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X-711-77-28

THE 1976
GODDARD SPACE FLIGHT CENTER BATTERY WORKSHOP

NOVEMBER 1976

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

N80-16195

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NOVEMBER 9-10, 1976

Chairman
Gerald Halpert

LB-200
JRF

November 1976

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

PREFACE

The papers presented in this document have been derived from transcripts taken at the Ninth Annual Battery Workshop held at the Goddard Space Flight Center on November 9 and 10, 1976. The transcripts were lightly edited with the speaker's vugraphs assembled at the end of each presentation for uniformity.

The Workshop was attended by manufacturers, users, and government representatives interested in the latest results of testing, analysis, and development of the sealed nickel cadmium cell system. The purpose of the Workshop was to share flight and test experience, stimulate discussion on problem areas, and to review the latest technology improvements.

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INTRODUCTION

G. Halpert
Goddard Space Flight Center

I would like to welcome you to the Goddard Space Flight Center and the Ninth Annual Battery Workshop. The objective of this workshop is to provide a forum for the exchange of information on the latest results of testing, analysis and development of sealed nickel cadmium cells and batteries and developments in the nickel-hydrogen system. Based on your comments of past meetings, the workshop series has succeeded in meeting its objectives; however, there is more to be done to meet the long-life high-reliability goals of future missions. We are confident that this workshop will continue to serve this purpose.

To set the stage for this workshop it is desirable to know NASA's role in space power and what approach is being taken towards meeting these goals. To provide this background, we have with us Mr. Jerome Mullin, Chief of the Space Power program (Code RP), Office of Aeronautics and Space Technology, at NASA Headquarters. Although he is somewhat new to the field of electrochemical power systems, he has been at NASA Headquarters for the past several years as Program Manager of Electric Propulsion. I would like to present to you Jerome Mullin who will speak on NASA's objectives in the space power program.

NASA OBJECTIVES AND THE SPACE POWER PROGRAM

J. Mullin
NASA HEADQUARTERS

I want to thank Gerry and welcome you to the Goddard Battery Workshop. What I would like to do today is review NASA objectives for the space power program in such a way as to reflect what we think the future direction for NASA is likely to be. We do not have a large budget in the area of chemical power, for example, we represent roughly a million and a half dollars with 27 or 28 people located at the various Centers. The objective of this program, while limited in dollars and manpower, is to provide the seed capital for major advances in power systems.

(Figure 1)

The total area of space power systems represents about 120 people at the various Centers and approximately $7 or $8 million in R&D contracts. The overall objective is to provide the technology basis for future high-power and long-life space energy systems at improved specific mass and cost.

Forty years is the kind of investment horizon one thinks about for the central power stations. We are now aiming specifically at a 10-year life for many of these space systems, batteries quite specifically. And we think that we are going to put some numbers in the areas of mass and cost because it becomes important in trying to justify our programs.

VOICE: Is that milliwatts or megawatts?

MULLIN: Megawatts.

(Figure 2)

The power program as it is presently structured is broken into four areas that are cited on the chart: solar cells and arrays, chemical energy conversion and storage, thermal energy conversion, and the area of power systems which is sometimes called power conditioning.

We are also working on arrays of solar cells, high-power arrays, with the objective of providing power levels of up to 100 kilowatts. And what drives us--and you might be interested in this because it does affect the chemical energy storage--are applications having to do with the use of the shuttle in space, what used to be called the space station. You might also be interested to know that two major studies are going on at Marshall and JSC which are looking at this type of application for future NASA programs. All of these studies have shown an increase in power requirements, implying extraordinary increases of energy requirements, particularly for low-earth orbit.

The explicit goals for chemical energy conversion and storage are to double the operating life of the primary and secondary batteries, and to reduce fuel system mass and cost. As far as the long-term goals are concerned, we think an order of magnitude is not unreasonable in terms of battery performance. And again, the idea of utility-type use of power in space may require us to develop maintainable semi-permanent megawatt hour energy storage systems.

In thermal energy conversion, we are working towards a demonstration of high-power systems which are cost and mass competitive with solar photovoltaics for earth orbital application. We don't see a near-term application for a high-power dynamic system that is not cost competitive with solar photovoltaics. In other words, we don't see nuclear electric propulsion type applications nor the need to develop the power systems that are consistent with such applications in the near future.

In the near term, we are also aiming to reduce the cost and mass of the lower-power nuclear and solar dynamic energy conversion systems. In the future, we are attempting to provide the basis for a nuclear electric propulsion option for the planetary applications. And again we are aiming at the critical technology for megawatt power systems.

We do plan, for example, in the space construction base studies a tradeoff between the solar-powered alternatives and nuclear-powered alternatives I mentioned before. In the area of power systems, it is our feeling now that this work should be oriented toward multi-kilowatt applications. In the area of the lower-powered system, our major thrust, as was indicated in the first chart, is to extend life, particularly in hazardous environments.

(Figure 3)

What we are trying to do is improve the efficiency of solar cells and their radiation resistance. We are reasonably optimistic about the progress being made in this area. A lot of this progress stems from the large-scale investment being made by ERDA in the low-cost silicon solar array project. We would expect, within the next year or two, to be in the pilot production of the very thin silicon solar cells.

We are also working toward the design of high-power solar arrays. For example, we intend to fly an array at 15 kilograms per kilowatt, or for those who like to think the other way, 66 watts per kilogram, as a flight test on a shuttle in 1980. The roof section of this solar array was just tested about three or four weeks ago in a KC-135 zero G test. We are also working on an array that has three times the power output or 200 watts per kilogram. We also think that we can produce between 4 and 5 kilograms per kilowatt for an advanced lightweight solar array--incidentally, making it very difficult for the nuclear power people, who have to provide shielding in an earth orbital application, to compete.

(Figure 4)

I suppose this is the area of interest to most of you here. We had set a goal of doubling the primary and secondary battery performance. Now you will notice on these charts that cost goals are important. Sam Bogner will describe to you a cooperative effort that involves the Air Force, Goddard, Lewis and JPL with objectives of trying to double the performance of the Ni-cad. In our Goddard program we are trying to demonstrate the test methodology to verify our ability to predict performance.

In the fuel cell area we are currently working on cells with performances better than that which is now available on the shuttle. It is directed toward the OTV type application to use common propellant tankage with the propulsion system, as there seems to be a system advantage in this approach. We are also looking to reassess the regenerative fuel cell electrolysis system for energy storage on high-powered systems in low-earth orbit. Previous studies have indicated, on the basis of availability, battery systems for this type of application.

(Figure 5)

In thermal energy conversion, we are looking for high power, and the objective here is high power for static and dynamic systems which are competitive with the solar photovoltaic as we indicated before. This year we are working to define a high-power Brayton program. This is consistent with a drive at ERDA to obtain support for advanced space reactor programs which might be approved for DOD-NASA type operations. So we think a high-power Brayton is a reasonable alternative to look for in the conversion system. As a consequence, we are looking at the constraints of the high-powered Brayton program now. We are also working in the area of thermionic diodes with the objective of trying to obtain adequately high efficiency for a heat-pipe, reactor-type system.

In the area of the lower-powered system, we have been developing methods to better integrate RTG's into the spacecraft. And the major thrust in this effort, you will notice, is reducing cost. For example, looking at lower-cost fuels for the RTG's, looking at higher efficiencies from selenides, again reducing the amount of isotopes that are required. Some alloys have been identified with very high potential efficiency in the area of thermoelectrics.

We are currently developing some Brayton cycle components for the joint ERDA/NASA program, with the objective of flying a 1/2 to 2 kilowatt nuclear dynamic isotope system in about 1980 or 1981.

(Figure 6)

In the area of power systems which have mainly been power conditioning in the past, we are attempting to develop the critical component technology for multi-kilowatt applications. That is a top-level objective.

In the area of the lower-powered systems, again it is the battery life that is the objective. Modular active redundant power processing. We are looking at automated power systems management, particularly for deep space missions. We are also looking for the kinds of systems appropriate for inbound missions; for example, solar thermoelectric generators. These then are the objectives as we currently see them. Aiji Uchiyama has recently presented an integrated nickel cadmium battery program that was very well received by the NASA Centers and our Research and Technology Advisory Committee (RTAC) on space propulsion and power.

(Figure 7)

This is a chart that Uchiyama used in his presentation to the RTAC. I wanted to point out that the key here is the reasonably clear objectives. If anybody has any comments, I hope you would let me know through the appropriate NASA personnel.

SEIGER: Yardney Electric

What is the program and the schedule?

MULLIN: Of the Ni-cad battery, I assume?

Well, Mr. Bogner will cover that in his session. It is the program that we are looking at to double life and energy density.

GASTON: RCA

On your chart on the battery storage systems, I didn't find the nickel-hydrogen system listed at all. Is that an oversight?

MULLIN: No, that is not true, we are interested in the nickel-hydrogen system. We are, in fact, evaluating nickel hydrogen batteries at Marshall. I think it is a question of how many words we can put on these charts. I think that it will change as time goes on as these systems are reviewed in the proper competitive arena.

DUNLOP: COMSAT

I would just like to point out, nickel-hydrogen has already achieved the goals put up there on that chart to be achieved by nickel-cadmium by 1981.

MULLIN: Dr. Ritner, who is in your organization and a member of RTAC, commented in his presentation made at JPL about two weeks ago, that this was a fine program and the proper direction to go with the nickel-cadmium. As far as alternative batteries, the present investment level that is being made by other organizations, appears to be appropriate. Ni-cad batteries have been viewed as the workhorse, have, in fact, been the workhorse for some time. I think decisions on power systems will be made on a systems basis as the opportunities for flight come up, and I am sure we will adjust our program accordingly. If we don't see the opportunity for improvement for these systems, then it would be pointless for us to invest further in them.

OBJECTIVE:	PROVIDE THE TECHNOLOGY BASIS FOR FUTURE HIGH POWER & LONG LIFE SPACE ENERGY SYSTEMS AT IMPROVED SPECIFIC MASS & COST.		
	TODAY	1985	2000
POWER LEVEL (MW)	10^{-3}	10^{-1}	10
LIFE (YRS)	5	10	30
MASS	-	-	-
COST	-	-	-

Figure 1. Space Power Systems

SPECIFIC OBJECTIVES & GOALS

SPECIFIC OBJECTIVES	NEAR TERM GOALS	FAR TERM GOALS
SOLAR CELLS & ARRAYS	● IMPROVE CELL EFFICIENCY (18%), RADIATION RESISTANCE (< 5%/YR.), MASS (< 4-MIL) & COST (5$/W) ● DEMONSTRATE HIGH POWER ARRAY DESIGN TECHNOLOGY (100 KW, 100 $/W, 5 KG/KW, 10 YR. LIFE)	● DEMONSTRATE CRITICAL TECHNOLOGY FOR MW SYSTEMS
CHEMICAL ENERGY CONVERSION & STORAGE	● DOUBLE PRIMARY & SECONDARY BATTERY SPECIFIC POWER & OPERATING LIFE ● REDUCE FULL CELL SYSTEM MASS & COST BY A FACTOR OF	● INCREASE BATTERY SPECIFIC POWER BY A FACTOR OF 10 ● DEVELOP MAINTAINABLE SEMI-PERMANENT MW-HR. ENERGY STORAGE SYSTEMS
THERMAL ENERGY CONVERSION	● DEMONSTRATE HIGH POWER STATIC & DYNAMIC SYSTEMS WHICH ARE COST & MASS COMPETITIVE WITH SOLAR PHOTOVOLTAICS FOR EARTH ORBIT ● REDUCE COST & MASS OF LOW POWER (< 2 KW) SYSTEMS	● DEMONSTRATE CRITICAL TECHNOLOGY FOR MW SYSTEMS ● PROVIDE AN NEP OPTION FOR PLANETARY MISSIONS
POWER SYSTEMS	● DEVELOP CRITICAL COMPONENT & SYSTEMS TECHNOLOGY FOR MULTI-KW APPLICATIONS ● DEVELOP LOW POWER SYSTEMS TECHNOLOGY TO EXTEND LIFE & ENVIRONMENTAL CAPABILITY	● DEVELOP SYSTEMS & COMPONENTS FOR MW OPERATION

Figure 2. Space Power Systems, Specific Objectives & Goals

NEAR TERM GOALS	APPROACH
● IMPROVE CELL EFFICIENCY (18%) RADIATION RESISTANCE (<5%/YR.), MASS (<4-MIL) & COST (5$/W)	● COMPLETE TECHNOLOGY ASSESSMENT OF WRAPAROUND CONTACTS, TEXTURED FRONT SURFACES, BACK SURFACE FIELDS, LOW COST RIBBON CELL & EPITAXIALLY GROWN JUNCTIONS BY _______ ● TEST & EVALUATION OF ADVANCED CELLS FROM NASA, ERDA, INDUSTRY, ETC. ● IDENTIFY & EVALUATE METHODS OF REDUCING RADIATION DAMAGE IN SOLAR CELLS ● PILOT PRODUCTION OF THIN (~3 MIL) CELLS BY ______ ● $5/W AUTOMATED PRODUCTION BY 1979
● DEMONSTRATE HIGH POWER ARRAY DESIGN TECHNOLOGY (100 KW, 100 $/W, 5 KG/KW, 10 YR. LIFE)	● COMPLETE FULL SCALE 12.5 KW, 15 KG/KW ARRAY HARDWARE BY MID 1978 (SHUTTLE OFT TEST 1980) ● DEMONSTRATE DESIGN FEASIBILITY OF 4-5 KG/KW ARRAY BY _____ ● DEMONSTRATE AUTOMATED LOW COST ARRAY MODULE FABRICATION BY 1980

Figure 3. Solar Cells & Arrays

NEAR TERM GOALS	APPROACH
● DOUBLE PRIMARY & SECONDARY BATTERY SPECIFIC POWER & LIFE	● DEVELOP 10 YR. NICD SECONDARY BATTERY AT 55 WH/KG BY 1981 ● DEMONSTRATE ADVANCED LOW COST TEST METHODOLOGY & VERIFY PREDICTION CAPABILITY ● DEMONSTRATE REMOTELY ACTIVATED AgO-Zn PRIMARY BATTERY AT 75 WH/KG BY CY 1979 ● DEMONSTRATE REMOTELY ACTIVATED PRIMARY BATTERY AT 220 WH/KG BY CY 1982 ● DEVELOP Ag-H2 BATTERY TECHNOLOGY AT 90 WH/KG BY 1984
● REDUCE FUEL CELL SYSTEM MASS & COST BY A FACTOR OF _______	● DEMONSTRATE MODERATE & HIGH CURRENT DENSITY FUEL CELLS CAPABLE OF USING PROPELLANT GRADE REACTANTS ● ASSESS TECHNOLOGY REQUIREMENTS FOR REGENERATIVE FUEL CELL APPLICATIONS

Figure 4. Chemical Energy Conversion & Storage

GOALS	APPROACH
DEMONSTRATE HIGH POWER STATIC & DYNAMIC SYSTEMS WHICH ARE COST & MASS COMPETITIVE WITH SOLAR PHOTOVOLTAICS FOR EARTH ORBIT	EXTEND BRAYTON LIFE TESTS TO 50,000 HRS. (10 KW_E) BY 1980
	DEFINE HIGH POWER BRAYTON PROGRAM BY 9/77
	DEVELOP & EVALUATE CESIUM THERMIONIC CONVERTERS & MATERIALS FOR EFFICIENCY ≥ 20%, LIFE > 10 YRS. BY 1979
	PROVIDE HEAT PIPE/MODULE SYSTEM TECHNOLOGY BASIS FOR OUT-OF-CORE NUCLEAR THERMIONIC POWER BY ______
REDUCE COST & MASS OF LOW POWER (< 2 KW) SYSTEMS	REDUCE S/C - RTG INTEGRATION COSTS BY DEVELOPING IMPROVED MODELLING TECHNIQUES
	EVALUATE CM FUEL FOR S/C USE
	EVALUATE SELENIDE MATERIALS FOR EFFICIENCIES OF 10-15% (COST ≤ $10,000/W)
	EVALUATE ALLOYS WITH POTENTIAL EFFICIENCIES OF ~ 25%
	DELIVER 0.5-2 KW BRAYTON CYCLE COMPONENTS FOR ERDA/NASA GROUND DEMO & ASSESS FLIGHT POTENTIAL BY 1978 (COST ≤ $5000/W)

Figure 5. Thermal Energy Conversion

GOALS	APPROACH
DEVELOP CRITICAL COMPONENT & SYSTEMS TECHNOLOGY FOR MULTI-KW APPLICATIONS	DEVELOP IMPROVED HIGH POWER COMPONENTS & MATERIALS INCLUDING CAPACITORS, SWITCH GEAR, DIELECTRICS, ETC.
	DEMONSTRATE INTEGRAL SOLAR ARRAY POWER CONDITIONING FOR HIGH VOLTAGE LOADS
	DEMONSTRATE MULTI-KW CAPACITOR DIODE VOLTAGE MULTIPLIER
	DEMONSTRATE MULTI-KW HIGH VOLTAGE DISTRIBUTION SYSTEMS
	UNDERSTAND S/C CHARGING & HV/SPACE PLASMA INTERACTIONS
DEVELOP LOW POWER SYSTEMS TECHNOLOGY TO EXTEND LIFE & ENVIRONMENTAL CAPABILITY	DEVELOP MODULAR, ACTIVE REDUNDANT POWER PROCESSING
	DEVELOP TECHNOLOGY FOR AUTOMATED POWER SYSTEMS MANAGEMENT
	DEMONSTRATE HIGH TEMPERATURE SOLAR POWER SYSTEMS TECHNOLOGY

Figure 6. Power Systems

- COORDINATED/INTEGRATED PROGRAM
- PROGRESS MADE IN WEIGHT REDUCTION
- PROGRESS MADE IN UNDERSTANDING LIFE/RELIABILITY MECHANISMS
- PROGRESS MADE IN SOLVING LIFE/RELIABILITY PROBLEMS
- APPEARS FEASIBLE TO INCREASE LIFE & USABLE ENERGY DENSITY BY FACTOR OF 2
- ALL CENTERS IN AGREEMENT ON PROGRAM & SCHEDULE

Figure 7

<u>Morning Session</u>

PROGRESS OF THE BATTERY WORKSHOP

G. Halpert, Chairman
Goddard Space Flight Center

As we start our first general session, I would like to review our progress during these past nine workshop years. One of the earliest nickel cadmium cell problems that I can remember was the glass-to-metal Sonotone cell seals that were slated for the Nimbus launch. The problem was that on the charge cycle at the c/10 rate the cell voltages were running at 1.71 volts. We called together a team of experts to determine if hydrogen was being evolved. It was obvious from the start that we needed a better understanding of the nickel cadmium cell so we initiated several new programs to identify the cause of these problems.

As early as 1966, Gould ran a program for NASA on separator technology. They had screened some 70 separator materials for nickel-cadmium-sealed cells, and they found that the Pellon nonwoven nylon was the separator that best did the job, and we are still using it today. They also identified polypropylene as a possible separator material. About that time, we were doing computer-operated battery tests at the Martin Company, and Inland Test Laboratories was doing test and evaluation work for the Air Force. We were also getting some failure analysis on test cells from both Martin and Inland, and we were beginning to learn that separator dryout, carbonate contamination and plate structural changes were the major causes for cell degradation.

The Crane facility came into being about this time, and as you know, we are still using their operation today. Then we looked at the work on the positive electrode by Seiger, Carson, and Kroger; and Will on the negative. About 1968 a problem surfaced with regard to the OAO cells. It seems that these cells had a significantly higher precharge than we expected and we were getting close to hydrogen evolution. A meeting was called at Goddard, which turned out to be the first--really the forerunner of the Battery Workshop. Those present, in addition to Gulton Industries, were the Pellon Corporation, other battery manufacturers, battery users, and government representatives. The question discussed at this meeting was whether the wetting agent in the separator or the precharge procedure was causing the difficulty. As a result, wetting agents were no longer acceptable in the cell.

A partial solution to precharge came about in the following manner: the manufacturer revealed his method of precharge, which prior to that time had been considered proprietary—and we made some adjustments. I don't believe we ever really decided on what the solution to that problem was, but we had a successful OAO flight. It became necessary, however, to investigate in more detail what was going on in the nickel-cadmium cells, particularly with regard to plate processing and plate materials.

Beginning in 1968 investigations of manufacturing processes and material properties were initiated. Significant work was done at Tyco in sintering and impregnation techniques and at Eagle-Picher on process variables. At Gulton we actually operated the furnace and impregnation facility to try to understand the process; we also started work on plaque materials at Gould. There was some work done by Battelle on various kinds of plaque and plate materials sponsored by the Air Force. The result was a mini-revolution which has led to a new relationship between the manufacturer and users. In existence today are the Manufacturing Control Documents (MCD's) which describe in detail the manufacturing operations and quality control procedures. The openness on the part of the manufacturer was an aid in identifying problem areas so that solutions could be found. I must say that we are pleased with this relationship and with the growth of our standardization program. However I want to point out, as our legal people will be sure to do, that the manufacturer is entitled to his proprietary process. We want to be certain that this does not lead to the situation that we had in the past, namely that the proprietary processes were used to hide problem areas. As I see it, we should minimize these problems in the future because we know more, the manufacturer knows more, and the manufacturer knows that we know more. There also appears to be a willingness on the part of the manufacturer, the user, and the government to discuss problems openly rather than hid them behind proprietary secrecy.

VIBRATIONAL EFFECTS ON SEALED NICKEL-CADMIUM CELLS

S. Gross
Boeing Aerospace Company

The purpose of this investigation was to determine what happens to sealed nickel-cadmium cells under strenuous vibration. We wanted to find out where the cells failed, and what we could do about it. We used prismatic 10-ampere-hour sealed GE cells. In all fairness to General Electric, I should point out that the failures we experienced were, in many cases, under fairly strenuous vibration environments, more than we ordinarily might experience in aerospace applications.

(Figure 8)

We found five important failure modes numbered in the chart. The first and foremost--probably the most important one, was the failure of the plate tabs at the location where they are welded to the comb. Secondly, breakage to the tabs near the plate. Number three, breakage of the cell cover around the terminal. And four, breakage within the ceramic seal itself. Finally, on item five we got breakage of the comb and stud to terminal weldment.

(Figure 9)

When you have a complete failure it is fairly easy to detect. But if you have a partial failure, it is quite a bit more difficult.

We got indications of partial failures by lower capacity and by lower tolerance to overcharge as well as increased resistance. Additionally, there are intermittent or only loosely connected parts within cells that have failed and this results in a low-open circuit voltage after charge, and a high-open circuit voltage after discharge.

(Figure 10)

One of the common tests to find if there has been a failure from vibration, is to run a discharge at high rates before and after the vibration. This is shown here. Normal discharge before vibration of 30 amps; after vibration we obtain a much reduced voltage. And in this case, we have a jagged voltage profile typical of an intermittent contact with plate tabs.

(Figure 11)

Breakage of the weld between the terminal stud and the comb is one of the serious failures we observed. This sketch is not accurate, but it illustrates the problem. The assembly is made by drilling a hole in the comb and inserting a stud and then welding. This results in a notch remaining, and the crack starts at this notch under vibration. Then the crack propagates across the weld. This was solved by going to a vacuum brazing instead of welding, and thus avoiding the notch.

(Figure 12)

Up at the top of the chart is a more accurate representation in this photomicrograph of that weldment between the terminal stud and the comb. And you can see where the notch, where it has propagated, is broken across the comb. An in the bottom of the chart can be seen some of the damage to the terminal assembly.

(Figure 13)

The failures of the tab weld were probably the most common and the most bothersome failures that we experienced. We ran a series of metallurgical investigations to try to find out what was happening. And we did get increased grain growth and oxidation zones in the region of the weld. But we couldn't pin these down to be the causes of the failure. Neither could we blame the failures on stress corrosion or hydrogen embrittlement, nor oxidation. We did find that the fractures occurred within the comb, and that they were initiated by brittle fatigue failure, and then they ended up as a ductile tearing of the tab.

Because fatigue was indicated to be an important effect here, we ran some accelerated tests, accelerating the fatigue effect. This was done by loading a plate, with a 1 1/2 pound weight suspended directly over the weld point, and then rocking the assembly back and forth plus or minus 20 degrees. The results we got were a very wide distribution of the number of cycles to failure ranging between 46 to over 55,000 cycles.

Additionally we ran some tests comparing assemblies that had been welded in helium versus assemblies that had been welded in air, and we found no significant differences on which we concluded that oxidation was important. Because of the wide distribution of failures, we concluded that it would not be wise to depend on the strength of the tab to take up the loads under vibration.

(Figure 14)

The results of those accelerated fatigue tests are shown here. We had three samples, each of which had about 20 plates. And in each case we got a very wide distribution. The classical fatigue damage occurs in three stages: starting with work hardening, then the initiation of a crack, and finally the crack propagation. We didn't determine which of these three steps was the critical step for these cells.

(Figure 15)

In order for the tabs to be loaded, you have to have movement of the plate. Plate movement was reduced by friction within the cell, and we determined that the critical friction element is between stainless and the filling polypropylene which wraps around the plate stack. For this reason we ran friction tests between these materials. In this particular chart we ran some friction tests on the cells, in which we cut the cell open so that we could pull on the plate stack and obtain friction within the cell. We ran it in two ways, so that in one way we had a spring-loaded, calibrated spring load compressing the entire cell. And we had an alternative arrangement that we could compress only the plate stack.

(Figure 16)

The static friction tests on materials were done with stainless steel wetted with KOH and the polypropylene materials in the as-received condition, with about ten micro-inches centerline average roughness. And also in the sandblasted condition. In addition we tested some other materials, Hypalon, nylon--just those two. This was done in a classic manner where friction coefficient is a function in the inclined plane juncture.

(Figure 17)

The results of the friction tests showed that the polypropylene friction was not particularly sensitive to contact stress, nor was it particularly sensitive to whether the surface had been artificially roughened or not. We got a value of about one-third for prolypropylene and a little higher for the nylon and still higher for the Hypalon.

(Figure 18)

When we ran tests with the cell assembly--it had been cut open--and we pulled it with a cell under compression, we obtained forced time curves that looked like this. And the peak of these curves, each one of these, represents the point at which the sliding starts within the cell.

(Figure 19)

Plotting this data, we obtained the extraction first to start movement within the cell as a function of the compression load on the cell stack alone. The slope of this curve is the friction coefficient at each local point. And the friction coefficients we got this way were quite similar to those we obtained with just the pure materials.

(Figure 20)

This is the data we obtained when we loaded the entire cell. At the lower compression levels the load is taken up entirely by the electrode stack, and at the higher compression loads, there is a distribution of the loads between the stack and the cell case.

(Figure 21)

Taking the two previous curves, we plotted them together in this chart, we have the solid line. Then by analysis, we calculate the effect of a cell that had not been cut, which becomes the dotted line. And we are plotting here the force required to start movement within a cell, compression load on a cell.

(Figure 22)

Using the previous data to calculate the dynamic load required for the cells to start moving within the cells function compression. Compression is seen to have a significant effect on reducing this function.

(Figure 23)

Now when a cell is compressed, there is a relaxation of load time. This shows some of the typical data, where the load gradually reduces and then levels off to a steady value. In this case, it reduced to 70 percent of the initial value.

(Figure 24)

The visco-elastic behavior of a cell is, of course, what governs the relaxation of loads with time. One can use a variety of analytical models to represent this viscoelastic behavior. This is the one that we used, in which the behavior is represented by a series of parallel arrangements of strings, dashpots and gaps, each one of which has its respective constants.

(Figure 25)

Taking the previous data, we then developed this design curve which included appropriate engineering safety factors; the basis being that there will be no load exerted on the plate tabs during vibration. And we would have two curves, one for the initial effects with no relaxation of the plate, and one with the plate relaxed.

Typical aerospace requirements are for under 15 G's, and it appears that the relatively modest compression loads can take care of that. For load vibration requirements in the 20 to 30-G range, it appears--it is quite difficult to meet the requirements without cutting into the safety factor, the engineering design safety factor, or allowing some of the load to be taken up by the tabs.

(Figure 26)

We confirmed the principle that compression does improve resistance to vibration in this test with four cells. Cells three and four were uncompressed, and failed at 25 and 30 G's, whereas cells one and two were compressed with fairly modest levels of 12 psi, failed 10 G's higher.

(Figure 27)

Compression has other effects that are important. At low compression levels, the natural frequency of the cell and battery are quite close together, whereas at higher compression loads, the natural frequency diverges.

(Figure 28)

Now this modal separation between the cell and battery is very important. If, as in the curve at the left, the battery case and the cell had a nearly identical natural response, then there is amplification of loads into the cell. Whereas, in the right curve, if there is a separation between the natural frequency, you don't get this amplification, and you get correspondingly lower loads into the cell. Another thing that is useful to do is to move the battery case curve over to the left to increase the modal separation. This can be done by attention to the battery case design, and also using lower modulus materials like magnesium.

(Figure 29)

One of the remaining questions is what would happen--what happens as a result of compression on the cycling behavior? We didn't get a complete answer to this, but we did get a data point at which we tested two groups of cells, one compressed to 25 psi, and one compressed to 75 psi.

We have an accelerated test of two cycles per day. Most of the cycles at 105 and 100 degrees Fahrenheit. Depth of discharge were 60 and 30 percent. After three months of testing, we obtained only minor differences between the two groups as shown in our next chart.

(Figure 30)

The overcharge voltage and the end-of-discharge voltage was comparable for both groups. In addition, there was no systematic differences between the two groups, neither was there any difference in capacity.

(Figure 31)

One of the areas that further work could be revealing, is in the visco-elastic behavior of cells, and also what the long-term effects on cycling of compressed cells might be. Finally, it would be worthwhile to improve mechanical design so that there is little or no need for some depression.

DE BAYLO: RCA American Communications

In your initial test where you described the modes of failures that you have seen, can you define the vibration profile and axis that you subjected the cells to? And also, can you define the type of configuration or mounting fixture the cells were compressed?

GROSS: In order to determine vibration loads, we looked at a variety of vibration requirements for a number of previous spacecraft applications. We settled on just simplifying the subject by using essentially constant G-squared loading in the range of 100 to about 2000 G's with tapered corners.

What was the second question?

DE BAYLO: Can you describe the type of--the axis of vibration, and also the type of experience. Were the cells under compression?

GROSS: We vibrated in all three axes. Typically we vibrated for two or three minutes in the X, Y and Z axes. We did it in the customary manner of using a large mass and attaching the test parts to the large mass. We built a special test fixture--we had to build special test fixtures in order to subject the cells to this kind of regime. In one case, for example, we had to hold down some cells without compressing, so we had to find some kind of an end attachment method. And I believe we ended up welding or brazing some materials on the sides of the cells, and we could then hold it down without compressing the cells.

KETTLER: Aerospace

Why did you run the tests? Have you observed flight failures, or is this terrestrial in nature?

GROSS: We have not observed any flight failures. We had been aware that other people have observed failures on the ground. I don't know of anybody who has observed a flight failure. But I know of a number of people who have had failures on the ground. Our reason for doing this test was to better understand what happens under a severe vibration requirement. Because we were concerned that we might run into some of the problems that other people have run into.

HELLFRITZSCH: Private consultant

If I understand you correctly, you once hit a range of 100 to 2000 G's at different levels, of course, keeping G-squared constant over the frequency range each time.

GROSS: G-squared per unit frequency is, I believe, the standard vibration parameter.

HELLFRITZSCH: Right

The question is, did they all fail even at the lowest level, like 100 G's? Or, there must be some level below which there were no failures, and, of course, above which there were many. What is that number?

GROSS: Well, it wasn't the 100 to 2000 G's. It is in the parameter of G-squared per unit frequency, when you integrate it you get G's.

HELLFRITZSCH: Was there any level in that capacity where there were no failures?

GROSS: Yes.

HELLFRITZSCH: And what was the highest level at which you tested, at which there were no failures?

GROSS: I believe the highest level was 35 or 40 G's. It was shown on a previous chart, that the highest level was 40 G's before we had a failure.

DILLON: JET Propulsion Laboratories

The whole philosophy you have taken on the G-squared, power spectral density, constant power spectral density and clamping the cells is my first question relating to the specific design cell as far as the failure mode. Secondly, the frequency really doesn't matter because what you are talking about is a dynamic load that exceeds a constraining force. And once you exceed the constraining force you excite the cell pack, you have a tab failure and fatigue analysis as you said.

The only comment I would like to make is tied to the specific type of cell design. I am interested as to why you didn't consider mechanical constraints within the cell as opposed to clamping the outside of the cell pack?

GROSS: The first thing that one naturally does is to find out how good a design is, how good it is without making any changes. And we wanted to find our what we could do with an existing design, to get the most out of it, without going to a redesign. I agree that if you were going to redesign for the very intense vibration environment, that a lot of things could be done differently. You could redesign the interior of a cell to constrain it better. But, we didn't. That would be step number two if there was a need to do so.

FORD: Goddard Space Flight Center

I would like to know the case wall thickness and what part do you think it played in this analysis?

GROSS: The case wall thickness is the GE 10 ampere-hour cell standard wall thickness. I believe it is in the order of 19 mils.

The case design is fairly important, and when you compress the cell, the entire cell, the distribution of loads is very important. And this would vary from cell to cell and design to design. As you start to compress, the loads are taken up initially by the cell stack and as you increase loading, the load starts to be picked up by the corners and the edges. It is conceivable that you could make a cell so flimsy and weak that the cell case takes hardly any of the load until the stack is compressed. On the other hand, it is conceivable that you could have a cell so stout that the electrode stack doesn't get very much of the load. So the numbers that we used were specific for this particular design. I think the principle holds.

BARNETT: Rockwell

About 4 or 5 years ago, we ran some tests on a 35-ampere-hour silver zinc like this, and we found that the most sensitive axis was normal to the plates, and didn't require plate motion. That the tabs could go resonance themselves. It has been several years now, but I think the frequency was 300 hertz to about 1700 hertz. And incidentally, that 100 to 2000 sounds like a frequency range rather than G level.

GROSS: That's correct.

BARNETT: We went up to about 1 1/2 G squared per hertz random, and we had tab failures which resemble something like you had. It was expanded metal, rather than solid metal. But they broke in the same areas. And we concluded that it was the natural frequency of the tabs more than the motion of the terminal in the plates that did the breaking.

GROSS: What was the basis for that conclusion?

BARNETT: Analysis, plus examination.

How did you determine when your plate stack started to move?

GROSS: There are two ways, visually on the mechanical test. And also by the shape of the force, force time curve under loading. We did find that there are--that the motions of the plate are quite complicated. One of the more important ones was a rocking motion, and we concluded that loading under either the X, Y or Z axis could produce a load on the tabs.

Vibration Failures

1. Plate tabs break at weld to comb
2. Plate tabs break near plate
3. Cell cover breaks around terminal
4. Ceramic seal breaks internally
5. Weldment of comb-to-terminal stud breaks

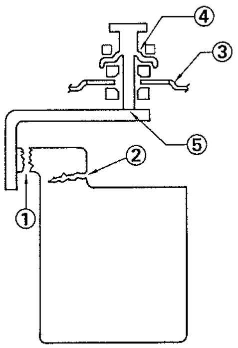


Figure 8

Effects of Partial Failures

- Lower capacity
- Reduced tolerance to overcharge
- Increased resistance ($\frac{dE}{di}$ or alternating current resistance)
- Low-open circuit voltage following charge
- High-open circuit voltage following discharge

Figure 9

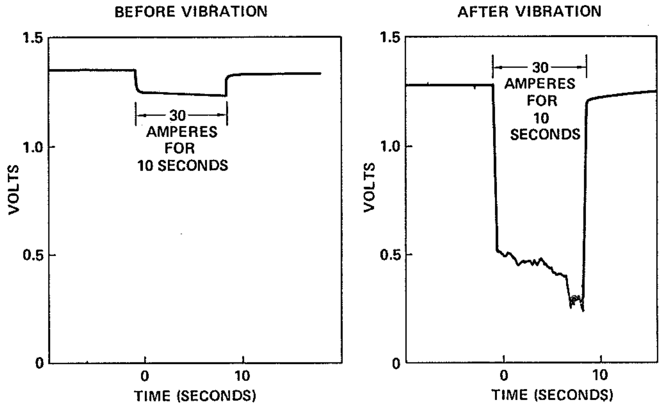
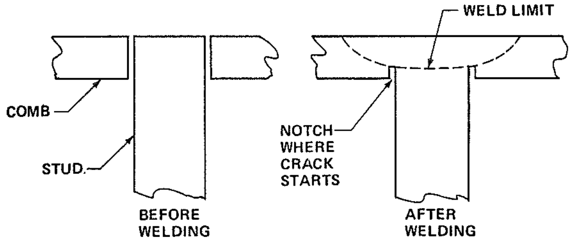


Figure 10

Terminal Stud-to-Comb Weld Failure



- Crack starts at notch, propagates across weld
- Solve by vacuum brazing instead of welding, avoiding notch

Figure 11

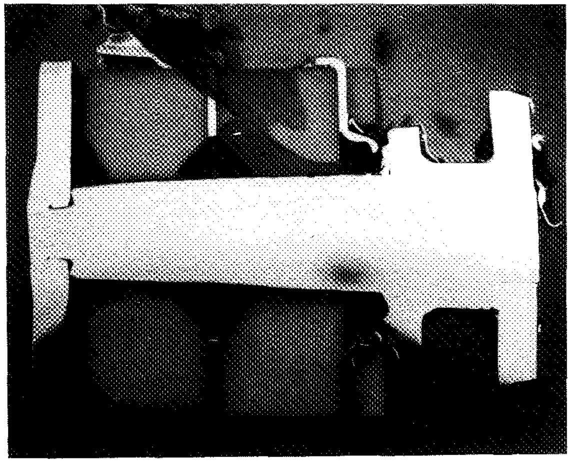


Figure 12

Failure at Tab Weld

- Metalurgical, electron microscopy and microprobe analyses
    - Melt-down welding generated grain growth and oxidation zones in tab
    - Fracture occurs within comb opening
    - Failure initiated by a brittle fatigue failure
    - Failure ends as ductile tearing of tab
    - No microstructure differences between failed and unfailed tabs
    - Stress corrosion, hydrogen embrittlement, or oxidation not important
- *Simulated fatigue tests*
    - Widely spaced failure group
    - No difference welded in air versus helium
- Conclude conservative design should not depend on tabs for vibration loads

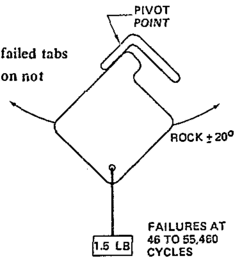


Figure 13

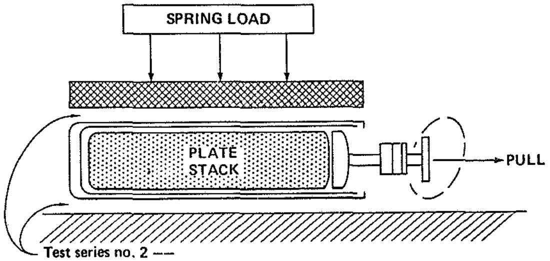
Tab-to-Comb Fatigue Test

Test	Number of plates	Cycles to failure
1	20	106 to 48,364
2	23	261 to 55,460
3	23	46 to 5,882

Fatigue damage stages–
- Work hardening
- Crack initiation
- Crack propagation

Figure 14

Friction Test on Cell



Test series no. 2 —
Insert spacers so plates are compressed but cell case edges are not compressed

Figure 15

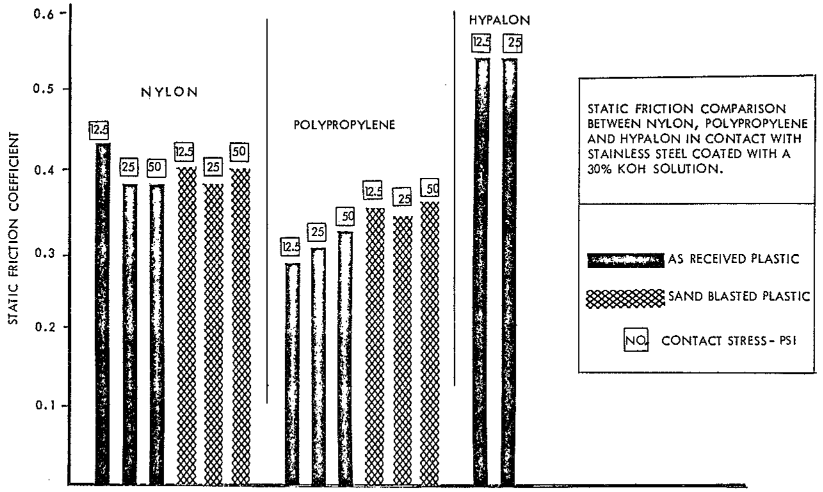


Figure 16

Tension Load Curves Obtained During Cell Compression With Small Bearing Plates

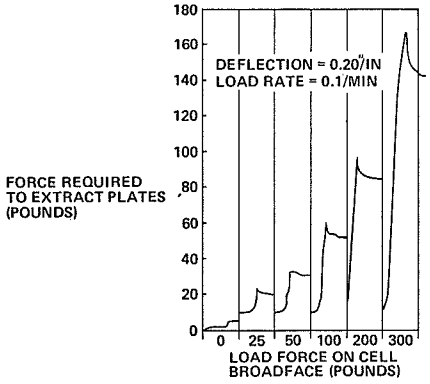
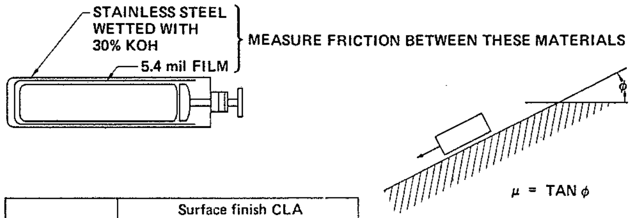


Figure 18

Static Friction Test on Materials



Film	Surface finish CLA	
	As received	Sandblasted with 100 mesh alumina
Nylon	18, 18	110, 100, 95
Polypropylene	10, 11	180, 180, 180
Hypalon		– –
Stainless steel	22, 28, 30	– –

Figure 17

Static Friction Test for Loading Only on Electrode Stack

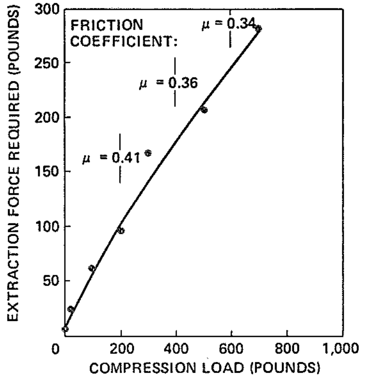


Figure 19

Static Friction Test for Load Distributed Between Electrode Stack and Cell Case

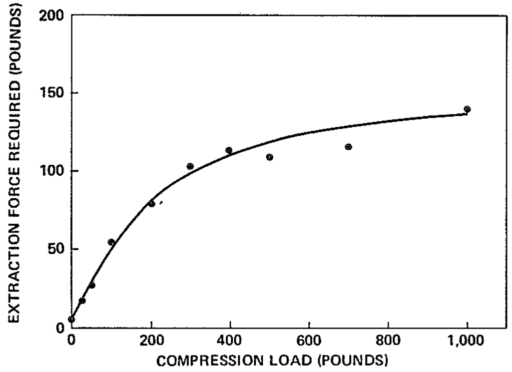


Figure 20

Forces Required to Slide Electrodes

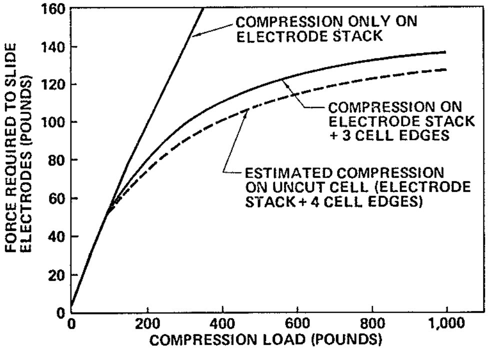


Figure 21

Calculated Dynamic Load at Which 10 AH Cell Electrodes Start to Slide Within Cell Case

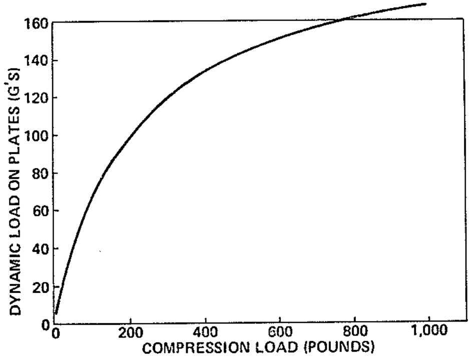


Figure 22

Relaxation of Plate Loading Under Cell Compression

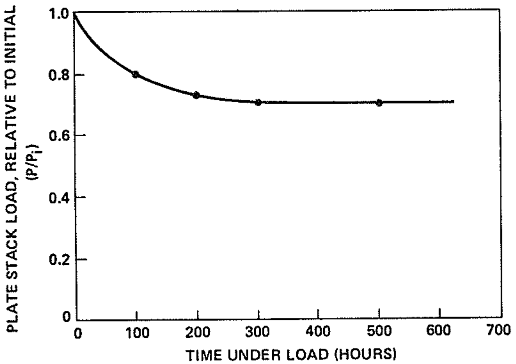


Figure 23

Analytical Model of Cell in Compression

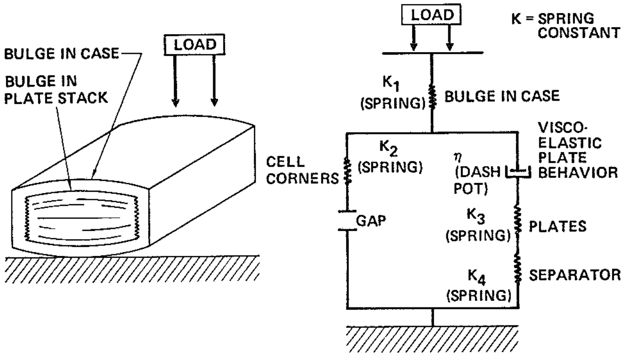


Figure 24

Vibration Tests Show Compressed Cells are Stronger

		Compressed cells 12 psi		Uncompressed cells	
Test	Test level (100 to 2,000 Hz)	Cell #1	Cell #2	Cell #3	Cell #4
1	20 G's	O.K.	O.K.	O.K.	O.K.
2	25 G's	O.K.	O.K.	O.K.	Failed
3	30 G's	O.K.	O.K.	Failed	
4	35 G's	Failed	O.K.		
5	40 G's		Failed		

Figure 26

Battery Cell Preload Required for Vibration

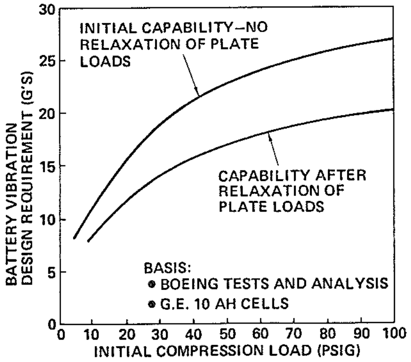


Figure 25

Compression Increases Cell Natural Frequency

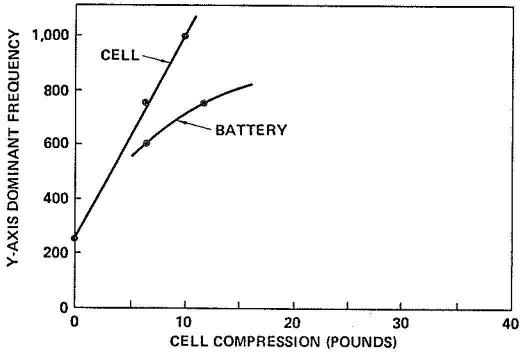
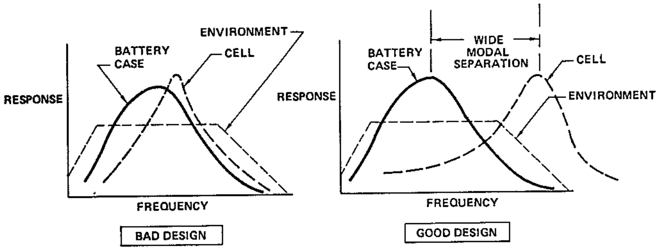


Figure 27

Battery Dynamics



Good battery design approaches

- Raise cell natural frequency by cell compression
- Lower battery case natural frequency by
  - (1) Battery case design
  - (2) Low modulus material, such as magnesium

Figure 28

Test for Effect of Compression on Cycling Performance

- Two test groups, compressed to 25 and 75 psig
  - 2 cycles per day
  - 105°F, 100°F, and 70°F
  - 60% DOD and 30% DOD
  - Occasional 100% DOD, then short test
- After 3 months, only minor differences

Figure 29

Performance Differences Between 75 psi and 25 psi Groups

Test	Difference–75 minus 25 value		
	Overcharge voltage	End of discharge voltage	Capacity to 0.9 volt
60% DOD Charge at 105°F, C/10 Discharge at 105°F, C/2	Same	-20 mV	
60% DOD Charge at 100°F, C/10 Discharge at 100°F, C/2	+2 mV	-3 mV	
30% DOD Charge at 100°F, C/10 Discharge at 100°F, C/2	+10 mV	+10 mV	
30% DOD Charge at 70°F, C/10 Discharge at 70°F, C/2	+3 mV	+2 mV	
100% DOD Charge at 100°F, C/10 Discharge at 70°F, C/10			Same

Figure 30

Areas Requiring Further Study

- ○ Visco-elastic properties of cells
- ○ Long-term effects of electrode stack compression
- ○ Mechanical designs to reduce need for compression

Figure 31

SEPARATOR MATERIAL

R. Griffin
Mallory Battery Company of Canada

One of the problems I have in the primary battery business, is to deal with the mountainous amount of separators that come out of supplies, and all the various dialysis and many other types of applications where membranes are being produced. As you are all probably aware, research in Japan, Europe and the USA (especially as measured by the patent literature) is quite tremendous. The number of these separators that reach the commercial market or even the separators for the nickel cadmium business is very small, as noticed by Pellon nylon being the most common word if you go back through the proceedings of this conference.

I thought today I would present some data on Pellon's latest material, not because I am promoting them, but just because they are of interest to me. I have some data on 2501, 2502, 2503, 2504, 2505, 2506. Now, the reason for looking at this material is that we are interested in reliability, just as you are. Except our sizes are often only one centimeter in diameter.

(Figure 32)

While we are heading towards the energy storage business of tremendous dimensional sizes, we wanted to know what the statistics are for these products. Each one that receives a sample from Pellon or from anyone else, is essentially a statistical point as far as we are concerned. What I would like you to think about is, is there any way in which we could get together to look at some basic parameters on these samples as we get them, so that we can help each other make a decision whether we should scale up? Now this is the common problem. All of us meet these five parameters very regularly in everything, but specifically in separators. And you will see that really, even when we were talking about it in past conferences most people refer to the materials as nylon, they don't often give any dimensions or even a code name, or what the statistical parameters were of that fabric when they put it in their cell.

Perhaps I might even suggest that even now when they have had 10 years life out of the cell, they may not even know what the initial parameters were of that material.

Moving on to Figure 33.

On the left-hand side, where you see plus or minus, that is supposed to be sigma, and the 6 underneath is supposed to be plus or minus, an X-bar, and then sigma. And if you move across, the 2504 is the standard product that is produced and has been produced for many years. An equivalent product is supposed to be 2501. On the right-hand side I have used a typical ASDM felt test, which is for my own purpose, but could be extrapolated to different types of weights, and the weight is either 0, which is normally termed 0 psi, or the 6 ounces, which in this case is on a rather sticky gauge with a one and a quarter inch diameter handle. The reason for this is, I was interested in whether change in the prime density in effect changes the parameter, the sigma parameter. And you can see that the sigmas are very close in each case. But the important point is that they have been reduced quite dramatically from 2504 to 2501.

So, if Pellon comes in the USA, you have new material, you now have a dilemma, because I think you have been asking for this new material from Pellon. Whether you really need it, you only know. The only problem is, it appears to be more reproduceable at this stage. Now this is based on three hand samples, 8 by 10 inch. So the next parameter is, what do we do? Do we buy 10,000 yards or 1000 yards or 100 square feet and then do all the measurements again? Or, can we combine our forces, and when we get the sample, compare notes and do it on the basis of the two common parameters that the industrial people have used to make the material, which is thickness and basis weight. So I suggest, and put these figures to you, as another way of improving our own reliability and our own selection procedures. Perhaps we should think about forming a consortium of people who measure thickness and weight, and pass the information between us in a free manner.

Now, I work in the primary business, so I have no interest in secondary cells. But I am very interested in the reliability of any new separator material. So here we have 2504, 2506. I have the 2505 figures. Essentially the first figures are somewhere between 19 and 25 for 2505. When we compare 2503 you get somewhere between 14 and 17. Now I believe they are the same weight and the Pellon--one question on this is that it wasn't their best run. So I say again, our major problem is not the new material, it is essentially how we check that the manufacturer did give us the material on a larger scale, which was the same material as we did all the tests on.

And that is the question. Is testing at this level worth it in terms of the large-scale production that we are going to use in our cells? I suggest that thickness and basis weight give us a starting point which lead to a specification and a sense of reproduceable reliability.

HELLFRITZSCH: Private consultant

I tried all the while you were talking to figure out what parameter you have up there. I gathered primary is the weight?

GRIFFIN: No, this is thickness in mils. My apologies. We missed off the word "mils." It is 40.4 mils, 11.4 mils, 4.2 mils, 0.3 mils, 12.7 mils, et cetera.

HELLFRITZSCH: And what sample sizes were the thickness based on?

GRIFFIN: 8 by 10 sample size

HELLFRITZSCH: How many?

GRIFFIN: There is 30 readings on each sample.

But the point is, even that 8 by 10, I don't know what size your plates are, but my sample size is normally one square centimeter. So this is the major problem that we are all living with every time we have a vendor coming to our facility, asking us to accept their products.

HELLFRITZSCH: And how uniform different sites set on the piece? Are they reflected in there?

GRIFFIN: Well the reason for doing pressure determinations, is to look for this point.

If you do just one thickness parameter, remember that in the ASTM they are very firm about measuring the actual time of exposure. That is, how long the anvil is on the sample. And in this case we chose 5 minutes for each reading. But again this is something--you know, you notice in the compression test there was a settling down period of 100 hours, so again this parameter is very important.

The other point is the anvil diameter again is another parameter the ASDM indicates you have to be very careful with. The point is that weight itself is going to be another parameter which you can't always be certain is going to tell you anything about thickness. And thickness can't always tell you anything about weight. So this is why the manufacturer runs both checks. And there is no manufacturer I know of that runs continuous thickness measurements.

There is a firm called Measurex, who runs on a paper manufacturing business. But none of the big manufacturers like Pellon or Chickopie or Johnson and Johnson have yet gone to a continuous thickness control or weight control on this type of fabric.

BELL: Hughes

What were the numbers you quoted again for 2505? You didn't have them on the screen, you just mentioned them.

GRIFFIN: 2505 at 0 psi is between 21 and 27, and it is 6 ounce deadweight. It is 19.5 up to 24.4 mils thick. While the 2503 at zero psi is 15 up to 18.2. These are X-bars, by the way. And the 6 ounce is 16.7, and then down to 13.9. 16.7 down to 13.9.

You realize, and I am sure you are all well aware of the statistical problems here. And we can go through sigma approach, or whichever you want to, but I think it comes back to essentially, that we have a problem that we get samples from any vendor, they probably take only one small piece and cut it up and we all get the same piece.

So your next problem is, why not ask them in three months time to come back to us again, and hopefully by then they have run it again. But as I understand it, Pellon and most of the other people run maybe 2000 or 3000 or maybe 4000 square yards at a time, and then send it out to everybody and hope that we can all make instantaneous decisions about whether we want to use it. The real answer is that our volumes may be--I don't know, in the battery business we can often consider 500,000 square feet as being a lot of material. But I am sure if we are going to large-scale energy sources, you are thinking much larger volumes than that. This means that you have to go through a series of intermediate testing stages. So this means to me that it is time for some collaboration to come through on this type of thing. I would be delighted to help in this way.

BELL: Did you do any work at all with very thin Pellon in the 5- to 10-mil range?

GRIFFIN: These are materials I had received from them in nylon recently. Most of their emphasis has been in polypropylene. We are very interested in the point bonded structures, but they are much thicker. They run about 20 to 30 mils. If you happen to be a European manufacturer, there are different types of Pellon, allegedly sold as being identical, but they are not. These are the FT series that you may have seen that are produced in England--

I think in Germany, actually, and sold in England and in France and Germany. The European nickel cadmium people perhaps, are using a different nylon than what we use in the United States.

The reason they gave for this pressure type testing is very important with polypropylene, because as you are all probably aware, the polypropylene acts like a volume dispenser of electrolyte, and the pressure on the polypropylene squeezes it out the ends, depending on what the type of structure is, or the type of fiber. So generally, this type of testing becomes even more critical with polypropylene structures.

CHOICE OF A SEPARATOR

1. WHATEVER IS AVAILABLE ON THE SHELF.
2. VENDOR ARRIVES WITH THE LATEST PRODUCT.
3. VENDOR ARRIVES WITH MATERIAL USED BY COMPETITOR.
4. VENDOR RESAMPLES UNTIL MATERIAL MEETS YOUR SPECIFICATION.
5. WHAT WAS YOUR APPRAISAL OF THE CELL? IS A BARRIER REALLY NECESSARY?

Figure 32. Choice of a Separator

PELLON NONWOVEN

RANDOM VERSUS UNIDIRECTIONAL NONWOVEN MANUFACTURE

	CODE	THICKNESS (MILS) 2504	2501	DEADWEIGHT ON ANVIL 1 1/4" DIAMETER
$\bar{x}$		14.4	11.4	0oz
σ		1.2	0.3	
$\bar{x}$		12.7	10.1	6oz
σ		1.3	0.2	
	CODE	2506	2502	
$\bar{x}$		18.5	14.0	0oz
σ		1.5	0.4	
$\bar{x}$		16.0	12.9	6oz
σ		1.3	0.6	
	CODE	2505	2503	
$\bar{x}$		23.7	16.6	0oz
σ		2.5	1.3	
$\bar{x}$		21.5	15.3	6oz
σ		2.0	1.1	

Figure 33. Pellon Nonwoven Random Versus Unidirectional Nonwoven Manufacture

MANUFACTURING VARIABLES

J. D. Armantrout
Aeronutronic Ford

We have all heard the trend towards higher energy density that we are trying to achieve in some of our systems, and specifically, I am going to talk on the 20 watt hours per pound nickel-cadmium battery which we have developed for the NATO III Communications Satellite.

(Figure 34)

Some specifics on this particular design positive electrode.

(Figure 35)

We have our 12 plates and our loading, which is indicated there. 12 1/2 to 13.1 grams per decimeter square on our loading in positive plates. And our negative plates, 15.2 to 16 grams.

I am just going to give this information as background for what I am going to comment on our variables here in a minute. We do use the 2505 Pellon material that you just heard some comments on, standard 30 percent KOH.

(Figure 36)

This particular design, is a nominal 20 ampere-hour cell, and you can see that we specify a minimum capacity on the positive of 22 amp hours; minimum negative of 35. Negative predischarge, which we will refer to as the ampere hour capacity removed from the negative electrode in a fully charged cell, the range being 7 to 12. And our percent of our excess negative, which is precharged, is 20 to 40 percent.

(Figure 37)

This particular design--and this is what we are talking about, manufacturing variables. The point here is that we are talking about our negative electrode efficiency relationship to peak cell voltage and overcharge. And the overcharge in this case is C over 10. We are talking about a temperature of--we have indicated 16 plus or minus 4 degrees C, probably pretty close to 16 degrees C.

We have a number of manufacturing lots here. We were talking about a range of 55 to 75 percent efficiency on the negative electrode. And you can see that as your cycle life begins to increase, immediately you see an increase in your peak voltage that tends to stabilize, usually after 25 to 30 cycles. And it can go up, and I will comment on that later this afternoon on some live test data.

The purpose here is to show the relationship of the negative electrode efficiency to peak voltage where your lower efficiency is definitely contributing to higher charge voltages.

(Figure 38)

In this particular graph we are comparing the same cell lots that I just commented on in the previous graph. We are looking again at a baseline. We begin with our lot 1 engineering model cell lot, and this is a comparison to that cell lot of the subsequent production runs. And you can see the relationship, the efficiency relative to the total negative-to-positive ratio.

(Figure 39)

Our general conclusion, of course, is that the negative electrode utilization variable has a significant effect on the cell negative-to-positive ratio.

We have lower efficiency of the negative electrode results and more divergent and higher peak cell voltages could increase cycle life. And we feel that the minimum negative electrode utilization requirement should be controlled to preclude long-term peak cell voltage problems which are related to inadequate overcharge capacity. That is essentially all I have on manufacturing variables.

LACKNER: Defense Research Establishment, Ottawa.

One of the slides you had where you are relating end-of-charge voltage with cycle life, you had percentages relating to curves. And I didn't quite understand what the significance of the different curves were.

Could you show that chart again, please?

(Figure 37)

ARMANTROUT: I think you were referring to the various lots where I have 55 percent efficiency?

The top curve is 55 percent utilization, or efficiency, whatever you want to call it. As we come down on this curve, the two center lots are 65 percent--the lower lot or lot 1 on the bottom portion being 75 percent. The peak voltage therefore increases with your lower negative electrode efficiency, and that being the 55 percent curve.

LACKNER: Are you saying that lower utilization led to a higher --

ARMANTROUT: That's right, exactly.

SEIGER: Yardney

Have you looked at the electrodes, say by scanning electron microscopy, to see whether there has been any change in the distribution or the crystal habit or anything about it? And also, were these made by vacuum methods?

ARMANTROUT: We have not done that analysis that you are referring to.

As far as the vacuum, no.

SEIGER: How were these made?

ARMANTROUT: This is an Eagle-Picher process standard. Well, it is actually a lightweight design which is not exactly standard, but we feel that it is becoming standardized.

SCOTT: TRW

How are you defining efficiency, and how did you measure it?

ARMANTROUT: We are looking at the theoretical electrochemical capacity. And then what you can measure. If we say we have 10 ampere hours, we can measure 7 ampere hours. That is 70 percent efficiency.

SCOTT: Is that measured flooded?

ARMANTROUT: This is starved.

20 WATT HOUR PER POUND NICKEL CADMIUM
ENERGY STORAGE FOR THE
NATO III COMMUNICATION SATELLITE

Figure 34

CELL GENERAL COMPONENT DESIGN CHARACTERISTICS

• POSITIVE ELECTRODE	12 PLATES, LOADING: 12.5 TO 13.1 GRAMS/DECIMETER SQUARE TOTAL ACTIVE MATERIAL WEIGHT: 99 GRAMS TOTAL PLATE WEIGHT: 210 GRAMS WITH TABS
• NEGATIVE ELECTRODE	13 PLATES, LOADING: 15.2 TO 16.0 GRAMS/DECIMETER SQUARE TOTAL ACTIVE MATERIAL WEIGHT: 133 GRAMS TOTAL PLATE WEIGHT: 216 GRAMS WITH TABS
• SEPARATOR MATERIAL	2505ML PELLON NYLON WRAP CONFIGURATION: ACCORDION STYLE
• ELECTROLYTE	30 PERCENT BY WEIGHT KOH SOLUTION ELECTROLYTE QUANTITY: 74 GRAMS (~17.8 PERCENT OF TOTAL PLATE WEIGHT)
• TERMINALS	DUAL CERAMIC TO NICKEL SHAFT FEEDTHROUGHS ASSEMBLY WEIGHT: 16 GRAMS
• CELL CONTAINER	MATERIAL/THICKNESS: 304L STAINLESS STEEL SHEET 0.030 cm THICKNESS CONTAINER WEIGHT: 58 GRAMS

Figure 35. Cell General Component Design Characteristics

Electrode Capacity Characteristics[1] Summary

Characteristic	Electrochemical Capacity (Ampere-Hours)	
	Maximum	Minimum
Total positive	26	22
Total negative	42	35
Negative predischarge[2]	12	7
Percent of excess negative precharged (%)[3]	40	20

1. Rated positive cell plate capacity is defined as 20 ampere-hours.
2. Negative predischarge - the ampere-hour capacity removed from the negative electrodes of a fully charged cell.
3. Total negative - total positive = excess negative.

Figure 36

Cell Negative Electrode Efficiency As Related to Cycle Life
Peak Voltage Characteristics in Overcharge for C/10 rate (16 ± 4°C)

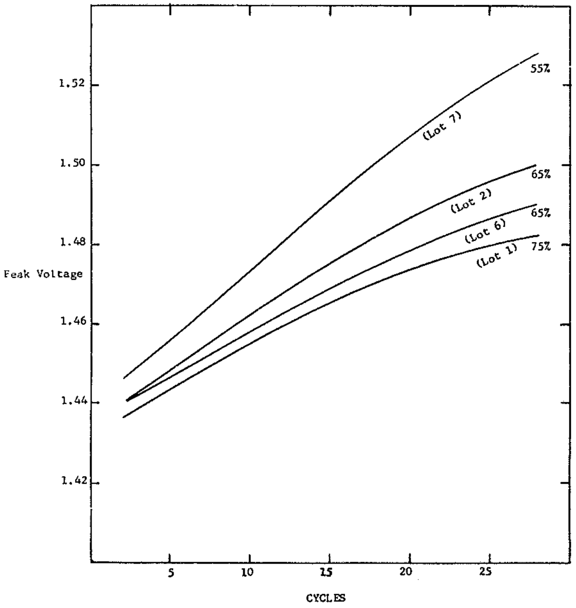


Figure 37

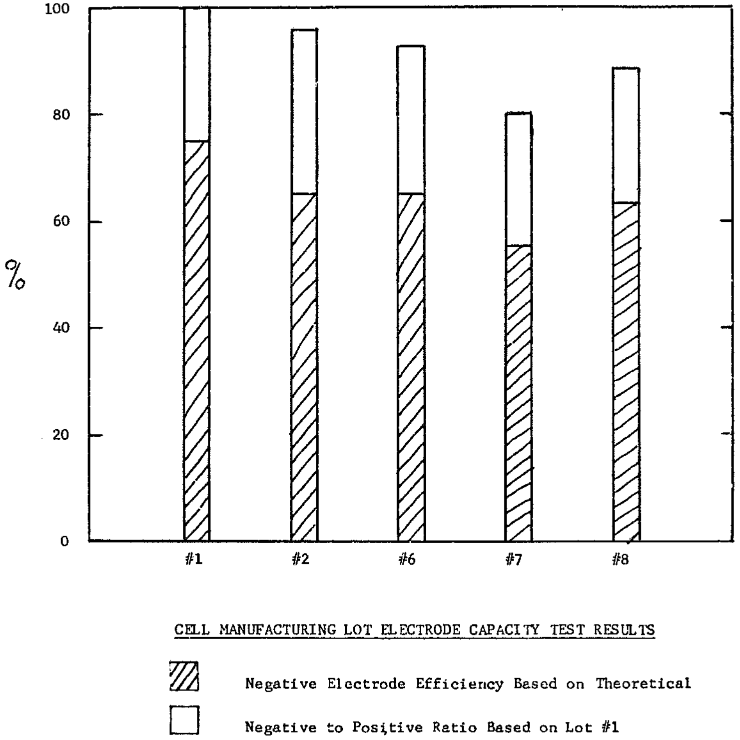


Figure 38

GENERAL CONCLUSIONS

- THE NEGATIVE ELECTRODE UTILIZATION VARIABLE HAS A SIGNIFICANT EFFECT ON CELL NEGATIVE TO POSITIVE RATIO
- LOWER EFFICIENCY OF THE NEGATIVE ELECTRODE RESULTS IN MORE DIVERGENT AND HIGHER PEAK CELL VOLTAGES WITH INCREASED CYCLE LIFE
- MINIMUM NEGATIVE ELECTRODE UTILIZATION REQUIREMENTS SHOULD BE CONTROLLED TO PRECLUDE LONG TERM PEAK CELL VOLTAGE PROBLEMS RELATED TO INADEQUATE OVERCHARGE CAPACITY

Figure 39

LIGHTWEIGHT CELLS IN BATTERIES

I. Schulman
TRW Systems

This morning I would like to discuss the work we have been doing for the past few years at TRW. This is the program concerned with the manufacture of lightweight cell and battery systems. The principal investigator of this program is Paul Ruderman who could not be here this morning. The objective of this program is to increase the battery system energy density to 20 watt hours per kilogram.

(Figure 40)

What I am describing is a total battery system which includes bypass electronics and the charging, the weight attributed--which you attribute to the charging circuit also. And there was also concern with a 65 percent depth of discharge of actual capacity. So if these figures look a little lower than you would expect, that is the reason.

We also wish to extend the battery life to 10 years in synchronous orbit.

(Figure 41)

The program plan and status is as shown. In 1974, we evaluated and characterized high-energy density electrodes. These electrodes are made from both electrochemically deposited processes, and vacuum impregnated processes. We build inside the laboratory cells, from these electrodes, and we also determine reverse cell characteristics to accommodate deep reconditioning.

In 1975 we concluded our laboratory cell cycling tests, performed teardown analysis, and then we initiated cycling a first-generation flight quality, lightweight cell. These were cells we obtained from commercial organizations, and they represented at that time, the lightest weight cells they were able to manufacture. We also evaluated thin-wall cell packaging with packaging 12 mils thick stainless steel. This year we are completing the cycling of the first generation cells. We have completed. We performed a teardown analysis, and we started procurement of a second generation flight quality cell. These are made with electrochemically deposited material, and they are made by Yardney Corporation.

We are starting to design and to build a prototype lightweight battery and that will be the 21.4 watt hours per kilogram system. Next year we expect to complete the testing of the prototype lightweight battery, complete a 10 year cycling simulation of these--at least the second-generation cells and the battery, perform the teardown analysis. And then start on our evaluation of the third-generation cell, which we expect to have a titanium cell case. And we hope to procure these third-generation cells.

(Figure 42)

We have prepared the lightweight electrode capacity for the laboratory cells and these electrodes were both manufactured by vacuum impregnation, and electrochemically impregnated. And the weight comparisons for the lightweight electrode capacity includes both types.

We compared that with the standard electrode capacity and you can see there is a definite increase--decrease in weight of the lightweight over the standard electrodes. We also show the volume comparisons.

(Figure 43)

This graph shows the electrode evaluation that we conducted on the laboratory cells. The circles represented the recondition to a 0 volt situation. And it was down to 65 percent depth of charge, also at 15 degrees Centigrade. So we tried to idealize the conditions. And you can see that by the dashed lines, it would seem at least that the electrochemically deposited electrodes represented by that cell design 2, seem to outperform those with vacuum impregnated electrodes.

Now again, as I stated before, both of these plates had approximately the same loadings. These cells, by the way, were 11-plate laboratory cells, 5 positive and 6 negative. The cycle was approximately a 10-hour cycle. We did this to speed things up. It was our method of simulating a geosynchronous orbit and speeding it up at the same time.

(Figure 44)

Now based on the results of the tests and the teardown analysis, we concluded at least for these laboratory cells, that the vacuum impregnated positive electrodes showed problems of voltage degradation, capacity degradation, swelling of the electrode and separator dryout. And the cells with the electrochemically impregnated positive electrodes, showed none of these problems.

(Figure 45)

While we were doing this, as I stated, we were also running a cycling program on the first generation cells, which represented commercial organizations' output. And they had vacuum impregnated electrodes.

They lasted between 5 and 7 years of geosynchronous orbit type of cycling, at a 60 percent discharge of measured capacity. Again the cycling temperature was 15 degrees C. and we did recondition to 0 volts. But that didn't seem to help matters much in this particular case. They were removed from the test once they fell below the one-volt minimum. So there we have between 5 and 7 years life.

(Figure 46)

We compared on our teardown analysis, the vacuum impregnated positive electrodes from the laboratory cells and from the first-generation cells versus the electrochemically impregnated electrodes. You see the first three we are discussing positive. The first one is the vacuum impregnated. You see that it went from an initial average thickness of 38 mils to 44 mils, while the laboratory electrochemically impregnated remained at 37 mils. Also from the first-generation cells, which were vacuum impregnated, it went from 28 to 32 mils. The negatives remained as they were originally. There seemed to be no swelling of negatives, regardless of the process by which they were manufactured.

(Figure 47)

Now that swelling seems to lead to something else we measured, and that is the electrolyte content in the core components in measured graphs of squared decimeters. Again there was a laboratory cell which I haven't reported on, this fellow, which had a positive made by electrochemically impregnated means, and a negative by vacuum impregnation. And in that case the separator had 2.8 grams per square decimeter.

Now the laboratory cell with the positive made with the vacuum impregnated process, you can see the separator contained on teardown analysis, 0.3 of a gram per square decimeter, and the positive had increased to 7.8 grams per square decimeter. And these two cells were loaded with the same amount of electrolyte at initiation for probe and the laboratory cell with both electrodes electrochemically impregnated seemed to be similar to the one where there was only one electrochemically impregnated. Again, the first-generation cells, showed the same sort of phenomena as the laboratory cells when they are made with vacuum impregnated materials.

(Figure 48)

Now on the second generation lightweight cell that is being made by Yardney, 34-ampere hour design, it is made with electrochemically impregnated electrodes using single terminal in our effort to save as much weight as possible. And they do, I believe, have a slightly increased quantity of electrolyte so that we can obtain reliability and the life we desire.

(Figure 49)

Now when we compare the second generation against what we call the standard 34-ampere hour cell--now of course there is no standard 34-ampere hour cell that I know of, so these are projected figures from a standard 20. It is what the 34 would come to if it were made. It is obvious that we are using on the standard, a cell wall thickness of 29 mils, and therefore you have a tremendous increase in weight. There is 260 grams over 85 grams. Of course, this can be diminished by lowering the cell wall thickness. And you know, you can play with these numbers any way you would like. However, there is a decrease in positive electrode weight and negative electrode weight which is significant, I think, in terms of the overall cells.

(Figure 50)

In terms of watt hours per kilogram, when we compared the second-generation lightweight cell and battery versus a standard, again projected standard, a 34-ampere hour cell and battery based on 100 percent depth of discharge, we expect 44 watt hours per kilogram on the lightweight, and 31.9 on the standard. And 65 percent--this is just arithmetic from here on in.

Now the 28-cell battery system, as I stated, includes both the charged electronics--of course you would normally put in a PCU--and it also includes the bypass electronics. This particular system we had in mind uses bypass electronics because we are working for cell redundancy rather than battery redundancy. So we are putting the additional weight into the cell and into this particular battery system and using one battery where in other types of systems you maybe use two or three batteries to obtain the reliability figures that you are trying to--you set as a goal. We have also put down projected weights when using a cell with a titanium case. And there we are projecting 50 kilowatts--50 watt hours per kilogram.

(Figure 51)

We have a breakdown of the weights of the components and the remaining parts of the battery system itself. Now we have projected again the design concept from a FLTSATCOM program. Again, FLTSATCOM is not a 34-ampere hour system, but we have again just scaled the weights up, And we have done this for a 28-cell system. Again, FLTSATCOM is not a 28-cell system, if anyone raises that question, but these are projected weights.

If FLTSATCOM were a 28-cell system, we would find that we would have a 33.16 kilogram weight with the battery mass itself. And you can see what we have put down for battery packaging, thermal control, V&H shield, protective electronics, and again the charge control electronics which would not necessarily be in the battery package. But we have included that so we have everything associated with the battery which should be.

And we project a 21.4 watt hour per kilogram for second-generation lightweight, and 23.5 watt hour per kilogram for the third-generation lightweights which we will start next year. Again, these are at 65 percent DOD, actual compact capacity.

(Figure 52)

Projected third-generation lightweight cell will feature the titanium cell containers. We are hoping for an improved loading of negative electrodes. Again a high electrolyte of wetness factor, and we expect a cell energy density of 50 watt hours per kilogram. As we showed in the last Vugraph, there is going to be a reduction in the overall battery system.

(Figure 53)

Now, as far as our package itself is concerned, there are certain features which are reasonably novel. We have an aluminum treated thermal shim on the cells. Most people are using thermal shims of one sort or another. We are plating aluminum on to the cells. I don't have a Vugraph, but I do have a photograph if anybody would like to see that, of a cell with the aluminum plating on it. And this can be insulated by hard anodizing. Now we don't advise not using an additional electrical insulator between cells. However, with the hard anodizing, you don't have a single-point failure situation.

We do have a titanium alloy end plate for the rather high-yield-strength to density ratio shown. We do have a new interconnection concept. One of the problems with battery design is that you have to have a terminal, and generally they are 50-pin connectors. And how do you pick--you may use 28 of these positions out of a 50-pin connector for your power leads, and how do you connect these leads to a terminal on a cell? It is hard to set up 14 leads to a satellite.

So we have a new interconnection concept. However, that is about as much as I would like to comment on at this time.

(Figure 54)

We have a rather simple picture of what this is going to look like. We are showing it as a 14-cell package. There will be two 14-cell packages with the bypass electronics, et cetera, between. Basically there are just two end plates, each one with the plugs on the end of them, mounted. And there is a center plate, too. Simple drawbolts between the end plates and you see a heater across the cells on top. Now we have done preliminary analysis of this design and thus far it looks pretty good. Of course, if we get a shaker, we may change our minds, but we will see.

(Figure 55)

To summarize, a battery system has been developed which yields at least, to use a second-generation cells, 21.4 watt hours per kilogram and a 65 percent DOD. We have improvements in mind for cell design which will reduce or improve the energy density ratio to 23.5 watt hours per kilogram. And there has been a certain amount of new technology developed as far as the titanium end plates, the aluminum plated thermal shims, the anodized--anodizing the shims for electrical insulation, and the new terminal concept.

FORD: Goddard.

Irv, on one of your Vugraphs, you said something to the effect that the new generation of cells, you will do something with negative loading. I don't know whether it will improve it, increase efficiency--would you elaborate on that a little bit?

SCHULMAN: Well, we are trying to get our vender to work towards a more porous electrode and higher negative to--higher negative loading.

We think that it is feasible, and that he can do it.

FORD: You did say higher negative loading?

SCHULMAN: That's right.

We are quite aware of the problems that we have had in certain programs with high negative loading, but we think with this new negative, with this new impregnation method, that these problems may be avoided. At least we are going to have a crack at it and see what comes from these loadings.

PASCHAL: Marshall Space Flight Center

Irv, how did you get the improvement in wettability, third-generation cell?

SCHULMAN: No, this is the same improvement that we have in the second generation. It is just that we have the same vender, and he just adds more electrolyte.

PASCHAL: More electrolyte.

SCHULMAN: That's right.

ROGERS: Hughes Aircraft

I am interested in your aluminum plating. I am wondering whether you have considered the fact that you have a bimetal strip, and as it expands and contracts, what effect does this have?

SCHULMAN: We have tested that in programs and we found it is all right.

We have put it through, you know, pressure tests. It doesn't crack off. One of the concerns we are having is with the anodizing, whether that will embrittle it. So it is still a little up in the air. But the coating itself seems to be perfectly all right.

MAURER: Bell Labs.

Two questions. The first I almost hesitate to ask. You said you listed the problems with the vacuum impregnated electrode, and that the electrochemical process didn't show any of these problems.

What problems, if any, do they show?

SCHULMAN: Well, the problem of getting the vender to make a delivery of materials and stuff like that. They are logistic problems more than anything else. We don't know of any real problems as yet, but we haven't done that much work with them. There may be problems which may show up in the future.

MAURER: The other comment was that, as a characteristic of electrochemical positives, they show 115, 120 percent theoretical capacity under certain charge rates and temperatures. And in general, as the temperature goes down, the lower the charge rate to get that increase. Now is this 15 degrees low enough to get you into that high efficiency region which would improve your energy density?

SCHULMAN: No.

I think that probably we would be down even lower than 15 degrees. Fifteen degrees was chosen because our laboratory was setup for those particular conditions. We would prefer to work at between around 5 to 10 degrees Centigrade.

MAURER: We typically get that increase at 0 degrees Centigrade at the 20-hour rate.

SCHULMAN: Okay.

NAPOLI: RCA American Communications

You showed a chart with a 28.6 watt hours per cell energy density. To what DOD was that, before?

SCHULMAN: 65 percent.

NAPOLI: 65 percent. Is that the goal you are trying to achieve?

SCHULMAN: No. We expect that we may be able to go much deeper than that. The fact is we have programs where we have cycled cells at 75 percent DOD quite successfully, too.

DUNLOP: COMSAT

Do you know the loading levels that were used in the electrochemical impregnation? Can you express that, by the way, in grams per centimeter cubed?

SCHULMAN: I don't know if I have them here, but I can get them for you, Jim.

DUNLOP: Well, it is interesting to note. I don't know what the loading levels that are specified today. We reported a year ago on cycling of the Bell

Laboratory type electrochemically impregnated positive electrodes that were made at Eagle-Picher, and those electrodes have performed with no expansion up over 1000 cycles.

Now, if the loading levels on those electrodes are about 1.6 grams of active material, that is nickel hydroxide plus cobalt hydroxide plus water per centimeter cubed of pore volume. If you take a conventional chemically impregnated electrode, you typically find about 2 grams of active material per centimeter cubed of pore volume.

That electrode that you reported on, the chemically impregnated electrode, is that a conventional chemically impregnated electrode?

SCHULMAN: Well, Harvey, you made--as I remember, both electrodes, both chemically and electrochemical impregnation, had, as closely as possible, the exact same loading. So we are comparing electrodes.

DUNLOP: Well I am equally surprised at that statement, because we did, in fact, run a long-term test with chemically impregnated electrodes with reduced loading levels, down to the same kind of loading levels that we have with electrochemically impregnated electrodes. And those electrodes, the expansion on those electrodes with long-term cycling, between 1000 and 2000 cycles is much less than the conventional chemically impregnated electrodes at the 2 grams per centimeter cubed.

SCHULMAN: I agree with you.

I can remember work done on the aircraft cells, where we reduced loading to about two-thirds of normal loading and found a reduced swelling. But then, that doesn't get you a high energy density system.

DUNLOP: I would agree.

Just one more comment.

Our experience has been similar to what you have had. There are two advantages that you see with the electrochemically impregnated electrode. One advantage may be in part due to the reduced loading. But certainly you don't see this expansion with time.

The second one is that you do see much better utilization of the active material, and it is about 20 percent or better utilization of the active material.

SCHULMAN: The fact is, I was chatting with Harvey and Harvey passed the same remark.

Harvey, would you like to give your--

SEIGER: I was going to give one more thing.

There is a reduced corrosion as well, and I think that this permits the plaque to be--you are making the plaque stronger, and you are keeping it stronger.

