NASA Conference Publication 2041

The 1977 Goddard Space Flight Center Battery Workshop

A workshop held at
Goddard Space Flight Center
Greenbelt, Maryland
November 15-17, 1977

NASA

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Gerald Halpert, *Chairman*
Goddard Space Flight Center

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PREFACE

The papers presented in this document have been derived from transcripts taken at the Tenth Annual Battery Workshop held at the Goddard Space Flight Center on November 15 to 17, 1977. 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 all to the 1977 NASA Goddard Battery Workshop. We are pleased to have so many familiar faces in the audience and also pleased to see some new faces joining us this year. We hope you all participate actively in the questioning in order to make this another successful Battery Workshop year.

This year's workshop has been extended to three days to accommodate the large response to requests for papers and to offer sessions on two subjects not included in past workshops.

In addition to two sessions held in the past, a session will be on satellite operations by satellite operations personnel, who actually work with the spacecraft, turning it on and off, and providing for the needs of the experimenters. As you know, the experimenters and the users have more to say about power system once a spacecraft is in orbit than the power system engineer. In this session operations personnel are going to describe some of their experiences and give us a better insight on what really happens in the world of satellite operations.

The second new session is related to the growing interest in the shuttle payloads. This includes among other systems the interest in lithium. If you were to have said a few years ago that lithium would be discussed at the Battery Workshop as an electrochemical system for space use, one would have been surprised. But today we have speakers from Langley, Marshall, and Johnson Space Centers who will talk about their experiences with lithium. There will also be a film to preview. As a related topic, there will be talking about the shuttle safety consideration.

In addition, we have also included a discussion on the results and life predictions from the accelerated test program. We should have a good discussion about this significant amount of new data. There will also be some discussion of the standard battery and a large power system including the 25 kW space power system.

All this will be in addition to the continued work on upgrading of components and materials and at least six papers on reconditioning which should generate a lively discussion.

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In summary, we have rather a full program with several interesting topics to be discussed. We have left time on Wednesday afternoon for some open discussion.

I am looking forward to a productive meeting and hope that you will be satisfied with the results.

SESSION I

IN-ORBIT FLIGHT EXPERIENCE

D. A. Baer, Chairman
Goddard Space Flight Center

SPACECRAFT OPERATIONS

D. A. Baer
Goddard Space Flight Center

This session will be a little different from sessions in previous years. In the past we have heard about cell components, cell design, and battery and cell testing. We have also had a few presentations on battery performance; however, these presentations were given from a battery engineering viewpoint.

During this session you are going to hear about the battery from the people who have to live with the satellite once it is launched. That is the people from the control centers. Hopefully from these presentations we will get a little better insight into things we have done right, and probably a lot about the things we have done wrong. And maybe we can improve the designs in the future.

The format of this session will be for the battery engineer or power system engineer associated with the program to give a brief description of the battery and power system design. That will be followed by presentation of flight performance by an engineer from the control center.

ITOS POWER SYSTEM DESIGN

A. F. Obenschain
Goddard Space Flight Center

I thought we would start off with a brief description of what the ITOS power systems look like. It is a rather conventional RCA/AED design from the mid-sixties.

(Figure 1)

There is a set of three solar arrays which are directly connected to an unregulated power bus that runs along here. The upper end of the voltage is controlled at approximately 38 volts by nine shunt dissipator legs. Each of the two 6 ampere hour batteries is controlled with an individual current limited v versus t battery charger. The batteries are then discharged through diodes in parallel back to the load bus. The loads are distributed between an unregulated bus and also a regulated bus through series dissipated 24.5 volt regulators. One regulator at a time is coming on. It is a rather conventional unregulated bus distribution system.

(Figure 2)

The next viewgraph shows a few charactertistics of the battery pack. The spacecraft, as I mentioned, was developed by RCA/AED. The cells are from G.E. Gainesville. There are two 23 series connected cells in each pack with a capacity of 6 ampere hour. Each battery weighs 9.08 kilograms. The charge control is a taper charger with multiple temperature control. The nominal operating range is 10 to 35 degrees C. There is a C/4 or 1.5 amp per battery charge rate until you get to the taper charge, where the taper charge is then determined by the battery voltage and temperature.

There is a ground commandable trickle charge. There is not an automatic reduction charge to trickle charge. We will see what the effects of that are a little bit later when we get into the flight experience. The depth of discharge is nominally 15 percent with a maximum of 24 percent.

(Figure 3)

Finally to look at the V/T curve, because this again will have an influence on what we talk about later, the two curves right here are the upper and lower tolerance. As you see, for a 23 cell battery, nominally you work

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between about 35 volts at 0 degrees C down to somewhere in the order of about 32 volts or a little bit less at 40 degrees C. This curve was used for many, many years on the ITOS program successfully. But as the later missions came along and the charge characteristics themselves began to change, we did start to have some difficulties.

OPERATIONS

(Figure 4)

Normally when you come out of an eclipse and you are coming into sunlight, this is the characteristic the battery sees. You go through a period of constant charge at a C/4 until you hit the V versus T, and where you hit it depends on what the sun time is. A 45 degree sun angle is a lot better for the spacecraft so you have a lot more available charge. You hit it a lot faster and you taper down, taper along. For 60 degrees sun it just takes you longer, but you still taper down. You essentially get to the same place.

And this is what you would like to see. You would like to see something in here on the order of about C/25. It would be a nice taper at the end, but certainly no greater than C/10 to C/15.

(Figure 5)

The top curve is the sun, the percent of deep orbit in sun. The top two curves are the battery temperature, battery 2, battery 1. And then down here we have voltage, battery 2, battery 1.

You can see that after about nine or ten months in orbit the battery charge current of battery number 2 started coming back up. The V/T curve was too high, and one of the batteries just started taking more charge than it should have. And its temperature started going up correspondingly. Where you notice this dip here, they had to turn that battery into a trickle charge and essentially just used the other battery in trying to load the spacecraft so you maintain a reasonable charge without a significant overcharge into battery number 1, with battery number 2 into a trickle charge, which is C/40, 150 mils nominal.

At this point right here they decided to try to turn the battery number 2 back on again. You see that immediately within a very few days it went right back up to a temperature of close to 40 degrees C. They had to take it back off again. And this is how they are having to run the spacecrafts. They have to continually watch the temperature of the two spacecrafts. As the temperature

of a particular battery starts to rise, they have to take it off and put it into a trickle charge mode and let the other one essentially carry the entire load until it also runs into a problem.

(Figure 6)

This is number 3, a later satellite. Here we see a little bit different characteristic for the sun time because it is a slightly different clock orbit. Notice that the battery voltage of both batteries, again for you know a relatively long period of time, six to eight months after a launch, is going along very nicely with a few excursions in temperature. But for the most part the end-of-charge is very nominal. In fact, here on battery number 2 you see something like a C cover 24 is a nominal end-of-charge taper, whereas at this point right here, battery number 1, is up to C/15 and the battery temperature starts to rise. At that point battery number 1 was then put into trickle charge, and the temperature stabilized and it went to a rather low value.

(Figure 7)

And here is the same satellite with just a little bit later—the extent of the previous curve. But we started running into a problem with both batteries simultaneously. They were starting to get hot, so we put both of them in a trickle charge. They remained there for a period of time.

Historically what they are trying to do on all the ITOS spacecraft right now routinely is they maximize the load by turning on instruments that maybe one would not like to be on so that they can minimize the charge into the batteries by just taking it out of the array and putting it into the load as opposed to having it available for batteries.

They monitor the array current and the battery temperature. When the battery temperature starts to get above a preset limit of about 25 degrees C, they just put that battery into trickle charge and then let the other one take the load until it also runs into a small problem.

The spacecraft have flown for years now and they have never had a battery problem. It is an operational matter, not really a battery performance. Batteries seem to be presenting when they are discharged hard very close to what the rate of capacity was.

DISCUSSION

GROSS: Boeing. You referred to voltage as being the criteria that was changing. I wonder if you really meant current.

OBENSCHAIN: I meant current.

ROGERS: Hughes Aircraft. Is that a negative system, or will the diodes impact?

OBENSCHAIN: No, it is a negative system. In fact, probably everything you will see here in the next four presentations are all negative systems.

