage divergence is high, it is indicated that approximately equal numbers of cells are migrating to high and low groups. If average voltage at EOC is dropping, and divergence is high, it may indicate that too many cells are moving to low values, and reconditioning is advisable. If average voltage at EOC is dropping, and voltage divergence is low, then the charging scheme should be reevaluated, since the total charge may not be great enough. If average voltage at EOD is low, and divergence is small, the DoD should be evaluated. If DoD is small in relation to projected capacity, then real capacity may be lessening in response to the memory effect. If average voltage at EOD is low, and divergence high, then "memory effect" is definitely indicated, especially if DoD is low with respect to projected capacity.

3.0 Therapeutic and Prophylactic Procedures and Prolonging the Life of Ni-Cad Cells.

3.1 Prophylactic Procedures.

There are three main points to be made in regard to protecting the viability of nickel-cadmium cells: one, cells should be protected from reversal during deep discharge; two, cells should be protected from destructive overcharge and the accompanying generation of non-recombinant hydrogen; and three, ambient temperature should remain relatively stable.

The charging regime is one area in need of research. Since charging, just as discharging, "ages" a battery, optimal charging strategies need to be developed which minimize the "wear and tear" on the ni-cad cell. It is certain that some charging patterns are more destructive than others, and it is probable that different charging schemes will be found optimally beneficial at different times in the battery life cycle. That is, while it will undoubtedly be found that some charging procedures are undesirable under any circumstances, it may be discovered that a scheme judged optimal for a "new" battery will prove less desirable than some other at a later time in the battery's life cycle.

3.2 Therapeutic Procedures.

Only two long term therapeutic procedure are available in most ni-cad battery applications: reconditioning and variable DoD. As explained above, reconditioning, to a high degree, undoes the destructive "memory effect" in applications where consistently low DoD levels are utilized. On the other hand, variable DoD levels somewhat eliminate the "memory effect", but may not be feasible in some applications. Since reconditioning procedures make the battery unavailable for a period of time, it may be advisable to use a combination of reconditioning and variable DoD to prolong ni-cad cell life, where the application is amenable.

3.3 Prolonging the Life of the Battery.

As stated in section 1.1, the life expectancy of nickel-cadmium cells is not unlimited. Critical or damaging faults due to poor construction or material can only be avoided through strict quality control. However, much can be done in the proper design of the components of the application to prolong ni-cad life expectancy. The steps advised in section 3.1 should certainly be taken. Further research should be made on the topics of optimal charging regimes, variability of DoD, and timing of reconditioning. Only by stringently controlling other variables can valid conclusions be reached as to the effectiveness of the therapeutic measures mentioned above.

Some suggestions for further testing may be in order:

1. Preventive reconditioning or DoD.
If the application permits, reconditioning or variance of DoD should be done before the first indications that capacity is diminishing. That is, do not allow the "memory effect" to become established in the "youthful" period of the battery's life.
2. Prevention of destructive overcharging.
Charging limits should be set conservatively and monitored closely. Failure to fully charge the cells may actually be beneficial, resulting in an inadvertent variance in DoD, while overcharge cause heat generation and increase in internal cell pressure through generation of hydrogen, and could never be deemed beneficial.
3. Replication of discharge curve by charge curve.
As mentioned above, development of optimal charge regimes could have great impact of life cycle pro-longment. Further testing in this area could reap great rewards.

APPENDIX B

NICBES DATA FILES

Fault file - Contains a fault flag = 1 if there was a fault
= 0 if no fault was detected.

Current file 1 - Contains the current orbit number and
a reconditioning flag for each battery
= 1 for reconditioning
= 0 no reconditioning.

Current file 2 - Contains Phase (charge or discharge)
Day_min

Current from 13 SPAs (Solar Panel Array)
Current from 3 Busses
Average Temperature for 6 Batteries

Current file 3 - Contains 6 Battery Cell Voltages (23 per battery)

Data file 1 (6x12) - File contains battery voltage taken at EOD per
orbit for last 12 orbits.

Data file 2 (6x12) - File contains the battery voltage at high in-charge
for the last 12 orbits. There are 23 cells per battery.