DUNLOP: Right.

KRAUSE: Hughes

I want to make a general comment that not only applies to something you said, but I guess a comment I made last year. I keep hearing a recurring theme on a lot of the work that people are doing in terms of energy density improvement. That is, they are basing a lot of their evaluations or directions of their design, on the results of accelerated tests. And last year, I think, I asked somebody to tell me how we could correlate some of the accelerated tests that are being run, with the real-time effects of geosynchronous orbit. For example, I have run 4000 cycles at 60 percent depth of discharge, on a conventional cell. I can't get 40 years out of that cell in synchronous orbit. I know I can't.

SCHULMAN: How do you know that?

KRAUSE: We have run some for 5 years, 6, 8 years, that is about it. That is all it will make.

My point is that these designs you are working on in your evaluation is based on accelerated testing. Some of the other lightweight batteries are run also. Do you feel comfortable with projecting long-term synchronous performance? That is my question.

SCHULMAN: I think it is a very pertinent and valid question. I don't know any other way of doing it.

KRAUSE: Okay, fine.

OBJECTIVE:

- INCREASE BATTERY SYSTEM ENERGY DENSITY TO 22 Wh/kg (10 Wh/lb) COMPARED WITH PRESENT FLIGHT CAPABILITY OF 15.4 Wh/kg (7 Wh/lb)
- *EXTEND BATTERY LIFE TO 10 YEARS IN GEOSYNCHRONOUS ORBIT*

Figure 40

PROGRAM PLAN AND STATUS

- 1974
  - EVALUATE, CHARACTERIZE, AND COMPARE HIGH ENERGY DENSITY ELECTRODES
  - BUILD AND CYCLE LABORATORY CELLS FROM THESE ELECTRODES
  - DETERMINE REVERSED CELL CHARACTERISTICS TO ACCOMMODATE DEEP RECONDITIONING
- 1975
  - COMPLETE LABORATORY CELL CYCLING TESTS
  - PERFORM TEARDOWN ANALYSIS OF LABORATORY CELLS
  - INITIATE CYCLING OF 1st GENERATION FLIGHT QUALITY LIGHTWEIGHT CELLS
  - EVALUATE THIN WALL CELL PACKAGING
- 1976
  - COMPLETE CYCLING OF 1st GENERATION CELLS
  - PERFORM TEARDOWN ANALYSIS
  - PROCURE 2nd GENERATION FLIGHT QUALITY CELLS AND INITIATE CYCLING
  - BUILD AND BEGIN TEST OF PROTOTYPE LIGHTWEIGHT BATTERY (21.4 Wh/kg SYSTEM)
- 1977
  - COMPLETE TESTING OF PROTOTYPE LIGHTWEIGHT BATTERY
  - COMPLETE 10 YEAR CYCLING SIMULATION OF 2nd GENERATION CELLS/BATTERY
  - PERFORM TEARDOWN ANALYSIS OF 2nd GENERATION CELLS
  - EVALUATE TITANIUM AS A CELL CONTAINER MATERIAL
  - PROCURE 3rd GENERATION FLIGHT QUALITY CELLS (50 Wh/kg) AND INITIATE CYCLING

Figure 41

LIGHTWEIGHT ELECTRODES EXCEED STANDARD ELECTRODES IN CAPACITY BOTH PER UNIT WEIGHT AND PER UNIT VOLUME

ELECTRODE	LIGHTWEIGHT ELECTRODE CAPACITY	STANDARD ELECTRODE CAPACITY	CAPACITY INCREASE OF LIGHTWEIGHT OVER STANDARD ELECTRODES
WEIGHT COMPARISON			
POSITIVE	0.120 Ah/g	0.090 Ah/g	33%
NEGATIVE	0.168 Ah/g	0.118 Ah/g	42%
VOLUME COMPARISON			
POSITIVE	0.406 Ah/cm^3	0.327 Ah/cm^3	24%
NEGATIVE	0.554 Ah/cm^3	0.439 Ah/cm^3	26%

Figure 42

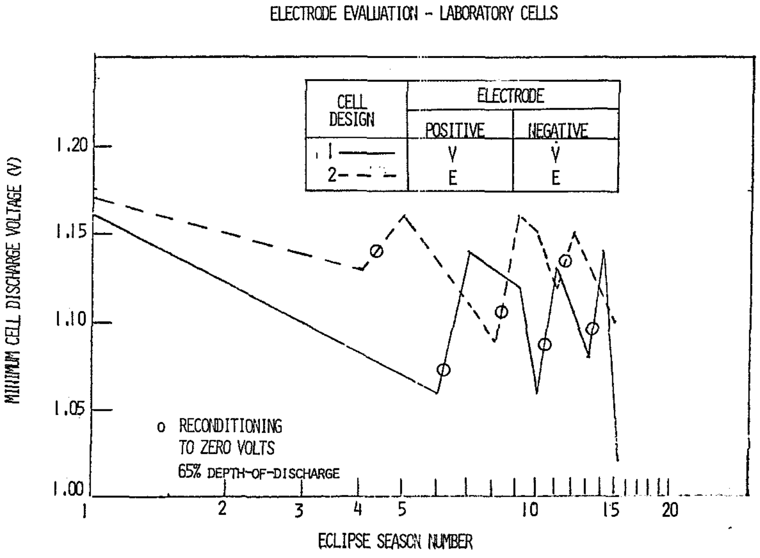

ELECTRODE EVALUATION - LABORATORY CELLS

Figure 43

CELLS WITH VACUUM IMPREGNATED POSITIVE ELECTRODES SHOW PROBLEMS

- VOLTAGE DEGRADATION
- CAPACITY DEGRADATION
- SWELLING OF ELECTRODE
- SEPARATOR DRYOUT

CELLS WITH ELECTROCHEMICALLY IMPREGNATED POSITIVE ELECTRODES DO NOT EXHIBIT THE ABOVE PROBLEMS

Figure 44

1st GEN CELLS (44 Wh/kg VACUUM IMPREGNATED ELECTRODES) FAIL AFTER 5 TO 7 YEARS OF GEOSYNCHRONOUS ORBIT CYCLING TO 60% DOD (AT MEASURED CAPACITY)

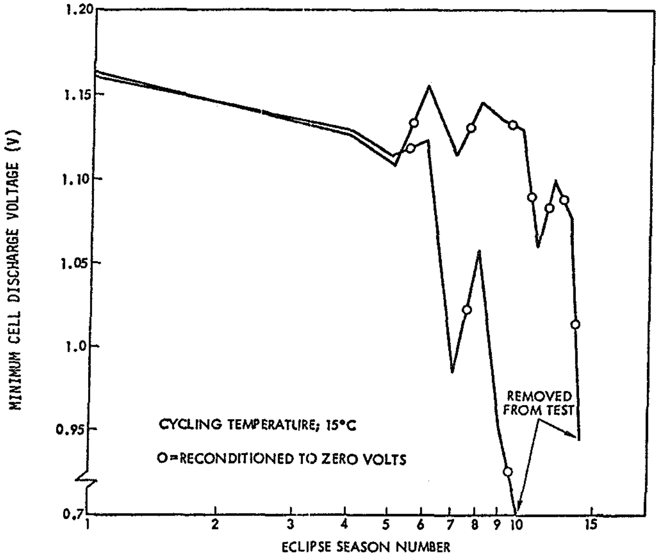


Figure 45

VACUUM IMPREGNATED POSITIVE ELECTRODES FROM LABORATORY CELLS AND FROM 1st GEN CELLS SWELL AS A RESULT OF CYCLING

	ELECTRODE TYPE	INITIAL AVERAGE THICKNESS (mils)	AVERAGE THICKNESS AFTER CYCLING (mils)
LABORATORY	Pv	38	44
LABORATORY	Pe	37	37
1st GEN	Pv	28	32
LABORATORY	Nv	37	38
LABORATORY	Ne	40	39
1st GEN	Nv	27	28

Figure 46

POST CYCLING ELECTROLYTE CONTENT IN CORE COMPONENTS IN g/dm^2

CELL TYPE	ELECTRODE COMBINATION	SEPARATOR	POSITIVE	NEGATIVE
Laboratory	P_eN_v	2.8	4.7	6.5
Laboratory	P_vN_v	0.3	7.8	5.1
Laboratory	P_eN_e	2.6	6.4	7.0
1st GEN	P_vN_v	0.2	2.3	1.7

USE OF VACUUM IMPREGNATED POSITIVE ELECTRODES RESULT IN SEPARATOR DRYOUT

Figure 47

SECOND GENERATION LIGHTWEIGHT CELL (YARDNEY 34 Ah) FEATURES

- ELECTROCHEMICALLY IMPREGNATED ELECTRODES
- SINGLE TERMINAL TO SAVE WEIGHT
- INCREASED QUANTITY OF ELECTROLYTE

Figure 48

WEIGHTS OF INDIVIDUAL CELL COMPONENTS 34 Ah LIGHTWEIGHT CELL (2nd GEN) AND STANDARD AEROSPACE 34 Ah CELL*

COMPONENT	LIGHTWEIGHT 2nd GEN		STANDARD	
	GRAMS	PERCENT	GRAMS	PERCENT
POSITIVE ELECTRODES	329	33.1	392	29.7
NEGATIVE ELECTRODES	360.5	36.2	458	34.7
SEPARATOR	14.5	1.5	21.5	1.6
ELECTROLYTE	156	15.7	132	9.9
** CONTAINER	85	8.5	260	19.7
LINER	16	1.6	8	0.6
COVER/COMB	34	3.4	50	3.8
TOTAL	995	100.0	1321.5	100.0
** CELL WALL THICKNESS	.012"		.029"	

* BASED ON SCALED UP VERSION FOR COMPONENT WEIGHTS.

Figure 49

ENERGY DENSITY IN WATT-HRS PER KILOGRAM OF THE 2nd GEN 34 Ah LIGHTWEIGHT CELL AND BATTERY VS A STANDARD 34 Ah CELL AND BATTERY

COMPONENT	DEPTH-OF-DISCHARGE (PERCENT OF MEASURED CAPACITY)	PROJECTED LIGHTWEIGHT 2nd GEN	STANDARD
CELL	100%	44.0	31.9
CELL	65%	28.6	20.7
28 CELL BATTERY SYSTEM (INCLUDING CHARGE CONTROL)	65%	21.4	15.4
PROJECTED CELL WITH TITANIUM CASE	100%	50.0	31.9

Figure 50

WEIGHT OF COMPONENTS AND ENERGY DENSITY OF SECOND AND THIRD GENERATION 34 Ah LIGHTWEIGHT NICKEL CADMIUM BATTERY VS FLTSATCOM TYPE 34 Ah BATTERY

	DESIGN CONCEPT FLTSATCOM	2nd GENERATION LIGHTWEIGHT	3rd GENERATION LIGHTWEIGHT
28 CELL BATTERY MASS (kg)	33.16	27.75	24.73
BATTERY PACKAGING MASS (kg)	5.05	1.38	1.24
THERMAL CONTROL MASS (kg)	1.48	0.63	0.63
V&H SHIELD (kg)	0.33	0.33	0.33
PROTECTIVE ELECTRONICS (kg)	3.79	3.79	3.79
CHARGE CONTROL ELECTRONICS (kg)	2.80	2.80	2.80
TOTAL (kg)	46.61	36.68	33.52
BATTERY SYSTEM ENERGY DENSITY* (Wh/kg)	16.9	21.4	23.5

* AT 65% OF MEASURED CAPACITY

Figure 51

PROJECTED THIRD GENERATION LIGHTWEIGHT CELL FEATURES TO MEET 22 Wh/kg BATTERY SYSTEM GOAL

- TITANIUM CELL CONTAINERS
- IMPROVED LOADING OF NEGATIVE ELECTRODES
- HIGH ELECTROLYTE WETNESS FACTOR
- CELL ENERGY DENSITY OF 50 Wh/kg

THIS THIRD GENERATION CELL WOULD RESULT IN A 3.2 kg (7 lb) REDUCTION IN BATTERY WEIGHT OVER PRESENT 28 CELL, 34 Ah LIGHTWEIGHT BATTERY SYSTEM DESIGN

Figure 52

LIGHTWEIGHT BATTERY PACKAGE FEATURES

- ALUMINUM PLATED THERMAL SHIMS (11 MILS THICK)
  - EXCELLENT CONTACT WITH BATTERY CELL
  - ELECTRICAL INSULATION BY HARD ANODIZING
- TITANIUM ALLOY END PLATES
  - HIGH YIELD STRENGTH TO DENSITY RATIO (120 - 130 KSI)
- NEW INTERCONNECTION CONCEPT
  - NO TERMINAL BOARD REQUIRED
  - WEIGHT SAVING

Figure 53

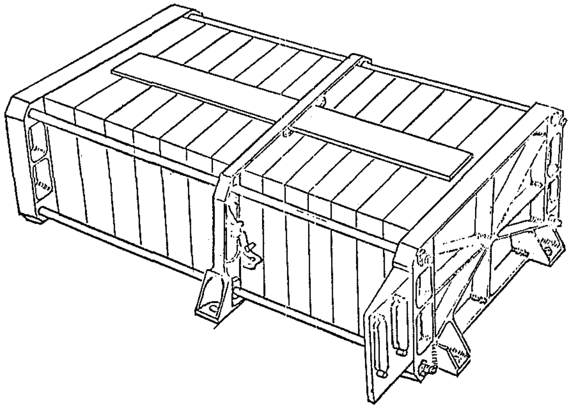


Figure 54

SUMMARY

- A BATTERY SYSTEM HAS BEEN DEVELOPED WHICH YIELDS 21.4 Wh/kg AT 65% DOD
- IMPROVEMENTS IN CELL DESIGN COULD RESULT IN A BATTERY SYSTEM ENERGY DENSITY OF 23.5 Wh/kg IN 1977
- NEW TECHNOLOGY HAS BEEN DEVELOPED IN BATTERY PACKAGE TO IMPROVE RELIABILITY AND REDUCE COST AND WEIGHT
  - TITANIUM END PLATES
  - ALUMINUM PLATED THERMAL SHIMS
  - ANODIZING SHIMS FOR ELECTRICAL INSULATION
  - NEW CELL INTERCONNECT CONCEPT TO ELIMINATE TERMINAL BOARD

Figure 55

CYCLE LIFE PERFORMANCE TESTING, HELIOTEK 50-AMPERE HOUR CELLS

D. Pickett
WPAFB

The cells we tested and are reporting on today were made under contract for us by Heliotek, which was a division of Textron, Inc. They have now changed their corporative entity and the name is changed to Spectrolab, and are no longer in the battery business. But the fellows that made them still are. They are at Yardney now.

But even though we don't have a manufacturer for this particular cell now, it is a nonproprietary design, and anybody can make it. And I think you will be very interested in the data that I have to present, because it is a real--well, not a real life or real time geosynchronous orbit testing of the cell, but it is an accelerated test. In fact, we got it from TRW, the test procedure. But it does show what one can experience with electrochemically impregnated plates in satellite cells.

(Figure 56)

As Gerry mentioned, Jim Harkness is a coauthor with me on this work. He did all the testing. I simply added on the test design and test procedures.

(Figure 57)

The cells as shown here, this is a 15-ampere hour cell, and I am showing it in comparison to a Gulton cell of about 1968, 1969 vintage. So it is actually a smaller cell, supposedly to give the same capacity. And the energy density of the conventional cell is about 15 to 16 watt hours per pound, whereas the new cells were supposed to have an electrochemical capacity of something like 20 watt hours per pound.

(Figure 58)

Okay, we are testing three designs and we arrived at these designs as a result of a study by Dr. Puglisi and Dr. Seiger at Heliotek. These are the parameters we came up with for a 20-watt hour per pound cell. Design 6, 11, and 15 are the numbers--these are numbers that came out of the computer program for the number of variations we tried, and there were quite a few, something like 40, 50 or more.

The thickness in plate for the positive was 32 and 36 mils. For the negative, 36, 32, and 38. As it turns out we decided that design 11 was probably the best design of all, but we tested the others briefly. To give you some idea of how the capacity was balanced in the plates, I'll show you this chart (Figure 59). We figured that we would need about 55 ampere hours of capacity to get the 21 hours per pound we were seeking, with about 11-ampere hours of precharge on something like 79 percent of utilization of the negative plate.

(Figure 60)

I will just go over these charts briefly because I did show them at the last workshop, but these are the parameters and the cell rates and the electrolyte rates we had for the various cells.

(Figure 61)

For design 11--this is polypropylene separator now, this is page 1. The dry weight was about, on the average of 1,230 grams, and in activated 1,400 and about 190 grams of electrolyte. You will notice that the charge pressures on all of these are very low, and this was experienced throughout the synchronous orbit test as well.

(Figure 62)

These are cells with nylon separator material and it merely shows the same parameters that you saw on the other slide. There were 35 cells in all on test. Twenty of these with polypropylene and 15 with the nylon.

(Figure 63)

Okay, the tests were broken down into four phases, an acceptance testing which is not only used at Crane for all incoming cells to go on test, then a precycle testing that we did in addition to the Crane test. The reason we did these was that the cells came in low in capacity, we wanted to give them a few cycles to see if the capacity would come up. And also we added a little more electrolyte to them.

While I'm thinking about it, I might mention that all of these cells were equipped with pressure gauges. The picture I showed you did not have one on it, but all cells on test have pressure gauges. When we went into the actual cycle life performance testing, we had five battery packs all together, four with four cells in pack of design number 6, and then eight cells with design number

15, and the rest were all using design number 11. We had one cell that we have done a post-mortem analysis on thus far and I will show that information.

(Figure 64)

Okay, this simply shows the acceptance testing that the Crane normally performs on incoming cells, the purpose of course is to evaluate cells for physical defects, seal quality, and the capacity and so forth. I won't elaborate on this because I am sure you are all familiar with the Crane test procedures.

(Figure 65)

This shows the geo-synchronous orbit test that the cells were subjected to. You notice these are not 24-hour cycles, they are 12 and 16 hours. This is identical to the test that Fleet Satcom is using, and this test regimen was kindly provided by Dick Sparks of TRW. We wanted to run some of these cells to compare the results with what the Fleet Satcom cells are doing. An initial depth of discharge maximum was about 60 percent of nominal capacity. We later had to reduce this to something like about 50 percent or less because of problems we encountered with low end of discharge voltage and so forth.

(Figure 66)

The results of the test thus far are summarized on this chart, and sadly enough we had to pull all the polypropylene cells off tests because of low end of discharge voltages and high charge voltages.

Apparently the reason this was occurring was because of insufficient electrolyte in the cells. We found after we started to run the nylon cells we added more electrolyte and we didn't have the problem. We also noticed that in the initial cycling test that we ran, that we were experiencing the same type of effect with the nylon cells but upon adding more electrolyte the problem seemed to disappear to some extent anyway.

(Figure 67)

I'll just go briefly through the voltages that we've seen on the other nylons that are still on test.

This is the capacities, ampere hours in ampere hours out of the pack with the nylon cells. The first and second shadow periods and the lines up at the top are the ampere hours in and the ones on the bottom are the ampere hours out.

(Figure 68)

There was shadow one and two. This is three and four.

(Figure 69)

This is five and six.

(Figure 70)

And they then completed their six shadow period. They're in the seventh now. Okay, these are some of the charge and discharge voltages.

Okay. The X is the average end-of-charge voltage. The Y is the low end-of-charge voltage. The Z is the high end-of-charge voltage, and the asterisk is the high end-of-discharge voltage, the dot is the low end-of-discharge, and plus is an average. And on shadow two you can see we're getting low end-of-discharge voltages on this pack.

(Figure 71)

Okay. And you can tell we still persist.

(Figure 72)

Then we reduce the depth of discharge and we no longer see the low end-of-discharge voltages.

Now for the post-mortem of the one failed cell that we had with the polypropylene separator.

(Figure 73)

In spite of the low capacities we were getting, we found that taking the plates and giving them a poretic capacity test we got 115 percent utilization out of the positive plate and 73 out of the negative. And the measured flooding capacity of the positive was 66.8 ampere hours and that of the negative was 63.8 so we're not getting all the capacity out of the cells we should. Okay, what's the problem ? It seems apparent to me that the cells didn't have enough electrolyte. This is no fault of the manufacturer because this is the first time that anybody has reported making a sealed aerospace cell using electrochemically impregnated plates. It's my contention that you are going to need more electrolyte when you make cells with these plates. They soak it up pretty readily.

It is still some mystery why we're not getting all the capacity out, but the only thing I can blame it on at the present is the insufficient electrolyte. And I would certainly be welcome to any comment from anybody else as to why we aren't getting the capacity out of these cells that we should.

SCOTT: I noticed at the end of that last chart it showed something about shorted cells.

PICKETT: Right. Good point. We had a polypropylene cell short. That's the one where we did the post-mortem analysis. We found that when we opened the cells that all the separator material had decomposed. Now we noticed that when we give these any appreciable amount of overcharge at all that they will heat up in a hurry. I might mention that the pressures here in these cells were never above, except on rare occasions, 5 PSIG. So apparently what is happening is the oxygen that comes off as a result of overcharge is recombining rapidly on the negative and it does it at a fairly high rate. At such a high rate, it must burn out the separator material or something to leave the thing open for shorts. And that's my analysis of what happened in that case.

SCOTT: Is that the same cell that you were saying failed by drying out or whatever you are saying happened because of low electrolyte?

PICKETT: Right.

SCOTT: Did you do an analysis for electrolyte in the separators as part of your analysis?

PICKETT: I don't think that was done by the Crane people, no.

SCOTT: One more question. In looking at the overall discharge voltage curves--I am thinking that in some of the similar tests that we ran when we analyzed low end-of-discharge voltage on 50 ampere hour cells by the way, we can see that the main place where the low end-of-discharge voltage occurred was at the very end of discharge and all the rest of the curve was just fine. Was that the case in your tests where you got the low end-of-discharge voltage?

PICKETT: Well, we have only seen, what we did on this one pack of nylon cells. I won't bore you with all the other curves that we had, but we did have some that reached the low end-of-discharge voltage before the capacity was taken out.

GROSS: In your last chart, you showed a negative/positive ratio of less than 1. Can you comment on that?

PICKETT: Yes, I showed you that. Actually when we did a chemical analysis of residual positive and negative capacity we found 0 positive capacity, residual positive capacity we found something like 2 ampere hours per charged plate.

NEWELL: Could you tell us about how much electrolyte you had in those cells in terms of ampere hours capacity? Did you do an analysis to find out where your electrolyte was, for example how much was in the positive, how much in the negative and how much in the separator of the fail cells?

PICKETT: In answer to your second question, I think I've already answered that, I said we did do an analysis on the electrolyte distribution and the amount of electrolyte in the cells in the first few charts I presented indicated I had roughly 200 grams of electrolyte per cell. Now I did add some more during the precycle testing. I added anywhere from 8 to 15 cc of electrolyte in addition to that. So in answer to your question, it was roughly about 5 grams of electrolyte per ampere capacity.

BOGNER: Did you attempt to run a reconditional cycle on the cells?

PICKETT: Yes, we did run some packs with reconditioning but the ones that are shown here had no reconditioning. Reconditioning under these circumstances was not very beneficial you know, because we are trying to lower these after discharge because apparently they are electrolyte limited. In other words, in answer to your question Sam, it is kind of ambiguous at the present as to what reconditioning would do in this case.

ROGERS: In your first slide, you showed a chart with a capacity, I think 55 ampere hours for the positive? Then you said special nickel hydroxide or something?

PICKETT: That's nonutilizable capacity in the cell Howard.

WILLIS: One possible reason for having to add electrolyte later on is because, what we found when we were building cells with electrochemically impregnated positives, insufficient evacuation prior to electrolyte fill. If you don't pump all the air out then the electrolyte won't get into the small pores and I think the evacuation time necessary is on the order of 15 to 20 minutes for a cell at least 30 ampere hours. The final air that comes out has to come out by diffusion and that's a long process. Once all the air is out the correct amount of electrolyte will get to where it's supposed to go and you'll find you won't have to add electrolyte after that.

PICKETT: I believe they were vacuum filled, were they not Harvey?

SEIGER: They were vacuum filled and I have a couple of slides in my pocket to show that there is a dependency upon how the electrodes are made and we'll go into that more. You are right, you are basically right. As we increase the loading level of the negative the time or the process becomes more critical. And we have to be more careful as we go to higher loading levels.

ROGERS: Okay.

SEIGER: I think we discussed this a couple of years ago. I gave a presentation here about 1973 or so in which we found that it was difficult indeed, that there was air entraped in the negative electrode and that's the culprit. And even though we were aware of that and we did things, well we'll look at the distributions of active material in the plate later this afternoon. I think it will become more interesting and more apparent why we have to do the pumping. I should also point out that when we filled these cells expected in design 11 to get 208.7 grams of electrolyte into it and I believe design 11 came out to 192 grams of electrolyte. Something like that, and we thought that we were close enough, we started with pencil and paper, that's it, that's fine. As it turns out we were wrong, we should have had a red flag waved and said we're low, be careful and we weren't careful. Dave found that out later.

ROGERS: Is there a connection between the fact that you had to add electrolyte and the short evacuation time? For example, how long did you evacuate Harvey?

SEIGER: I don't remember, do you remember? Not long at all, two minutes.

GRIFFIN: Could you give us some idea of what the thickness was of each separator type, and if possible the code type?

PICKETT: I believe the nylon was 2505 Pellon and GAF WEX polypropylene and the thickness was about 8 mils, 8 to 10 mils was that right Harvey?

SEIGER: The electrode spacing was 6-7 mils.

GRIFFIN: The reason I mention that is that the WEX is no longer available as you probably know. The second point is that it used to weigh between 8 and 12 mils as I can recollect and this is a major problem in putting a cell together. So we were asking the thickness. That's why I'm asking was there a 100 percent inspection of every piece of separator that went into the cell?

PICKETT: I'll let Harvey answer that since he and Vince made the cell.

SEIGER: We did investigate the separator. As far as I'm concerned I think the most key parameter is the weight per unit area that you have been calling basis weight. Then we have to insert that into a cell and the other key parameter, as far as I'm concerned, is interelectrode spacing. There is something else that is very difficult to get and when it's at the interelectrode spacing that we design for we have to ask a question about tortuosity. I don't know how to answer that question, but the internal impedance and the performance of the cell depends very much upon the material of which it's made, the interelectrode spacing, and the weight per unit area.

GRIFFIN: Do you recollect that Dr. Lackner used to do a surface roughening on this polypropylene? He used to use a mangle and put it through a mangler. There is some point here that actually the fibers that stand up act as wetting agents or something in that similar vein. This means that you don't leave a flat surface against the electrodes, you have something penetrating the electrodes. In the case of the wax it was a very shiny surface, there was no surface finish. Did you do any further treatment to the polypropylene or is it just used as received?

SEIGER: Polypropylene was used as received. We did determine that whether we had taken that particular polypropylene, sent it out for a plasma treatment. With a plasma treatment it would wet almost immediately. The sample line next to it, we'd come in the next morning and we would find it was equally wet, it just took a longer time. The rate of wetting differed. We could also accelerate the rate at which electrolyte is absorbed by the separator even by polypropylene without any treatment by evacuating it first.

GRIFFIN: But the assumption with the electrodes is there are no closed pores, is that correct? If you're talking about impregnating electrodes, the impression I get from the discussion is this is shield, there is no closed pores. That everything is accessible to penetration. Is that actually so?

SEIGER: You have to talk about the size of the vacancies of the pores because it is getting more capillary as you get--particularly to heavier loading levels. And that's what's giving us the problem of getting into it. I believe that the separator is wet, it is the negative electrode that is our problem of getting electrolyte into that and the air out of it.

CYCLE LIFE PERFORMANCE TESTING OF HELIOTEK 50 AMPERE-HOUR CELLS

BY

DAVID F. PICKETT AND JAMES HARKNESS

Figure 56

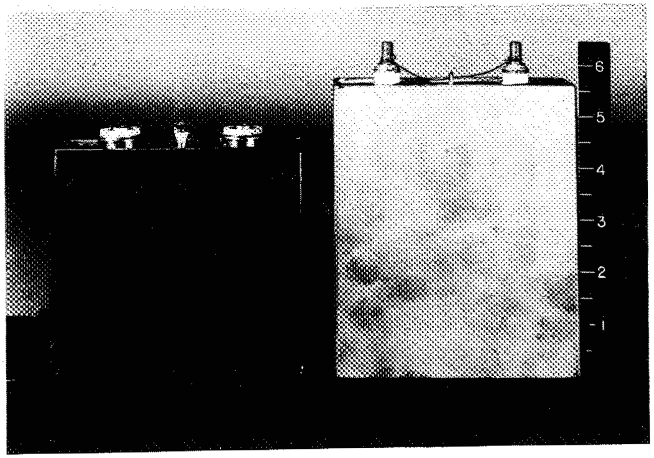


Figure 57

ELECTRODE DESIGNS FOR 20 W-H/LB NICKEL-CADMIUM CELL

DESIGN NR.	POSITIVE ELECTRODE THICKNESS (INCHES)	POSITIVE ELECTRODE SINTER POROSITY (%)	POSITIVE ELECTRODE NR. OF PLATES	NEGATIVE NEGATIVE ELECTRODE THICKNESS (INCHES)	NEGATIVE NEGATIVE ELECTRODE SINTER POROSITY (%)	NEGATIVE NEGATIVE ELECTRODE NR. OF PLATES	CELL WEIGHT (GRAMS)
6	0.036	82	14	0.036	90	15	1484
11	0.032	84	16	0.032	90	17	1478
15	0.036	84	14	0.038	90	15	1475

Figure 58

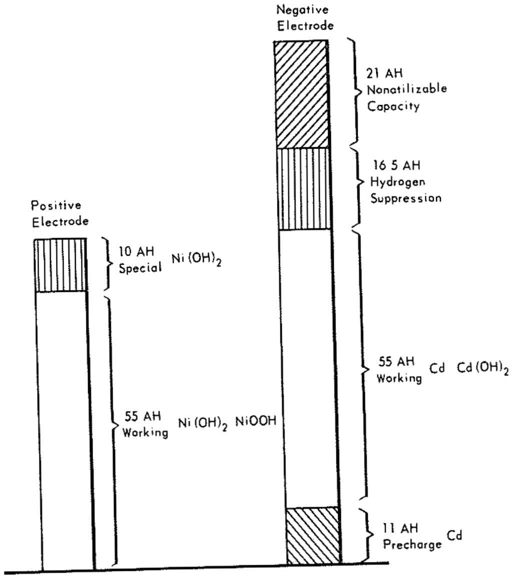


Figure 59

PHASE I CELL DATA

DESIGN	S/N	WEIGHT DRY	(GRAMS) ACTIVATED	ELECTRO-LYTE WT	C/2 CAP. (AH)	W-H LB	MIDPT. VOLTAGE	EOCV (VOLTS)	EOCP (PSIA)
15	14	1192	1390	198	49.6	20	1.21	1.437	15
	15	1194	1392	198	51.7	20	1.21	1.435	15
	16	1191	1398	207	51.2	20	1.21	1.436	15
	17	1186	1386	200	50.0	20	1.20	1.435	15
	18	1182	1381	199	50.8	20	1.21	1.430	15
	19	1178	1377	199	50.4	20	1.21	1.438	11
	20	1186	1377	191	48.8	19	1.20	1.434	10
	21	1189	1380	191	48.8	19	1.21	1.433	15
	$\bar{X}$	1187±6	1385±8	198±5	50.2±1.1			1.436±.002	14±2

Figure 60

PHASE I CELL DATA

DESIGN	S/N	WEIGHT DRY	(GRAMS) ACTIVATED	ELECTRO-LYTE WT	C/2 CAP. (AH)	W-H LB	MIDPT. VOLTAGE	EOCV (VOLTS)	EOCP (PSIA)
11	02	1241	1427	186	54.6	21	1.20	1.442	11
	03	1216	1408	192	50.8	20	1.21	1.437	9
	04	1224	1406	182	50.8	20	1.21	1.434	11
	05	1235	1414	179	50.0	19	1.21	1.438	12
	06	1233	1418	185	50.8	20	1.21	1.434	15
	07	1217	1407	190	50.0	20	1.21	1.435	13
	08	1224	1404	180	50.4	20	1.21	1.433	11
	09	1223	1414	191	49.6	19	1.21	1.424	13
	$\bar{X}$	1227±3	1412±3	186±5	50.9±1.2			1.435±.004	12±2
06	10	1200	1396	196	45.0	18	1.20	1.427	21
	11	1208	1405	197	47.9	19	1.20	1.455	23
	12	1216	1402	186	51.7	20	1.21	1.446	15
	13	1212	1395	183	50.0	20	1.21	1.458	10
	$\bar{X}$	1209±7	1400±5	190±7	48.6±2.1			1.446±.014	17±6

Figure 61

PHASE II CELL DATA

DESIGN	S/N	WEIGHT DRY	(GRAMS) ACTIVATED	ELECTRO-LYTE WT	C/2 CAP. (AH)	W-H LB	MIDPT. VOLTAGE	EOCV (VOLTS)	EOCP (PSIA)
11	22	1188	1384	196	50.0	20	1.21	1.434	10
	23	1181	1380	199	50.8	20	1.21	1.430	11
	24	1179	1372	193	50.6	20	1.20	1.434	9
	25	1187	1377	191	50.0	20	1.21	1.426	8
	26	1182	1376	194	51.3	20	1.21	1.426	8
	27	1188	1383	195	51.8	20	1.21	1.425	10
	28	1187	1379	195	51.1	20	1.21	1.426	10
	29	1188	1379	191	51.5	20	1.21	1.424	9
	30	1167	1371	184	51.5	21	1.21	1.424	9
	31	1202	1395	193	52.1	21	1.22	1.427	10
	32	1188	1389	201	50.1	20	1.22	1.428	9
	33	1178	1370	192	51.1	20	1.21	1.419	10
	34	1189	1386	197	52.0	21	1.21	1.424	9
	35	1195	1385	190	51.5	20	1.21	1.425	8
	36	1185	1375	190	51.7	21	1.21	1.430	10
	37	1179	1378	199	48.0	19	1.21	1.423	10
		1186.±6	1380±7	194±4	50.9±1.1	20	1.21	1.426±.004	9

Figure 62

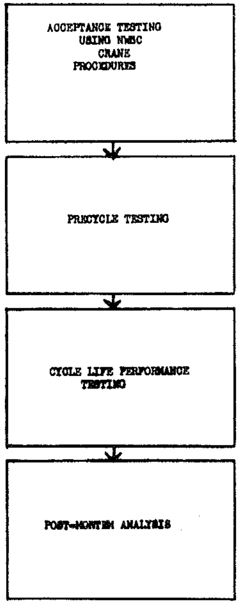


Figure 63

SEALED NI-CD CELLS TEST

ACCEPTANCE TESTING FOR
SEALED NI-CD SPACE CELLS

PURPOSE: TO EVALUATE CELLS FOR PHYSICAL DEFECTS, SEAL QUALITY, AND AMPERE-HOUR CAPACITY.

1. LEAK TEST 1 & 2
2. CAPACITY TEST
3. INTERNAL SHORT TEST
4. CHARGE EFFICIENCY TEST
5. OVERCHARGE TEST #1 & #2
6. PRESSURE VS. CAPACITY TEST
7. LEAK TEST #3

Figure 64

SEALED NI-CD CELLS TEST

(DISCHARGE PERIODS FOR 12 & 16 HR
ORBITS VERSUS CYCLE NUMBER)

Cycle #		Seasons 1-5 Charge Hrs.	Seasons 1-5 Charge Min.	Seasons 6-10 Charge Hrs.	Seasons 6-10 Charge Min.	Seasons 1-10 Discharge Minutes
1	45	11	40	15	40	20
2	44		32		32	28
3	43		25		25	35
4	42		20		20	40
5	41		17		17	43
6	40		13		13	47
7	39		10		10	50
8	38		7		7	53
9	37		4		4	56
10	36		2		2	58
11	35		0		0	60
12	34	10	58	14	58	62
13	33		56		56	64
14	32		54		54	67
15	31		53		53	68
16	30		52		52	69
17	29		51		51	70
18	28		50		50	70
19	27		50		50	71
20	26		49		49	71
21	25		49		49	72
22,23	24		48		48	72

Figure 65

STATUS OF 50 AH CELLS PRIOR TO REMOVAL FROM
CYCLE LIFE TEST

CELL NR.	COMMENT	FINAL AH CAPACITY	CELL NR.	COMMENT	FINAL AH CAPACITY
PACK 250D, DESIGN 11, POLYPROPYLENE			PACK 250E,	DESIGN 15, POLYPROPYLENE, RECOND.	
02	Shorted after shadow. # 3 Cycle # 155 - Failure anal. Short top of pos. plates		14	Completed shadow #4- cycle 210- cycle 210 - discont.	33.7
03	Removed at start of shadow #2 - cycle 59 - high volt.	20.0	15	Same as above	30.0
04	Completed shadow # 4 - cycle 210 - discont.	30.0	16	Same as above	30.0
05	Removed after shadow # 3- Cycle 155 - Low EOD volt.	37.0	17	Removed at start of shadow # 2 - cycle 60 - High voltage	23.1
06	No voltage after shadow # 4 - cycle 204	37.0	18	Removed during shadow #4 Cycle 165 - High voltage	33.0
07	Removed after shadow # 3 cycle 155 - Low EOD volt.	37.0	19	Removed following shadow # 3 - cycle 155 - Low EOD voltage during Shadow # 3	35.2
08	Completed shadow #4 - cycle 210 - discont.	29.5	20	Same as above	35.2
09	Same as above	35.1	21	Same as above	[illegible]
PACK 250 G, DESIGN 11, NYLON, RECONDITIONED AFTER SHADOW					
25			PACK	250F- All cells remain on test	
29					
33	Removed after shadow # 4 Cycle 155 - High volt.	20.9			
34					
35	Removed during shadow #3 Cycle 120 - High volt.	33.9			
36					
37	Removed after shadow #2 cycle 105 - Low EOD Voltage	24.9			

Figure 66

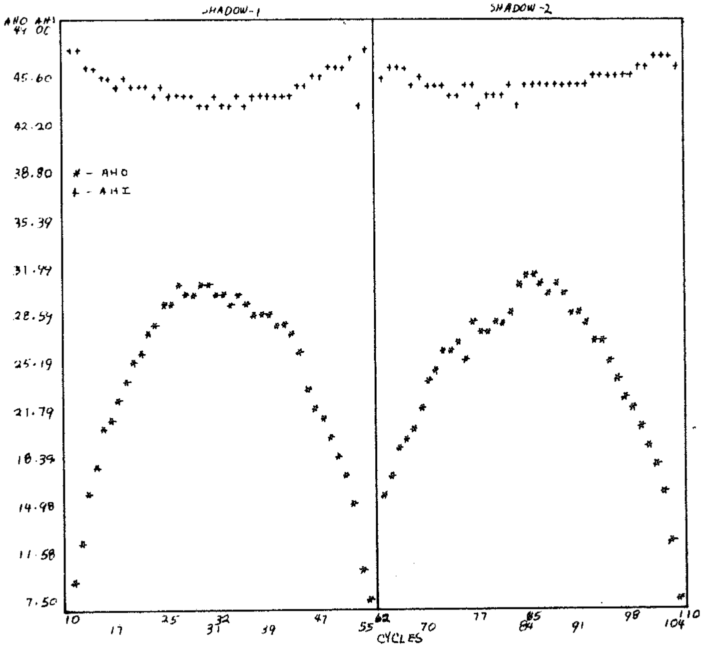


Figure 67

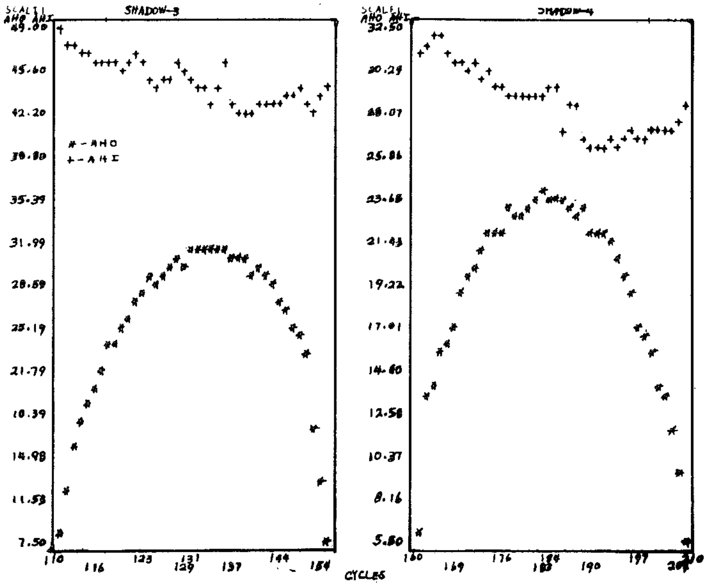


Figure 68

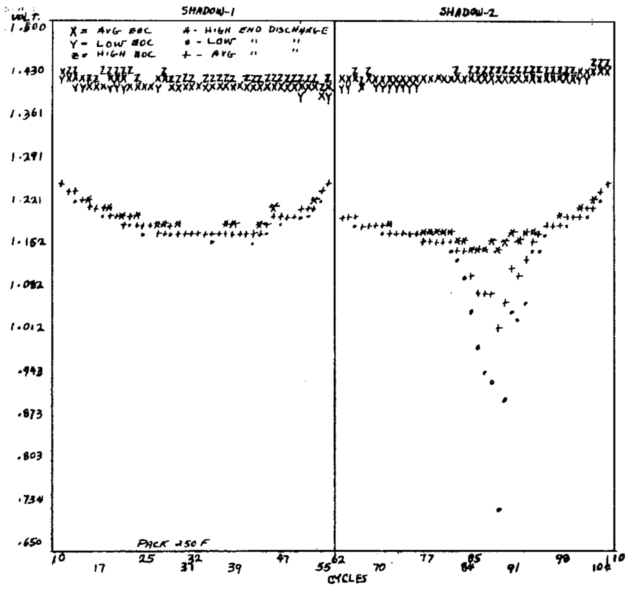


Figure 70

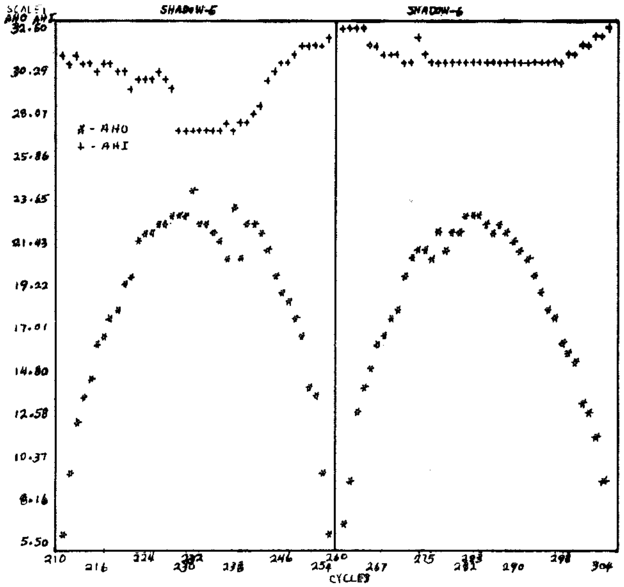


Figure 69

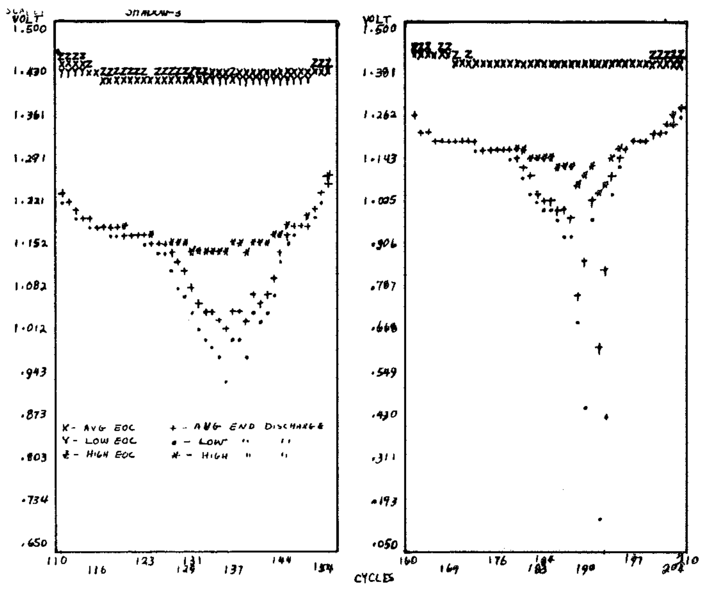


Figure 71

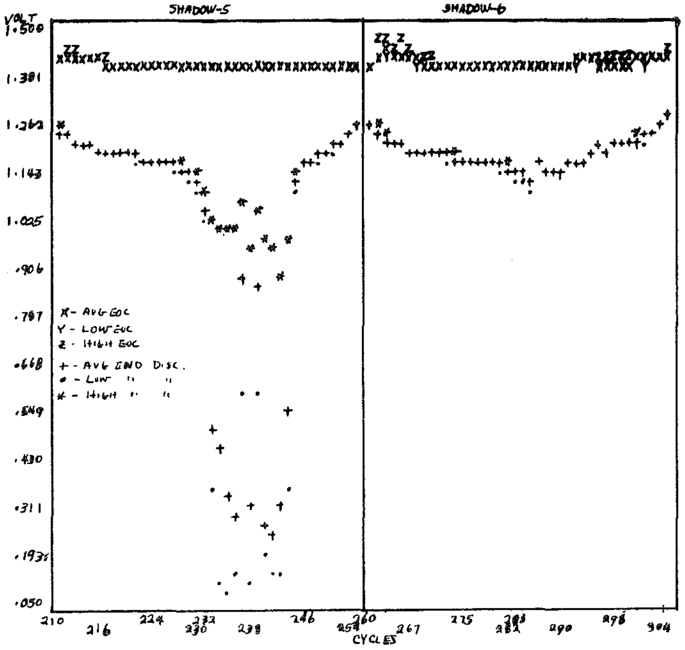


Figure 72

POST MORTEM OF FAILED CELL

THEO. POS. CAPACITY (FROM CHEM. ANAL.) = 57.856 A-H

THEO. NEG. CAPACITY (FROM CHEM. ANAL) = 81.603 A-H

MEAS. FLOODED POS. CAPACITY = 66.789 A-H

MEAS. FLOODED NEG. CAPACITY = 63.869 A-H

THEO. NEG./POS RATIO = 63/789/66.789 = 0.956

MEAS. NEG./POS RATIO = 81.603/57.856 = 1.41

% UTILIZATION OF POS. = (66.789/57.856) X 100 = 115.4

% UTILIZATION OF NEG. = (63.869/81.6034) X 100 = 78.26

FAILURE DUE TO SHORT
ALL SEPARATOR MATERIAL DECOMPOSED ON SHORTED PLATES

Figure 73

ACCELERATED TEST

D. Mains
Naval Weapons Support Center

Our name has been changed to the Naval Weapons Support Center, but Crane is still one of the more recognized acronyms. To bring you up to date on the status of the accelerated test program we have had 35 packs that have failed and are now in the process of being chemically analyzed. We have 43 test packs that are on test and 7 yet to go on test. The analysis, as I say, is under way. So far we have computerized all of our data that has been made available.

We have also obtained the programs to convert the analysis from the laboratory information, engineering units and grams per cc on the electrolyte, the separator tests, positive and negative plate chemical analysis, and the positive/negative electrochemical analysis. These results are now available and we have been utilizing it.

We also have been working on our prediction techniques. At the present time the techniques that have been approached, and are under way, is the progression analysis using the 8 factors of the test design along with the time to discharge to voltage for variables in the model. These have shown some encouraging results, in some sense it is a little bit better than what we expected and I won't go into that at this time. But they have shown some results now.

Another analysis was using the regression analysis with the 8 factors, and also the historesis area that was arrived at by John Waite. This again has been showing some results, and finally a study in the change over life of the characteristics of the charge-discharge curve. In this area we are just beginning to obtain results, we haven't really defined our direction if it's going to be that beneficial or not.

Some modifications that we're planning to try, one is to use other voltages than the 1.25 number which has been used for many years. And to try to use times reached at certain portions in the charge curve. To date we have not been pursuing the charge portion of the curve to any great degree.

Another area is to define the time to voltage on the charge and discharge with the rate historesis data. Also to use the time to discharge for nonvoltage levels to another, and to also do the same thing on the charge side.

Another area is to study the regions within the matrix that the regression analysis does not work in. As I mentioned earlier there have been a few areas where the results were much better than anticipated. There are areas in which we have no correlation, no encouraging results at all. And the idea is to look at the test design and see if those particular regions stay outside of the prediction area. We may have over stressed the cells to the point of nonlinear type failure mechanism.

Finally, we are continuing with the data collection and data handling. We have been getting various inquiries in certain areas of the test matrix. And to date we have been handling all the data as one full unit. We are now in the process of converting this down to where each individual pack will be accessible in itself so that if someone is looking for data on a particular set of test conditions, we will be able to supply them. We are also working on some editing programs that will identify environmental variations that occurred "bad data points," this type of information. So the data is being prepared. If one of the techniques we are using is not satisfactory we still have the raw data that we can use.

So this brings you up to date very briefly on the type of effort we are making. The next paper will also cover some of the results that have been obtained to date.

HALPERT: I might add that with all the data and techniques that are now available do you have some idea on how you would handle the data in terms of prediction. I am sure that either Don or Floyd or anyone involved with the program would like to know. So if you would send them to the proper people we would certainly consider putting it into the program.

FORD: At this point I would like to make a comment. I know that Crane has been asked several times for data on accelerated tests. There is an enormous amount of data on magnetic tapes, we will entertain any request that you see fit if you have a need, if you would like to take a specific look at some portion of the test or some data, and you want to do an independent analysis. I'd like to have this request in writing, but we can not respond to every request. You just can't say I want the data on accelerated tests. We'll ship you a box car of magnetic tapes, if we could afford it. We can't afford that, but I just want to point out to you, if you do want some of the data and you would like to take a look at it independently, be very specific about what you want and I would like you to send the request to me in writing. I have instructed Crane that the data requests that come to me will not interfere with their program. For the simple reason we have a very tight schedule. I hope by next January, January 1978, we have the final results on accelerated tests. At the next workshop we can give you some very conclusive results on what's happening.

ACCELERATED TEST

P. McDermott
Coppin State College

I have been looking at the accelerated test results more from the point of view of the chemical changes that are going on. Not as much in terms of the statistical analysis or the regression analysis. What I am trying to do is track some of the changes that are occurring in the cell, the cell components as they are under going accelerated testing, and try to correlate this with the failure modes or modes of degradation.

I'm really trying to assess whether the cells are dying an unnatural or natural death. The reason is, if we're going to try to correlate the accelerated data with real life testing, we had better have a pretty good handle on why the accelerated tests are failing. So, the outcome will in effect correlate with the regression analysis in the sense that we may have to drop out certain test cells in parameter and as Don pointed out, because they may be nonlinear and may not really contribute at all to the final regression analysis.

The first thing I looked at were changes in the electrolyte, that is what goes into the cell and what comes out of the cell.

(Figure 74)

First starting with the cells that are in the uncycled load. These are the 6 ampere GE cells, and what I have here is the electrolyte data. The percent of electrolyte, you can see here in column B, shows the variations that we have in the accelerated test program as far as the physical parameters are concerned with a low of 22 percent and a high of 38 percent. Thirty and thirty four are the range in which we have KOH concentration. You can also see in the volume of the electrolyte we range roughly from 17.5 to 18, 19, through 21. Included also was the ampere hours in precharge.

Now here we show the grams of KOH initially in the cell. This is just determined by the concentrations times the volume of the electrolyte.

In column F I show the grams of KOH which is found in the extract and you will notice that pretty much down the line there turns out to be about two and a half grams of KOH difference between that in the extract and that which was initially in the cell. And that is shown here the grams of KOH unextracted. Now the grams of carbonate found in the extract is fairly constant, 1.2 to 1.46 there.

So that you notice these two columns, the grams of unextracted KOH and the grams of carbonate in the extract is fairly constant, even though we had greatly differing amounts of KOH in the beginning. Now if you take the difference in milliequivalents between the KOH which was unextracted and the carbonate which was found in the extract, you find that a fairly constant amount which I translated into grams of KOH. And it turns out to be roughly 1.2 to 1.48 and here's an average here of 1.33. What that means is the amount of KOH that we put in and the amount that comes out is either OH or carbonate, there is still an amount of KOH that is not found.

Now this could be that the potassium is being tied up somewhere in the plate structure so that when we actually undergo the extraction we are not getting it. I did a correlation between columns here and it shows that there is a very good correlation between the amount of KOH initially in the cell and the amount of KOH in the extract as we would expect. Also a fairly good correlation between the grams of KOH unextracted and the grams of carbonate in the extract. What this means is some of the KOH that goes in is in a sense extracting carbonate out of the plate and that's why we're finding it in the cell extract. This lack of correlation between grams of KOH initially in the cells and the grams of carbonate in the extract tell me that the carbonate is not getting into the cell via the electrolyte but rather it is there in the plates and is pulled out during the extraction procedure.

(Figure 75)

In the next chart I will show you the graph which gives the grams of carbonate in the extract versus grams of unextracted KOH, and you will see a fairly linear relationship here. I also put scales of milliequivalents on the top and bottom. As you see here, here's that 1.33 average gram that is if there was no carbonate in the cell we would still have 1.3 grams of KOH not found. The linearity of this, we might also notice the slope of the line, shows that if you reflected this line milliequivalent axis you get about 10 milliequivalents of carbonate and also reflecting it on this axis you get 23 to 33. So the slope of the line corresponds very well with the milliequivalent per milliequivalent KOH to carbonate.

(Figure 76)

Now let's look at a pack which has undergone cycling. Those were the uncycled cells which we were showing. Here the parameters, this is pack 72N temperature. This is for those of you who have read into it. This is a star point cell, 40 degrees C, 60 percent U of D charge rate of 1 c, discharge 8 percent, recharge 140, and these are the physical parameters down here.

Now in the cycle history, we see that the cells taken at 50, 100, and 150 are scheduled removals. That is these are cells that are pulled off before cell failure for analysis.

These next cells here, 1,700, 1,350 and so forth. The top three were removed for pressure failures. They had transducers on them. These two were removed for safety reasons, it looked like the pressure in them was also building up. They didn't have transducers on them but they went ahead and took them off. If we look at the gas sampling data on it we will see a high degree of hydrogen in the cells--except for one odd-ball cell here. Hydrogen seems to predominate.

(Figure 77)

Now lets take a comparative look at the cells in pack 72N, again the grams of carbonate in the extract versus the grams of unextracted KOH. And I put down here for comparison the data from that previous graph where we had 1.33 here and these are the uncycled cells.

Now we notice this time an interesting fact that the--it seems like the data points are now along a line which goes through the origin. In other words what we are now doing is extracting all the potassium back out with the carbonate. And if you look milliequivalent per milliequivalent here carbonate against OH, the line, the slope of the line again conforms 75 milliequivalents here and here so that any point along that line going through the origin there would mean that you are in effect, recovering all KOH that you put in the cell. Which suggests that as you get an uncycled cell some of the potassium is tied up in the plate. And interestingly enough the ratio of the equivalents of potassium per equivalents of positive active material in the uncycled cell here is roughly one to fifteen and some people have suggested that the potassium can be tied up to the active material in the positive plate with a ratio of 120, so we are at least within the ball park. I think that Falk and Salkind have a reference to this in their book. Notice here too that we have--the boxes contain the cycle numbers in which the cells failed, well except for these which are scheduled removals, and we see how the carbonate is increasing from the uncycled cell here roughly 1.2, up to 3 for the low number cycle, up to four and a half for those which have received 1,700 cycle. And this is a very high amount of carbonate when you compare it with the OH that was originally in the cell.

(Figure 78)

What I show here is some other changes which are occurring in the cell. This is chemical capacity. On this side we have ampere hours of negative and positive capacity, now this is chemical not electrochemical. And down here the ampere hours of charged negative when the cell is discharged, so this would be an indication of precharge. And the difference here between the positive and the negative would be an indication of the overcharge protection that the cell has. And as we see in the low cycled cells 50, 100, and 150 there is quite a bit of overcharge protection whereas in cells with 1,350 and 1,700 cycles you have practically lost all the overcharge protection. This behavior would correspond with the fact that we are showing hydrogen gasing as the failure mechanism for cells at 1,300 and 1,700 cycles.

(Figure 79)

Now, in the next chart I show the changes in the pack 72N cells with cycling. As regards the grams of separator this is dry weight of separator that is lost, I'm having here an average of the cells at 50, 100, and 150 that is a low cycle cells, versus the cells removed at the high cycle. We find that we lose about a half a gram of separator, we also have a loss of in the amount of OH and a gain in the amount of carbonate, and a loss in the amount of overcharge protection. What I did was just a rough computation here, this is based on the calculation similar to those made by Lim and Margerum in last years battery conference, in which they showed what changes you would expect in the battery if the nylon were degraded. And just using this loss of 0.5 grams it shows a loss of KOH and a gain of carbonate, and a loss in overcharge protection.

Now these don't correspond exactly, but they are at least going in the same direction. I might point out here if instead of using the cells 50, 100, and 150 I had used the base line cells, the uncycled cells, these would come out fairly close. That is the predicted changes in the cell due to nylon degradation would come out fairly close to the actual.

(Figure 80)

Now, why are we interested in this nylon degradation. Well, here is one of those things which I think would lead to a natural death rather than an unnatural death of a cell. That is if your cycling a cell at very high temperature you are in a sense promoting a degradation which may not occur at all in a regular cycle regimen at 10 degrees and 0 degrees. Some of the parameters in the accelerated test program are variations in depth of discharge, 60 percent depth of discharge, 100 percent of depth of discharge. Others are variations in charge rate and discharge rate. Some of these parameters may in fact, not be exaggerated in the sense of a regular cycle regimen. 80 percent depth of discharge or a 60 percent is not unusual, but a 60 degree centigrade temperature is very unusual. So what we would like to do is try to distinguish between those factors which maybe degrading only one component of the cell rather than the whole cell. I would call natural death, I guess, of a cell the component failure of the cell mimics the degradation that you would see in a real life time cell. The positive plate starts giving out, the negative plate gives out, the separator gives out and they all are aging at the same rate. Whereas if you have in the accelerated test only one of those components aging very quickly and knocking the cell out, then I would consider this sort of unnatural.

Now here shows the time of--this is the degradation of nylon, temperature versus time and this is again taken from Lim's work, and it shows how dramatic this nylon degradation goes with the rise in temperature. Here is the 10 degree Centigrade degradation, it takes 50 years to degrade 10 percent. As we work up the scale 30 degrees takes roughly 8 years. This is a log scale. So I drew it in, these are now the temperatures that were working in terms of the accelerated test program, 17 months for 40 degrees, five and a half for 50, and 6 weeks for 60. Now he estimates that a 10-percent degradation is enough to knock out the overcharge protection and leads to cell failure.

We had an interesting cell pack out at Crane which showed that it was at 60 degrees. There was one pack which was on 60 degrees but it had to be taken off after 13 cycles. And then it was put on a normal test parameters and we found out there that it failed after what, 2,000 cycles Don? Whereas the normal test of parameter cells are still going on. So just that 13 cycles at 60 degrees was enough to shorten the life considerably. And they were also, I think, held at 60 degrees for three weeks, so just being held at three weeks you can see it was in the ball park here for the nylon degradation.

So, just to summarize what I'm looking at, is the cell failure mechanisms in the accelerated test program, in order to distinguish between cell failures which may be correlatable to real life and those which are not. I think this will help us in two ways: one, it may improve the prediction model if we could select out those test parameters which are not really correlatable to real time. Pull those out of regression and see if we can improve the regression. Also it might help in a practical way when we actually start using the accelerated test procedure to predict failure for a lot of cells. Now there are two ways of approaching this, one is a sampling procedure, and the other is a 100 percent, what I will call a 100 percent procedure. For example, if you take a lot of 100 cells from a manufacturer you may take 20 of those cells, run it through an accelerated test matrix and determine or predict the life of the other 80 cells. You know in a sense the strong was 20, or another use of accelerated test procedure could be to take all the 100 cells but you only subject them to a few cycles and if the prediction models shows this is possible, and we are working on this, then in a sense you are taking every cell in your lot and you are not only predicting its life, but you are in a sense predicting which cells are less efficient that the other cells. So you are saying--it is not just a sampling procedure, but it may be a selecting procedure. Will it be good to know which conditions really damage the cells or reduce their real time life, and so if we are studying the degradation mode it may be that 50 cycles on a cell at certain test conditions do not really degrade the life, the real life of the cells very much. And this I would say would be the optimum use of such an accelerated test procedure. That's all.

GROSS: Wouldn't the regression analysis project the data down to a room temperature level? So that the effect of the high temperature acceleration gets cancelled out?

MC DERMOTT: It will do that, but you have to go, in a sense, in a linear fashion or if you do nonlinear regression, if you do a curve linear regression you have to, in a sense, have a smooth curve, that is your degradation failure up a high temperature can't all of a sudden come down and go to a quantum lead you know for the low temperature real time environment. Now one important point in there, is say a class transition of nylon which occurs around 40 degrees. You would be breaking hydrogen bonds and so this would accelerate the nylon degradation at a much higher rate than the low temperature. This is just an example of an effect at the accelerated condition which is not curval linear, that is not a smooth curve.

There would be another problem say where your cell failure is a pressure failure in the accelerated test program. It really is not a failure for the cell, that is the components of the cell are still in fairly good shape, but you have selected a temperature, or a charge rate, or something else which is so high that you are essentially gassing hydrogen when under normal conditions you wouldn't be. So you would have to look at those in terms of not having them weigh too heavily in the test matrix. So looking at both the test parameters and degradation modes which are not considered normal, we will have to figure those into the final regression.

SCOTT: Also, what fraction of the tests are conducted at 20 degrees C or below?

MC DERMOTT: Not much. I think the majority of the cells--40 to 60, there is a large number--there's a number of cells at 50 degrees and then there are less at 40 and 60, if I'm not mistaken. There are very few at 20 and 60. I'm sorry--there's a lot at 40, there's a lot at 50, and then less at 40 and 50. Is that right? 40 and 60?

MAINS: There's one pack at 60, one pack at 20, one, the large numbers are at 30, 40, and 50. And then there's a very small number at 0 degrees, I think 2 pack Centigrade.

SEIGER: It would appear that in light of the separator degradation data, the nylon that the cell life is really extended at low temperatures. Could we see some advance in the program or else put in so that the lower temperature would be favored?

I want to point something else out, that at about 40 degrees Fahrenheit (5, 10 degrees Centigrade) we are observing that some electrodes, positive electrodes and cells are delivering more capacity than they do at room temperature. If you couple these two together we can get a cell life improvement and a capacity improvement by operating at a somewhat lower temperature. Would it not be wise to incorporate that into the program?

MC DERMOTT: Well I think the original matrix was chosen to avoid the low termperâtures simply because cycling would last so long that it wouldn't be considered accelerated anymore. In other words, you are choosing that as one of the things which is accelerated. The problem is that some of the parameters are roughly in the ball park. That is the range of say depth of discharge, if I'm not mistaken, most are what 60?

MAINS: Would be about 40 percent.

MC DERMOTT: Forty percent depth of discharge. That's sort of a mild--not mild but it's not extreme. Whereas the temperatures are all sort of up in the extreme range, depth of discharge, charge rate and so forth are tolerable. So we're going to have to somehow weigh that when we get the total regression scheme going. I don't know if I answered your question but it was selected so that it would accelerate the degradation.

SEIGER: Fine. I think I gave Gerry something to look forward to for the next time.

GRIFFIN: The method of analysis for the calculating KOH, was anything new there or just the standard technique?

MC DERMOTT: Standard technique.

SCOTT: You used the term potassium analysis. Did you actually analyze potassium or were you analyzing for hydroxide?

MC DERMOTT: No, we were analyzing for hydroxide, assuming potassium was the counter ion. We actually didn't go--although we have checked other plates for potassium and even long term cycle plates don't show that much potassium in them. We did look at uncycled plates to see how much potassium was in it. Have you done that? Has anyone else? Have you seen that correlation?

SCOTT: Is it not known that potassium is absorbed independently of hydroxide on the positive electrode. So that you shouldn't really associate potassium directly with hydroxide in terms of the analysis unless you actually determine potassium separately?

MC DERMOTT: Well, there would have to be a counter ion there for all the hydroxide and the carbonate.

SCOTT: Yes, but what?

MC DERMOTT: I think it is potassium, but we can discuss that afterwards.

A. Cell id Number	B. % KOH in Electrolyte	C. ml of Electrolyte in cell	D. Amp-Hrs Precharge	E. Grams of KOH initially in the cell*	F. Grams of KOH in Extract	G. Grams of KOH unextracted (E.-F.)	H. Grams of K_2CO_3 in Extract	I. Difference in Meq's between KOH unextracted and K_2CO_3 in Extract	J. Difference (Column I) expressed as grams KOH
029	30	17.5	2.8	6.77	4.57	2.20	1.22	21.46	1.20
038	30	21.5	2.8	8.39	5.69	2.65	1.44	26.49	1.48
067	34	18.5	2.5	8.37	5.45	2.92	1.41	22.79	1.28
001	22	19.5	2.8	5.17	2.72	2.45	1.46	22.60	1.27
013	30	19.5	2.2	7.54	4.96	2.57	1.41	25.47	1.43
230	38	19.5	2.8	10.20	8.01	2.19	1.11	23.04	1.29
056	30	19.5	3.3	7.54	5.11	2.42	1.29	24.47	1.37
213	30	19.5	2.8	7.54	5.23	2.31	1.21	23.80	1.33
									1.33 Average

.99 -.50 .85

Correlations Between Columns E, F, G. and H.

	E.	F.	G.	H.
E.	1	.99	-.18	-.50
F.		1	-.29	-.58
G.			1	.85
H.				1

* This number is arrived at by considering the Volume and % KOH introduced into the Cell

Figure 74. Analysis of Electrolyte from Uncycled Cells in the Accelerated Test Program.

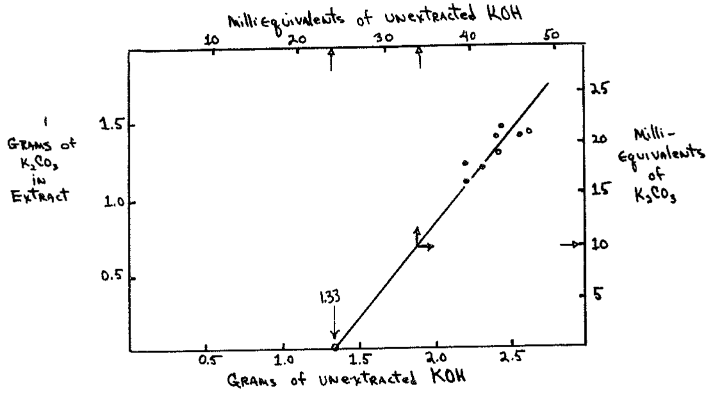


Figure 75. Grams of K_2CO_3 in Extract of Uncycled Accelerated Test Cells Versus Grams of KOH which was not able to be Extracted.

Cycle Parameters

Temperature °C – 40°
Depth of Discharge – 60%
Charge Rate – 1 C
Discharge Rate – 8 C
Percent Recharge – 140%
KOH Concentration – 30%
Amount of KOH – 19.5cc
Precharge – 2.8 Ah

Cycle History

Cell Number	Completed cycles	Mode for Removal*	Gas Sampling After Removal % H_2	% O_2	% N_2
1	1351	P	82.0	2.0	15.5
2	1717	P	73.5	5.0	20.5
3	1352	P	21.0	11.5	67.0
4	1717	A	62.0	15.0	22.0
5	1717	A	71.5	0.0	23.0
6	150	R	69.0	2.0	28.0
7	100	R	81.0	3.0	15.6
8	50	R	54.0	3.0	43.0

* P – Pressure failure (over 250 psi)
A – Cells Removed for Safety Reasons (No transducers, but indications of High Pressure)
R – Scheduled Removals (Cells did not fail)

Figure 76. Accelerated Test Program Pack 72 N.

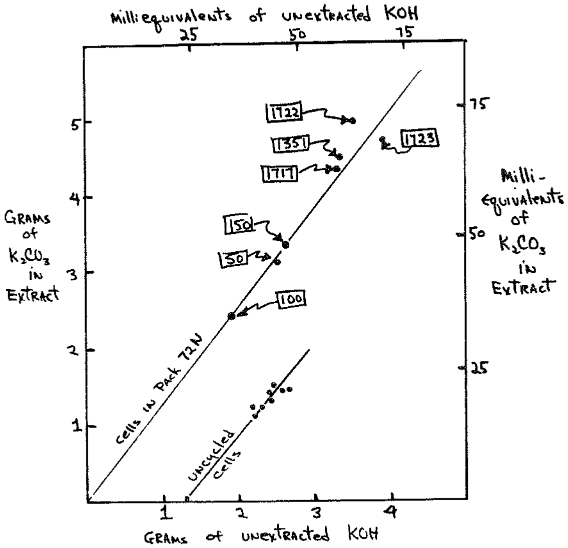


Figure 77. Comparison of Extracts of Cells from Pack 72N and the Uncycled Cells in the Accelerated Test Program. The Numbers in the Boxes Near the Data Points Indicate the Cycle of Cell Failure.

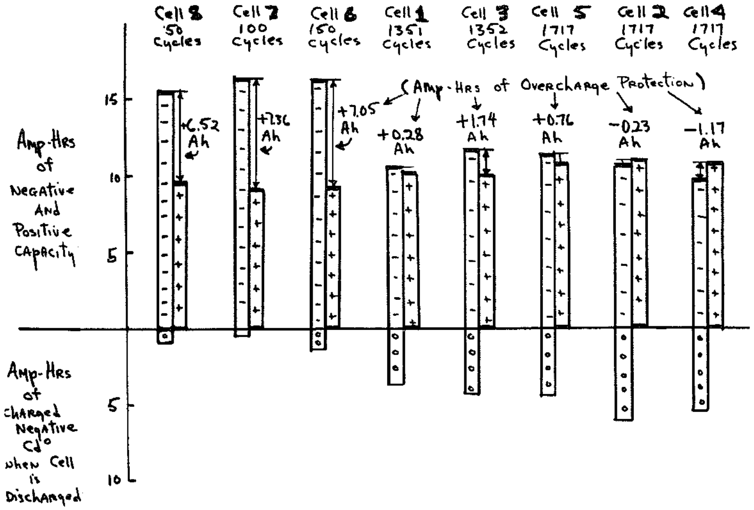


Figure 78. Cell Capacities (Chemical) for Pack 72N.

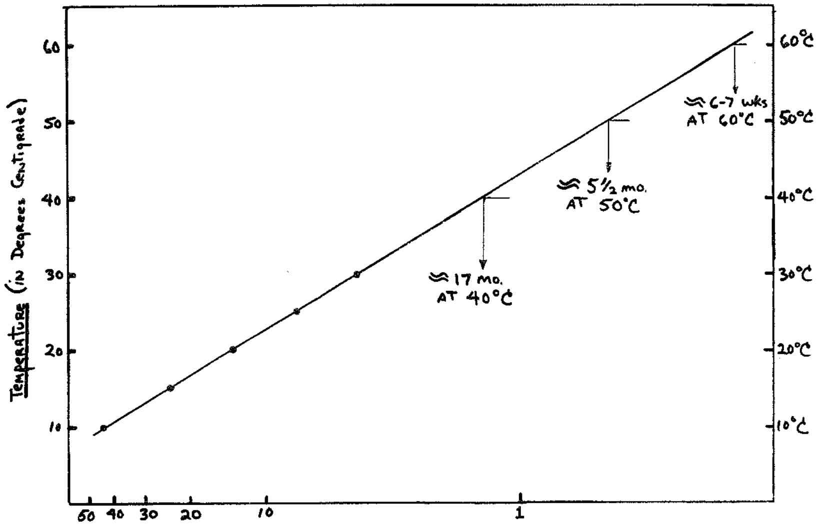


Figure 80. Time Required for the 10% Degradation of Nylon in 34% KOH at Various Temperatures.

	A. Average of Cells Removed At 50, 100 And 150 Cycles	B. Average of 3 Cells Removed At 1717 Cycles	Differences Between Columns Ⓐ And Ⓑ.	theoretical Changes in A Cell Due To the complete oxidation of 0.537 g. of Nylon in the Seperator *
Grams of Seperator (Dry)	2.070	1.533	0.537 g. loss	0.537 g. loss
Grams of KOH	5.529	3.962	1.567 g. loss	2.767 g. loss
Grams of K_2CO_3	2.979	4.369	1.390 g. Gain	3.924 g. Gain
Amp-Hrs of Overcharge Protection	6.97	−0.64	7.61 Ah. loss	4.13 Ah loss

* See "Chemical and Electrochemical Studies on Nylon Separator Degradation," H.S. Lim and J.D. Margerum, 1975 GSFC Battery Workshop.

Figure 79. Changes in Pack 72N Cells with Cycling.

JPL TEST PLAN FOR EVALUATION OF NEW TECHNOLOGY, NICKEL-CADMIUM CELLS

R. S. Bogner
Jet Propulsion Laboratories

My topic for this morning is the JPL test plan for evaluation of new technology Ni-cad cells.

(Figure 81)

I have been informed that I have about ten minutes to get through this discussion, so I may just flash some slides. The objective of the test plan was to compare different Ni-cad cell types to determine life in comparison to the Goddard Space Flight cells on the accelerated life test program, with the sample of about 50 cells. The second objective was to determine if the regression equation for the life of the Goddard Space Flight cells is appropriate for other cells and cell sizes.

(Figure 82)

So the experimental design for the JPL test is determined by the Goddard Space Flight design. Goddard utilizes a one-quarter by two to the eighth fractional factorial experiment. They are evaluating eight quantitative factors at two levels, and they are evaluating five cells for treatment, which makes 320 cells. Now the only thing I am talking about here is the fractional factorial part of the experiment. And they also have star point and center point evaluations, which we are not trying to evaluate.

The JPL experimenter has an additional variable, which we call a "T" or a cell type. There are also two considerations for designing the experiment. We had a small sample size, we couldn't go through 300 and some cells again. So, our cell sample sizes were limited to 50 cells. We also assumed that three of the quantitative factors were fixed, and may be different from those in the factors were fixed, and may be different from those in the Goddard test cells. So we say that their effects will become compounded with the cell type; those factors of KOH concentration, precharge and the volume of the KOH.

(Figure 83)

The next slide lists the particular factors which are being evaluated in both programs. The eight quantitative factors in the Goddard Space Flight design is the temperature, depth of discharge, charge rate, discharge rate, percent of recharge, KOH concentration, precharge, and amount of KOH.

And as I stated before, the JPL design includes the last three factors in with the cell types since these are all fixed by the particular cell design that we have.

(Figure 84)

This shows the table of the 64 treatment combinations in the Goddard Space Flight experiment. The presence of a letter in the column means that that factor appears at a high level. And for any fixed level of f, g, and h, there are eight treatment combinations. And those are the ones that are underlined. So those are the particular treatment combinations that the JPL test is evaluating out of the 64 possibilities. And the matrix selection that we used was f is high, g and h, low.

(Figure 85)

The next slide shows the actual values of the matrix of factor combinations. Now we are using six cells per pack, for a total of 48 cells, and we are pulling one cell out for analysis at 50 percent of life, which is an estimation, and they are coming pretty close on their estimation. Also, since Goddard has been testing these cells at Crane, they have a pretty good idea how long they will last. So we are coming close to the 50 percent evaluation. And you can see that the factors that they are evaluating are pretty high extremes; high temperatures, high DODs, high charge rates, high discharge rates, high recharge rates.

(Figure 86)

Particular cells that we are evaluating in this program, we have 100 cells from SAFT, which are 6-ampere hour cells. Some of the design features of the cells are increased separation, two layers of the separator, 50 cells each with the Gulton seal, 50 cells with the Ziegler seals. Other than that, the cells are identical.

They have used the SAFT aerospace plates in their cells. They have 100 cells on order from EP, which were just delivered about a week or two ago.

Fifty of the cells are the Bell and Western Electric cells. I have listed 25-ampere hour capacity. They range from 25- to 30-ampere hours.

These cells use electrochemically loaded plates, polypropylene separators, Ziegler seals and negative-to-positive ratio of 2 to 1.

The other 50 cells are a lightweight cell design which has been discussed this morning, at approximately 20-watt hours per pound, 20-ampere hours cells. These are standard EP loading process, preswell positive electrode. They use higher porosity plaque than normal.

(Figure 87)

This shows a picture of a couple of cells. This cell is the 20-ampere hour lightweight cell by Eagle-Picher. This is the Bell Telephone cell, and this is the pretty much standard 20-ampere hour cells that we are using today.

(Figure 88)

Some of the concerns that we have with the test program are including the factors f, g and h in the cell type. Material ratio was not a factor in our testing. And the effect of the cell size, most of the Goddard--I think the Goddard cells are all 5-ampere hour cells, and ours are varying from 6 to 30. Also the time from manufacture to the time of starting the test. There has been some problem getting all the cells on test in a short time after manufacture. But, it is one of the problems we have to live with.

GRIFFIN: Mallory. The amount of money going into this type of testing, is there a direct relation here between the amount of quality you are putting into the cell? If this amount of money going into testing, was put into making the cell, would you get a better product? Do you really need all this testing? Are you over-testing? This is my question. Have you considered both aspects?

BOGNER: Yes. I think we have considered both aspects, and there is always a decision of how do you want to test. And we felt in accelerated tests it is better than trying a real-time test, because you need information rapidly. Also, eventually, as Pat McDermott was saying, maybe you can set up an accelerated test and only test 10 or 12 samples or maybe even fewer. But you have to go through this matrix to find out what accelerates a test, what causes a failure and that sort of thing.

LACKNER: Defense Research Establishment

I might have missed the point, but what is the significance of the star point or the center point evaluation?

BOGNER: Star point goes to more extreme limits than the tests that were shown here; 60 degrees C on the high end. I don't know what the exact numbers are. It has been published.

LACKNER: It has been?

BOGNER: Yes, by Goddard and Crane.

GASTON: RCA

Did you start this test--or when is the starting date when you expect to start this test?

BOGNER: The SAFT cells have started the testing. The cells from EP, the 20-watt hour per pound cells and the Bell Western Electric cell, we just received that a week ago, so we haven't started. We will be starting possibly in six to eight weeks.

DUNLOP: COMSAT

I would like to point out that there are two schools of philosophy here, and several laboratories have chosen the other school. We at COMSAT, as well as Telesat Canada, have chosen to do real-time testing. We now have seven years of real-time testing on cells of the intercept 4 vintage. We have from Telesat--we work closely with Telesat on the real-time test programs. We have up to five years of real-time testing on these programs. And we have started some recent Telesat, particularly in COMSAT, on a real-time basis that are between one and two years old.

I do think that there is an important point that needs to be made. There are certain things that have come out of the real-time testing programs that I doubt you would have ever seen on any accelerated test program. And those results, some of them have already been reported in the literature here and other places, and I am sure there will be further reports coming in in the future. I do think though, that there is room for both kinds of programs, and that there is a good chance for exchange of information.

BOGNER: As has been stated earlier, some of the accelerated tests may cause other failure modes you don't get in real-time tests.

But the other problem is, how you make an improvement and how you check it out within a short length of time. We can't test for seven years.

DUNLOP: Yes you can. That is the point.

BOGNER: Yes, we can test for seven years. But--

HALPERT: You never get the same cell again.

KRAUSE: Hughes

I guess that is the point about knowing what it is that you are working with at the start of this test, and whether you can reproduce it later. Sam, have you attempted to do any kind of detailed analysis on samples of cells going into the test?

BOGNER: There will be analysis of the cells as received.

KRAUSE: Okay.