FORD: NASA Goddard. I would like to make a point which you can follow for the rest of the morning. The system that Rick just presented has a heritage of about 1964-65. When we go through several satellite programs, some of these systems are more recent heritage and some of them go back in the early sixties and some of them go through their own evolution, change, in voltage versus temperature characteristics. And I think the point I want to ask you to follow this morning is very carefully follow V versus T characteristics because two days later or one day later we are going to get into talking about volts, cells, and components of degradation. And what you are going to see this morning in all of this is that basically the overcharge characteristics of cells has come down since about 1970. And we are using much lower V versus T today to achieve the same C to D ratio as we were in the sixties or late sixties.

LACKNER: DRE, Canada. What do you mean by a negative system?

OBENSCHAIN: The positive is grounded. Everything is in relationship to ground. So it is minus 38 volts within shunt, and then the regulator is put at a minus 24-1/2 volts.

Just as a point of interest that has nothing to do with this, but everything really on these systems goes back to the very early sixties when they had a problem getting the NPM transistors. And so they used to use the PST's. And then when the NPM's became available and the high power applications instead of just changing over to a positive system they already had enough instruments and equipment developed, so they just kept on using the negative.

WESTROM: Goddard. Can you tell me how long those batteries are supposed to last?

OBENSCHAIN: Everything was a one year mission. They have all lasted between two and three years nominally, some as much as four.
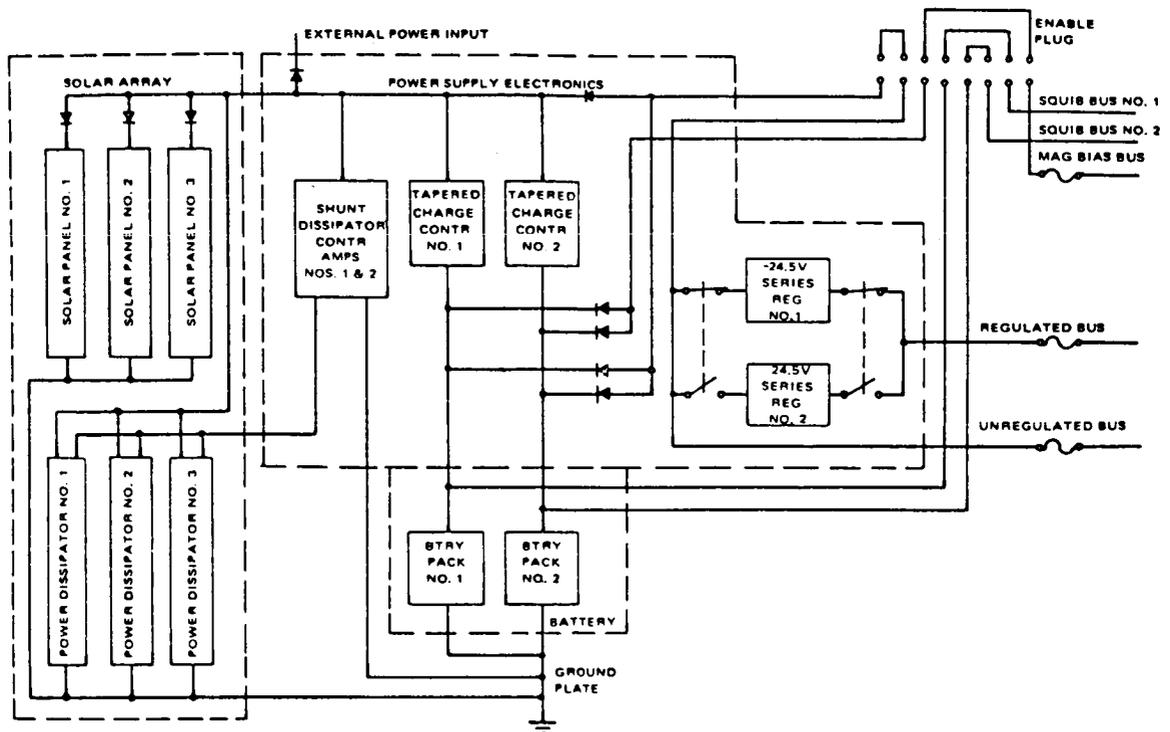
Figure 1. ITOS Power Supply Subsystem Block Diagram

CONTRACTORS

	SPACECRAFT: RCA/AED
	CELL: GE
BATTERIES PER SPACECRAFT	2
CELLS PER BATTERY	23
STORAGE CAPACITY	6 AMPERE-HOURS
WEIGHT (PER BATTERY)	9.08 KG
CHARGE CONTROL METHOD	TAPER CHARGING WITH VOLTAGE AND TEMPERATURE CONTROL
OPERATING TEMPERATURE	10° TO 35° C
CHARGE RATE	C/4 (1.5A) PER BATTERY (MAXIMUM) TAPER CHARGE RATE DETERMINED BY BATTERY VOLTAGE TEMPERATURE C/40 TRICKLE CHARGE VIA GROUND COMMAND
DEPTH OF DISCHARGE	24 PERCENT MAXIMUM 15 PERCENT NOMINAL

Figure 2. ITOS Battery Design
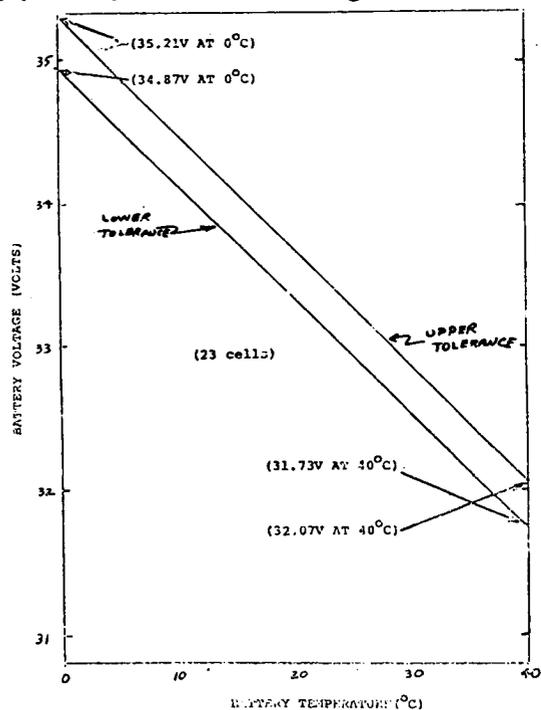
Figure 3. ITOS Voltage Limit Versus Temperature