Data file 3 (6x12) - File contains the recharge ratio = AHO/AHI per orbit
for 12 orbits.

Data file 4 (6x36) - File contains cell voltages at EOD, with the high
value, low value and average of all values, in this order per orbit for
the last 12 orbits. So a row contains 12 high values, 12 low values and
then 12 average values.

Data file 5 (6x36) - File contains cell voltages at high-charge; high,
low and average of all values, in this order, per orbit for last 12
orbits. Each row contains 12 high values, 12 low values and the 12
average values.

Data file 6 (6x23) - File contains 23 cell voltages at EOD for each
battery, from the latest orbit.

Data file 7 (6x23) - File contains 23 cell voltages at high-charge for
the latest orbit.

Data file 8 (6x48) - File contains the average of the six temperature
sensors (degrees C) per battery, at two minute intervals
(1min,3min,...95min) over the latest orbit.

Data file 9 (6x12) - File contains the average battery temperatures per orbit for the last 12 orbits. This is the average of the temperature averages in Data file 8.

Data file 10 (6x46) - File contains the 23 cell pressures taken at EOC and then the 23 cell pressures taken at EOD for each battery in the last full orbit.

Data file 11 (6X12) - File contains the time on trickle charge for each battery per orbit for the last 12 orbits.

Data file 12 (6x49) - File contains battery current during reconditioning, at 2-minute intervals, for last reconditioning of each battery. It is recorded every 2 minutes, only when battery reconditioning flag is 1 and only for one orbit. Column 1 contains the orbit number for which reconditioning is occurring. The file contains zeroes until a battery is reconditioned.

Data file 13 - File contains AHO summed over discharge phase per orbit for last 12 orbits.

APPENDIX C

NICBES ADVICE ANALYSIS

For reconditioning, 11 conditions need to be checked for a particular battery:

1. EOD voltage strongly down, in-charge divergence strongly up => reconditioning advised.
2. EOD voltage strongly down, in-charge voltage strongly down => recondition soon.
3. EOD divergence strongly up, in-charge divergence strongly up => strongly rising divergence indicates reconditioning.
4. Voltage trends strongly down or down, recharge ratio and divergence trends strongly up or up => reconditioning is indicated by all 5 trends.
5. Recharge ratio strongly up => reconditioning indicated.
6. In-charge voltage is down or strongly down, in-charge divergence is up or strongly up => reconditioning recommended.
7. EOD voltage down or strongly down, in-charge divergence up or strongly up => reconditioning indicated.
8. EOD and in-charge divergence both up => consider reconditioning.
9. Recharge ratio up => consider reconditioning.
10. Both EOD and in-charge voltages down => consider reconditioning.
11. None of the above => no need for reconditioning at present.

To determine if the charging scheme for a battery should be changed, nine conditions are checked:

1. Temperature strongly up, EOD pressure greater than 120, EOC pressure greater than 140 => overcharging causing high pressure.
2. In-charge voltage strongly up => check for overcharging.
3. EOD pressure greater than 110, EOC pressure greater than 135 => charge rate may be too high.
4. EOD voltage strongly down, in-charge voltage strongly down => undercharging may be seriously affecting capacity.
5. EOD voltage down, in-charge voltage down => undercharging.
6. EOD voltage strongly down or down, in-charge voltage strongly down or down => undercharging may be causing loss of voltage.
7. EOD voltage down, in-charge divergence greater than .8 => undercharging may be causing loss of voltage.
8. EOD voltage strongly down, in-charge divergence greater than .8 => undercharging may be causing serious loss of voltage.
9. None of the above => no need to change charging scheme.

Six conditions are checked to advise as to battery workload change:

1. EOD voltage down, EOD divergence down, AHO average less than 25 => loads probably too light.
2. EOD voltage strongly down, EOD divergence strongly down, AHO average less than 5 => losing capacity due to memory effect, try heavier load.
3. AHO average greater than 14 => possibly destructive overwork.
4. AHO average greater than 9 => heavy workload.
5. EOD voltage down or strongly down, EOD divergence down or strongly down, AHO average above 6 => losing capacity, consider reconditioning.
6. None of the above => no need to change workload.