JPL TEST PLAN

- OBJECTIVE
    - COMPARE DIFFERENT Ni-cd CELL TYPES TO DETERMINE LIFE IN COMPARISON TO THE GSFC CELLS ON THE ACCELERATED LIFE TEST PROGRAM WITH A SAMPLE SIZE OF ABOUT 50 CELLS
    - DETERMINE IF THE REGRESSION EQUATION FOR LIFE OF GSFC CELLS IS APPROPRIATE FOR OTHER CELLS

Figure 81

JPL TEST PLAN

- EXPERIMENTAL DESIGN
    - JPL TEST DESIGN DETERMINED BY GSFC DESIGN
    - GSFC UTILIZES 1/4 x 2^8 FRACTIONAL FACTORIAL

        8 QUANTITATIVE FACTORS AT TWO LEVELS

        5 CELLS PER TREATMENT OR 320 CELLS TOTAL
    - JPL EXP ADDITIONAL VARIABLE "T" CELL TYPE
    - TWO CONSIDERATIONS FOR DESIGNING EXPERIMENT
        1. ONLY 50 CELLS AVAILABLE
        2. 3 OF QUANTITATIVE FACTORS FIXED AND MAY BE DIFFERENT. THEIR EFFECTS WILL BECOME "CONFOUNDED" WITH CELL TYPE

Figure 82

JPL TEST PLAN

- EXPERIMENTAL DESIGN (CONT)
    - 8 QUANTITATIVE FACTORS IN GSFC DESIGN
        - a. TEMPERATURE
        - b. DEPTH OF DISCHARGE
        - c. CHARGE RATE
        - d. DISCHARGE RATE
        - e. % CHARGED
        - f. KOH CONCENTRATION
        - g. PRECHARGE
        - h. AMOUNT OF KOH
    - JPL DESIGN INCLUDES FACTORS f, g AND h IN WITH CELL TYPE

Figure 83

JPL TEST PLAN

- EXPERIMENTAL DESIGN (CONT)

TABLE OF 64 TREATMENT COMBINATIONS GSFC EXP							
(1)	cdgh	abcg	abdh	bdefh	bcef	acde	aef
abc	abdf	fh	cdf	acdeg	aeh	bde	bcegh
bcdeg	beh	ade	acegh	c	df	abfh	abcdf
adefh	acef	bcde	bef	ab	abcdgh	cg	dh
e	cdef	abcefh	abdef	bdg	bch	acd	agh
abce	abdegh	eg	cdeh	acdfh	af	bd	bcf
bcdfh	bf	ad	acf	ce	degh	abeg	abcdeh
adg	ach	bcd	bgh	abe	abcdef	cefh	def

- THE PRESENCE OF "a" MEANS THAT FACTOR APPEARS AT ITS HIGH LEVEL
- FOR ANY FIXED LEVEL OF f, g and h THERE ARE 8 TREATMENT COMBINATIONS
- MATRIX SELECTION: f HIGH; g AND h LOW

Figure 84

JPL TEST PLAN
MATRIX OF FACTOR COMBINATIONS

FACTOR	a	b	c	d	e
CELL TYPE PACK NO.	TEMP °C	DOD %	CHG RATE	DISCHG RATE	RECHG %
1	50	80	C/2	4C	140
2	30	40	2C	4C	200
3	30	80	C/2	C	200
4	50	40	2C	C	140
5	30	40	C/2	4C	140
6	50	80	2C	4C	200
7	50	40	C/2	C	200
8	30	80	2C	C	140

SIX CELLS PER PACK - 48 CELLS TOTAL

ONE CELL FOR ANALYSIS AT 50% OF LIFE

Figure 85

NEW TECHNOLOGY/DESIGN EVALUATION

- 100 AEROSPACE CELLS BY SAFT 6 Ah CELLS
  - INCREASED SEPARATION - TWO LAYERS
  - 50 CELLS EACH GULTON SEAL, + 50 EACH ZIEGLER SEAL
  - SAFT AEROSPACE PLATES
- 100 CELLS ON ORDER FROM E.P.
  - 50 CELLS SAME AS BTL/WESTERN ELECTRIC - 25 Ah
    - ELECTROCHEMICAL LOADING
    - POLYPROPYLENE SEPARATOR
    - ZIEGLER SEALS
    - NEG: POS RATIO 2:1
  - 50 CELLS LIGHTWEIGHT DESIGN - 20 Wh/lb-20 Ah
    - STANDARD E.P. PROCESS LOADING
    - PRESWELL POSITIVE ELECTRODES
    - HIGHER POROSITY PLAQUE

Figure 86

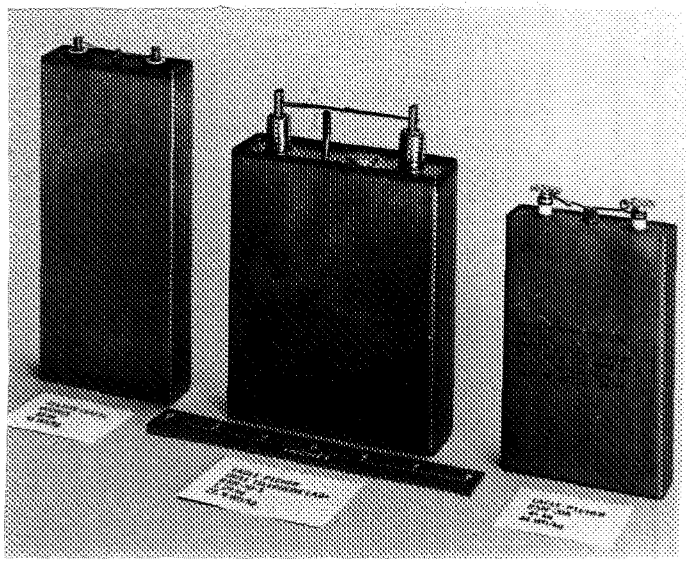


Figure 87

JPL TEST PLAN

- CONCERNS
  - INCLUDING FACTORS f, g AND h IN CELL TYPE
  - MATERIAL RATIO NOT A FACTOR
  - EFFECT OF CELL SIZE
  - TIME FROM MFG TO START OF TEST

Figure 88

Afternoon Session

CELL DESIGN

D. Baer, Chairman
Goddard Space Flight Center

My presentation will be a comparison of the 6 and 12-amp hour cells manufactured for the IUE program, including comparison of cell design, a little bit of manufacturing data, and also some of the acceptance test data done at GE and Goddard.

(Figure 89)

They are both General Electric cells with dual nickel braze, ceramic to metal seals, pellon 2505 separator. Negatives are teflonated, and they went through GE's proprietary carbonate reduction process. We have a goal to reduce the loading by 10 percent, and also have more KOH, 4 cc's per rated ampere hour.

(Figure 90)

There were some differences in the cell design, a little different configuration. The 6-ampere hours had 10 positives and 11 negatives; the 12's had 11 positives and 12 negatives, which resulted in the plate areas being a little bit--the 6-ampere hours was 47 percent of the 12-ampere hour plate areas, not a direct 2 to 1 scaledown.

The containers were also different with the 6-ampere hour being drawn, and the 12 ampere hour was a welded can.

(Figure 91)

Here are some pertinent manufacturing data. Rather than read all the numbers off, I am not going to go down and read all the numbers, I will just point out some things. The 6-ampere hour was a little bit heavier loaded, not by design, but just happened that way.

But as you can see, the theoretical--oh, incidentally, the last column over is the 12-ampere hour divided by two for comparison purposes. But the theoretical, they ended up with the 12 having more capacity, and that is because of the slight increase in the relative plate area.

Flooded cell tests don't reflect the theoretical capacity in that the 12's had a little less, nominally speaking, than the 6's. They both had good negative-to-positive ratios, and the precharge was set by oxygen venting.

The electrolyte--we got a little more electrolyte in the 6's than the 12's. Part of that is because I think we were a little gutsier the second time around. The major difference--in fact, the only real difference I could see, as far as the manufacturing data goes, was the wetout time for the separator, with 39 seconds on the 6, and 410 seconds on the 12.

Because of the 6's increased wetout time we turned the separator sample and the data over to our Materials people, Aaron Fisher and Fred Gross. And they did find the wetting agent, a slight trace of one, polyoxyethylene.

Todate it doesn't seem to affect the cell's performance at all. But then again, we don't have any life cycles. GE had promised they were going to change the spec on that and tighten it up, so that this won't happen again.

The other interesting thing is that there wasn't any other obvious indication of the wetting agent. For example, the total organics of the 6's was less than the total organics of the 12's. So really, the only thing that indicated the wetting agent, you know, without really going and looking at our IR traces, and a few other things, was the wetout time.

(Figure 92)

Here is a comparison of the pressures, with the 6's running a little higher than the 12's, which I attribute to the extra KOH.

(Figure 93)

And here is a comparison of the cell voltages. As you can see, they are all pretty uniform. All the voltages are the same with the possible exception of 35-degree voltages, which are running a little lower for 6-ampere hour cells. Also, in the next slide you will see that the capacity, relatively speaking, for the 6's was also a little lower at 35. They didn't track quite the same.

(Figure 94)

This is plot of capacity versus various tests that were done at GE and Goddard. The 12-ampere hour capacity is divided by two to be on the same scale for comparison. As you can see, they track pretty well. The trends are all the same. There is the 35 degrees, and you can see they kind of level off in the second 25-degree test, rather than dropping off like it did on the 6. The dotted trace is the 12-ampere hour data. Then at 0 degrees C, had a dropoff in capacity. When we got into our tests here at Goddard, the capacities were back up again. But then they just continued to drop until the bottom kind of fell out at 0 degrees C. However, after 10 cycles at 10 degrees C, the 10-degree capacities were up in both cases, at least to what they were back during the GE tests, and they are more than the initial 10-degree capacity test here at Goddard. And also the 20-degrees capacity, the last one, is more than the first 20-degrees C test at Goddard.

Now I attribute the falloff in capacity at 0 degrees to the cell being negative limited on discharge. And I think it is possible that the teflon might also cause that to be a little worse than you normally expect, because it is a barrier to the KOH and I think it might take a few cycles for it to get proper distribution electrically in the cell. I hope later in the panel discussion we will get into a little more about the negative fading and the moving around of precharge, which has been discussed before in the workshops.

(Figure 95)

Here is another plot of a third electrode during discharge at two different temperatures; the squares being the 25 degrees, and the black dots are the 0 degrees C. As you see on the 25 degrees at the end of discharge, nothing much happens. But at the 0 degrees, the bottom falls out on that, and essentially tracks your cell voltage. With the third electrode going negative, negative to a negative 0.13 volts. And we have seen this in varying degrees throughout all the testing.

One other point I might add is, we have also cycled five cells. We had five cells on a cycling test 24-hour orbit, and initially we saw about 6.3 ampere hour capacity at 0 degree C.

Now after about 45 or 50 cycles, we ran another capacity test similar to the first one, and we got 7.1-ampere hours. So it does, indeed, look like we do have a recovery of the negatives after cycling.

ROGERS: Hughes Aircraft

Have you considered the effects of trace of wetting agent on the performance of the teflon negative?

BAER: Well, the 12 didn't have any wetting agent in it.

ROGERS; But you were mentioning that there might be traces.

BAER: Yes. That is in the 6-ampere hour cell. It was not in the 12. And the data we have so far, they both look almost identical. So like I say, so far I haven't seen any ill effects from the wetting agent.

SEIGER: Yardney

The third electrode going negative, did I understand you to say that it is correlated with the negative electrode exhausting at zero degrees ?

BAER: Well, much as we can correlate it.

You know it is right at the knee. When your cell starts losing capacity, the negative goes too. The third electrode goes and is referenced thru a resister between the negative terminal and the auxiliary terminal.

SEIGER: And that is the negative that did go ?

BAER: I don't know what it would be. I can't see pressure dropping off.

SEIGER: And that was a ratio of--negative-to-positive ratio, 1.85 to 1 ?

BAER: Yes.

KRAUSE: Hughes

We have 7-amp hour GE cells that we run on occasion into negative limiting on discharge. It is fairly common, especially so, we think, because we do set the precharge--we require them to set the precharge extremely low. And we see the same kind of thing without teflon in the negatives.

BAER: Well I have seen this before.

KRAUSE: We think it is due to having a very low precharge initially, which does change as you cycle the cell. And we have experienced the same thing and we will cycle them and come up--it won't limit the negative to zero C after 15 or 20 cycles.

BAER: May I turn around and ask you a question ? How much precharge did you have in the cells ?

KRAUSE: A little over 3-ampere hours. About 3 1/2-ampere hours.

BAER: So that is about half of what the rated is. About what these were running, too. That is that the 6's and 12's were somewhere between 40 and 50 percent of the excess negatives. I am a little reluctant to go any more than that.

KRAUSE: We don't worry about this because we don't normally discharge the batteries in this manner.

BAER: As long as you aren't discharging to zero state of charge, that is all you need.

6 Ah AND 12 Ah IUE CELL DESIGN

- GENERAL ELECTRIC CELL
- DUAL, NICKEL-BRAZE, CERAMIC-TO-METAL SEALS
- PELLON 2505 SEPARATOR
- TEFLONATION OF NEGATIVE PLATE, LEVEL I
- CARBONATE REDUCTION PROCESS
- P.Q. PLATE WITH LIGHT LOADING
  GOAL: 10% REDUCTION IN LOADING
- HIGHER QUANTITY OF KOH
  GOAL: 4cc/RATED Ah

Figure 89

DIFFERENCES IN CELL DESIGN

- NUMBER OF PLATES: 6 Ah – POSITIVES – 10
  NEGATIVES – 11
  12 Ah – POSITIVES – 11
  NEGATIVES – 12
- PLATE AREA: 6 Ah CELL PLATE AREA IS 47% OF 12 Ah CELL PLATE AREA
- CELL CONTAINER: 6 Ah – DRAWN CAN
  12 Ah – WELDED CAN

Figure 90

MANUFACTURING DATA

	6 Ah	12 Ah	12 Ah/2
LOADING – POSITIVE AVERAGE	12.72gm/dm^2	12.52gm/dm^2	
NEGATIVE AVERAGE	16.2 gm/dm^2	15.7 gm/dm^2	
THEORETICAL CAPACITY – POSITIVE	10.13 Ah	21.23 Ah	10.61 Ah
NEGATIVE	18.19 Ah	36.94 Ah	18.47 Ah
FLOODED CELL TESTS – POSITIVE AVERAGE	7.81 Ah	15.5 Ah	7.75 Ah
(ECT) NEGATIVE AVERAGE	14.48 Ah	29.2 Ah	14.6 Ah
NEGATIVE/POSITIVE RATIO	1.85:1	1.88:1	
PRECHARGE SET (BY O_2 VENTING)	2.84 Ah	5.7 Ah	2.85 Ah
ELECTROLYTE (31% KOH)	4.17cc/ RATED Ah	3.83cc/ RATED Ah	
DIFFERENCE: SEPARATOR SET OUT TIME (AVERAGE)	39 SEC	410 SEC	

Figure 91

G.E. ACCEPTANCE TESTS

CHARGE TIME	RATE	TEMPERATURE	AVERAGE CELL PRESSURE	
			6 Ah	12 Ah
48 HR.	C/10	22°C	16 PSIG	8 PSIG
24 HR.	C/10	35°C	8″ Hg	12″ Hg
72 HR.	C/20	0°C	24 PSIG	11 PSIG

Figure 92

G.E. ACCEPTANCE TESTS

CHARGE TIME	RATE	TEMPERATURE	VOLTAGE RANGE 12 Ah. MIN.	VOLTAGE RANGE 12 Ah. MAX.	VOLTAGE RANGE 6 Ah. MIN.	VOLTAGE RANGE 6 Ah. MAX.
48 HR.	C/10	22° C	1.435 V	1.442 V	1.428 V	1.443 V
16 HR.	C/10	22° C	1.438 V	1.449 V	1.439 V	1.445 V
24 HR.	C/10	35° C	1.393 V	1.419 V	1.386 V	1.398 V
72 HR.	C/20	0° C	1.469 V	1.488 V	1.466 V	1.483 V
48 HR.	C/20	10° C	1.446 V	1.463 V	1.450 V	1.460 V

Figure 93

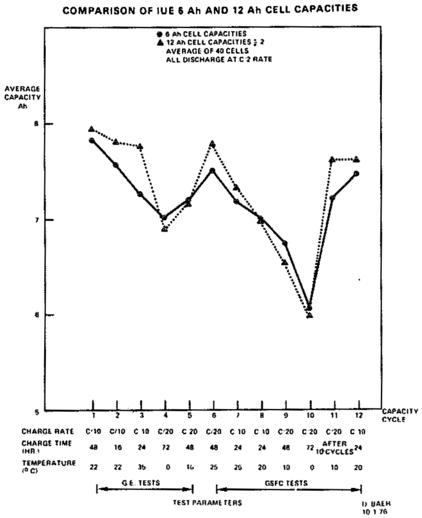


Figure 94

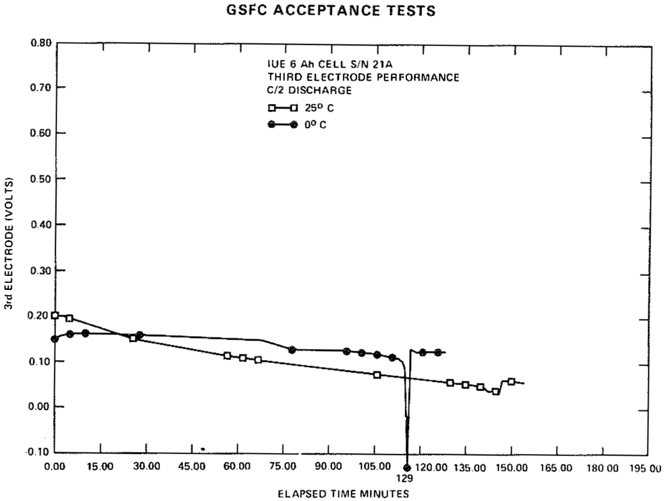


Figure 95

CELL DESIGN

G. Halpert
Goddard Space Flight Center

At this point I would like to report on the Standard 20-ampere hour nickel cadmium cell program. Unfortunately, we are not at the point where we have any test results to talk about, but we can give you some features that will be included in the Standard cell design. I might start off by saying that standardization is an important factor at Goddard and within NASA. As a matter of fact, I have a list of items that are now considered standard equipment in the NASA system.

(Figure 96)

Specific information on these items is available in what is referred to as the CASH handbook, the Catalog of Available and Standard Hardware. It is understood that the project people who cannot use the standard hardware will have to ask for waivers citing reasons why the existing standard equipment cannot be used. As you will notice there are five items in the list that are related to space power. There is the 20-ampere hour cell and battery, a Standard solar cell specification and the PRU; and down here toward the bottom of the list is the specification for the electrical power bus system for large unmanned earth orbital spacecraft.

(Figure 97)

Last year I gave a review on the basics of the Standard cell program. I can recall that the key requirements where the dimensional envelope, the case material which was fixed at 304L Stainless Steel, two ceramic/metal terminals, and the non-woven nylon separator. The most important of the new requirements is the buyoff review at the plate and material level before assembly of cells. We are now at that point in the schedule. The final item is the requirement for a 20-ampere hour cell weight of less than one kilogram, which we are sure is going to be met.

(Figure 98)

With regard to the four companies involved in producing standard cells. We now have generated four MCD's and have designated numbers describing the four cells and Standard cells with signal electrodes, which will be produced under this program. Each of these MCD's include a sixfold set of documents in one volume. A second volume, which is proprietary, will be kept at the manufacturer's facility. We have agreed with each contractor to produce the standard cells to these preliminary MCD's.

The preliminary non-proprietary volume of the MCD's have been delivered to Goddard. We will have to make some minor changes, add some tolerances, and modify some values by the time the cells are delivered. Included in the six parts of the non-proprietary MCD are flow charts, traveller plans that follow the cells and materials as they go through the process, a set of operations, a set of quality control documents that follow the operations, data sheets, and obviously, the drawings that go with the quality control documents.

(Figure 99)

We are almost at the point of cell assembly. The cell assembly step will be followed by electrolyte fill and test, and finally delivery of the 54 cells from each of our manufacturers. The most difficult part of this operation is to prepare a matrix of operations to determine where the vendor(s) have included steps requiring waivers from the 75-15000 specification.

It has been most difficult to compare each MCD with the 74-15000 specification; however, it is most important to ensure that the manufacturers are at least complying with the intent of the specification. We are now preparing this matrix so that we will maintain these four cells at a competitive level. After delivery of the cells a final revision to the MCD will be made. Then a new specification will be prepared resembling a procurement specification for a user to purchase the standard 20-ampere hour cells.

(Figure 100)

Finally, the 30 cells will be qualified at Crane in a test program that looks like this. The battery module consisting of 21 standard cells and one with signal electrodes will be prepared by the successful standard battery contractor. Four battery modules will be assembled and qualified. As I have said, the additional 30 cells will be subjected to a qualification test at Crane Test Laboratories. Crane will conduct some general performance tests, vibration tests, chemical analysis, and then will perform a life test which is analogous to real time testing. We will test some cells in the accelerated test program utilizing only those tests that appear to be predictive.

(Figure 101)

Here are some specific features of the four cells. The dimensions are listed for the four manufacturers. All are slightly different, as are the MCD's, but all fit within the envelope dimension requirements. The case thickness does vary from one to another by that given. The liner is a little different for each one as you see. And the seals and the electrolyte are pretty much the same.

(Figure 102)

With regard to additional design data, this is the way the cells will look. As you see, they are all a little different, including the number of plates, the thickness, and how they are made.

Obviously there are different processes in plaque making between the dry powder and the slurry method; the substrates are different as you see; there are three different methods of impregnation. Loading is also different, the loadings shown are specific to the standard 20-ampere hour cell for each manufacturer and does not reflect any cell that has been made to date or will be made in the future. It is only the standard cell, listed in each MCD document, as the level required. There is a tolerance for each of those numbers which is listed in the MCD document. In essence, that is the situation with regard to the standard cell program. We do expect to have cells by the first of January, and we can then start testing.

MUELLER: McDonnell Douglas

I notice that of the 54 cells you had 24 cells, devoted to the manufacture of the battery, which leaves as I understand it, two spares.

HALPERT: There are 22 cells in each battery, which will include a signal electrode cell. There will be two spares for the manufacturer.

MUELLER: Then how many of those 24 are third electrode type?

HALPERT: Two.

GANDEL: Lockheed

There is enough difference in each one of these four batteries, so in effect, you really end up with four standards. And then extrapolating, someday we will have enough test results to know which one is best.

HALPERT: In effect there is one standard. If a project manager is given a task of building a 20-ampere hour battery, he will have four manufacturers to choose from on a competitive basis. The standard 20-ampere hour cells will have a nominal capacity of 24 plus or minus 2 ampere hours. Each will have a certain weight, and each will have a certain dimensional requirement, which will have to fit within the required envelope. So in essence, it is the same cell, made differently, but it is the same package.

LACKNER: Defense Research

On the four manufacturers, they have different impregnation techniques, and have different loading processes. Are you saying that there is a correlation between the impregnation technique and the loading factor?

HALPERT: What I am saying, that for each manufacturer selected, the manufacturer's design will have to meet the requirements of the 24 plus or minus 2 ampere hours per cell, based on his own impregnation technique. He has chosen a specific loading factor based on his process to meet that requirement. We have not instructed the manufacturer what to do as far as loading is concerned. We do not feel qualified to be able to tell him how to make his cell. We have given him the requirements, he has the contract to build us cells with a capacity of 24 plus or minus 2-ampere hours. He knows the life and reliability we are interested in.

LACKNER: Well essentially you are looking for a performance specification?

HALPERT: With regard to the four standard cells, we ultimately will look for a performance specification and price, because the project manager is going to be interested in price.

STEINHAUER: Hughes

You said 24 plus or minus 2 ampere hours. Does that mean you are willing to accept a deviation in a single manufacturing lot that large?

HALPERT: As I recall, our statement of work requires the lot to be plus or minus 5 percent, and we would like to have that in every lot that is being built from now on. But I am not sure we can get that. But certainly we do not want one cell 22 and one cell 24.

HELLFRITZSCH: Will any of the manufacturers be allowed to change any of the details in their method of making this, based on first cut? Then again the second cut?

HALPERT: Up to the time the first cells are produced they will make revisions reflecting what they have actually done, because what they have documented is not always what they are doing in practice. So there will be revisions to the MCD when the final cells are delivered. At that point the MCD will be fixed, so to speak. And unless there is a need to make a change for materials that are no longer available there will be no revision or deviation from that MCD. These standards will remain fixed for at least the next five years.

NASA STANDARD COMPONENTS*

20 AH NiCd CELL

20 AH NiCd BATTERY

SOLAR CELL SPECIFICATION

POWER REGULATOR UNIT (PRU)

FIXED HEAD STARTRACKER

DRY GYRO REFERENCE INERTIAL HEAD

REACTION WHEEL

PROPELLANT CONTROL ASSEMBLY

INITIATOR

PYROGEN IGNITER

ELECTRICAL POWER BUS SYSTEM FOR LARGE UNMANNED EARTH ORBITAL SPACECRAFT SPEC

TRANSPONDERS STADAN AND TDRSS COMPATABLE

REACTION WHEEL

STAR TRACKER

COMPUTER LARGE AND SMALL

10^8 TAPE RECORDER

10^9 TAPE RECORDER

TELEMETRY AND COMMAND COMPONENTS

HYDRAZINE APS

SOLID STATE MEMORY

ROCKET EXHAUST EFFLUENT DIFFUSION SYSTEM

*INFORMATION IN CATALOG OF AVAILABLE AND STANDARD HARDWARE (CASH) CONTRACT NASA HQ CODE KC.

Figure 96

STANDARD CELL REQUIREMENTS

- CAPACITY AT 24 3°C AFTER 24 HOUR CHARGE AT C 10 RATE
  24 2 AMPERE HOURS MAXIMUM PRESSURE 75 psi
- DIMENSIONS

	MINIMUM		MAXIMUM	
	CM	IN	CM	IN
H (TOP OF CASE)	16.09	(6.34)	16.79	(6.61)
W	7.493	(2.950)	7.658	(3.015)
T	2.159	(0.850)	2.332	(0.918)
H (TOP OF TERM)	17.424	(6.860)	18.059	(7.110)

- CASE
  304 L STAINLESS STEEL
- TERMINALS
  CERAMIC METAL
- LUGS
  4 HOLES POWER 2 HOLES SIGNAL
- SEPARATOR
  PELLON 2505 ML
- BUYOFF REVIEW
  PLATE TESTS COVER
  SEPARATOR TESTS CASE
  PLATE WEIGHT SCREENING
- WEIGHT
  LESS THAN 1 Kg

Figure 97

STANDARD 20 AH NICKEL-CADMIUM CELL

	MCD	STD CELL	STD CELL IN SIGNAL
EAGLE-PICHER	RSN 20 3	RSN 20-3	RSN 20 3S
GENERAL ELECTRIC	232A2222AA-84	42B024AB06	42B024AB07
SAFT AMERICA	MCD NAS 0300	805129	805136
YARDNEY ELECTRIC	MCD 21406	YNC 20.1	YNC 20.2

Figure 98

STANDARD 20 AH CELL TO BE COMPLETED

- BUYOFF REVIEW
- CELL ASSEMBLY
- CELL TEST
- DELIVER 54 CELLS JANUARY 1, 1977
- MCD MATRIX TO ASSUME REQUIREMENT CONSISTENCY
- FINAL MCD REVISION
- PREPARE SPECIFICATION

Figure 99

STANDARD CELL QUALIFICATION

	DESIGNATED USE EACH VENDOR				
	STD CELLS	CELLS WITH X DUCER	CELLS WITH SIGNAL	CELLS WITH SIGNAL AND X DUCER	TOTAL
BATTERY MODULE(1)	22		2		24
ACCELERATED TEST(2)	4	4			8
GENERAL PERFORMANCE(2)	2	2		2	6
VIBRATION CHEMICAL ANALYSIS(2)	2		1		3
LIFE TEST(2)	8			2	10
EXTRA(2)	2		1	2	3
	40	6	4	4	54

(1) CELLS WILL BE SELECTED FROM MANUFACTURERS DATA FOR BATTERY QUALIFICATION.

(2) CELLS WILL BE SUBJECTED TO INITIAL PERFORMANCE TESTS AT THE NAVAL WEAPONS SUPPORT FACILITY, CRANE, INDIANA.

Figure 100

STANDARD 20 AH NICKEL CADMIUM CELL

DESIGN DATA - 2

	E-P	GE	SA	YEC
NO. OF + PLATES	11	11	9	8
NO. OF - PLATES	12	12	10	9
THICKNESS OF + PLATES CM(IN.)	.066(.026)	.069(.027)	.088(.0346)	.094(.037)
THICKNESS OF - PLATES CM(IN.)	.076(.030)	.080(.0315)	.090(.0354)	.104(.041)
PLAQUE PROCESS	DRY POWDER	SLURRY	SLURRY	SLURRY
SUBSTRATE MAT'L	Ni SCREEN	Ni PLATED STEEL SHEET PERFORATED	Ni PLATED STEEL SHEET PERFORATED	PERFORATED Ni SHEET
IMPREGNATION PROCESS	FLEISHER	CHEMICAL	CHEMICAL	E-I
LOADING + GM/DM^2	8.91	11.94	14.55	12.72
LOADING - GM/DM^2	13.13	14.92	17.70	15.82
INTERELECTRODE MM SPACING (MILS)	.191-.254 (7.5-10.0)	.175-.213 (6.9-8.4)	.178-.272 (7.0-10.7)	.287-.340 (11.3-13.4)

Figure 102

STANDARD 20 AH NICKEL CADMIUM CELL

DESIGN DATA - 1

		E-P	GE	SA	YEC
CELL DESIG.		RSN 20-3(S)	42B024AB06/7	805129/36	YBC20.1/.2
DIMENSIONS CM(IN.)	HT	16.51(6.50)	16.13(6.35)	15.44(6.07)	16.75(6.60)
	W	7.54(2.97)	7.61(3.00)	7.58(2.98)	7.61(3.00)
	TH	2.235(0.880)	2.286(0.900)	2.248(0.918)	2.286(0.900)
	HT (TERM)	17.78(7.00)	17.55(6.95)	17.59(6.93)	17.93(7.06)
CASE THICKNESS		.056(.022) DRAWN	.048(.019) WELDED	.048(.019) WELDED	.041(.016) WELDED
LINER		POLYPROP 5 MIL	POLYPROP 5 MIL	NYLON 5 MIL	TEFLON 5 MIL
SEAL		GE TUBE	GE TUBE	SA	ILC
ELECTROLYTE		31%	31%	31%	34%

Figure 101

BATTERY CELL DESIGN PRIORITIES FOR GEOSYNCHRONOUS ORBIT COMMUNICATIONS SATELLITE

R. Steinhauer
Hughes Aircraft Company

Having been in the battery field for the last four years and being in at the system level on satellites with the program office, one sees different priorities; namely, the first priority for the battery generally comes on communications satellites from the customer. And that comes in terms of a communications subsystem payload, which is generally 80 percent of the power requirement of the satellite. That requirement is then interpreted by a systems engineering organization to the power department, who then interprets it to a cell manufacturer, and hopefully all this plays together. What I wanted to do is to give you an overview of what a communications satellite system is, and how we get to a battery.

(Figure 103)

A commercial satellite system is generally a multi-hundred million dollar investment that includes the satellite the tracking, telemetry and command ground stations, and then the communications ground station which generally dictate planning employed for these types of systems because they are very large investments. Your satellites aboard the satellite are--the batteries are 1 percent, usually, of the satellite cost.

(Figure 104)

With regard to the mass of the batteries, they are generally about--a little less than 10 percent, 7 1/2 percent of the on-station mass, after your apogee motor suspendables are out. And they are about 3 1/2 percent of the launch mass. Generally, on a communications satellite we are required to supply during eclipse periods, heating to 100 percent of the full spacecraft load. And that is over the mission of the satellite. In other words, you don't have the capability to reduce loads as one might on a scientific satellite, to select which experiment you might want on or not.

(Figure 105)

The effect of the space shuttle on satellite batteries, is something to be considered at this time. The price of the launches, as I understand, will either be proportional to the length of the satellite, plus its support hardware of the 60-foot bay of the shuttle, or the mass of the satellite. And in comparison to other satellites carried on the same launch.

Geosynchronous orbit satellites, at least early in the shuttle, I don't believe will easily be serviceable by means of the shuttle. In other words, we are not going to be able to go up and replace batteries. However, the mass and the volume of the batteries will not be limited as for Atlas Centaur/Delta launches.

(Figure 106)

Requirements for communications satellites, because of the long-term planning in the lifetime that we need, we really need a 10 to 15-year battery for geosynchronous orbit. This will require something like 50 to 80 percent depth in 1000 to almost 2000 charge/discharge cycles.

Now I am not stressing the high depth, but I am stressing the charge/discharge cycles. That high depth number of 80 percent is on there strictly to accommodate other uses of that battery that people have planned aboard the spacecraft. We are getting into the augmented electrically heated clusters which everyone sees a battery sitting on board a satellite as free power during solar illuminated periods. This could add something like 30 to 60 cycles per year on the batteries, and up to these higher depths. The point I am really trying to make is that the life limiting features of these satellites have previously been batteries, travelling wave to, or hydrazine attitude control system.

With the shuttle, a lot of these limitations are alleviated and even on conventional launches. The life limiting feature on communications satellites is clearly the battery. My point is, we should look at what we are doing to cell designs with regard to long life. It is attractive to go after high energy density. But, we need a long-life battery, even if it is a penalty.

DUNLOP: On the cost of the battery or the cost of the cells, what portion of that cost is spent to buy the cells, and what portion of that cost is to put them into the satellite?

STEINHAUER: A spacecraft battery complement of something like a 25-cell battery, the cell cost may be in the range of $400 a cell. And maybe there is 50 cells on that battery. The installed battery cost after all the testing programs and so on, if you are installing batteries for a spacecraft, is something like $150,000 to $200,000. So you can see that cell cost is very small.

I think added money into the cell cost--that is really--you have got to improve that component, and perhaps that is money well spent.

DUNLOP: Thank you, Bob.

Bob and I have been associated with each other for seven years. So the arguments that he presents here, I feel akin to, and obviously support his points. I think that in our management the key thing for battery is reliability. And I think Bob did a nice job bringing that point out.

COHN: retired

I would like to make a few comments on your presentation, which I liked. First of all, I think it puts the importance of the standard battery in its proper perspective.

Second of all, I think you didn't really say enough about the importance of the electronic equipment which may be your real limit on the life of your satellite.

And thirdly, I would like to suggest you take another look again at some other regimes of running batteries, such as the Chrysler people developed at Michoud about five or six years ago, which will help you to get longer life for your battery. And that has been pretty well documented.

GROSS: Boeing

You indicated that the mass and volume of batteries is not limited for the shuttle boost application. I think many of us here have had the experience during the early planning of a spacecraft application, where it appeared that we had all kinds of weight and volume available for batteries, in the final analysis that usually turned out to be wrong. And you most always end up weight critical.

So I still believe in the old Army phrase, "I'll believe it when I see it," unless there is some good hard supporting data.

STEINHAUER: May I comment on that a little further.

I think that we are going to be in a weight squeeze. But it is a question on how its going to be compared with other payloads on the shuttle. And if you are willing to pay an extra portion, you can carry a heavier battery, if it will get you more life.

GROSS: How can you get more weight by paying more?

STEINHAUER: Take up a greater proportion of the bay, or correspondingly, more mass.

GROSS: Squeeze somebody else out?

STEINHAUER: Sure.

Commenting on the previous question, we have looked quite a bit at the electronic components and hardware life limitation, and in the past there has been some concern, for instance, on communication receiver, where I think most people are generally going towards a solid state type of common receiver. The life limiting features have been the traveling wave, too. But the hours have been improved from the standpoint of lowering current densities on cathodes.

But we do--it has been easy in the past for people to point to the other guy has always been a life-limiting feature. I am trying to make another point.

BATTERY PRIORITIES

COMMUNICATIONS SATELLITE SYSTEM COSTS

- Commercial satellite systems represent multi-hundred million dollar capital expenditures that include:
  - satellite
  - telemetry, tracking and command ground stations
  - communications ground stations
- Decade planning usually is employed for satellite communication systems
- Batteries represent up to 1% of the satellite cost

Figure 103

BATTERY PRIORITIES

GEOSYNCHRONOUS ORBIT COMMUNICATIONS SATELLITE BATTERIES

- Currently represent about 7.5% of on-station mass (3.5% of launch mass)
- Shall provide full satellite power during eclipse operation (no load reduction)

Figure 104

BATTERY PRIORITIES

SPACE SHUTTLE EFFECT ON GEOSYNCHRONOUS ORBIT COMMUNICATIONS SATELLITES

- Shuttle launch costs are proportional to:
  - Length of the 60-foot long bay used by the satellite, or
  - Mass of the satellite

  compared to other payloads carried on the same launch
- Geosynchronous orbit satellites will not easily be serviceable by means of the shuttle
- Battery mass and volume not limited as for Atlas-Centaur/Delta launches

Figure 105

BATTERY PRIORITIES

ENERGY STORAGE PRIORITIES FOR COMMUNICATIONS SATELLITES

1) 10 to 15 Years Geosynchronous Orbit Lifetime
   - 50 to 80% Depth-of-Discharge
   - 1,000 to 1,950 Charge-Discharge Cycles
2) Improved Energy Density, But Not At Expense Of Life

Figure 106

NICKEL-CADMIUM, STATE-OF-THE-ART ASSESSMENT OF COMMUNICATIONS SATELLITES

S. Krause
Hughes Aircraft Company

Bob's talk was kind of alluding to what I am going to say this afternoon. I was going to talk about an overview of future requirements for ni-cad barriers for geosynchronous communications satellites. But I think Bob has done a pretty good job on that. I think that we are pretty convinced, notwithstanding the direction that NASA may be heading in some areas, for very high energy density, high-powered energy density systems.

We think that with the shuttle era, that mass is not as critical in batteries, and that most communications customers would rather have a very long-life system, 10 to 15 years.

(Figure 107)

So I was going to use some data from one of our typical synchronous satellite battery life tests that we are running, that I think is truly representative of the state-of-the-art of nickel cadmium designs over the last two or three years of user data, to try to give you a view where we think we are in terms of lifetime for that type of application. And then some of the wearout mode problems, and just briefly summarize what we think we have to do to get a very long life Ni-cad system.

We are very heavily involved in nickel hydrogen at Hughes, but we are also fairly conservative. And hopefully nickel hydrogen will prove to be all that it is presently touted to be today. But, we would like to have a backup going, and we think nickel cadmium will still serve some useful functions for quite some time.

(Figure 108)

Jim felt somewhat disabused that NASA didn't include the nickel hydrogen up there on their advanced planning for the next few years. The data that I am going to use to--as I say, it is representative of the state-of-the-art--is two years--we are at the point now where we are two years into a real-time life test. The test is actually almost three years old now, with the analysis only up to the two-year point.

The storage mode is trickle-charging about C/36. It is a--we are running a real-time synchronous orbit of loads and temperature and charge rates similar to what we are running in orbit. It is a 10-ampere hour GE cell. And again, I think that the performance of cells other than GE cells probably generically fall in the same category. I think there are certain aspects of the data that I will present that are applicable to all cells, although there are, of course, some things that are specific to the GE cell performance.

(Figure 109)

And as I say, this is sort of representative of the state-of-the-art as well as--and has similarities to the cells manufactured by other people. Here, for example, is a comparison of electrode thickness versus time. Here we have measured electrodes in the dry condition before they go into cells. Here are measurements after the cell is wetted, after acceptance tests and measurements at the one and two-year points.

As you can see, and again as everyone expects, the electrode thicknesses increased very sharply as soon as they become wetted. Even over the first year or so, there is an increase in the electrode thickness. However, it appears to be leveling off, and there doesn't appear to be any change. This may be due to several things. One is that these cells are fairly wet compared to a typical cell. And also, they are in a trickle charge storage mode.

And a lot of people that we deal with are looking at cells that are in an open circuit storage mode, and I think they may see some difference here. But again I think this is fairly representative and if one wants to make a straight-line projection there, it doesn't look like the electrode thickness is going to increase very much more as a function of time. I didn't have the temerity to draw in little dotted lines, so I will let you all try to project them in your own way. But I don't think this is particularly a life-limiting problem at this time.

(Figure 110)

We don't really have to look at this whole thing. I am going to throw this up here pretty quickly, and then take it off.

This morning there was some talk about utilization of the electrodes. These two columns here represent the utilization of the cadmium electrodes and nickel electrodes in the two-year cells. As you can see, our experience has been that the electrode utilization is fairly high and fairly stable. Generally it starts out, actually, at about 75 percent for cadmium electrodes, and it has been going up slowly with time.

We think that due to the presence of silver in the GE electrodes, which GE has a patent for. There has been a lot of controversy over it. We have had a lot of our customers asking about the silver. But really it appears to be very effective in this particular test in this application, especially with the trickle-charge storage mode.

(Figure 111)

Let me just direct your attention to several things of interest. This is a comparison here of the beginning of life cell analysis compared to one-year and two-year points. And you can see, starting at the top, the inactive overcharge protection.

The residual cadmium hydroxide that is normally unavailable is going to zero. That is, we are getting more and more of the electrochemically available overcharge protection operating in the cell. As you can see here, it is going up with time. And again, we think that is due to the presence of silver. The electrochemical available positive capacity doesn't change much with time, as you can see here. The electrochemical available precharge also appears to remain relatively stable over the first two years, although the unavailable precharge is going up, which is reflecting some nylon degradation. The rest of the numbers aren't too significant.

(Figure 112)

This is a cell capacity versus time to one volt. It is fairly stable, although we do see some fading, if you look at the 115 capacity.

(Figure 113)

We also looked at the electrolyte in different parts of the cell to see where it is going and what it is doing. The electrolyte in the separators are the function of time. It is self explanatory.

There we can see after two years, there is about 16 percent of the total electrolyte volume in the cell, found in the separators. Where that thing is going to bottom out, I don't know. That is the one aspect or one parameter in the cell that sort of disturbs us, really, more than anything else.

We do know from tests that we have run, that the separator content in the electrolyte can go to a fairly low level, lower than where it is, and get fairly good operation. But then it is sort of a threshold effect. If you lose another 1 or 2 percent the cell just goes to pot very, very rapidly. Right now the cell is looking pretty good at that separator electrolyte content.

(Figure 114)

Where is the electrolyte going? Everybody knows it is going into the plates. That is what it looks like for these particular cells. Again I am at the point that this is sort of representative of a fairly normal 10-ampere hour cell built about three years ago.

(Figure 115)

It is possible that electrochemical plates and chemical impregnated plates, which these aren't, might improve that somewhat.

Cadmium migration into the separator--at least the cadmium that you find in the separator--there is more cadmium migrating than just what you find in the separator. This seems to be fairly linear. And if you again project a line out there to perhaps six or seven years, you might be up somewheres to about a gram in this 10-ampere hour cell, which has about 63 grams of cadmium in the negative. So one gram of cadmium doesn't appear to be of any significant concern.

(Figure 116)

We have been running tests for teflonated negatives and it would probably improve that somewhat. So we don't think cadmium migration is going to prove a particularly significant problem in a geosynchronous application any longer.

This is the total cadmium in the nickel electrodes. As you know, we do find cadmium that isn't precipitated in the separators, in the nickel electrode, and you can see the rate of migration here is starting to turn over and stabilize. Again, if one looks out some seven years, you may be up to 5 or 6 grams. Again that doesn't represent a significant problem. We have had cells of similar size operating with 10 grams of cadmium in the positives, and it doesn't really make any difference.

(Figure 117)

That is a cross plot where you have a rate of migration to the nickel electrode. It is slowing down after the first few years.

(Figure 118)

This is a plot of migrated cadmium that is found above the surface of a negative electrode. Not in the separator, but attached to the negative electrode surface.

As you can see there, after about two years, we see about a one mil layer of cadmium on the surface of these electrodes. Again, it is not a particularly significant or astrounding number, and we are not too concerned with that.

(Figure 119)

I will show you some pictures of what that looks like. I got this photograph sort of mixed up a little bit.

The beginning of life crystal structure is shown over here; after one year over here; and after two years over here. Now what this is mainly illustrative of is that you have many, many small, fine-grained crystals when the cell is brand new. Crystal size gets a little larger, the number of crystals gets a little smaller, and so here at the two-year point you have less crystals and they are slightly larger. But again, if you project that continued kind of rate of change in the crystal structure on the surface of the cadmium electrode, it is nothing to be too alarmed about in terms of five, or six or seven years lifetime.

(Figure 120)

These are cross-sections of the negative electrode from this--the shiny marks, which are the plaque, you can see some cadmium crystals on the surface. And as I said here at the two-year point they represent about one-thousandths of an inch migration above the surface.

(Figure 121)

Here are some fractured cross sections where you can also see the crystals laying up on the surface. Here is what they look like at the one-year point; here is the edge of the plaque, and there are some large crystals, slightly larger, at the two-year point than at the one-year point.

(Figure 122)

One of the other problems we experienced with normal nickel cadmium cells at this time, especially using a nylon separator, is loss of overcharge protection.

As you can see in this cell the overcharge is going down. It is a fairly high number right now. As you have seen on that table before, in this 10-ampere hour cell we still have about 8 ampere hours of overcharge protection available. The interesting thing is that we see loss of overcharge protection in polypropylene cells as well. This is not, of course, due only to nylon degradation. But you do get enough discharged cadmium migrating from the negative plate to get some loss in overcharge protection on the negative, even if you have a separator that is not degrading.

(Figure 123)

I am leaving out a lot of details and lots of test data to give you an overview. I think that the predominant wearout mechanisms in today's nickel cadmium cells, primarily electrolyte redistribution of dryout seems to occur whether you have nylon or polypropylene. It may occur at different rates. The nylon holds on to the electrolyte a little better, but eventually if you are trying to talk about a 10 or 15-year battery, you are going to face dryout with a conventional design.

Voltage fading, I didn't really show an example of it here, but I think most people who have cycled Ni-cads know that the voltage does fade, and again whether you have a nylon or a polypropylene cell, it certainly is a problem over the long term. And loss of overcharge protection both by nylon degradation, or as I said in cells that have polypropylene, you can still get sufficient cadmium migration to get some loss in overcharge protection.

(Figure 124)

In summary, it is that the state-of-the-art in Ni-cad, the one I can go and buy today which is represented by the kind of data I have shown you, if you project all those cell parameters, plus we have other test data on longer term tests which are probably not nearly controlled quite as well as this one, they tell us that the existing designs are capable of about six to seven-year operation in geosynchronous orbit at about 55 percent depth of discharge, which is where these cells operate at. That is my assessment of the state-of-the-art in Ni-cads.

As I mentioned, nickel hydrogen is coming along, which will operate potentially at higher energy densities, probably has an inherent capability of longer life. But until that really happens, until it is really well in hand, we are working toward longer life Ni-cads to back up the nickel hydrogen. And we think that the shuttle launch era will allow some deemphasis on the energy density improvements except for special application.

There are still going to be uses for high-energy density nickel cadmium, but we don't think that geosynchronous communications satellites, or even geosynchronous science satellites are the place where the high-energy density Ni-cad is absolutely necessary. So we think that energy density can take a second priority to lifetime improvement.

Now I guess I am really here as a rebuttal witness to some of the things we are probably going to hear later, and some of the things this morning, only in terms of trying to present a slightly different perspective.

But, although energy density improvement is important, we think there is a place for long-life batteries, and we don't want to see little effort in that area, or a great deal of effort in the energy-density area at the expense of long-life batteries.

We think that to get a Ni-cad that will last 10 years or even longer, will take a great deal of creative thought. Really, new materials are going to be required. You can't use nylon for a 10-year battery. I think there is little doubt that its chemical instability doesn't really allow you to operate for 10 years.

What about polypropylene? I guess some of the Canadians have had some success in operating batteries for 10 years. But the rest of the world seems to be having some difficulty with it. And, of course, polypropylene is polypropylene is polypropylene. There are so many different kinds and they behave in so many different ways, some are more predictable than others.

I think we may have to consider entirely new separator systems, and really apply some nickel hydrogen technology, some of the things we have been learning in nickel hydrogen in the last several years, back into Ni-cads to really look at electrolyte transfer and understand what it means; to look at oxygen management and understand what it means; to look at the real honest-to-God separator characteristics that are required for a Ni-cad at the fundamental level and apply these into completely new, next-generation nickel cadmium designs as a backup to nickel hydrogen, as well as in those areas where very long-life Ni-cad might be better applied than nickel hydrogen, perhaps where there are volume restrictions, for example.

So that is the conclusion of my comments. As I say, I offer this as perspective rather than having a significant technical content.

SCHULMAN: TRW

Have you considered deep reconditioning in your observations?

KRAUSE: In terms of improving lifetime?

SCHULMAN: That's right.

KRAUSE: Yes. We are running experiments on some internally-funded programs on reconditioning. The Telesat people have been running some experiments on some of their live tests with deeper reconditioning than have previously been employed on satellite systems. And I think both we and they are finding some improvement in cell capacity, cell voltage characteristic, I should say, with reconditioning.

We have some reservation about extremely deep reconditioning such as going down to 0 volts or even running some batteries in reverse. I know some people have been talking about running whole batteries down at low rates. Our concern there is that we have observed in old cells that have a fairly high cadmium content in the separator, that you can get a short by cadmium reduction in the separator, if you reduce the voltage of the positive electrode sufficiently.

SCHULMAN: Well, I just wanted to state that we have--one of our programs, again an accelerated life program, 30 seasons, and that is the equivalent of 15 years life, using deep reconditioning. And the performance of the cells--the cells look today exactly as they did when they were brand new.

KRAUSE: I don't doubt that. As I said this morning, I have run cells 4000 cycles at 60 percent depth of discharge. We have taken them apart and they do look like brand new. If you are using nylon, though, an accelerated test at a good temperature, isn't really going to tell you how that nylon is going to degrade over 7 to 10 years real time, because the nylon hydrolysis is time and temperature dependent, rather than cycle dependent.

SCHULMAN: Yes. We had somebody here who just stated that at temperatures below 20 degrees C., you can measure nylon in terms of from 50 to 10 years life.

SCHULMAN: Now, that is partly true. They are using the data developed at the Hughes Research Labs last year. But they have since--since determining the reaction energy, the activation energy necessary for the nylon hydrolysis to occur, there have been some updates of the data which indicates there is some electrocatalysis by nickel, for example; that some of those rates that have been looked at a year ago, perhaps were a little optimistic.

COHN: I want to ask you whether you have considered preconditioning in addition to reconditioning. And specifically if you could preswell and allow for the growth of your plate, if you have a plate that grows and you know how much it is going to grow now, if you could allow for that, whether you might avoid your electrolytes being squeezed out of the separator and avoid some of your migration problems and other problems due to starvation by preconditioning.

KRAUSE: It is a good thought. I don't see why it wouldn't work.

SEIGER: I have two questions.

First, you show about one mil of negative active material going on to the surface. One mil per side would give you two mils. I believe that is the kind of thickening that you did show for the negatives?

KRAUSE: Yes.

SEIGER: So that would account for all of it. So the plaque material itself really didn't change its dimensions?

KRAUSE: Not that we are aware of.

SEIGER: That is question one.

Question two: We heard this morning that there is about \$1.5, \$1.6 million budgeted by Headquarters. And you are asking for a rather ambitious program. How is this money going to be funnelled out in order to get the work going?

KRAUSE: You must keep in mind that I don't only aim my comments at NASA. There are others who are in the business of using batteries who may wish to develop them. The people who buy the payloads on the satellite, for example; the Air Force, even aerospace companies who are interested in getting a leg up on the rest of the market.

DUNLOP: This is a different comment.

On the price of electrodes, I would like to add a comment to what we have observed. I agree with you up to about two or three years. What we have observed is that after about two or three years in real-time synchronous orbit, you have only put on 200 or 300 cycles, and at that point in time you don't see very much expansion of your positive electrodes. And as a matter of fact, up to almost five years--beyond five years, the positive electrode does start to expand. We have this data available. It expands significantly from five years on up to ten years. It will almost--it will expand and almost double its thickness over that period of time. And I have--will bring in some--and this we have observed on Telesat cells on a real-time five-year test, as well as our own real-time seven-year test. Now I am going to bring some of that in and show that expansion. What we see is a movement of the acting material which is actually compacting with the active material toward the surface as it expands. And if you do a microporosity of the electrodes, you will find that you do have a significant increase in the micropore structure of the positive electrode in the region around one micron, which does then serve as a means of siphoning your electrolyte away from your separator.

So, I think the way your curves are, are right up to a point on your positive electrode. If you carried that out to this 10-year concept, you are going to see from five years on, a significant expansion.

KRAUSE: Right.

We also have some data, as you know, we have run on Intelset four type cells for the last five, six years, which do show thickening with time, especially as the corrosion of the plaque begins to take place. I wasn't, though, considering, for five to seven-year operation, that we had a significant problem in that area. But for 10 years there is no question, and we are convinced that we are going to have to go to electrochemically impregnated plates for longer life.

NAPOLI: RCA American Communications

You stated that if you go down to deep preconditioning there is a possibility of shorting after a cell has had several years on it?

KRAUSE: We have observed this several times.

NAPOLI: How did you observe it? How does it manifest itself?

KRAUSE: When we would take cells out of a life test to analyze, we would take it down to 0 volts. And from there make some precharge measurements. And at the time that we approach 0, or go past 0, we can observe a significant shift in the cell voltage. And then when we continue to run the cell in reversal, you can get a sudden dropoff from the negative plateau, which indicates that the negative is out of capacity. The cell will run at a negative 200 millivolts forever.

NAPOLI: What are the ages of the cells that you had the problem with?

KRAUSE: I recall several of them in the three to five-year age bracket.

NAPOLI: Were these subject to periodic reconditioning such as they have had in synchronous orbit?

KRAUSE: Yes.

NAPOLI: Twice a year in reconditioning data?

KRAUSE: Right. Of course, reconditioning on the satellite is down to perhaps 1.1 volts at the lowest. This was an artificial experiment to analyze the cell that took us down to a low voltage. Now at that time we observed that we had several shorts occur.

NAPOLI: Why go to 0? Why not just stop at some voltage less than 0--above 0? What is the advantage of doing that?

KRAUSE: Well there is no advantage in reconditioning down to 0 volts that I know of. There is a trend that shows that going down to 1 volt, maybe to half a volt is of value. Going to 0 volts, though, I don't have any data on it. I am not advocating it. I am saying, apart from reconditioning tests that we have run while we are analyzing cells for another purpose, we have observed shorting taking place when the cell is taken down to 0 volts.

NAPOLI: You said through 0. You said at one point you reverse the cell.

KRAUSE: We had one cell where we didn't even go past 0 and it shorted. I wasn't advocating going to 0 volts for reconditioning. I hope you didn't misunderstand me. I just said we have observed cells taken down to that voltage that have shorted.

THIERFELDER: General Electric

What was the temperature, or the temperature range in this two-year test that you ran?

KRAUSE: This particular test?

THIERFELDER: The two-year test.

KRAUSE: During the sunlight periods between the eclipse seasons, it averaged around 17 degrees C.

And during the eclipse periods it would run as high as about 15 C down to a low of about 4 degrees C.

THIERFELDER: This one was between 4 and 17?

KRAUSE: Yes.

When you go into a shadow the battery starts to cool down to around 4 degrees C. And you come back up at the end of charge to about 15 degrees C. And then in the long solstice, sun solstice periods between eclipses it is about 17 C.

STAEHLE: Westinghouse

In the process of this analysis, did you look at the change in internal resistance and possibly separator activity?

KRAUSE: We didn't do that. Some people had been doing it though, and I think that kind of data is available. In general the impedance goes up as a function of time from a normal cell of several milliohms up to--I have seen them as high as 20 ohms.

STAEHLE: In particular, I wondered if you had correlated that work with cadmium migration?

KRAUSE: No.

BOGNER: I would like to make a comment here, that just because the voltage doesn't drop it doesn't necessarily mean the cell is shorted. There may be some other things going on. Also, if you charge it back up it may work.

KRAUSE: If you get enough cadmium in the positive it does act as an antipolar mass, which will give you that effect. But we have tried to charge them up and they are dead.

- OVERVIEW OF FUTURE REQUIREMENTS
- STATE-OF-THE-ART
- PREDOMINANT WEAR-OUT MODES
- SUMMARY

Figure 107. Nickel-Cadmium Cell Design State-of-the-Art Assessment

- NICKEL-CADMIUM CELLS WERE ANALYZED:
  1. BEGINNING OF LIFE (BOL)
  2. AFTER 1 YEAR
  3. AFTER 2 YEARS
- STORAGE MODE - TRICKLE CHARGING C/36
- SIMULATED SYNCHRONOUS ORBIT CHARGE-DISCHARGE SCHEDULE

Figure 108. Life Testing 2 Year Report Real Time Testing of 10 AMP Hr Nickel-Cadmium Battery Cells.

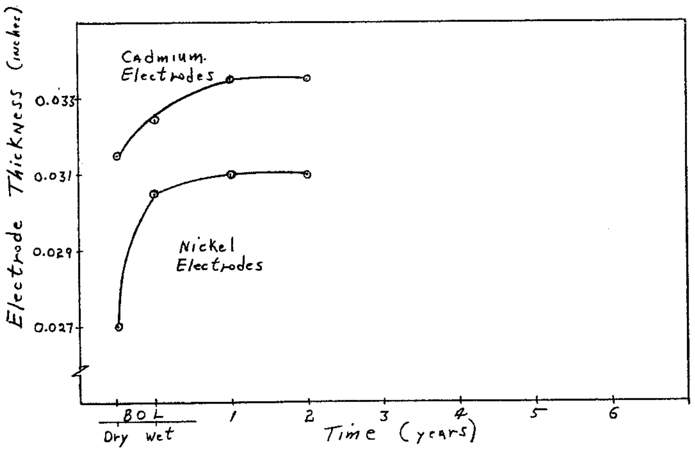
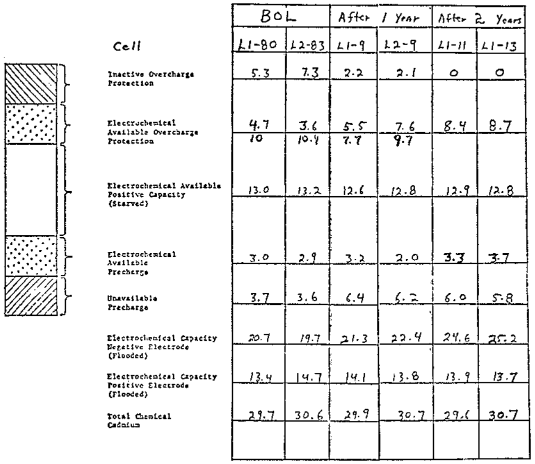


Figure 109. Electrode Thickness Vs. Time

ELECTROCHEMICAL ANALYSIS	CELL NUMBER	
	L1-11	L1-13
	(Ampere Hours)	
Cadmium Electrodes	24.6	25.2
Nickel Electrodes	13.9	13.7
CHEMICAL ANALYSIS		
CADMIUM ELECTRODES		
Unavailable Cadmium as Cd^{o}	6.0	5.8
Cadmium Hydroxide	23.6	24.9
Total Cadmium	29.6	30.7
NICKEL ELECTRODES		
Unavailable Nickel as Ni^{+3}	4.5	4.4
Nickel Hydroxide	14.4	13.6
Total Ionic Nickel	18.9	18.0
PERCENTAGE UTILIZATION		
Cadmium Electrodes	83%	82%
Nickel Electrodes	74%	76%

Figure 110. Electrochemical and Chemical Analysis of Cell Electrodes



Cell	BOL		After 1 Year		After 2 Years	
	L1-80	L2-83	L1-9	L2-9	L1-11	L1-13
Inactive Overcharge Protection	5.3	7.3	2.2	2.1	0	0
Electrochemical Available Overcharge Protection	4.7 10	3.6 10.4	5.5 7.7	7.6 9.7	8.4	8.7
Electrochemical Available Positive Capacity (Starved)	13.0	13.2	12.6	12.8	12.9	12.8
Electrochemical Available Precharge	3.0	2.9	3.2	2.0	3.3	3.7
Unavailable Precharge	3.7	3.6	6.4	6.2	6.0	5.8
Electrochemical Capacity Negative Electrode (Flooded)	20.7	19.7	21.3	22.4	24.6	25.2
Electrochemical Capacity Positive Electrode (Flooded)	13.4	14.7	14.1	13.8	13.9	13.7
Total Chemical Cadmium	29.7	30.6	29.9	30.7	29.6	30.7

Figure 111. Electrode Balance

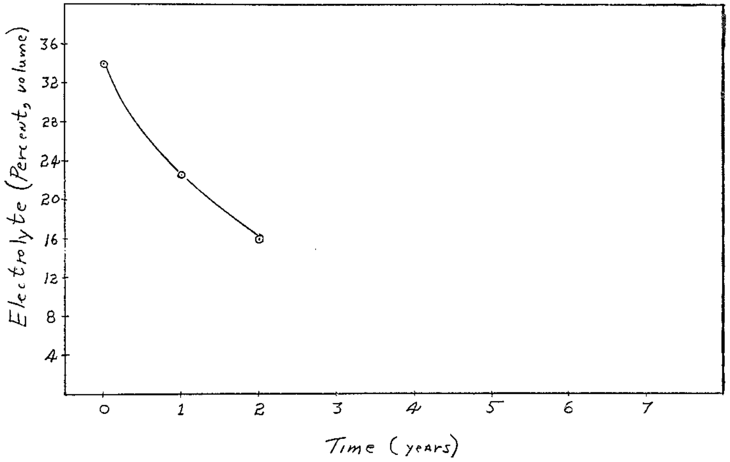


Figure 113. Electrolyte in Separators Vs. Time

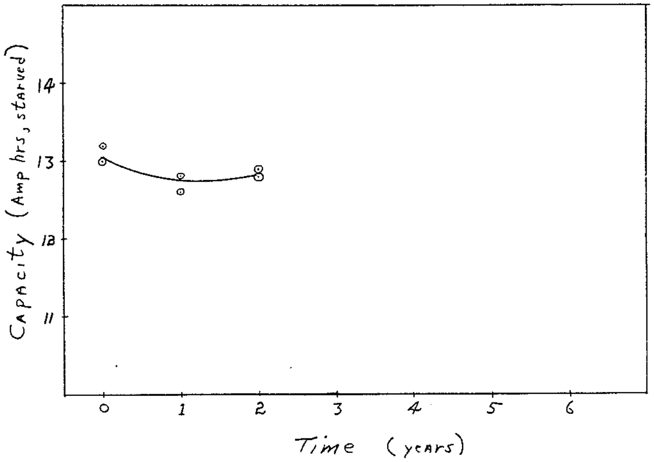


Figure 112. Nickel-Cadmium Battery Cell Capacity Vs. Time

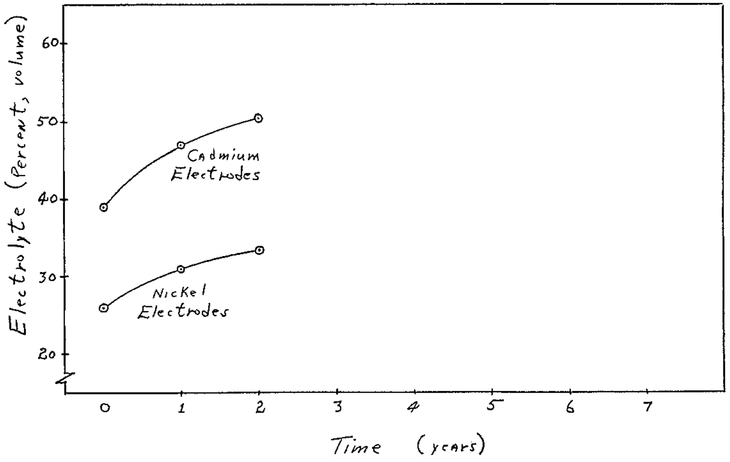


Figure 114. Electrolyte in Electrodes Vs. Time

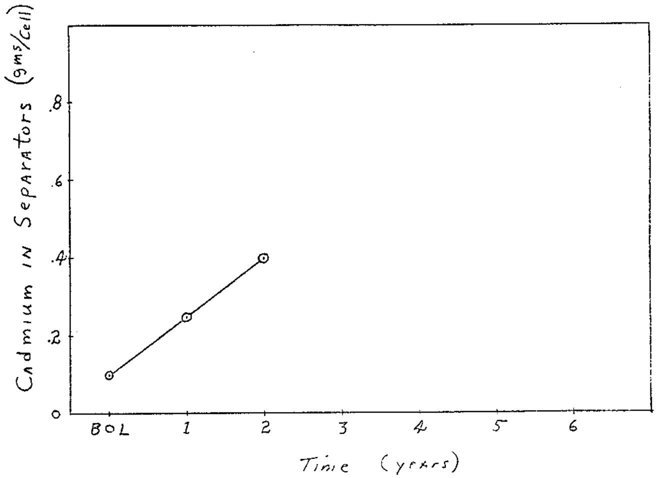


Figure 115. Cadmium in Cell Separators Vs. Time

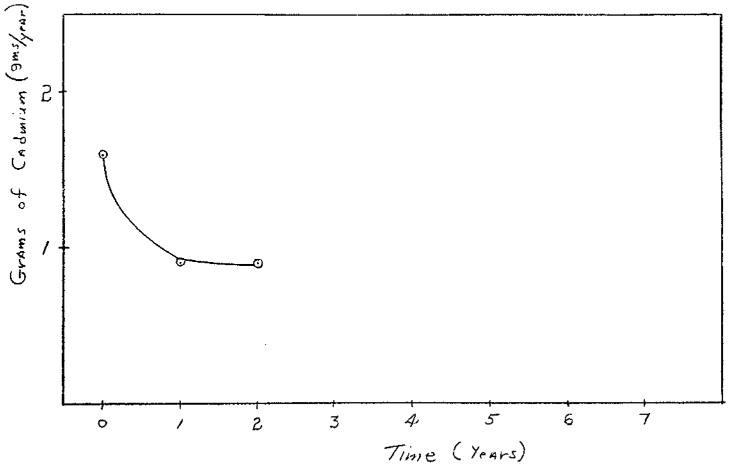


Figure 117. Rate of Migration of Cadmium to the Nickel Electrode

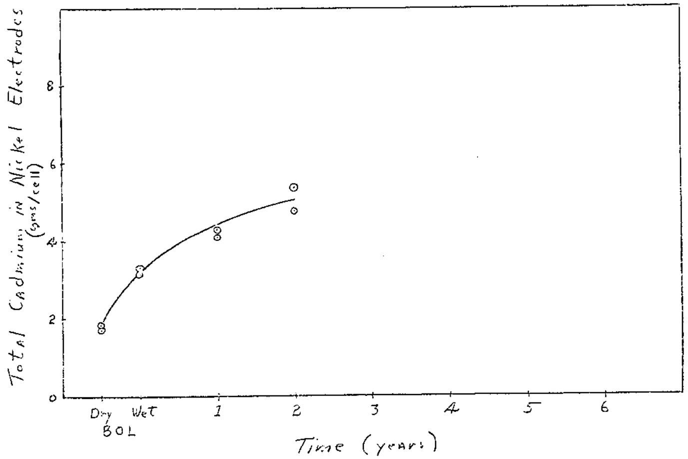


Figure 116. Total Cadmium Migrated to the Nickel Electrode Vs. Time

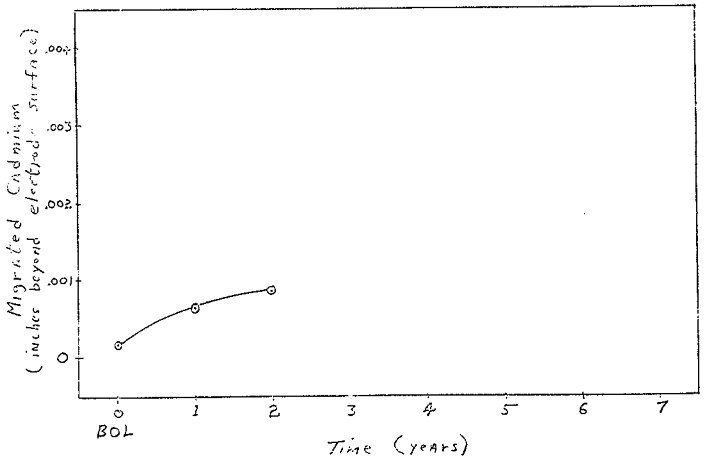


Figure 118. Cadmium Migration Vs. Time

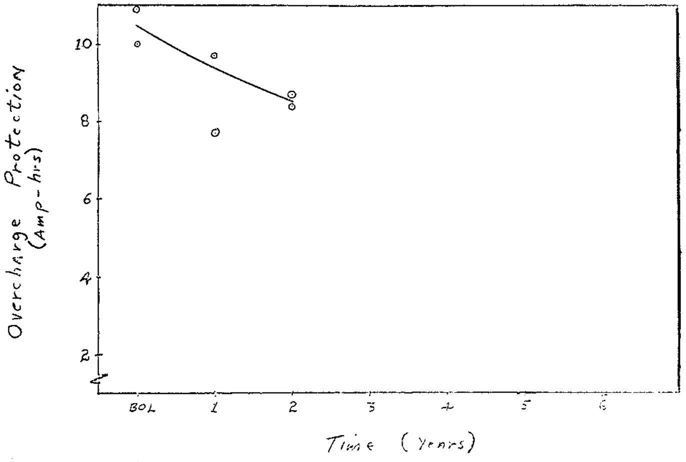
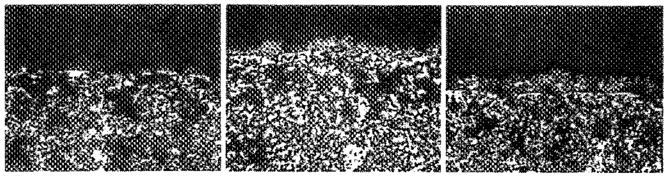


Figure 119. Loss of Overcharge Protection Vs. Time

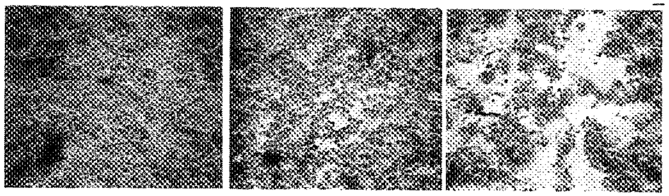


BOL AFTER ACCEPTANCE CROSS SECTION AT 90° CADMIUM ELECTRODE 340 X

AFTER 1 YR CROSS SECTION AT 90° CADMIUM ELECTRODE 340 X

AFTER 2 YR CROSS SECTION AT 90° CADMIUM ELECTRODE 340 X

Figure 120. Metallographic Photographs X-Sections of Cadmium

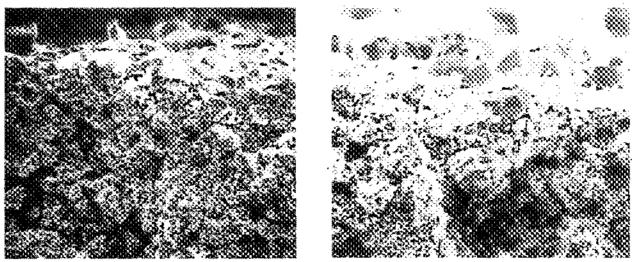


BOL AFTER ACCEPTANCE TESTING CADMIUM ELECTRODE SURFACE 200 X

AFTER 1 YR CADMIUM ELECTRODE SURFACE 200 X

AFTER 2 YR CADMIUM ELECTRODE SURFACE 200 X

Figure 121. SEM Photographs Cadmium Electrode Surfaces



AFTER 1 YR SEM PHOTOGRAPH FRACTURE FACE CADMIUM ELECTRODE 500 X

AFTER 2 YR SEM PHOTOGRAPH FRACTURE FACE CADMIUM ELECTRODE 500 X

Figure 122. SEM Photographs Cadmium Electrodes, Fracture Face Surface

- PREDOMINANT WEAR-OUT MECHANISMS
    - ELECTROLYTE REDISTRIBUTION OF "DRY OUT"
        - NYLON OR POLYPROPYLENE
    - VOLTAGE FADING
        - NYLON OR POLYPROPYLENE
    - LOSS OF OVERCHARGE PROTECTION
        - NYLON DEGRADATION
        - CADMIUM MIGRATION

Figure 123. Nickel-Cadmium Cell Design State-of-the-Art Assessment.

- SUMMARY
    - EXISTING NICKEL-CADMIUM CELL DESIGNS ARE CAPABLE OF 6-7 YEAR OPERATION IN SYNCHRONOUS ORBIT AT UP TO 55% DOD (BASED ON ACTUAL CAPACITY).
    - THE SHUTTLE LAUNCH ERA WILL ALLOW DE-EMPHASIS ON ENERGY DENSITY IMPROVEMENTS EXCEPT FOR SPECIAL APPLICATIONS.
    - THE SHUTTLE LAUNCH ERA WILL ALLOW IMPROVEMENT IN NICKEL-CADMIUM CELL LIFETIME WITH ENERGY DENSITY A SECONDARY CONSIDERATION.
    - ENTIRELY NEW MATERIALS AND TECHNOLOGY MUST BE IMPLEMENTED IN NICKEL-CADMIUM CELL DESIGNS IF LIFETIME IS TO BE EXTENDED TO 10 YEARS AND BEYOND.

Figure 124. Nickel-Cadmium Cell Design State-of-the-Art Assessment.

DESIGN DETAILS, 50-AMPERE HOUR CELL

W. Scott
TRW Systems

I have been asked to present a brief summary of the details of the design of one 50-ampere hour cell that we have had quite a bit of experience with over the past several years in connection with the general interest in defining a 50-ampere hour cell for the NASA standard cell and battery program. This cell was the one that was used in the long-life battery development program for the Air Force, which program began in 1970. And for those of you who might be interested, the final report on that project was distributed in August of this year. The hardware objective was a 1 kw battery system intended primarily for use in synchronous orbit applications with a design goal of 95 percent reliability for seven years in synchronous orbit. The outline drawing of the cell as finally developed is shown here.

(Figure 125)

The general dimensions were those in existence at the time when the design of the cell was finalized. I believe that was about 1971. And they correspond to the standard cell dimensions of a General Electric cell at that time. This cell was, finally developed as a General Electric item. I believe you will find that the overall dimensions shown here were--do conform to the present dimensions of the 50-ampere hour standard cell outline drawing.

(Figure 126)

This slide shows a little greater detail of the cover and terminal configuration. This was a developmental cell and because we intended to do a lot of special testing on the ground, we had a number of special fittings; one being the demountable cap shown here, to which we could thread on a fitting for taking on and putting off pressure transducers. Also we had two additional feed troughs which were used for convenience in monitoring internal auxiliary electrodes during the ground test program.

The terminals as you can see, are a relatively large adaptation of the butt seal geometry that has become standard now at General Electric. Actually the dimensions of these terminals was--this pulse was about three-eighths inches in diameter. The design requirement was that these cells, these terminals could be operated at the 100 amps continuous for a certain period of time.

(Figure 127)

The actual hardware is shown on the left, compared to the 24-ampere hour cell configuration which is still roughly about the same dimensions as they exist today.

(Figure 128)

I have listed here some of the essential design parameters. As you can see, the cell weighs 4 1/2 pounds. When new it delivered an average of 60-ampere hours to one volt at 25 amps room temperature for an energy density of 16 watt hours to one volt. Sixteen positive plates, 17 negative; 1.6 minimum negative-positive ratio flooded electrochemically measured.

Two different separators were used throughout the program. There were about an equal number of cells. Approximately 200 cells were built altogether in this program. Roughly half were made with polypropylene WEX 1242, with pellon nylon 2505. All of the cells had two oxygen electrodes. They had two because we wanted to compare the results of operating an oxygen signal electrode connected to the case with that from an oxygen electrode isolated from the case, that is connected to one of the isolated terminals in the cell. The second phase design also added a reference electrode, which was not in the earlier configurations.

(Figure 129)

We did quite a bit of reliability engineering on the inside of the cells. And as a result, came up with a number of improvements in the details of assembly of the cell pack to facilitate the relatively large and heavy components inside the cell. And this is a photograph of the cell pack and the terminals and combs during assembly. It shows that the tabs were all extra long and were preformed prior to assembly in order to reduce the stress on the corners of the plates.

Also, not visible here is a set of insulating spacers which were added throughout the entire pack, that simulated the separation that the plates would see after the separator was present. And the preforming and welding of the tabs was all done with those separator spacers in place. And then when they were removed and separators added, there was no additional bending or stressing of the tab area in order to get the proper spacing for the final separator material.

(Figure 130)

The design of the oxygen signal electrode was a special problem. What I call the initial signal electrode location was at each end of the cell, with a separator layer around each one, a wick and a shim over on the outside to compress the electrode and the wick up against the edge of the plate. As you can see, they were located here in the side view.

The results of that particular placement were not very good. It appeared that the electrolyte quickly dried out from the wick in that location, and the oxygen signal became very unreliable. Some of the details of those results were presented in the Power Sources Symposium in June. I won't go into that any further here. But as a result of that experience, we went back and redesigned the cell with respect to the positioning of the oxygen signal electrodes.

(Figure 131)

And to conclude we ended up with the oxygen electrodes buried in the pack as we wanted again to compare the results of the two kinds of connections to the case. You might wonder how we managed to get them in there without excessively overcompressing the plates or the separators.

(Figure 132)

It was done roughly as shown here by relieving an area on one of the negative plates, by machining off the center and interposing an extra layer separator here and here, and adjusting the dimensions to come out right.

(Figure 133)

I have a photograph on one of the special negative plates where the two oxygen signal electrodes went. Incidentally, a failure analysis following life testing showed that there was no appreciable--any special effects whatever that occurred because of the fact that this area of the negative plate was machined out. The areas were perfectly clean, undeformed and we could find no undue problems at all resulting from that machining operation.

(Figure 134)

This shows two of the signal electrodes in one cell mounted in a special bag that was fitted around the positive plate that was adjacent to that negative plate you just saw. And you can see there is a special layer of separator here that is sewn with pockets to fit these two. The results from that configuration were so superior in all respects to the results we got with the oxygen signals located on the edge of the plates. You might wonder why we didn't--as long as we wanted to remove the oxygen signal electrode from the edge, why we didn't just simply put it on the outside of the outside negative plate. The answer is that there were other significant problems involved. One of them being that you get excessive drying of the adjacent separator material due to excessive compression in that location. And we considered that drying was our major problem. Also there was considerable experience with shorting between the oxygen signal electrode and the adjacent plate because of excessive compression, if you do not provide the kind of relief for the thickness of that electrode which we did by machining the extra negative plate. Now we could have machined the outside negative plate. However, there are other reasons which I won't go into, which led us to the conclusion that it would be better to put it inside the pack, rather than on the outside.

Now I will conclude this by showing you the battery systems that these cells went into.

(Figure 135)

This is a diagram of the one kW battery system. In this case the system includes all the charge and discharge controls and the thermal control system that were associated with the battery. And you see here the cells are packaged at this end. The electronics charge control are all here at this end. And below, in this particular case, we have a heat pipe thermal control subsystem that was required because of the contractual requirement that this battery be able to operate anywhere within a very large spacecraft without any auxiliary thermal control equipment.

(Figure 136)

This is a photograph of a system during assembly which illustrates the type of constraint that was designed for the cells. These are all aluminum parts in this case. We have a design update now in which all of this structure, or most of it, can be made of magnesium with a significant savings in weight.

It shows one pack of six cells in place. This battery, by the way, has 24 cells rather than 22 because of the requirements for this 95 percent reliability in seven years. This battery also has, for this particular application, individual cell bypass electronics for both charged and overdischarged. And there as you can see on that blue PC board, it is sitting up on top of the cell pack.

(Figure 137)

And this, finally, is a view of the completed battery subsystem on a test stand. Here you see the heat pipes down here. And in this case, each cell was equipped with a pressure transducer by which we came to complete a continuous pressure data throughout the life testing.

As some of you may know, the program consisted of the building of three such batteries and the three were life tested for different periods of time. And the results were reported in the final report that I mentioned.

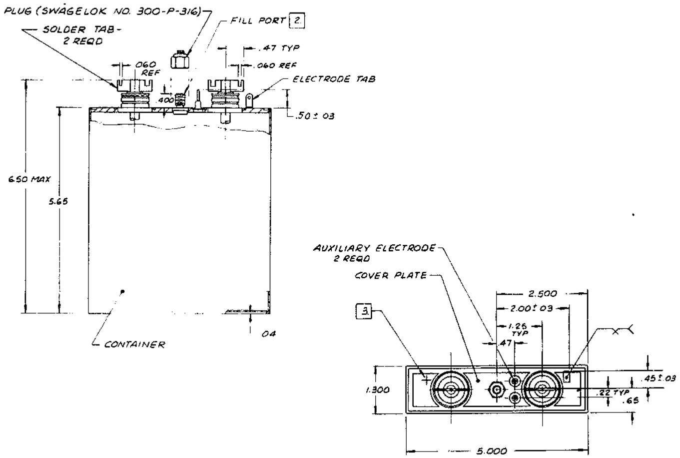


Figure 125

CELL TERMINAL CONFIGURATION

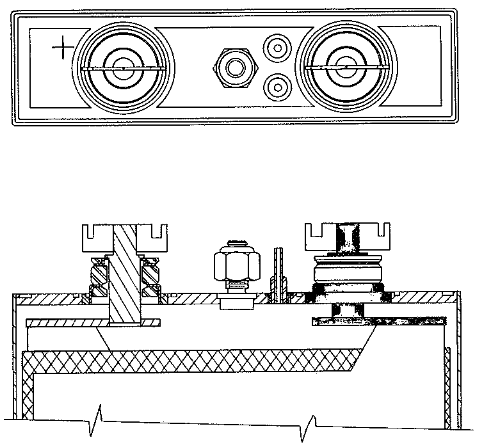


Figure 126

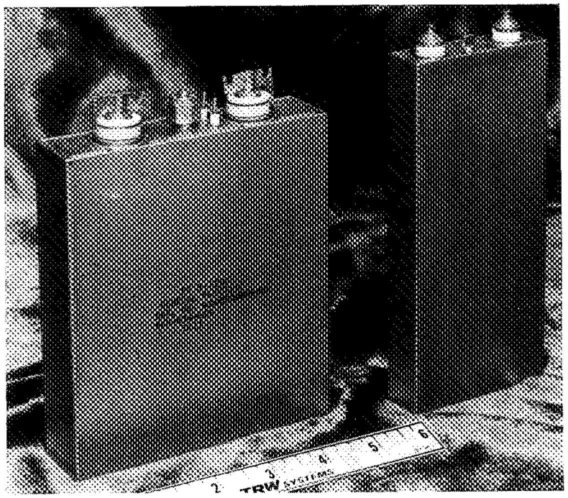


Figure 127

DIMENSIONS:	5 INCH WIDTH X 6 INCH HEIGHT X 1.3 INCH THICKNESS
WEIGHT:	4.50 POUNDS
CAPACITY:	60 AMPERE – HOURS TO 1 V AT 25 A
ENERGY DENSITY:	16.0 Wh/LB (DISCHARGED TO 1 V AT 25 A)
CONTAINER:	TYPE 304 STAINLESS STEEL, 0.032 INCH THICK
POWER TERMINAL SEALS:	HIGH-PURITY CERAMIC; ALL NICKEL BRAZE MATERIAL BUTT-TYPE GEOMETRY
AUXILIARY TERMINALS:	TWO AVAILABLE
ELECTRODES:	16 POSITIVE AND 17 NEGATIVE PLATES; NEGATIVE/ POSITIVE CAPACITY RATIO: 1.60 MINIMUM (FLOODED)
SEPARATORS:	NON-WOVEN POLYPROPYLENE OR NON-WOVEN NYLON
AUXILIARY ELECTRODES:	TWO O_2 ELECTRODES IN ALL DESIGNS ONE REFERENCE ELECTRODE IN FINAL DESIGN

Figure 128

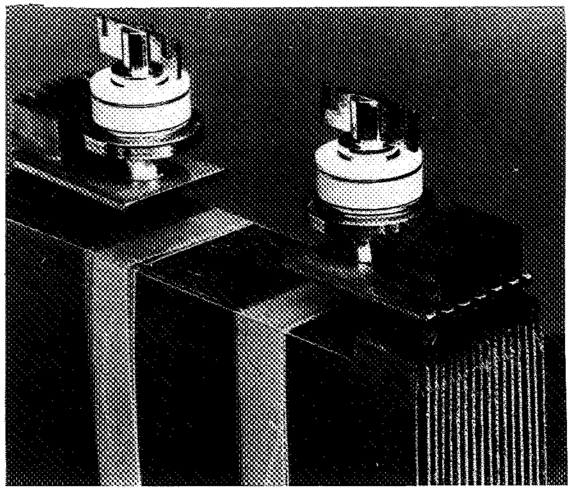


Figure 129

50-Ah NiCd CELL (PT3-1055)
INITIAL SIGNAL ELECTRODE LOCATION

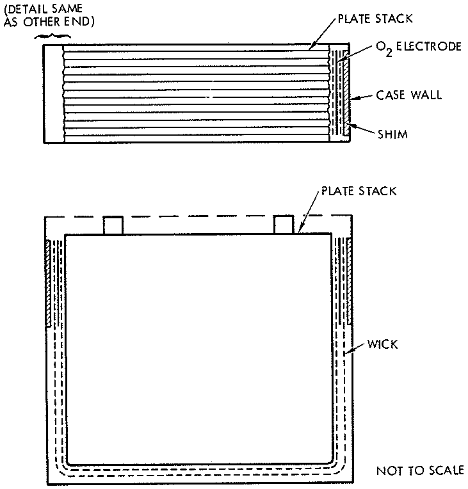


Figure 130

50-Ah NiCd CELL (PT3-1055)
FINAL AUXILIARY ELECTRODE LOCATION

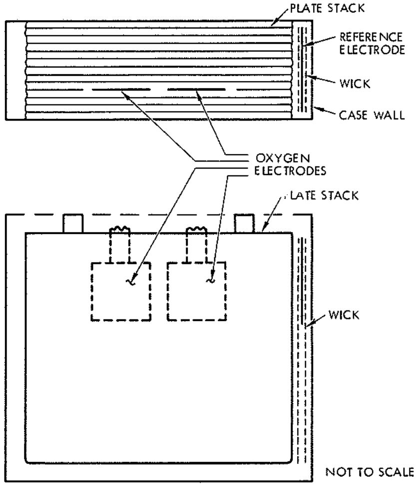


Figure 131

50-Ah NiCd CELL (PT3-1055)
OXYGEN SIGNAL ELECTRODE MOUNTING DETAIL

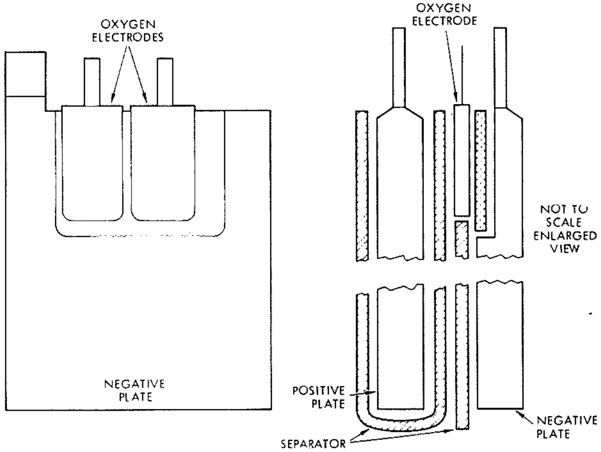


Figure 132

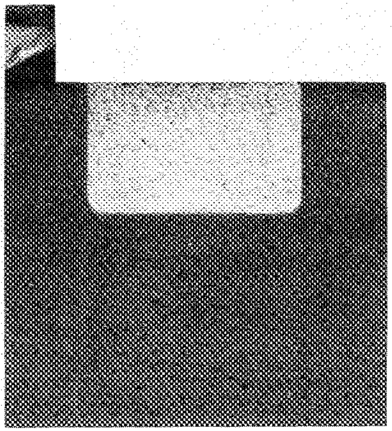


Figure 133. 50-Ah NiCd Cell (PT3-1055) Negative Plate Modified for Signal Electrode.