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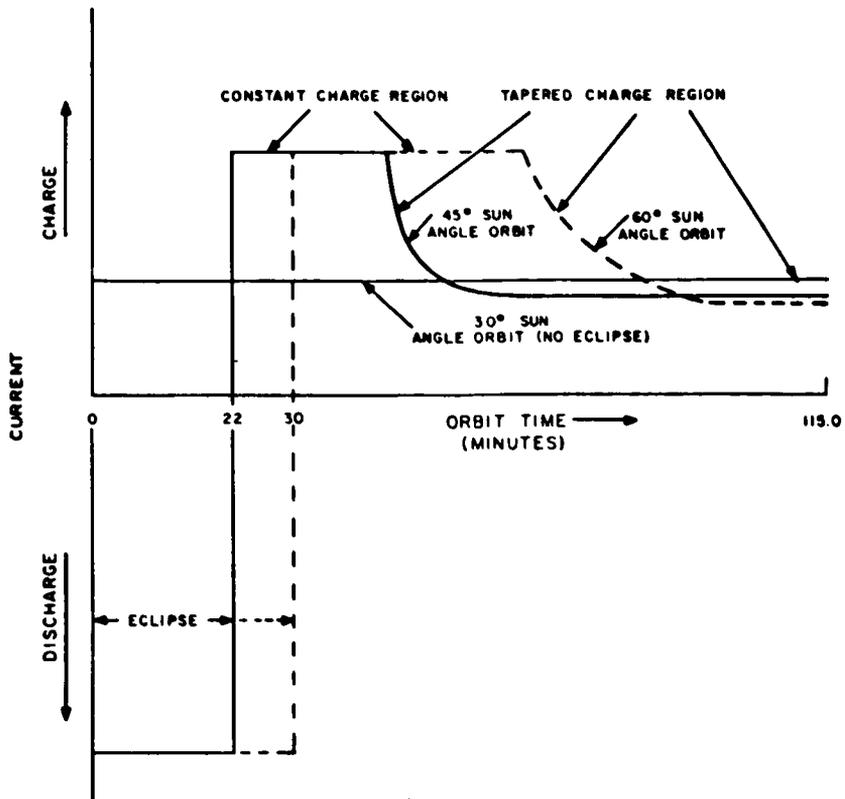
Figure 4. Battery Charge-Discharge Current
Profile Over an Orbit Period
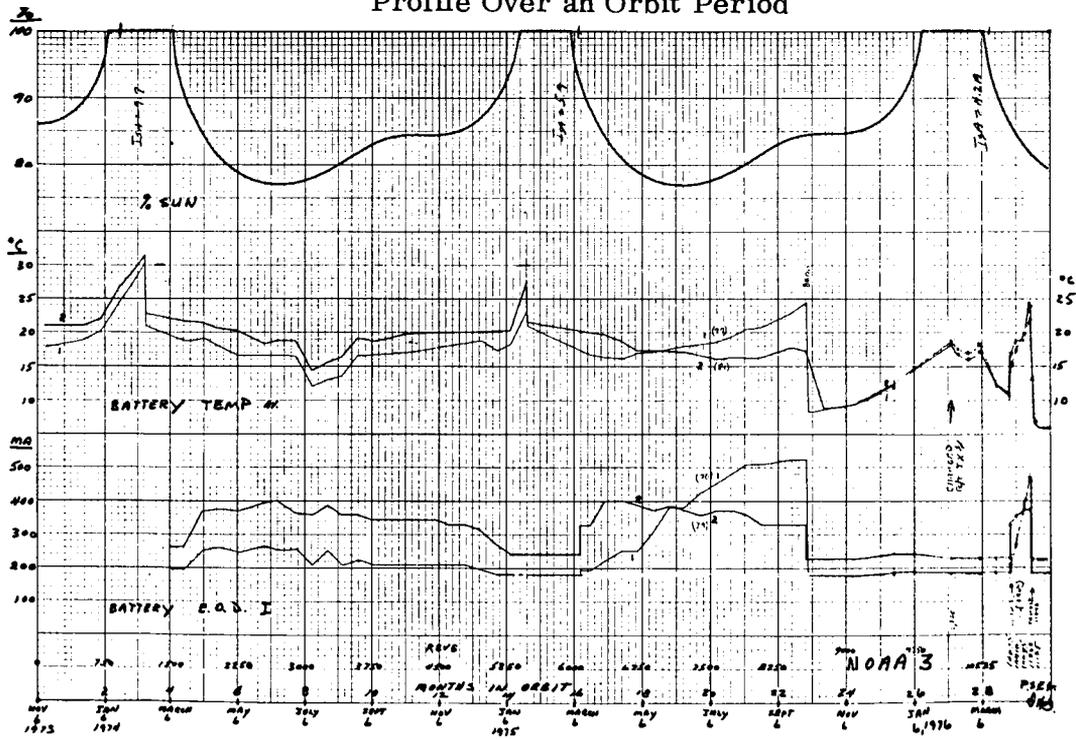
Figure 5

Figure 6

Figure 7

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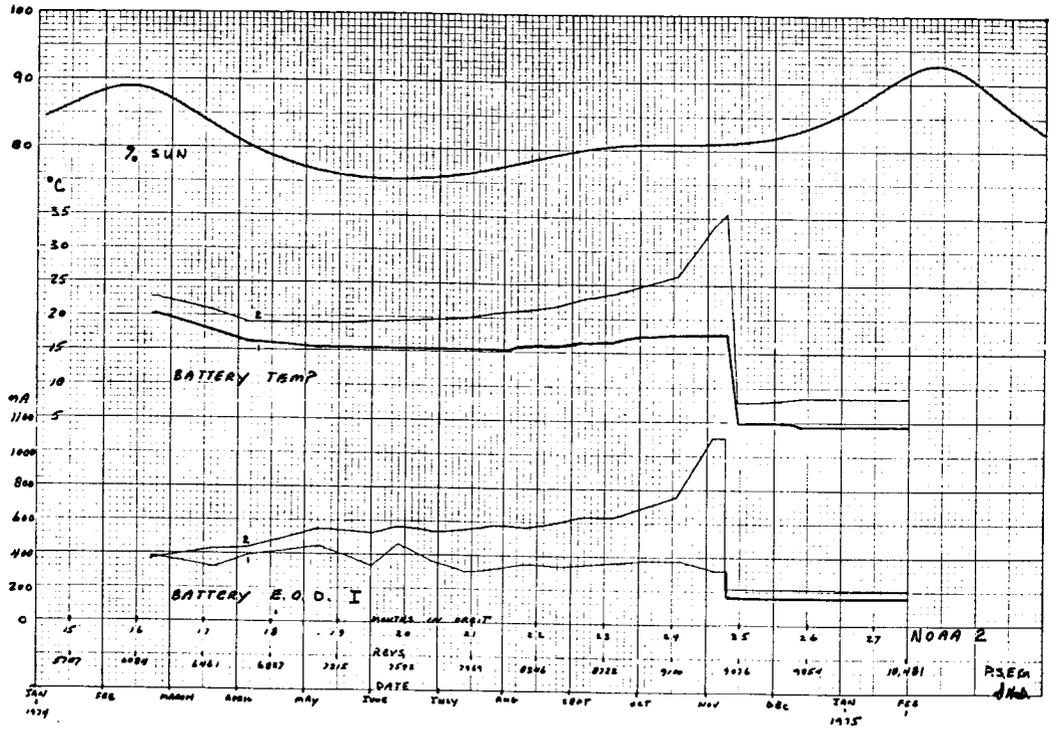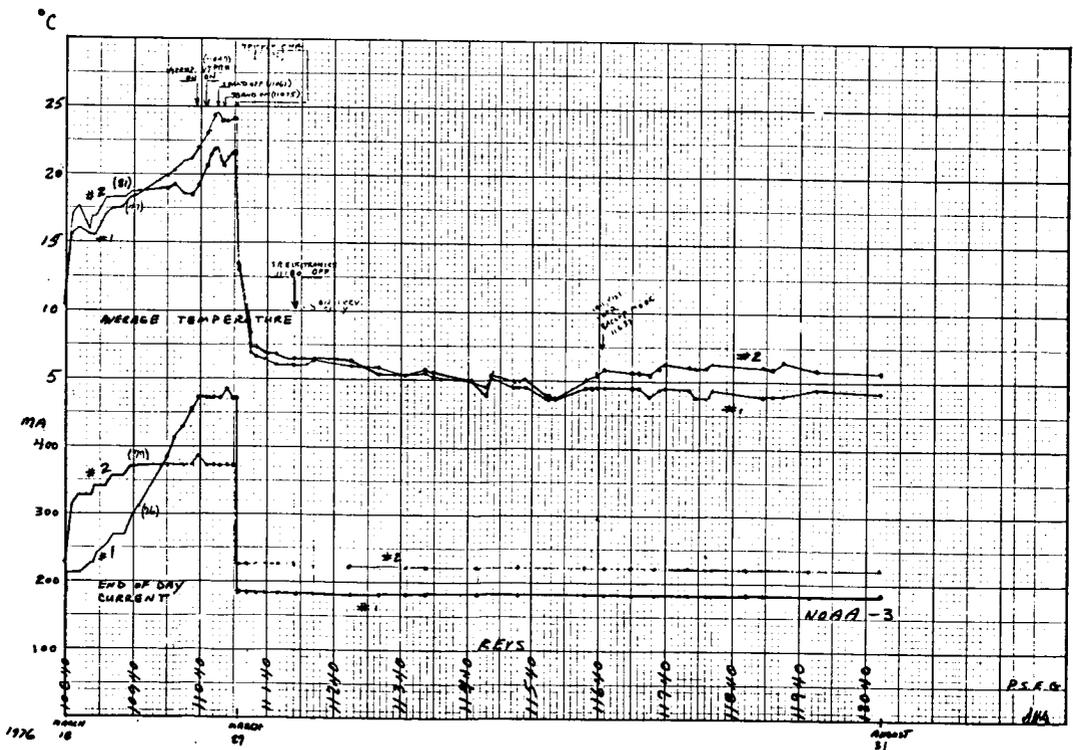
ATMOSPHERIC EXPLORER

A. F. Obenschain
Goddard Space Flight Center
and
P. Brandt
RCA Service Company

INTRODUCTION

(Figure 8)

OBENSCHAIN: AE is a 1971 power system design, but again using the heritage of the ITOS system. We have two rings of solar arrays. We again have the nine shunts to control a 38 voltage from the high end. We have three batteries now, each one with its own individual battery charger. The battery charger has been modified to present a high temperature cut-off, to present a little bit different V/T curve to the batteries, and again the discharge in parallel to an un-regulated bus. Now we have gone to pulse with modulated switching regulators as opposed to series dissipative. And we also now have an undervoltage system on the spacecraft to try to protect the battery should the large loads be presented to the batteries, greater than what they could really support.

(Figure 9)

Again, RCA/AED came up with the spacecraft design, G.E. Gainesville cell. They are on three batteries. There are 24 cells per battery, of which two of them are third electrode cells. The nameplate capacity of the cells, as in the case of ITOS, is 6 ampere hours. The weight is a little bit down, 8.9 kilograms per battery, although we put an additional cell in. We have again taper charge and voltage control. We have signal electrode control of the batteries. From a systems standpoint it was never used as anything but a telemetry function. We had some operational problems when we tried to use it -- actually put the batteries into a trickle charge.

We also now have a high temperature cut-off of 37 1/2 degrees C. The nominal operating temperature of the batteries was 0 to 30 degrees C. In fact it was designed to work at 11 degrees, a controlled baseplate. During the first year of the mission the batteries normally work there, but after that the orbit had changed enough and things had degraded enough inside the spacecraft that the battery temperature range sort of widened up a little bit.

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We have a nominal C/4, an amp and a half taper charge, charge to a taper charge. We have a C/40 trickle charge rate, again when it was effected by one of the two third electrode cells. Again, as I mentioned, we do not use that operationally except as telemetry. And we have a nominal 18 percent depth of discharge, although we do get 40 percent on occasion. As Phil Brandt will discuss, we run the thing at undervoltage periodically just to get the maximum out of it.

(Figure 10)

There were three spacecraft in the series. Two of them are still operating. One will be four years old in December, and another one will be two years old a couple of days ago I guess or in a couple of days. So, the birds have operated very well.

The interesting thing here is, as Floyd brought up, this is the previous V/T curve on the AE-C, which is the first of the two birds that is now operating. We took this V/T curve, which is essentially just an extrapolation for 24 instead of 23 cells in the ITOS curve. You notice we are in a little bit of excess of 36 volts, 24 cells. That is a little bit over 1.5 volts per cell at 0 and then down to 30 we are a little bit over 34 volts.

Two other hard lines, solid lines, are what we call the standard, Goddard NASA standard, whatever they are, levels 5 and 6. For AE-D and AE-E (the only spacecraft that is presently operating) we took a V/T curve and just simply laid it in the middle there. You will notice a difference between the two. When Phil talks he will explain the difference in the performance and you will see again the first bird, the V/T curve was high. We have had difficulties with the battery overcharging and the battery performance. Where the V/T curve is lower and more in line with the overcharge characteristics of the cells we are getting nowadays, the performance has been excellent.

OPERATIONS

BRANDT: This just shows the kind of eclipse we have, typically 1971, 1972.

(Figure 11)

Roughly there is 30 minutes of eclipse, and it is a 90 minute orbit. So, there is 30 minutes eclipse, 60 minutes charging.

(Figure 12)

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This is a typical experiment sequence, one in which we had trouble, if I can explain a little bit.

At the bottom I am showing experiments operating, the tape recorder coming along in the experiment, in cycles like that. During this time, no operation, just basically the receiver is running and that is about it.

Some more experiments, more experiments. These dark things are eclipses. Here I am showing ground contact. What happened in this particular sequence is we were operating for actually two, operating it and charging the batteries during sunlight, but also operating the bird at the time, 6 amps coming out of the battery during eclipse. Here is a time like that. Here is one.

And what happened is that batteries were just decaying and not getting charged, just running down in essence. And at the end we had what we call an undervoltage, and that is when the bird essentially shuts itself off.

Up at the top these numbers are showing the third electrode signal voltages. Normally they run I think it is about five-tenths of a volt when the battery is fully charged. Oh, these points are all just real time contacts that I had a chance to get the data from. Notice you are going from .36, three one, two three, two one. Here is the last one out here, .19. And that is about when the bird went to undervoltage.

The point of this is that when battery designers design batteries you think that you are going to charge for so much and discharge for so much. But actually here is a place where we are operating the thing not in the way you people thought that we should operate it.

(Figure 13)

The other problem we are having now is the batteries on C are getting old. They are heating up, and we are having the same problems Rick discussed on ITOS. We have got to take the batteries off charge.

But another problem that I have noticed on one of the batteries on the old bird (the bird that has been in orbit for four years) is we took it off charge and one here the circles are voltage and the triangles are for battery temperature. I don't know if you are interested in numbers. But we took it off charge, which means essentially the battery is not being charged and is not supplying any of the load that I know of. So it is sitting there all by itself, and look how it decays from one o'clock in the morning to one, two, three o'clock in the afternoon. It decayed from 32 volts. Well, that is misleading because that is being charged. Here 30 volts to 28.5 all by itself, self-discharging.

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The other interesting point is that when we put it back on charge, which is over here, of course the voltage jumped up, but the temperature started rising like crazy too. This surprised me, so what I thought I would do is on the newer bird I would disconnect the battery and watch it the same way. And that is this line. Obviously the battery holds its charge and holds its voltage on a good battery. This other battery that is much older falls down.

DISCUSSION

RITTERMAN: TRW. Do you have any idea as to the extent of self-discharge of the cell battery as far as ampere hours go? How much per hour?

BRANDT: Well, roughly this was decaying at 0.1 volt per hour.

RITTERMAN: What is the ampere rate?

BRANDT: I can't tell that. I just don't know. Just judging by telemetry from the spacecraft I can't tell. The whole exercise I went through doing this was to try to determine that, but I just can't tell what the current is.

NAPOLI: RCA. I gather from all this overcharging problem that we have here that we are overcharging as the battery gets older for a specific V/T curve? Is that correct? Are you inferring that maybe the design, the future design, should have a selectable curve that give you a charge rate --

BRANDT: I don't know.

BAER: I think we really aren't inferring anything. That is just what happened.

NAPOLI: The second question is if you do go to a lower charge rate with this type, do you have the ability to recharge the battery when you come back into sunlight with that lower charge rate?

BRANDT: Yes, we could by turning off the experiments, in other words, shutting down the bird.

NAPOLI: A compromise.

BRANDT: That is what we do in operations. We are constantly juggling between running experiments, charging the batteries, and watching the temperatures.

OBENSCHAIN: Goddard. I think I can answer your question. Your second question, is there a compromise along the V/T curve? The answer is no. What Phil was talking about is the fact that we have not enough solar array power to really run the bird and charge the batteries at the same time. You have to turn off the experiments. He charges the battery, runs the experiments and runs the battery. There are two different things. This is a lack of array capability. What you were referring to was the V/T curve. This V/T curve right here when you have 100 percent sun and there is sufficient array energy does permit full recharging the battery.

NAPOLI: It also allows overcharging.

OBENSCHAIN: No. It limits overcharging. The AE-E, the flight curve across there, that bird right there, as I showed you, at a lower V/T curve, when that bird is less than 100 percent sun it operates beautifully. It tapers right down to C/20. It does not overheat. It does not overcharge significantly enough so that you start raising up the temperature. On AE-C, which is most of the data presented along the curve here, you do get overcharge. So I am not saying we ought to have a multiple V/T curve. I think you can select the V/T curve which is a very good compromise. I think we did on AE-E. I think we have demonstrated it now. It is over two years old or in a couple of days it will be two years old. We have never had a battery temperature problem. We never had any kind of a fading problem or anything. It is working nicely. It is the same cell as we flew in AE-C. They are both G. E. 6 ampere hour cells from the same lot.

NAPOLI: What is the final charge rate when you get down to the lower end of that?

BRANDT: About 150 mils.

OBENSCHAIN: That is the C/40.

FORD: Goddard. I guess the point that I would like you to go back to is after you have had the batteries in the older bird on open circuit you said you put them back on charge and you immediately had a temperature rise.

BRANDT: Yes.

FORD: I think that may be the part that we are getting confused about. Do you ever feel or do you have any insight as to what caused that? Or do you just hold it up as something you observed?

BRANDT: It is something we observed. Why, I don't know.

To contradict Rick a little bit, we have begun to notice on E one of the batteries is starting to behave the same way, starting to get a little hot when you go to charge.