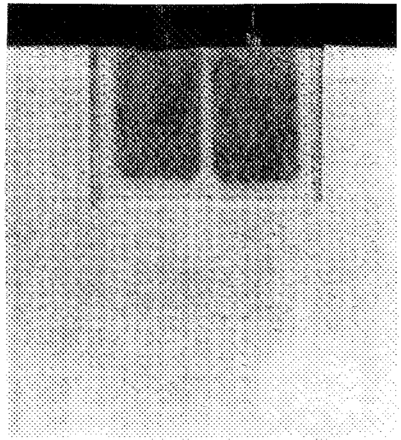


Figure 134. 50-Ah NiCd Cell (PT3-1055) Signal Electrodes Mounted in Special Separator Bag.

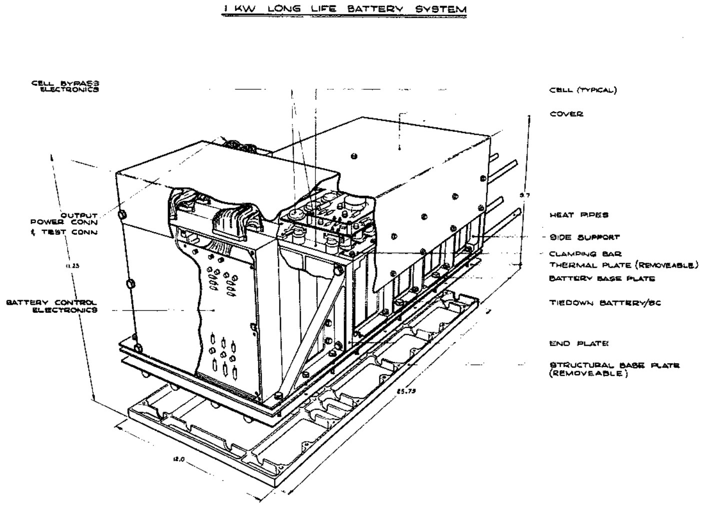


Figure 135. 1 KW Long Life Battery System

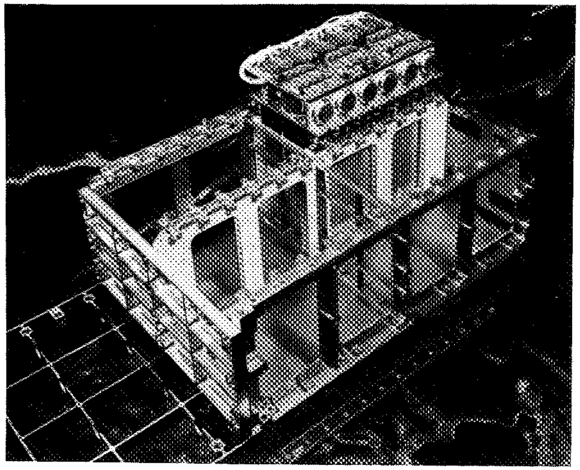


Figure 136

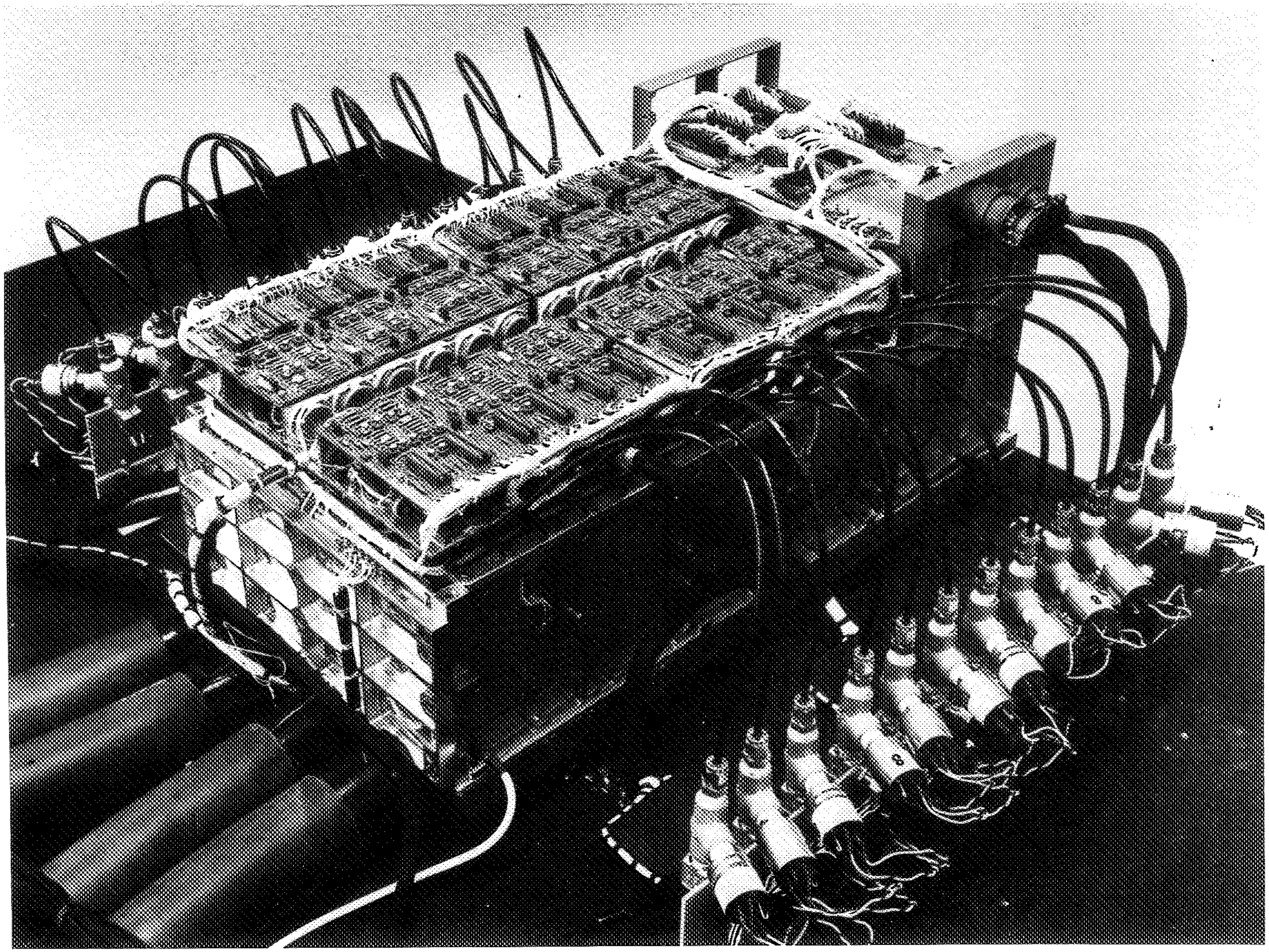


Figure 137

PANEL/ATTENDEE DISCUSSION ON CELL DESIGN

BOGNER: This afternoon we are going to have a panel/attendee discussion on cell design as it relates to energy density and life reliability. The panel members that we had initially were myself, acting as chairman; Sid Gross of Boeing; Bill Harsch was initially going to sit on the panel, he sent us a substitute, Lee Miller; Ron Haas of Aeronutronic Ford couldn't make it; Ed Kipp of SAFT didn't make it. We have Irv Schulman of TRW down on the end, and Harvey Seiger of Yardney Electric.

To open the discussion, I will show a cell with some weight breakdown. Now the weight breakdown may vary a little from cell to cell; this particular one happens to be a Gulton cell of a few years ago.

(Figure 138)

Here we have a separator which weighs approximately 12 grams; a ceramic seal and comb, together with a header, about 33 grams; positive electrode 261 grams, negative electrode 305 grams, electrolyte 88 grams, and the stainless steel, 173 grams. So you can see if we want to reduce the weight of this thing, the areas that we have to work on. The primary weight contributer is the stainless steel case, which in this case is about 20 percent of the weight of the cell, positive and negative electrodes which are roughly 30 percent of the cell. And if we could reduce the cell size a little bit, we can reduce the weight of the electrolyte as well.

(Figure 139)

Another way to look at it is a bar-chart. This is the common, flight-proven cell. This is based on 20-ampere hour cells, because these weights and energy densities vary slightly with the size of the cell. This is what we are calling the flight-proven cell. This is the type of cell we have been buying in the past five or six years, approximately 88 kilograms, 33 watt hours per kilogram, or 15 watt hours per pound.

Then we have what we call recent developments, which is the EP type lightweight cell, and something the Air Force has been working on with Heliotek, which are about 66 kilograms and give about 44 watt hours a pound--44 watt hours per kilogram, 20-watt hours a pound.

And this is the 1980 goal that we set, which is 55 watt hours per kilogram, or roughly 25 watt hours per pound.

(Figure 140)

This slide shows the breakdown of the components. What you see, as we go down in weight, the nature of the areas that were using weight in the casing, header and the grid and plaque area, particularly when we get out here. There will be some slight change, maybe, in the active materials, depending on what kind of materials we use and how efficient the material is.

WILLIS: Why don't you improve the utilization by employing 100 percent depth of discharge?

BOGNER: That is a possibility. Right now we are talking about the so-called absolute energy density. That is the full energy density you get from discharging a cell down to one volt. The thing that you are referring to is what we might define as effective energy density, what is it actually used at DOD during its particular use regime? And we would like to work with both, if we feel we can increase the absolute energy density and possibly also increase the effective energy density.

VOICE: Sam, were your goals based on some assumptions regarding maximum actual depth of discharge that you think you were going to use? They have to be related.

BOGNER: I don't know if I understand the question.

VOICE: You said your goals on your chart were the absolute.

BOGNER: Yes, that is full discharge values.

VOICE: In order to establish those goals you must have some goals for utilizing the energy density in back of your mind, or some relationship between the two.

BOGNER: We would like to get up to 80 percent DOD at the same time.

VOICE: In all applications.

BOGNER: That primarily would be synchronous use.

This brings up another interesting point. Perhaps it has been hinted at a few times, but maybe we need different designs for different applications. In other words, near earth orbit is usually at a higher rate, while synchronous planetary type use is usually at low rate applications. And as far as I know most of the cells we are getting now are primarily one design, trying to use for both applications. And I think we could probably go to thicker electrodes, which would decrease weight, because you eliminate some substrate that is not usable.

I didn't mention that about 50 percent or better of the weight of the electrodes is still inactive weight, just carrying the active material. So another way we thought of doing it was to use pressed powder electrodes.

I know that has been tried in the past, and Lewis Research Center is working on nickel electrodes. At present, nobody is working on a pressed cadmium electrode. Lewis Research Center will start on that. That type of electrode has been used in silver-cad cells so that there is a good possibility that for some special applications in Ni-cad, they could be used in a Ni-cad cell. Somebody may question the life reliability, but I don't have any answers on that. It is something we would like to find out about.

MILLER: My only comment was concerning the pressed cadmium electrode. Eagle-Picher has manufactured a pasted cadmium electrode which they have used in nickel-cad. It has not really been used in the sealed variety yet, but it is a possibility that it could be successfully used in application. Of course, without the sinter, it would offer very much higher energy density.

DUNLOP: If I could, Sam, I think we should define what we are trying to do here. If your objective is to make a lighter weight nickel cadmium cell, that is probably a possibility. And at the same time, let's say possibly improve the reliability.

Now if you start with a standard cell, I think it runs somewhere between 15 and 17 watt hours per pound. That is what a standard nickel cadmium cell that we bought back in 1970 weighed. That is the energy. If you discharge it, you get about 17 watt hours per pound.

BOGNER: That may be a little on the high side.

DUNLOP: That is on a cell basis.

By the time you got it into a battery, the usable energy density for the battery dropped all the way down to about 6 watt hours per pound. The available energy density was about 12 to 14 watt hours per pound. Those are approximately the numbers we had in 1970.

The objectives that have been defined today is to try to push that energy density from a usable energy density for synchronous from something like 6 watt hours per pound up to about 9 watt hours per pound. That is the number that was used in the presentation earlier today.

And the question is, what can you do? The question you seem to have posed, if I interpret it correctly, is what can be done to achieve a usable energy density of something like the 10 watt hours per pound, or a cell energy density of something like 20 to 25 watt hours per pound?

Is that what you are trying to do?

BOGNER: Yes.

DUNLOP: Okay.

I think one way you can do that is reduce the size of the case. In today's case technology, we use 19 mils thick. And I think you would like to cut that weight down from 19 mils down to about 12, 10 to 12 mils. Is that correct?

BOGNER: That has been done by EP cells.

DUNLOP: Okay.

I think maybe that is a good starting point. How reliable is a 10 mil thick can? Is that reliable?

BOGNER: Harvey has a comment.

SEIGER: Usually at panel discussions, each speaker is asked to speak for a few minutes, and I did prepare a few words, and I brought some slides with me, and I wonder whether now would be a propitious time to go into it. I think it is right to the topic.

BOGNER: Okay.

SEIGER: I am a proponent of electrochemical impregnation, and I am also very much concerned with the air that is entrapped in the negative electrodes, and tried to get it out. And I am concerned with increasing the energy density and improving reliability and cycle life. And we started some work in that way. Now, any of these facts that we have, any data that we have on the positive electrodes prepared by electrochemical impregnation will be covered tomorrow in the nickel hydrogen section by Dr. Vincent Puglisi.

I did bring some slides along on the negatives, and they are very interesting. They are interesting from two points of view. The particular slides that I brought have loading levels that are of 2.5 grams per cadmium hydroxide per cubic centimeter of void volume, and there has been no thickening. The utilizations are high. They are usually in excess of 80 percent, and we have some now--I have reported some in Las Vegas, impregnated to a 2.2 gram per cc loading, in which the utilization was 94 percent. And this is at formation. Now the third interesting aspect can be seen in Figure 141.

This is a negative electrode about 86 percent porous, that has been impregnated by the electrochemical impregnation at high temperatures. The loading level on this, as I indicated, is 2 1/2 grams per cc. Now, when the impregnation is done, there is a mixture of cadmium and cadmium hydroxide present within the plate. We have taken that plate out, we have oxidized it so that what we are looking at now is air cadmium oxide.

This particular SEM happens to be in the middle, located midway between the surface and the grid. Had we looked below the surface and near the grid, I would be showing the same kind of slide. What we see here, if you look very carefully, are the so-called gala forms of cadmium hydroxide, and the size of most of the crystals are about one micron. Now we take the selector and we put it through a formation cycle, four cycles of formation, and we look at it again, once discharged. Now I will have to show you several slides.

(Figure 142)

We are looking pretty close to the grid. And what you can see, if you look carefully, is some twinning of the crystals. And also, the crystals have grown from about the 1 micron size to about 10 microns. The line at the bottom is a 1 centimeter line. The magnification of the scanning electron micrograph is 1000-fold.

Now you can see that we did have a 10-fold increase. However, as I stated that the electrochemically deposited material was placed into the structure uniformly, this is near the grid. May I have the next slide, which is taken in the center, halfway between the surface and the grid.

(Figure 143)

The crystals do not show as much twinning. They appear to be about the same size. They appear to be slightly less densely packed in there. Now, may I have the next one, which is just under the surface.

(Figure 144)

If you look very carefully, you will see some crystals of the gamma nickel hydroxide. The surface is virtually bare. This is a very unique type of structure. We don't know what it will perform like as we keep cycling it, but it should be interesting. Let's go back to the second slide.

(Figure 142)

With this kind of packing, I believe that the difficulty in eliminating the air from the negatives it is apparent that we had material in there. So that the capillary sizes are such, that as Dr. Willis pointed out this morning, you have to pump on it quite severely in order to get out the last traces of air that are entrapped in the negative electrodes, and I believe that is the problem.

(Figure 145)

Sam asked for information on reliability and life. And there are certain things that we have to consider, and I have put some of them on, which is a thickening of the positive electrode, which is an important problem because this is compressing the separator, it is driving electrolyte out on the separator, there is a volume change between the separator and the positive on a one-to-one basis. And if you are going to squeeze electrolyte out of the separator it will go into the positive. When you take the cell apart releasing it, the separator will thicken. You go to measure it and you will find that there is less electrolyte in the separator.

Cadmium migration. We have been hearing it is important.

The electrolyte redistribution, we are back on that. There are two ways. There is the entrapment, there is the thickening of the positive, and then there is the degradation of the separator. That involves water.

We are interested in sinter corrosion, and we would like to start with a strong plaque, and we want to impregnate it in such a way that we are not corroding it, and hopefully, therefore, any corrosion that will occur will occur at a slower rate, and perhaps we will get a longer life cell.

We are interested in stabilizing the oxygen recombination rate, so that we always have a good oxygen recombination. That will stay the same in an aged cell the same that it is in a new cell. Part of this is tied up with the cadmium migration, part of it is tied up with electrolyte redistribution.

The nitrate and carbonate. Well, we know that if we are going to operate at lower temperatures, we must eliminate the carbonate and the nitrate. It is detrimental, it increases the self discharge rate of the cell.

If we are going to use an auxiliary electrode, we want it stable. And I think it has its place, it served a function in OAO-2; I believe it can serve even greater function if we can improve the entire cell and not lose the sensitivity of the auxiliary electrode upon cycling. And then we have heard this morning about the vibration effects. We want to consider all of these as we improve the cell design.

(Figure 146)

And if we are going into a cell design, there are a lot of parameters that we have to look at. And we have looked at this. The work that I am describing here was supported by Wright Patterson Air Force Base. I want to thank Dr. Pickett for all his help and encouragement.

In the electrode, we have to look at porosity because there is an influence between the porosity and the utilization of the active material of the positives. We have to look at the thickness. You have to maintain the thickness because of that separator that is in there, and we want to maintain the proper dimensions.

We have to consider the void volumes of the separator, the positives, the negatives, in order to get the electrolyte in there properly; and how to design the plaque so that we get all of the parameters that we want.

We have to be careful about our loading levels because there is a relationship between the loading level of the positives and the utilization, and we will hear more about that tomorrow.

The grid weight is a factor we can't play very much with unless we change the grid itself. We have to figure out if we want that void volume, and we want to get that weight in there, what the sinter weight should be. And therefore the plate weight, the number of plates, the plate area is a very important parameter because there is an effect of charge rate on the charge efficiency. And this was published back in 1962 at the Power Sources Conference. I think it was called the Battery Conference at that time. That showed that we do want to charge an electrode at a current density that is in excess of 7 milliamperes per square inch. So we have to consider the area when we design a cell.

The capacity. That is given to us by our customers, who have to know what the utilization is. In the case of the positives it is a function; in the case of the negatives it appears to depend upon how we make it and what we do with it.

And then there is the residual void volume of the positive, the negative and the separator, and that will tell us how much electrolyte you are going to put into the cell, because I don't talk milliliters or grams of electrolyte per ampere hour. I express it somewhat differently. I like to talk about the full level of the residual voids when everything is in the discharge state.

Then, of course, there is the negative-to-positive capacity ratio, and we have been hearing some questions about it this morning. We have been looking at a 1.5 to 1. Perhaps that should change. Perhaps it should be higher, perhaps it should be lower. I don't know. But this is given to us by a customer and we have to factor it in.

Okay. That is all the things we have to do with the electrodes.

Then we have the separator, the materials, its density, its thickness, its interelectrode spacing, the area, its porosity, and then again its residual void volume, because we are putting electrolyte into it.

And then the electrolyte. We have a full level. I said I would like to talk about the voids that are filled, and the degree of filling them. And then there is the density of the electrolyte. And these are all parameters, the density of the electrolyte affects the weight of the cell.

Now, before we are even through with our electrochemical parameters the thermal people have been telling us that there is an optimum plate width-to-weight ratio. They talk about an aspect ratio between the electrode that we must include in our cells. And that is affected, in turn, by the plate thickness, by the the interelectrode spacing, and the electrolyte fill level.

I have 28 items on that board, and in order to sit down and do a cell design of 28 items, it is a little difficult. And what we did was write a computer program for cell design, and the program was given in the final report from Heliotech to Wright Patterson.

(Figure 147)

I will read the computer readout of that design as we go along.

Dr. Puglisi wrote the program, had the functions put into it, and it is only a coincidence that the particular one that I chose is Design 11. I thought it was the best and Dr. Pickett thought so too. And when he spoke about a second make of cells, he specified Design 11.

Now, let's look and see what the computer printout did for us. Because we have heard about the performance this morning, let's see what this did. It told us that we are going to use a 32-mils thick positive electrode; the porosity was going to be 84 percent; and the loading level was going to be 1.9 grams per cc of void.

We almost made that. The first two numbers, I think, were awfully close. And now we have the void volume, per cc. That is residual void volume.

We have our sinter weight; grid weight is input into the program; we have the active material weight that has been given to us, and complete weight.

Now we have a theoretical capacity, and that is put out by the computer so we don't have to calculate it. It gives us our ampere hours per gram.

We have the predicted for motion capacity. We have a density, an ampere hour per cubic inch that is predicted for motion. And we have an ampere hour per gram figure.

Now when we make a sealed cell, we generally find that about five-sixths of the capacity that we measure in formation is not present in the sealed cell. And this is put into the program. So the sealed cell capacity that is predicted, is less than the formation capacity. It is even less than the theoretical capacity. And naturally we degrade for weight and volume ratios.

The plate area turns out to be 277 square inches, and the total plate weight is 487.9 grams.

Negative electrodes. Program told us 32 mils, 90 percent sinter porosity, which we did not make, we had 88. It asked for a loading level of 2.16. We did not reach a loading level of 2.16, it was more like 1.8, if memory serves me correctly. And we wound up with a ratio of negative-to-positive instead of 1.5 to 1, we wound up with a ratio of about 1.2 to 1.

And we have our void plot. All the parameters such as the sinter weight, the active material weight are read out by the program.

Separator, we start with one that is 15 mils thick, it has an 80 percent porosity. And by the time we get it into the cells, we have a 6 mil interelectrode spacing and the porosity in the cell is 48 percent.

The cell is constructed of 16 positives, 17 negatives. The dimensions of the cell are given, the stack rate is given, the dimensions of the can that fit around it are spewed out by the computer. And then we wind up at a residual void volume in the three major components, the positive, the negative, the separator; we have our inputted weights in the cover assembly, and we wind up saying we want 209 grams of electrolyte, and that the total cell weight will be 1478 grams.

As a matter of fact, we were about 20 or 15 grams shy in electrolyte. The flag was waving on us. I just figured, that is pretty good, we have got about 192 grams of electrolyte in when the program said 209, that should be good enough. I'm sorry, it wasn't. We didn't know it at the time. The actual weight came down to be a little bit less--I believe about 1440 grams, and that is the way we have been designing the lighter weight cells.

But we did take into account all the parameters that are entailed in the cell. And it appears that there are about 28 of them, and the list may not be complete.

BOGNER: Anybody have any comments on that?

ROGERS: Hughes Aircraft

Harvey, you mentioned that you didn't meet the goal on the loading level, and I guess it raises a question that I have run into. You have a nice cell design, and you talk about positive capacity. What can manufacturers achieve in terms, if we ask for a certain capacity, what kind of, let's say, reliability--well, reliability is the wrong word--quality control, can you achieve in production, so that when we order a cell with a certain loading, we are going to get somewhere, anywhere near it?

SEIGER: Let me turn this around.

We have made a cell that was shy of electrolyte. It was the first time this cell was made.

Actually, before we had an electrolyte redistribution problem, we did very close to performance. If you saw Dr. Pickett's curves this morning, the one that was outstanding was the hand-made, one-cell 0-2 that was right to what we wanted. It gave something like 52.6 ampere hours and was designed to deliver 55. We have yet to make some more cells and take care of that problem with the electrolyte redistribution. That is the air that is entrapped in the negative electrodes.

Now, what kind of spreads can we expect?

Let me put it this way: I have some numbers here that I wasn't prepared to show. But it shows that our variability, our coefficient of variability in the positive electrode is about 3 percent in formation.

ROGERS: What does that mean?

Seiger: It means that those delivering between 40--let me call off the numbers to you. I have delivering between 47, 48 ampere hours, 5; between 45 and 46 ampere hours, I have 20; I have 3 delivering between 43 and 44 ampere hours; and 2 delivering between 41 and 42 ampere hours. I think that is pretty close.

ROGERS: What was the goal?

SEIGER: The goal was 43.

The negatives don't do quite as well.

DUNLOP: Along the same line Howard, Eagle-Picher made us the electrodes that we are using for the flight battery on the NTS-2. That is a nickel hydrogen battery. And they use, as you know, the Bell Laboratory process to make those electrodes. It is an electrochemically impregnated process.

One of the things that was very interesting in that program was that I think in any electrochemically impregnated process, you do get a weight gain on your electrode that you can use to determine very closely what the amount of active material, as opposed to, say the chemical impregnation process, where your weight gain is not a good indication of the amount of active materials because of the corrosion that is incurred during the impregnation process.

Supposedly, one of the big advantages of electrochemical impregnation is that you don't get any corrosion. It turned out that what Eagle-Picher did for us is that they took the distribution of electrodes that were made, weighed all of them, and the distribution--like anything that you are going to get a distribution, they threw out the extreme. Then they weight-matched the electrodes to come up with the cell stack. And those cell stacks are matched extremely well on a capacity basis.

Typically, we get on those cells at a given temperature, say room temperature, we will get 40-ampere hours plus or minus 1-ampere hour in capacity. And we have delivered those cells to the Navy and they have made capacity checks from time to time. And each time they do it, they get an extremely repeatable number.

Now they do keep those cells shorted during the storage period. But--and they do a capacity check, each time they get--at a controlled temperature--each time they get an extremely repeatable number. That is in a battery.

So that means the entire battery is very--they don't run each cell down in the battery. They get about 40 1/2 ampere hours each time they run a capacity check.

So there is an indication here that if you do go to the electrochemical impregnation process, whether it is Yardney's process, or the Bell Lab process, or the Pickett process, that you have about three big advantages, other than the other things we talked about today.

One being that you can use the weight gain of the electrode as an indication of the amount of active material you have in your electrode. And two, that can use that, the weights of your electrode, to match your cells up to get a very well-matched electrode stack. And I think if Lee Miller would comment on this, he did that in a computer program, he matched those electrodes in a computer program.

MILLER: I guess I won't have any comment on that subject. We have been using a computer program. It is pretty straightforward, and we matched them with respect to weight to get the best distribution with available electrodes. Like Dr. Seiger, I did prepare a Vugraph, which I would like to use while I am here.

With respect to the argument that I think we talked about this morning, is there any merit in pursuing the high-energy density nickel cadmium system, I don't think at this time that we know that the high-energy density system is any less reliable than the heavier version.

I don't think that we know that the high-energy density system will run, will operate any less time than the heavier version. So I think if we don't pursue this, we might end up flying a lot more weight than what is really necessary. And it is weight that can be better used, I am sure, in these satellites, or satellites with some other application.

We can achieve high-energy density systems with either nickel cadmium or nickel hydrogen, as Jim has mentioned. I would like to restrict my comments strictly to the sealed nickel cadmium at this time.

(Figure 148)

Just to pick a standard, we can take what I refer to as the standard 20-ampere hour cell. We designate it as the RSV20-3, and it weighs approximately 25 grams, which, if you consider a plateau voltage of 1.2 volts, and a maximum, a nominal capacity of about 26-ampere hours it gives you about 17 watt hours per pound.

There are several approaches that you can take to reduce this weight. I think they are really tied up in two areas; electrode group and the cell container. Electrolyte would stay pretty much the same, The tabs, the other components in there wouldn't really change from lightweight to the heavier cell design.

If you increase the loading on your electrodes with the corresponding reduction in the nickel in the sinter, primarily this is obtained in the negative sinter, you can reduce the electrode group by 17 percent. This breaks down to approximately 7 percent increase in loading, and approximately 10 percent decrease in the nickel in the sinter.

But the really major gain can be obtained in the container by going to the 12 mil 304 stainless steel container. We reduced the weight by a factor of 58 percent. And we come out with a cell with an energy density of 22 watt hours per pound, versus 17 watt hours per pound.

DUNLOP: How do you go from a 19 mil container to a 12 mil container, and reduce your weight by 58 percent.

MILLER: Well, you also have lightweight terminals introduced in there. The whole container is reduced.

BOGNER: Some of those containers were heavier than 17 mils. They were up in the 20's.

MILLER: I should qualify that.

DUNLOP: Well, this is a standard here. You don't want to necessarily compare the worst. The one we were using, most of us using, was 18 or 19 mils.

BOGNER: That was on a 10 ampere hour cell.

DUNLOP: No, on a 15, 20-ampere hour cell.

MILLER: The 19 mil is a fabricated can, and we use a deep drawn can. It is about 25 mils.

Okay. I say that design is an actual design, actually being flown in space at this time.

DUNLOP: Before we go, there is an interesting point.

What is the competence level? Is it a problem or not to make a 12-mil can?

MILLER: No, it has to be fabricated. We can't use the deep draw process.

DILLON: JPL

I would like to respond to that.

We took a four month--under the direction of Sam Bogner, a four month effort looking at a systems mechanical approach to reducing the weight of this thing. And most of that effort was spent in trying to define why it was designed to the way it was designed.

For example, everybody knows that these things don't burst around the pressures that they work at. As a matter of fact, there has been Martin Company, Denver, and other companies have given reports that say that 20 mil cans don't burst until you get to about 1200 psi.

So we asked ourselves at JPL, what is the requirement? If the requirement is only 200 psi, then we can build a can with much thinner walls and save a lot of--then what I am trying to say is that we can attack it from a strength standpoint and come up with a thickness and a material of an appropriate size.

DUNLOP: But did you do that?

I am in that same situation. We are going to go to a 12 mil can.

MILLER: I will tell you something. Yes, we did a systems approach, a computer model and it turns out that you cannot analytically man rate the existing cans that we have now, because--let me expound that a little bit.

The reason why the 304L was chosen, we look at it now, was because of its ductile properties. It stretches and it doesn't burst. As you go thinner and thinner with that, you are losing the burst pressure, unless you are going to let it stretch further.

Inconel and 718 and other materials that you look at don't have that ductile property, so as you go thinner with those, in fact your burst pressure is going to come down.

DUNLOP: I beg to differ with you.

You can make an Inconel can and make it work very well.

MILLER: And you are not going to back off a 304 burst requirement?

DUNLOP: Let me just ask this. If you want to find out how good a can is, you do have to either do--you have to do a fatigue, some type of a fatigue analysis on the can.

MILLER: Okay.

DUNLOP: I am not professing to be a materials structural analyst. But I do know that we have gone through exactly the same analysis for lightweight cans with TRW, and we spent a lot of money for them to do this very thing.

BOGNER: Let me ask you, was that cylindrical cans?

DUNLOP: No, that was definitely materials.

What you are looking for is, when you get a certain material of a certain thickness, what you have to look for is about four or five things:

You look for hydrogen embrittlement, you look for corrosion, you look for propagation, crack propagation with fatigue cycling over a pressure range that you intend to manually operate at if you are going to operate over any pressure range.

So, you need to go through these parameters, you need to know what your burst pressure is. Not only at the beginning of life, but after this can has been subjected to, say 5 or 10 years of operation in KOH. Or, you would like to know this. What it is going to behave like after 5 or 10 years in KOH in a hydrogen-oxygen environment.

Now I think what I am saying here is, I am just asking you if you have gone through any type of--do you know what the burst pressure is, for example, on this can? Simple question.

MILLER: This can that Sam was talking about?

DUNLOP: Right. A 12-mil can. What is the best pressure on a 12-mil can?

MILLER: 1200 psig.

BOGNER: I think we found it burst around the same areas up around the top, is that correct?

MILLER: Fairly well average.

DUNLOP: Is that a theoretical number for a burst, or based on straight calculation?

MILLER: That is experimental.

DUNLOP: Should be very close, by the way. Usually your burst pressure occurs, the can will burst at the weld, and that is usually lower than your theoretical.

What is your theoretical on that can?

There is a yield and a burst. What is the theoretical yield, theoretical burst? I am just asking this question --

MILLER: Theoretical burst on that can is much lower than actual. Much, much lower. Because you cannot model the deformity that takes place in the can? In other words what actually happens with the can is that it deforms into a pressure vessel, in the form of a pressure vessel --

DUNLOP: Yes, I see. Suppose you contain the cell in the battery pack, what does it deform to.

MILLER: You only contain, in most applications, the broad surfaces.

DUNLOP: I am just curious as to how much reliability there is. If you are going to commit a whole spacecraft program to this design, we would like to know before you do that, what kind of reliability you have in that can, what kind of reliability you have in the guy being able to make those welds, et cetera. Because in our case, for example, as was pointed out earlier, in a communications satellite, we may be--we are just as interested in reliability as you are in cutting out some weight. So you want to make sure before you commit a very large spacecraft program to this kind of a can design, that you know you are going to have reliability.

I am just asking what type of insurance--I know you are going to go to this, but I am looking for some assurance that the work has been done to verify.

MILLER: Okay.

I think you misunderstand me. I am not a proponent of the 12-mil can, all right. I am saying that before you can attack the problem of reducing the weight of the existing Ni-cad cell, you have to define the requirements that you are going to design a lighter weight version to.

And as far as I can see, to this day, those mechanical design requirements have not been defined. And until you do that, you can speculate 12-mil cans, 5-mil cans or whatever, and you don't know where you are at. That is the point I was making.

SCHULMAN: Jim, I have a test report with me called "Pressure Testing of Lightweight Nickel Cadmium, Eagle-Picher Cells," which is concerned with the 12-mil can. I will be glad to go through it with you afterwards.

I think the burst test in this particular program is 1250 pounds--psi, rather. There is one here that was--well, they have a few. One cell burst at 1600 psig. But we can go through this.

We are satisfied at TRW that there is no problem at this time with 12-mil cans.

FORD: I would like to make a point. I think we are skirting the issue here. We are talking about nitpicking the design of a cell to death. Let's hear from--let Lee finish his presentation, let's hear from the other panel members. Let's put one of those charts back on the board and see where the real weight savings are.

You are talking about a few grams here and there. How are we going to get that big jump we are looking for in 5 to 10 years. I think we ought to be looking at that problem. The name of the game in this discussion is cell design versus energy density. Well, let's get it back in perspective and look at it that way.

MILLER: Okay. I believe I am supposed to go on with presentation now.

Design B is just like Design A. The only thing we changed from the 304 stainless, 12 mil and we go to Inconel 718, 5 mil thickness. And in this case we would realize an 80 percent savings in container weight. And that would result in a 24 watt hour per pound cell.

Design C is just like Design D, except in this case we changed from the chemical impregnation process to the electrochemical impregnation process. Here we expect a greater efficiency in both the positive and the negatives, and so--which I think in the positives is in excess of 100 percent, and in the negatives is in the order of 80 percent. We get an additional energy density advantage without the weight increase, and we are up to 26 watt hours per pound.

Design D is a little bit further out. Of course, one of the biggest wastes of weight, let's say--not waste--but, one of the biggest deadweights in the cell is the sinter. And in Design D we consider the possibility that the sinter can be reduced to almost half by what we call a sinter skeleton.

In this work which we did several years ago, and we didn't really pursue it very far, because we didn't think that the lightweight sinter would work with the chemical impregnation process. By the chemical vapor deposition, I believe is the name of the process, we applied Nicolon to an organic felt, and then we subsequently burn this felt out. And that left us a sinter approximately half the weight of the existing sinter, in which the filaments are solid Nicolon.

And it really made a significant jump, like a magnitude of ten, with respect to surface area. I think that this particular sinter would really lend itself to the electrochemical impregnation process. If we are successful in this area, we would again get the 80 percent savings with respect to container, which hasn't changed, but we would see a 40 percent savings with respect to the electrode group and realize a sealed nickel cadmium cell with energy density in excess of 30 watt hours per pound. I think that is all I want to say about the Vugraph.

I guess you are probably thinking which side I am on with respect to the energy density question. However, tomorrow I am going to present a paper on a sealed nickel cadmium cell that is even heavier than today's low-energy density cell.

BOGNER: Does anybody have any comments.

Well, from that presentation, it sounds like it should be pretty easy to obtain our goal.

GRIFFIN: Mallory

Is this 718 Inconel commercially available or is it something specially developed for you?

MILLER: No, it is commercially available.

GRIFFIN: What is the 304 and the 718. What are the factors that you were looking at? Could you tell us, was it strength? Besides the lightness, were there certain factors that led you to those two?

MILLER: I think the 304 was derived because of its stability with respect to caustic. It has a certain strength factor. We are trying to go to a thinner design with the Inconel 718, but maintain the strength. And we know from the literature that the 718 in the age-hardened condition is almost four times as strong as the 304 stainless.

GRIFFIN: Thanks very much.

ROGERS: Lee, you did mention in the age-hardened condition, which I would agree with. However, that is assuming that you are going to glue it together and not weld it?

MILLER: No, we will weld it.

ROGERS: Do you thicken it at the welds, or what?

MILLER: No.

ROGERS: Then I guess I don't understand how it is going to hold together because you lose the hardening when you do the welding.

MILLER: To start with, once you have welded the container, the actual container without the cover, this can be age-hardened in this condition. And then you have the problem of putting the container on. And we know if this is done by the electron beam process, you maintain the material strength because of the less heat involved in that process.

DUNLOP: That is if you cross-section electron beam weld zone, you do find a heat-treat region. But in the case that he is talking about putting the cover on, you probably got a lip region there anyway, which gives you twice the normal thickness. However, I think in any welding process, when you get down below 10 mils, even with electronic beam welding, you have to have things very well controlled in order not to have a problem with your welding itself.

MC HENRY: Bell Laboratories

I think you have to be very careful when you start taking the sinter away. It is a lot of weight, but in any impregnation process, it is very much dependent upon the sinter. If you vacuum impregnate, you corrode half the sinter. And if you don't have much in the first place, it will all fall to pieces.

Electrochemical, you usually don't corrode. But it is very sensitive to the sinter. And you can't electrochemically impregnate any old kind of sinter. It must have the right kind of porosity, and pore sizes and things of that kind. It is sensitive to that kind of--you know, to the structure. And you are not sure that you can sinter any--I mean impregnate any kind of sinter. It must be compatible with the design.

GROSS: On that point, during the Apollo program, the electrodes that were developed for the nickel--for the hydrogen-oxygen fuel cell for Pratt-Whitney, were developed by Clevite, and they went through a number of evaluations; one of which was for an electrode--a sintered electrode made without a grid. And the grid is a very heavy part of it. I haven't seen any work on the use of electrodes without grids since that time. I don't know what the battery manufacturers would say to the possibility of getting rid of that grid.

SCHULMAN: Sid, I believe years ago, Sylvania had a program of making gridless electrodes on nickel cadmium cells without grids, and they went out of business very quickly. They failed in their attempt. The electrodes did not hold up.

I would like to just bring a point up --

GROSS: Why?

SCHULMAN: I don't know. I think they just fell apart. They just couldn't make it. They tried for many, many years. That was the basis of their cell, a gridless electrode, and it just failed.

BOGNER: How about the perforated metal grid, or the wire grid?

SCHULMAN: Well the perforated metal has distinct advantages over the wire. The wires always found a way to hit another wire on another grid. You know, they curl. They are almost dynamic.

GROSS: Do I have to tell you the story about the spider?

SCHULMAN: No, you don't.

I just wanted to bring up a point to Jim on the weight gains. There are methods of measuring weight gains on vacuum impregnated plates, and that is done by the total hydrate method in which you not only measure by weight gain, but also by hydrogen deduction of the material. And these are reasonably accurate in judging the effect it will have on the cell performance.

One thing that people have --

DUNLOP: Let me ask you a question.

Do you think that could be used in --

I had a little problem with that. It is true that with the electrochemically impregnated electrode, you can use the weight of the electrode to get a very close matching from the capacity point of view. And the argument seems to be that there is no corrosion, therefore there is practically no weight. The other argument, by the way, is that you need an extremely uniform plaque.

So now you have a couple of variables here. I have never been able to--we have never been able to really quite accomplish the same thing with electrodes made by SAFT, for example, who did, in their production of aerospace cells, also use weight matching. And they weighed all the electrodes, then took what they call--they did a distribution on their electrodes, and they tried to match by weight, too. But they did not come out as close as we have come out with these.

SCHULMAN: On the Helio program today, SAFT is matching cells based on electrode weights. And they are, in fact, putting a distribution of weights into a cell. They have gone further than that. They are matching on a base of total high grades in a plate and their results are very, very close matching.

DUNLOP: Right.

So far, I think we agree. I mean we both like matching, and we both like electrochemically impregnation.

SCHULMAN: Yes, there is no question about it. Certainly I am very excited about the electrochemical impregnation.

BOGNER: Why can't we go up then, to say like a 90 percent porous grid sinter?

SCHULMAN: We have recommended that on the negatives plates, that we approach that--not exactly 90 percent, we talked about 86 and 88 percent for the negative electrode. And we were trying to get Harvey to agree with us.

HARVEY: Once we go up--one of the things that we want, we want a good sinter. And if we are going to go up to an 88 or 90 percent porosity and we have made it, and we have impregnated it with both negatives, and we have also looked at some positives, we have to add a performer in order to have a good sinter. And that is going to impact cost.

And I keep having people ask me, well, how much do these cost? And, why should they cost more? Why don't they cost less? So it is all cost. Sure we can make it. I would have no objection on the negative electrode to go up to about an 88 percent porosity. Ed McHenry was very close. We have impregnated negatives as high as about 90 percent porosity and we find essentially the same kind of utilization and no problem impregnating the negative.

The positives is a different story. In the positives there is a utilization and you must know the process. We have been developing some equations for impregnation of the negative and the positives. There was a paper at Power Sources and another one at Las Vegas on the theoretical aspects of it. And I think that as long as we know what we are dealing with in the parameters of the plaque, we can indeed make the impregnation process work.

However, there is an interaction between the performance of the plates, the porosity and the--impregnation level and porosity are going to impact how the plate performs.

PUGLISI: Yardney

We are, by the way, presently making an 87 percent porous negative. And one of the reasons why we don't look at a 90 percent porous negative is--sinter porous--is because the electrical resistance, if you just look at the Air Force report out of Heliotek, shows that the electrical resistance of that plate starts to take off in that region of about 90 percent. And I don't see how, if you remove the grid, you are going to improve that. The situation is going to become much worse.

In addition, as McHenry was pointing out, the electrochemical impregnation process is one which requires a--it is an electrical process that requires a service to conduct electricity. If you start removing that service you are not going to get the deposition as you are getting it now.

HALPERT: I would like to follow on by covering the material that Bon Steinhauer mentioned this morning, and that is if you could get a reliable cell that was had in the last 10 years, where you are sure of the depth-of-discharge that you needed to get down to capacity on a regular basis for a long period of time, would you indeed--and I ask the whole panel--go to a 90 percent porous plaque, or would you prefer something that is even less porous so that you can get better utilization out of your plates for a longer period of time? Forget about the weight being a significant factor at the moment. Which way would you go?

SEIGER: When we impregnate the negative, the bulk of the material that is being deposited is cadmium hydroxide. There is some cadmium being reduced from the cadmium hydroxide. And therefore, in the discharge state we have the most voluminous matter. As we charge it it goes to a more dense material, which means that we are really not stressing that negative electrode due to the changes of volume of the active materials.

A different story with the positives. I don't know if Dr. Puglisi brought any slides of positives. In the negatives you saw that the crystals were lying in the pores. In the positives it is a different story. The material is sitting on the sinter.

And here you have the material that is changing its density as you go from charge to discharge, and you are going to be getting something like heat stresses, which means that you will be fatiguing, and for that reason I think we need a rather strong plaque for the positive electrodes if we want it to last for a long time. And we also want to not overload it, to be careful about the loading. I think we are very fortunate that it appears that the optimum is not in a highly-loaded area, but less than highly loaded, that we will get maximum ampere hours per cubic inch and per gram.

BOGNER: Most of the failures I heard about really weren't related to plates falling apart. They were related to the separator degradations and that type thing.

Did I hear wrong?

SEIGER: You are hearing electrolyte redistribution; you are hearing separator degradation; and you are hearing positive electrode swelling. And the positive electrode swelling is interacting with the separator.

DUNLOP: Going back for a minute, I think Gerry's question was not--was how--was what depth of discharge are you willing to go to or-- Look, the question is, how much energy can you utilize out of that battery? Not how much energy you can get on the first cycle.

And that is what the system designer has to live with, is what the usable energy density of the battery is going to be. And that is affected--the biggest effect on the usable energy density is the depth of discharge that you are willing to use on the battery.

And so, if you make a 20 watt hour per pound cell, and only use 5 percent, it is still only a 5 watt hour per pound battery. If you make a 20 watt hour per pound battery and you use 50 percent, you have got a 10 watt hour per pound battery. And that is the key in this argument.

HALPERT: What I would like to know is, if you wanted to go to 50 or 60 or even 75 percent depth of discharge on a near-earth orbit, what kind of a plaque would you make? Would you really make a 90 percent porous plaque and fill the active material in the way you said? Would you make a 60 percent porous plaque on the positive?

I am asking the designers and the people who are talking about cell design, what kind of a system would you make? Forget about the weight. What kind of system would you make in terms of the plaque?

It is open to anybody to answer.

MILLER: I will make one response to it.

Our experience is with the plaque that is around 85 percent porous; we have gone up closer to 90 percent and could tell no difference between the performance of the plaques. So I guess I would have no reason to want to use a heavier plaque on the negative electrodes. I agree with Dr. Seiger on the positives. Retain a heavy plaque there.

SCHULMAN: You know, I think that you are putting the onus, to a certain extent, on the cell vendor, to make a cell on which you can perform some minor miracle. I think the problem may be with the user himself. Does the user use the cell under the most ideal situation for the cell to perform in the way you would like it to perform?

For instance, are you using it in the correct temperature range? It seems obvious to me that you are not going to get good cell performance if you are going to be up around 30 degrees Centigrade, when you should be down around 5 degrees Centigrade. I think you can get excellent cell performance on at least synchronous orbit if you go to deep reconditioning. We probed at TRW to our own satisfaction. And we have a--I think there will be a report given tomorrow on reconditioning, which we have 30 seasons at about 70 percent depth of discharge actual capacity.

HALPERT: That is for synchronous?

VOICE: Is that real time or accelerated?

SCHULMAN: That is accelerated. Obviously we haven't spent 15 years in the program.

HALPERT: Okay.

I am still charged with the problem on a near-earth orbit. I want to tell my project manager that I can run his cells at 50 percent depth of discharge. That immediately means that he has an increase of energy density of 100 percent. And that is important to him.

It is important because he may be able to put lighter-weight cells--less amount of batteries on the spacecraft. So how do I get that, and what kind of design do I have to use?

Is it just lightening the can? Is that the only thing?

SCHULMAN: No, no. Of course not.

I will give you a gut feeling on that; that is all I can give you at this time. The are indications that nickel hydrogen has recently gone--some cells have gone at 80 percent depth, something like 4000 cycles, which means that at least the positive plate is capable of doing it.

It seems to me if that is the case then we should--the culprit--the nickel cadmium cannot do it, it has got to be in the negative plate. And that is where the emphasis has to be placed.

GROSS: Gerry --

ROGERS: I think I better interrupt you here, because it is my cells he is talking about.

We did have--in fact, I guess we have two or three cells with full size pineapple-shape electrodes which have gone over 4000 cycles. However, one cell does appear to have undergone some loss of capacity of a Bell process--this was done at Tyco--electrochemically impregnated electrodes. And with that, I would like to bring up an additional point, and I have a feeling it isn't simply percent of capacity that you have to worry about, but it is also current density. And people have not mentioned that.

GROSS: Gerry's problem, I think, is a very significant one. It is to me, because I think it points out that really we don't have the data. And in order to make significant strides in energy density and life, we really have to have all the data for that problem and all the other factors that--all the 28 items that Harvey listed on his slide.

And until we start getting the actual data that allows us to make the design trades and optimizations, we are merely guessing, or waving our arms.

COHN: Could I bring out one more point in there that I don't remember seeing among the 28 factors.

You also must consider how are you going to charge and discharge the cell, and what kind of control you have on the cells and on the battery as a whole. As we know from basic studies, the cadmium has a tendency to grow crystal size. So if you can manage somehow, by power conditioning, to avoid a crystal size growth, you may be able to get longer life without straining a gut by running that battery properly, and I don't think we have ever tried on a battery as a whole, except perhaps TRW--I am not sure if they tried to do that or not.

DUNLOP: Just one comment. There has been a lot of positive electrodes made by electrochemically impregnated electrodes, or made by reduced loadings of the chemical process which have demonstrated 4000 cycles or more. That is valid.

And that is the result of a significant reduction in the loading of the active material with a reduction from around 2 grams of active material per centimeter cubed, which is typical, down to about something like 1.6. And I think there has been data generated for a number of these electrochemically impregnated electrodes at several different laboratories which has shown at least a capability for 4000 deep discharge cycles for those type of positive electrodes without significant swelling.

FORD: When you talk about cell design, you talk about what is on a piece of paper, but that is not what comes out of the production line. I think we ought to address that subject here today, reproduceability, or the lack thereof.

One of the goals of the standards program, is to try to get cells that are reproduceable from lot to lot, from day to day and from year to year. Now we have come to this workshop since 1968, and we talked about cell characteristics, cell failure, mode cell degradations, you name it. I don't know about you, but I have never flown the same battery twice, and I don't think we have the capability to build identical batteries or identical cells. Sure, we can build identical batteries because the cells have a basic configuration. You can't build identical cells.

We are tied to a commercial process by and large. It has inherent limitations. And I think therein we are pushing the technology to the limit based on the limitation of the process. Until we are willing to commit some resources to upgrade our technology--and maybe the new impregnation process will do this--we have got our backs against the wall.

One of the most astonishing things that has come out of this standard cell program, is a lack of repeatability. Just in the basic impregnation process I have seen this over a dozen flight programs, where we cannot get the same loadings twice in a series of two or three months. It just seems basically impossible to attain.

Now how do we tackle a problem like that?

We are talking about aerospace cells. We are not talking about commercial cells. I think that is a very fundamental issue because I differ with some of the points made today. I think we have the technology to build a 10-year battery in synchronous orbit at 60 percent depth-of-discharge, but we don't have the capability to manufacture it. That is where the problem is. Now until we recognize that and start dealing with improving energy density, we have got to come to grasps with the way to produce scientifically, get the art out of it and make it a science to produce battery cells reliably, repeatably.

This morning with reference to two different synchronous orbit programs, I happened to know--just based on the dates and how long the cells have been in the test, the cells were probably made two or three years apart. And you say, well, I got it from the same manufacturer. That is great. He may have used the same cardboard cartons that he had two years ago. But that is probably the only similarity in the cells.

I think that it is time that we put things in perspective. We can talk about doubling energy densities. But until we can make a plate reproduceably from day to day and year to year, we don't know where we are. Therein lies the fallacy in the data base. We don't really have the same data base. What data we have is based on something we don't know what it was to start with.

GROSS: Floyd, why don't you continue.

FORD: I do want to make one final point, and that's the negative/positive ratio. I know how it all got started because I was involved with it back in the early days. I was one of the first presenters' here to talk about the OAO battery problems. Since that time negative/positive ratios have gone off the top. Why? Because the cell design is being driven by desire for increased energy density. Gentlemen you don't get there from here without new technology and that's what we've been trying to do for five years.

I see numbers like 1.8, 1.9, 2.08 negative/positive ratio. I have to ask the question, why? Some of the older cells have been on Crane test. Whatever you believe in the Crane data, it shows some cells will last a long time. Those cells were built with 1.2 to 1.3 negative/positive ratios. Why do those cells work? Have we stopped to take a real hard look at it? Have we stopped to take a hard look at why today cadmium migration is being cited as one of the typical problems of synchronous orbit. When some of the older cells that I have seen torn apart, cadmium migration was almost to the point you could ignore it. There were other problems that caused it to fail, but it wasn't cadmium migration.

Gentlemen, I think we had better back up and take a hard look at the basic cell design and how we got where we are today.

Thank you.

KRAUSE: I have got to say something to you. You may not like it, but I have seen three companies go into business and out of business in the custom battery aerospace nickel cadmium business. T. I., Tyco, and then Heliotek.

You get up and you say, you have got really to look at these designs, we're buying a commercial product. I agree with you one hundred per cent. Where was all that support when those guys were trying to do fundamental level work from NASA. Support from NASA did not seem to be forthcoming when T. I. was in the business doing some excellent fundamental level work in nickel cadmium in trying to improve energy density in life time. Tyco was doing the same thing, Heliotek was doing the same thing. I didn't see the kind of support that you are calling for now.

I think it's a little late, unfortunately, unless some of the existing cell vendors today are going to get into that business and take fundamental level approaches because they're still going to require support from NASA. And I don't see in a million and a half bucks that we're going to get anywhere.

BOGNER: Why don't they use their self support?

FORD: You made your comment at the wrong part of the meeting, that should have been made this morning.

GROSS: Ford, I just happen to have a slide for you. On the subject of negative/positive ratio and precharge.

What I am trying to do is stimulate some interest in this subject to get some ideas out. What I have plotted here is a precharge as a function of negative/positive ratio and put in some data points as existing design points. There's a variety of them.

I also have shown some lines showing the precharge as a function to express the different ways and values of the fraction of the positive capacity both for the precharge and for the excess discharge cadmium.

The NASA spec. is the green point, 1.5 negative/positive ratio with forty-five per cent of the excess as pre-charged. The red points are a bunch of design points. Now somewhere in this--there lies a zone in which it is unsatisfactory to operate and in the middle--in here someplace is a zone where it is satisfactory to operate. I rather arbitrarily sketched in some lines here of 10 percent, both excess discharge cadmium and 10 percent of fractional deposit of capacity as being the limit. This data point down here are some cells that failed because they were outside that limit. That is the OAO, the spare OAO cells that Floyd Ford tested, but the data goes all the way out as Floyd mentioned, out to negative/positive ratios 2, all the way down to 1.3. So, this raises a number of questions.

The first question is--it's all related to the question of is the NASA spec. point a good point? Is that a good design point? Do--is there an acceptable range? Is this a good range? Are there some design applications where people would recommend not using the NASA spec? And, perhaps the manufacturers would be in a good position to answer the question of would they recommend departure from the NASA spec. on that point.

I'm turning it open as a question to anybody now for a comment. All we're trying at this point to stimulate some discussion and comment on this subject. And prefer data and information. Anybody got any information?

FORD: Yes, I'll make a comment on the spec. because I think the spec. can be relied on. I think the 1.5 is a number that was developed in fact about six years ago based on empirical data somewhat arbitrarily selected. I think the important point is get your utilization up, particularly get that negative utilization, I think that's what we've got to try to take a look at. Specifying that under certain test conditions that the negative utilization has to be a minimum of 60-70 percent whatever the magic number is and I think if you start off with a good high utilization in negatives I think you can build cells for less excess negatives and that's based on one assumption, that the negative plate design and the negative process is such that it maintains a fairly effective utilization through the life of it.

GROSS: What about the existence of minimum discharge cadmium and a minimum of precharge? Is there any data on this? Anybody know about the existence of such a minimum? Harvey?

SEIGER: It's going to be a little difficult because we haven't got everything for the electrochemically impregnated plates, but for the vacuum immersion I did determine that there were some minimums. And the minimum--remember anything I say is on early cycling, they're not long term, long range. I'm not testing cells to death. I find that first, that there's an interaction between the positive and the negative, that if I want to maximize the dischargeable capacity of positive electrodes I need a precharge. And the amount of precharge comes out to be about 20 percent of the positive capacity, I have to put that onto the negative.

I find that there is some other number that raised itself, that if at the end of charge if the negative electrode was in excess of 90 percent charged semidry --

MILLER: Let me interrupt you if I can. This precharge has been bothering me for a long time.

You just made a comment that you put the precharge in it so you get the full positive capacity, is that what you said?

SEIGER: That's what I found.

MILLER: What do you want to use a full positive capacity --

SEIGER: Because I want to maximize things.

MILLER: Because when they put the cell into use they only use 60 percent, 50 percent 30 percent --

SEIGER: I still have to get capacity. I don't know all the answeres, but I would still like to finish answering the question. When you are working these two numbers, that you ought to stay below 90 percent, state of charge of the negative at the end of the charge--and I think I would like something like 80 percent--there is a ratio that works out of that that is about 1.25 or 1.3 to 1.

MILLER: As I see some of the failure modes --

SEIGER: That might not be a minimum.

BOGNER: We're running out of excess capacity on the high end, why not start out with the cell new. There's no precharge in it and let it build up? Has that been tried?

DUNLOP: Yes, it has, but with no precharge you still have about 10 percent--the nickel cadmium is about 10 percent. That's what you can't utilize so that no matter what you do you start out with about 10 percent.

BOGNER: I didn't mean to interrupt you too much Harvey.

SEIGER: I think I have finished that. Now that we're talking about electrochemically impregnated negatives reducing higher utilizations as I said earlier, we're seeing utilizations in excess of 90 percent for negative electrodes. But if you ask me what is it a thousand cycles down stream at low earth and synchronous orbit, I have no answer. But I do see the high utilizations and I'm still waiting. Are we writing a statement of work here, are we going to get money to start investigating to learn these things? Or are we just going to just talk about it? It's fun talking about it.

BOGNER: We have to find out what we really know now before we can write an adequate --

SEIGER: Let me point something out, as we look at these new E. I. electrodes we see lots of differences. We see--we have determined that the corrosion in both the positives and the negatives is less than one percent. If you're really fastidious, you can wind up with a process in which there is no corrosion. Whereas if you do the vacuum immersion as Ed Mc Henry pointed out the corrosion is very little at the beginning, but as you keep cycling, impregnating in the Fleischer process the corrosion, or the rate of corrosion accelerates. And that's why there is so much corrosion in that. We have differences.

Let me point out something else, here we have electrodes that are delivering like 25 percent more capacity per unit volume at a full discharge, in a positive electrode. Now if we take advantage of that, that additional 25 percent, I want you to look at it as the number of ampere hours that's discharged from the unit volume. We are stressing that more. We are stressing it 25 percent more and that depth of discharge is probably not the right parameter if we want to understand what's going on.

We should talk about how many ampere hours we are extracting per unit volume, not depth of discharge. The negatives, we see high utilizations, we see the surfaces bare--that most of the material is inside. I can't tell you a thing about how it will perform later on. We have to learn these things, maybe we can pull down those ratios, with the high loading levels, and the high utilizations we should be able to pull down on the design of the negative and increase the watt hour per pound ratio. But you are going to have a sacrifice as Floyd pointed out between the energy density and the negative/positive ratio. It showed up in the computer design too.

VERVILLE: I would like to make a comment that kind of ties in. I think we're going around the point.

We're trying to improve the utilization and we're trying to improve the loadings. Has anyone looked up the fair size distribution we have on the plates? Not just the total porosity per se, because some of the things we did a long time ago tells us that if we had large pores we would get better utilization because we have a larger surface area to work with. More current densities than if we had many small pores. Many small pores were clogging it up when we're impregnating it so our total surface area is less. Now because as Floyd mentioned earlier, when we're doing a weight gain sometimes we have a certain capacity, sometimes you don't have a capacity. Could this be because we do not have a uniform pore size distribution? If we did have a uniform pore size distribution, or if we could say that the optimum pore size is a certain volume then we may get more uniformity, we may learn a lot more. Has anyone looked at that aspect?

SCHULMAN: I think SAFT in France has records on pore size distribution since they started sintering. I don't know exactly what they do with these records, but I do know they have a complete set of records of pore size distribution on every lot sintered.

VOICE: Do they have uniform pores?

SCHULMAN: They have a distribution, I don't know what you mean by uniform pores. Every process has a distribution.

DUNLOP: Just one comment on that. SAFT made us a bunch of electrodes with different loading levels with the same plan and one of the things they did do is a micro pore symmetry measurement on those electrodes. These were positive electrodes. One of the amazing things about that was something I mentioned earlier was that it was cycling. We started out with one thing and then with cycling we get significantly different pore size distribution with time.

SCHULMAN: One other comment I would like to make about this corrosion business on the positive plates on the vacuum impregnation. You should understand that the vendor depends on corrosion for about 15 to 20 percent of his total high grade positive loading. So that corrosion of the positive plate is not done by chance but is rather done by design.

GROSS: You can't get away from it.

SCHULMAN: Yes, you can. You can decrease the amount of positive corrosion by working your acidity just to prevent the--oh, just to go against the solubility product of your nickel hydroxide and your cadmium hydroxide. In other words you can work it up to a point.

MILLER: I would like to back up to the positive/negative ratio. One comment on the pore size distribution. I think probably Bell had done more work in that area recently. Maybe one of them would like to make a comment on it after I finish here. I don't think that anyone can really answer the question what is the optimum negative/positive ratio? Or what is the optimum distribution between the charge and discharge species? I think we can't do this for the same reason that we can't say whether the high energy density nickel cadmium is reliable or not. We can answer the short term question. We know that the high negative/positive ratio results in a cell that gives you very good oxygen recombination characteristics. Gives you a low charge voltage particularly at low temperatures, but I don't know of any test that ran for 7 or 10 years in which we had the ratio at 1.3 and a ratio at 1.7 and the distribution at 30-70 or 40-50.

GROSS: One thing we can do Lee is look at how the present designs are working. If we have a cell that has been made to 1.3 ratio or some other number and they are becoming negative limited we think there is a pretty good chance we should be raising that number. So, the first thing to do is look for the data to guide us and that is why I raised or put the first question up on the slide asking the question are today's nickel cadmium cells negative limited much of the time? And secondly, should we permit negative limited operation some of the time? Because if we don't then we're going to have to raise the negative/positive ratio and this is going to cause us--this is going to cause us weight. So, I think that there are many occasions when we do operate negative limited and we have to establish if there is a requirement whether or not we are going to allow it. Floyd?

FORD: You're talking about negative limited on--are you distinguishing between the high side and low side, top end and bottom end?

GROSS: I'm talking about discharge.

FORD: Okay.

GROSS: Cells work pretty good when they're new, then after they have been cycled, especially in low temperature or a higher rate they become negative limited. This happens all the time. If we insist that they are not negative limited under those conditions, then we are going to have to improve or change the cell designs that we are using today.

BOGNER: The material would be negative limited, Doug, how do you say they're negative limited?

GROSS: I'm asking for the data. I have the impression that sometimes they are.

SCOTT: I have a lot of data which says that at high depth-of-discharge they certainly are, but I think that we have to also consider what factors contribute to this condition. Possibly, if we could maintain the utilization of the negative that we would not have to put in more to begin with and I would think that we would want to look at that. As far as I know, I don't know whether everybody, or anybody understands clearly what factors contribute to the long term utilization of the negative electrodes. Certainly electrolyte must. So we come back to the electrolyte starvation problem or distribution problem again. I think those two problems probably have to be looked at together.

MC HENRY: Well, our problem is the same today as it has been from the very beginning. We are the users, we wish to buy a small number of cells. The people who make them will sell us what they have got, and they are not going to put an effort into making what we want. The reason is because they can't make money and we can not expect them to try to make what we want and then go out of business for having spent all their money on the research and we still only want to buy one of them after they have gone to all this trouble. So if we want the thing, there are millions of dollars of money that has to be put into building this thing, scaling it up, making the same thing two times in a row. We can't do that. They have never been able to make two electrodes that are the same, and the reason is they can't make money doing it. And we have to somehow--I think we should forget the battery manufacturers' altogether and somehow set up a small company, everybody feeds in a little bit of money. They do this you know. What we want is simply distant from what they want to give us, and you can talk for a thousand years and they will still never make anything the same way twice and you can run all the tests you want, but you've taken the first step in an arbitrary direction and then whatever you learn from this first step is useless because you don't know which way you went in the first step--you know--you don't know what you started with. So your results mean nothing. You know, not totally nothing but we're always hampered by the fact that you don't know what we started with and there is no way in this world that we can ever get the same thing again unless you just either spend the money yourselves or pool it and have somebody do it.

But that is our trouble, we can't get started. We can't do the same thing twice. And until we do you aren't getting anywhere and there's no sense talking to battery companies because they aren't going to do it.

BOGNER: Well I'm sure we could go on with this for several hours.

MILLER: I think the battery manufacturer makes every effort to give you what you want. I think he goes out of his way to give you what you want. He has to make a profit that's true, it's a necessity to stay in business. I am not sure just specifically what areas you are having a problem with, but it costs more to give you exactly what you want. Is a battery manufacturer to be held responsible for this? He has to operate in our economy and this costs so much. If he were actually misleading you or decieving you or something that would be another question.

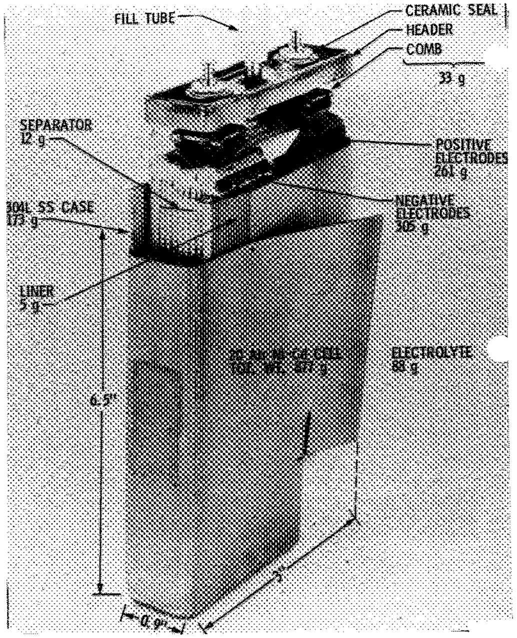


Figure 138

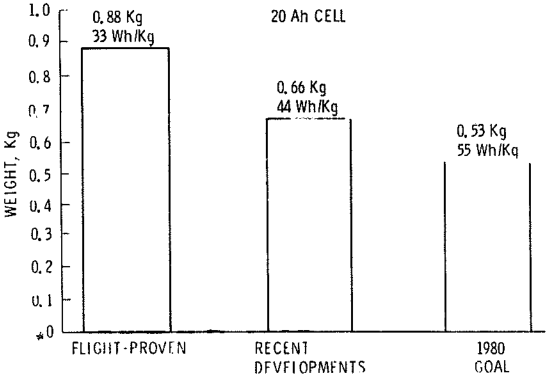


Figure 139. Coordinated NASA Ni-Cd Battery Technology Program, Energy Density Factors.

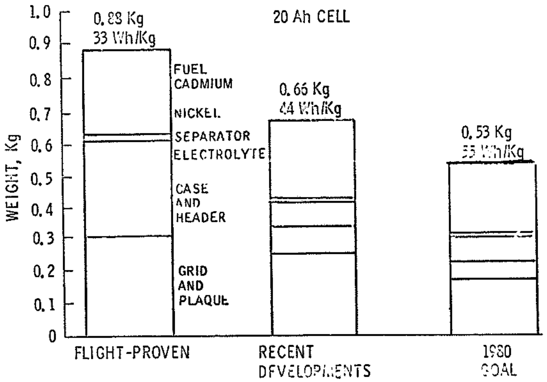


Figure 140. Coordinated NASA Ni-Cd Battery Technology Program, Energy Density Factors.

Figure 141

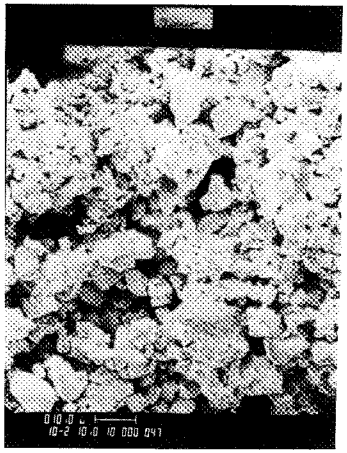


Figure 142

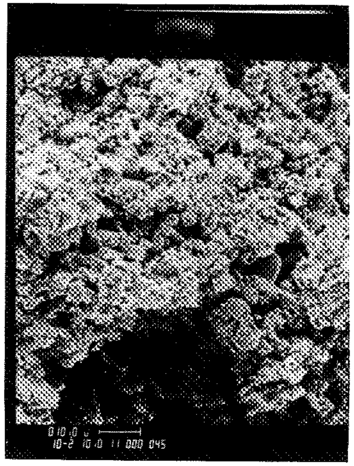


Figure 143

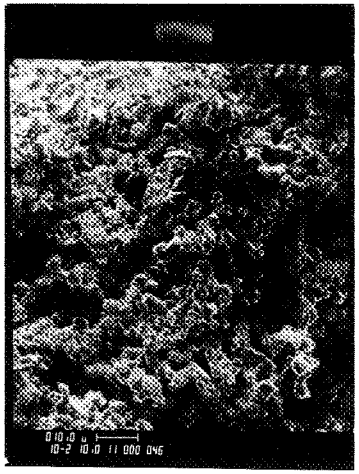


Figure 144

RELIABILITY & LIFE

POSITIVE ELECTRODE THICKENING
CADMIUM MIGRATION
ELECTROLYTE REDISTRIBUTION
SEPARATOR DEGRADATION
SINTER CORROSION
STABILIZATION OF O_2 RECOMBINATION RATE
NITRATE & CARBONATE ELIMINATION
AUXILIARY ELECTRODE STABILITY
VIBRATION EFFECTS

Figure 145

ELECTROCHEMICAL DESIGN PARAMETERS

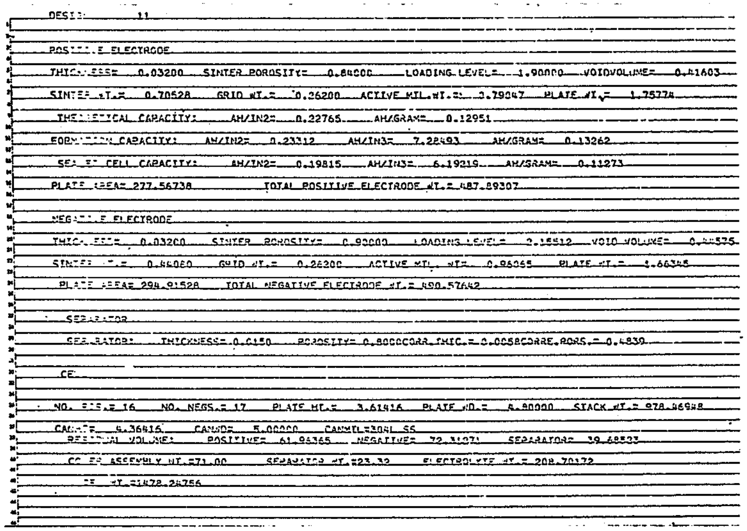
ELECTRODE
1. POROSITY
2. THICKNESS
3. VOID VOLUME
4. LOADING LEVEL
5. GRID WEIGHT
6. SINTER WEIGHT
7. PLATE WEIGHT
8. NUMBER OF PLATES
9. PLATE AREA
10. CAPACITY
11. UTILIZATION
12. RESIDUAL VOID VOLUME
13. CHARGE CURRENT DENSITY
14. NEGATIVE TO POSITIVE CAPACITY RATIO

SEPARATOR
1. MATERIAL
2. DENSITY
3. THICKNESS
4. INTERELECTRODE SPACING
5. AREA
6. POROSITY
7. RESIDUAL VOID VOLUME

ELECTROLYTE
1. FILL LEVEL
2. DENSITY

THERMAL CONDUCTIVITY OPTIMIZATION
1. PLATE WIDTH TO HEIGHT RATIO
2. PLATE THICKNESS
3. INTERELECTRODE SPACING
4. ELECTROLYTE FILL LEVEL

Figure 146



```
DESIGN        11

POSITIVE ELECTRODE

THICKNESS=  0.03200  SINTER POROSITY=   0.84000    LOADING LEVEL=   1.90000   VOIDVOLUME=   0.41603

SINTER WT.=  0.70528   GRID WT.=  0.26200   ACTIVE MTL.WT.=   0.79047   PLATE WT.=   1.75774

 THEORETICAL CAPACITY:    AH/IN2=   0.22765    AH/GRAM=   0.12951

FORMATION CAPACITY:    AH/IN2=   0.23312    AH/IN3=   7.28493    AH/GRAM=   0.13262

 SEALED CELL CAPACITY:    AH/IN2=   0.19815   AH/IN3=   6.19219   AH/GRAM=   0.11273

PLATE AREA= 277.56738          TOTAL POSITIVE ELECTRODE WT.= 487.89307

NEGATIVE ELECTRODE

THICKNESS=  0.03200   SINTER  POROSITY=   0.90000    LOADING LEVEL=   2.15512   VOID VOLUME=   0.44575

SINTER WT.=  0.44060   GRID WT.=   0.26300   ACTIVE MTL. WT=  0.96065   PLATE WT.=   1.66345

 PLATE AREA= 294.91528   TOTAL NEGATIVE ELECTRODE WT.= 490.57642

  SEPARATOR

  SEPARATOR:   THICKNESS= 0.0150   POROSITY= 0.8000CORR.THIC.= 0.0058CORRE.PORS.= 0.4839

 CELL

NO. POS.= 16   NO. NEGS.= 17   PLATE HT.=   3.61416   PLATE WD.=   4.90000   STACK WT.= 978.46948

CANHTE=   4.36416    CANWDE=   5.00000    CANMTL=304L SS
  RESIDUAL VOLUME:    POSITIVE=  61.94365   NEGATIVE=  72.31071    SEPARATOR=  39.68523

  COVER ASSEMBLY WT.=71.00      SEPARATOR WT.=23.32     ELECTROLYTE WT.= 208.70172

    CELL  WT.=1472.26756
```

Figure 147

PERCENT WEIGHT SAVING VERSUS STANDARD 20 AHR
RSN-20-3 SEALED CELL (825 GRAMS, 17 WHR/LB.)

DESIGN	A	B	C	D
ELECTRODE GROUP	17%	17%	23%	40%
CELL CONTAINER AND TERMINALS	58%	80%	80%	80%
ENERGY DENSITY	22 WHR/LB.	24 WHR/LB.	26 WHR/LB.	31 WHR/LB.

DESIGN A - LIGHTWEIGHT 304L SS CONTAINER (12 MIL) AND TERMINALS.
DESIGN B - HIGH STRENGTH INCONEL 718 CONTAINER (5 MIL) AND LW TERMINALS.
DESIGN C - HIGH STRENGTH INCONEL 718 WITH ELECTROCHEMICALLY IMPREGNATED ELECTRODES.
DESIGN D - LW NICKEL MATRIX WITH INCONEL 718 CONTAINER AND ELECTROCHEMICALLY IMPREGNATED ELECTRODES.

Figure 148

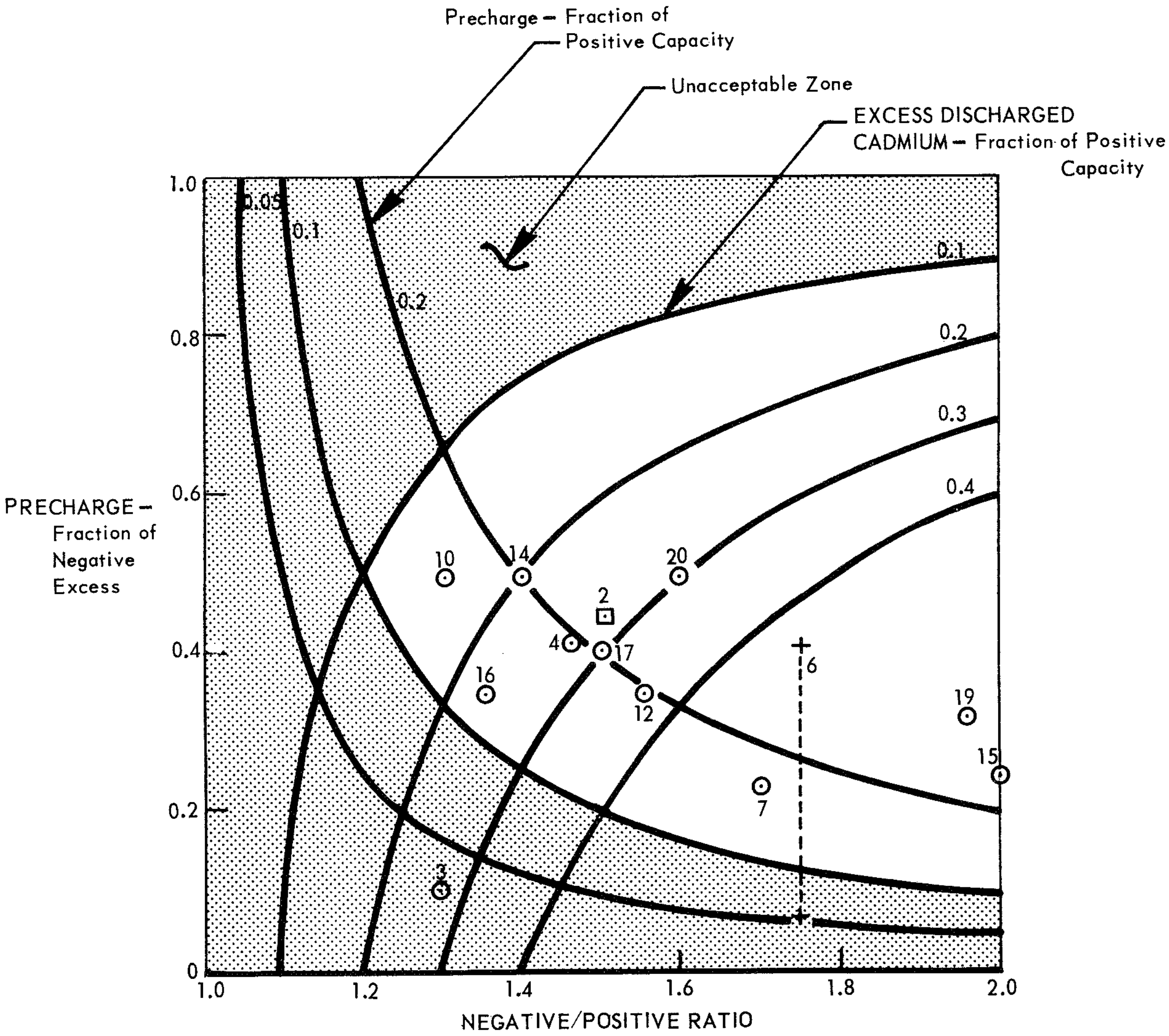

Precharge — Fraction of Positive Capacity
Unacceptable Zone
EXCESS DISCHARGED CADMIUM — Fraction of Positive Capacity
PRECHARGE — Fraction of Negative Excess
NEGATIVE/POSITIVE RATIO
1.0
0.8
0.6
0.4
0.2
0
1.0
1.2
1.4
1.6
1.8
2.0
0.05
0.1
0.2
0.1
0.2
0.3
0.4
10
14
20
2
4
17
16
12
6
19
15
7
3

Figure 149

SPECIAL PRESENTATION

Gerry Halpert: At this time I would like to turn the meeting over to Floyd Ford of GSFC who will make a special presentation.

Floyd Ford: Most of you have known Tom Hennigan longer than I have but I have one advantage, I had the opportunity to work for him for the better part of 10 years and never a better supervisor or boss have I ever had or would ever hope to have than working for Tom Hennigan.

As you know, Tom, along with myself and a number of others who have been part of this workshop, we felt that since you retired this year it would be appropriate to give you a small but yet a very sincere form of recognition for what you have done, what you have meant to us here at Goddard and we hope what you have meant to those out there in whatever company or industry you come from. So without further delay I would like to present to Tom Hennigan a scroll signed by all the participants at Goddard and those attending the 1976 Workshop in recognition of his contribution. It reads as follows, "This scroll is presented to Thomas J. Hennigan by the participants of the Goddard Space Flight Center Battery Workshop in recognition of his many years of devoted effort and dedication to disengaging the art from the science in Aerospace Cells and Batteries. Presented this 9th day of November, 1976." Tom.