FORD: GSFC. I would like to address your first question. But I would like to defer that until later on in the morning because one of the characteristics we have seen on old spacecraft of old batteries is apparent softening of the V/T way down after the cells begin to wear out, meaning that for a given design it may be adequate for two year life, but if you are really going to push that operation into like four or five years that V/T curve for the early life may not suffice for later life. So I think we might get into that a little later.
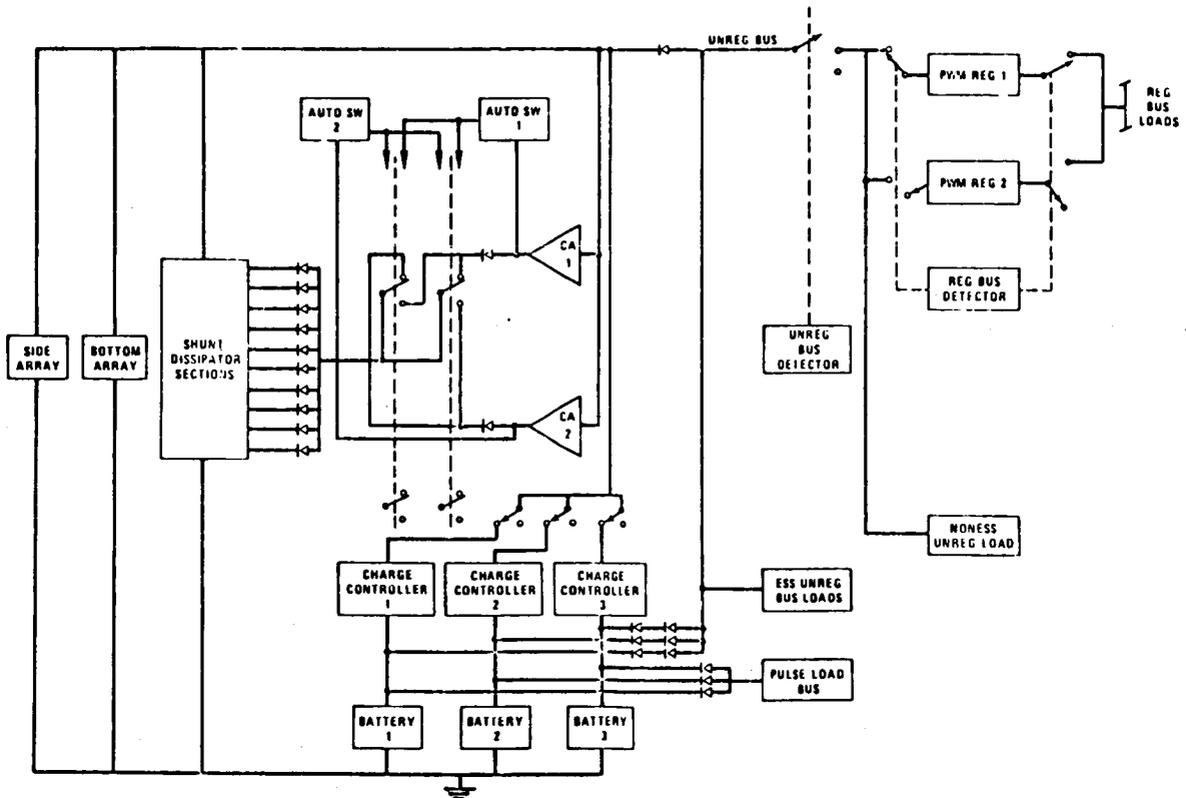
Figure 8. Power Supply Electronics Block Diagram

CONTRACTORS	SPACECRAFT: RCA/AED
	CELL: GE
BATTERIES PER SPACECRAFT	3
CELLS PER BATTERY	24 (TWO SIGNAL-ELECTRODE)
STORAGE CAPACITY	6 AMPERE-HOURS (NAMEPLATES)
WEIGHT (PER BATTERY)	8,90KG
CHARGE CONTROL METHOD	TAPER CHARGING WITH VOLTAGE AND TEMPERATURE CONTROL
	SIGNAL-ELECTRODE CONTROL OF BATTERY OVERCHARGE
	TERMINATION OF ALL CHARGE AT BATTERY TEMPERATURE OF 37.5^0 C
OPERATING TEMPERATURE	0^0 TO 30^0 C
CHARGE RATE	C/4 (1/5A) PER BATTERY (MAXIMUM) TAPER CHARGE RATE DETERMINED BY BATTERY VOLTAGE AND TEMPERATURE
	C/40 TRICKLE CHARGE WHEN FULL RECHARGE, AS DETECTED BY ONE OF TWO SIGNAL ELECTRODE CELLS, IS ACCOMPLISHED
DEPTH OF DISCHARGE	40 PERCENT MAXIMUM
	18 PERCENT NOMINAL

Figure 9. AE Battery Design

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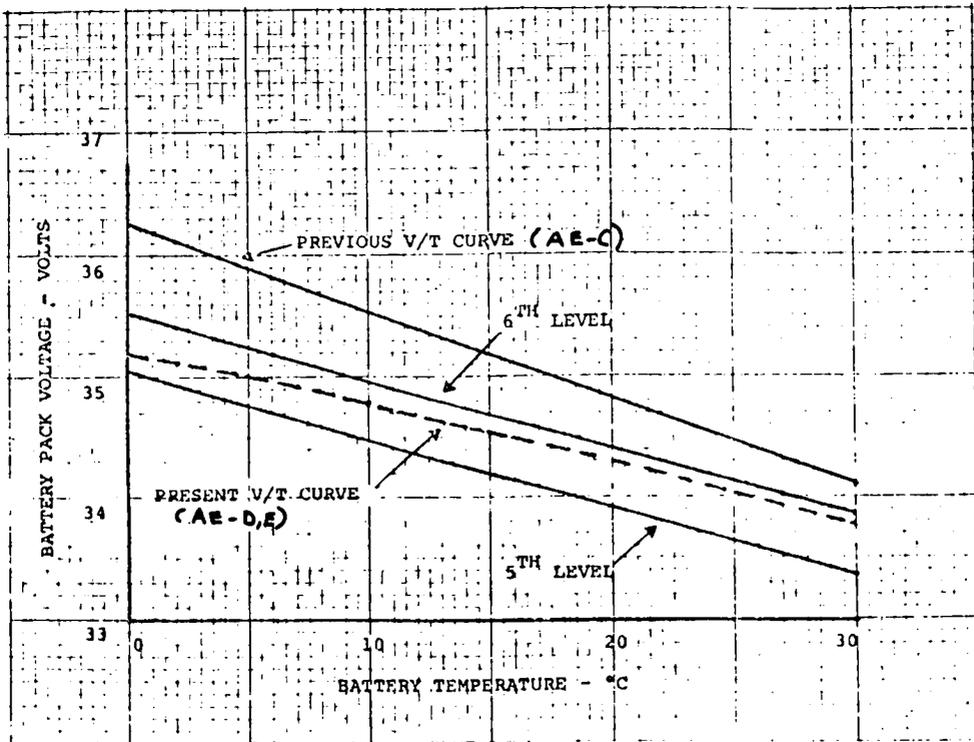
Figure 10. Battery Voltage/Temperature Limiting
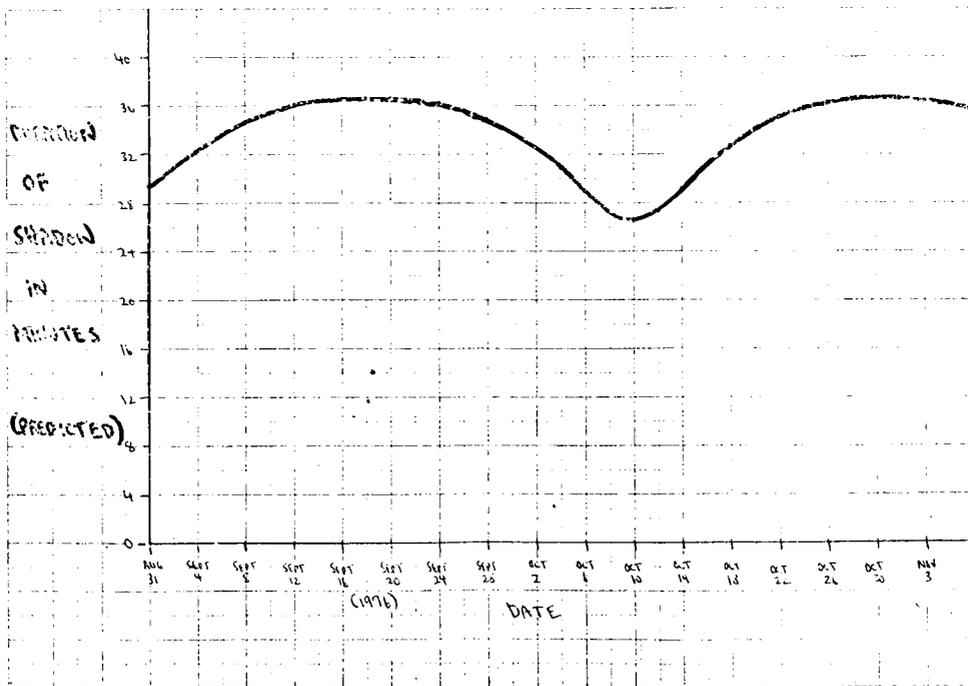
Figure 11. Prediction of Duration of Shadow for 21st and
22nd S/C Turnarounds for AE-C
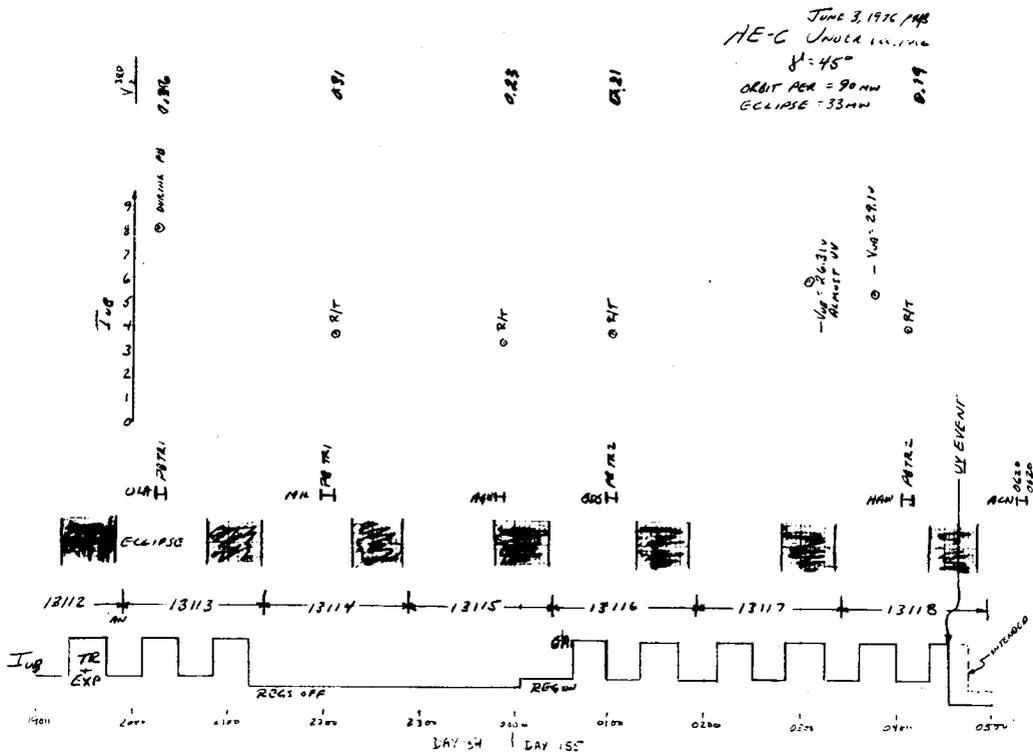
Figure 12. AE-C, Under Voltage (6-3-76)
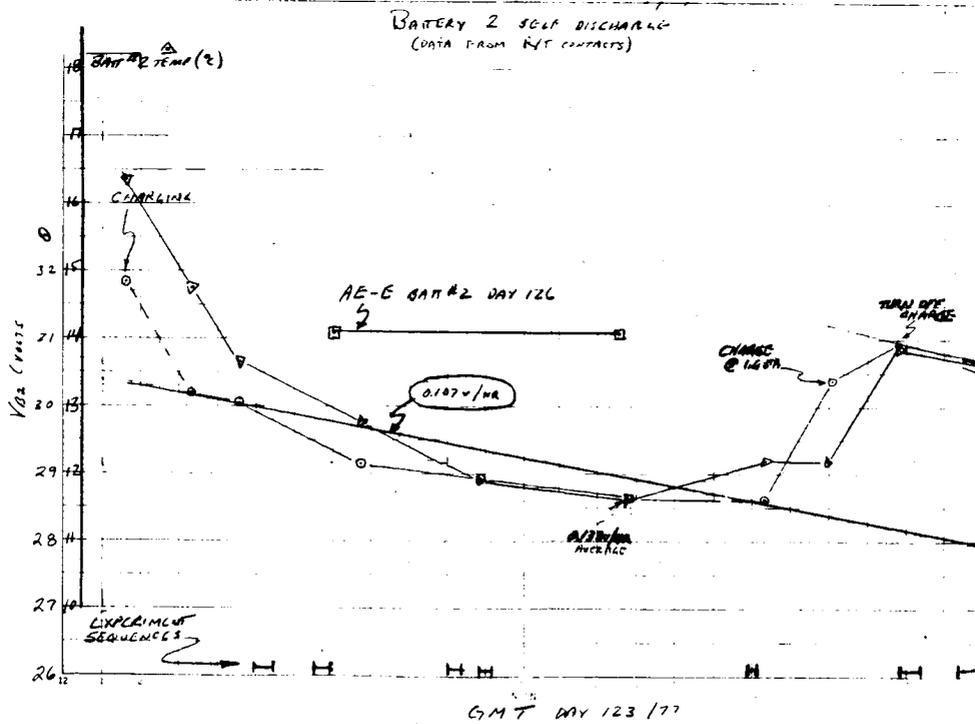
Figure 13. AE-C, Day 123 (5-3-77)

NIMBUS AND LANDSAT

D. A. Baer
Goddard Space Flight Center
and
D. Wise
General Electric Company

INTRODUCTION

BAER: The next satellite to be discussed is the Landsat, which was formerly the Earth Resources Technology satellite, and Nimbus. Here again we have an early 1960 design, and it is still being used mainly from the viewpoint of not redesigning the system and has been relatively successful even with its faults.

They are both very similar, almost the same satellite at least functionally. There are some subtle differences in it, so we are kind of lumping the presentations together.

(Figure 14)

G. E. was the prime contractor. RCA did the storage module, and the cell was manufactured by General Electric. The cell is a 4 1/2 ampere hour nickel cadmium cylindrical cell, 23 cells connected in series formed the battery. The storage module weight was 7,020 grams, about 15 1/2 pounds. The reason it is called a storage module is there is also electronics in the same box as the battery. And the electronics in this case weighs on the order of about one and three-quarters pounds. There are eight batteries on the spacecraft.

(Figure 15)

As far as charge control goes, there is a current limit of 1.1 amps. There is a temperature compensated voltage limit. However, most of the charge control is by use of auxilliary loads, switching off and on. Because the voltage limits are so high it is used more for safety than anything. There is also a temperature cut-off at 43°C, and that cuts the current back to .15 amps. And these batteries can be removed from the main bus by ground command.

(Figure 16)

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Okay, here is the V/T curve. You can see it is a little higher than what is normally used in practice today. The curve falls somewhere in between these two tolerances.

On the cell level at 0 degrees C it is about 1.50 to 1.52. At 20 degrees C it is about one four six to one four eight. At 40 it is about one four two to one four four. I said that is a little higher than most designs used today.

(Figure 17)

Okay, the power system, here again we have a negative bus system with the shunt dissipate driver through this transistor that is located over in the storage module, and there are eight storage modules. That clamps the solar array bus at about a minus 40.

One difference on this diagram between Landsat and Nimbus is you have this extra payload regulator. That is on Landsat, and it is not on Nimbus. Here are the aux loads that are coupled in by ground command, five of them, and depending on what the loads are it depends on how many aux loads are on. So, essentially what he has to do is he has to know how much he is going to take out during the night and what the loads are going to be on during the sun. And then he selects his aux loads to limit the current to the batteries to get a C to D of about 1.10 to 1.15. The battery is coupled to the solar array bus through the charge controller, and that is where your voltage and current and temperature limits are -- in the charge controller.

During the night the battery is coupled, diode coupled, to the unregulated bus, and there are also these relays which allows you to remove any one battery off the line.

Here are the regulators which regulate at about minus 24.5, the regulator bus. And about the only other thing of interest is there is a fuse tap. That is used to blow the fuses if your loads get too heavy. The regulators don't have enough to blow the fuses in all cases.

Okay, that is about it as far as design constriction goes.

NIMBUS OPERATIONS

WISE: The Nimbus spacecraft initial design life was six months to one year.