(Applause)

Tom Hennigan: This is really a surprise.

(Laughter)

I'm kind of speechless. I really appreciate this scroll you have presented to me. It seems like we have made progress, or at least we are now more aware of what's going on. I can remember our first workshop, nobody even knew what the separator material was made from. Some had the suspicion it might be nylon.

(Laughter)

But I think it is the progress we have made that allows us to speak intelligently to the battery manufacturer and when he talks to us, we know what he is saying. I think we have reached--let's say the engineering stage, the science stage is up to you.

(Applause)

Second Day Morning Session

TEST AND FLIGHT EXPERIENCE

W. Webster, Chairman
Goddard Space Flight Center

We are going to present several papers this morning on battery reconditioning and flight experience. The work that we are doing at Goddard is an engineering evaluation on the limitation of parallel battery operation; that is, if you have two batteries being charged off a single charger and there's a delta T between one battery with respect to the other, what will happen to the pressure? What happens to the end-of-charge current? In addition, we are evaluating the eight-level charger that appears in our standard specification.

We are also doing some base line tests on two 22-cell batteries. Each battery contains one-third electrode cell and two pressure transducers. We have finished the base line tests, and we've started that portion of the test program where we are deliberately offsetting the temperature of one battery from the other, and we're controlling the charge voltage of the hot battery. It is anticipated that we'll be through the temperature matrix by Christmas; at least that's what project management would like. If we make this schedule, our next phase of operation will be to mismatch the impedance between the two batteries and see what effect this has. Then, we will change the state of charge between the two batteries, having one lower than the other. And the last thing we will investigate is the effect of a shorted cell.

So, while I do not have a presentation available, we hope by this spring there will be an X-Document explaining what the problems and solutions are. We hope it will be of benefit to the power system community. In conclusion, we have established a standards office at GSFC with a new approach towards standardizing the manufacture and design of batteries.

RECONDITIONING OF RCA SATCOM BATTERIES IN ORBIT

J. Napoli
RCA American Communications

I'd like to give you a little background on the SATCOM cell, their history, and how long they're operating. The SATCOM design is a direct energy transfer power system. We have three batteries of 22 cells each, and on a parallel charge; that is, each battery has its own charger. And they have 22 cells in each battery.

The first F-1 spacecraft was launched in December of 1975. We have just about completed one year's operational experience or history with the cells. We have reconditioned the cells twice in orbit, down to about 0.091 volts per cell, and I'd like to show you some of the curves that we've generated from telemetry. These curves are actually telemetry data. There's no averaging, there's no smoothing of curves just to make a nice presentation. So if you see some points that really are not explainable, it could be possible because there are load differences in the spacecraft at the time the telemetry was taken.

These batteries were put together by the RCA Astroelectronics Division in Princeton, New Jersey, and they're GE cells.

(Figure 150)

The basic cell design characteristics are shown here. They're 12-ampere hour nameplate, with an actual capacity down to the operating voltage of the system of 14-ampere hours. We have teflonated negatives; I guess the other programs have that too, with the IUE program, that I know of that's current. We have a single positive isolated or insulated terminal. Again, there are 22-cells per battery.

(Figure 151)

The operating characteristics of the battery are shown. We have 58 percent maximum DOD discharge during the peak eclipses, and that's 58 percent of the nameplate rating. We actually have 48 percent of the 14-ampere hour capacity.

On the second spacecraft--I mentioned the first spacecraft was up since December. The second spececraft was launched in March. That's what we designated as the F-2, and it has gone through one and a half eclipses, and it has only seen one full reconditioning. And that was during this part full eclipse. The F-2 has a daily depth of discharge of 28 percent.

The batteries have three different charge modes, both on F-1 and F-2. We have C/10--a high charge rate--and we have C/20, which also includes a V/T taper. And then we have a C/60 charge rate. The operating temperatures are between 2. 5 to 15 degrees C average, and we recondition batteries at the cell level, twice a year.

(Figure 152)

This chart shows the actual F-2 voltage during reconditioning. And the Xs that you see on the plot, which are not filled in, are the actual temperatures when we go through the reconditioning cycle. As you can see, we started out at approximately 32 volts, and this is the time it takes to come all the way down to 2 volts per battery. We do not monitor the individual cell voltages. We actually throw 1 ohm shorting resistance across each of the cells, and then we monitor the terminal voltage on the whole battery pack at this point.

NAPOLI: At this point over here, we had to interrupt the deep discharge, because the temperatures were getting rather high, and they actually got up to about 25 degrees centigrade. So we took the batteries off deep discharge, and you can see temperatures drop down again at this point. We resumed the deep discharge, so you can see this is why this voltage came up at this point. And we continued discharging down to 2 volts, and as soon as we took the batteries off deep discharge, it automatically shot right back up to about 25 volts in a short period of time.

I indicated that was one of the F-2 batteries.

(Figure 153)

This was the F-1 battery. This is on a different scale. This is the F-1 battery prior to going into the spring eclipse of this year. You can see that the curve pretty much follows the same pattern, except again, we had to take the batteries off of deep discharge, because of temperatures generated by internal heating.

VOICE: What's the time scale?

NAPOLI: The whole process takes from 1600 to about 1900 the following day. It's about 24 hours to complete the whole thing; that's including the disabling of batteries. Normally, the total time on discharge is about 21 hours.

We looked at the time on deep discharge from one eclipse reconditioning to the next, and there's only a disparity of about five to ten minutes of total time for the discharge for getting down to 2 volts. So, if you're looking at how many ampere hours we took out, it's about a five to ten-minute difference, and I think that's in the noise. At least, we think so.

What does this all mean when you want to see what the effects of reconditioning are?

(Figure 154)

Well, this is a plot of points that are plotted approximately every two to three days on the F-2 battery. I'll go through this chart rather slowly. The points that you see here are points for the three different batteries. Again, it's raw telemetry data converted to engineering units, and the curves are not smoothed out for the sake of presentation.

This is at calendar day 104, when we finally went operational with the full load. At approximately day 234, which was about a week before going into the full eclipse, we reconditioned the batteries. And then the very next end-of-discharge voltage; these again are plots of end-of-discharge voltage during the daily 28 percent DOD on the F-2 spacecraft. After reconditioning, you can see that the end-of-discharge voltage came up pretty significantly. In fact, it's higher than what it was at the very beginning of operational life. It's down to where I guess you would consider a virgin cell or pre-cycle kind of performance here.

Plotted along with this--I only have one point here, because we don't have daily discharges on the F-1 spacecraft--we have the F-1 end-of-discharge voltage after this reconditioning at around the same time. So the asterisks and the square with the dot are the F-1's, compared to the F-2. So you can see that they are approximately around the same.

Now, we continued plotting the F-2 data. And as of last week, which was approximately day 304 in the year, you can see where the voltages have come down to. So you can see that there is, at least from day 234 to day 305, better than two months--you can see the kind of improvement we have after reconditioning. Two months thereafter, you can see that we still are maintaining end-of-discharge voltage levels higher than we were prior to going into the reconditioning.

We don't know, again, what the real, long-term effects are, and we hope to get a better handle on it. We think right now that this will be an improvement in maintaining our capacity at an operating system voltage for the next, hopefully, seven to eight years of the spacecraft's life. These batteries are designed to give us an eight-year mission. I'm sure lots of you will feel it's a pretty optimistic goal. But in the common carrier business, in the commercial satellite business, this is what we're designing our spacecraft for.

That's about the end of my presentation. Again, it's just really an experience that we're going through right now. I don't know of anyone else--possibly, maybe some military programs--that are doing reconditioning down to approximately 0 volts per cell. I don't have--I haven't seen any data in orbit. I think this is about the first that I've seen available.

KRAUSE: Hughes

On your F-2, are you cycling those batteries on a daily basis ?

NAPOLI: Yes. On the F-2, we have to rewind the solar panels about 360 degrees, because of a spacecraft blockage. It's an RF cable that got in the way of the solar array drive during the launch. And we actually can go through it, but we'd rather not. The solar array drive is designed for a military program that rotates on a daily basis anyway.

So we do have a pedigree of the solar array rewind on a daily basis. So it's an automatic operation that we have as a result of a daily DOD of 28 percent. But that, again, is 28 percent of nameplate, not of actual. That's based on the 36-ampere hours. If you worked it around 14-ampere hour capacity, it would be less than that.

CELL DESIGN CHARACTERISTICS

- 10 AMP HOUR NAME PLATE (12 A. H. ACTUAL)
- TEFLONATED NEGATIVES
- PRISMATIC CELL CASE
- SINGLE POSITIVE ISOLATED TERMINAL
- 22 CELLS PER BATTERY

Figure 150

BATTERY OPERATING CHARACTERISTICS

- 58% MAXIMUM D.O.D. DURING ECLIPSE
- F-2 DAILY D.O.D of 28%
- C/10 C/20 AND C/60 CHARGE RATES
- OPERATING TEMPERATURE 2.5 TO 15°C AVERAGE
- RECONDITIONING AT CELL LEVEL TWICE YEARLY

Figure 151

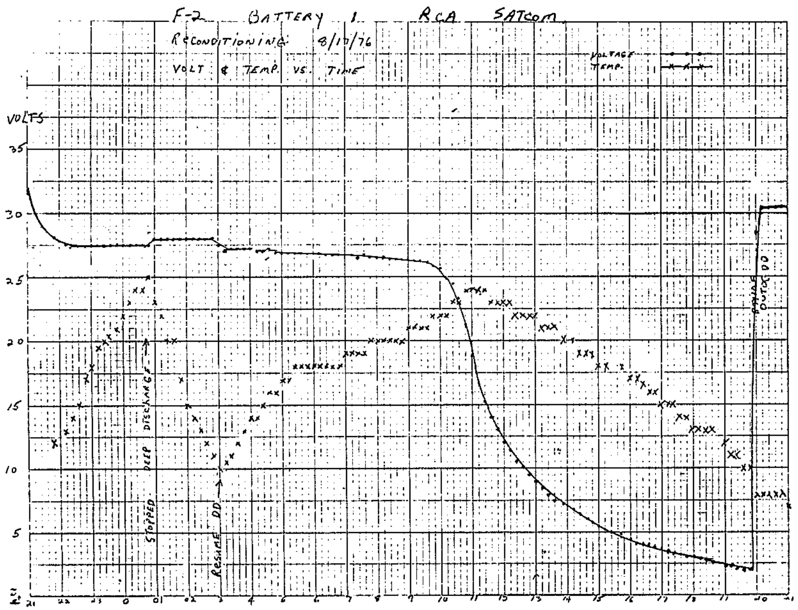


Figure 152

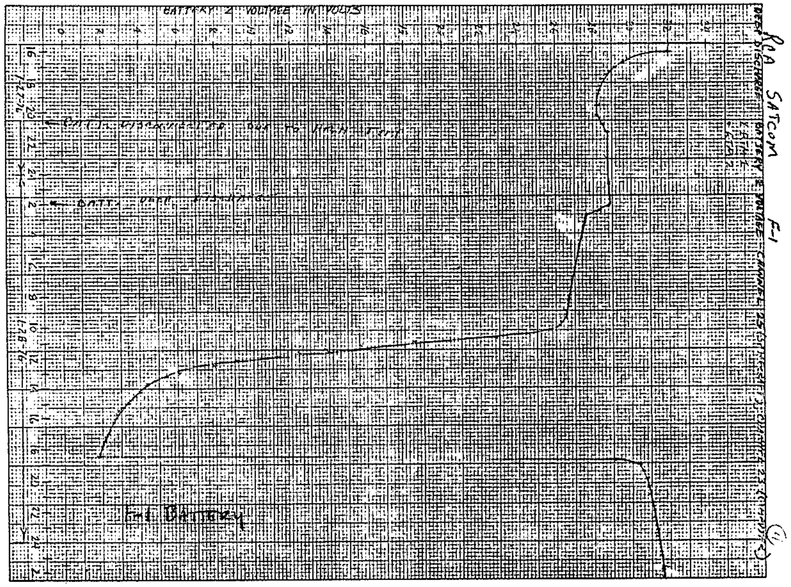


Figure 153

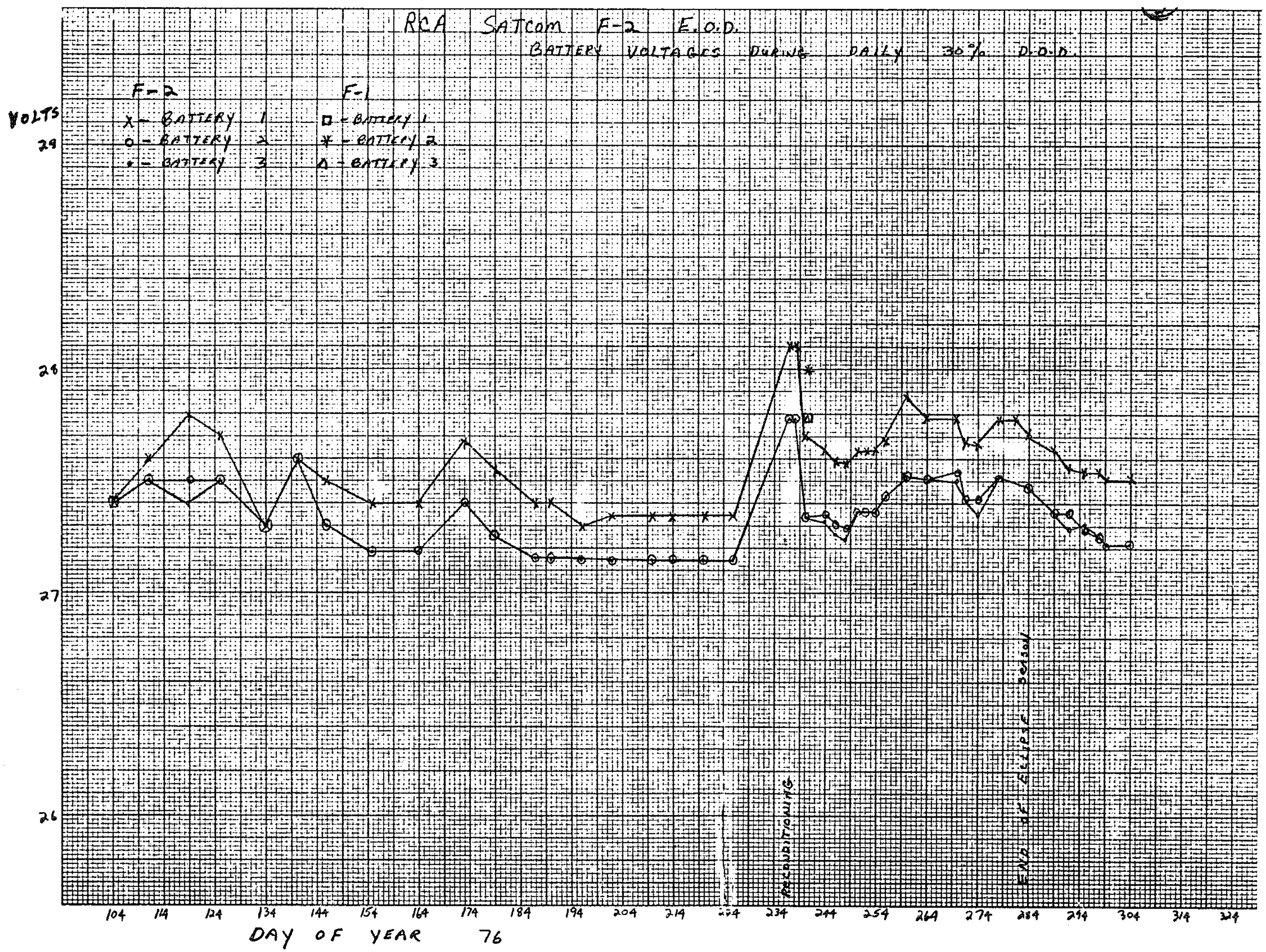
RCA SATCOM F-2 E.O.D.
BATTERY VOLTAGES DURING DAILY 30% D.O.D.
F-2
X - BATTERY 1
O - BATTERY 2
• - BATTERY 3
F-1
□ - BATTERY 1
* - BATTERY 2
Δ - BATTERY 3
VOLTS
29
28
27
26
RECONDITIONING
END OF ECLIPSE SEASON
104
114
124
134
144
154
164
174
184
194
204
214
224
234
244
254
264
274
284
294
304
314
324
DAY OF YEAR 76

Figure 154

PERFORMANCE CHARACTERISTICS OF RECONDITIONED BATTERIES ON THE CTS

J. Lackner
Defense Research Establishment, Canada

Today, I'd like to present some real-life data on battery reconditioning that we have with our Communication Technology Satellite. CTS is an experimental geosynchronous communications satellite that was launched the 17th of January, 1976, from Cape Canaveral, as part of the joint U.S./Canadian program between the Communication Research Center, Department of Communications, and NASA/Lewis Research Center.

The batteries are two 24-cell, nominal, 5-ampere hour nickel-cadmium cells, and the essential cell characteristics are: GE manufacture, bought to CRC specifications, EQ 0401 and EQ 0402; polypropylene separator, low carbonate, low pre-charge, with a maximum of 20 percent pre-charge, and an enhanced high-temperature design.

The operational characteristics: both batteries are permanently connected to the housekeeping buss through a common diode rail. They are operating in a parallel mode which places them in diodes. The common diode rail has a drain of 30 milliamps on each battery, resulting in a daily DOD of around 12.5 percent on each battery; or, if one battery took the whole load, it would be 25 percent. Recharge can be at C/10 or C/20 to a 1.4 charge/discharge ratio.

During the eclipse season, the power demand is a maximum 60 percent DOD on each battery during the peak eclipse day. In the worst-case conditions, one battery may have to supply 85 percent DOD in the temperature range of minus-5 C to plus-40 C. So far, we haven't had the worst-case condition.

The spacecraft operates at a design temperature of 25 C, with a passive thermal control. However, battery heaters are available in case of low temperatures. During ground testing, it was possible to monitor individual cell voltages. However, once in orbit, only the total battery voltage was available. The recondition interval was approximately every eight weeks, but definitely at least once before an eclipse season, and once after an eclipse season.

Now, to give you a brief spacecraft chronology: the cells were built in the period between January and April of 1974. They were tested in-plant from April to June of 1974, and they were delivered on the 24th of June, 1974. We did qualification tests at CRC between July and December of 1974. An engineering model battery was installed in August 1974. The engineering model stayed on the ground. Flight batteries were installed in May 1975, and the spacecraft ground tests were from May to December. The launch was the 17th of January 1976. The spacecraft arrived on station, and the solar array deployed, on the 1st of February 1976. The first eclipse season was mid-March, 1976, to about mid-April, 1976. The second eclipse season was 1st of September to the 16th of October 1976. So we have two eclipse seasons under our belt.

The recondition cycles were done on the 8th of September 1976; that is, after three months of ground tests. A month later, after we'd gone through thermal vac at NASA/Lewis, one month before launch at Cape Kennedy, and after we had arrived on station with the solar arrays deployed in February, we did another reconditioning; and one before the first and one after the first eclipse season.

(Figure 155)

This slide is on the engineering model--it shows us some of the observations that reconditioning does give us a positive benefit, particularly if it's possible to discharge each individual cell down to 0 volts, and if it's possible to maintain battery capacity to at least 95 percent of nominal, measured to 1 volt in the discharge.

Now, in the engineering model, we were able after one year of ground tests to take the battery out and discharge it down to 0 volts with individual cell control. As the capacity came out--this is the capacity that we got if the battery came out, so we're hitting about 4 amp hours under very low voltage--after we had given it one reconditioning, we were able to get back our nameplate capacity. And we gave it a second reconditioning, and we were able to get just about the maximum. The battery has an actual of around 5.5 amp hours.

(Figure 156)

The effect of a double recondition is better than a single recondition. But for maximum benefit, the second recondition should be as soon as possible after the last one. Otherwise, any material that you may have reactivated seems to get covered over again.

Now, on October the 20th--this was after the second eclipse season--we seem to have a drop-off. This is the value we had just before we went into the second eclipse season, and you'll notice there's sort of a drag-out characteristic. When we reconditioned right after, we gained a lot of wattage and improved things. This is a deeper discharge, down to about 0.9, 0.85 volts per cell. And we're still getting a slight curve; it isn't dropping straight down.

WEBSTER: Joe, what is your right axis?

LACKNER: The right axis refers to the deeper discharge. These three curves here refer to--the left-hand axis, once we hit 24 volts here, we continue discharging down, and we're now referring to this axis here. We didn't want to change the graphs to include that scale.

(Figure 157)

There appears to be a drop--there's a definite shift to a lower voltage discharge curve with time, showing a slow drag-out voltage characteristic. And all of these reconditions were done to a 1-volt average cutoff, or to 24 volts for the total battery.

Now, September the 27th, this recondition was done at NASA/Lewis, and we had individual cell control, where we could monitor the cells until the lowest drop-off came. So we were able to get the maximum out of the battery. After that period, we were only able to monitor the total battery voltage. So we got a bit of a drop-off in capacity between the ground tests at NASA/Lewis and just before launch. And to explain that, there were three geographical moves of the spacecraft: the move from Lewis to Goddard, from Goddard to the Cape, and it was rather buttoned up. Some of our heat dissipation was a little bit off. But we still got a nominal.

There were several reconditions in between. But on August the 15th, just before the second eclipse season, you notice we're getting a lower voltage. And over here, there's sort of a drag-out characteristic, as if there's a shift to a lower voltage.

Now, some of the things we noticed; that there appears to be a drop in the end-of-charge voltage, as noted during the daily recharge periods, as the period between reconditions extends. Now, the charge following the recondition, you've got a higher end-of-charge voltage, and a more defined voltage peak, so that when we've put back in what we've taken out, we find the voltage hits the peak and starts to decline a little bit. And if it's a long period after reconditioning, that peak seems to be a little less defined.

Okay. We chose the reconditioning program to maintain our batteries, because we're operating in a non-ideal mode; namely, 25 degrees C ambient, and continuous low-rate discharge of approximately C/200, and a passive thermal control. For reasons of weight, and because we had a two-year mission, we couldn't prevail upon the spacecraft people to put us in a lower-temperature operating mode.

Now, any comments are welcome on the nature of the mechanisms that are taking place during the capacity fading, and on reconditioning. It would be interesting in finding out some non-destructive analytical methods to check some of the cells.

We have a last slide, which shows a new theory we developed to explain what happens inside the battery.

(Figure 158)

FORD: Joe, you didn't address the specific cell design: electrolyte quality, plate loading, etc. Do you have details on that?

LACKNER: I think any details on that, I would refer to my good friend Guy Rampel.

RAMPEL: General Electric

I could refer you to the MCD documents.

SCOTT: TRW

What was the discharge rate used for those discharges?

LACKNER: The reconditions were at the C/3 rate. We had reconditioned resistors put on specifically, and they were 18-ohm resistors. A fixed resistor discharge takes approximately two and a half to three hours.

SCOTT: That's as a battery?

LACKNER: As a battery.

SCOTT: Was it done the same way when you let the cells down?

LACKNER: Right--now, with the exception of the engineering model. With the engineering model, we were able to take the battery out and short out the cells with the 1-ohm resistor.

PASCHAL: Marshall Space Flight Center. How long did you hold the voltage down to 0?

LACKNER: They were held down overnight, 16 hours.

DE BAYLO: RCA American. Did you indicate that you had daily discharge cycles?

LACKNER: Yes, we do. Well, both batteries are permanently connected to the housekeeping buss, and as a consequence, they have a common diode rail drain of 30 milliamps for each battery, or 60 milliamps per watt. They share the load. Whichever happens to be the highest voltage battery will take most of the load. Or, if they balance out, they'll take 30 milliamps. So that works out to be about 25 percent on one, or 12.5 percent.

DE BAYLO: And can you also explain, by the end-of-charge voltage; you said you had a degradation. Do you take the batteries off charge, or--

LACKNER: No.

Normally, if you take a voltage/time curve, when you reach about 100 percent to 120 percent of what you've taken out--now, we have current sensors and a computer, which tell us what we're taking out. And it's designed that once we put 140 percent back in, it tells us we can cut off the charge. Now, at that point, the voltage will hit a peak, and start to decline.

Now, what happens right after recondition; this is at its maximum of around--oh, 35.5 volts. As the time progresses further away, this peak tends to go lower, and it could be as much as a half a volt to 0.7 volts lower before the next recondition.

Now, when we do another recondition, this bounces back up again. And the other thing we find is that this, instead of being a nice peak like that, tends to be like that almost. And we have found out that if we continue the discharge, the computer will say that DOD equals 0 at this point here, which--we have to give it more charge to get the peak.

So, it almost seems as if there's being a--we're not able to utilize the charge, or there's something being covered over that we're not able to get at. And when we recondition, we're able to strip off whatever it is that we've buried deep, and get a more characteristic curve. So what is happening--what are we hiding, what are we fading away, or what is being buried? This is what we'd like to find out.

DE BAYLO: And at the point where you reach 140 percent, do you then cut back to a lower charge rate?

LACKNER: No, we just shut it off. So really, that's not a good way to operate. Because we're either on a low-rate discharge for 21 hours of the day, or on open circuit.

MUELLER: McDonnell Douglas.

I'm still not clear on how you did this reconditioning. As I understand it, you did the reconditioning by discharging on a battery basis. You just hung a resistive load across the battery, and took it down to how many volts?

LACKNER: Up until the 20th of October, we took it down to an average of 1 volt per cell, for 24 volts.

MUELLER: 24 volts?

LACKNER: Now, what we did, having two batteries; you just recondition one at a time. We kept the other one alive.

MUELLER: But you discharge on a cell basis. You discharge on a battery basis.

LACKNER: It's on a battery basis. We have no way of monitoring individual cells once it's in orbit.

MUELLER: Thank you.

HALPERT: Goddard.

Can you tell us how many cc's of electrolyte per ampere hour were in this cell?

LACKNER: I think it's on the order of around 2.5. Does that sound reasonble?

RAMPEL: General Electric

I want to remind Gerry, and the audience too, that what you had said before; the cell had polypropylene separators. And so, you want to relate the number of cc's per ampere hour, and take into consideration that you have polypropylene in the cells. And that makes a difference.

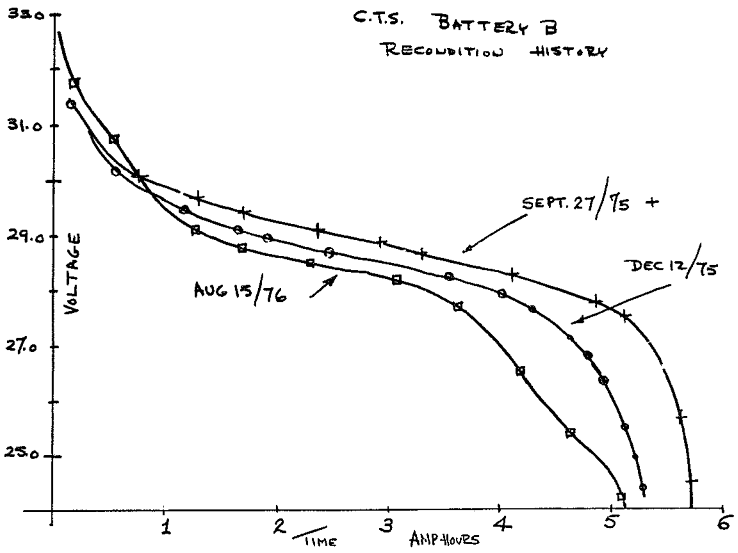


Figure 155

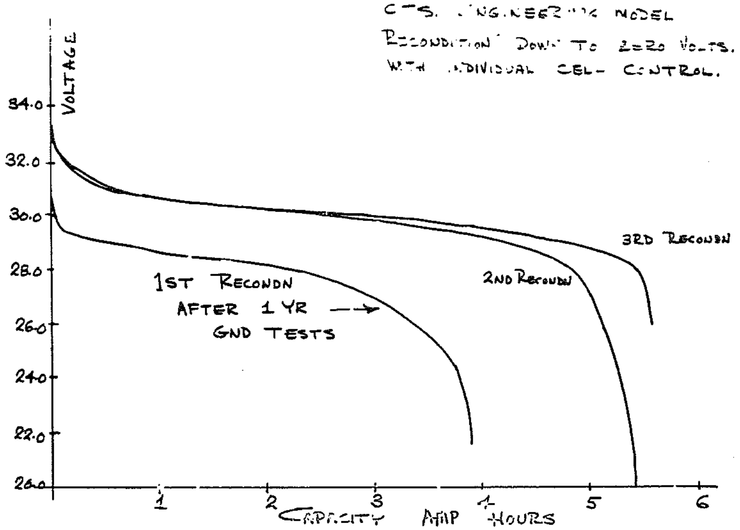


Figure 157

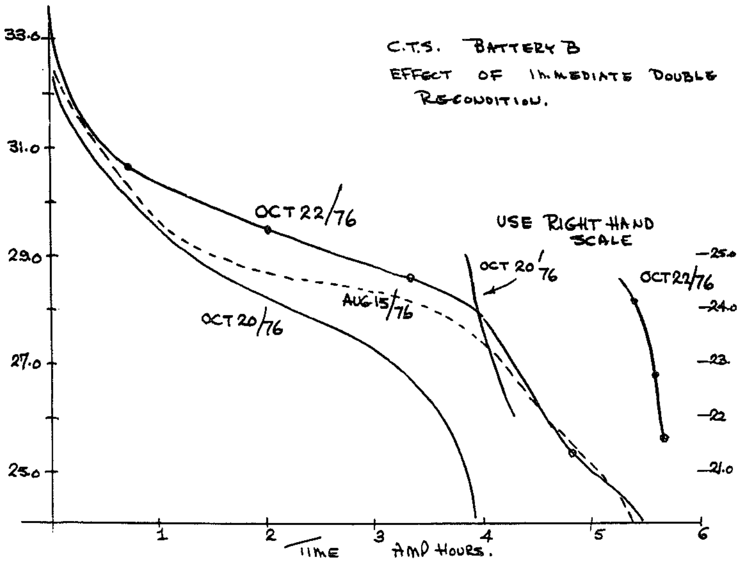


Figure 156

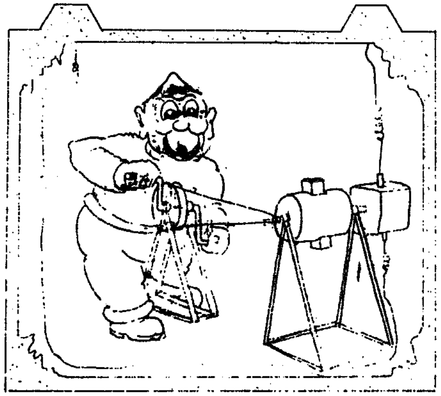


Figure 158

LIFE TESTS AND RECONDITIONING

W. R. Scott
TRW Systems

Before starting my talk about life tests, which take place on the ground, I'd like to respond to one question raised earlier. I believe it was either last year or the year before, we presented a plot of data from a spacecraft in flight, where the batteries were being reconditioned by allowing them to discharge down to 0 volts between every eclipse season. And I don't have that plot with me, but you might check back in the proceedings. And the results have been very good; that is, the end of minimum, end-of-discharge voltage, and the battery capacities, are holding up extremely well.

NAPOLI: RCA

How many years do you have on that?

SCOTT: I believe about three years now.

I'd like to present some data on ground life tests involving reconditioning. The first data I want to present is from the long-life battery development program, where I have the data from two life tests; one lasting for 14 eclipse seasons, and the other lasting for 10 eclipse seasons. These are so-called accelerated synchronous orbit type tests, in that the cycle during eclipse seasons was shortened to 12 hours, and the time between eclipse seasons was shortened to six days. There were no other accelerating factors involved, except the omission of those time periods and operating periods.

The first test data I want to show you is on a battery made with polypropylene separators.

(Figure 159)

Last year, I presented partial results from this test. This plot is the complete test through 14 eclipse seasons, and here we are plotting an average cell voltage and minimum and maximum individual cell voltage. Whereas, I believe the data I showed you before was just battery voltage curves.

As you can see here, the average voltage on the first eclipse season started at about 1.165 volts, trended down here. And at this point, we did a reconditioning after this eclipse season, after number 5. Then, we continued on without any reconditioning until after we had completed eclipse season number 12. We reconditioned again and then continued on until the end of the test.

On this particular test, reconditioning was done by a predesign procedure involving putting the battery on a 10-ohm resistor, and allowing the battery voltage to discharge down to approximately 0.9 per volt per cell average. And that was done the same way both times. You can see that the battery voltage was increased, as you see there at this point, and quite a bit less, if anything, there. But at least the downward trend in the voltage was arrested here, and of course was restored quite a bit there.

WADHAM: Telsat-Canada

What's the depth of discharge on that?

SCOTT: The depth of discharge, the maximum during eclipse season, was 84 percent of nominal, which is very high. This was a development program, and we were pushing for the highest depth of discharge that we felt we might be able to get away with.

I want to point out one more thing, and that is the effect on the individual spread in cell voltages. Notice the first five eclipse seasons, when no reconditioning was done, that the voltage spread became very large, and the lowest cell was below 0.95 volts at this point. Then, that spread was decreased considerably, but not greatly. The lowest cell was still below 1 volt after this reconditioning, and then as you see, it tended on down at the very end. The lowest cell voltage was about 0.5 volt.

Now, I want to contrast that with another similar plot of the same kind of battery, except there was one main difference in design, and that is that the second battery was made with nylon separators.

(Figure 160)

But, I don't think that difference in itself is of great significance right now. Here is a similar plot of 10 eclipse seasons with the same type of load profile and depth of discharge. And here, the battery was allowed to go for five eclipse seasons with no reconditioning.

At that point, the lowest cell was at 0.65 volts. Then, it was reconditioned in the same way that the first battery I showed you was, with the built-in 10-ohm resistor. And here, there was essentially no effect on the voltage trend whatsoever.

Then, after the sixth eclipse season, a special load was arranged, and a 25-ohm resistor was put across the battery, and the battery was allowed to discharge down to about 0.5 volt at the battery terminals. Actually, in this case, 3 volts at the battery terminals. Then, as you see, after that, here was the average cell voltage, and you see the spread into maximum and minimum cell voltages is vastly decreased. As a matter of fact, it was almost the same as it was after the first eclipse season. And following that, no further reconditioning procedures were done, and as you can see, the trend is very much the same as it was at the beginning of the test.

So, during this test, only these two reconditioning procedures were applied; one going to only 2.9 volts per cell, the other going down to 3 volts at the battery level. So actually, you can see that prior to this first or second reconditioning, the behavior of the battery with the nylon separators was actually not quite as good as that with the polypropylene separators.

So, I think the effect that the separators were different in these two batteries, I think, is not the main point to be considered here. The main point is that after a battery has been discharged extensively, particularly at high depths of discharge, the method of reconditioning is very important. And a discharge to a relatively high battery voltage becomes less and less effective as the number of cycles increase. So one has to use a different approach, and discharge the cells to a much lower voltage, in order to obtain a significant effect.

In addition, I'd like to give you an update on the life test which is still in progress on a fleet Satcom battery. This test consists of two 12-cell packs, one of which began the test with no reconditioning. The other began the test with a more or less standard reconditioning procedure, involving discharge down to about 0.9 to 1 volt per cell.

(Figure 161)

The lower dotted curve represents the plot that I just showed you for the polypropylene battery. The upper curve is the data from the FLTSATCOM life test.

This upper curve is from the pack that was reconditioned from the beginning of the test. However, the first part of the test that is indicated here was done at a 63 percent depth of discharge reconditioning to 1 volt per cell; and then to simulate the effect if one battery failed, we shifted to 75 percent depth of discharge and continued on, and again still reconditioning to 1 volt per cell after each eclipse season.

(Figure 162)

This chart adds in the data for the pack that was not reconditioned at all under the same test conditions--the lower curve, as indicated here. And you notice that at approximately the tenth eclipse season or the eleventh, that it reached 1 volt per cell. And at that point, that pack was discontinued.

Its upper curve is the upper curve from the plot I just showed you, on a different scale. And now, at this point, the method of reconditioning was changed from discharging to 1 volt per cell, to letting the battery discharge down to near 0 volts on a fairly high resistor. And at this point, you can see the end-of-discharge voltage increase to this point, trended down here. There was an adjustment of the control temperature, because something had happened to the temperature control. And from there on, we see the results. And right here, we're at eclipse season number 30, with essentially no downward trend in the minimum end-of-discharge voltage.

This test is continuing. We don't know when it's going to quit. There is no indication of any degradation in the cell electrical performance, in the pressure characteristics, or anything else that looks ominous. So we intend to continue this test as long as we can, to see just what the alternate mode of failure may be under these test conditions.

NAPOLI: RCA

Can you state again, what was the temperature associated with this test?

SCOTT: I believe some of the temperature data was presented last year. But for now, the temperature of this test ranges from between about 5 and 15 degrees Centigrade. It operates at near 5 degrees during charging. And then, the temperature is programmed up to around 15 degrees during the discharge, to simulate the spacecraft platform.

NAPOLI: I'm trying to understand why we have note three there; why that recovery is so much better in--what is it--the 20th eclipse season.

SCOTT: As I mentioned here, the control temperature had slipped and allowed this temperature to get up near 25 degrees. And it was readjusted there. I can't be positive that that was the only cause of that shift, but that was, in fact, the only change that was made at that point.

NAPOLI: That's only the single reconditioning? There's no double reconditioning?

SCOTT: No double reconditioning. This process requires approximately 100 hours, because of the relatively low rate. That is, the average rate is around C/100, C/150. Of course, on a resistor, it starts at a higher rate, and of course as the voltage drops, the current drops. And the current at the end of the discharge is about 25 milliamps. This was about 24 for automatic.

MAURER: Bell Labs

Are you discharging the battery, not individual cells, and some cells are going into reverse?

SCOTT: That's correct. In fact, I believe that at the last count, approximately eight of the eleven cells are reversed at the end of this discharge in this pack. The voltage of those cells at the end of the discharge ranges from about minus 50 to minus 150 millivolts. In looking at the charging characteristics, we see no anomalies in terms of charge voltage; that is, the voltage picks up immediately after going on charge, and there doesn't seem to be anything that looks like a shorting effect going on.

BELL: Hughes

Are any of the cells in the life test equipment gauges or pressure transducers?

SCOTT: Yes, one of them is. However, unfortunately, it has turned out to be one of the cells that has never been reversed during the test, so we don't really know exactly, on this test, what the relationship is between reversal and pressure. However, we did have pressure transducers on all cells in the 1 kW prototype life tests, and we do have extensive data in there relating to pressure, with reversal characteristics.

BELL: Did you notice any deformation of the cell case walls?

SCOTT: None whatsoever. I think if we did in this case, in this test, we would probably stop the tests. I'd like to say one more thing. That is that the question of shorting was raised yesterday in connection with reversal of cells during this type of reconditioning. We have observed a total of something like 10 or 12 cells during the various life testing and reconditioning of this type over the last several years, which cannot be driven to a highly reversed potential during reversal or during determination of precharge. That is, when they are discharged into reversal, the voltage will hang up at or between 0.1 and 0.2 volts, and will remain there indefinitely.

SEIGER: What discharge rates?

SCOTT: We have observed discharge rates from anywhere from about C/10 up to C/2. It doesn't seem to matter. In fact, in one experiment, we tried to drive the thing out of this condition by going up to a C rate temporarily, and it didn't change the voltage at all. But we didn't do that extensively.

What I'd like to indicate further is that we have done every kind of conceivable test for a short that we could on these cells, and there was no test whatsoever of a shorted condition. And as soon as you start to charge them, they charge normally, they accept charge, and there doesn't seem to be any real indication of a true shorted condition.

We believe, or we are hypothesizing, that there may be some kind of an enhanced hydrogen recombination condition going on in these cells, which allows them to operate in this mode. But we don't know for sure right now.

KRAUSE: Hughes

We've observed the same thing, as I mentioned yesterday. We hypothesize that it's a cadmium-oxygen cell that's developed when you run under reversal; you see the same thing. You can run them forever, and you'll never get a negative cut-off, down to minus 1 volt.

We think, with the amount of cadmium that's over the positive plate, and the oxygen coming off the negative in reversal, that you're getting a cadmium-oxygen cell reaction which will just go on forever.

SCOTT: But have you related that quantitatively to the amount of cadmium in the positive to see how long you can expect that to go on?

KRAUSE: No, we haven't done that yet. My point yesterday, though, about the shortage was that we don't particularly recognize that as a shortage condition. But we have observed cells we've taken into reversal, and then turned around to recharge, and they no longer will charge above a few millivolts. This has happened rarely.

SCOTT: I recognize that the problem certainly has occurred. I just wanted to point out that it is apparently not a general thing, and that particularly in this case, at least under these test conditions, we have these eight or nine cells that have been reversing every time during this test, and they show no sign of any adverse behavior at this point.

SEIGER: Yardney

I've observed these kinds of things several times. I've taken cells at C/2 discharge rates, and have observed that they will stay down there at about minus 0.2 volts for hours. I have been able to make these cells, however, go to minus 1.5 volts by discontinuing the discharge, waiting overnight, and then putting them on again the next morning. The next morning, we will immediately go to the minus 1.5 volts.

Now, I don't think that there's a short in those cells. I don't know what's going on, but I don't think a short can disappear overnight spontaneously of itself, sitting on an open circuit.

There's something else that I have also done with cells of this type that have this peculiar behavior. I have gone into them with tubes and collected the gas, and I've been able to identify the gas as hydrogen that my positive exhausted at first. And then, I actually plotted the rates, and compared the rates to what the theoretical rate should be. And the plots indicate that the hydrogen evolution starts increasing, reaches about half of theoretical, turns around, and comes down.

Now, I could have this thing sitting there at minus 0.2 volts, with an occasional plup, plup of gas coming out of that tube--perhaps, you know, 0.5 cc of gas every minute or so.

SCOTT: Yes, we have made gas volume measurements a few times, and generally observed little or no gassing once the potential settles down during this kind of discharge. We have also observed--incidentally, most of the time that we have observed this effect has been with the cell in its original starved condition. We have seen that several times when we have added electrolyte to flood the cell that we no longer get this condition. It seems to disappear. So, this is why we tend to feel that it's some kind of a gas transfer, either hydrogen or oxygen.

NAPOLI: RCA

I think I'm a little bit confused now between what Stan says and what Dr. Scott is saying. Yesterday, I asked the question, how did Stan know that the cell was shorting? How was the short manifested in the cell? And he told me that he had to open the cells, and he found that there was a cadmium bridge.

Now, this morning, you tell me that the cell didn't recharge; that it only got as high as several millivolts. The question I have for Dr. Scott is, did you analyze some of these cells?

SCOTT: Yes, we have taken a number of them apart. But we have not been able to locate or identify any particular thing that tells us what's going on.

NAPOLI: This cadmium bridge kind of thing is not apparent in the cells that you're analyzing?

SCOTT: Well, you know, it's extremely difficult to say what you might have had when the cell was together after you've taken in part, particularly as far as identifying at least maybe a small, possible cadmium bridge. We certainly have not seen anything that we could say positively looked like a cadmium bridge.

Of course, essentially all of the cells that we have looked at have come from synchronous orbit tests, rather than from short orbit tests, so that the number of cycles has been quite a bit fewer than other people might have been experiencing. And we generally have much less cadmium migration under those conditions than in a short orbit.

MAURER: Bell Labs

We've made gas measurements similar to what Dr. Seiger described, and we get essentially the same results. Hydrogen evolution is occurring first, so it's the positive electrode that's reversing. We tend to observe it happening more often in cells that are relatively more starved than others, and cells that have no cadmium on the positive and on the separator.

I have a wild theory that says that it's the result of electrolyte concentration gradients. You're producing water at one electrode, and OH ions at the other. And in the very starved state in the cell, you develop what amounts to simply a crystal bridge across the separator to give you the short. And if you interrupt the discharge or run it at a low enough rate, then you don't get enough concentration gradients, so the crystals dissolve or they re-dissolve when you interrupt the discharge, so that you break the short and the cell will function normally again.

I think it's something like that rather than cadmium.

STEINHAUER: Hughes

Partly in light of Dean's comment, and in light of the fact you said you used a 10-ohm resistor and then a 25-ohm let-down resistor, have you attempted to optimize reconditioning with regard to the current density versus a temperature spectrum? In other words, could these low rates lead to the bridge-type phenomenon? Is there a range of current densities for a particular temperature that will minimize cell divergence? Have you done anything along these lines?

SCOTT: Not really. Our rates for allowing the battery to discharge to a point where we feel that any cells are going to be reversed are presently dictated only by some limited experiments, measurements that we have made, to relate--try to find the maximum current at which the cell will not generate appreciable pressures of hydrogen gas during reversal. We have done a certain amount of experimenting in that direction, and that indicates that the maximum --at least, after a certain number of ampere hours of reversal--the maximum safe rate is something less than C/100. But that's about all we've done.

SEIGER: When I've done these reversal tests, and I've looked at gas, I have had it both on cell semi-dry; I've also had it on some cells that were so flooded that you could look through--we had plastic tops on it, and we could look through, and we had it flooded, and the electrolyte was above the level of the plate. And we got this minus 0.2 volt phenomenon in those.

I should also comment that at the time that the cell went into a voltage reversal, we had a Lackner demon in there with the straw sucking on the electrode, like it just disappeared on us. It went down.

Another comment that I'd like to direct to Dr. Maurer is that I have been observing this phenomenon more in cells with intra-electrode spacing that is pretty close. We've reduced the intra-electrode spacing, the probability of encountering such a phenomenon is higher. As a matter of fact, I think you could design and build a cell with a very thin separator that would do this each and every time. I'd be afraid to build it; I have done it, and I was afraid that customers would not like to have a cell that had an inexplicable performance.

SCOTT: Yes. That experience is borne out by some work done quite a few years ago at Sonotone, where they were looking at the effect of high compression on the performance of the cells. And in almost all the cells where they had the high degree of, in this case, just simply spring compression, they could not reverse the cells.

MAURER: I concur with that. We see it, again, more often in cells under higher compression. Our normal cell has a fair amount of compression when it's sitting in the can, and the higher that compression level, the more the tendency to run into this problem. And I think some work, as you say many years ago, has shown that there is not enough time during normal discharge for the electrolyte to move from outside to the inside of the stack.

So that, the amount of electrolyte that you need in the core to support discharge--because the positive is taking in water during discharge; if there isn't enough water in the cores of the positive and the separator to support the complete discharge, the capacity will be limited. And even though there's plenty of liquid surrounding the core--say it's in a flooded state, with compressed--the discharge will still be inhibited. So that cells that are more starved will tend to show this effect, and cells with higher compression will tend to show the effect more.

SEIGER: I think in the past 10 minutes, we've started to behave like a workshop in which one is trying to help another. And therefore, I'd like to bring out a paper by Quintin and Valtange, about 1952; in Compte-Rendues where they've done an oxygen recombination as a function of the intra-electrode spacing. And they spotted two particular regions, and one very close region, they were getting some awfully high currents through without getting any gas evolution. That happened to be oxygen.

HALPERT: This phenomenon was first noted in 1968 during the analysis of the Gulton 6-ampere hour cells from the Martin Company and AMF Company test programs. It was reported in GSFC X-Document X-735-69-25, p. 63, that during the discharge to determine which was the limiting electrode, the voltage decreased to -0.15 volts at the c/2 rate. As the discharge continued at the same time the pressure started to drop and the voltage slowly increased to -0.05 volts. After overdischarging for 17-ampere hours without change the discharge was terminated and the cell charged for 3.1 ampere hours. It continued to be cycled for six months in its normal mode before the test was terminated.

This occurred on cells from three different operating groups. Two groups were discharged to 1 volt on each cycle after being charged only 3 ampere hours and the third was discharged to 1 volt and shorted for a total 90-minute period every fifth cycle. The overdischarge phenomenon may therefore be related to the fact that the cells were fully discharged either regularly or occasionally, a process that occurs on reconditioning.

GASTON: RCA

It has been my experience with reconditioning that you should discharge as low as possible without reversing. Perhaps the answer is, if you're reconditioning batteries, you have some mechanism to prevent a cell reversal. We have done that at RCA on all the spacecraft where we do have a reconditioning circuit incorporated. We don't have any cell reversal.

SCOTT: But are you saying that you have a definite reason for not wanting to reverse any cells ?

GASTON: I haven't seen any beneficial effect of reversals.

SCOTT: I have a counter to that, and that is we ran a controlled test of groups of cells in which we purposely took the cells out of the circuit as they reached 0 volts, and we let another almost identically-tested set of cells go on down below 0 volts. The effect on the packet that was not discharged to 0 volts was very small. The effect on the ones that were allowed to reverse was very marked, very much improved.

GASTON: Was that on polypropylene cells or nylon cells ?

SCOTT: Both.

GASTON: Both ? I have not observed it on nylon cells.

SCOTT: Well, this was at 80 percent depth of discharge. You know, you have to be careful. Because I think the results that might be relative to, say, a 25 percent depth for short orbit may be not the same as for 80 percent depth in a synchronous orbit.

GASTON: That's possible. That's my experience.

BETZ: N.R.L.

Dr. Scott, I'd like to confirm that shortly after I got some information on this data from Dick Sparks, we had a life cycle test going with--oh, about 7500 cycles, and they are polypropylene separators. It's a near-earth orbit type life cycle test, 18 percent depth of discharge--you see, we had quite a bit of voltage divergence, and also capacity. In some capacity tests, some cells were substantially limited.

They have not affected the useful depth of discharge at 18 percent. We tried the reconditioning technique you recommended, or essentially that type, and we put it back on life cycle. And within 200 cycles, we had a shorted cell.

A few other comments. The cell that did short was initially quite a good performer. It was one of the better three cells. The worst performer still has its partial short, as indicated by a low end-of-charge voltage and a low capacity. Three of the cells reversed relatively substantially. It's a six-cell battery. We terminated when the fourth cell was going into reversal.

One of the three cells that was substantially reversed was slightly bulged. The other two showed the characteristic where the cells began to go to low and reversal voltage, and then rose back up toward 0.

So, for a short orbit test with this type of reconditioning, I think you'd certainly have to do some more testing in that area before you can say, yes; this is a good way to go for short-orbit, near-earth orbit type testing. And it may just be that with the deep discharge, you have to go farther for the reconditioning. With a shorter discharge, you really don't have to go that far, anyway.

FORD: You've shown two different tests. I assume they're different cells, and probably different time frames; at least, they're manufactured at different times. Have you looked at the results of your reconditioning? Have you looked at the manufacturing data to find out if there's any correlation with any of these factors?

What I'm suggesting is simply that I don't deny that reconditioning has positive effects. But I'm convinced that reconditioning, or the degree of improvement that reconditioning can bring about, is a function of the basic cell design, and what went into it when it was built.

SCOTT: Well, all of the cells that I showed you data for today were at least pretty close to the same design, although there may be minor process differences between them. They were all GE cells, and the plates were made by essentially the same process. They were made--well, I can't guarantee you exactly how much they were the same. But they weren't made by two different manufacturers.

The treatment of the plates, generally speaking, was the same, and so on. So, you know, I can't identify anything in particular there.

FORD: Let me suggest something as a hypothesis because we've been looking at cells with successive starved conditions versus cells which, for practical purposes, are almost flooded. And from that test that we got as an observation, what we've seen is the fact that it looks like you've got basically two problems which reconditioning does in fact get around or enhance the characteristics.

Basically, you've got one of electrolyte management; that is, in each real starved or ultrastarved cell. But once you get an excess amount of electorlyte in the cells where we worked with recently--we're talking about at least, on the GE design, 4 cc's per rated ampere hour--it looks like, then, you get away from the effects of electrolyte management, and get into the true effects of the negative electrode.

And what we have learned, after 550 cycles from the 12 ampere hour IUE cell that I reported on last year, that this is 550 cycles at 10 degrees C at 50 percent depth of discharge for a 24-hour orbit; this was 1 hour discharge, 23 hour charge, and we never charged above C/10. But after we ran those 550 cycles, we found the cells to 1 volt, at the C/2 rate, delivered about 12-ampere hours.

However, in trying to simulate a condition that the spacecraft would have to live with in going under voltage, we dropped to C/10, which is a much lower power level as far as the spacecraft is concerned. But in doing that, we found more ampere hours in those cells than we got out initially. And based on the data--and Dave Baer talked about this a little yesterday--based on that data, we know, one, the cells were showing the characteristic tendency of negative limited conditions after the 550 cycles. And what we feel like was happening is that we were able to get the capacity out of the negative, but we were only able to get out at the lower rate.

Now, you look at some initial manufacturing data, where you found a plate ratio test in flight conditions. We know that the negative capacity is a function of rate, even when it's new. There's no reason to believe that function isn't changing with life. So what I'm suggesting is, you've got a negative. Once you get enough electrolyte in your cell, then you're looking at a different mechanism than what you're looking at without significant electrolyte.

SCOTT: In general, I read you, and I agree. And we do know two things. One is that the electrolyte level and the 50 ampere hour cells for which the first data I gave you apply--the electrolyte level was pretty marginal. It was like 2.5 cc's per ampere hour. And we do also know what the main reason for the lower voltages of the cells that were at the low end was because of negative limiting.

But I'm not proposing reconditioning as a cure-all. But certainly, as long as we have certain cells made in a certain way, and maybe are unable to do something about it for the moment, certainly, it is apparently able to cope with a considerable range of operating problems.

GRIFFIN: Mallory

Could I ask for some clarification? As I understand it, going back maybe two or three years ago, I think it was WEX 1242 that was used in Scott's study at TRW. But I'm not certain about the other gentleman that spoke earlier. Certainly, in those days polypropylene was available in many different forms. The original diameter of the Hercules fiber was about 15 microns in diameter, and the present W. R. Grace and Company fibers are microfibers which are much thinner, and the amount of electrolyte and the equilibrium is quite different in the two situations.

What happens in your nickel-cadmium cell, I don't know, because I don't know what the pressure ratios are. But I would suggest, to make it easier for everybody to understand; I'd advise to specify the fiber for it, so we can understand exactly how many cc's of electrolyte you have, and whether it's a function of separator or just a function of your cell manufacture.

1-kW BATTERY SYSTEM PROTOTYPE S/N 1-2 LIFE TEST
MID-ECLIPSE-SEASON EOD CELL VOLTAGE DATA

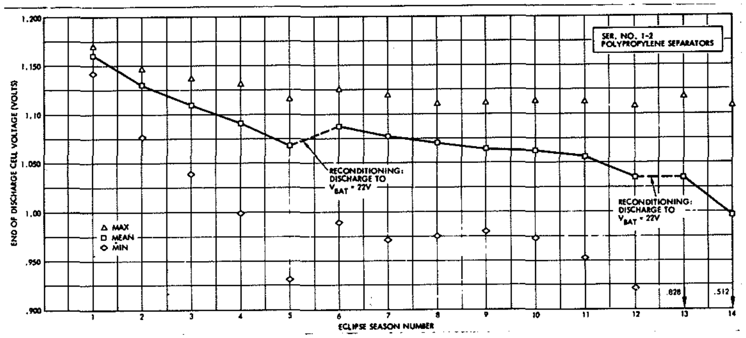


Figure 159

1-kW BATTERY SYSTEM PROTOTYPE S/N 1-3 LIFE TEST
MID-ECLIPSE-SEASON EOD CELL VOLTAGE DATA

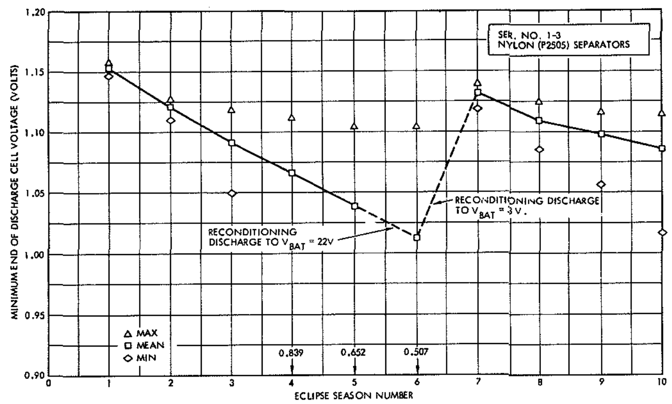


Figure 160

NICKEL-CADMIUM BATTERY DEEP DISCHARGE PERFORMANCE
WITH RECONDITIONING TO 1.0 VOLT PER CELL AVERAGE

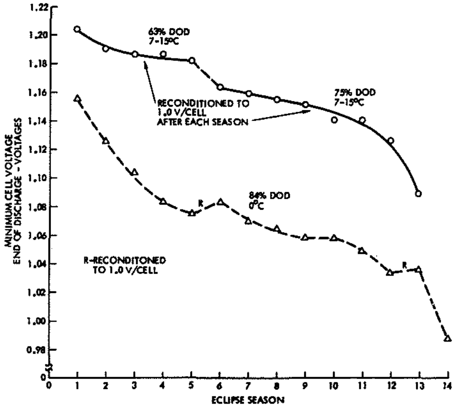
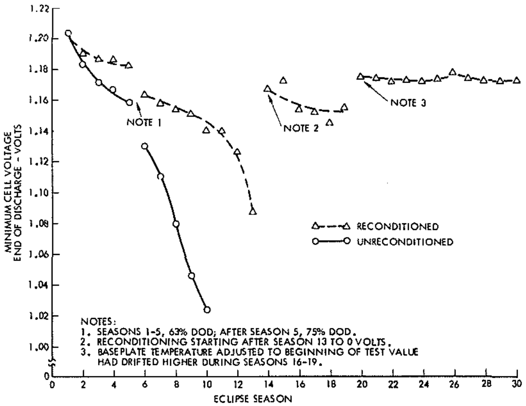


Figure 161

NICKEL-CADMIUM BATTERY LIFE TEST PERFORMANCE
WITH AND WITHOUT RECONDITIONING



NOTES:
1. SEASONS 1-5, 63% DOD; AFTER SEASON 5, 75% DOD.
2. RECONDITIONING STARTING AFTER SEASON 13 TO 0 VOLTS.
3. BASEPLATE TEMPERATURE ADJUSTED TO BEGINNING OF TEST VALUE HAD DRIFTED HIGHER DURING SEASONS 16-19.

Figure 162

CYCLE LIFE AND STORAGE TEST RESULTS

R. S. Bogner
Jet Propulsion Laboratories

The topic this morning is the nickel cadmium cycle life and storage test results.

(Figure 163)

The outline of the presentation gives a description of the test cells, previous test history, cycle test outline, cycle test results, and then we'll go into the storage test outline and storage test results.

(Figure 164)

These cells are the 1968 vintage when we were starting on our Mariner Mars 1971 program, and we bought 30 cells from each of three manufacturers at that time for evaluation: General Electric, Gulton Industries, and Eagle-Picher. The cells were tested at JPL. They were given a mechanical inspection, AC impedance test, internal short test, overcharge and electrolyte leakage test, and then three 100 percent DOD cycles at room ambient temperature.

(Figure 165)

This is a photograph of the cells with Eagle-Picher on the left, the Gulton Industries in the middle, and the General Electric on the right.

(Figure 166)

Previous test history on these cells before we put them on the cycle test was that we went through what we call a mission profile test, which lasted 10 months. We saw approximately four 50 percent DOD cycles simulating prelaunch and launch testing; six months of trickle charge simulating the cruise period to the planet with a continuous 0.65 amps trickle charge. And then, we performed five cycles at monthly intervals at 100 percent DOD.

The battery packs tested we designated as GI I and GE I. They were tested at 10 degrees C. Battery packs GI III and GE IV were tested at 24 degrees C. That was during the mission profile test. And the temperature that we measured between the cells was generally about 5 degrees C higher than the ambient temperatures. Pack GE IV was on an open-circuit stand during the six months' cruise period, and received 100 percent DOD monthly cycles.

(Figure 167)

The packs consisted of four 5-cell packs, and we tested those later during a cycling test as 10-cell batteries. The 12-hour cycle we designated Battery A; that was made up of GI I and GE I cell packs. The 33-hour cycle, called Battery B, was GI III and GE IV. The 12-hour cycle test regime consisted of discharging at 6.4 amperes for two hours, which gave us a 54 percent DOD in the rated 20 ampere hour capacity. The actual capacity of the cells was up around 25, 26 ampere hours. They were charged at 2 amps to 14.4 volts cutoff. Then they were switched to 0.65 amp trickle charge until the next discharge period.

The 33-hour cycle regime was discharged at 5.4 amps for three and a half hours. This represented a 95 percent depth of discharge on the rated capacity. The charge regime was the same as on the 12-hour cycle.

(Figure 168)

Rather than try to go through all the data, I have a plot here of the end of the discharge voltage versus the cycle life. So the top one shows the GE cells, the bottom shows the Gulton Industry cells. And you'll notice, during approximately the first hundred cycles, we got a very rapid dropoff in voltage, and that was due to the problems we had during testing.

The base plate temperature; we operated these tests with a cold plate, and the cold plate was sunk to 60 degrees F. During our initial cycling, our high rate charge was not cut off, and we were charging continuously at the high rate, C/10. And the actual cell temperatures were going up around 100 degrees. We made some adjustments there just before a hundred cycles, and controlling the charge and reducing the base plate temperature another 20 degrees F made a considerable improvement there in the discharge voltage.

The notes designated 2 show where we reconditioned the cells. They were usually discharged on a pack basis down to an average of 1 volt per cell, and then shorted out with a 1 ohm resistor across each cell for 24 or 16 hours.

(Figure 169)

This slide shows the end-of-discharge voltage for the cells on the 12-hour cycle.

By the way the previous slide (Figure 168), if you want to consider it, is an accelerated synchronous orbit test representing 19 years of cycling.

(Figure 170)

Back around 1968 and 1969 there wasn't much known about storage conditions, and we queried most of the people in the business. So we set up a little storage test--a parametric temperature charge test. Each pack was tested at minus 4, 10, 25, and 38 degrees C; and each pack was charged at 0. 5, 1, 2, and 4 amps, and all the discharges were at 10 amps to 5 volts per pack.

After we got through that test, we put them on a storage test. The storage conditions that we tested were as follows: they were discharged shorted and discharged open circuit, and charged open circuit. And this particular storage test was run at 10 degrees C for six months.

(Figure 171)

After the storage period, we measured the a.c. impedance. This was measured with a Keithly 503 milliohm meter, 40 hertz square wave. After the storage, we went to three cycles on the cells. The cells that were stored charged were discharged first, and the conditions of the cycles were a charge at 2 amps for 24 hours, 24 degrees C; and were discharged at 10 amps to 5 volts until or unless the first cell went to 0 volts in the pack.

(Figure 172)

The results of the cells charged and standing open circuit: the Gulton Industry cells, pack V, delivered 15 ampere hours; the GE pack V cells delivered 2.2 ampere hours, but that was due to one cell that apparently had a short in it. The results on the a.c. impedance test are shown. We didn't see any significant difference, really, in the storage conditions on the GE and GI cells, but there was a considerable increase on the impedance on the Eagle-Picher cells. You can see it went up to 6 to 30 milliohms versus a couple milliohms before the test.

(Figure 173)

Now, the discharge capacities and voltages compared before the storage conditions and after the storage conditions; the capacity of all the cell packs was as good or better after storage. And in voltages on discharge, there was no significant difference. The charge voltages: the first cycle, all packs, had a higher charge voltage, and some of them up to 660 millivolts, with the Eagle-Picher cells being the highest. By the third cycle, there was no significant difference in the voltage levels of the cells.

The conclusions from this test are that no one storage was significantly better than the other. However, I want to caution the fact that this test was only for six months, and it was a reduced temperature of 10 degrees C.

NAPOLI: This is six months after how long the cells were manufactured?

BOGNER: This was probably a year and a half after the cells were manufactured.

NAPOLI: You've got a decision to fly those cells for a long-term mission. Would you fly them? I'm saying long-term; several years.

BOGNER: You mean considering they were a year and a half old?

I think they would be good enough to fly; not after going through the testing that we went through, but under storage conditions.

NAPOLI: What I'm alluding to is that, if you had to make a decision on cells that were, say, two years old, and then you had to fly them and try to get seven to eight years out of them, would you want new cells or would you, after storage--

BOGNER: Well, it depends on how you stored them, you know, before.

NAPOLI: Take one of your three cases.

BOGNER: Well, we prefer the storage shorted and discharged. And if we would plan to be using them two or three or four years after we purchased them, I think we would be better off also if we did store them at a reduced temperature. If you stored them at room temperature out in a storage shed, you may go up to 100 degrees, and I really don't think that's good for them. I think TRW is running a test with some Air Force work, and you're up to how many years storage and you don't see any significant difference?

SCOTT: Four years.

GASTON: RCA

Sam, your data shows either one of these three storage techniques is equal. But yet, you just commented that you prefer to keep them shorted discharged. Why?

BOGNER: Well, I wanted to caution that this was only a six-month storage period, and it was at reduced temperature.

GASTON: We had some previous results from Crane that showed it ought to be one or the other; it was discharged shorted.

Ni-Cd CYCLE LIFE AND STORAGE TEST RESULTS
OUTLINE

- TEST CELLS DESCRIPTION
- PREVIOUS TEST HISTORY
- CYCLE TEST OUTLINE
- CYCLE TEST RESULTS
- STORAGE TEST OUTLINE
- STORAGE TEST RESULTS

Figure 163

Ni-Cd CYCLE LIFE AND STORAGE TEST RESULTS
TEST CELLS DESCRIPTION

- 1968 - 30 CELLS EACH, 3 MANUFACTURERS, 20 Ah RATING
  - GENERAL ELECTRIC (GE)
  - GULTON INDUSTRIES (GI)
  - EAGLE PICHER (EP)
- CELL ACCEPTANCE TESTED AT JPL
  - MECHANICAL INSPECTION
  - AC IMPEDANCE TEST
  - INTERNAL SHORT TEST
  - OVERCHARGE AND ELECTROLYTE LEAK TEST
  - 3, 100 PERCENT DOD CYCLES AT ROOM AMBIENT TEMPERATURE

Figure 164

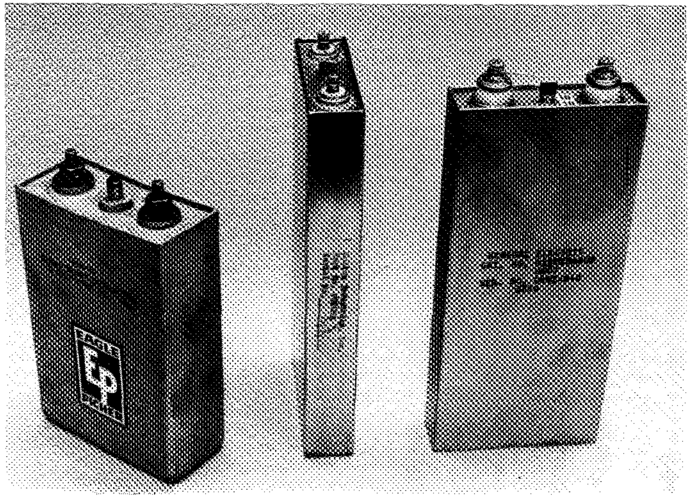


Figure 165

- MISSION PROFILE TEST OF 10 MONTHS
  - 4 CYCLES AT 50 PERCENT DOD
  - 6 MONTHS T. C. AT 0. 65A
  - 5 CYCLES AT MONTHLY INTERVALS, 100 PERCENT DOD
- BATTERY PACKS GI-1 AND GE-1 TESTED AT 10°C
- BATTERY PACKS GI-3 AND GE-4 TESTED AT 24°C
- TEMPERATURE MEASURED BETWEEN THE CELL 5°C HIGHER
- PACK GE-4, OC STAND, 100 PERCENT DOD MONTHLY INTERVALS

Figure 166. Ni-Cd Cycle Life and Storage Test Results, Previous Test History.

Ni-Cd CYCLE LIFE AND STORAGE TEST RESULTS
CYCLE TEST OUTLINE

- FOUR, 5-CELL PACKS, 2 GI, 2 GE
- TESTED AS 10-CELL BATTERIES
    - 12h CYCLE, BATTERY A, GI-1 AND GE-1 CELL PACKS
    - 33h CYCLE, BATTERY B, GI-3 AND GE-4 CELL PACKS
- 12h CYCLE TEST REGIME
    - DISCHARGE AT 5.4A FOR 2h 54 PERCENT DOD
    - CHARGE AT 2A to 14.4V
    - SWITCH TO 0.65A FOR UNTIL NEXT DISCHARGE
- 33h CYCLE TEST REGIME
    - DISCHARGE AT 5.4A FOR 3.5h 95 PERCENT DOD
    - CHARGE SAME AS 12h CYCLE

Figure 167

Ni-Cd CYCLE LIFE AND STORAGE TEST RESULTS
33h CYCLE TEST RESULTS
5-CELL PACK END OF DISCHARGE VOLTAGE vs CYCLE

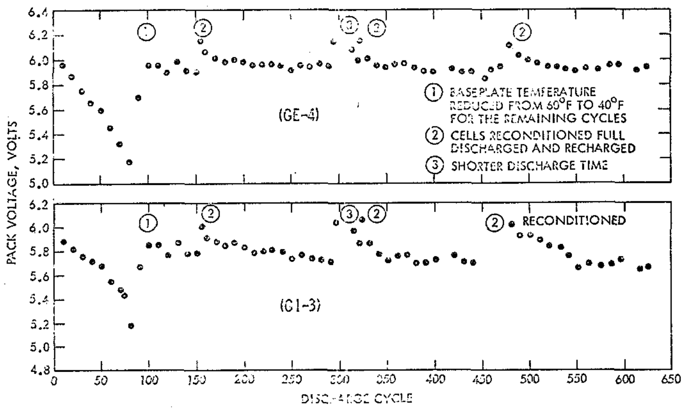


Figure 168

Ni-Cd CYCLE LIFE AND STORAGE TEST RESULTS
12h CYCLE TEST RESULTS
5-CELL PACK END OF DISCHARGE VOLTAGE vs CYCLE

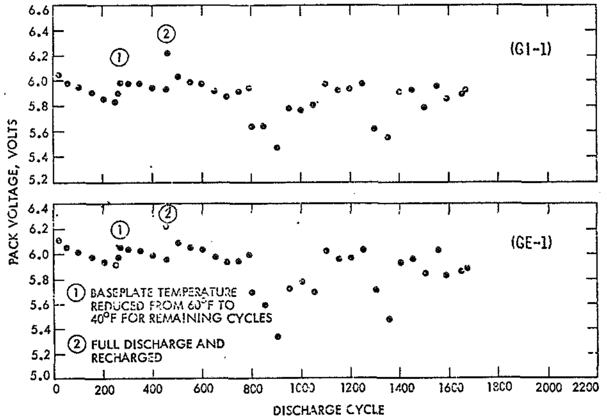


Figure 169

Ni-Cd CYCLE LIFE AND STORAGE TEST RESULTS
STORAGE TEST OUTLINE

- PREVIOUS TEST HISTORY
    - PUT ON PARAMETRIC TEMPERATURE/CHARGE TEST
    - EACH PACK AT -4°, 10°, 25°, 38°C
    - EACH PACK CHARGED AT 0.5, 1.0, 2.0, 4.0A
    - DISCHARGES ALL AT 10A TO 5.0V PER PACK
- STORAGE CONDITIONS
    - DISCHARGED - SHORTED PACKS GI-6, EP-6
    - DISCHARGED - OPEN CIRCUIT PACKS EP-5, GE-6
    - CHARGED - OPEN CIRCUIT PACKS GI-5, GE-5
    - STORED CELLS AT 10°C, 6 MONTHS

Figure 170

- AC IMPEDANCE MEASURED
    - KEITHLY 503 mΩ METER -40 Hz SQUARE WAVE
- THREE CYCLES AFTER STORAGE
    - CELLS STORED CHARGED WERE DISCHARGED
    - CHARGE - 2A, 24h, 24°C
    - DISCHARGE - 10A TO 5.0V OR 0.0V FOR A CELL

Figure 171. Ni-Cd Life and Storage Test Results, Storage Test Outline (Cont'd).

- CHARGED OPEN CIRCUIT PACKS

GI-5 15Ah
GE-5 2.2Ah DUE TO ONE CELL

- AC IMPEDANCE

CONDITION	PACK No.	ACCEPTANCE mΩ	STORAGE mΩ
CHG/O.C.	GI-5	3.2 - 3.8	2.6 - 2.7
	GE-5	1.9 - 2.0	2.1 - 2.0
DISCHG/O.C.	EP-5	1.6 - 2.0	11.0 - 50.0
	GE-6	1.9 - 2.1	2.4 - 2.6
DISCHG/SHORT	EP-6	1.3 - 2.0	6.0 - 36.0
	GI-6	3.5 - 4.0	3.6 - 3.8

Figure 172. Ni-Cd Cycle Life and Storage Test Results, Storage Test Results.

- DISCHARGE CAPACITIES AND VOLTAGES
    - CAPACITY ALL PACKS - AS GOOD OR BETTER
    - VOLTAGES NO SIGNIFICANT DIFFERENCE
- CHARGE VOLTAGES
    - FIRST CYCLE - ALL PACKS - HIGHER UP TO 600 mV/PACK
    - BY THIRD CYCLE - NO DIFFERENCE
- CONCLUSION
    - NO ONE STORAGE WAS SIGNIFICANTLY BETTER THAN THE OTHER
    - CAUTION - TEST WAS ONLY 6 MO AND AT 10°C

Figure 173. Ni-Cd Cycle Life and Storage Test Results, Storage Test Results

ACCELERATED LIFE TESTS ON NATO III BATTERIES

J. D. Armantrout
Aeronutronic Ford

This is going to be a continuation of information that we've been presenting over the past several years.

(Figure 174)

This particular battery sampling is the lightweight, "20 watt hour per pound" battery. And we'll just show this for information purposes.

(Figure 175)

This program consists of our cell validation, which is burn-in cycling. We do 20 cycles at 50 percent depth of discharge, and then do a number of functional performance tests which usually consist of low and high-temperature capacity tests. We reported last year on the battery development tests, and I refer you to those minutes.

The engineering model battery was put on to a real time synchronous orbit, charge-discharge simulation. It was a two-year test. We had a total of 616 cycles simulating 14 equinox seasons. Our temperature was essentially room temperature; it did vary with the air conditioning and things like that, so I've indicated 21 plus or minus 5. It was probably about 21 to 22 degrees C. This is a little warmer than we actually would have it in an orbit. Probably a more representative temperature would be 10 to 15 degrees C.

We have a C/4 discharge rate, maximum eclipse is 1.2 hours. As you can see, we've got a tri-sequence charge rate, which is a little different than some other people are using. It consists of 5 minutes C/10, and then 10 minutes open circuit. We have three batteries, and we sequence between the three batteries.

At the end of the second, fourth, sixth, eighth, tenth, twelfth, and fourteenth eclipse seasons, we did a five-day overcharge at about C/45, and measured capacity on half of the battery pack. The other half was just put on open circuit. It was overcharged at that time, but it was not discharged for capacity until the end of the test.

The capacity checks that we performed at those points in time had the effect of a reconditioning per se, if you want to say a C/2 rate is a reconditioned rate. It's a little more than what we were talking about earlier this morning. We've indicated here our cell positions 11 through 20, where the cells which we did the capacity check.

(Figure 176)

Don Briggs had shown some of this data last year, and this is a continuation of the results. What we're trying to show is the effect of capacity degradation that did occur, by the measurements that we took at the second, fourth, sixth, and so forth, seasons. You can see that we started out with a nominal 20 watt per hour cell, and we were about 80 percent of that capacity at the end of the test. The voltage degradation; you can see that occurred.

One thing that was interesting here, and the next figure shows it a little better, was the cell divergence. We indicate on the top the charge in end-of-discharge cell voltage between the unreconditioned and the reconditioned packs. We seem to have our maximum divergence about five seasons into the test, and then it didn't matter whether it was reconditioned or not, because the cells seemed to come together, as you can see.

(Figure 177)

This is a 20-cell battery, and you can see we're around 28 volts end-of-charge at the top. That's just prior to our max eclipse cycle. And we've shown here the minimum voltage reached at the maximum eclipse for each of the seasons. You can see the range between the unreconditioned and the reconditioned half-packs in the battery.

(Figure 178)

Our general conclusions were that our lightweight battery packaging design did demonstrate the capability to meet our seven-year mission requirements, based on the accelerated tests that we ran. The reconditioning under these conditions tends to improve our early-life discharge voltage performance, and interestingly enough, the end-of-life discharge capacity characteristics.

It wasn't clear from the other information I've shown you, but we found that the reconditioned portion of the battery had approximately 25 percent more capacity at the end of the test than the unreconditioned. Implementation of our lightweight battery design concept in spacecraft designs, we feel, can increase the communication payload capability, or we can improve our subsystem reliability by decreasing the battery depth-of-discharge for extended life, perhaps up to 10 years.

Our lightweight battery packaging design optimization is independent of the battery cell manufacturing processes and designs, and therefore can be readily applied to existing or new battery cell designs. There was a comment made yesterday about--we're looking for reliability. And what we've tried to do with this concept is, we've gone to the lighter depths-of-discharge to get that reliability. And we can do that because of the lightweight cell.

BOGNER: JPL

Did you attempt to recondition the unreconditioned half of the battery at the end of the test, and did it show up as well?

ARMANTROUT: We did a number of the capacity tests at the low and high temperatures again. We attempted to do it. We got approximately a 10 percent increase, but we just didn't seem to ever recover that capacity. We got a little bit of it.

We had to disassemble the battery at that point in time, and unfortunately, we had accumulated a lot of data. And I think we could have continued to cycle it. We might have gotten more capacity. Another thing that you have to realize here is that this charge rate that we're using probably wasn't really overcharging the battery. And I think Dr. Scott has indicated, in some conversations with me, that if anything, he sees his capacity getting better in some of his life tests on positive. I didn't necessarily see that in this test.

KRAUSE: I think one of your conclusions implies that there is a direct correlation between depth-of-discharge and extent of lifetime. Do you feel the reduction in depth-of-discharge will allow battery operations up to 10 years? Do you have any data on that?

ARMANTROUT: We're just--well, there's a number of Crane tests which--I think there's GE cells and--I don't know; perhaps Dave or Floyd would want to comment. But there are various depths-of-discharge, various temperatures, and I think that data pretty much shows that the lighter depths' total accumulated cycles--it's an easier load, so to speak.

I know there's other failure mechanisms here. But I feel that 50 to 60 percent right now is all I would really prefer to go, although I'm very interested in some of the data that's showing 75 to 80 percent.

WADHAM: Telsat Canada

Do you have any evidence to show that this tri-sequence charging system, C/10, is of any benefit over charging at an average rate of C/30?

ARMANTROUT: Well, there are charge efficiencies to be considered here, and we did feel that it was, for example, better to charge this system at C/10 rather than going to a C/30 constant current, definitely. It's a temperature-dependent thing, too.

KRAUSE: Do you have any analysis data that you've been developing, any on the Eagle-Picher NATO III cell design, with regard to some of the parameters and components of the tests that you're running, and how they're changing, like electrolyte distribution, plate thickening, etcetera.

ARMANTROUT: We're starting to do some of that right now. I don't have anything that I can report at this time, but I'm sure that by next year I will have.

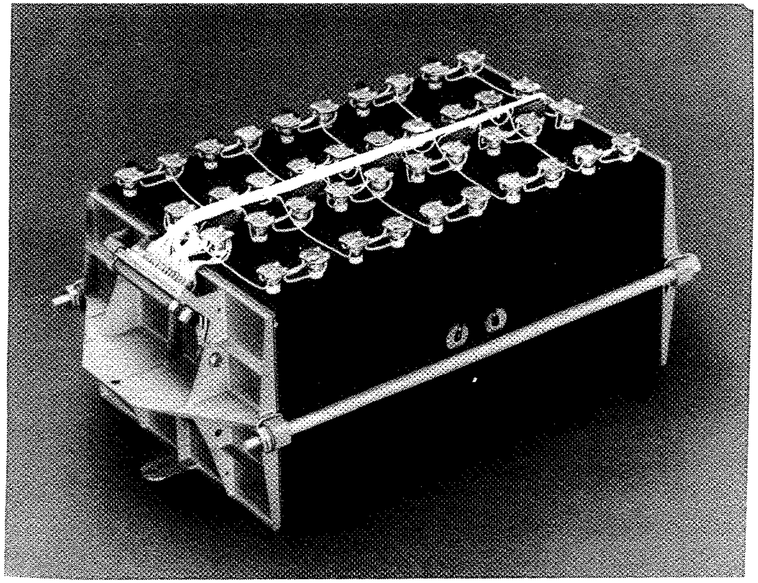


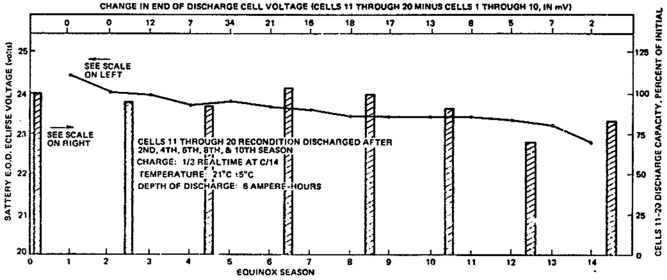
Figure 174. NATO III Battery Assembly

NATO III ENGINEERING MODEL BATTERY LIFE TEST DESCRIPTION

- CELL VALIDATION (BURN-IN CYCLING AND FUNCTIONAL PERFORMANCE TESTS)
- BATTERY DEVELOPMENT TESTS (SEE 1975 GSFC BATTERY WORKSHOP MINUTES)
- REAL TIME SYNCHRONOUS ORBIT CHARGE/DISCHARGE BATTERY OPERATION OVER A 2-YEAR PERIOD (INCLUDES A TOTAL OF 616 24-HOUR CHARGE/DISCHARGE CYCLES SIMULATING 14 EQUINOX SEASONS AT 21 ± 5°C)

DISCHARGE PERIOD	0 to 1.2 HOURS AT C/4 RATE
CHARGE PERIOD	24 to 22.8 HOURS AT C/14 TRI-SEQUENCE RATE
OVERCHARGE PERIOD	5 DAYS AT C/45 RATE FOLLOWING COMPLETION OF 2nd, 4th, 6th, 8th, 10th, 12th AND 14th EQUINOX SEASONS PRIOR TO RECONDITIONING
RECONDITIONING	CAPACITY MEASUREMENT MADE AT C/4 RATE ON CELL POSITIONS 11 THROUGH 20 FOLLOWING OVERCHARGE PERIOD. (RECONDITIONING NOT PERFORMED ON CELL POSITIONS 1 THROUGH 10)

Figure 175



NATO III Battery Equinox Season Life Test Results

Figure 176

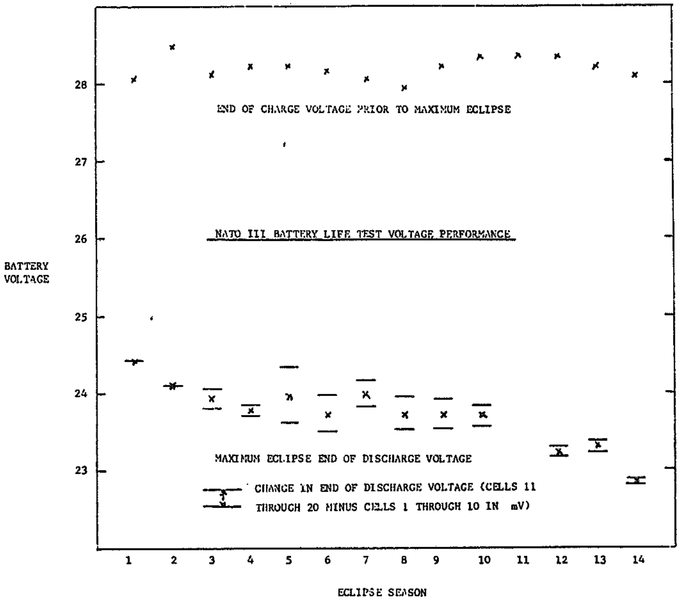


Figure 177

LIGHTWEIGHT BATTERY PACKAGING DESIGN DEMONSTRATED CAPABILITY TO MEET 7-YEAR NATO III MISSION REQUIREMENT BASED ON ACCELERATED LIFE TEST RESULTS

RECONDITIONING UNDER ACCELERATED LIFE TEST CONDITIONS TENDS TO IMPROVE EARLY LIFE DISCHARGE VOLTAGE PERFORMANCE AND END OF LIFE DISCHARGE CAPACITY CHARACTERISTICS

IMPLEMENTATION OF LIGHTWEIGHT BATTERY DESIGN CONCEPT IN SPACECRAFT DESIGNS CAN INCREASE THE COMMUNICATION PAYLOAD CAPABILITY OR IMPROVE SUBSYSTEM RELIABILITY BY DECREASING THE BATTERY DOD FOR EXTENDED LIFE UP TO 10 YEARS

LIGHTWEIGHT BATTERY PACKAGING DESIGN OPTIMIZATION IS INDEPENDENT OF BATTERY CELL MANUFACTURING PROCESSES AND DESIGNS, AND THEREFORE CAN BE READILY APPLIED TO EXISTING OR NEW BATTERY CELL DESIGNS

Figure 178. General Conclusions

HEAO CELL PARAMETRIC TESTS

E. Paschal
Marshall Space Flight Center

I want to present the results of the parametric testing on the HEAO cell. This is a comparison between two production runs, approximately a year apart. The designs between the two production runs are different.

The cell itself is a 20-ampere SAFT cell, and the parametric test was run by TRW in both cases.

(Figure 179)

The parametric tests on each group of cells were basically identical. In each case, there were seven four-cell packs. There were two packs run at 5 degrees C, two packs run at 15 degrees C, and two--three packs at 15 degrees C, and two packs at 25 degrees C. The depth-of-discharge for the first 500 cycles on each test was on the order of 22 percent. The charge rate on six of the packs was 9 amperes, and on seven packs, it was at 6 amps.

On the second production run, the charge current was lowered to 6 amps on the first six packs, and increased to a 9-amp charge rate on the Gulton packs.

Some of the data on the two production groups are, as indicated, on the board. I might state that this first group of cells consisted of 28 cells. There were other cells that were produced at the same time that were delivered for integrational testing at TRW. The other groups for integration testing out of the first production run had somewhat higher positive capacities than what is shown on the board here.

The plate loading between production groups 1 and 2 was substantially different. The loading, both positive and negative, on group 2 is lower. As you see, the positive capacity is fairly close between groups 1 and 2 for these first 28 cells. The negative capacity is substantially higher for the first group of cells. The negative/positive ratio is high.

If we come on down on the first group, 46.5 ampere hours negative capacity under formation ratio tests, post rinse is 44, and the final cell ECT capacity was 48 ampere hours. As you will note, the negative/positive shows around 1.2, 1.5, 1.74 on the final.

Group 2, as I pointed out, has a similar capacity on the positive plate, all the way through. The goal was 27.5 to 28 ampere hours on the final cell. It was fairly close. This last group is representative of the flight group. The other formation groups are fairly close to the data that I showed you for group 2 for flight.

The electrolyte for group 1 is 69 cc's. The electrolyte for the second group is 66. I might point out that the fabrication of the second group is basically the same as the OAO cell. There was an effort to go back and build as close to the OAO cell as we could.

(Figure 180)

As I pointed out, both of these sets of data are based on similar tests. The test regime was approximately that of the HEAO, namely 56 minutes of sunlight and 36 minutes eclipse period. This is a near-earth orbit type of test. The curves are for the first 500 cycles. There were additional tests beyond that, but I think that the information I'm going to show you will be comparable to the next thousand cycles on the second group. So I've only plotted the first 500.

Packs 1 and 2 were at 5 degrees C. The difference between the packs is that pack 2 was run at a somewhat higher recharge fraction. Cycling was to a specific voltage limit, and there was an effort to hold a specific recharge value, a target recharge value. Packs number 3 and 4, and number 7, are at 15 degrees C, and in this instance, packs 3 and 7 were run at the same recharge. Pack 4 was at a somewhat higher recharge fraction.

The difference between pack 7 and the other two packs is that pack 7 was the lower charge rate; namely, 6 amps, versus 9 amps for packs 3 and 4. The 25 degree C packs are packs 5 and 6. These also are 22 percent depth-of-discharge. Pack 6 is at a somewhat higher recharge fraction than the pack 5.

If you will note, pack 2 is on the order of 18 ampere hours; this is just as a rough comparison. Pack 6 is around 11 ampere hours.

(Figure 181)

I have on this chart a similar plot for the second group of cells. And as you will note in all cases, the capacity is considerably above that shown on the first chart. Here again, we use the same packing designations; packs 1, 2 and 7 are 5 degrees C, packs--excuse me; packs 1 and 2 are 5 degrees C, and packs 7, 3 and 4 are 15 degrees C. Packs 5 and 6 are at 25 degrees C. The target recharge fractions are as indicated, and these are the same values that were used on the first run.

The 500-cycle figures that I quoted are considerably lower than even that shown at 1,000 cycles for the second run. So, what we have done in this case is looking at the initial plate that I showed is reduce the amount of loading on the negative plate. The negative/positive ratio is considerably less on the second group of cells. The plate loading on the negative plate is considerably less, and as a result of the test, I wanted to compare the differences between those two. I felt like this would be of interest. I plan to document this in a formal paper later on.

FORD: Have you run any plate utilization tests to try to determine the utilization of the negative response of these plaques?

PASCHAL: I have not, no.

PARAMETRIC TEST GROUP PARAMETERS

	GROUP 1	GROUP 2
FORMATION CAPACITY (AH)	SN	TD
POS.	27.1	28.63
NEG.	46.5	38.71
N/P	1.72	1.35
POST RINSE		
POS.	29.7	27.83
NEG.	44.4	41.17
N/P	1.5	1.48
FINAL CELL		
POS.	27.16	28.17
NEG.	48.0	43.0
N/P	1.74	1.53
ELECTROLYTE	69	66

Figure 179

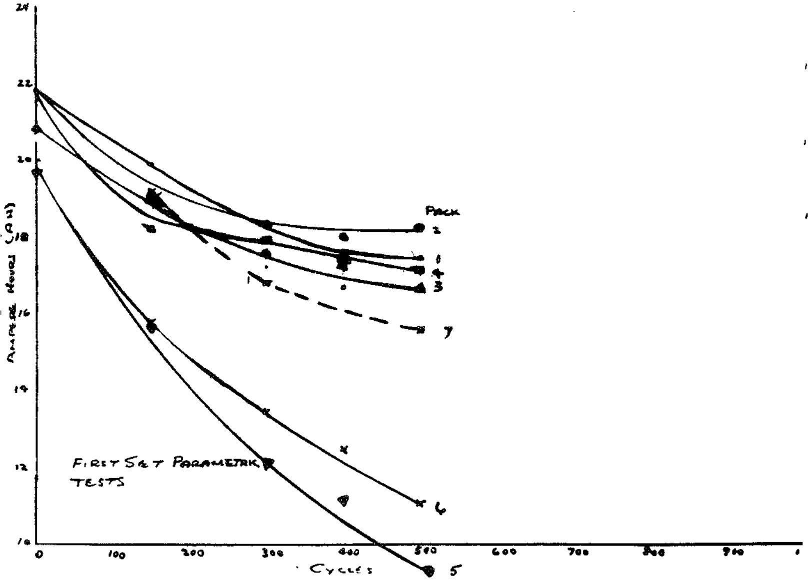


Figure 180

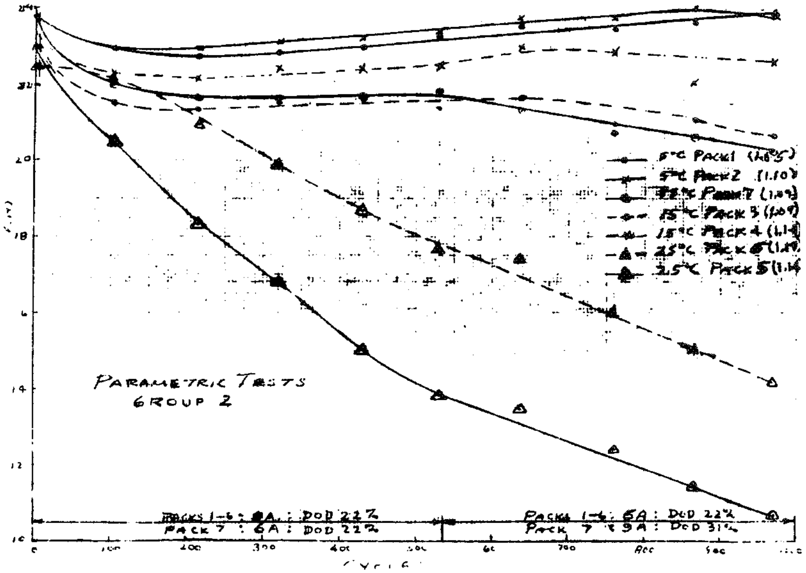


Figure 181

NICKEL HYDROXIDE ELECTRODES

J. Dunlop
COMSAT Laboratories

I'm going to discuss some of the results we have from our work on nickel electrodes, both the conventional type of nickel electrodes, the Bell Laboratory type of nickel electrodes and the Yardney electrodes. In addition, I'm going to discuss briefly some of the work that we have done in conjunction with Telesat Canada, showing the effects of cyclic life on nickel electrodes.

(Figure 182)

This is a comparison of electrochemically and chemically impregnated nickel oxide electrodes that we are currently working with. In the first group is the Intelesat IV-A type electrode. The weight of an individual electrode is 23.02 grams. The porosity of that electrode, determined from our analysis, is 83.3 percent; that is, the porosity of the electrode, of the plaque, including the perforated iron. If you actually looked at the porosity of the electrode without the perforated iron, it would be up to about 87 percent.

The measured capacity for that one electrode is 2.67 ampere hours. The measured capacity per gram of nickel hydroxide in ampere hours per gram is 0.252, which means that the percent utilization on that nickel electrode is 87.2 percent. We're utilizing 87 percent of the nickel hydroxide.

The loading of that electrode is 1.93 grams of active material per centimeter^3 of void volume--I'm sorry, that's for the nickel hydroxide alone. If you add in the fact that there is, in addition to nickel hydroxide, cobalt hydroxide, cadmium hydroxide, and hydrated water, the actual loading level for the active material of the dried electrode is 2.31 grams of active material per centimeter^3 of void volume.

We do this same type of a comparison for Eagle-Picher type of electrodes that are made using the Bell Lab process. These are the electrodes that we have in our NTS-2 nickel hydrogen flight experiment. The weight of the electrode is shown here. The plaque porosity there is 81.2 percent; again, that's the plaque porosity, including in this case the nickel screen. It's an actual porosity of the plaque, including the nickel screen; if you took the nickel screen out, the porosity would be about 80 percent for the plaque alone, without the screen.

The measured capacity is shown here. The measured capacity for a gram of $NiOH_2$ in that electrode is 0.324. The utilization for the nickel hydroxide alone is 112 per centimeter electrode of the theoretical, based on the one-electron transfer. If you add the cobalt hydroxide, the utilization--that's the sum of adding the amount of nickel hydroxide plus the cobalt hydroxide--the utilization is 105 percent. If you add the hydrated water, it drops down to about 97, 98 percent, right around 100 percent.

The loading of the nickel hydroxide per centimeter^3 of void volume, for just the active nickel hydroxide alone, is 1.31. For all the nickel hydroxide, cobalt hydroxide, and hydrated water, it is 1.56. Now, this is one of the major differences that you'll see between the electrochemically-impregnated electrodes and the chemically-impregnated electrodes, and that is a significant reduction in the loading level of the active material per centimeter^3 of void volume.

If you go to the Yardney electrode--this happens to be one group of electrodes that has been made and delivered to us by Yardney--these electrodes have been made to come up with a loading level of about 1.6 to 1.7 grams of active material per centimeter^3 of void volume. If you're looking at this electrode, you have 12.5 grams, is the way--the porosity for this electrode is actually 80.1 percent. That's the plaque porosity, including in this case perforated nickel. If you took the perforated nickel out, the plaque porosity is about 85 percent.

The reason I keep mentioning these numbers: this was discussed in some detail yesterday during the group discussion up here as to what plaque porosity we could reasonably go to. And the comment was made that we could possibly go up to levels as high as 90 percent for the plaque. The plaque is already, in most cases, running somewhere around 83 to 85 percent. If you take the porosity of the plaque and put it on these electrodes that we're looking at, it's not a real major difference that you're talking about. But I'm not sure that we would really want to increase the plaque porosity above the levels that we're currently seeing.

The percent utilization for this electrode is quite good. It turns out to be 121 percent for the nickel hydroxide alone. If you add in the cobalt hydroxide, it is 105 percent, and if you add in the hydrated water, it is about 98 percent or so. So, it's very similar to the Bell Lab electrode.

The loading levels are very similar, too. We're talking about something on the order of 1.67 grams of active material per centimeter^3. The 1.78 number was a number that we got from Yardney, and the difference is that we dry them much longer than they do, and we drive off considerably more. I think the difference is that we're driving off considerably more water in the drying process than they do.

(Figure 183)

This shows an analysis of these electrodes breaking down on a percent by weight basis the loading of the various electrodes. Here again, we're talking about a GE electrode using the Intelsat IV battery, having for an electrode weight about 23 grams; Bell Labs about 11.4, and Yardney about 12.5. These are cylindrical-type electrodes, made specifically for nickel hydrogen cells.

Percent by weight of nickel hydroxide in the General Electric--this is what we call a standard chemically-impregnated electrode--is 46 percent by weight nickel hydroxide. Bell Labs is around 36, and Yardney around 34-35. Notice again the significant difference; loading levels for the nickel hydroxide significantly lower for the electrochemically-impregnated electrodes currently being made. They can actually make higher loading levels; I think they do this. You can actually get loading levels up to about 1.9 or 2.0 grams of active material per centimeter^3. The reduced loading levels give you--are done on purpose to give you better utilization of the active material in your electrodes.

Percent by weight of cobalt in these electrodes is 2.67 for the GE, 2.3 for the Bell Lab, and 5.3 for the Yardney. I'm not sure; there seems to be some question as to exactly how much cobalt is needed in these electrodes. That's one of the variables that I don't think we do have a firm grip on. However, I think some additional work might be done in this area.

In terms of the percent by weight nickel sinter, notice that for the GE electrode, only 25 percent by weight of the electrode is actually nickel sinter, and 20 percent by weight is the perforated iron. So if you add those two numbers together, you have approximately 45 percent of the total weight of the electrode is due to the plaque. But only 25 percent of it is actually nickel sinter. So the ratio of nickel hydroxide to nickel sinter is almost 2 to 1 nickel hydroxide greater than nickel sinter.

If you look at a Bell Lab electrode, 48 percent by weight of that electrode is nickel sinter. Only 8 percent of the weight of that electrode is due to the nickel screen that's in there. Summing those two numbers up, the screen plus the sinter, comes out to about 57 percent. And the ratio between the nickel hydroxide and the nickel sinter is less than 1, whereas the ratio here was almost 2 to 1.

The same thing applies for the Yardney electrode that we're using here. You have a much greater ratio of nickel sinter to nickel hydroxide, and that may be one of the key reasons why you're getting better utilization, and certainly one of the key reasons why you probably don't get as much expansion on those electrodes in the cycle.

The density for those electrodes; as you might expect, the GE comes out to be more dense than either the Bell Labs or the Yardney electrodes. The measured capacities shown here, and again, the ampere hours per gram number down at the end there is very interesting, because even with those significantly reduced loading levels that you've used in the Bell Lab and Yardney electrodes, your ampere hour per gram numbers are greater. So I think this is a very good indication of the fact that even for aerospace batteries, for years, we've been making electrodes the wrong way; we've been putting too much stuff in there. And it does not--it's like trying to stuff too much in the package, and it doesn't necessarily buy you any better energy densities.

As a matter of fact, it doesn't improve the energy density at all. And if you looked at this electrode after 1,000 cycles or 2,000 cycles, you'd find that these electrodes are giving you much better capacity, usable capacity, than the General Electric.

(Figure 184)

This is data that we have taken from electrodes from Telesat Canada. This is a cross-section of a conventional chemically impregnated electrode, and you're looking at results of the scanning electron microscope.

Well, the cross-section of the electrodes (the strange looking thing in the middle here is simply the perforated iron). This happens to be a Telesat electrode, which is made similar to the Intelestat IV electrode that I spoke of before. And now, if you look at the top picture, the black holes are voids, the bright areas are the nickel sinter, and the gray areas are the active material. And you'll notice that we do see a tendency for the active material to be deposited near the surface, even on a new electrode. But the active material is distributed somewhat uniformly--well, not uniformly. But it is distributed throughout the electrode. It tends to form pockets close to the surface.

These cells were run by Telesat on a real time basis simulating their eclipse performance very accurately. And periodically, they provided these cells to us, and we perform an analysis for them. This cell had been run for--the second electrode here was taken out of a cell that had been run for 18 months.

Now, notice; you see a trend occuring here. You notice that the void volumes in the center of the elctrode are increasing, and you notice that the active material is moving toward the surface and compacting. By the time you get down here--this is 37 months of real time testing--and you will notice a significant amount of movement of the active material toward the surface, and a compacting of that active material.

Now, this electrode is one of these electrodes that has--these electrodes were loaded at about 2.3, something around 2, 2.3 grams of active material per centimeter^3 void volume. And with cycling, this is the phenomenon we have been observing.

Now, in addition to what we see here, we do one other thing. We take these electrodes out, and we look at the porosity distribution in this electrode, and how that's changing in time. That was another subject that was brought up yesterday.

(Figure 185)

I don't happen to have data for the particular electrodes we show here right now; I don't happen to have it on a slide, so I'm going to use the SAFT data, which is very similar. We had SAFT cycle conventional chemically-impregnated electrodes--for us. The 100 percent SAFT electrode has a loading level of about 2 grams of active material per centimeter^3 of void volume. The 69 percent electrode has a loading level which is roughly 70 percent of that, or approximately 1.4 grams of active material. And the 84 percent in that order of 1.6, 1.7 grams of active material.

You'll notice what happened here. This is a new SAFT electrode, uncycled; and here is your results of your microporosity measurements, looking at--this is the pore radius in angstroms; this is at the low end of the scale. Now, if you look at that same SAFT electrode and look at it after it's gone through 1,888 cycles, this curve shows what you see in terms of the microporosity. What you're noticing here is around 1 micron; you see in order of 10 increase--this is 10 times the increase in the microporosity of pore sizes in that 1-micron region. And our results, combining this work with the work that I showed you on the previous slide; the indication here is that the large increase in the micropore structure of the positive electrode is a result of this compacting of the active material; because, in addition to the large increase in the micropore structure, you also have this electrode expanding by about 2 to 1.

So, you have a big increase in the void volume in the center. And you also have a big increase in the very compact material at the electrode surface.

And this compacting at the electrode surface over time does act as a wicking device to suck the electrolyte out of the nylon-type separator, for example.

MC DERMOTT: Are you saying that as the active material moves toward the surface, you're creating a larger number of small pores? It seems like it would be the opposite--at the surface, but not in the interior.

DUNLOP: There's a big increase in the large pores in the interior, and there's a big increase in small pores at the surface. As you saw on that slide there, we have--the micropore structure is increased by a factor of 10. I didn't go through all the data, but if you look at these quick tear-downs, and try and determine where your electrolyte is, you find that you have a redistribution of electrolyte. You find that your positive electrode has much more electrolyte in the positive electrode than it did originally.

And if you do a calculation on the micropore increase, and the volume of that micropore region, just calculate it out. You find that you get a very good match between the added electrolyte that you have in the positive electrodes.

MC DERMOTT: But it's not the interior of the plate that's doing the wicking. It's right on the surface there, with the compacting active materials?

DUNLOP: Exactly.

By the way, the other thing I did want to show you is, we took some data that was treated yesterday that shows that initially, when you first add water, that you get an expansion. Then it flattens out. That was some data that was presented by Stan Krause. But we see the same thing on these electrodes. But then, you do thickness measurements, you don't see any real thickening up to about 200, 300 cycles. And by the time--for example, with the Telestat electrodes, you got to 37 months, you're beginning to see about a 10 to 20 percent increase in thickness. And then, by the time we get to about five years, we're beginning to see--or 500 cycles--we're beginning to see this thing start taking off a little faster. Then by the time you get to about 1,000 cycles, you're looking at a thickness increase of almost 1.7 to 1.

So, I think with cycling, you see this effect continuing as you go on. And obviously, if you look at these closely, you can see that you're really cracking up your structure of your sinter, too; and you're breaking it up, and you're getting an expansion of the whole electrode structure.

HALPERT: Would you care to make a comment with regard to the amount of electrolyte; whether that effect would be effectively increased or decreased with an additional amount of electrolyte?

DUNLOP: Well, the amount of electrolyte, I believe, is very close to 2 grams. It's about 2 grams per ampere hour, something like that. I really don't remember.

HALPERT: What is your feeling with regard to whether you could keep the active material in the center of the plate if you had more electrolyte?

DUNLOP: Well, Gert's point was that we've seen the same expansion take place whether we do these with nickel hydrogen or with nickel cadmium. With the nickel hydrogen we did not stop; the nickel hydrogen cells were run non-stop; exactly the same thing.

FORD: In the photomicrographs you showed, that was the Telesat cell, or was that the nickel-hydrogen?

DUNLOP: The scan electron microscope? That was the Telesat cell.

FORD: And was that a test when you had an open-circuit series, or was it always on some charge-discharge machine?

DUNLOP: It's open-circuit storage. We do the same thing for our own cells on trickle charge, too; and we showed that data, I think, last year at this Goddard conference on the Intelsat IV-type cells. I don't really see a big difference. The same effects seem to be going on. By the way, there is a slight difference.

DE BAYLO: You indicated the improved performance of the electrochemical process was due to less loading of the plate. Do you feel that this is strictly a function of the loading, or does it have anything to do with the process that was used?

DUNLOP: I think it's both. If we did the same kind of scanning electron microscope in cross-section of an electrochemically-impregnated electrode--Dr. Seiger might have some with him--you see a much more uniform distribution of the active material around the sinter to begin with, rather than these pockets of active material closer to the surface. And that, in itself, obviously has a big advantage in utilization. And you'll notice that the utilization numbers for electrochemically-impregnated electrodes are 20 percent better; and at low temperature, you've got even a bigger--as I mentioned before, these numbers were numbers based on measurements at ambient temperature. If you drop the temperature down to 20 degrees C, you pick up another 20 percent; your utilization numbers are spectacular for these electrochemically-impregnated electrodes.

And that's why, even with the reduced loading levels that you're looking at, you're seeing equivalent, usable ampere hours per gram numbers. Now, in addition to that, you don't see this expansion effect. We have a certain amount of data that's available today on electrochemically-impregnated electrodes with cycling. A lot of it, you know--unfortunately, we haven't got slides on it, but you just don't see the same expansion phenomenon occurring with those electrodes.

At least, eventually it happens, by the way, if you run it long enough. Somebody has to push--usually, electrochemically-impregnated electrodes are going to behave, are going to do things, too. But they're about four times better than conventional, chemically-impregnated electrodes in terms of cycling lifetime.

BOGNER: Do you see the same migration to the surface?

DUNLOP: Well, we haven't. We've only gone up to a couple thousand cycles on the electrochemically-impregnated electrodes, and we haven't seen nearly this. We see the same trends occurring, but at a much slower rate. So let me just put it that way.

HALPERT: The question is: if you were to load the plates with the same loading in grams per cc of void volume that you're using in the vacuum-impregnated plates, as you are doing on the electrochemically-impregnated plates, would you see a similar utilization?

DUNLOP: Well, we did that with the SAFT program two years ago. The data that I presented from Laboratories De Marcoussi was data on electrodes made by SAFT using three different loading levels. And those cells have been run for over two years now, and most of them died.

The worst electrodes, on a cycling basis, were the ones that were 100 percent loaded. You could run those things for maybe between 1,000 and 1,500 cycles, and then they just became very difficult to work with. The electrodes that had the loading levels of between 84 percent, which is what we're using, roughly; it's at around 1.6--and even lower--they do show us, as you saw; we still get this slow change. You still get this micropore structure change. But your expansion takes place much slower, and some of those electrodes have run up through, what; 4,000 cycles three times; a significant improvement.

As a matter of fact, on the basis of the result of that work, DeMarcoussi doesn't understand why SAFT makes their electrodes the way they're making them now. Because those electrodes that were loaded to 84 percent gave better capacity after 1,000 cycles than 100-percent load electrodes, and they gave somewhat better utilization. But they don't match, they don't do as well as, these electrochemically-impregnated electrodes.

Is that a pretty good summary of what we've seen? I think so.

HALPERT: Did they use the same loading per cc of void volume, not the same loading per area?

DUNLOP: Yes, it was the loading--the 100 percent number corresponds to the standard electrode of 2 grams of active material per centimeter^3 of void volume.

They used the standard process. And if we do an analysis, their standard process--using a 100-percent electrode--it comes out to be 2 grams. Now, what they did was, they only used three impregnation processes. They just did a corresponding less number of impregnations.

SEIGER: I'd like to make a comment to Gerry; that we've impregnated very lightly by vacuum methods--when I say very lightly, I mean one cycle. And what we observed is that the bulk of the material is just under the surface--it's not in there uniformly. And it would be difficult for us to look at it and say, well, we loaded this to 0.6 gram per cc.

Now, I think, as a consequence of this repeated cycling--incidentally, it also occurs very markedly in the negative, if you do the vacuum impregnation; you can actually trace it by the white going in--that you are building up from the outside in. I believe that's what gives you the gradient of the distribution of the material.

I want to add one other thing. I think you neglected to point out that there's less corrosion in the electrochemically-impregnated. And I want to add one other thing about corrosion; that if you a vacuum impregnation, the corrosion is very low at the beginning. And then, as you keep impregnating it, the corrosion rate accelerates. So with the lightly-loaded electrodes, there is less corrosion.

DUNLOP: I tell you one thing. Obviously, these kind of results make us a little leery, obviously, of these arguments that are sometimes presented about increasing your loading levels and reducing your sinters on positive electrodes to decrease your energy density on day one. I mean, those are some of the kind of things that were discussed yesterday, and have been the kind of thing that the aerospace industry has been doing, to the detriment of reliability in cycling, based on our results.

BOGNER: We still don't know the optimum range.

DUNLOP: We certainly have got some very good indications of what can cause the problems.

(Figure 186)

MAURER: Most of our work at Bell Labs is on long-term overcharge kinds of tests, and we've done only very limited work on cycling. But one of the stress tests that we perform on our electrodes is a very high-rate cycle.

This is a flooded cell cycling at the 10 C charge rate for 100 percent overcharge and a discharge at the 10 C rate to take it down to a volt. This is repeated continually. And the capacity is measured by the time to 0.8 volt in seconds. So, this is a 12-minute cycle repeated continually. And here are the electrochemically-impregnated electrodes and commercial vacuum-impregnated electrodes that we took out of a commercial sealed nickel-cadmium cell. And you see this roughly as a factor of difference in cycle number to an equivalent capacity phase point.

And to compare this to the relationship of this kind of a cycle test to a sealed cell, we ran a study that we reported on at the ECS meeting in Cleveland several years back, showing the effect of cobalt in the electrochemically-impregnated electrode on a test just of this sort. And what we found is that if we had no cobalt, this fading would occur in roughly 200, 250 cycles. If you had 5 percent, the equivalent fade would occur at 1,000 cycles or so, or several thousand cycles. And beyond 5 percent, there really wasn't very much effect with cobalt, as long as you had some there. The cycle life was extended to the thousand-cycle range.

We put electrodes with no cobalt; now, this is an electrode that would have a 250-cycle life, let's say. We put that in a sealed cell and cycled it at a more moderate rate, 10 hour rate, with only 40 percent overcharge. And under those conditions, that electrode lasted for over 1,000 cycles before we terminated the test without any fading. So, the percent overcharge that the electrode gets has a pronounced effect on its cycle life.

So, if you use the same factor here, you're talking about going from a few thousand cycles to perhaps tens of thousands of cycles in a sealed cell.

COMPARISON OF ELECTROCHEMICALLY AND CHEMICALLY IMPREGNATED NICKEL OXIDE ELECTRODES

TYPE	POSITIVE ELECTRODE WEIGHT (g)	PLAQUE POROSITY (%)	MEASURED CAPACITY (Ah)	MEASURED CAP PER g OF Ni $(OH)_2$ (Ah/g)	PERCENT UTILIZATION OF Ni $(OH)_2$ (%)	LOADING OF Ni $(OH)_2$ PER cm^3 OF VOID VOLUME (g/cm^3)	LOADING OF ACTIVE MATERIAL PER cm^3 OF VOID VOLUME (g/cm^3)
CHEMICALLY IMPREGNATED ELECTRODES							
GE INTELSAT IV-A Ni Cd	23.02	83.3	2.67	0.252	87.2	1.93	2.31
ELECTROCHEMICALLY IMPREGNATED ELECTRODES (BELL LABORATORIES PROCESS)							
EP NTS 2 Ni H_2 LOT 2	11.42	81.2	1.34	0.324	112.1/105.6	1.31	1.56
YARDNEY Ni ELECTRODES	12.5	80.1	1.5	0.350	121.3/105.1	1.33	1.67/1.78

Figure 182

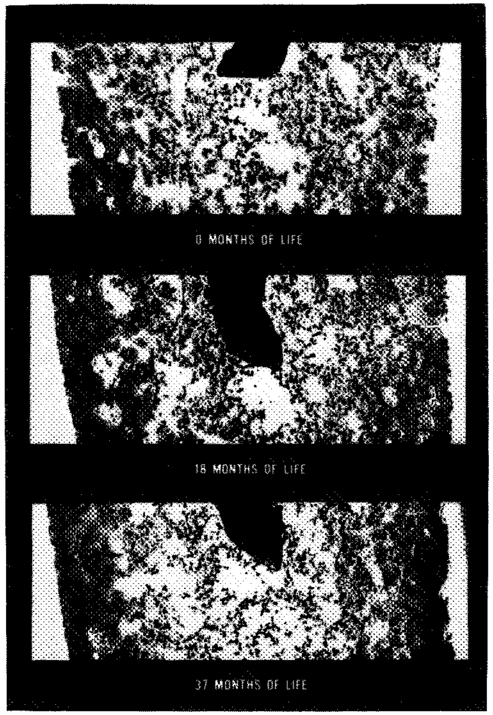


Figure 184

ANALYSIS OF ELECTROCHEMICALLY AND CHEMICALLY IMPREGNATED NICKEL-OXIDE ELECTRODES

TYPE	POSITIVE ELECTRODE WEIGHT (g)	PERCENT BY WEIGHT Ni $(OH)_2$ (%)	PERCENT BY WEIGHT Co $(OH)_2$ (%)	PERCENT BY WEIGHT Cd $(OH)_2$ (%)	PERCENT BY WEIGHT Ni SINTER (%)	PERCENT BY WEIGHT PERFORATED Fe (%)	DENSITY (g/cm^3)	MEASURED CAPACITY (Ah)	CAPACITY (Ah/g)
CHEMICALLY IMPREGNATED ELECTRODES									
GE INTELSAT IV-A Ni-Cd	23.02	46.0	2.67	2.70	24.9	20.0	3.49	2.67	0.116
ELECTROCHEMICALLY IMPREGNATED[a]									
BELL LABS EP NTS-2 LOT 2 Ni-H_2	11.42	36.2	2.3	--	48.23	8.8[b]	2.94	1.34	0.117
YARDNEY Ni ELECTRODES	12.5	34.26	5.30	--	39.83	17.13[c]	3.11	1.5	0.12

[a] The percent by weight of the nickel sinter for these electrochemically imprenated electrodes is approximately 50% compared to only 25% for the chemically impregnated electrodes.

[b] Nickel screen.

[c] Perforated Ni.

Figure 183

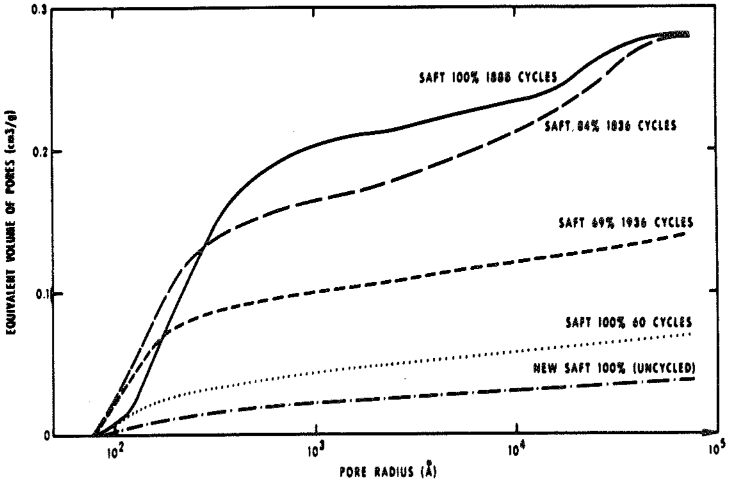


Figure 185

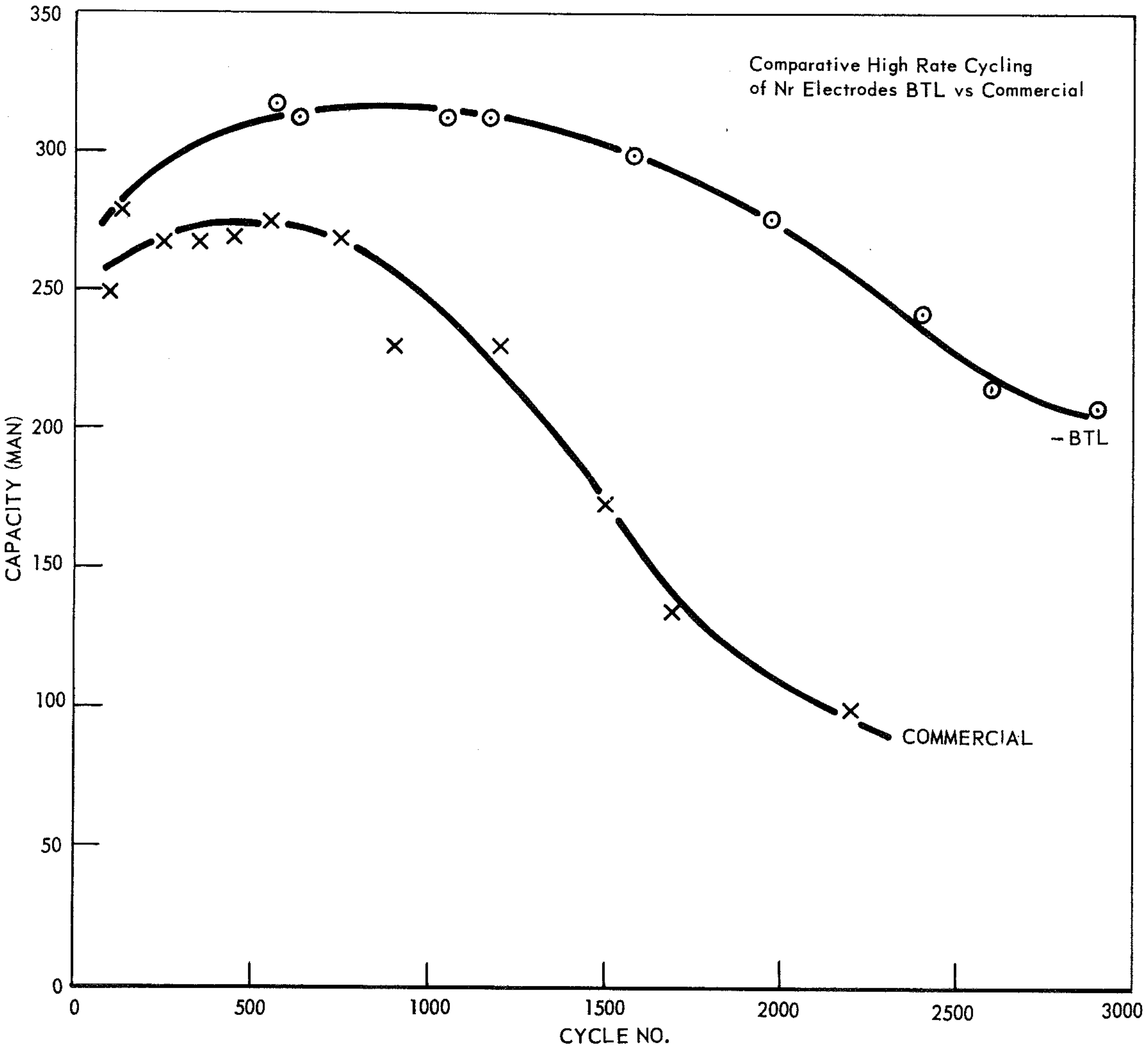

Comparative High Rate Cycling
of Nr Electrodes BTL vs Commercial
CAPACITY (MAN)
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
CYCLE NO.
BTL
COMMERCIAL

Figure 186

VIKING BATTERY GROUND AND FLIGHT TEST RESULTS

B. Newell
Martin Marietta

I was a little hesitant about coming up here and talking about the Viking cells, since they're polypropylene cells. And after hearing so many bad results from yesterday, or at least poor results, I was a little encouraged to see that the Canadians have a successful program in polypropylene.

The Viking mission is kind of a maverick, in the respect that I've heard a lot of talk about near-earth and synchronous orbits, and we've got kind of a peculiar one. The Viking cells actually did not perform much of a function until after we got to Mars, which actually took us about a year, and got down on the surface. So it's a little peculiar.

(Figure 187)

I brought along a picture of what the battery looks like. This is an example of what can happen when you run out of space to pack these things in the bird. There's actually two batteries there; 8 ampere-hour cells built by GE. The heat transfer method on that particular battery was through a center shelf, which actually extends up through the center here, and the cells were epoxied to that shelf, and carry heat into the lander structure.

The lander had a real peculiar thermal problem. On the Mars surface, it's colder than blazes, and during the transfer, or the flight from Earth to Mars, why, of course, it was in similar to a synchronous orbit.

Presenting a little bit of material here about the cell itself in terms of the mission, it's been like a textbook operation. There's not really anything to report. The battery's doing tremendous. It's sitting there on the ground, basically performing a load-leveling function, and operating between a temperature of 50 to 70 degrees Fahrenheit.

(Figure 188)

The Viking program did have one or several peculiar requirements. One of them was, the battery had to be sterilized, so I can show you what we accomplished in that type of respect. We had two requirements for sterilization: one, at the component level, in which we gave it an exposure to 233 degrees Fahrenheit for 54 hours, and that doesn't include an 85 to 90-degree per hour ramp up and ramp down temperature. And after the battery was put on the spacecraft, why, they sterilized the spacecraft again at 254 degrees for 40 hours. At least, that was the requirement.

And, just in case sterilization catches on, the last thing that's there will tell you how to do it without damaging your battery excessively. In fact, we really didn't see any damage at all after sterilization. But we discharged the battery down to 27 volts at the typical C/2 rate, and then 1 ohm to each cell for 24 hours, and then left the battery in an open-circuit condition with the cells open-circuited, and exposed it to the heat.

We did find that the first charge after sterilization, the battery did exhibit a high impedance characteristic, and we had to stay at the lower rate. We used anywhere between C/15 to C/10 rate, and didn't really run into any problems. You will see a little elevated voltage as compared to some of the later charge cycles.

(Figure 189)

A short summary; it's a typical prismatic cell with the 304L stainless steel case. We used the GE all-nickel braze terminals, and we used them in all the cells, and we never had one leak, so we're quite pleased there. There's 11 positive, 12 negative cells. We did use the Pellon FT 2140 enamel non-woven polypropylene, which I believe was manufactured in Germany, and is probably the one key to the successful development of that cell. Thirty-four percent KOH at the time of fill; electrolyte quantity--I put up limits there, but a typical quantity was around 22. 5 cc's, which is slightly under the typical 23 cc parameter, the number that was previously talked about.

We had a complete separator wrapped around the plate pack, to keep the outside negative plates wet, and we had a solid polypropylene sheet for a case liner. And the weight of the cell ranged around 373 grams; that's a lot average.

(Figure 190)

I want to present a few of the peculiar manufacturing processes that we did use. During the testing of the cell down at GE before they sealed it, we exposed the cell--or GE did--to heat for 24 hours, and then during the overcharge test with an electrolyte adjustment; and I think that's probably the key to how we got our electrolyte quantity a little bit higher, and we got away from the dryout problems that other people have talked about. And we also used the carbonate reduction process; that's a GE process.

(Figure 191)

I want to show you basically some of the characteristics of the cells. With the requirements that we had to spend about a year getting to Mars, we did an in-flight checkout, and changed the batteries, used them for a couple months. We were interested in, you know, what the self-discharge rate was; tried to see what would happen if we let the battery sit around in an open-circuit condition.

So, we did this test here, and I notice that the days are missing there at the bottom; I don't know where they went to. But that is days, and we went up to 100 days on that test. And that's the self-discharge rate for the particular cell we had, and that is based on the actual capacity of the cells. We got 15 cells and cycled them at a C/2 rate to a 1.48 volt cutoff, and a C/2 discharge down to 1 volt. After we established the capacity, then we put it on an open-circuit stand.

(Figure 192)

We did do quite a bit of trickle charging during the period after the launch. In fact, after we completed our in-flight checkout, which started at about 60 days after launch. And we put one of the four batteries on each vehicle on the C/40 trickle charge and maintained it there until we approached Mars. And as you can see, when we discharge after trickle charge, we see a loss in voltage, but not much of a loss in capacity. And when we did a recharge, we recovered quite a bit of the voltage, but we still lost some out towards the end there. It appears like the cell can handle itself pretty well, and can take a lot of trickle charging.

(Figure 193)

Here's a little bit of the in-flight data, as compared to the acceptance test data on the battery. And we plotted the discharge, which we took with three batteries that went on trickle charge, and discharged them down to 27 volts and let them drain down solely on the telemetry signal conditions load. And it appears that we lost quite a bit of voltage during that time, where we used them to support the in-flight checkout. But most of that support was, you know, very minimal, and only occurred when there were peak loads in the test periods. And we were a little discouraged to see this loss.

But we know, after we put the cells on cycling, that we recovered that voltage right away; one or two cycles, and we were right back up to where they were before.

(Figure 194)

This probably is of a little more interest to you, because it represents some of the results of our life-cycle testing. And last year we reported the results down through about into here, and we're now up to 12,000 cycles. We're testing at a 20 degree C temperature, and we've pretty well stabilized it at a recharge fraction of 1.1. And our test conditions are that we're doing a C/2 discharge for 30 minutes, and then a C/2 discharge for either 0.5 to 0.8 of an hour, depending upon recharge fraction.

We did recondition the battery after 8,568 cycles, and I'll show some data after the next couple of slides.

(Figure 195)

This plot shows how the end-of-charge voltage is behaving during the cycle testing that we're doing. It's pretty stable up to 12,000, and not really establishing any trends. And this, of course, was the point where we reconditioned. And at that point, we discharged the battery, recharged it at about a C/15 rate for 24 hours, and then did a capacity test, 1 ohm to each cell, and went back and recharged it again for another capacity test; and then went back and got our cycle ratio.

(Figure 196)

The end-of-discharge voltage for this particular battery--by the way, this is a 23-cell battery; we took one of the cells out way back, and did a failure analysis; it's for another Viking effort--this particular data does show somewhat of a trend in reduced voltage at the end of discharge, and it looks like it's going to take us quite awhile before we get to where we'll have any problems about meeting the criteria.

(Figure 197)

Here's the battery voltage on the reconditioning cycle, where we want to see what these cells were doing to support the Viking requirement. This is the discharge after the recharge at a C/15 rate for 24 hours, and it was done at a C/5 rate. The reason we picked that is, it fits the load at the distance that the lander vehicle had for discharging in flight, and you can see that we had a significant recovery in both capacity and voltage after we recharged after the 1 ohm for 24 hours.

We, I believe, got around 6.4 ampere hours for this discharge. And after reconditioning, we were back up to 8 ampere hours.

(Figure 198)

Cell voltages; I pulled the data for the worst case, and the best and the worst of these cells in the 23-cell pack, to see what the spread was there. And you can see they track pretty similarly, except for a little difference in capacity. And last of all, I threw in a general charge-discharge curve.

(Figure 199)

So, if any of you are curious to see how they compared to the nylon separator cells, why, there's some data to compare it with.

SEIGER: How much electrolyte did you wind up with after your adjustment, your heat treating and the adjustment of the electrolyte?

NEWELL: That was the range of the final electrolyte adjustment. Now, I don't have any data to define what it was before we did the heat treatment. But generally, we talk like we gained roughly 1 to 1.5 cc's. That's kind of a general number. I don't think I can really tie it down any closer than that.

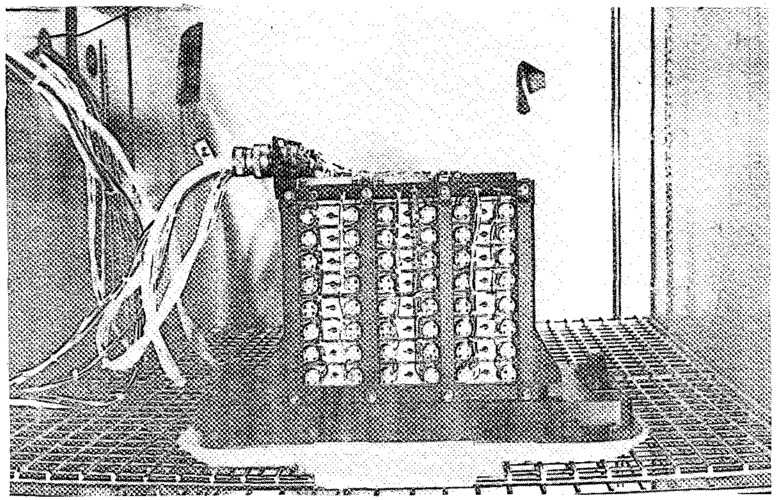


Figure 187. Viking Battery

o	CASE	304L STAINLESS STEEL
o	TERMINALS	G.E. - ALL NICKEL BRAZE
o	PLATES	11 POSITIVE, 12 NEGATIVE
o	SEPARATOR	PELLON FT2140 NONWOVEN POLYPROPYLENE
o	ELECTROLYTE	34% KOH
o	ELECTROLYTE QUANTITY	21.5 TO 23.5 CC (TYPICAL)
o	PLATE PACK WRAP	SEPARATOR WRAP AROUND PLATE PACK
o	CASE LINER	POLYPROPYLENE SHEET
o	WEIGHT	373 Gm-LOT AVERAGE

Figure 189. Cell Description

<u>REQUIREMENTS</u>

- COMPONENT STERILIZATION
  EXPOSURE TO 233°F FOR 54 HOURS
- SPACECRAFT STERILIZATION
  EXPOSURE TO 254°F FOR 40 HOURS

<u>PRE-STERILIZATION CONDITIONING</u>

- DISCHARGE BATTERY TO 27 VOLTS AT C/2 RATE
- ONE OHM EACH CELL FOR 24 HOURS
- OPEN CIRCUIT BATTERY AND CELL TERMINALS
- FIRST CHARGE AFTER STERILIZATION AT C/10 RATE OR LESS

Figure 188. Sterilization

- CELLS HEAT TREATED AT 257°F FOR 20 HOURS PRIOR TO FINAL ELECTROLYTE QUANTITY ADJUSTMENT
- ELECTROLYTE ADDED (REMOVED) DURING AN OVERCHARGE TEST TO ADJUST OPERATING PRESSURE TO A NOMINAL 20 PSI
- CARBONATE REDUCTION PROCESS USED

Figure 190. Unique Manfacturing Processes

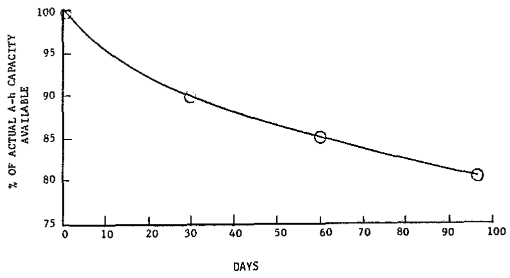


Figure 191. Cell Self-Discharge Characteristic for 70°F.

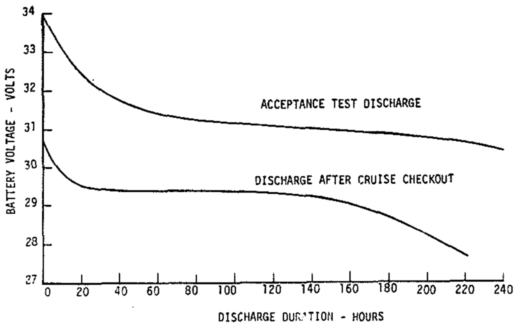


Figure 193

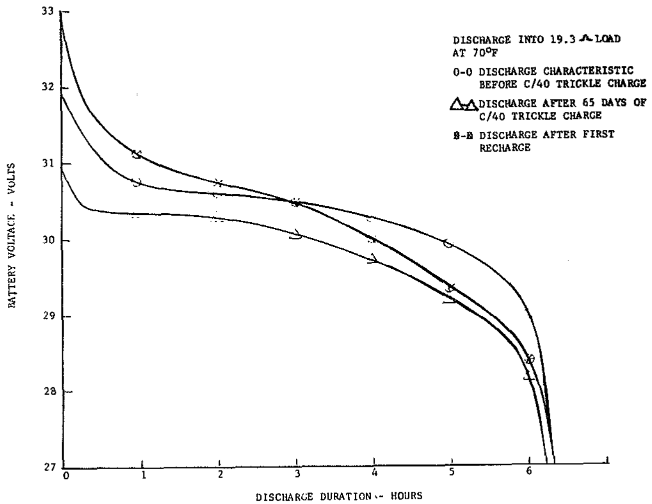


Figure 192. Effects of Trickle Charge on Battery Voltage.

CYCLE NUMBER	TEMP	RECHARGE FRACTION
0 - 5000	40°C	1.1
5000 - 5550	40°C	1.17, 1.3, 1.6
5550 - 5650	25°C	1.17
5650 - 6300	0°C	1.02, 1.05, 1.1, 1.17
6300 - 6900	20°C	1.02, 1.1, 1.2, 1.06
6900 - 7700	20°C	1.1
7700 - 7775	20°C	1.0
7775 - 8000	20°C	1.1
8000 - 12000	20°C	1.06 - 1.1

- TEST CONDITIONS C/2 DISCHARGE - C/2 CHARGE FOR 0.5 to 0.8 HOURS
- BATTERY RECONDITIONED AT 8568 CYCLES AND DELIVERED SLIGHTLY OVER 8 A-h.

Figure 194. Life Cycle Testing Summary

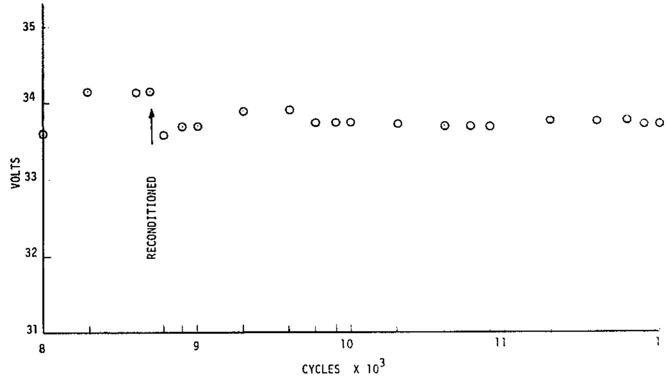


Figure 195. Battery End of Charge Voltage

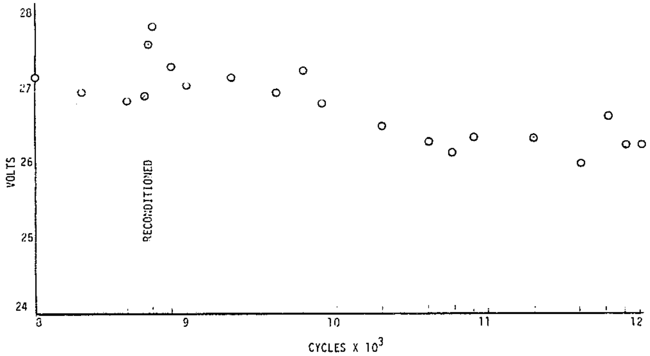


Figure 196. Battery End of Discharge Voltage.

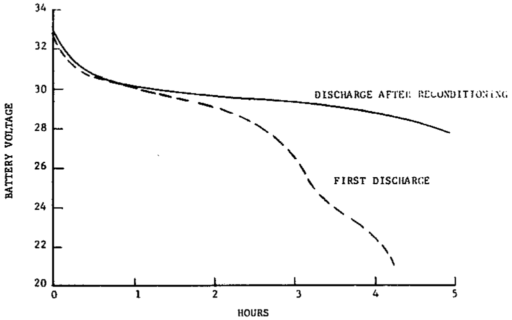


Figure 197. Battery Voltage Characteristic After 8568 Cycles.

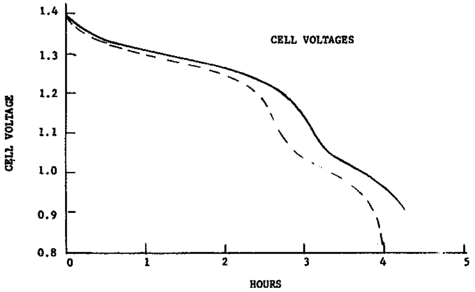
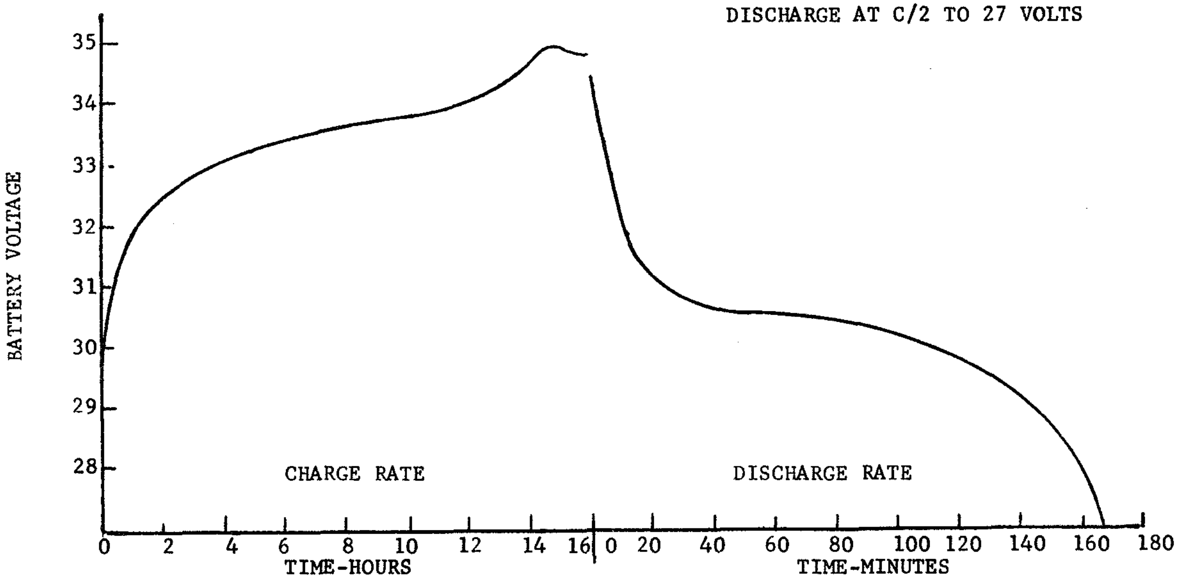


Figure 198. Cell Voltage Characteristic After 8568 Cycles.



TEST TEMP. 70 ± 3°F

CHARGE AT C/10 FOR 16 HRS

DISCHARGE AT C/2 TO 27 VOLTS

BATTERY CHARACTERISTICS AT ACCEPTANCE TEST

Figure 199

VIKING ORBITER BATTERY DESIGN AND PERFORMANCE

R. S. Bogner
Jet Propulsion Laboratories

My topic is the Viking orbiter battery design and performance. I'll also talk about the system design and show photographs of the spacecraft and the battery, discuss a little battery performance mission simulation test that we ran, and then present some battery performance on the actual mission of the VO I spacecraft; and briefly summarize some of the problems we had during the procurement and building of the battery.

(Figure 200)

The system design was a redundant system, and the requirement was that there was no single-point failure. Therefore, during the mission, we limited the battery depth of discharge to 45 percent of actual capacity, and we had two batteries in the spacecraft. And therefore, if one battery happened to fail at any time, the other battery would support the load, which would go up to 90 percent depth of discharge. And this is on actual estimated capacity of the battery, which is around 35 ampere hours. The cells were rated at 30 ampere hours.

The battery discharge voltage limit was 27 volts. The battery contains 26 cells. Therefore, we can go up to practically 1 volt per cell. The charge control on the spacecraft was a preset voltage level, or timed sequence with an on-board computer. We used two constant current chargers, which would charge at three rates. The high rate was 3 amps, medium rate 2 amps, and the low rate, or trickle rate, was 0.65 amps, which was approximately the C/40 rate.

Now, we had safety backups to the chargers. We had parallel thermal switches that would cut the chargers off at 30 degrees C. We later found a failure mode in the charger. The charger could essentially go on limited current, which would bypass that switch; so we added another thermal switch which would cut off the charger completely at 40 degrees C.

The thermal control on the spacecraft was activated with louvers. The battery spec temperature range was 0 to 21 degrees C, and we also provided reconditioning loads of 30 ohms.

(Figure 201)

This is the configuration of the Viking orbiter, and you can see the location of the batteries under the solar panels and the drawing of the louvers.

The orbiter with the lander is on top in the clam shell, and it's being completely encased. To give you some idea of the size, each of those solar panels is about 10-feet long. And the total spacecraft that's sitting there is about 14 to 15 feet high.

The battery chassis is completely machined out of magnesium with individual cell compartments. The cell, prepared and ready to go into the chassis, you notice has little pads which are spaced to prevent the cell from touching the edge of the pockets in the chassis.

This particular battery was not the flight model. We made a change because we learned there's a vibration problem, and that the web at the top with all the little holes in it was later made solid--this area here. There are two of the thermal switches, and the third thermal switch is not shown on this particular battery. And the piece in the center is the temperature transducer.

The cell in this battery was 1.07 kilograms, and the total cell weight in the battery was 28 kilograms, or 62 pounds. And the total battery weight, after potting, wiring and soldering, was 33 kilograms, or 73 pounds.

(Figure 202)

The next figure shows some data from the mission simulation test, and this is an occultation test after simulating nine months' cruise. In this period, it was kept on constant trickle charge, approximately 0.65 to 0.7 amps. So we have the cycle number versus the capacity output, and the top scale shows the end-of-discharge voltage versus the cycle number. And just for the heck of it, we also had a Mariner 1971 battery that had been on constant test for approximately five years. We put it through the same type cycle regime, and the solid dots represent the 1971 Viking, or Mariner-Mars, battery performance which was a 20-ampere hour cell versus the 30-ampere hour cell.

(Figure 203)

This figure shows a typical discharge-charge cycle near the center of the occultation period. And that's 400 and some days after we simulated our launch. We did not recondition this battery.

(Figure 204)

This shows some of the results of one battery on the Viking orbiter. We've got the discharge number versus battery DOD, which is this line, and the discharge time in minutes.

Now, where you see that little glitch here in the curve, where they reprogrammed the spacecraft--because they were starting to go beyond the 45 percent depth of discharge limit that we had established, so they had to cut back on the power levels by cutting off some of the science systems.

(Figure 205)

This graph shows some of the occultation periods up to 16, which is near the maximum depth that we went; discharge time in minutes. This is the battery voltage during the occultation portions. The top curve is the discharge current in amps during the various occultation periods, and if you compare some of these discharges on the actual flight battery with some of the discharges that we performed on the mission test battery, you'll see that they're very similar.

There was one difference. These are constant power discharges. In our test battery, we discharged constant current, but we were still pretty much on the plateau of the battery. So it didn't make that much difference in the discharge current, because they were fairly constant currents anyhow. These little blips on the ends of the discharges was where we started to share with the solar panel as we came out of the occultation.

(Figure 206)

This shows a typical charge cycle; the upper curve showing the battery voltage during charge, the lower curve, the circles, is the battery temperature. So you can see that we're operating at a pretty nice temperature range during most of the trickle charging. When the battery was completely charged, we were operating around 15 degrees C. In this particular charge, we switched to low rate. This was not switched on the voltage, but this was switched on a time sequence, and we estimate how much time will be required to charge the battery. And this is programmed into the computer on the spacecraft. And we were calculating that we should recharge about 105 percent of what we took out in the previous cycle; and this particular one shows that if we were using the voltage cutoff, they're almost identical. So, we're able to predict the performance on this battery quite closely.

(Figure 207)

To briefly summarize some of the problems we had--because each one of these items could be a topic for a half-hour discussion--we had quite a few problems in the cell procurement, primarily the schedule, because we had to scrap out the first four lots of plates. Then we ran into the internal short problem which I discussed last year at this meeting; and, by the way, we're continuing testing some of those cells that failed internal short. And the mission test battery has two cells in it that failed that internal short test, and we can't tell the difference in those cells versus the good cells.

So, the internal short test is not a very good test. We ran into cell vibration problems, where the plate tabs were breaking, very similar to the breakage that Sid Gross showed yesterday. As that turned out, we were over-testing, and the result affects the fact that we lowered the level of the test. We ran into a couple of high-impedence cells on the test battery; this was during integration testing. And we had the fine controls and limits that they should handle the battery too during the integration testing, but it seems that they didn't follow them, and they left the battery in random condition, open circuit, for various periods of time.

We got the battery back in the lab, and we discharged it down to recondition it. And on the next discharge, or charge cycle, we found two or three cells that went up over 2 volts at a C/10 rate. We were never able to bring those cells back into a proper operating condition. So, they would deliver 26 ampere hours down to 1 volt, and if we continued to discharge, we could get to 35, 36 ampere hours all the way down to 0 volts, and there was a constant slope on the discharge curve.

And finally, we had an accidental power turn-on on the launch pad, and this was about a day before the launch. And we think it was due to a lightning storm, which caused some cross-ups on some telephone lines which operated the spacecraft from the blockhouse, which is about eight miles away. I came in the next morning and found the battery down to 8 volts.

Our advice was to remove them and replace them, which would mean that those batteries, after we took them off and looked at them and found out what really happened: the type of rates, power level it was on, how the spacecraft performed. We really don't think that the batteries were damaged, but that took us three or four weeks to find out, and we didn't have that kind of time while we were on the launch pad.

KIPP: It looks like you determined at what level of vibration you could break cell tabs off at. Can you tell us what it is?

BOGNER: Bob Dillon, do you recall the levels? I don't have the figures; I can look it up.

DILLON: 11.3 gr, and that's random.

KIPP: Can you tell us for how long?

DILLON: Well, it was a five-minute test, and I believe the power spectrum density was about 0.1 g^2. I'm not sure.

KIPP: Was that five minutes to scan the whole?

DILLON: Don't forget, these cells were not preloaded. There was no pre-load of the size that Sid discussed yesterday. He discussed the various areas of strength in plate tabs due to the amount of pre-load.

KIPP: When you say pre-load, you mean--

BOGNER: I think I'd have to correct you on that. In the battery, they are not pre-loaded. As you saw, they're dropped in the cavity and potted.

Now, where we were breaking cells was where we tested a group of cells, and they were preloaded, and on a big vibration fixture. This was individual cell vibration tests in that case, and we ran into problems. And we were testing at that time to two times, double, the length of the TA level, and I don't recall the exact TA levels.

KIPP: Okay. You're saying then that the large fixture would not be strained?

BOGNER: Not in the battery. But when we were running the tests on--I think we vibrated 30 cells in a package, and that package was constrained, and I can't tell you all the limits that it was constrained to.

KIPP: What I don't understand was when you said they're not pre-loaded.

BOGNER: They're not in the battery. But this particular test where we did break the cell tabs, they were not in the battery at that time.

KRAUSE: Hughes

That's sort of a strange package design, Sam, where you don't have any pressure or strain on the cells. Do you notice any difference in the long-term electrical performance, say, between that design and the Mariner 1971 design, where the cells were pressured?

BOGNER: Well, I can't say that we have noticed anything yet. We've done about a year and a half's test data on this, compared to the 1971 program on this. We've got five and six-year data, with most of that internal charge. And perhaps next year, I can summarize some of that where we've gone through reconditioning. We can see all kinds of crazy discharge curves.

WEBSTER: Sam, what was the thickness of the walls of the cells when they were under strain? What was your case thickness, do you know?

BOGNER: 21 to 23 mils. We had some other problems, though, with those cells. Like I said, we ran into a rash of short test failures, which apparently didn't mean too much. They have a low level of electrolyte; there's about 70 cc's of electrolyte in those cells, and they deliver like 35, 36 ampere hours; interelectrode spacing, if you calculate it out, versus the thicknesses that are used, is 5 to 6 mils.

MIKKELSON: Convair

What did you do to correct your vibration problem when the tabs broke? Did you do anything?

BOGNER: No, we did a lot of talking. Like we said, we were overtesting. We went to the so-called QA level, which is--I don't know; twice as much as the actual flight. Then we also lengthened the time that we vibrated at each of these levels, went through random and sine and what have you.

FORD: This subject of compression versus non-compression is particularly worth pursuing for a minute. It's not that simple; you've got to look at the cell itself. We've talked about bulged cells, or cells with convex versus concave cases. Now, if I understand, both of these cells had convex cases.

BOGNER: Yes. We had a problem, which we didn't list on the problem summary--many of the cells coming in over our spec limit on thickness. So they were bulged.

FORD: And you also mentioned calculated interelectrode spacing; about 6 mils, I heard you say. That was based on the non-expanded?

BOGNER: That was based on the plates at manufacture.

FORD: The point is that if you have this design, you put it in an environment that it will slide in and be potted in. If you do get additional plate capacity, which you know we get in certain types of electrodes, you're going to have a compressed stack anyway, whether you compress it or not, unless you let it expand. And if the pack environment does not expand, you end up automatically compressed.

What the pre-load is, and what you've got, I don't know. But what you don't have are cells with plates just hanging there, without any mechanical pressure on them.

SEIGER: And if the plates swell, if the positive plates swell, then your interelectrode spacing does down. And if you're using an on 2505, if the interelectrode spacing goes below 4.7 mils, the impedance of the cell starts to rise. And it goes down about another mil, and it starts to rise spectacularly.

BOGNER: Pretty soon, we end up with a solid separator.

SEIGER: That occurs at about 2 mils.

MIKKELSON: Since you and Mr. Gross have both talked about broken tabs, this is just a general question. What, if anything, can be done to prevent this from occurring, or do you really think it's a problem that's worth worrying about?

BOGNER: Well, it depends on the environmental requirements of the particular spacecraft that you're working with, really. And we overtested. I wanted to do that on purpose, because they make us go through vibration levels at the battery level. You put them on the spacecraft, you have to go through a vibration on the spacecraft, and then they launch the darn thing.

So I was just trying to get some additional information, and we ran into a problem. We considered putting shims inside the cells, to prevent the pack from moving, but we never did.

THIERFELDER: General Electric

On that vibration, did you have any accelerometers on the individual cells, to see what kind of amplification you were getting? Because if you're only putting 11.4 in, it doesn't seem a very high vibration level.

BOGNER: Well, okay. That was on a big, solid vibration fixture. So, at the cell level, we weren't getting that kind of amplification. On the battery, we did that, and we measured the amplification factor.

THIERFELDER: But when you had the failure, you did not know what the amplification was?

BOGNER: Not really, no. But it shouldn't have been that much in the fixture we were using.

WADHAM: Telesat Canada

I want to make a comment on this packing business that Floyd Ford was referring to. We had an interesting experience with one of our cells. As Jim has explained, we send them to him periodically for analysis, and we noticed that one of these cells which we sent, measuring it in a pack where the cells are compressed; we measured a particular cell characteristic, a particular capacity. When Jim measured it at Comsat after delivery, we found there was quite a significant increase in capacity, which was probably due to the fact, I think, because the cell was being allowed to expand when it was taken out of the pack.

BOGNER: I guess that's a possibility.

By the way, on this vibration, we went through an analysis, and calculated--well, the cycle numbers the plate tabs could stand before they would burst. And in going through the analysis, and trying to find out what the material was, we found that the material that they make the substrate which the plaque is on is probably the poorest material you can use, as far as standing up to vibration.

HALPERT: I'd just like to make a comment with regard to those cells. We have had a related experience using the 30-ampere hour GE cell. We found, in our particular application, that we were having the problem with capacity; this was with regard to the Tiros N cells.

In relating the loading to the current density we found that the scale-up in plate area from a 20, 6, or 12 to a 30 was not in a direct ratio. Therefore, the manufacturer was trying to get a 30 percent increase in active material into the plate with only 15 percent increase in plate area and thus was overloading a significant amount. When we did the scale down where the cell was originally considered a nominal 30-ampere hour cell, we had to reduce it to a nominal 26.5-ampere hour cell, because that was the only reasonable, in our opinion, rating that could be associated with the amount of area we had in that cell.

So, in the case of the 30-ampere hour cell that Sam was describing, I would suggest, knowing the values that we have, that there was an excessive amount of loading in those plates; much more than we really would have, even on a 20 or a 6 or a 12, which we now know is still too much. So we were significantly overloading, and it could cause significantly more expansion than we would normally have.

BOGNER: That's probably true.

- REDUNDANT SYSTEM - NO SINGLE-POINT FAILURE
    - BATTERY DOD LIMITED TO 45% OF ACTUAL CAPACITY
    - BATTERY DISCHARGE VOLTAGE LIMIT 27V
- CHARGE CONTROL
    - A PRESET VOLTAGE LEVEL OR
    - TIMED SEQUENCE
- TWO CONSTANT CURRENT CHARGERS THREE RATES
    - HI - 3.0A MEDIUM - 2.0A LOW - 0.65A
- SAFETY BACKUP TO CHARGERS
    - PARALLEL THERMAL SWITCHES - 30°C
    - ONE THERMAL SWITCH - 40°C
- ACTIVE THERMAL CONTROL - LOUVERS
- BATTERY SPEC TEMPERATURE RANGE: 0° TO 21°C
- RECONDITIONING LOADS: 30 Ω

Figure 200. The VO Battery Design & Performance, System Design.

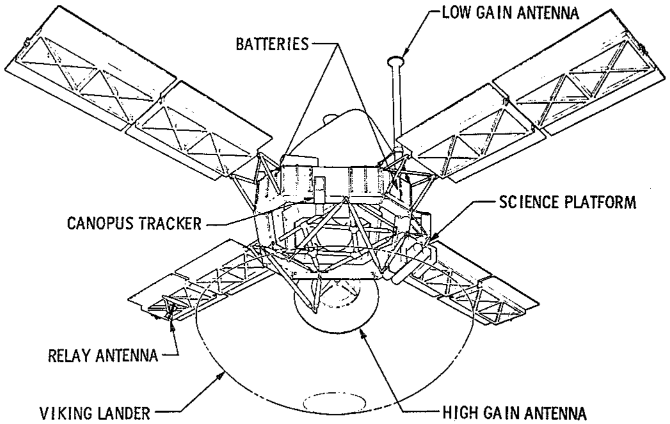


Figure 201. Viking Orbiter Configuration

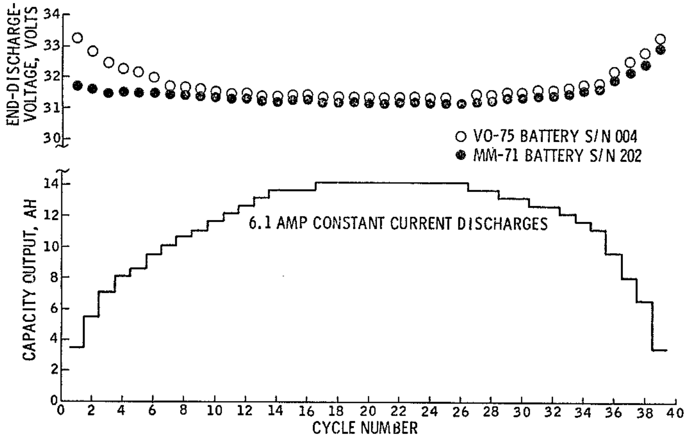


Figure 202. The VO Battery Design & Performance, Viking Orbiter Mission Simulation Test, Occultation After 9 Months Cruise.

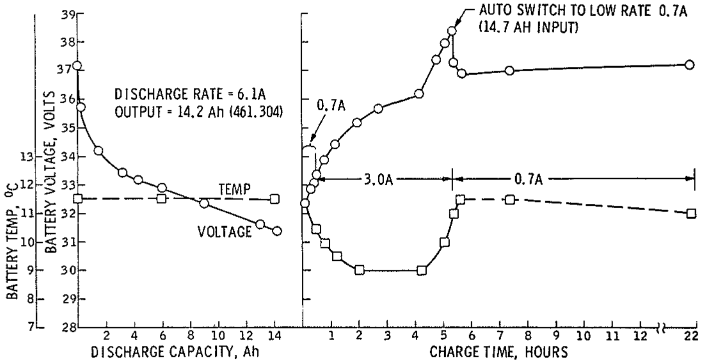


Figure 203. The VO Battery Design & Performance, VO-75 Mission Simulation Life Test Battery S/N 004 Occultation #20 Discharge/ Charge 7-3-75 (L+402 Days).

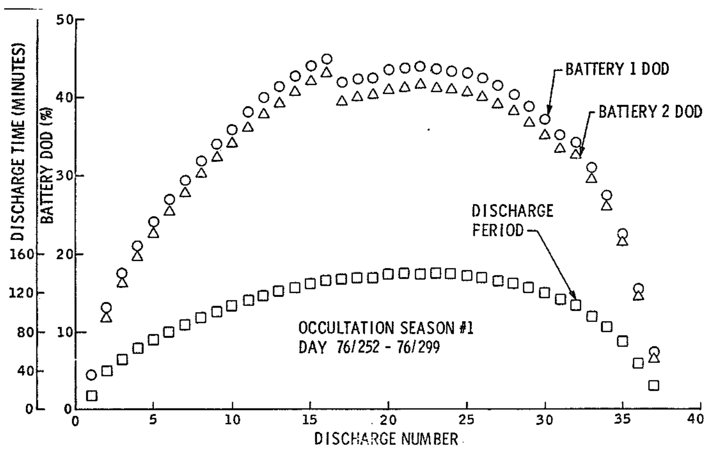


Figure 204. The VO Battery Design & Performance, Viking Orbiter #1 Battery DOD, 100% DOD=35Ah.

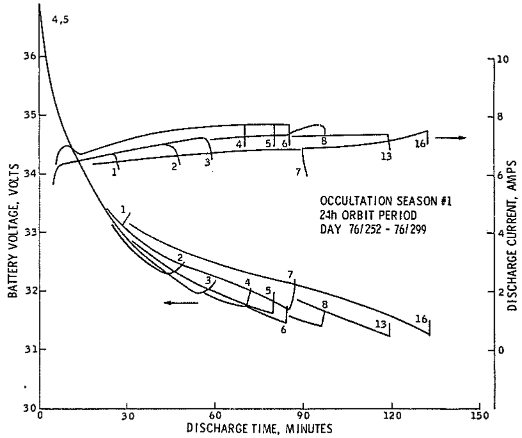


Figure 205. The VO Battery Design & Performance, Viking Orbiter #1, Battery #1 Discharge Performance.

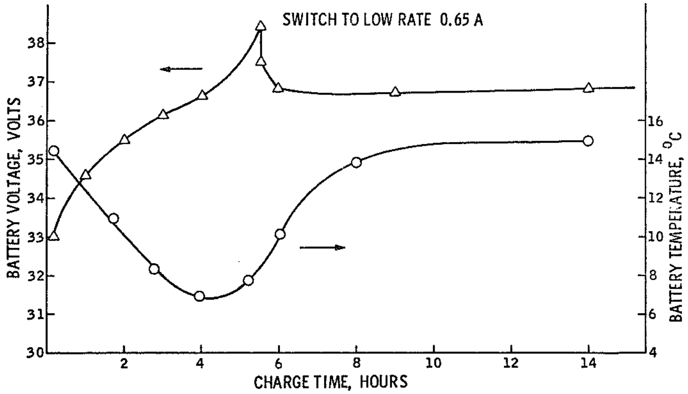


Figure 206. The VO Battery Design & Performance, Viking Orbiter #1 Battery #1, Typical Recharge, Occultation #21, Day 283.

- CELL PROCUREMENT
- INTERNAL SHORT TEST FAILURES
- CELL VIBRATION - PLATE TABS BROKE
- HIGH IMPEDANCE CELLS ON TEST BATTERY
- ACCIDENTAL POWER TURN-ON ON LAUNCH PAD.

Figure 207. The VO Battery Design & Performance, Problem Summary.

NICKEL HYDROGEN BATTERY HAZARDOUS TEST FACILITY

M. Gandel
Lockheed

I don't like using the term, hazardous. It's kind of in poor taste. But in making our plans awhile back for testing nickel hydrogen battery cells, there were two prime considerations. One, in having a container with hydrogen, and considering the possibility of leakage, we wanted to assure that we did not have any closed space where hydrogen could collect and mix with air, and form an explosive mixture which would be anywhere from 4 percent to 196 percent hydrogen.

The other consideration was simply working with a pressure vessel going up to several hundred psi. There was just simply the hazard that would be associated with any container, of hydrogen, or otherwise. And in working with developmental hardware particularly, even though you may have safety factors of 4 to 1; or, in many cases, we're using cells as low as 2 to 1, there is going to be the time when a cell is going to let go.

And with those two considerations, it led us into the design, away from the classical nickel-cadmium testing, which we would do in a closed temperature chamber. If you did go to a closed chamber, you certainly want to have it with an explosion-proof variety. But any kind of electrical testing, you do have a sparking potential just from the hardware you're using.

(Figure 208)

And so, in trying to satisfy those two major conditions, we designed this test facility. And you can't see it in this view; the roof of the chamber is too offset, perforated steel plates, so that in the event there were shrapnel, certainly, it couldn't do anything but damage the ceiling.

The other factor is, we have Lexan polycarbonate sheets, which form the doors around the chamber. And in figuring out what kind of thickness or protection we want to provide there, I went through the logic of preventing a chain reaction explosion. Let me amplify that.

If you had one cell bursting into shrapnel, what would be necessary, what would the mass and the velocity of that piece of shrapnel have to be in order to penetrate a neighboring cell, then postulating continued cells bursting? Anyway, that led to selection of a quarter-inch thick Lexan sheath.

The cooling system in here is watered glycol, which is the total refrigeration system. It is below the Lexan, which has the chambers containing the cells. There is a four-battery, four-temperature capability, and the total system can handle 40 cells, monitoring them and controlling them.

The system contains high-pressure and high-temperature cutoffs, being that it's run continuously around the clock. And in the event of any cell reaching a pre-set pressure, or a pre-set temperature, the system will shut down.

(Figure 209)

The side view here at the bottom; there are a couple of rotometers which give us adjustment on the flow to each of the cooling systems. And with two refrigeration systems, we're able to get our four different temperature capabilities.

(Figure 210)

Then, lastly, this is the fixturing box for a ten-cell, 20-ampere hour battery. Each of the cells has a pressure transducer mounted on it.

KRAUSE: Hughes

We've taken a similar approach, a very similar type of apparatus that you have for nickel-hydrogen testing. I only wanted to comment, instead of quarter-inch Lexan, we're using quarter-inch steel.

GANDEL: On that, actually, Lexan, having that view capability of closed text fixtures, doesn't need too much.

KRAUSE: We call our box the bomb shelter. That's our nickname. I don't know what you call yours.

GANDEL: Right. The Lexan is for show, and might just as well be opaque.

BARNETT: Rockwell

Have you calculated the TNT equivalent of the energy density in your calculations ?

GANDEL: I haven't. But what is the equivalent? I heard it once; that the energy density of a nickel-hydrogen cell is about half that of TNT. I don't know.

BARNETT: We've calculated it at 102 grams. I just wanted to know if you had independent assessment.

ROGERS: Hughes

To get the energy density you're talking about, Marty, you have to build up a stoichiometric mixture of oxygen and hydrogen, which is really next to impossible, because you have a platinum electrode which would ignite at the 5, 6, 7 percent level. So you really don't have that energy available, in a practical sense.

GANDEL: Well, I'll just dispute it in this regard. If you had the cell leaking into a closed dome, you could have it.

ROGERS: Well, I hope you don't design that way.

Ours is open at the top in the standard dimension. Ours is open, with a very heavy wire mesh screen, and the room is very large. The only thing it would do is, it would hurt my plants if it went off.

GANDEL: Hurt your plants?

DUNLOP: If you actually look at most nickel-cadmium cells after they've been running for four or five years, you can find much more hydrogen in an awful lot of nickel cadmium cells. And you find a much more dangerous situation than you find in most nickel-hydrogen cells.

GANDEL: I think, too, that going to the lighter weight cans, that maybe we should review all NiCad testing.