(Figure 18)

As you can see from the chart here we had good luck with them. Nimbus 3 was launched April 14, 1969, and it was eventually turned off in January of 1972, with two and three-quarters years of operation. Nimbus 4 went from April 8, and then in October of this year, seven and a half years of operation. Nimbus 5 is still operational. It had five years of operation. Nimbus 6 is still operational.

There were batteries turned off on 3 and 4. Batteries 5 and 6 have had no batteries turned off to date. None of the battery problems that occurred have effected mission operation.

(Figure 19)

The orbital period is 107 minutes, which is 34 minutes a night, 73 minutes a day. During the first year the battery temperatures averaged 20 to 24 degrees. The system battery capacity, 4 1/2 ampere hours, is 20 on the 160 ampere minutes. The depth of discharge was typically 14 to 15 percent and dropped to 4 to 5 percent after seven and a half years of operation. This is primarily because at the beginning of the spacecraft life you have all the experiments operating. As each experiment drops out, of course the load reduces. Then as you have problems with the batteries, the remaining good ones can still carry the load without effecting the mission.

The maximum charge voltage was 32.7 to 33 volts. The discharges were approximately 28.2 to 28.7. On the Nimbus type spacecraft for a period of time the loads were always relatively constant. In other words, they would go into a mode of operation with a set of experiments and they would last for three or four or five months or until they were through with that experiment or it had failed. So, it set at a relatively constant load on the bus throughout its life.

With the method of charge that Dave Baer has described, we typically would have 25 to 26 amps at charge and about 1.1 amps at discharge respectively.

(Figure 20)

Okay, with the method of charge that we are using the match of the batteries is very important. If the electrical characteristics were mismatched, the charge and load sharing would tend to spread. Or if the temperature would spread it would also force the battery to start spreading and charging, load sharing.

They have had C to D ratios as high as 4.8 to 1. And the temperatures have been as high as 43 degrees among individual batteries. As mentioned, the warm batteries are the ones that are the more susceptible to the runaway.

Nimbus both 3 and 4, were okay for seven years. The other six bat-
teries had various problems where they were turned off and on. At the present
time the spacecraft is -- They have an attitude control problem when the space-
craft goes like into deep orbit and then turns around. This presents a special
problem in the fact that the batteries that were in the sun going forward, suddenly
turned around, are still facing the sun and they don't get their proper cooling.
So they have a very hotspot on that spacecraft.

Battery spread went up to 18 degrees from a nominal of 9 to 10. And
then batteries 3 and 4 eventually became mismatched.

(Figure 21)

Okay, these are two examples of the batteries that became mismatched.
By mismatched, what we really mean is that generally the charge here starts
to increase and the load share decreases and then the temperature starts rising.
The C to D ratio.

At night, in battery number 5 there, 28.93 ampere minutes of discharge,
load share about 12.8, this 28.2, battery temperature around 21. Charge share
went up to 37, so that means C to D ratio about 1.281. I guess that would be an
example of a good battery pack.

The mismatch there is shown on the right with battery 7. The discharge
amp minutes is 20. Go down to the charge, there is 5.8. You have a 2.781
charge/discharge ratio. And the temperature is up five degrees. That is nominal.

(Figure 22)

This shows that on the left is the night and on the right is the charge.
This left scale on discharge is as you can see the numbers there, 1.1 and .63.
That shows you typically how a discharge is done. As the voltage goes down,
the current goes up. You have a constant power and voltage.

Over here in the daytime now this shows typically the way the charge
current would go. You can see the scale right over here. This would be a
normal.

(Figure 23)

This is sort of a very vivid graph that I will just show you basically.
In this area here is the C/D ratio varying all over. The voltages are up here.
The temperature is this dashed line. They have various charge sharing, load
sharing.

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This is when the problem started occurring on battery 7. They tried various things, such as lowering the voltages and attempting to see if the battery recovered, trying to overcharge, and cycling it, and almost everything. Nothing would finally work, so eventually they shut the battery off. And on this particular system we have approximately a 25 milliampere telemetry circuit which will discharge the battery. So, if you turn it off at some convenient time in the daytime, then if you wait approximately two months the battery will discharge down to 1.1 volt per cell, or about 25 1/2 volts. At that time we turn it back on. Now when they turned it back on you can see dramatic change here. You can see that everything just straightened out immediately. The C to D ratio was great. The charge, load sharing completely got together. The temperature was steady, and the voltages were steady.

So, this is typical. We call this a restoration cycle, not a conditioning. But we call it a restoration cycle in our nomenclature. This is typically what we do on Nimbus and also on Landsat. It seems to help very much.

(Figure 24)

This is just what I have mentioned before. We can turn the battery off and wait until it gets down to 26 or 25 1/2 volts and then turn it back on, and you have seen the results on the previous graph. It was successful with batteries 4, 6, and 7 on Nimbus 3 -- 3, 4, 6, and 7 on Nimbus 4. It did not work, however, on battery 2 of Nimbus 4.

Another technique that sometimes works is that if you operate the system -- Well, if you see this starting to creep up and you know it is going to run away soon, if you operate the system deliberately at lower voltages and lower C to D ratios, sometimes then when you go back to normal the battery will return to normal. If that does not work, then the second recourse is to turn it off.

LANDSAT OPERATIONS

(Figure 25)

WISE: Now turning to Landsat, we are on a 910 kilometer circular orbit. It is ground synchronous and initially sun synchronous. The orbit period is 103 minutes, 72 minutes day, 31 minutes night. On Nimbus the sun comes directly to the front of the spacecraft. It is in the plane of the orbit because it is a high ending orbit. In our spacecraft, though, the sun is over 33 degrees to the left nominally. It is actually about a plus or minus 7 degree variation throughout the year because of the sun's being directed to the earth.

We launched Landsat 1 in July, 1972. Today it is going through orbit 27,060, which is approximately two, five, years of very good operation. Landsat 2 was launched in January of 1975 for over 14,330, and not 14,330 years. It is only 2.7 years. The batteries have not limited mission operation.

(Figure 26)

This is just a rehash in a more simplified form of the block diagram system. We have the solar array and the shunt aux loads. We have a charge regulator. We have two with modulated regulators. And on this particular space-craft the smooth loads come off the service regulator. Pulse loads where they have a lot of inverters and so forth come off the payload regulator. And we have a special series of loads that are solenoids and very heavy loads, pulsed loads, that come off it, shuttered and so forth, that come off the pulse load bus, which connect it directly to the battery.

This particular technique, using the battery to buffer those heavy loads, works very well.

(Figure 27)

Nimbus, as we mentioned, had a very steady load. On Landsat we have a highly variable load. So the depth of discharge, 9 to 16 percent. When we reach 16 percent it would be necessary to turn off the paylods because if we operated it any lower we may drop out of regulation.

At the present time now we are 8.2 to 10.3, and we also only have four batteries on at this time. I will explain why that is working well. The temperature was initially 20.4 to 25.7. We are now 18.7 to 26.6. We have hit peaks up to 40.2. And the main reason is that the spacecraft is drifting. The initial 33 degrees sun angle has moved over to around 48 as you can see down below here. As we go to that higher sun angle though, the day-night changes. Where we started out with a 73-minute day and 30-minute night, we now have an 83-minute day and 20-minute night. The short night prevents us from cooling the spacecraft properly. In addition as we get towards five here we get some degradation of the thermal surface which helped contribute to warmer temperatures. The temperature at present is 18.7 to 26.6. We are going to be winding though toward the higher temperatures. Temperatures on the sunny side of the space-craft are about 32, but they are presently off. Those temperatures there reflect the four working batteries which are opposite the sun.

The C to D ratio was .06 to 1.17. We are now about 1.15 to 1.33. The reason the C to D ratio has to increase is that initially we had very good --

mismatch. With eight batteries they should be 12 1/2 percent, the charge and load sharing. That will run typically from 12 to maybe 12.8 on both of them at initial conditions. At end of life, like they are now, it will run from 11.5 to 14. The batteries that are taking more than their share on charge prevent us then from getting the correct account of the other batteries because we have to work on it as a total system and not as an individual battery when we control the charge. So this means the C/D ratio has to slightly increase. This means then that some batteries are getting larger than desired C to D ratio. Others are getting just a correct amount.