DUNLOP: Let me say one more thing about light-weight cans. There's one interesting thing about them. In the analysis that TRW did for us, if you do a crack propagation analysis, you can determine for a given thickness whether, once your crack propagates, whether you will get an explosion or whether you'll get a leak. And that depends on the thicknesses. I don't care whether it takes you 50 or 100,000 cycles, or whatever to get a crack. Eventually, any crack can propagate through any thickness of can. But the trick is to know what your safety factor is over a leak which would burst once you get a crack propagation.

It turns out that many of these increment things--for example, stainless steel is much lower in terms of there is no margin. That 304L stainless steel, there's absolutely no margin. But there's about a 4 to 1 margin with a 20-mil can, even at a pressure of 400 or 500 psi.

FORD: Goddard

I would just like to point out, not just on nickel hydrogen, but on cadmium, there have been a few--fortunately, very rare--very violent explosions of nickel cadmium cells. One I can remember very vividly. It happened at Crane about five years ago, when we were running our experimental cells on electrodes; and it's fortunate that they're rare, and fortunate that there's been nobody hurt.

But I know that it has happened, and it is not explained by the conventional pressure rupture explosion. It's very obvious that something happens in that cell to create intense heat, so that in most cases I can cite that the nylon separators disappeared.

WEBSTER: Question, though, for clarification. Is it a misassumption I'm making that no one's ever had a nickel-hydrogen cell go off, or that hasn't happened yet?

GANDEL: I've only heard it happening once.

ROGERS: The explosion we had--we did have an explosion--was about the level of a 0.38 special, not any more than that. It did not blow the cell up. It threw a valve. It did stretch a few bolts, I think, and it occurred in the very earliest days of our testing. It was a hydrogen-oxygen explosion, and I will make the comment that we have never had any explosion since. We don't expect it, and in a properly-designed nickel hydrogen cell, there's no reason to even consider that it could happen. And I'll be addressing that right after lunch.

NAPOLI : Excuse me. Are you talking nickel-cadmium or nickel-hydrogen?

ROGERS: Nickel-hydrogen.

DUNLOP: I'd just like to quote you a reference. Karl Kordeson gave a paper at Brighton in September. He took either C or D-sized cells--I forget which--nickel-cadmium cells, and made them nickel-hydrogen cells. And he claims they went through a very careful analysis, and he claims that cell is much safer than the nickel-cadmium cell that they make. And they took that up all the way to the vice-president of the corporation, and they decided, without any modification to a standard D-size configuration, you have--they even throw these things in fireplaces, for example. It's got a nice self-discharge mechanism, the nickel-hydrogen cell.

Actually, the cell that he's made--I'm not quoting; I'm quoting Union Carbide now--Union Carbide has taken the position that it's a safer cell than the nickel-cadmium cell.

GASTON: RCA

Just one quick comment. When you're testing nickel-hydrogen cells, do you include the rupture test, what you can do to the outside of the chamber? I know that's what I--

GANDEL: In nickel-hydrogen testing?

GASTON: Yes, high-pressure rupture tests.

GANDEL: That would get awfully cumbersome. It would get into a number of cells.

GASTON: Well, if you have a large number of cells, true.

GANDEL: In fact, then your ducting to the outside becomes a real big hazard.

GASTON: No, you lead it. Well, of course, the outside; you can always put it to the management later on, when it becomes cumbersome.

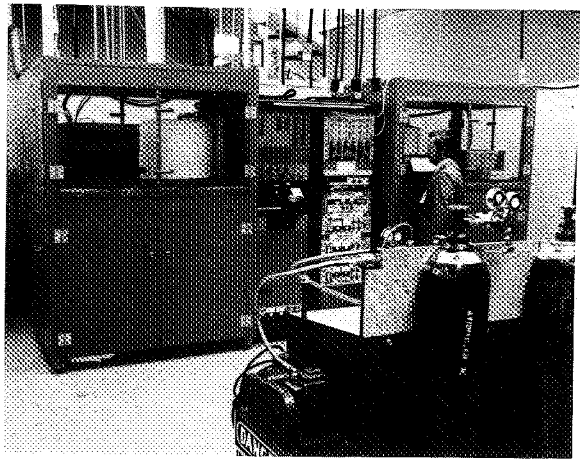


Figure 208

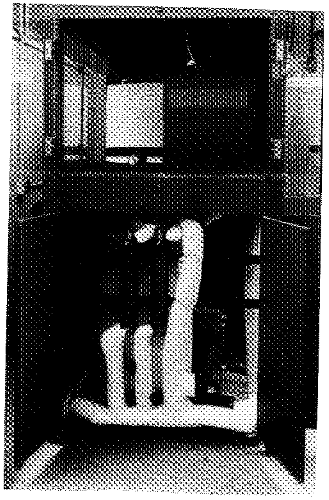


Figure 209

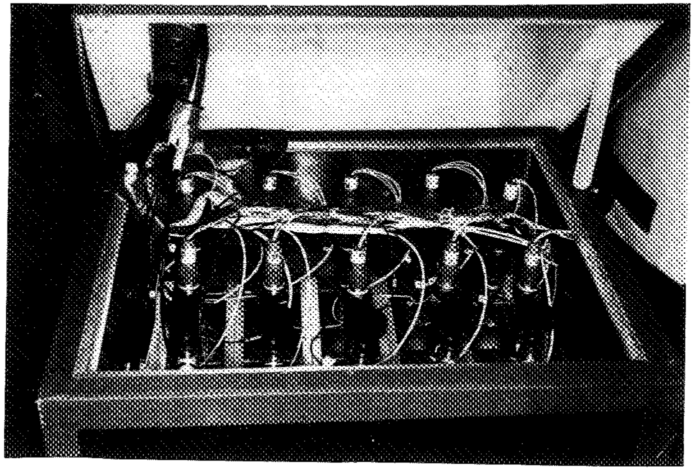


Figure 210

Second Day Afternoon Session

NEW DEVELOPMENTS

F. Ford, Chairman
Goddard Space Flight Center

The fourth and final session of the 1976 Workshop was titled New Developments and under that title comes a range of subjects we will discuss. On the agenda for this afternoon is a discussion on silver-zinc, silver-hydrogen, and then we're going to inject one paper on the technology improvements on the nickel-hydrogen applicable to the nickel-cadmium technology. And then, we're going to launch right into nickel-hydrogen, and spend the remaining hour or so discussing nickel-hydrogen development.

PIONEER VENUS PROBE BATTERY PROGRAM

J. E. Bell
Hughes Aircraft

This is going to be just a brief review of some of the problems that we faced in the Pioneer Venus program during the design phase. The program intends to drop four battery-powered probes on the Venus surface, primarily to measure the atmospheric conditions on Venus, and they're not really surface explorers. And some of the design problems that we are encountering are the space and weight restriction in the forward portion of the probe; the probes are rather small-shelled vehicles. The large probe is about 30 inches in diameter, and the small probes are about 16 to 18 inches in diameter. And they're divided into three parts, and the forward part is the battery compartment. The forward shelf of the forward part is the battery location.

(Figure 211)

Some of these design problems; first of all, we required a high energy density battery because of the space and weight restrictions. And we are intending to encounter a severe high-g environment during entry into the Venus atmosphere. The small probes' qualification environment is approximately 706 g. The large probe high-g environment is at the 500 g level.

During the ground-testing portion of the spacecraft, the battery will be buttoned into the probe, and the temperature environment at the Cape will cause some internal energy losses that are not recoverable. And just before and just after Venus entry, the battery will be required to fire pyrotechnic devices.

We have a combination of a high current requirement, plus a requirement for a long-term open circuit stand without appreciable loss in battery capacity. These two features are rather difficult to design into a silver-zinc battery. What we did to meet these requirements is the subject of discussion this afternoon.

(Figure 212)

The requirement for the battery is an 18-month design life--that's 12-months' life prior to launch, and a 6-month design life in space. The battery depth of discharge is approximately 80 percent for both batteries, and you see the high g levels that are required. The acceptance levels are approximately equal to the actual entry into the Venus atmosphere. The qualification levels, if passed through, would provide the safety margin.

The high current pulses that you see, the battery will be required to maintain; in the large probe, about 17 amperes constant discharge on entry into Venus, and the small probe about 2.5 amperes. Superimposed on this pre-load are the two pulse requirements that you see there.

(Figure 213)

The temperature regime of the two batteries: equal for both large and small probes. The 140 degree temperature is the temperature just prior to impact, as the Venus environment is rather inhospitable. The low temperature the battery sees is just prior to entry; the battery temperatures will be approximately 20 degrees Fahrenheit at entry. And it's been determined that with the plate area that we have to provide battery voltage to fire the pyros, we need a battery temperature of about 50 degrees. So we mounted internal heaters in the battery to assist in meeting this 50-degree requirement to fire the pyros.

(Figure 214)

Here are some design features of the individual cells. Some of those 6-digit numbers in there are just used partly, so disregard them. This is rather self-explanatory. The volume of each battery, you see there by the length, width and height, amounts to about 340 cubic inches for the large probe, and about 133 cubic inches for the small probe. The two battery capacities there; the large probe is a 40-amp hour nameplate and the small probe batteries are 11-amp hours for nameplate.

The two heaters; the large probe heater is about a 47-watt heater, the small probe heater about a 20-watt heater. And for additional thermal control, we have vacuum-deposit aluminum on the surface of the battery case to provide extremely low emissivity.

(Figure 215)

The cell itself is an Eagle-Picher design. The case material is styrene acrylonitryl, not Bakelite. Nineteen plates in the large probe cell, 11 plates in the small probe cell, 160 square inch active area in the positive plates gives you about 110 milliamp per square inch current density during the 17 ampere constant current portion of the discharge, and about 350 milliamps per square inch during the pyro firing.

The same on the small probe; 31 square inches. You've got a 2.5 amp discharge; you can do the arithmetic there. It would be a 14.5 amp-hour pulse on top of that, gives you about 600 milliamps per square centimeter.

Plate additives recommended by Eagle-Picher: electrolyte concentration, about 1.5, specific gravity 45 percent, separator system is six layers of the 193 PUDO-type separation; this is to improve wet standbys. The PS 18 is a cell sealant. During the high-g vibration environment, the plate pack is restrained internally from the cell with the HYSOL restraint system, negative to positive active material ratios, silver foil tabs with plate leads, zincate additive.

A study done by Eagle-Picher indicated that none of the cells would reach over 20 psi internal pressure. And we have designed a 40 psi relief valve for the cell design, basically because we need to insure reliability in the battery, rather than have a sealed cell where a rupture within the cell case could cause an opening within the cell. We decided it would be better to relieve the pressure; even if the cell was not functioning, we'd still have continuity through the cell.

(Figure 216)

Internal structure of the Eagle-Picher cell; this is a side view and edge view. The high-cell restraint is at the bottom of the cell, and on both sides of the cell, totally enclosing the silver foil tabs.

(Figure 217)

Detail of the pressure relief valve. We've changed from cotton to Pellon above the Bunsen-type release.

(Figure 218)

The material portion of the titanium battery case is 90 percent titanium, 6 percent aluminum, 4 percent vanadiam alloy. It's about a 40-mil titanium sheet, joined together by electron beam welding. The attached brackets are machined from titanium bar stock by electrical discharge machining. Some of the break and yield figures for the titanium case--and the titanium case is stressed for the high-g condition.

(Figure 219)

The battery itself consists of an encapsulated monoblock of cells. In the large probe, we have 19 cells, three layers of five cells, one layer of four cells. Between the layers, we have epoxy fiberglass stiffeners, and between the first two layers and the last two layers we have a heater sandwiched between two layers of epoxy fiberglass stiffeners.

(Figure 220)

The thermal switches which shut the heater off after the battery temperature has risen to the approximately 50 degree level are mounted on the outside of the case. Thermistors to sense battery internal temperature for telemetry purposes are attached to the intercell connectors, which are in turn tied directly to the plate stack itself. The entire monoblock is encapsulated with a 50 percent equal by weight mixture of F-Bond 828, Burstan 140, with microballoons, and caps that surround the intercell connections and harnessing. This is so the encapsulated monoblock assembly could be machined to fit snugly into the titanium case.

(Figure 221)

The small probe assembly is similar, except you have 20 cells in a 6-5-5-4 ratio. Identical internal construction with the large probe, with the heater sandwiched between the epoxy-fiberglass stiffeners, stiffeners primarily to transmit the high-g entry loads to the case wall, rather than leaving it go through the cells. The high-g loads are in the direction of the plate stack itself.

(Figure 222)

Preliminary high-g tests and studies have determined it was the safest way to enter Venus.

In conclusion, the unique features of the design that we feel are worth mentioning: we have an extremely low packaged to unpackaged volume ratio for both large and small probe designs; the packaged battery in the large probe is only 8 cubic inches larger than the encapsulated monoblock, and the small probe is 18 inches larger, due to the slightly different cell arrangement. The thin wall construction of the cells allows for maximum capacity within the cell at minimum volume expense. The titanium case is a precision dimension electron beam-welded, not seam-welded, electron beam-welded sheet titanium. And the other day, we heard mentioned about remotely activated silver-zincs achieving a 40 to 50 watt hour per pound.

In the large probe design, what we are doing is using a secondary silver-zinc in a primary application, where we charge the battery on the pad, and then it is in a cruise phase for approximately 120 days until Venus entry. And the 40-ampere hour nameplate so far, in acceptance tests to date, has achieved approximately 50, 52-ampere hours during the initial cycles. We hope that we can launch by the fifth cycle, the minimum number of cycles to reduce cycling losses.

The small probe design, due to the larger cell packaging to active material ratio, is slightly lower in energy density. The calculations are achieved through approximately 30-volt nominal operating voltage. The large probe battery weighs 28 pounds, achieving approximately 50-ampere hours; the small probe design weighs 11 pounds, 11-ampere hours--that's 11-ampere hours nameplate; the actual capacity achieved for the small probe was approximately 14-ampere hours.

Also, we didn't want the battery to become a heat sink for all the power electronics and science instruments in the probe. So we thoroughly decoupled it with a 0.003 inch air gap from the beryllium shelf. And we put a rather highly-reflective surface with the vacuum deposit aluminum coating on the case.

GROSS: Boeing

Does the battery have to work during the deceleration?

BELL: Just immediately prior to entry, and just after, it has to fire the pyros, both large and small. And then it has to operate in this constant current load for about 20 minutes prior to entry, through about a 1 hour to an hour and 20 minute descent.

GROSS: So the answer is yes?

BELL: The answer is yes.

GROSS: How are the plates oriented relative to the direction of deceleration?

BELL: The deceleration is through the plate stack, through the broad base.

MIKKELSON: Convair

You mentioned in your cell that the relieve valve, you went from cotton to Pellon?

BELL: Yes.

MIKKELSON: What's the function of the Pellon?

BELL: Just to entrap any electrolyte spray that might get past the Bunsen.

DESIGN PROBLEMS:

- HIGH ENERGY DENSITY BATTERY REQUIRED BECAUSE OF SPACE AND WEIGHT RESTRICTIONS.
- STRUCTURAL AND ELECTRICAL INTEGRITY MUST BE MAINTAINED THROUGHOUT HIGH-G ENVIRONMENT.
- TEMPERATURE ENVIRONMENT CAUSES INTERNAL ENERGY LOSSES.
- HIGH CURRENT PULSES REQUIRED TO FIRE PYROS AT LOW TEMPERATURES.
- HIGH CURRENT REQUIREMENT NOT COMPATIBLE WITH REQUIREMENT FOR LONG TERM OPEN CIRCUIT STAND UNDER NORMAL OPERATING CONDITIONS.
- SURVIVE CRUISE AND COAST PHASES WITHOUT OPEN OR SHORTED CELLS.

Figure 211. Pioneer Venus Probe Battery Program.

REQUIREMENT	LARGE PROBE	SMALL PROBE
DESIGN LIFE, MO	18	18
MISSION ENERGY REQUIRED, A-HR	23.65*	5.52
MAXIMUM BATTERY DOD, PERCENT	80*	80
HIGH G CAPABILITY, G		
QUALIFICATION	500	706
ACCEPTANCE	400	565
BUS VOLTAGE RANGE, VDC	25.2 TO 30.8	25.2 TO 30.8
HIGH CURRENT PULSE LOADS, MAX, A	39 PULSE + 17 PRELOAD	14.5 PULSE + 2.44 PRELOAD
PYROTECHNIC BUS VOLTAGE UNDERLOAD, VDC	≥14.88	≥14.95

*WITH PRESENT DESIGN (40 A-HR), 84.5% DOD IS REQUIRED

ENVIRONMENTAL REQUIREMENTS PER ENVIRONMENTAL DESIGN AND TEST SPEC, SS31639-002

Figure 212. Large and Small Probe Spacecraft Battery Requirements Primary.

TEMPERATURE RANGE, °F	QUALIFICATION	ACCEPTANCE
OPERATING	+10 TO +140	+20 TO +122
NONOPERATING	-22 TO +140	-11 TO +122
SURVIVE LONG-TERM OPEN CIRCUIT STAND WITH PREDICTABLE CAPACITY LOSS		
DEVELOP REQUIRED BATTERY HEATER POWER AT LOW TEMPERATURE WITH HIGH EFFICIENCY		
SURVIVE CRUISE AND COAST PHASES WITHOUT OPEN OR SHORTED CELLS		

Figure 213. Large and Small Probe Spacecraft Battery Requirements (Cont) Secondary.

FEATURE	LARGE PROBE	SMALL PROBE
CELL TYPE	SECONDARY SEALED SILVER-ZINC	SECONDARY SEALED SILVER-ZINC
CELLS	19	20
PYROTECHNIC FIRING TAP	12TH CELL	13TH CELL
WEIGHT, LB	29.5 MAX	11.7 MAX
SIZE, IN.		
LENGTH	13.09	13.15
WIDTH	7.58	3.83
HEIGHT	5.66	4.180
RATED CAPACITY, A-HR	40	11
NOMINAL VOLTAGE, V	27.8	29
CONNECTORS:		
FLIGHT	908298-3 (25 PIN)	908298-2 (15 PIN)
TEST	908371-5 (31 PIN)	908371-5 (31 PIN)
THERMISTORS	908631-32 1 FLT AND 1 TEST	908631-32 1 FLT AND 1 TEST
THERMOSTATIC SWITCHES	908340-22	908340-22
(2, PARALLEL CONNECTED)	42°F MIN, 55°F MAX	42°F MIN, 55°F MAX
HEATER	909129-1	909128-1
SURFACE EMISSIVITY	0.1 OR LESS	0.1 OR LESS
RELIABILITY	0.981	0.980
ELECTROLYTE TRAP	IN VALVE COVER	IN VALVE COVER

Figure 214. Probe Spacecraft Battery Design Features.

FEATURE	LARGE PROBE	SMALL PROBE
CASE MATERIAL	BAKELITE, C-11	BAKELITE, C-11
POSITIVE PLATES	9	5
NEGATIVE PLATES	10	6
ACTIVE AREA (POSITIVE), IN^2	159	31
PLATE ADDITIVES (NEGATIVE)	3% HgO	3% HgO
ELECTROLYTE CONCENTRATION, % KOH	45	45
SEPARATOR SYSTEM	6L PUDO 193	6L PUDO 193
EPOXY SEALANT	PS-18	PS-18
PLATE PACK RESTRAINT SYSTEM	HYSOL	HYSOL
ACTIVE MATERIAL RATIO (ZnO/Ag)	>1.20:1 (BY CAPACITY)	>1.26:1 (BY CAPACITY)
PLATE LEADS	SILVER FOIL TABS	SILVER FOIL TABS
ELECTROLYTE ADDITIVE	ZnO	ZnO
PRESSURE RELIEF VALVE, PSIG	40 ± 10	40 ± 10

Figure 215. Cell Design Features

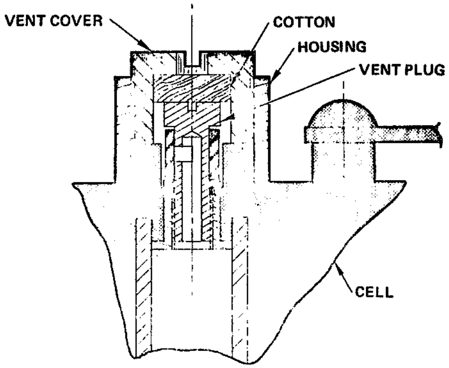


Figure 217. Probe Battery Pressure Relief Assembly.

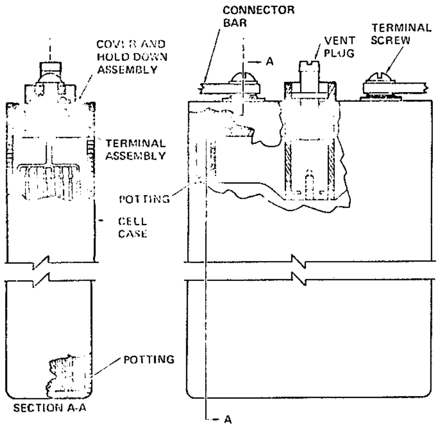


Figure 216. Silver Zinc Cell Assembly.

- WELDED CONSTRUCTION
  MATERIAL 6Al4V TITANIUM (ANNEALED)
  MACHINING – ELECTRON DISCHARGE MACHINING
  WELDING – ELECTRON BEAM
- MINIMUM WELDED STRUCTURAL PROPERTIES
  130,000 PSI ULTIMATE
  120,000 PSI YIELD
  8-10 % ELONGATION
- BRACKETS PROVIDED FOR HARNESS TIE POINTS
- INSPECTION REQUIREMENTS
  X-RAY, DIE PENETRANT, VISUAL
  WELD SAMPLES
- STRESSED FOR HIGH-G CONDITION

Figure 218. Large and Small Probe Batteries, Battery Case.

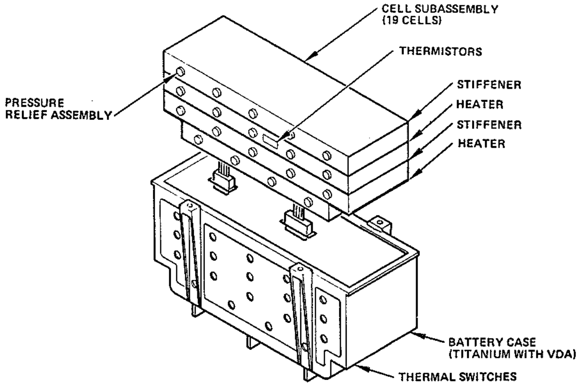


Figure 219. Large Probe Battery Assembly.

- VACUUM-DEPOSITED ALUMINUM ON TITANIUM CASE
- BATTERY THERMALLY ISOLATED FROM EQUIPMENT SHELF
- HEATERS TO MAXIMIZE VOLTAGE DURING PYRO PULSE
  - TIMER ACTIVATED
  - INCREASE BATTERY TEMPERATURE FROM +20° TO +50°F
  - THERMAL SWITCHES TO PROVIDE BACKUP CUTOFF
- THERMAL SWITCHES (2)
  - OPEN/CLOSE RANGE OF 42° TO 55°F
- THERMISTOR FOR TELEMETRY UP TO PROBE SEPARATION

Figure 220. Large and Small Probe Batteries, Thermal Control Provisions.

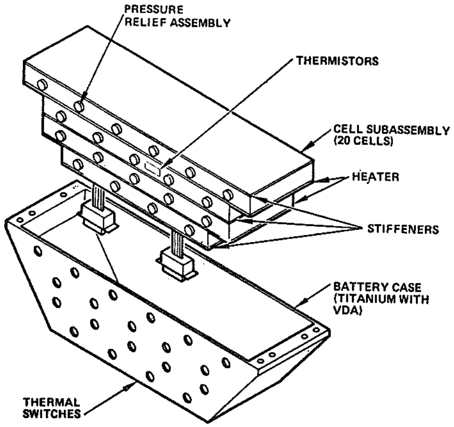


Figure 221. Small Probe Battery Assembly.

UNIQUE FEATURES:

- LOW PACKAGED/UNPACKAGED VOLUME RATIO - LP 1.02:1.0
  SP 1.157:1.0
- INTEGRAL FIBERGLASS STIFFENERS FOR CELL WALL REINFORCEMENT AND LOAD TRANSFER.
- THIN CELL WALL (0.040") CONSTRUCTION FOR MAXIMUM CAPACITY AND MINIMUM VOLUME.
- PRECISION DIMENSIONED ELECTRON SEAM-WELDED SHEET TITANIUM CASE.
- HIGH ENERGY DENSITY SECONDARY DESIGN (RELATED TO SEVERE ENVIRONMENTAL REQUIREMENTS).
  - LARGE PROBE DESIGN - 50 WH/LB
  - SMALL PROBE DESIGN - 40 WH/LB
- THERMALLY-DECOUPLED MOUNTING AND LOW EMISSIVITY VACUUM-DEPOSITED ALUMINUM CASE COATING.

Figure 222. Pioneer Venus Probe Battery Program.

SILVER-HYDROGEN LIFE TESTING

J. D. Armantrout
Aeronutronic Ford

The work that we've been doing has primarily been the result of Ron Haas' investigation into the silver-hydrogen system. So I am essentially just giving you some data that he had assembled.

(Figure 223)

This is our basic plate arrangement as it's assembled in a demountable lab pressure vessel. The hydrogen electrode typically has a platinum loading of about 10 milligrams per square centimeter, and a gas facing porous Teflon backing. We have fuel cell grade asbestos, which has been manufactured by Johns Manville. It's 10 to 20 mil. We have the astro power separator commercially available through Yardney, and that is a ceramic plastic film on a treated fuel-cell grade asbestos.

The silver electrode is fabricated in accordance with standard techniques used in silver-zinc and silver-cadmium cells.

(Figure 224)

This is the typical voltage charge-discharge characteristics for the cell that we're running a live test on right now. You can see as we get into overcharge oxygen is generated, we found in our testing that this oxygen was displacing electrolyte out of the separator into the cell container. So we imposed a voltage clamp, about 1.66 volts, which is shown there on the right-hand side of the graph.

The next slide will make this a little more clear, but this is essentially a 2 amp-hour cell, being cycled at 60 percent depth of discharge. And it's just room ambient conditions. The charge rate is C/about 4.5, based on the actual capacity.

(Figure 225)

This is the results that we've obtained to date. We began in December of 1975. You can see, after about 500 cycles, our voltage was going down. We then added approximately 5 or 6 grams of 30 percent KOH. The voltage recovered, and then immediately started going down again, as we approached about 750 cycles. At that time, we added electrolyte one more time, and imposed the voltage clamp. Since that time we have not seen the fading that we saw earlier in the test. And it appears that we're going to surpass 2,000 cycles here pretty soon. The real purpose of the test was to evaluate life-cycle capability of the astro-power separator in an accelerated test. And so, it's strictly an engineering-type configuration.

(Figure 226)

Our conclusions to date are that the silver-hydrogen energy storage system has, or appears to have, a demonstrated cycle life capability of at least 2,000 deep depth of discharge cycles, and a calendar life of at least one year. Our second conclusion is that the optimum charge control of silver-hydrogen cells improves the cell performance, and eliminates cell stack electrolyte loss. We feel that replacement of the nickel-hydrogen system with the silver hydrogen should significantly improve the space battery energy density and simplify the electrolyte and thermal management requirements.

We might expect an increase of, say, 50-60 percent, depending upon emission load or program requirements; as far as increase in energy density or total weight of the system reduction, that is.

In summary, based on these assumptions, we feel that the silver-hydrogen cell is capable of long calendar life. We certainly need more testing, but I think that this data is encouraging that we have. There is other data on the astro-power separator which was, I believe, NASA and JPL; and have, in silver-zinc cells, cycled the separator for five or six years. So we feel like it's really something that's worth looking into.

HOLLECK: EIC

How thick were your silver electrodes?

ARMANTROUT: I'll find that out for sure, but it's a standard electrode. It's nothing special.

HOLLECK: Electrodes go anywhere from 8 mils to--

ARMANTROUT: I would say 10 or 15, but I can get that precise number for you.

HOLLECK: I think your data is very encouraging, but I tend to disagree with your statement that electrolyte management is easier in silver-hydrogen than in nickel-hydrogen. Because in silver hydrogen, you do have to contend with substantial changes in electrolyte volume and concentration, which is much, much more important.

ARMANTROUT: I understand. I think we're saying that with the separator system that we're looking at, it may not be as much of a problem.

WARNOCK: Wright-Patterson

What was the basis of your statement that it would ease the thermal problems compared to the nickel-hydrogen?

ARMANTROUT: We said we thought it would simplify electrolyte; it's our own management requirements. That was just an initial conclusion, and I guess I would refer you to Ron on that, because I am just more or less reading what he had prepared for this.

KRAUSE: Hughes

John, you are charge-controlling a 1.6 volt clamp. You're introducing quite a bit in the upper plateau capacity, presumably by clamping at that point. What do you think the effective energy density of a lightweight cell is, using that kind of charge, would be?

ARMANTROUT: I'd say 40, 50 watt hours per pound.

KRAUSE: Really? We did some studies on silver-hydrogen cells. Even assuming that we could use the upper plateau capacity--I think our stack was, admittedly, a little more complicated in design, because we were handling oxygen management within the stack, and not having to go to the clamp; and we were looking at somewhere, perhaps, 30 to 35 watt hours per pound as being a pretty realistic number.

I would like to know how you arrived at the 40 to 50.

ARMANTROUT: I can show you some data later on.

DUNLOP: Comsat

You show in your separator configurations asbestos, and you've got your astro power, and then you've got asbestos. Now, if you're going to add electrolyte to draw all this separator up, it's very difficult to see how you can come up with the kind of energy density numbers that you're talking about, and at the same time talk about the quantities of electrolyte in the separator that you show in the diagram that you've used.

Now, I wonder if you're not--I wonder; it's more interesting, really--it would be interesting to see if you could really build something that would give you 40 watt hours per pound using the kind of configuration that you've been showing.

WARNOCK: Since Ron isn't here, I ought to mention that he published some energy density projections a couple years ago. And at that time, his energy density projections were based on so-called prismatic sphere-like pressure vessels, as opposed to the cylindrical vessels that may or may not--

ARMANTROUT: This is a prismatic arrangement.

SULKES: U. S. Army Electronics Command

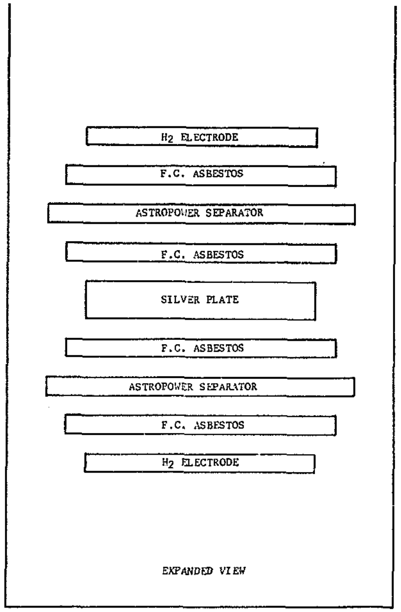
Is pressure control feasible for the silver-hydrogen, as compared to the nickel-hydrogen?

ARMANTROUT: Same problem.

ROGERS: Hughes

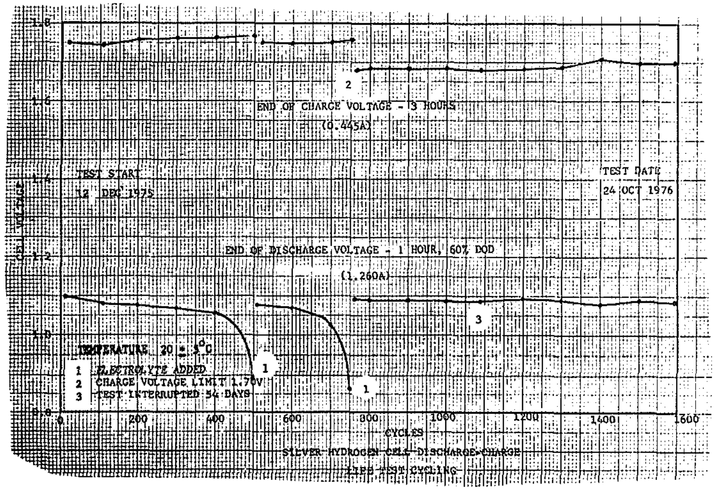
I'm just wondering; on your separator system, whether about 50 mils asbestos, essentially, isn't going to give you an awful high voltage drop, and add to your thermal problems inside the cell. It seems like a very, very thick separator system.

ARMANTROUT: Well, that's probably true to a certain degree. But as I said, in the configuration that we put together, it seems to be working very good. And it's unique, I think, to the astro power separator, frankly.



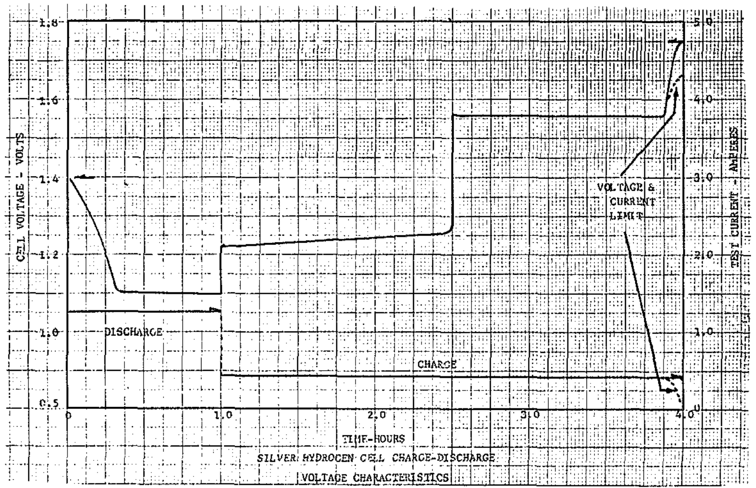
SILVER-HYDROGEN CELL STACK CONFIGURATION

Figure 223



SILVER-HYDROGEN CELL DISCHARGE-CHARGE LIFE TEST CYCLING

Figure 225



SILVER HYDROGEN CELL CHARGE-DISCHARGE VOLTAGE CHARACTERISTICS

Figure 224

CONCLUSIONS

1. THE SILVER-HYDROGEN ENERGY STORAGE SYSTEM HAS A DEMONSTRATED CYCLE LIFE CAPABILITY OF AT LEAST 2000 DEEP DEPTH OF DISCHARGE CYCLES AND A CALENDAR LIFE OF AT LEAST ONE YEAR

2. OPTIMUM CHARGE CONTROL OF SILVER-HYDROGEN CELLS IMPROVES CELL PERFORMANCE AND ELIMINATES CELL STACK ELECTROLYTE LOSS

3. REPLACEMENT OF THE NICKEL-HYDROGEN SYSTEM WITH SILVER-HYDROGEN SHOULD SIGNIFICANTLY IMPROVE SPACE BATTERY ENERGY DENSITY AND SIMPLIFY ELECTROLYTE AND THERMAL MANAGEMENT REQUIREMENTS

Figure 226

ADVANCED SEALED NICKEL-CADMIUM DESIGN

L. Miller
Eagle-Picher

As Floyd has said, what we've done is come up with a new concept of sealed nickel-cadmium cell design, based upon the advanced electrode stack technology that was devised for the nickel-hydrogen or the metal-hydrogen system.

(Figure 227)

What we have here is a stack. It's obviously conventional in all aspects, except when we come to the negative electrode. Instead of having a 30-mil negative, we have two 15-mil negatives. They are split: that's where we got the term, split negative electrode design. And in between the two, we insert the same gas spacers we insert in the nickel cadmium system.

You have the positive separator here on both sides, and the negative split in between, and just this repeated conventional cell stack. As additional modification, on the back of the negatives, adjacent to the gas spacer, we have applied a thin film of Teflon, not shown in this design. There is one other design innovation in this concept; that we have taken the gas electrode from the nickel-cadmium system, and wrapped it around this electrode stack, instead of connecting the gas electrode to the negative terminal, as has been done in the past. It's a recombination electrode.

The gas electrode is connected electrically to the positive terminal. And the purpose of this design is to recombine the hydrogen gas.

(Figure 228)

To evaluate this concept, we built a series of sealed nickel-cadmium cells in the designs shown here. The capacity of the cells was approximately 20-ampere hours. We didn't have the thin negatives; all we had was the conventional 30 mil negatives and 26 mil positives.

So, to simulate this thin negative design, rather than come up with a cell that had a large excess in negative capacity, we just doubled up the positives. And then, each of the two double positives was interfaced with a single negative. So, instead of coming up with a 20-amp hour cell which had a negative/positive ratio something in excess of 2 to 1, these cells had a ratio of approximately 1.3 to 1.

In design A, we used the conventional nylon separator material. That's really the only design variable in that cell. Design B; again, it has the conventional Pellon for separator material, but in this case, we applied that film to the back side of the negative electrodes. In design C, we used an inorganic separator; this is a non-porous or low-porosity separator.

There is one feature about this design, and it's that, like the split negative, we've introduced a superior path for the oxygen to get back and recombine at the negative electrode. We're no longer confined by the restraints of having a high-porosity separator material. In addition, we can operate, or should be able to operate, the cell at a much higher electrolyte level, because again, the electrolyte cannot interfere with the gas that's passed back to the negative electrode.

Okay; design C did have the asbestos and the inorganic separator, low-process separator. This would not work in a conventional cell, because it's not porous enough so the gas could get back through that. This design C did have the gas electrode design incorporated into it.

Design D is also an asbestos separator cell. It doesn't have either the Teflon or the gas electrode. Design E; we're back at the Pellon 2505, and this does include the Teflon film. The last design, design F, again is asbestos, and it includes the Teflon film.

(Figure 229)

To evaluate the performance, we subjected all the test cells to an overcharge to 200 percent of their capacity at a C/5 rate, at a temperature of 20 degrees C. Most of the cells reached a low-equilibrium pressure with respect to gas recombination--approximately 30 PSIG--except for one cell. This was D; it's the asbestos separator cell, and it looks like possibly we exceeded the hydrogen overvoltage potential on that cell with the gas hydrogen in it.

You can see that the voltages on the asbestos cells are somewhat higher than the nylon cells. I'm not sure whether this really can be attributed to the asbestos material, or the fact that we had to use available components for these type cells, for the stack cells. And the stack with the asbestos was a very loose-fitting stack.

Design C is also an asbestos cell with a high voltage, which probably should have exceeded the hydrogen overvoltage potential with this one. But this one incorporated the gas electrode, so it probably was recombining the hydrogen gas generated at that rate on overcharge. Design F, again, was an asbestos cell. Its voltage wasn't quite as high as design C or D, but it had the Teflon film, which probably may have had some effect with respect to charge voltage.

(Figure 230)

To evaluate the benefit of the gas electrode in the cells, we took the three nylon cells, subjected them to a 200 percent charge again at a C/10 rate at 0 degrees C. As you can observe, I'm sure, all three cells exceeded their hydrogen overvoltage potential. However, they've got cell B, which is the only one that had the gas electrode, was capable of recombining the hydrogen gas generated, and stabilized at a very low equilibrium pressure, approximately of 10 PSIG. Both the other cells, as you can read up there, had to be cut off at 100 PSI, and they returned about 120 percent of their capacity.

(Figure 231)

With this last series of tests, we took those same three cells again and started to increase the electrolyte. We wanted to see just how much electrolyte we could add over what was presently used today. I think as a standard, I think we're using about 3 cc per ampere hour.

At the first shot, at all three cells, we went to 3.8 cc per ampere hour, and all the cells worked at that level. We then increased it by another quantity, up to 4.3 cc per ampere hour, and design A and B, as you can see--although design A managed to stay in, it was still operating at very high pressure; design B had to be taken off when it exceeded the 100 PSIG limit.

However, you notice that design E, back in the negatives, is still operating at a very low pressure, even at that high point of the electrolyte.

We then took the cells one more level, and came up to 4.8 cc per ampere hour. All cells had to be taken off charge when they exceeded the 100 PSIG limit. However, I'd like to point out that design E went all the way up to 230 percent of its capacity before it had to be finally taken off. In other words, it was still recombining at that level electrolyte very well, and only very gradually came up to that pressure.

ROGERS: Hughes Aircraft

I'd like to make a comment on your use of the hydrogen electrode as an oxygen-hydrogen recombination electrode; that if you generate oxygen before you recombine hydrogen, which I think is what happened in your design, because of the very low oxygen overload that you have in a hydrogen electrode, you may end up corroding the electrode--losing platinum--because if you're using a conventional nickel-hydrogen electrode, it's got a nickel substrate. It's not really intended as an oxygen electrode, and you may find it deteriorates gradually.

MILLER: If I'm using a conventional--

ROGERS: Hydrogen electrode.

MILLER: You mean the expanded?

ROGERS: It's a nickel substrate, and it's not really meant as a fuel cell electrode. They're usually gold-plated for this service.

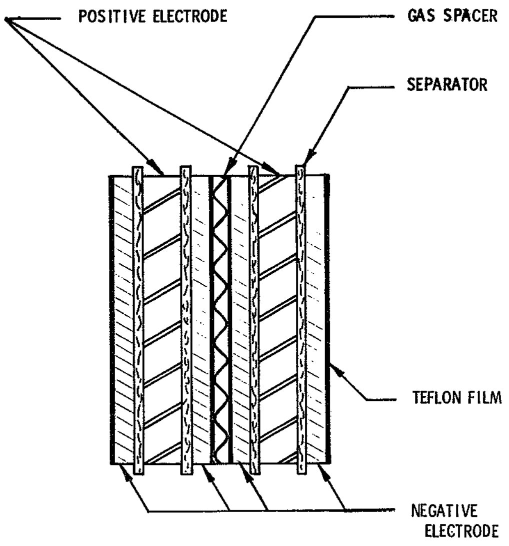
MILLER: No, the gas electrode is teflonated platinum, the catalytic electrode right out of the nickel-hydrogen system.

ROGERS: As I'm saying, you're probably going to run into trouble in sustained service.

MILLER: I'll take that into consideration. Thank you.

SEIGER: If you're using a catalyzed electrode, and have not connected to the positive electrode, how are you controlling oxygen evolution, which will occur at a fairly rapid rate upon platinum? And further, how could you distinguish whether you are evolving oxygen or consuming hydrogen? The electrons will go in that path the same way.

MILLER: My assumption was that the potential was high enough that in a normal cell, under those circumstances, we would be evolving hydrogen gas.

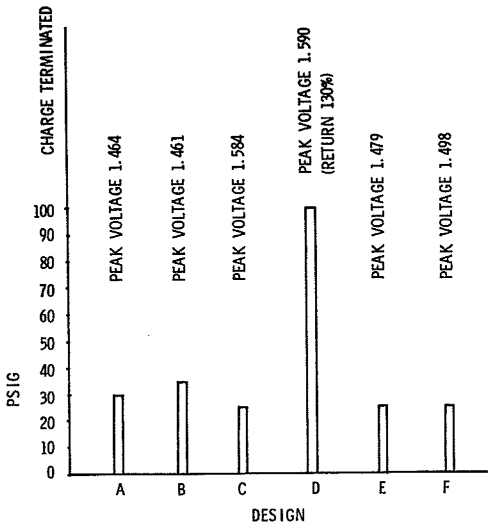


SEALED NICKEL-CADMIUM
"SPLIT NEGATIVE" ELECTRODE
STACK DESIGN

Figure 227

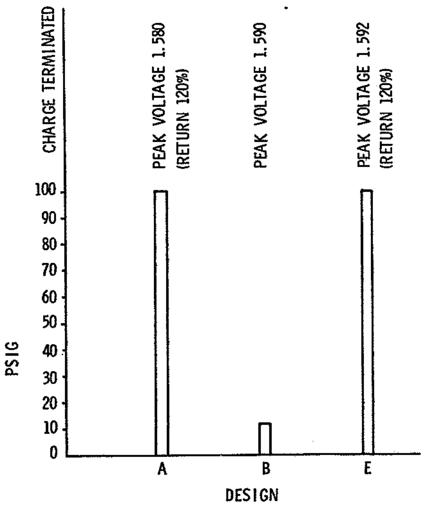
DESIGN A	NON-WOVEN NYLON (PELLON 2505) SEPARATOR MATERIAL.
DESIGN B	NON-WOVEN NYLON (PELLON 2505) SEPARATOR MATERIAL WITH GAS ELECTRODE.
DESIGN C	ASBESTOS MAT (FUEL CELL GRADE) SEPARATOR MATERIAL WITH GAS ELECTRODE.
DESIGN D	ASBESTOS MAT (FUEL CELL GRADE) SEPARATOR MATERIAL.
DESIGN E	NON-WOVEN (PELLON 2505) SEPARATOR MATERIAL WITH TEFLON FILM.
DESIGN F	ASBESTOS MAT (FUEL CELL GRADE) SEPARATOR MATERIAL WITH TEFLON FILM.

Figure 228. Cell Design Definition



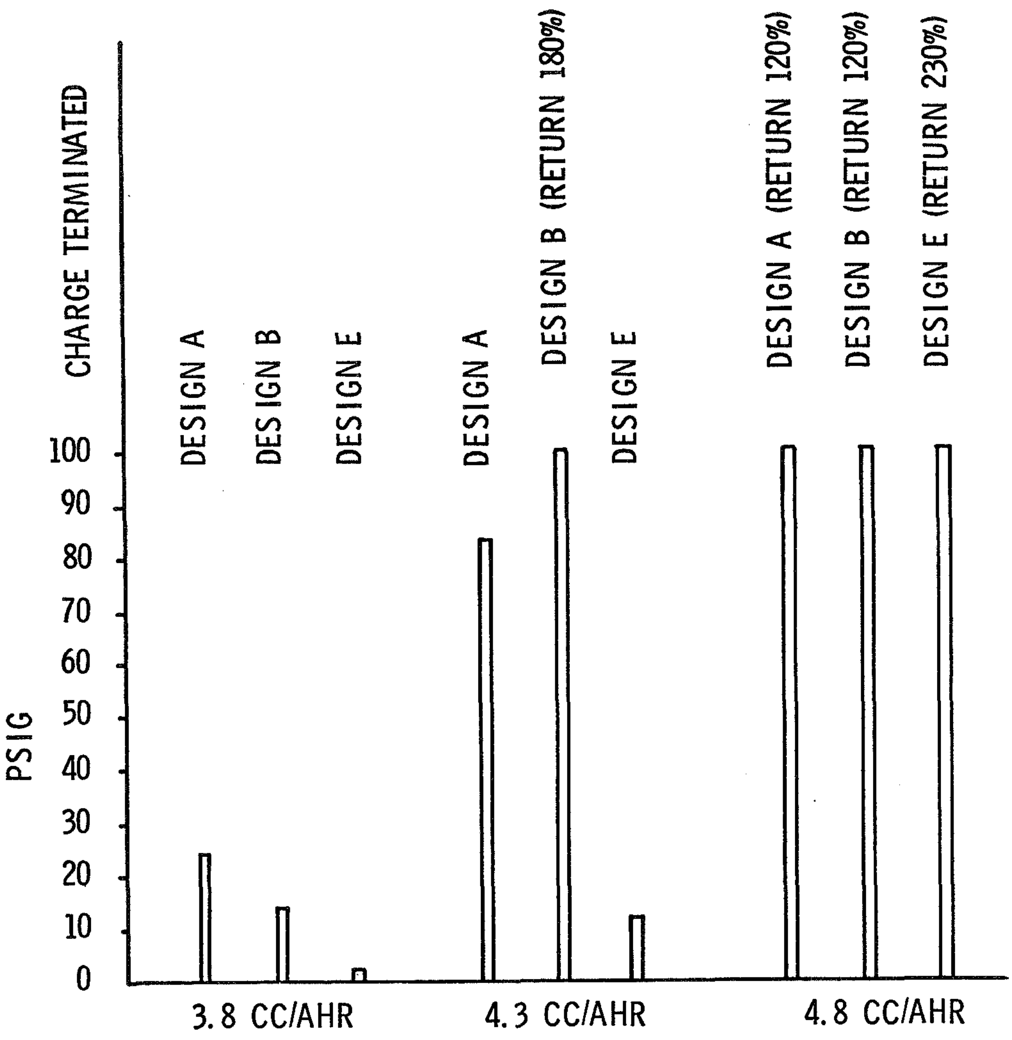
OVERCHARGE PRESSURE CHARACTERISTICS
CHARGE 200%, RATE C/5, TEMPERATURE 20 °C

Figure 229



GAS ELECTRODE VERSUS NON-GAS ELECTRODE DESIGN
CHARGE 200%, RATE C/10, TEMPERATURE 0°C

Figure 230



OVERCHARGE PRESSURE VERSUS ELECTROLYTE QUANTITY

CHARGE 250%, RATE C/10, TEMPERATURE 20 °C

Figure 231

FAILURE MECHANISMS IN NICKEL-HYDROGEN CELLS

G. Holleck
EIC Corporation

Last year I presented an analysis of the nickel-hydrogen system, with the conclusion that the main problem areas in current designs are associated with oxygen management and electrolyte management. At that time, I proposed solutions to these problems. Today, I will present the main results of our experimental investigations.

(Figure 232)

Now, let me point out, before I start, that the nickel-hydrogen system has relatively few problems. And when I speak of problems here; that is, if you push any system, you run into problems somewhere. The conditions that our investigation was geared to were near-earth orbit conditions, which is 90-minute cycles, and approximately two C rate discharge and C rate discharge. And when I talk about overcharge, I also mean C rate overcharge. So that is somewhat different than when you talk about overcharging in comparable systems.

The work carried out by EIC Corporation includes component-level investigations which are geared to identifying the important steps and the mechanisms associated with oxygen management and electrolyte management, then to come up with an improved design and to demonstrate its feasibility in experimental cells, and then to build experimental cells for more extensive tests.

As I mentioned, the problem was carried out for the U.S. Air Force as a subcontract to Hughes.

(Figure 233)

The investigations--and I will not be able to present all these results in detail to you, due to the time limitation that I have--but I will point out to you what we have investigated, and pick out the most important parts, and give you more detail on those. If you have any more questions, I will try to answer them afterwards.

One subject of investigation was the electrodes, and we looked at positive plates and at negative electrodes. For positive plates, we basically looked at the effect of the electrode substrate on oxygen evolution, and we looked also at two types of electrodes, which I will identify in a minute, with respect to electrolyte distribution and retention.

All of the electrodes were impregnated by the Air Force. One electrode was an Eagle-Picher plaque, which was a very close pack with a screen substrate. And the other plaque, I think, was a Gould plaque, with a perforated metal sheet as a substrate. The negative electrodes were prepared and characterized by ourselves, but I will not go into this.

One of the main problems is oxygen recombination in these cells, and specifically we looked at oxygen evolution. You have oxygen involving an overcharge as the product of the electrode, and we looked at where and in which way the oxygen evolves, and what effect separator materials have on the location of this oxygen evolution. Then, the oxygen has to diffuse to the hydrogen electrode, platinum, the catalyst electrode, where it can recombine or reduce. We look at the oxygen reduction at the catalyst electrodes, and then you have what I call trapped oxygen, which includes what you maybe may have heard as chemisorbed oxygen, which is--it's more entrapped, it's not really chemisorbed, and it's all oxygen. But it has a very important effect on cell design, because it can amount to up to 20 percent of the capacity. And you have to incorporate it into your pressure vessel design.

The next item is electrolyte loss. Experiments in the past have shown that, upon extended cycling, you do lose electrolyte from the cell stack. And the question is, what is the mechanism of electrolyte loss? And then, naturally, how can you prevent it? We have looked at electrolyte entrainment in the gases involved, evolved hydrogen and oxygen, and the gases can carry electrolyte with them. We have looked at the possibility of weeping of hydrogen electrodes. Such effects are known on fuel cell electrodes, oxygen reduction; and we have looked at electrolyte displacement, that is, electrolyte being pressed out of the positive electrode at the cell stack by evolved gas, for example, especially oxygen on overcharge.

And then, I mentioned we have looked at prevention of electrolyte loss, and specifically looked at the use of electrolyte reservoirs for that purpose, and at the possible use of hydrophobic membranes as areas for electrolyte. And we looked at wicks, not to prevent electrolyte loss, but as a possible means to return lost electrolytes to the cell stack.

Let me quickly point out, I will say a little bit more about oxygen evolution and oxygen reduction. Trapped oxygen, we found, is proportional to pressure. And I will leave it at this. It can go up to 20 percent of the capacity at 500 psi, and as I said, it varies with the design pressure.

With respect to electrolyte loss, we have made measurements of the entrainment, and we found that electrolyte entrainment in the gases is very low, and for practical applications negligible. We have not detected any electrolyte loss by weeping on properly designed hydrogen electrodes.

We have made measurements of hydrophobic membranes, and we have found that some hydrophobic membranes do retain electrolyte, some others don't. And unless there are specific questions, I will not go much into this at the moment. And we have measured the rate of electrolyte transport in wicks. The other items, which I have left out, I will discuss in a little bit more detail.

(Figure 234)

The location of oxygen evolution is, evidently, in such a cell where you have the electrode here, and you can clamp the separator. For example, various materials are to the one side, and you can measure quantitatively the gas evolved on each side.

(Figure 235)

These are the results; and let me just point out a few items here. The nickel electrode; we found that the gas evolution on nickel plates is not uniform. You have a preferred oxygen evolution at one side or the other, and if you look with a microscope at the surface, you'll find also that the bubbles emerge mainly on holes or imperfections or cracks in the electrode surface. That holds for any of them, with respect--for example, this is illustrated here with screen nickel electrode. You'll have 75 to 25 percent of the oxygen at one side.

Now, the other thing that I want to point out; let's say an asbestos separator onto one side of the nickel electrode. You practically stop completely the oxygen evolution on this side, and all the oxygen is pressed toward the back side, emerges on the back side of the nickel electrode. If you do the same thing with a perforated, if it's an electrode with a perforated substrate, this is only partially true.

You have also favored oxygen evolution on the opposite side. But obviously, it is more difficult. You cannot easily suppress oxygen evolution completely. It tends to show that perforated sheet is more of a barrier to the electrode than a screen substrate.

We have earlier, also made electrochemical measurements on such electrodes, and they confirm the same problem that you have in the nickel hydrogen cell, where you use the electrode only from one side. It is preferential to use an electrode with a screen substrate, rather than with a perforated sheet substrate.

(Figure 236)

That is more important at higher rates. At low rates, the difference is not so significant.

Now, the question: is oxygen reduction at the height of an electrode? The conditions are quite different from what you normally find in, say, fuel cells. What we have measured here is, for example, oxygen reduction with 1 and 5 percent oxygen and helium; you cannot easily measure it in hydrogen. But it is convenient to measure in helium, and you see you get a plateau at about 30 milliamps per square centimeter; and approximately five times that with 5 percent oxygen and helium.

The absolute value depends on the type of hydrogen electrode, and Howard will mention some items here. We have found, without going into details, that the limiting step is gas diffusion, oxygen diffusion in the gas phase pores of the Teflon-bonded electrode. Now, in our case, it's not in the backing, but in the gas pores of the Teflon-covered electrode, there were diffusion limitations.

This naturally has important implications on the oxygen concentration; that you do accumulate an equilibrium in continued overcharge in a nickel-hydrogen cell.

(Figure 237)

The major item of electrolyte loss on the cell stack, as I mentioned, is the electrolyte displacement. And we measured it in the arrangement shown here. The package shown here is vacuum-impregnated, and then we let the electrolyte drip off. When we move this catcher underneath, and we charge the electrode, and we collect the droplets coming off.

(Figure 238)

This gives you some results. And here, if you just look in this column, I have expressed the amount of electrolyte on the positive plate--we have expressed the expelled electrolyte as a fraction of the electrolyte that is contained in the positive plate. And you see the values are approximately between 10 and 30 percent; and there is some variation in these measurements. They are quite tricky because of the small amount hangups.

These measurements were done at 1 atmosphere, and the current density was adjusted. The gas evolution volumes were equal to that you would have at 500 psi at a C-rate overcharge. And to demonstrate that it is realistic, I have a measurement which we did in a pressure vessel with 20 milliamps per square centimeter at 500 psi, and the values are comparable to what you have here.

(Figure 239)

Another item which I think is extremely important, not only for nickel hydrogen but also for nickel cadmium is the question of electrolyte distribution and electrolyte retention. And if you vacuum-impregnate a new system, that is, if you do it well--it is completely filled. And that is an easily defined state. But if you now remove electrolyte from an array of components, it is extremely important to know where does the electrolyte that you remove come from? Which components dry out first, so to speak, and which stay wet? We have done quite a number of these experiments.

This is one example; where we had an array of components marked up here. And what happens here; I've plotted the electrolyte as a function of the saturation of the whole package. When you start to remove electrolyte from this package, the electrolyte comes out initially practically exclusively out of these two components, which are of very similar type. This is your well-known nylon 2505, and only after this nylon has lost practically all its electrolyte do you start to lose significant electrolyte either from the electrodes or from the nickel. This is a non-impregnated nickel plaque, and you see it starts to lose electrolyte before the impregnated plaque, which is reasonable.

Also, what is important here is the asbestos and the nickel plate go pretty much parallel, so they very effectively compete with each other for electrolyte.

(Figure 240)

Now, the main conclusions of this component-level investigation can be summarized as: the oxygen concentration is determined by the diffusion path, and that is a combination of the gas phase plus the electrode you have. And the principal electrolyte loss mechanism is electrolyte displacement. And --well, solutions to these problems can be found in an appropriate stack configuration and sequence, and by use of reservoirs.

(Figure 241)

And I want to show you now the two designs that we have developed to overcome these difficulties. This is basically your standard back-to-back arrangement of hydrogen electrodes and two back-to-back nickel electrodes. The main variation here is incorporation of a reservoir in the back of the nickel electrode, which can supply, accept and supply, resupply--accept the displaced electrolyte from the electrode, and after the oxygen has dissipated, resupply it to the oxygen electrode. And we have also incorporated here, as a further barrier, a microporous Teflon layer.

In the second design I will show you the oxygen coming out here still has to go around the stack and re-enter in the gas stream to the side, and react at the hydrogen electrode. And the oxygen reduction will occur primarily on the outer rim. You have a fairly--depending on the dimensions and the reaction rate--a fairly steep gradient of oxygen reduction at the outer rim of the electrode.

(Figure 242)

The second cell stack design is a series configuration--not series, excuse me; a single-cell configuration where you have a hydrogen electrode, separator, nickel electrode, and now the oxygen--and you repeat this. The oxygen that is evolved at this nickel electrode comes off the back of the electrode, just has to travel across the gas space, and reacts uniformly at the next hydrogen electrode. And you go on through the cell stack.

The only problem that you run into; if, at the end of the cell stack, where you get an asymmetry, and you have to provide for a return of either oxygen or water if you react the oxygen with the hydrogen on the extra electrode. You have a vehicle, for example, that you can use to return the electrolyte, the water, from the end of the stack back to the top.

(Figure 243)

Now, we put together stacks in boiler plate test shells. They were equipped with oxygen sensors in the cell case, and the mandrel had a conical shape so that the displaced electrolyte will flow down here. It's measured in a conductivity cell here.

(Figure 244)

That is a typical--nothing special on this recording of voltage, pressure, and oxygen concentration in such a cell.

(Figure 245)

More dramatically, this is an extended overcharge, C/2 rate in this case; and the limiting oxygen, constant oxygen values, oxygen concentrations, are somewhat below 0.2 percent of oxygen in the hydrogen gas of this cell.

(Figure 246)

A typical recording of the displaced electrolyte during cycling. The main electrolyte is displaced during the first cycle, during the first overcharge. But there continues some electrolyte loss, which tapers off eventually during further cycles.

(Figure 247)

These are some test cycles of 10-ampere cells. This is a conventional--well, base line cell. All cells have asbestos separators, but no special reservoir. And I just want to point out one thing: disregard the many numbers. If you had 8 amperes, which is a little bit less than C rate on a natural basis, we get about a little bit over 10.4, 10.5 ampere hours at 1.2 volts mid-discharge. If you go to 20 amperes, to the 2C rate, the voltage drops to 1.07, and the capacity to 1 volt goes down to 8.

(Figure 248)

This is an analog, a test regime for the same cell, except we add the same configuration. We added the reservoir; nothing else. And you see again practically identical behavior; 9 amperes instead of 8 doesn't make any difference.

If you go to 20 now, the voltage stays higher, and you have very little difference in capacity. So, it's a very clear indication of the electrolyte limitation on the high rate behavior of the cell.

(Figure 249)

The identical behavior with the recirculating cell as one might expect, it also has--I just want to point out, you have the same voltage--1.07--here, and here the same capacity.

There's one other item which I don't want to go into. We naturally also have used these cells; for example, we overcharged them for 12 hours with 12 amps for 109 hours; that is, over the bus C rate for more than 100 percent. And there is no problem with the oxygen accumulation in these cells, but there is a problem with the thermal management in these boilerplate cells; they do get too hot, and you get water transfer from the stack to the cell case. And so, they tend to dry out.

(Figure 250)

So, we come to the conclusion. The lack of electrolyte limits the high rate performance of the cells. The main electrolyte loss mechanism is displacement, and--what? We knew before high thermal gradients, naturally, cause water loss from the cell stack, and we have also proved that very conclusively by analyzing the liquid that we collected from the cell case. It was almost pure water. And oxygen concentrations can be kept well in acceptable arrangement values, even with conventional arrangements, if you have appropriate spacings and hydrogen electrodes.

Trapped oxygen is somewhat larger in cells with the reservoir, because you can also trap oxygen in the reservoir. You have to consider that if you want to optimize this thing, so that it does not do that.

(Figure 251)

We have built four cells on this basis. These are 10-ampere hour cells with full stack components, or just a lesser number of plates, which we have been able to use for extensive cycle testing, and they are on test now.

FAILURE MECHANISMS IN NI/H_2 CELLS
ANALYSIS AND SOLUTIONS

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WORK PERFORMED UNDER SUBCONTRACT TO HUGHES AIRCRAFT COMPANY FOR U.S. AIR FORCE AERO PROPULSION LABORATORY, WRIGHT-PATTERSON AIR FORCE BASE, DAYTON, OHIO.
CONTRACT NO. F33615-75-C-2025.

Figure 232.

ELECTRODES
- POSITIVE PLATES
- NEGATIVE ELECTRODES
  - – PREPARATION AND PERFORMANCE

OXYGEN RECOMBINATION
- OXYGEN EVOLUTION
- OXYGEN REDUCTION
- TRAPPED OXYGEN

ELECTROLYTE LOSS FROM STACK
- ELECTROLYTE ENTRAINMENT
- WEEPING OF HYDROGEN ELECTRODES
- ELECTROLYTE DISPLACEMENT

PREVENTION OF ELECTROLYTE LOSS
- ELECTROLYTE RESERVOIRS
- HYDROPHOBIC MEMBRANES
- WICKS

Figure 233. Investigations

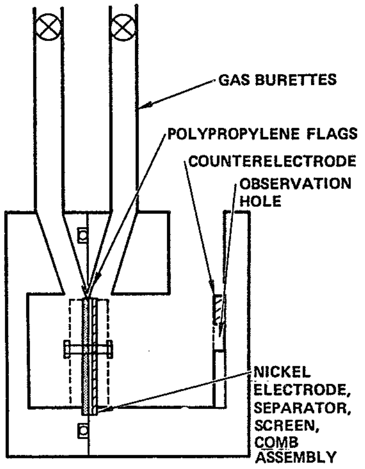


Figure 234. Plexiglass Cell for Measuring Location and Rate of Oxygen Evolution.

CONFIGURATION	AT 0.73 MA/CM^2				AT 0.36 MA/CM^2			
	(CM^3/SEC, CM^2) X 10^5		%		(CM^3/SEC, CM^2) X 10^5		%	
	BACK*	FRONT*	BACK*	FRONT*	BACK*	FRONT*	BACK*	FRONT*
PERFORATED NICKEL	2.56	1.59	61	39	1.14	0.59	66	34
PERFORATED NICKEL/NYLON	3.30	0.97	77	23	–	–	–	–
PERFORATED NICKEL/NYLON	3.07	0.97	76	24	–	–	–	–
PERFORATED NICKEL/ASBESTOS	3.04	0.85	78	22	0.57	0.23	71	29
SCREEN NICKEL	2.41	0.80	75	25	1.50	0.42	78	22
SCREEN NICKEL/ASBESTOS	3.97	0.08	98	2	–	–	–	–
SCREEN NICKEL/NYLON	3.93	0.06	98	2	–	–	–	–
SCREEN NICKEL REVERSED/ASBESTOS	3.51	0.42	89	11	–	–	–	–
SCREEN NICKEL REVERSED	0.97	3.46	22	78	–	–	–	–
SCREEN NICKEL/ZITEX	2.42	1.59	60	40	–	–	–	–
SCREEN NICKEL/POLYPROPYLENE	3.5	0.9	80	20	–	–	–	–

*LOCATION RELATIVE TO COUNTERELECTRODE. SEPARATORS ALWAYS FACED COUNTERELECTRODE

Figure 235. Oxygen Evolution at Positive Plates During Overcharge.

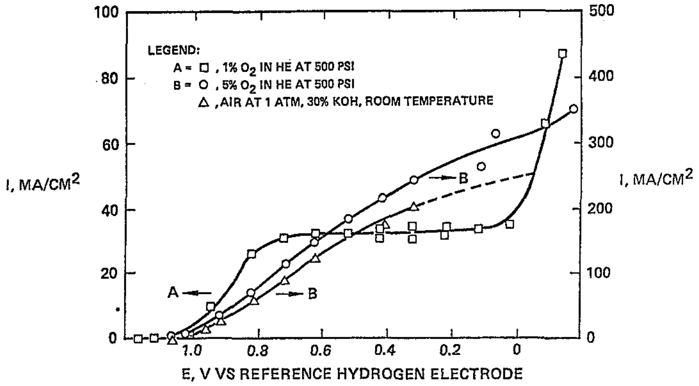


Figure 236. Oxygen Reduction at a Gas Electrode (TFE Bonded Pr).

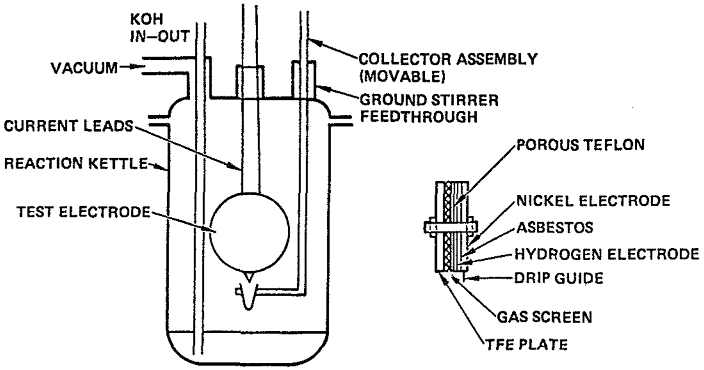


Figure 237. Experimental Arrangement for Measuring Electrolyte Displacement

ELECTROLYTE DISPLACEMENT FROM POSITIVE NiO PLATE

NICKEL SINTER WITH MESH SUBSTRATE, ELECTROCHEMICAL IMPREGNATION

ELECTRODE NO.	CURRENT DENSITY, MA/CM²	DISPLACED ELECTROLYTE	
		CM³	% OF ELECTROLYTE IN POSITIVE PLATE
1	1 TO 4	0.075	17.7
1	4.1	0.023	5.5
2	4.1	0.056	13.0
2	0.86	0.054	12.8
2	0.45	0.031	21.5
2	0.45	0.15	35.8
3	0.45	0.075	17.8
3	0.86	0.12	28.8
4 (34 ATM)	20.0	0.046	11.0

Figure 238

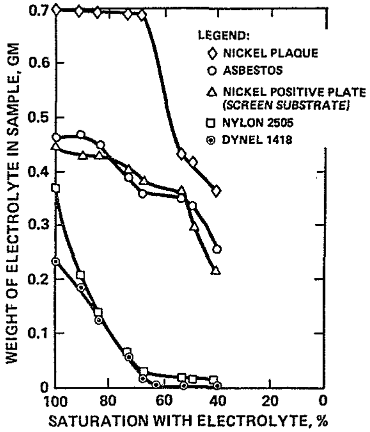


Figure 239. Electrolyte Distribution in an Array of Components.

MAIN CONCLUSIONS

- **OXYGEN CONCENTRATION DETERMINED BY DIFFUSION PATH**
- **PRINCIPAL ELECTROLYTE LOSS MECHANISM – DISPLACEMENT**

SOLUTIONS

- **APPROPRIATE STACK CONFIGURATION**
  COMPONENT SEQUENCE AND DIMENSIONS
- **INCORPORATION OF RESERVOIRS AND MEMBRANES**

Figure 240

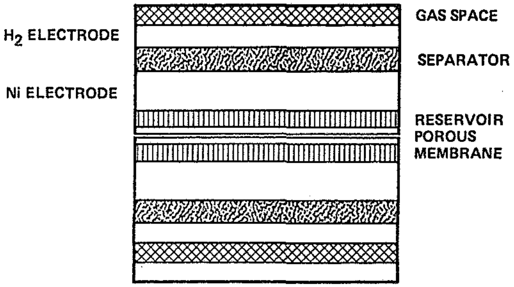


Figure 241. Design I – Back-to-Back Positives.

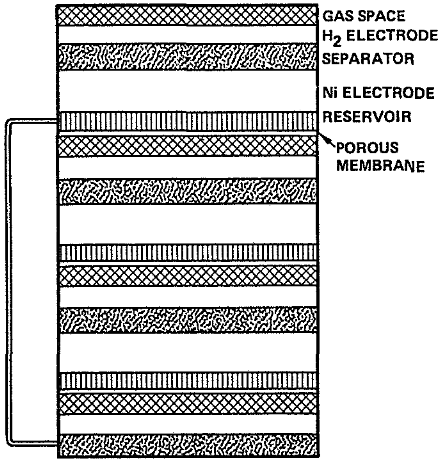


Figure 242. Design II – Single Positives

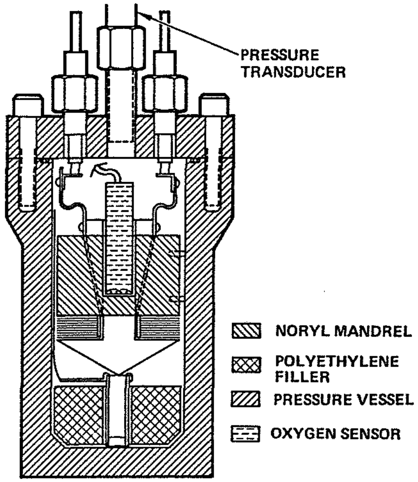
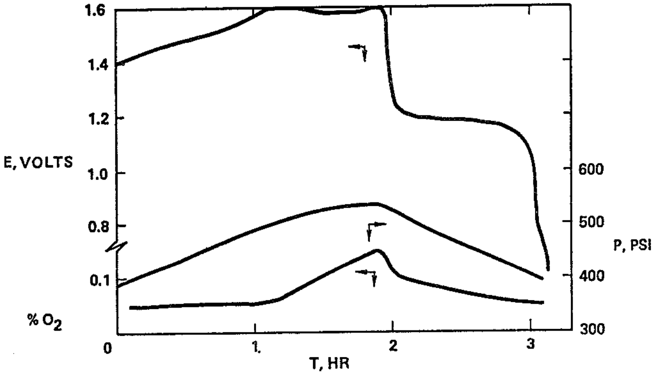


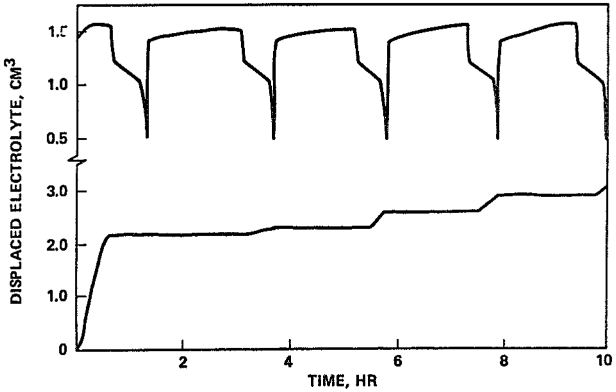
Figure 243. Boilerplats Test Cell



POTENTIAL, PRESSURE, AND OXYGEN SENSOR RESPONSE DURING TYPICAL CYCLE FOR CELL 1

CHARGE/DISCHARGE AT 8A

Figure 244



ELECTROLYTE DISPLACEMENT DURING CELL CYCLING AFTER REIMPREGNATION WITH KOH

Figure 246

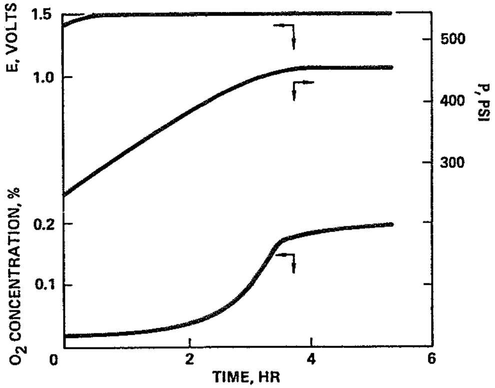


Figure 245. Oxygen Sensor Response During Extensive Overcharge.

CYCLE NO.	CHARGE				DISCHARGE		CAPACITY, A-HR		PRESSURE	
	I,A	T, HR	E, 0.5 V	E_{MAX}, V	I,A	E, 0.5 V	TO 1 V	TO 0.5 V	LOW	HIGH
18	8	1.90	1.48	1.62	8	1.20	10.40	11.20	200	420
19	8	1.90	1.50	1.62	8	1.20	10.08	11.20	340	490
20	8	1.90	1.50	1.62	8	1.19	10.08	11.12	340	490
21	8	1.90	1.50	1.62	8	1.19	10.08	11.20	335	490
22	8	1.90	1.50	1.62	8	1.19	10.08	11.20	332	482
23	8	1.90	1.50	1.62	8	1.18	10.16	11.20	340	490
24	8	1.90	1.50	1.62	8	1.19	10.24	11.36	330	480
25	8	1.90	1.50	1.62	8	1.20	10.40	11.36	338	490
26	8	1.90	1.50	1.62	8	1.20	10.40	11.36	340	490
27	8	1.90	1.50	1.62	8	1.20	10.40	11.36	342	490
30	8	1.90	1.50	1.62	8	1.20	10.40	11.60	328	490
34	8	1.90	1.50	1.62	8	1.20	10.80	11.92	328	485
35	8	1.90	1.50	1.62	20	1.07	8.00	12.00	338	490
36	8	1.90	1.52	1.61	8	1.20	11.04	12.00	332	496
37	8	1.90	1.52	1.61	8	1.20	10.80	12.00	330	495
42	8	1.90	1.52	1.61	8	1.22	10.80	12.16	338	495
46	8	1.90	1.52	1.60	8	1.22	10.80	12.24	338	490
47	8	1.90	1.51	1.61	20	1.08	8.0	12.00	335	480
48	8	1.90	1.52	1.61	8	1.20	10.4	11.60	335	495
55	8	1.90	1.52	1.61	8	1.20	10.4	12.00	335	500
60	8	1.90	1.52	1.61	8	1.20	10.4	12.00	330	490
65	8	1.90	1.53	1.62	8	1.18	10.56	12.00	320	480
70	8	1.90	1.54	1.62	8	1.17	10.80	12.40	330	495
75	8	1.90	1.54	1.62	8	1.17	10.80	12.40	328	490
79	1	18.0	1.46	1.51	5	1.25	10.75	12.10	335	488
80	8	1.90	1.54	1.62	8	1.20	11.20	12.40	338	400
82	8	1.90	1.55	1.61	8	1.19	10.80	12.40	332	510
90	8	1.90	1.54	1.62	8	1.19	10.56	12.16	330	500
92	8	1.90	1.54	1.62	8	1.20	10.56	12.16	330	500

Figure 247. Typical Cycle Test Data for Baseline Cell.

CYCLE NO.	CHARGE				DISCHARGE		CAPACITY, A-HR		PRESSURE	
	I,A	T, HR	E, 0.5 V	E_{MAX}, V	I,A	E, 0.5 V	TO 1 V	TO 0.5 V	LOW	HIGH
2	9	1.9	1.54	1.63	9	1.22	9.45	10.35	450	595
3	9	1.9	1.55	1.65	9	1.23	9.90	10.80	450	598
4	9	1.9	1.55	1.65	9	1.23	9.90	10.80	445	590
5	9	1.9	1.55	1.66	9	1.23	9.90	10.80	440	585
6	9	1.9	1.55	1.66	9	1.23	10.26	11.25	440	590
7	9	1.9	1.55	1.66	9	1.22	10.35	11.25	450	590
8	9	1.9	1.55	1.66	9	1.22	10.35	11.25	440	590
9	9	1.9	1.55	1.66	9	1.22	10.35	11.25	445	595
10	9	1.9	1.55	1.66	9	1.22	10.35	11.25	430	585
11	9	1.9	1.56	1.66	9	1.22	10.53	11.43	435	578
12	9	1.9	1.56	1.66	9	1.22	10.80	11.70	435	582
13	9	1.9	1.56	1.66	9	1.22	10.80	11.70	428	582
14	9	1.9	1.56	1.66	20	1.12	10.00	11.60	430	570
16	1	18.0	1.44	1.49	5	1.24	10.25	11.20	410	540
18	12	1.0	1.54	1.63	20	1.10	9.20	11.00	420	550
25	12	1.0	1.55	1.64	20	1.10	9.60	11.60	425	555
35	12	1.0	1.56	1.64	20	1.11	9.60	11.40	420	550
45	12	1.0	1.56	1.64	20	1.12	9.60	11.60	415	540
55	12	1.0	1.56	1.64	20	1.12	9.80	11.80	420	550
65	12	1.0	1.56	1.64	20	1.12	9.60	11.20	420	550
75	12	1.0	1.57	1.65	20	1.11	10.00	11.60	410	540
85	12	1.0	1.57	1.65	20	1.12	10.00	11.60	415	550
100	12	1.00	1.58	1.66	20	1.12	10.00	11.60	410	540
104	8	1.00	1.56	1.58	8	1.22	7.00	7.60	–	–
112	8	1.90	1.52	1.60	8	1.24	11.60	12.40	–	–
115	8	1.90	1.52	1.62	8	1.25	11.20	12.16	–	–
120	8	1.90	1.52	1.60	8	1.22	11.60	12.80	–	–
125	8	1.90	1.50	1.55	8	1.23	11.28	12.48	–	–
130	8	1.90	1.52	1.60	8	1.23	11.36	12.64	–	–
136	12	1.00	1.55	1.63	20	1.12	10.00	12.00	–	–
140	12	1.00	1.56	1.65	20	1.12	10.00	12.00	–	–
145	12	1.00	1.56	1.65	20	1.12	10.00	12.00	–	–

Figure 248. Typical Cycle Test Data for Reservoir Cell.

CONCLUSIONS

- LACK OF ELECTROLYTE LIMITS HIGH RATE PERFORMANCE
- MAIN ELECTROLYTE LOSS MECHANISM IS DISPLACEMENT
- HIGH THERMAL GRADIENTS – H_2O LOSS
- O_2 CONCENTRATION ACCEPTABLE IN CONVENTIONAL ARRANGEMENT, LOWEST IN RECIRCULATING CONFIGURATION
- TRAPPED O_2 LARGER IN CELLS WITH RESERVOIR

RECOMMENDATION

- CELL CONFIGURATION WITH OPTIMIZED RESERVOIRS

Figure 250

CYCLE NO.	CHARGE				DISCHARGE		CAPACITY, A-HR		PRESSURE	
	I,A	T, HR	E, 0.5 V	E_{MAX}, V	I,A	E, 0.5 V	TO 1 V	TO 0.5 V	LOW	HIGH
45	12	1.40	1.55	1.61	20	1.12	10.80	12.00	330	472
50	12	1.70	1.53	1.60	20	1.12	11.00	12.50	340	485
55	12	1.80	1.53	1.60	20	1.10	10.50	12.00	–	–
61	1	18.0	1.46	1.48	5	1.25	10.50	11.65	–	–
62	12	1.50	1.58	1.63	20	1.10	10.50	12.50	–	–
63	8	1.90	1.55	1.62	8	1.17	6.40	7.20	–	–
70	8	1.90	1.55	1.60	8	1.20	8.00	9.00	295	430
75	12	1.90	1.57	1.62	20	1.15	7.75	9.50	–	–
85	12	1.90	1.58	1.63	20	1.12	7.00	9.50	–	–
95	12	1.90	1.60	1.65	20	1.07	6.00	8.50	–	–
105	8	1.50	1.53	1.60	20	1.10	9.50	11.00	–	–
107	5	3.00	1.52	1.56	20	1.10	9.50	11.50	–	–
109	5	6.00	1.53	1.55	20	1.08	9.00	12.50	–	–
145*	8	1.50	1.48	1.55	20	1.12	9.50	11.00	250	370
155	8	1.50	1.50	1.56	20	1.12	10.00	–	260	390
165	8	1.50	1.50	1.55	20	1.12	10.50	–	290	390
175	8	1.40	1.51	1.56	20	1.13	10.00	–	290	410
185	8	1.40	1.52	1.56	20	1.12	10.00	–	300	420
195	8	1.40	1.52	1.56	20	1.12	10.00	–	300	415
205	8	1.40	1.50	1.56	20	1.12	10.00	–	300	410
215	8	1.40	1.51	1.56	20	1.12	10.00	–	290	400
225	8	1.40	1.50	1.55	20	1.12	10.00	–	290	395
235	8	1.40	1.50	1.55	20	1.13	10.00	–	300	415
245	8	1.40	1.50	1.57	20	1.13	10.00	–	380	495
305	8	1.40	1.51	1.57	20	1.12	10.00	–	400	485

*CELL REIMPREGNATED AFTER 144 CYCLES

Figure 249. Typical Cycle Test Data of Design II Cell.

1. ASBESTOS BASELINE
   (ELECTROLYTE, REFERENCE ELECTRODE, O_2 SENSOR)
2. RESERVOIR, BACK-TO-BACK (RAI POLYPROPYLENE)
   (ELECTROLYTE, REFERENCE ELECTRODE, 3 THERMOCOUPLES)
3. RESERVOIR RECIRCULATING
   (ELECTROLYTE, REFERENCE ELECTRODE, O_2 SENSOR, 1 THERMOCOUPLE)
4. EIGHT CELL SERIES ARRANGEMENT WITH RESERVOIRS
   (ELECTROLYTE, 4 THERMOCOUPLES)

Figure 251. Cells for Extended Cycle Testing.

OXYGEN EQUILIBRIUM MEASUREMENTS IN NICKEL-HYDROGEN CELLS

H. H. Rogers
Hughes Aircraft

In this program I'll be talking about the same program that Gerhard Holleck discussed on failure mechanisms in nickel-hydrogen, which is sponsored by the Air Force. I'm also going to discuss a particular measurement that we made relating to the work that Gerhard was talking about on oxygen.

(Figures 252 and 253)

The work was undertaken as the result of a very large difference in an important parameter, oxygen concentration in the nickel-hydrogen cells. As Dr. Holleck pointed out, he saw concentrations well under 1 percent, whereas we were seeing oxygen concentrations anywhere from 2 to 10 percent.

We used ERC hydrogen electrodes. These were cells we had been running for some time. In the EIC cells, they used their own electrodes, which were made by an entirely different process, although they're all based on fuel cell grade platinum.

The objective of these experiments was to determine if these electrodes have different activity for oxygen reduction, which, in discussions with Dr. Holleck, was felt to be the most likely reason for the difference in the oxygen concentration.

(Figure 254)

Now, the apparatus--let's see if I can point out how it works--this is a glass vessel which Corning calls the Fleaker; it looks like a combination of a beaker and a flask--very convenient for electrochemical work, I might add. It has a very large stopper. Basically, what we do is float a hydrogen electrode on the surface of the 31 percent KOH electrolyte. The counterelectrode is a nickel ribbon that goes around. It isn't flat, it's just around the outside of the vessel. And we have a means of flushing with nitrogen, putting in our hydrogen, and then a means of preventing back diffusion of air, while keeping the pressure at 1 atmosphere.

The area of the hydrogen electrode is 4 square centimeters. Then, there is an oxygen electrode. This is a polarigraphic oxygen electrode which measures the partial pressure of oxygen in either hydrogen or nitrogen, and is sealed with an O-ring right there.

(Figure 255)

Now, the way we operated the system was to first calibrate the oxygen sensor using air, and then checking out its low-level performance on nitrogen with nitrogen. To run the apparatus, we first flush with nitrogen, then with hydrogen, close the inlet valve, and then turn on the current, so that we were generating oxygen at that sheet nickel electrode, and waiting for the concentration to stabilize; or, in other words, until the hydrogen electrode was reacting as much oxygen as was being generated, and you reach an equilibrium percentage depending on the activity of the electrode.

(Figure 256)

What we show on this chart is a typical tracing, in this case obtained with the EIC hydrogen electrode. But the tracings look very similar from various electrodes, and you have to go from right to left. And what would happen is, you'd build up and more or less flatten out, at which point we consider that our equilibrium reading, switch to the next current, and etcetera.

In this electrode, there is a residual background current which we simply subtracted from the actual current we got. There are better electrodes available, but I think this one happened to be a convenient size.

(Figure 257)

Now, let me see if I can go over some of the results we got. When we tested, basically, any electrode I could get my hands on; and, if you'll look at the 100 milliamp point, which is equivalent to something else, the EIC electrodes were uniformly very low oxygen percentage, just essentially what was reported in the EIC work. On the other hand, the ERC electrode, which is the electrode we had used, showed a much higher oxygen percentage.

In other words, instead of from point 1, basically, to point 2, it was merely 3 percent oxygen, a very large factor. One of the factors that did relate to the ERC electrode in its much lower recombination rate for oxygen was the backing, because we were able to pull off the backing, and ended up with about a little over 0.3 percent; in other words, almost an order of magnitude less oxygen equilibrium percentage.

Other electrodes we tested included a couple of Eagle-Picher electrodes, which tended to be closer to the ERC but not quite as high, and then there was one which was kind of different. It was an electrode from a previous --an older Tyco cell, which had an extremely high percentage even at very low rates of current. And this was attributed to a different grade of platinum being used.

So really, there are two factors in this. We've shown one. There is the effect of the backing. And second, there is a difference in electrode construction.

(Figure 258)

A particularly important point was to determine the effect of temperature, which was done on one of the Eagle-Picher electrodes. Increasing the temperature by more than 20 degrees centigrade only made a change in the current of about 20 percent. There were a couple of factors; one, you lose oxygen solubility, which tends to decrease your recombination rate. But the diffusion rate goes up. But since the solubility decreases faster than the diffusion rate goes up, you would expect a higher oxygen concentration, which is what we got. But it was only slightly higher.

(Figure 259)

We concluded from the work that the differences we had seen between EIC and Hughes cells were, indeed, accounted for by the differences in the electrodes. The reaction appears to be diffusion-limited, because of the small temperature coefficient which I just described. And the Teflon backing can reduce the recombination rate, if it's not properly selected.

I think it's important, and we feel quite important, to get an electrode which has been designed for a high activity with diluted oxygen. And finally, one should look at the oxygen recombination capabilities of the electrodes before you employ it in the nickel-hydrogen cell. And essentially, this is what we're going to do in building our cells, to avoid any possibility of high oxygen concentration.

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WORK SPONSORED BY

- AIR FORCE AERO PROPULSION LABORATORY
- "FAILURE MECHANISMS IN NICKEL-HYDROGEN CELLS"
- CONTRACT F33615-75-C-2025

Figure 252. Oxygen Equilibrium Measurement

BACKGROUND

- EIC CELLS
  LOW (0.1 TO 0.2%) O_2 CONCENTRATION
  EIC H_2 ELECTRODES
- HUGHES CELLS
  HIGH (2 TO 10%) O_2 CONCENTRATION
  ERC H_2 ELECTRODES

OBJECTIVE

DETERMINE IF ELECTRODES HAVE DIFFERENT ACTIVITY FOR OXYGEN REDUCTION

Figure 253. Oxygen Equilibrium Measurement

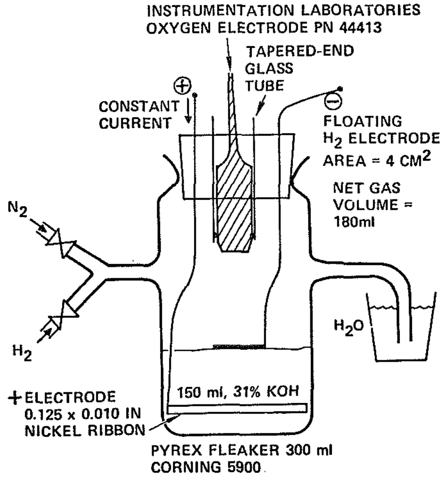


Figure 254. Oxygen Equilibrium Measurement Apparatus.

- CALIBRATE OXYGEN SENSOR WITH AIR AND NITROGEN
- FLUSH APPARATUS WITH HYDROGEN AND CLOSE VALVE
- TURN ON CONSTANT CURRENT AND WAIT FOR OXYGEN CONCENTRATION TO STABILIZE

Figure 255. Oxygen Equilibrium Measurement Procedure.

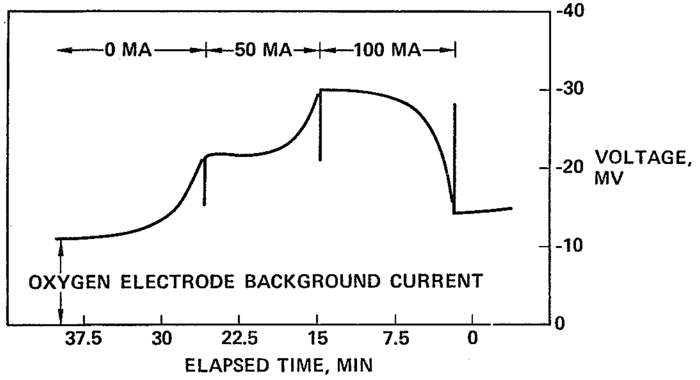


Figure 256. Oxygen Equilibrium Measurement EIC Hydrogen Electrode Recorder Trace.

- TEMPERATURE INCREASED FROM 22.5° TO 47°C
- CURRENT INCREASED ABOUT 20%
- O_2 SOLUBILITY LOWER
- DIFFUSION RATE GREATER

Figure 257. Oxygen Equilibrium Measurement

ELECTRODE DESCRIPTION	PERCENTAGE OF OXYGEN			
	25 MA	50 MA	100 MA*	257 MA
ERC, USED, CELL 16, 3 MG PLATINUM/CM^2	0.36	0.88	2.86	
SAME, SECOND EXPERIMENT		1.18		
SAME EXCEPT TFE BACKING REMOVED		0.18	0.34	
EIC, EARLY SAMPLE, ~10 MG/CM^2		0.09	0.15	
SAME, SECOND TEST		0.10	0.17	
SAME, THIRD TEST			0.19	0.41
EIC, SS35, 10.5 MG/CM^2			0.10	
EAGLE-PICHER, CELL 0004, USED		0.47	0.88	
SAME, SECOND TEST			1.40	
EAGLE-PICHER, CELL 33, USED			1.50	
TYCO, CELL L-2-2, USED	2.45			
UNICAN N-3N10 3/0 GS		0.73	1.43	
UNICAN UEP/N/5Ni 7-4/0			0.70	

*APPROXIMATELY C RATE

66445-69

Figure 258. Oxygen Equilibrium Measurement Effect of Temperature on Eagle-Picher Electrode, Cell 0004.

- DIFFERENCES IN OXYGEN CONCENTRATION IN EIC AND HUGHES CELLS ACCOUNTED FOR BY ELECTRODE DIFFERENCES
- REACTION DIFFUSION-LIMITED, INDICATED BY SMALL TEMPERATURE COEFFICIENT
- TFE BACKING CAN REDUCE RECOMBINATION RATE SIGNIFICANTLY
- ELECTRODES SHOULD BE DESIGNED FOR HIGH ACTIVITY WITH DILUTED OXYGEN
- ELECTRODES SHOULD BE CHARACTERIZED FOR OXYGEN RECOMBINATION BEFORE USE IN Ni–H_2 CELLS

Figure 259. Oxygen Equilibrium Measurement Conclusions.

DEVELOPMENT OF NICKEL-OXIDE ELECTRODES FOR USE IN NICKEL-HYDROGEN CELLS

V. J. Puglisi
Yardney Electric

We are presently engaged in a nickel-hydrogen program funded by Intelsat, and that's what I'd like to discuss here today. The purpose of the program is the development of an improved nickel-oxide electrode for use in nickel-hydrogen cells. The program has boiled down to, essentially, two major tasks. The first is the experimental investigation to obtain improved nickel-oxide electrodes, and the second task is the fabrication, with delivery, of this type of electrode to Intelsat.

(Figure 260)

The performance that we are looking for, and Intelsat is looking for, in these electrodes is a minimum 4,000 cycles at depth-of-discharge of 60 percent. In addition, as a goal, we're looking for 30 milliamp hours per square centimeter of electrode, and in the back-to-back configuration, this is equated to 60 milliamp hours per square centimeter of electrode.

(Figure 261)

To accomplish the goals, we have chosen to investigate these three areas. The first area is the electrochemical impregnation process, the second is the plaque porosity, and thirdly, the loading level of the positive electrode.

The electrochemical impregnation process has been previously reported on in the June power sources symposium, and I won't discuss it here today other than to refer you to the proceedings of that symposium. I would like to discuss the sinter porosity and the loading level. And as you can see, what we have up there, we've identified two levels of investigation for sinter porosity. We've identified 78 percent porous plaque, and an 82 percent porous plaque. For loading level, we've identified a loading level of 1.6 grams per cubic centimeter, and a second level of 1.9.

I'd like to first give you some background as to why these are levels one should investigate, and then I'd like to turn to some experimental data that we have obtained.

(Figure 262)

This is a calculated curve which is based on some experimental data. It has an experimental basis, and its capacity for unit volume is a function of sinter porosity. And again, the points are just calculated. This is based on a 35-mil plaque, with a loading level of 2 grams per cubic centimeter void. The peak of this curve maximizes at approximately 79 percent porous. This is capacity on a volumetric basis.

(Figure 263)

Now, I'll show you the capacity per unit weight as a function of sinter porosity. Again, this is based on 35-mil plaque, and a loading level of 2 grams per cubic centimeter of void. As you can see, the volumetric capacity per unit weight increases as the porosity increases. This is to be expected.

On the basis of these two curves, you can see, with the maximum loading or maximum capacity per unit volume in the 79 percent region, and this capacity per unit weight, which increases with porosity, one would want to stay in the region of approximately 78 to say, 83 percent porous, to obtain the beneficial--or, as a compromise, with these two types of considerations.

Now, turning to loading levels, we have indicated in the past that one does not want to exceed a certain loading level, because it increases the probability of introducing blisters.

(Figure 264)

Here's some additional reasons why one would want to stay at loading levels of about, say, less than 2 grams, or on that order; and why one would want to be in, say, the 1.9 region, or at least take a look at 1.9 grams per cubic centimeter of void, and not go any higher.

This is the curve of loading level as a function of process time. Now, this is corrected loading level; that is, corrected for anything which may have occurred and introduced additional void in the original plaque. As you can see--and another fact is that the process time is an indication of how much material has been loaded. So a plate loaded at 80 minutes is carrying more weight than one loaded at 40 minutes. As you can see, the loading level plateaus, the thickening increases, starts increasing at about 60 minutes, and at 100 minutes begins to rise more rapidly. And what this effect does is, even though you've actually put more weight into the plates on a volumetric basis, you haven't improved the plate. And toward the end, you actually start to see a diminishing effect here on a volumetric basis.

Now, we also show that we were going to investigate a 1.6 gram loading level. And some of the reasons one would want to do that can be seen from the following illustrations.

(Figure 265)

Here we have plotted utilization, as defined as amp hours delivered divided by ampere hours theoretically calculated, on the basis of the weight gain and the Faraday-type considerations. When we plot that versus loading level, surprisingly enough, this peaks in the region of about 1.6 grams per cubic centimeter of void.

There's also a fall-off on either side of that; loading levels of about 0.6 gram per cc of void as the utilization, and the 60.6 range, or 60 percent.

Now, I'd like to add--I don't want to mislead anyone here, because I do show some very high utilization values. This is not to say that you can build a cell and get these type of values. This was an experiment which was a defined test, which involved significant overcharge of the plates, high-rate overcharge. However, that curve is not the entire story.

(Figure 266)

We have, again, a plot of the same data. This is experimental data that was shown here yet. We plot vented capacity and normalized vented capacity, which is a merit factor which takes into consideration loading level, which is directly proportional to the kinds of utilization. And as you can see here, in the region of 1.6 to above 1.8 or towards 1.9 grams per cybic centimeter void, you have a leveling off. That is, they're essentially delivering the same amount of capacity.

To evaluate the sinter porosity levels, and the loading level, what essentially we did; we made four times the plate, the two loading levels and the two sinter porosities. We are using eight boiler plate cells; eight cells, or the two cells per electrode type.

(Figure 267)

Here we have the projected performance of these cells. Cells 01 and 04 are made with the 82 percent porous plaque. Cells 05 through 08 are made with the 78 percent porous plaque. I have identified the electrodes and the loading levels of the particular electrode, and I give here the average loading level of the individual cells. This is the theoretical capacity which was projected, on the basis of weight gain; again, this is a theoretical capacity expressed in terms of milliamp hours per square centimeter.

As you can see here from these numbers, each and every cell is projected to give us the goal of 60 milliamp hours per square centimeter, although these two aren't right then.

(Figure 268)

Now, I'd like to show you some actual performance data on the cells. Here, I've identified various cycles that have been carried out. F-3 corresponds to a third cycle electrical checkout, which was carried out to set the peak pre-charge and to insure that the cell was operating correctly. AST refers to Ambient Stabilization Test; we ran seven cycles. This is the average of the seven cycles to 0.85 volts; this is the capacity of the cycles to 0 volts. This last entry here is 30 additional cycles, and we're now in a phase where we're cycling the cells.

Let me make a further comment. Cell 1, during the interim time that we went from the electrical checkout to the stabilization test, developed a short, and we did not use it in this stabilization test. However, it was used in the cycle test, and that's why you see an entry down here.

Again, let me identify the 82 percent porous electrodes versus the 78. Those are cells 1 through 4, the 82 percent porous; and as a group, they are performing better than are the cells built with 78 percent porous plates. The 82 percent porous cells, loaded to the high level, which is approximately 1.8 to 1.9 grams per cubic centimeter, are not much better than the 82 percent porous electrodes that are lightly loaded, loaded in the region of about 1.6 to 1.7. I will show you some utilization numbers on the next slide.

What I would like to point out here is that, as a group, the 78 percent lightly-loaded cells seem to be performing, on the whole, worse than the other cells. Cell 07, which is a 78 percent porous--made with 78 percent porous electrodes, and heavily loaded--that cell is performing not much differently than are the cells 01 through 04. Cell 08 is the unique cell; and it's unique in that, first off, the capacity of it versus its mate is very dissimilar, not like the others.

Second of all, what we found was that the capacity did not improve during the stabilization tests. When we got to the seventh cycle, we discharged down to 0 volts, and found an unusually large amount of capacity between the cut-off voltages that we're using--0.85--and 0 volts, where you can see here it's on the order of 0.1 ampere hour. Here, it's more like--this is the cycle we're comparing it with--it's more like 0.35 ampere hours. So I think that this cell was performing abnormally at that point. On cycle 30 of the cycle test, again, we took the cells this time down to 0 volts, and measured the capacity. And again, you see that the 82 percent porous cells, with 82 percent porous electrodes, are performing and delivering about 3 ampere hours, regardless of whether they're heavily loaded or lightly loaded. Again, the 78 percent lightly-loaded cells are giving about what they were before, and it's not in the region of the others. Here, cell 08 has improved, and it is performing much like its mate. And that's not only an improvement down to 0 volts, but that's also an improvement to 0.85. And I'll show that with the following curve.

(Figure 269)

Here is a plot of the charge-discharge cycle of both voltage and pressure for cell 08 on cycle 30. As you can see, I present this for two reasons. First of all, it's typical of the others; but in addition, to show you that there isn't much capacity in this region--less than 0.85 volts.

(Figure 270)

I think to really compare the performance of the cell, this slide was made up. And again, here I've identified the cells. I've identified the electrode type as to porosity and as to loading level. These were the nominal values; here are the theoretical capacities that were projected, based on weight gain. This is again expressed in terms of milliamp hours per square centimeter of back-to-back electrodes.

Here, I show the results from the ambient stabilization test to 0.85 volts and to 0 volts. Again, cell 01 did not participate in these stabilization tests. However, you can see numbers to 0.85 volts for most of the cells are close to 100 percent utilization of active material. Again, cell 08 was delivering 79 percent to 0.85 volts. To 0 volts, some small improvement, not significant, except for in the case of cell 08, which was considerably more than down to 0.85.

In terms of the projected goal, 60 milliamp hours per square centimeter. Here, to 0.85 volts, you can see that we have exceeded the goal of 60 milliamp hours per square centimeter virtually in every case. Cell 05 is slightly less. Cell 08 is again low to 0.85 volts. To 0 volts, I've also calculated the same value, and here we show cell 08, which had an additional capacity.

On cycle 30, the values are calculated--utilization to 0 volts. And you can see we don't have the data to 0.85 in this case. But you can see that the matching of particular cells in terms of the utilization here, there's some divergence between these two cells. Here, cell 7 and cell 8 are in good agreement now.

In terms of the milliamp hours per square centimeter, again, the goal was 60. We're seeing 70 in many instances, close to 70 here. And again, these are--the two 78 percent lightly loaded seem to be the poorest performing electrodes.

At this point in time, we're still evaluating the electrodes. They're in cycle tests, as I mentioned. And I only show you data up to cycle 60. However, it looks like, on the basis of delivery capacity, that there are three types of electrodes which are performing well: the cell 01 and 02, which is the 82 1.9 more heavily-loaded plates; the 03 and 04, which are again the 82 and lightly loaded; and the 07 and 08, which are the 78 percent sinter porous plaque, and heavily loaded.

In terms of energy density considerations, on the basis of just the plaque, one would argue for the 82 percent porous plaque as being lighter than the 78 percent porous plaque. In the set of the 82 percent porous plaque, the 1.6 plates loaded in the region of 1.6 grams per cubic centimeter are given about the same capacity, and at a higher utilization. So you are more effectively using the material.

The reason I stress that the evaluation is still in progress; because of these considerations of the strength of the plaque. Again, the 78 percent porous plaque, heavily loaded plaque, is not far in terms of delivered capacity or sacrifice of some energy density. There's a weight consideration. And these long-term tests that we're now involved in may result in different types of conclusions on the basis of structural strength.

ROGERS: Hughes Aircraft

Did you give these plates any formation cycles before you started cycling?

PUGLISI: Which plates?

ROGERS: You had like 10 cycles capacity gradually increased. Were those plates formed before the cells were assembled?

PUGLISI: These plates were formed, yes. Here you see three cycles. Is this the data you were concerned about?

ROGERS: Yes, right.

PUGLISI: Okay. Here, the plates had just the three cycles, and then we went to the stabilization. Everything that's been done is shown here. There was some formation prior to cell assembly. Then the plates went through this recycle electrical checkout, with improvement of capacity with each cycle. And then they went into the stabilization tests, and that's what you see recorded there in cycles 1 through 7.

BOGNER: JPL

I think you ought to be commended on developing this kind of information. This is the kind we need. It's too bad you didn't use three points, because now you've only got a straight line. But on the estimation of the optimum porosity of the plaque, you said it was calculated. Is that based on the work that Jim Bene of the NASA/Langley did some time ago?

PUGLISI: Yes.

BOGNER: There's an error in that calculation, and your results are bearing that out.

MAURER: Bell Labs

What is the mean pore size on the plaques, and did you use pore formers for either of these?

PUGLISI: Yes, we did use pore formers. And we did some double air capacitance work, and we determined that this is the plaque made in the same manner as the old unit, or the unit that plaque was made of. The types of numbers that we're getting from that are like 10 microamps. This doesn't say anything about porous emission.

PROGRAM: DEVELOPMENT OF NICKEL [illegible]
FOR USE IN NICKEL HYDROGEN CELLS

TASKS:

1. EXPERIMENTAL OPTIMIZATION OF NICKEL OXIDE ELECTRODES
2. FABRICATION AND DELIVERY OF ELECTRODES TO INTELSAT

PERFORMANCE:

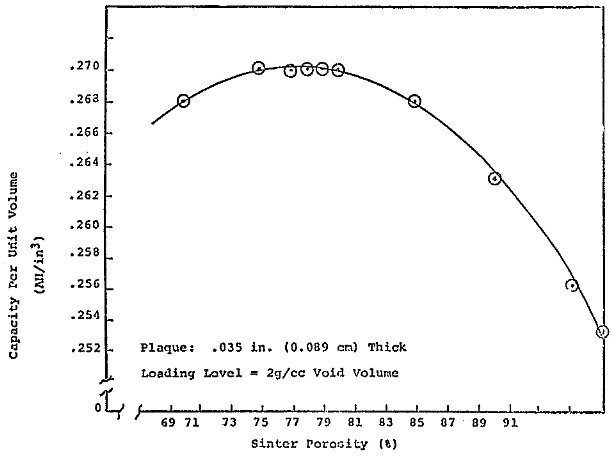
1. MINIMUM 4000 CYCLE LIFE @ 60% DOD
2. 30 mAH/cm^2 ELECTRODE (GOAL)

Figure 260

EXPERIMENTAL PARAMETERS INVESTIGATED

1. EI PROCESS	
a. SOLUTION CONDITIONS	MAKEUP, pH, ETC.
b. CURRENT DENSITY	0.054, 0.085 & 0.124 A/cm^2
2. PLAQUE SINTER POROSITY	78 PERCENT vs 82 PERCENT
3. LOADING LEVEL gNi(OH)$_2$/cc PLAQUE VOID VOL.	1.6 vs 1.9

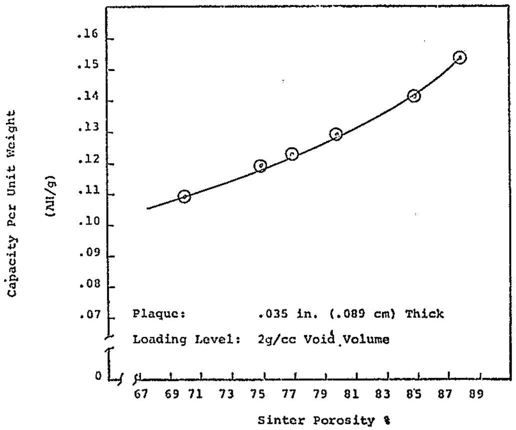
Figure 261



Plaque: .035 in. (0.089 cm) Thick
Loading Level = 2g/cc Void Volume

CAPACITY PER UNIT VOLUME
VS
PLAQUE POROSITY

Figure 262



Plaque: .035 in. (.089 cm) Thick
Loading Level: 2g/cc Void Volume

CAPACITY PER UNIT WEIGHT
VS
PLAQUE POROSITY

Figure 263

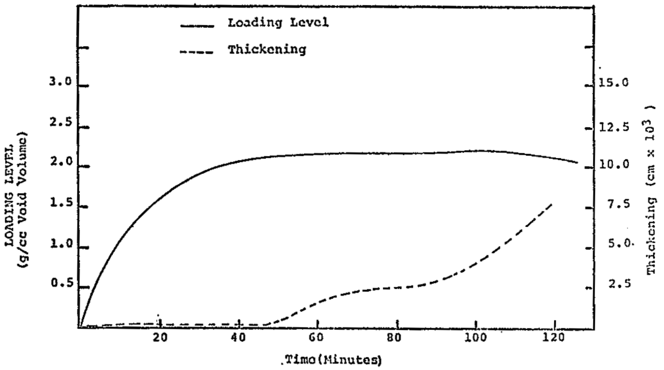


Figure 264. Loading Level Vs. Time

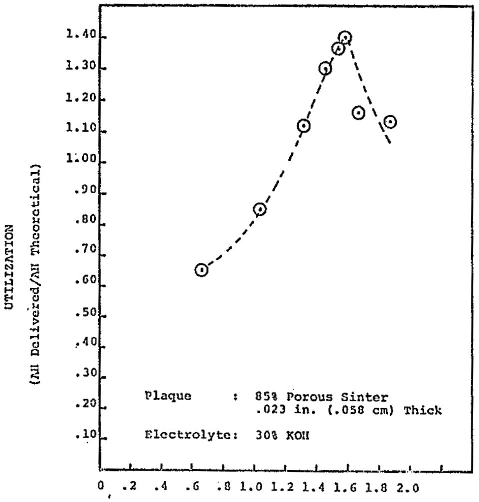


Figure 265. Loading Level (g/cc Void)

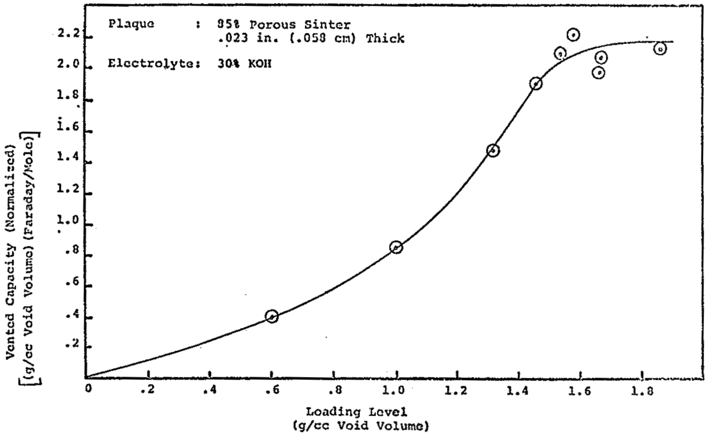


Figure 266. Vented Capacity Vs. Loading Level

CELL S/N	ELECTRODE POROSITY (%)	ELECTRODE S/N	ELECTRODE L+ (g/cc Void)	CELL AVG. L+ (g/cc Void)	CELL THEORETICAL CAPACITY AH	CELL THEORETICAL CAPACITY mAH/cm^2	CELL ENERGY DENSITY AH/in^3	CELL ENERGY DENSITY AH/cm^3
01	82	9-01 11-02	1.90 1.85	1.88	3.30	75	6.7	.41
02	82	2-01 2-03	1.83 1.83	1.83	3.30	75	6.8	.41
03	82	23-01 23-02	1.72 1.72	1.72	3.00	68	6.1	.37
04	82	22-02 27-02	1.65 1.70	1.68	2.93	66	6.1	.37
05	78	22-02 22-03	1.64 1.64	1.64	2.64	60	5.6	.34
06	78	10-02 10-03	1.63 1.63	1.63	2.64	60	5.6	.34
07	78	13-03 15-01	1.80 1.76	1.78	2.95	67	6.2	.38
08	78	13-02 17-02	1.80 1.78	1.79	2.99	68	6.3	.38

+ L=Loading Level

Figure 267. Cell & Electrode Data - First Build

CYCLE #	(AH) IN	CAPACITY AH TO 0.85 VOLTS FOR CELLS 01	02	03	04	05	06	07	08
F^{+}-3		2.67	2.87	2.87	2.97	2.32	2.48	2.32	2.17
$AST^{\pm}$-1	5.5	‡	3.27	3.16	3.21	2.47	2.80	2.99	2.40
-2	5.2		3.15	3.08	3.12	2.55	2.67	3.02	2.30
-3	4.9		3.10	2.97	3.02	2.57	2.75	2.90	2.32
-4	4.5		3.03	3.01	3.01	2.52	2.59	2.94	2.29
-5	4.5		3.12	3.07	3.07	2.50	2.62	3.00	2.35
-6	4.9		3.22	3.17	3.08	2.52	2.67	3.02	2.37
-7	4.9		3.22	3.10	3.02	2.57	2.70	2.97	2.50
$\overline{AST}$-7 (to .85V)	4.9		3.16	3.08	3.07	2.53	2.68	2.98	2.36
AST-7 (to OV)	4.9		3.36	3.17	3.12	2.62	2.80	3.08	2.85
C-30 (to OV)	*	3.12	3.09	3.11	3.15	2.47	2.68	3.07	3.01

‡ Cell 01 developed a short
+ 3rd cycle sealed electrical checkout
± AST = ambient stabilization tests; 1.5A charge and discharge
* Cycle Tests: C rate charge followed by 60% DOD (based on average cell performance)

Figure 268. NiH Electrochemical Test Data - Capacity.

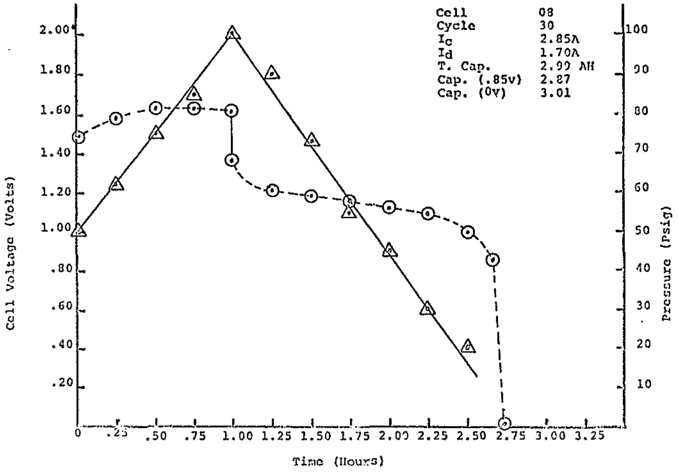


Figure 269. Cell Voltage & Pressure Vs. Time.

CELL S/N	ELECTRODE DESCRIPTION POROSITY-LL	THEORETICAL CAPACITY AH	THEORETICAL CAPACITY mAH/cm²	$\overline{AST}$-7⁺ UTILIZATION To .85V	UTILIZATION To OV	mAH/cm² To .85V	mAH/cm² To OV	C-30± UTILIZATION To OV	mAH/cm²
01	82-1.9	3.30	75	-	-	-	-	.95	70
02	82-1.9	3.30	75	.96	1.02	71	76	.94	70
03	82-1.6	3.00	68	1.03	1.06	70	72	1.04	70
04	82-1.6	2.93	66	1.05	1.06	69	70	1.08	71
05	78-1.6	2.64	60	.96	.99	57	59	.94	56
06	78-1.6	2.64	60	1.02	1.06	61	63	1.01	61
07	78-1.9	2.95	67	1.01	1.04	67	70	1.04	69
08	78-1.9	2.99	68	(.79)	.95	53	64	1.01	68

+ Ambient Stabilization Tests - Average of 7 Cycles: Discharged @ ~ C/2 rate = 1.5A

± Cycle Tests - Cycle 30 Data. Discharged @ ~ C/2 rate = 1.7A

Figure 270. NiH Electrochemical Test Data - Utilization.

CYCLE LIFE TEST AND THERMAL VACUUM TEST RESULTS IN NICKEL-HYDROGEN CELLS

R. Sayano
TRW Systems

My presentation will be divided into two parts. The first will deal with a summary of our life cycle tests on nickel-hydrogen cells of various vintages. We have been testing these for quite awhile; IRD program, nickel-hydrogen cells from 1974 on. The second part will be on the results of thermal vacuum tests we ran on 10-cell, 35-amp hour nickel hydrogen batteries that we designed and fabricated under the sponsorship of Comsat.

(Figure 271)

Figure 271 shows the number of cells that we identified as first, second and third generation, which are on or will be on life cycle tests at TRW. The first-generation cells, which are the Eagle-Picher prismatic spheroid, 20 amp power capacity; we have eight of these at the present time still running. We started off with a total of 10, I believe, and two came off the line about two weeks ago.

The ERC cells are the so-called inverted dome cells, and we have three of these on test, they are also 20 amp power.

The second-generation cells, except for the SAFT cells, came to us as a complement from our Comsat program. They were kind enough to let us keep it after our program ended with them, and we keep it on our life cycle testing. And these are of the Comsat design, the 50-amp hours; and as you can see, we have a total of seven on test.

The SAFT cell, which is the most recent cell we put on test, had started with six; and after one season, one of them failed, so we now only have five.

And the third-generation cells; these are the Air Force developed stack design as well as the Comsat-designed cells, with the electrochemically-impregnated positives. They will go on test in the near future.

(Figure 272)

This is the discharge profile of our eclipse season that we are using at TRW for the nickel-hydrogen life cycle tests. This is somewhat similar to the other accelerated life test profiles we used with geosynchronous. I would like to point out, the important part here is the 21st through the 25th cycle, which is our discharge point, and the DOD is rated at that point.

(Figure 273)

This chart is self-explanatory. It gives you the test conditions for the various-sized cells. The discharge current is constant at approximately C 1/3, I believe; the C/2 rate, and our duration of eclipse season lasts for 12 hours, with a recharge ratio of 1.2, excluding trickle charge. The accelerated test is done with five-digit trickle charge in between the 45 cycles; whereas, in the real time, we have 137-day trickle charge.

(Figure 274)

This is the result, up to date, of the first generation cells. The open symbols represent the accelerated testing, and the closed symbols, which you see there, represent the real time, and you can see that they track pretty well so far, and we only have something like three seasons on them. We've gone into the fourth season on the real time, and as far as accelerated, we're already all the way up to the 19th, and we do have some discontinuities--for example, here, at which point a reconditioning to 0 volts was conducted on the Eagle-Picher cells. And you can see the voltage came right back up.

There is another reconditioning, which was done in this region. We had a little bit of, we believe, a testing problem in which a large majority of our cells went under our voltage cutoff point, which is set at half a volt.

The ERC cells, as you can see, fall a little bit lower, and the end-of-discharge voltage; this is taken at the 23rd cycle, which is the deepest cycle of the eclipse season.

(Figure 275)

And then, so then the first generation cells started about a little over two years ago; 1974 was when the first set of cells went on test, and they were by far the largest numbers of seasons on them. This is the second generation cells, which went on test in 1975. These are 50-amp hour, ERC and Eagle-Picher cells of the Comsat design, as well as a SAFT 23-amp hour cell.

And now, we have a reverse. Now we see that ERC cells show a higher end-of-discharge voltage, and Eagle-Picher cells are lower. We have the SAFT cells, which only completed three seasons up to this point; even though, in the first chart I showed you for the Comsat-designed cell, we had various other components which we compared--for example, the different type separator--the presentation here will not go into that, since the number of cells are very limited, and we'll be comparing like one cell versus one cell. And that's an unfair comparison.

The second part of my presentation has to do with the thermal vacuum test and their results.

(Figure 276)

It was conducted on a 10-cell, 35-amp hour battery which was designed and fabricated for Comsat. This particular figure I'm sure you've seen already, since Bob Patterson last year presented the thermal design up to the point of testing. And what this really shows you is that we went through a complete thermal design of the battery from the cell level on up, to determine how the heat was transferred from the inside of the cell to the outside volume brackets, and subsequently to the radiative surface. And at that time, we concluded that the best design would be the bulkhead feed-through type mounting.

(Figure 277)

And this just shows how the cells were laid out. And essentially, this is the platform here. We have a girth band mounting bracket to the platform with the thermoco on the outside.

(Figure 278)

As part of the thermal design, one of the things we looked at was the actual bracket to hold the cells in place, the so-called girth band. And the size of the girth band was determined by thermal analysis. And what this figure shows is that if you assume a thickness between stack and housing of 50 mils, and you look at the temperature, the delta temperature between inside the stack, right about here, to the platform; then, after you have reached the bracket thickness of about 25 mils, you don't get much above that.

So, by making it thicker, making this bracket thicker, it doesn't help you any in terms of heat transfer. It might help you in terms of strength. We have the other case here, where we looked at--if you assume the 25 mil bracket thickness, what's the function of the temperature drop between the outside of the cell here to the pylon platform--that's the delta represented here. As you can see, the function is very, very low.

(Figure 279)

Now, all this resulted in a design of the mounting bracket which is shown here. I will not go into the other aspect, which is the actual mechanical stress analysis and vibrational testing at this point, because those are covered in detail. And I think Bob Patterson has covered those points on the last presentation.

(Figure 280)

In order to carry out a thermal vacuum test to verify our thermal design, we placed the entire battery in a simulated spacecraft. What we basically did was build a box, insulate it with various shieldings and insulation to make sure that all we had is radiation of the heat by the sides of the vessel, and also conduction through the girth band through the outside and through the secondary radiator, which is on the top.

(Figure 281)

The thermal vacuum test was conducted by taking a C/2 discharge rate for 1.2 hours, and we could go down to a 60 percent DOD, and kept cycling until we reached a steady state condition. And what this really shows is that--here's the temperature rise in the cell due to discharge, and a drop due to charging. And number 4 here represents a region in which we had to turn on the heater in order to maintain a temperature above 0 degrees. And you can follow the rest of it all the way up to the terminal charge point there, and you see that the temperature excursion is between 0 and about 14 degrees C. This is for 60 percent DOD.

(Figure 282)

We ran a similar test at 80 percent DOD and we had this result, which shows a slightly larger temperature excursion, from about minus 5 to 20 degrees centigrade.

That concludes my presentation. The details of this program, both the IR&D and the battery design and fabrication, can be found in the IR&D final report, and also the final report submitted to Comsat.

ROGERS: Hughes Aircraft

Where was the sensor located? You said cell temperature; where was that taken?

SAYANO: Where was that taken? I can't recall that. In the thermal vacuum test?

ROGERS: Yes.

SAYANO: I do not have a chart of the location of the sensors. But we do have them on the platform, as well as on the girth, as well as on the cell.

ROGERS: When you say, on the cell; where on the cell?

SAYANO: I don't know exactly where it was placed.

ROGERS: Well, the reason why I mention this is, in your graph, you showed a long delay between the end of charge, where you get a peak, and where the heat is suddenly turned off. And you're going into a trickle charge, and your major amount of heat would stop at that point, or soon after. And there seemed to be a long delay between the time of the cell peak temperatures, and that's why I asked the question.

SAYANO: I don't know exactly in detail where that thermocouple was placed.

KRAUSE: Hughes

Ray, I noticed some of the cells you're going to test, or cells under test, had nylon separators. What's your assessment of the long term viability of nylon in the life of the cell operation?

SAYANO: At this time, I personally don't have any, because I haven't had a real chance to go back and look at all the data in detail. I must mention that Bob Patterson, who has been very instrumental in conducting a lot of these tests, recently left TRW, and I've sort of stepped in. And I'm trying to catch up on all the data.

So, I would defer my comments on that until later on.

WADHAM: Wadham, Telesat-Canada

In your second generation cells, the ERC cells, there was sudden drop in voltage around about the tenth season. Do you know why that was? Sort of the inverse?

There was a sudden drop there. Yes, it dropped along about season number six in the ERC cells.

SAYANO: What was attributed to that drop?

WADHAM: Yes.

SAYANO: I have no explanation for that.

WADHAM: It was about the same amount as you improved in the reconditioning of the first cells. It's quite a significant drop.

SAYANO: I'm sorry, I don't have any explanation for that drop.

GANDEL: Lockheed

In answer to Stan Krause's question on the nylon cells, 20-ampere hour cells. We're approaching about 6,000 cycles, and I would say most of that testing has been on the level of about 23 C. So the nylon doesn't immediately flake away.

CELL TYPE	STACK DESIGN	POSITIVE ELECTRODE	NEGATIVE ELECTRODE	SEPARATOR	CAPACITY (AH)	QUANTITY
FIRST GENERATION	EP	EP-CI	EP	NYLON	20	8
	ERC	EP-CI	ERC	ERC-KT	20	3
SECOND GENERATION	INTELSAT	EP-CI	EP	NYLON	50	2
	INTELSAT	EP-CI	EP	ASBESTOS	50	2
	INTELSAT	ERC-EI	ERC	ERC-KT	50	3
	INTELSAT	SAFT-CI	SAFT	NYLON	24	5
THIRD GENERATION	AFAPL	EP-EI	EP	ASBESTOS	35	6
	INTELSAT	EP-EI	EP	ASBESTOS	35	6

EP = EAGLE-PICHER
ERC = ENERGY RESEARCH CORPORATION
EI = ELECTROCHEMICALLY IMPREGNATED
CI = CHEMICALLY IMPREGNATED
KT = POTASSIUM TITANATE

Figure 271. Nickel-Hydrogen Cells for Life Cycle Test (Accelerated and Real Time).

CELL SIZE, Ah	20	23	50
DISCHARGE CURRENT, A	13.3	15.3	25.0
CHARGE CURRENT, A	2.0	2.3	3.8
TRICKLE CHARGE CURRENT, A	0.2	0.5	1.5
MAXIMUM DOD, %	80	80	60

RECHARGE RATIO (EXCLUDING T/C)	1.2
BASEPLATE TEMPERATURE, °C	15
ECLIPSE SEASON CYCLE, HR	12
DURATION, DAY	22.5
NONECLIPSE SEASON DURATION, DAY	
ACCELERATED	5
REAL TIME	137

Figure 273. Cycle Life Test Conditions

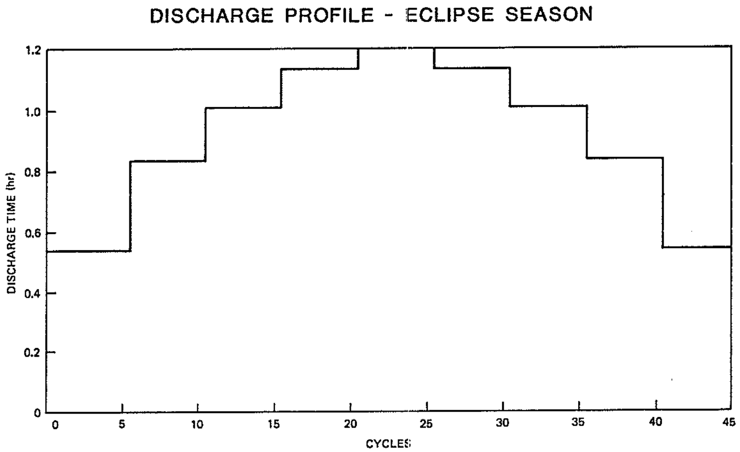


Figure 272. Discharge Profile - Eclipse Season

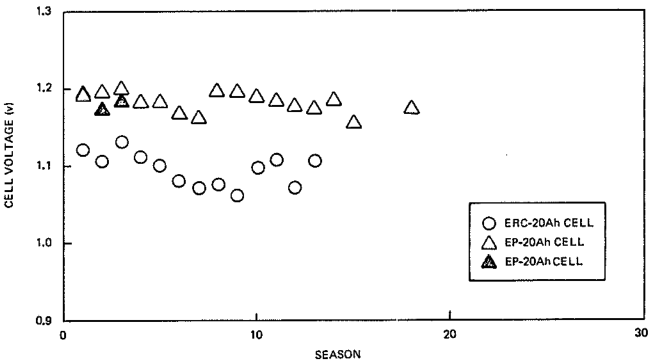


Figure 274. End-of-Discharge Cell Voltage (First Generation Cells).

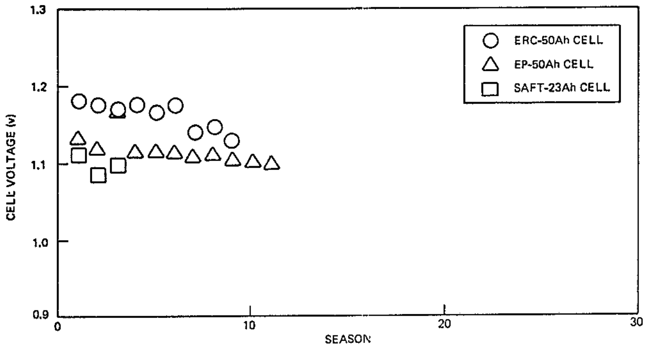


Figure 275. End-of-Discharge Cell Voltage (Second Generation Cells).

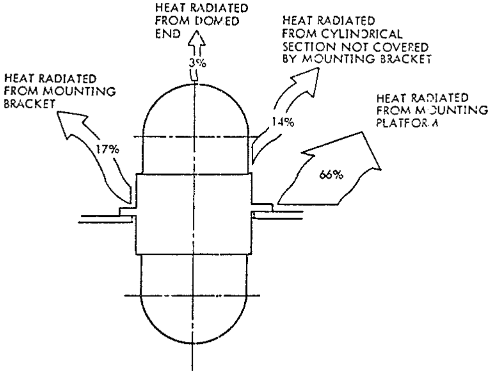


Figure 276. Thermal Design Required Detail Understanding of Heat Flow.

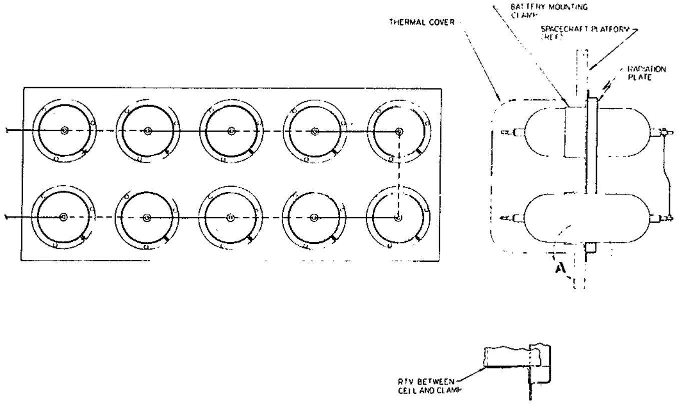


Figure 277. Bulkhead Feedthrough Mounting Technique Minimizes Weight.

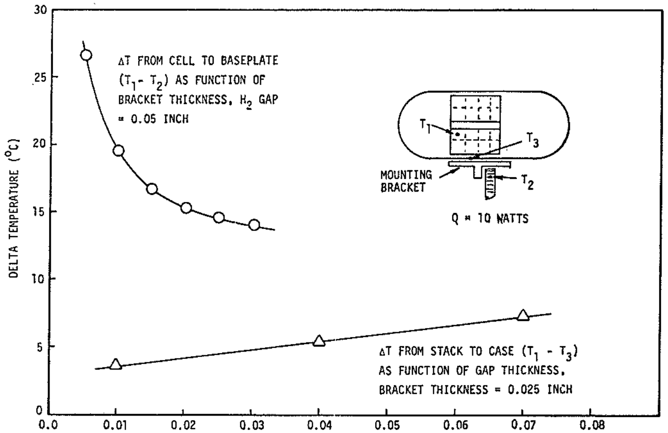


Figure 278. Mounting Bracket or Hydrogen Gap Thickness (Inches).

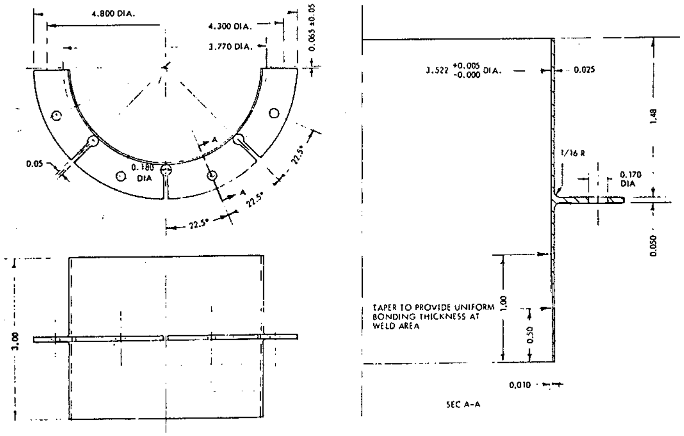
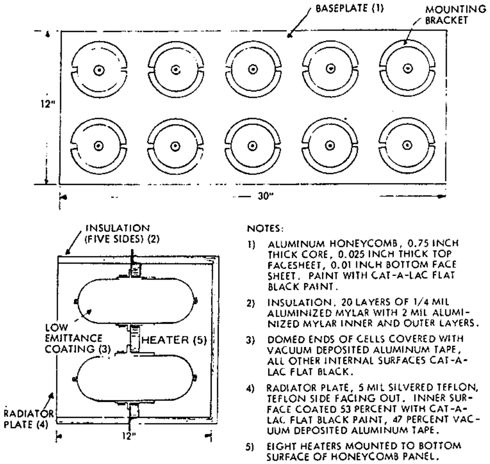


Figure 279. Mounting Bracket Design (Dimensions in Inches).



NOTES:

1) ALUMINUM HONEYCOMB, 0.75 INCH THICK CORE, 0.025 INCH THICK TOP FACESHEET, 0.01 INCH BOTTOM FACE SHEET. PAINT WITH CAT-A-LAC FLAT BLACK PAINT.
2) INSULATION, 20 LAYERS OF 1/4 MIL ALUMINIZED MYLAR WITH 2 MIL ALUMINIZED MYLAR INNER AND OUTER LAYERS.
3) DOMED ENDS OF CELLS COVERED WITH VACUUM DEPOSITED ALUMINUM TAPE, ALL OTHER INTERNAL SURFACES CAT-A-LAC FLAT BLACK.
4) RADIATOR PLATE, 5 MIL SILVERED TEFLON, TEFLON SIDE FACING OUT. INNER SURFACE COATED 53 PERCENT WITH CAT-A-LAC FLAT BLACK PAINT, 47 PERCENT VACUUM DEPOSITED ALUMINUM TAPE.
5) EIGHT HEATERS MOUNTED TO BOTTOM SURFACE OF HONEYCOMB PANEL.

Figure 280. Ten-Cell Nickel-Hydrogen Battery Thermal Control Design.

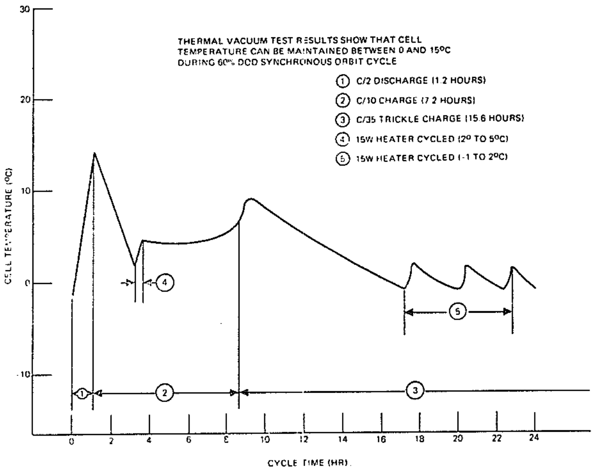


Figure 281

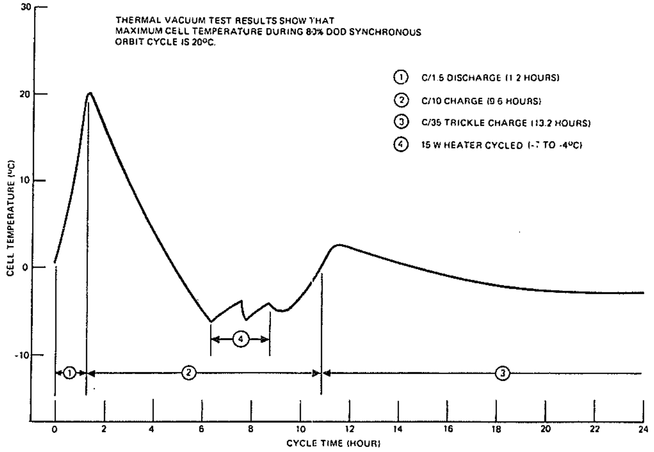


Figure 282

GSFC's POSITION ON THE NICKEL-HYDROGEN SYSTEM

F. Ford
Goddard Space Flight Center

At this time I think it's appropriate to try to answer some of the questions and to clarify Goddard's position on the nickel-hydrogen work. Now, we see a need for the nickel-hydrogen system in the future, and we think the work being done is very appropriate. On the other hand, in a situation like we're in, in a constrained economy, in a constrained budget--particularly, you heard the numbers that were mentioned yesterday--we have to set priorities. And the fact is, right now, Goddard has somewhere between six and ten different programs that are committed to Ni-Cad batteries. Nickel-hydrogen isn't going to help that one bit. In fact, if anything, the consequence of the nickel-hydrogen work, right or wrong, has been to drain some of the resources out of the technology area, to help us, you know, continue to work on the nickel-cad.

On the other hand, we have some other problems to look at, as far as nickel-hydrogen is concerned. If you assume that nickel-hydrogen was within the realm of tried and true technology, at least to go on a spacecraft, you have to look, not only at the energy density, but the volume. And I know of no existing satellite today where I could make the trade-off--and I emphasize existing, not those that are to be designed--but I know of none of these satellites in existence today that I could package a nickel-hydrogen with them and come up with an improved energy density system within the volume constraints that I have to live with on the cell level.

Now, there's a few things you have to realize. Basically, we have two types of satellites. We have the spinners, which usually fall in the communication class; and we have the pre-active stabilized. There has been a continuing trend over the 15 years of aerospace technologies to go from the spinning satellites to the pre-active stabilized.

It's also pretty well accepted that the spinners have much more room to work with. They're bigger satellites, usually, as compared with the pre-active stabilized. So it's not just the amount of energy density that we have to consider. It's a matter of the use of the volume made available to us.

ROGERS: Excuse me, Floyd, before you get off the volume issue. I just thought I could make a point. If it was financed, there's no reason why a much smaller volume nickel-hydrogen cell couldn't be developed by running at high pressure. So it is not inherently volume; it's the way it has been made up to now.

FORD: Okay. I'd like for you to follow up on that.

What do you consider as a realistic ratio of volume, compared with nickel-cad? I mean, can you get it down to 1.2? Do you even think it's competitive on a volume basis?

ROGERS: I couldn't give you a number, because we really haven't considered--we haven't been that interested in getting the volume down. What I'm saying is, the volume limitation that you see now is not realistic, and it could be much less.

FORD: Okay. The numbers that I came up with about a year ago were based on existing technology then; were about 1.4 increase.

SEIGER: A 40 percent increase in volume.

FORD: Yes.

HOLLECK: I think you can most certainly keep it within that. You can basically make it as small as the cell stack is. You can contain all the hydrogen in the cell stack. That's your limitation, and the cell stack doesn't have to be, really, any bigger than the nickel-cadmium, because all you do--you have the same nickel electrode, and all you do is replace the cadmium with the fuel cell electrode, which is not second. So if you want to go to the high pressure, you could.

GANDEL: Lockheed

On the volume discussion, the stack itself is about one-third the gross volume, and I think when you want to increase the pressure, or start collapsing that volume, you start getting into geometric constraints.

So, I would say that any projection that has to decrease that volume by more than a third will start to be impacting from the inside out. Now, I think on the satellites you mentioned, you see volume constraints. I see it from the other end, looking at some rather large satellites where volume isn't a constraint; where probably, the thermal constraints are the major ones. And along that line, I think the charge control for the nickel-hydrogen batteries will become more important. I think by the time another couple of years pass by at the workshop here, that should occupy as much discussion as the cell itself.

The general feeling is that you can equalize the cells by carrying the cell through overcharge, but there are some real limitations in going into full overcharge in the thermal aspects. So, at least, this is one area where I'm for putting more of our effort into, and I think, say, maybe in another year or two, we'll give you some inputs on that score.

FORD: I think that's a very valid point because even though a nickel-hydrogen can take continuous overcharge, there's not many thermal systems that I know of today that can withstand that type of thermal input on a continuous basis. And I agree; I think that is an area, from a systems viewpoint, we're going to have to be looking at very hard in the not-too-distant future.

ROGERS: Hughes

I just want to make a comment on the overcharge. We inadvertently put a couple of full-plate size, but only 1.5-ampere hour cells into 15 to 16-hour C rate overcharge. In the first place, the cells didn't seem to suffer at all. But the heat dissipation from these stacks is not realistic if you compare it to a full-size cell. So, I would certainly agree with Marty that the thermal is a very important thing. The system itself is inherently capable of taking in a lot more than it can get rid of in terms of heat.

HELLER: Hughes

I'd like to concur with Marty. You don't see severe volume constraint, but the thermal problem is the one to be reckoned with. I'd also again like to appeal that that system has got a long life. We'll take the energy density.

GROSS: Boeing

Howard, can you tell me as you raise the temperature gradient from 0 up to, say, 50 degrees? What's the problem on the temperature gradient of the nickel-hydrogen cell?

ROGERS: Well, if you look at it, I think I'd take each--we really haven't done it, so I'm only going to give you what I would expect. If you look at the hydrogen electrode, you're going to see increased polarization at low temperatures. On some low-temperature testing that was done at Tyco Labs, you could see they actually got into trouble at temperatures approaching 0; that's what I recall. And this is because of the polarization of the hydrogen electrode.

Then, as the cell overheated under high polarization, it started to work out. So you could get into some polarization problems with a hydrogen electrode with low temperature, if you're looking at a higher-grade cell. I don't think I have to go into the nickel electrode; that's the same as in the nickel-cadmium system. And the separator system; if you stick with nylon, obviously you don't want 50 centimeters. If you talk about something like asbestos, it'll probably handle it, and certain other inorganic separators can.

I guess I really don't see any constraints, other than the ones that we're aware of.

DUNLOP: Comsat

Well, as far as operating at high temperature, you can't, because you can't charge the nickel electrode period. But what we run into is, we have a flight battery--I think the Air Force has a flight battery, too--our flight battery has been going into this NTS-2 spacecraft. So we go through very carefully all of the thermal constraints involved in the battery design, including thermovac checkup.

Now, in that system, as in probably any large aerospace system, you're going to use a thermal control to minimize your overcharge by necessity, simply because you don't want to raise the temperature. And the interesting thing about whether you're talking about the particular design that TRW went through, or the design that we're using in the NTS-2--now, the design we use in the NTS-2 was shown last year; we brought that battery in, and set it on the desk--that same battery went through thermovac testing, and it uses a thermocouple, I mean a thermal transducer. It's sensitive to temperature.

When you come into the overcharge portion of the region, as soon as you do that in the three-axis stabilized system, the temperature goes up like mad, because your whole design is limited by your radiative area in any three-axis stabilized system. And so you jump, extremely sensitive to your overcharge rate; and what you do is, you design your radiative area to sustain whatever triple-charge rate that you select for your system.

In this case of the NTS-2, we selected a triple-charge rate of approximately C/40, C/60--okay, it's approximately C/60. So C/60 is at that continuous overcharge rate, it operates at about 5 C. And the temperature is very close on that spacecraft, by the way. It runs 5 degrees C, plus or minus 5 degrees.

BETZ: Naval Research

During the discharge peak, it goes up to about 15 C. But then, when you cool down, you can actually get to below 5 C in your deepest eclipse cycle, and then it swings around and comes right back. As the cell goes inefficient, it goes into overcharge. We use the rising part with the trickle charge.

DUNLOP: The other point that you mentioned is that, it's been mentioned several times; the nickel electrode gives you better capacity to act around 5 degrees centigrade. So the system is really designed to operate around that temperature, which turns out to be ideal for all things considered. And I think you would do this for any large battery system.

GROSS: According to the TRW chart, the peak temperature gradient occurred before you got into triple charge. So if you'd expect to complete the trickle charge at temperature gradients lower than peak gradient would occur before you completed the charge.

DUNLOP: Let me go back.

GROSS: I still raise the question whether the peak gradient is your major consideration, or the temperature gradient during trickle charge is your major consideration.

DUNLOP: We presented a very precise analysis of the temperature gradient of the nickel-hydrogen cell that we're using at the Atlantic City conference. The maximum temperature gradient that we see in this cell during--this is for synchronous, and you get a much different situation; we did it for both synchronous and low-earth orbit--the maximum temperature gradient--I'm going to ask Mr. Van Ommering.

VAN OMMERING: For the simplest two-type cycle, you look at the temperature gradient from the hottest point of the battery to the coldest point of the battery; they're not more than 6 degrees C. And inside the battery, the maximum gradient is about 2.5 degrees. This is the point where we are generating our maximum amount of heat. So it's not at all significant.

GROSS: Well, it certainly appears to be critical for the large sized cells, plus the larger ones you've been using.

DUNLOP: That's a 44-ampere hour cell at about 5 degrees centigrade.

GROSS: Then TRW has to put in extra metal to cut down on the gradient. So we can't accept the statement that there is a negligible thermal problem in the nickel-hydrogen system.

VAN OMMERING: One thing, I don't think there's any bigger thermal problem with nickel-hydrogen than with nickel-cadmium. If the battery delivers a certain amount of watt hours, and some form of eclipse, it is going to generate just about the same amount of heat in the nickel-cadmium battery as in the nickel-hydrogen battery. The gradient may be slightly larger because of the nickel-hydrogen cell voltage. But there really just is not all that much difference.

FORD: Let me inject something which will put it in perspective. In a nickel-cad system that's flying and operating properly, with proper charge control, good thermal projection capability, we have pretty well accepted--and this was arrived at through empirical and also through telemetry tests--that about 16 to 18 percent of the power being delivered at the terminal of the battery is being dissipated to heat during discharge; and further, that heat should represent somewhere between 80 and 90 percent of the heat generated throughout the orbit.

Now, I qualify that by saying, a properly-operating system. Now, if you go back to early days, this would not be the case. But systems flying today that were generated, and particularly those systems that are using the multiple B versus T that we have implemented on recent spacecraft, are operating in that mode. Now, the question is, can we apply the same basic criteria to the nickel-hydrogen; and further, has anyone really done any thermal studies on the nickel-hydrogen to see how they compare on a one-to-one with the nickel cadmium?

BETZ: Floyd, I think there's one thing that you have to consider in the nickel hydrogen, at least the way we're approaching it with NTS-2, and that is that it is a different system from nickel-cadmium. We don't really need voltage-temperature curves. We've implemented the battery into the satellite system independent, almost, from the rest of the satellite. It operates on a direct radiator basis looking in space, and its temperature is a function of its own dissipation, with very little input from the rest of the satellite--its own dissipation and its relationship with its radiator in space.

So, we can size the radiator for minimum overcharge condition for that radiation case. Then, we can compare and see what happens during the cycle. You can actually change the overcharge rate. We have an overcharge capability well beyond what nickel-cadmium can do, and we are in fact using the inherent overcharge capability of the nickel-hydrogen to say we can run using temperatures; let the battery get hot. And that will tell you, that's the obvious way of saying the battery is no longer efficiently charging. I'll take it on the basis of temperature; I don't need V/I curves, I don't need adhydrodes, I don't need anything else. I can tell by temperature that the battery is fully charged given those conditions.

DUNLOP: Fred made an interesting statement. But the same, we're just going through the three-axis stabilized design for Intelesat V, for insurance of volume. But you use exactly the same type of constraints for your battery for the Intelesat V that you do with cadmium. They have exactly the same kind of system. You have a three-axis stabilized system. If you picked a surface that's a constant radiator, then that is generally your starting point. And what you have to do is, you have to design your battery to the spacecraft sub-system, and you have to design your battery for certain operating conditions.

Now, I think what's confused this argument somewhat; everybody knows pretty well what the thermal equilibrium potential is for nickel-cadmium and nickel-hydrogen, and they're very similar. And so, if you have, for example, a discharge curve on a battery, you can take the difference between the potential of the cell and the equilibrium potential, and you can determine how much heat is being generated. Floyd's right; if you do that simple thing, you'll find out that roughly 15 or 20 percent--some percentage--of your total energy that's being delivered is dissipated as heat. That's a fairly straightforward thing.

So, if you just take the cell alone, you can do--you know what your heat, your cell--and the nickel-hydrogen cell has one advantage, by the way; in a cylindrical design, you have a center line temperature, and you're radiating out uniformly from the center line to your wall. So you can, knowing the thermal properties of every component within your cell, which we do--and we and TRW have thought of this--we put this into a computer program. And for any discharge rate, you can very precisely calculate, knowing the V-I curve, you can very precisely calculate how much heat is being dissipated.

And if you, for example, state that you're going to fix your case temperature, then you can precisely determine the difference in temperature between the center of your electrode stack and the wall. But now, in addition to that, you have to take into consideration how do you get rid of this heat from the wall to the space? How do you radiate the space? If you can't get rid of it in the space, the battery temperature will take off. So, that's the key to the design of any of these batteries, either nickel-hydrogen or nickel-cadmium; the key will simply come down to the size radiator you need to be able to operate in the steady-state trickle charge mode.

GROSS: What was the size of your cell in the Intelesat V?

DUNLOP: In the Intelesat V that you've just referred to, it is a flight battery that's been through thermovac testing. That's rated 35, but in reality, it's delivering 44 ampere hours capacity. And usually the power that it delivers is 200 watts? That's during discharge, about 300 watts for a one-hour discharge; 300 watts for a one-hour discharge. It'll discharge twice a day; that's a twelve-hour cycle, and that's a battery that's in the system right now. It's sitting there, ready to be launched in two months, and it's been through thermovac testing.

Does that answer your question?

ROGERS: I'd just make a comment that the system in a 90-minute orbit, at a high depth of discharge, is by no means even similar.

DUNLOP: Good.

ROGERS: One, you can tolerate higher temperatures in the cell stack, because the charge rate's different. By the same token, if you let the cell get into much overcharge, it's going to stew the cell stack. So you have a really different system. You've got to detect heat much faster. It just isn't the same thing. We will be studying this point; I'm not in a position right now to talk too much about it.

DUNLOP: Well, it's the same thing in regard to determining how you calculate the temperature. It's a matter of determining how you determine. You can take the same computer program and just change the charge/discharge rate, and change your heat sink, and you can determine exactly what your temperature probe ought to be. But we've already done that, Howard, for the same battery system. We could tell you exactly what it would run if this were a 36-minute orbit. But there's no magic.

ROGERS: That assumes that the oxygen profile is the same for lower earth orbit as it is for synchronous, which it is not.

VON OMMERING: You can actually predict how much oxygen you're going to generate in the cell at any particular point of time at any particular current. This is predictable with a fairly decent accuracy. So you can determine for a low-earth orbit the cycle for nickel-hydrogen batteries, say within 5 percent, how much heat you're generating at any point, charge and discharge. You input that into a computer program, and that's all you need.

ROGERS: I'd just make one additional comment on that. One, you're assuming the oxygen recombines immediately, which it does not. If there's some trapped oxygen which comes out during discharge, it's a much more complex situation than you're implying.

VON OMMERING: Well, I think that's where the 5 percent comes from.

MAURER: I have a comment on nickel-cadmium. Joe Lackner this morning asked for some ideas about testing components from nickel-cadmium cells to get at this problem of the voltage decay. I'd like to just suggest something here at the board, if I may. I'd just like to suggest cyclical voltametry as a useful tool you might use in this area.

(Figures 283, 284, and 285)

If you talk about the voltage decay curve that you get of voltage versus time on discharge (fig. 283, (A)), where you get a step in the cell discharge; if you look at a potential scan of that positive electrode, if you had taken it out before this discharge, what you would see now in voltage current scan (fig. 284) would be starting up in the oxygen evolution region and coming down. You see a discharge peak; it has a double discharge peak--there's two peaks there instead of one. Normally, you would see a single peak. But if you took this electrode out, you'd see this kind of peak. And if you scan back up, you see the usual charging peaks. And you can get this kind of an effect if you cycle high temperatures, or overcharge for a long period of time.

And, I would suspect you would--well, what it means is that there are two different species discharging in the cell; not a case of electrolyte distribution or passivating film or something, because you wouldn't be able to get two different peaks.

The other problem that we talked about before of the the discharge curves simply tailing off like this (fig. 283 (B)), instead of being nice and sharp; if you look again at the potential scans (fig. 285), normally with an electrochemically-deposited positive, you see two peaks on charge (A); whereas, in normal chemical ones, this oxygen is moved over slightly (B). So that I suspect the peak is there, it just is masked by the oxygen.

And then on discharge (C), you see a peak that is skewed, fairly flat-sided on the low potential side, due to the sharp knee. Now, if you scan the electrode only up to this point (D), and then discharge, what happens is that the peak moves slightly up, the voltage down and inside as it spreads (E). So you get something of that sort. Where this tail now is just the capacity coming out at this point (fig. 283 B(1)); and what you see many times on these discharge curves is a little bit higher voltage initially, like this (fig. 283 B(2)). So that if you only scan through part of the region, or through the full region, you get rather different discharge characteristics. And I think it would be worthwhile to explore this kind of thing further, with the kind of cell use profiles that you're talking about here. It might explain some of these factors, and what you can do about them.

For example, on a satellite, rather than doing this reconditioning cycle where you take everything down to 0, it might be worthwhile to take it up in voltage, up into this higher oxygen region, and then come back down to destroy tyis type of material. And that might be an area that we could look into.

LACKNER: If you continue charging, could you come back down and destroy that portion? How far would you have to go down?

MAURER: I said go up into this region. If you scan up into this region, this material would disappear. It will shift over to this end. I don't know--there is an effect on how far down; the shape of the curves is a function of how far down this way you go. This point is about 0 with respect to mercury. So, if you come down this far, you get a different shape than if you come down this far, and I don't remember what the relationships are; maybe just going more into overcharge, and drive yourself to the higher voltage, might eliminate some of this material

PICKETT: Wright-Patterson

What are the two discharge peaks due to in the chemically vacuum-impregnated electrode?

MAURER: I don't know what they're due to. I just noticed them.

PICKETT: This is just a positive plate that you're running against the mercury as an outside reference electrode?

MAURER: It's a potential scan apparatus, yes. It's a positive electrode. There's some counter off someplace else, and mercury reference, and you drive the working electrode with respect to the reference. But the conditions that give you those two peaks in the discharge tend to be the kind of conditions that you would imagine would dehydrate an electrode; your high temperatures, long overcharge, things like that. So the two peaks might be just different degrees of dehydration of the active material.

PICKETT: Do you have any good excuse why you don't see it in the electrochemically-deposited electrode?

MAURER: I'm just reporting some results that we did on some other electrodes.

WILLIS: Bell Labs.

Dean, you mentioned that you have to--it might be worth exploring a higher charge in order to promote this beneficial reconditioning effect. Well, the magnitude of the peak during charge is on the order of the one-hour charge rate. I'm just pointing that out. But if you want to explore those regions to get the cell voltages that high, you might have to employ charge rates approaching the one-hour rate. And that's going to lead us into some other problems, which you may not want to get into.

MAURER: Well, I'm suggesting that if you explore them, if you do it repetitively, you don't need to go nearly as high as you would if you were trying to wipe out something.

LACKNER: I just want to follow up that point. What I was pointing out in my paper was that, right after the reconditioning, we could get a higher end-of-charge voltage. But even if we continue the overcharge prior to a reconditioning, we can't get it to that higher voltage. So if you would try to explore that, it doesn't do you any good. So you have to recondition to get it to that point.

SEIGER: About 15 years ago, when we encountered the fading or the memory effect or the need for reconditioning, we had done work in two areas, both of which helped get rid of the fading of capacity. And one was an overcharge, we had a continuous overcharge for a long period of time; you're right. But it was not as effective as putting a short circuit on. With the short circuit, it would work virtually every time, and would work in one cycle. The continuous overcharge, you'd have to do--oh, about two of them with a 24-hour continuous overcharge in order to get rid of it.

I'd like to make another comment. The Russians have been doing some work at various charge rates, and various concentrations of electrolyte, and they've been investigating, for want of a better work--and I think I'm almost quoting them; they're calling one beta nickel hydroxide, and one other one gamma nickel hydroxide. And they show how that little step is due to gamma, and how they can induce both of them by bearing the charge rates and the degree of overcharge, particularly with more extensive overcharge. They are inducing more of what they are labeling gamma, and it might be that whatever they've been identifying as the beta and the gamma form are what you are seeing with the two steps.

MAURER: Well, this we tentatively labeled gamma, and this one beta. There's an alpha that occurs under some conditions on an electrochemically-deposited electrode at room temperature, not at boiling. If you do it on a thin-film electrode--MacArthur showed this--you can get an alpha peak that will gradually switch into a beta.

BOGNER: Yes, we ran into this. And if you recall, last year we were talking about the short test. We tried to accelerate the degradation in the cell, and we charged the cell at C/10, at 115 or 120 degrees per month. And we got that type of situation. We got more capacity, actually, out of it, and we got the two plateaus. Since that time, those cells have been put on a cycle test, along with some other cells. The same manufacturer built them a year apart. Two step plateaus showed up in one set of cells, and in the other set of cells did not show up.

So, I'm wondering if loading electrolyte concentrations would have some effect on that.

MAURER: Well, probably electrolyte concentrations. We found, too, that if you cycle up this valley, the discharge has 100 percent theoretical capacity. If you go up into this region, then you get that 10 to 20 percent extra. So this is the part that's accounting for the extra capacity.

DUNLOP: I want to just throw out about three observations I've seen connected to this.

If you take electrodes made by Eagle-Picher, the Bell Laboratory process; if we put these into a nickel-hydrogen cell and come up to a known formation or something, and leave these cells stand for some period of time open circuit, for some reason, when we try to make a capacity measurement, we don't have this great utilization number that we'd like to see. We measure something like--I think the numbers are like 35, 36 ampere hours down to 1 volt.

Now, we continue to discharge, get a fair amount of capacity down; 3, 4, 5 more ampere hours. We can overcharge that cell in cycles, overcharge it for two days, cycle it. We never can include this situation--we've done this three or four times. All we have to do to improve the situation is put a resistor across it for two days, come back; the thing comes up to 42 ampere hours capacity. And that certainly is an effect of the positive electrode. There's no negative cadmium electrode in this, and it's an effect that we observe on your electrochemically-impregnated electrodes.

Now, what I don't know about this is what happens if I put these things on continuous trickle-charge. Because our experience with conventional electrodes on continuous trickle-charge is that you get pretty good capacity when you discharge.

MAURER: Yes. When we continuously trickle-charge for long periods of time, like six months or more at the 20-hour rate, we don't see a step in the plateau. It all comes out at the higher voltage. My comment about going up into this region was really more that you might want to operate your cell that way all the time, just at a slightly higher voltage; not way high, but a slightly higher voltage might improve.

DUNLOP: By going to a slightly higher current? That may not be possible. It's not possible in a spacecraft. Your temperature--and we discussed this--you really can't arbitrarily do that.

MAURER: Not arbitrarily, but by design. It might be a region you could explore.

DUNLOP: Oh, by the way, it's interesting. We have another observation.

This is an interesting observation we tried in orbit. We have cells that are five years in orbit, six years in orbit, and voltage within the discharge looks terrible. We tried reconditioning and it still looks terrible. The only thing that we did to improve it was something that Marty Hill came up with, and that was to discharge at a high rate for one hour before starting a discharge. By doing that--and we tried this in orbit as well--by doing that, we are able to improve the end-of-discharge voltage on those batteries by almost 1 volt, which is quite significant. And it means the difference between making a sudden emission and not making it.

WILLIS: Bell Labs.

We attempted to add some additional cobalt concentrations to the impregnating bath when we prepared some sample positives. And the effect of increasing the cobalt concentration on the positive tends to shift these charging peaks in a negative direction, which means it's easier to fully charge that so-called beta peak with more cobalt.

With five percent cobalt, you're accomplishing other things besides shifting the peak slightly more to the negative. With more cobalt, let's say 10 percent, 15 percent, there's a noticeable shift in the negative direction, and it certainly is easy to fully charge the electrode with those concentrations of cobalt which may not affect the cycle life; for example, five percent, as was reported earlier, is probably all you need to get 2,000 or 3,000 cycles. But with more cobalt, it definitely shifts the beta peak in the direction of the alpha peak. And therefore, it's far easier to convert all the material at low currents.

We found that you could fully charge, fully convert all of the nickel-2 to nickel-3 at much lower currents than if you had no cobalt at all. With no at all it's difficult to convert that material. This is just what we found with voltamograms scans.

SEIGER: You mentioned thin-film electrodes, and I don't know if we can trust thin-film electrodes. Let me exemplify that. We see that when we do an electrochemical impregnation of cadmium hydroxide into nickel plaque, that the crystal form is the gamma, the prismatic form. Beauchamp, on a sheet, on a foil of nickel, deposited some material and his shows scanning electron micrographs that are the hexagonal beta form.

MAURER: We get that hexagonal beta form at the boiling in the sinter. I think we get alpha impregnation initially as well in the sinter. It's just that these peaks spread out so much that you can't tell the difference between an alpha and a beta and a sintered electrode.

SEIGER: I don't care how they call them. The electrodes are beautiful.

FORD: I'd like to make a comment on that, and I think I mentioned this last year, and I think it deserves another look. I'm not sure we understand the role that oxygen plays in a nickel-cad cell, particularly on the negative electrode. And some of the data we have indicate that the cells that are operating for long periods at very low pressures tend to have a more permanent loss of capacity than those cells operated for long periods at, say, moderate pressures. And I'm talking about, you know, around atmospheric, and I certainly don't understand that.

But it also stands to reason that the activity of oxygen on the surface of the negative may well, in fact, enhance the continuing activity of the negative in the electrochemical sense. So, in a nutshell, I'm suggesting that the chemical activity is very much tied to the electrochemical activity, and previous comments from past years say that we can operate batteries much longer if we don't overcharge them. I think we've got to be careful we don't go under too far and try to operate a battery, say, at a seven percent state of charge for extended periods, the data certainly indicates you might get in some problems with the negative electrode if you do that.

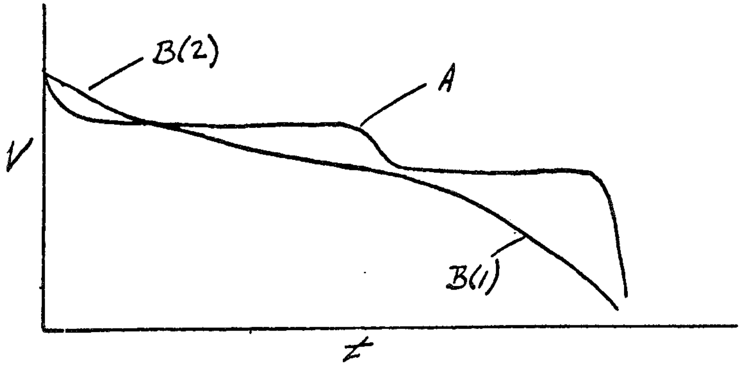


Figure 283

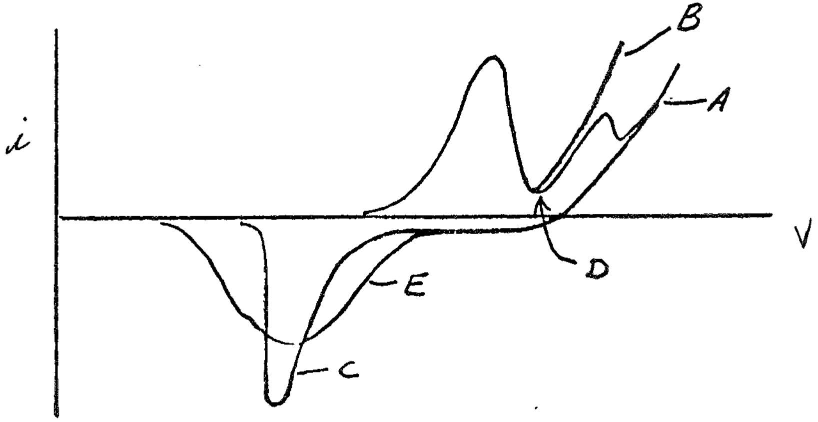


Figure 285

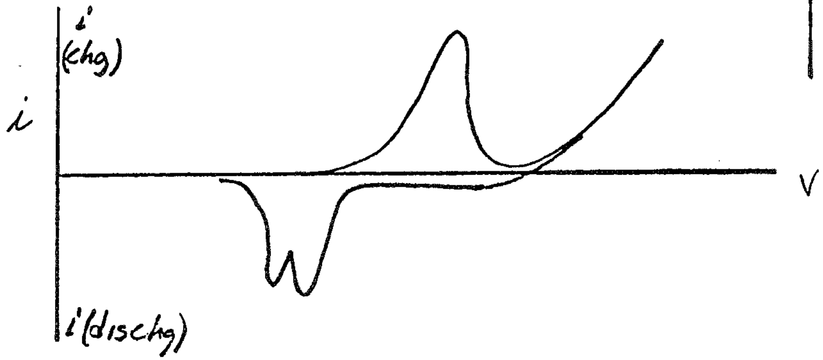


Figure 284

CONCLUDING REMARKS

Floyd Ford
Goddard Space Flight Center

Gentlemen that concludes all the scheduled presentations. I would like to reiterate that this is your workshop and without your participation, without your discussions and questions it could not be successful. So we solicit and invite each and everyone of you to mail us your comments or suggestions. We would like to know what your ideas are to improve the workshop next year.

We do try to keep it very informal, and one of the problems we run into, year after year, is trying to schedule or decide whether it should be a two or three-day workshop. Invariably, we announce three days; we get responses indicating that we only have presentations to cover a two-day session. But about seven days from the scheduled date the inputs start going up exponentially. So we apologize for squeezing a lot of information into a two-day period. On the other hand, we ask you to be a little bit more responsive because we would like to run this for three days, if the time merits. But we have to make that judgment before we send out the final announcement, and that's about 30 days prior to the actual workshop date. So keep this in mind next year when you get your cards requesting topics for submittal because it is important for us to know the intentions of those who are going to participate.

There being no further comments, on behalf of my colleagues, I would like to thank all those who attended and participated in the 1976 Battery Workshop. We look forward to seeing you next year.

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