Landsat 2, 10.5, 11 percent. We have 16 percent peaks. Let us talk a little about these peaks now. 16 percent of both cases are when we have a night playback, and so therefore we will go into night and we will discharge maybe down to 10 percent. The next 6 percent of discharge will be at a rate of C over 2, C over 4, in other words 1 amp to about 2.2 amps. So this makes a voltage problem because at those high discharge currents we get pretty large high arc offs. If we held the same depth of discharge throughout the two years here, 2.7 years, the temperature ranging to 23 initially. They are now 17 to 26. We have hit peaks of about 30. The C to D ratio at 0 is 1.05, 1.08. But even on this spacecraft we have the D to D ratio up now, 1.17 to 1.25. Sun angle has changed from 36 to 42. We have a slightly increased day and a slightly shorter night. That is the reason we have those higher temperatures.

(Figure 28)

Now, here is a little history of the restoration cycles that we described earlier on Landsat. Okay, let us go to battery 6 on Landsat 1. The first restoration cycle was at 3.7 years, and the second at 4 years. And you can see that when we turn it off we recovered, operated normally for a while, but then it reverted back to its old characteristics and ran away at the end. We turned it off at four years.

You find that battery 5, 6, 7 and 8 were off respective at 4.5, 4.7, 5.2, and 3.1 years. I think that is supposed to be 3.7, that battery. I made an error there. We had a switching anomaly which prevented us from turning the batteries back on. So when we got to the place that those batteries were required, the restoration cycle, we had to turn them off. But once they were off they could not be returned to service because of another switching problem on the spacecraft. It turned out, though, as you noted earlier, that we went to a longer day, shorter night. This meant that I could get by with less battery because the night discharge, you know, was smaller. Even though I had only four batteries, I am still holding only 10 percent depth of discharge. This is a case where the orbital drift parameters and the battery characteristics all worked out so we were able to keep the mission going.

On Landsat 2, battery 1 had four cycles, 1.7, 2.3, 2.7, 2.8 years. Battery 2 we had one cycle at 2.5. Battery 5 one cycle at 2.1. Battery 6, which has been our trouble battery, meaning to operate it is taking the most care, required -- well, you can see all the numbers there.

There is one, you know, trend that I can mention on this. If we had turned the battery off and let it discharge down to that 26 1/2 and then turn it on at about 25 1/2 volts, then we turn it back on, the battery operates very normally. And then eventually it will start creeping, where the charge share will go up gradually, the load share goes down, and the temperature stays relatively constant. Then, suddenly, at about the 14 to 30 orbit period, which is one to two days the charge share will go up dramatically, the load share will go down, the temperature will rise. At that point we shut it off.

Now if I turn that battery off the first time it will last maybe two to three months. The next time it will be 2 1/2 months, the next time two months, the next time one and three-quarters. What I have is the time of good performance after restoration cycle is decreasing, and now it is getting so that if I turn it off now I can only expect about two weeks of good operation before I know I will have to turn it off again.

We are still trying to keep it on because though we can operate the mission without it it makes the mission a little easier as far as scheduling. So we do go through the trouble of restoring the thing, getting back on line as much as we can.

As you can see, we have had quite a history. And those other batteries, like battery 2, it was only two and a half, battery 5 -- 2.1 years. They are working normally. We have had no need to turn them off the second time. So that is the end of my presentation.

DISCUSSION

GROSS: Boeing. What is the typical restoration duration?

WISE: Well, we don't control the point where we turn it off, in other words, the depth of discharge or the percent of charge at the time we turn it off. We just do it randomly and when it is convenient to us. But with the 25 milliamps to when we discharge it typically takes about two months.

GROSS: Two months?

WISE: Two months, yes. Now there have been intervals where for
some reason where we needed that battery on line where we turned it on in less
than a week. It had not gone through the full restoration cycle. When it comes
back on it acts as if it had. But let us suppose I had it turned off only for a week
and the battery voltage only dropped maybe to 27 1/2 volts, it will act normally
but maybe only for a week. If I had done that at 25 1/2 volts it would have lasted
for months.

GROSS: And do you start your restoration at the end of a charge or a
discharge?

WISE: It is in the middle of a charge. We are into the daytime. We
have a daytime contact, and I will just turn it off at some point. Now it has not
fully recharged. It has been down to 10 percent depth of discharge. I maybe
added another 2 percent. So I may be sitting at 92 percent state of charge. And
I turn it off and then let it go down to the 1.1 volts per cell.

SCOTT: TRW.   To what degree do you attribute the unbalance problems
between an inherent change in the IUE characteristics of the battery and differences
in the thermal environment of the different batteries?

WISE: I am not sure we can really distinguish the differences, but I
would say that if the thermal conditions had remained about constant that if sud-
denly the battery should fall it would have to be internal characteristics. That
is about the only way. We have no way of really distinguishing.

SCOTT: How you do characterize the uniformity of thermal dissipation
between all those different eight batteries as far as the design is concerned,
physically where they are placed and all that?

WISE: Because of the complexity of the thermal problem I am not sure
how to answer you. We have 18 compartments, and the batteries are spread
around these 18 compartments in a circle. On 16 of these compartments we have
active thermal shutters that if the night is long enough they will open, close, and
tend to cool the battery and keep it at within let us say 23 plus or minus 2. It is
possible that the battery gets a high C/D ratio that we can force the battery to
put more heat than the shutters can handle. Also we have other equipment in
those, and with the wide reverting modes we have and the self-generated heat
from the battery itself we have such a wild combination of circuit, you know,
conditions that I can't answer your question directly.

FORD: Goddard.   Would you comment on the restoration cycle and
what problem you are trying to solve? Load sharing on charge and discharge,
or either?

WISE: Yes, we start the restoration cycle, and we key it to the fact that we have a sudden rise in charge share, a sudden decrease in load share, and a sudden temperature rise of that battery pack above its normal operating conditions. At that time we will then switch into restoration cycle. We tend to try to catch it early for the reason that we felt that if you do go into this high C to D ratio you are not doing the battery any good. We could still operate with high C to D ratio and it wouldn't hurt the spacecraft, or we would still be getting some use out of it. But we felt if we turned it off early it may salvage the battery and allow a little more useful life in the long run.

UCHIYAMA: JPL. When you say you turned off your batteries you said you turned off everything, no load, no direct load?

WISE: Yes, there is no direct load on it. It is disconnected. The only direct load is the voltage telemetry circuit, which operates directly off the battery. And it is around 25 milliamps.

UCHIYAMA: So there is a slight load.

WISE: There is a slight load, yes.

PARK: Battery Development. I was just wondering if somebody in the meeting would comment on whether it would be better to have more discharge during this restoration period.

WISE: That would be an interesting question. On our spacecraft we could not do it. We have no way of doing it, but it might be an interesting thing. If you could explain the phenomena that is occurring, you might be able to figure out a better way of accomplishing it.

PARK: If anybody around here has tried that, testing it on the ground and found this sort of thing in ground testing. I could imagine that possibly it wouldn't take you -- maybe a week, you know, to make it behave or something like that, a matter of days even.

SCOTT: TRW. I would like to ask whether you know how much different the behavior of the battery is on that 25 milliamp load compared to just leaving it on open circuit on real open circuit?

WISE: I don't know because we have no way of going to open circuit. We are fixed to that mode. Helm Thierfelder was at G.E. and had tested some earlier ones. Do you have any idea? Have there been any tests that we compared self-discharge by the telemetry to the open circuit?

THIERFELDER: G.E. Well, if you just left them open circuit, it would take a lot longer than two months. It would take probably well over a year to get them all the way down. So that 25 milliamp load has a big advantage --

NAPOLI: RCA. Do you notice that when you are charging the batteries that there is a difference in voltage? Can you measure the voltage individually in each battery?

WISE: Yes. Each voltage is measured individually, but during charge and discharge they track very close together, within 10 millibels to one another.

NAPOLI: But when you are tapering off to the final charge are they within the --

WISE: Well, with the system that we use we just barely approach the taper curve, and they very seldom go into taper. In other words, the taper charge curve is set so that you get a 1.3 or something like that C to D ratio. And we don't normally shoot for that. We shoot for lower, so we don't quite reach the taper curve on most.

NAPOLI: What about on discharge? Do you see any difference between them on discharge?

WISE: Yes, on the way down they will vary a little bit. But they all end up, you know -- one will come down. Well, there are small differences. I would say they are insignificant though. They track very close both going up and coming down.

NAPOLI: It is only with currents that you really have a problem.

WISE: Yeah, the current vary a little bit. When the batteries are what I call normal they track fairly well also. It is only when they start getting this runaway condition that it starts creeping and then finally goes very suddenly that we have a problem.

BAER: I might add usually when you are running a system like this with batteries in parallel usually your voltages are going to track very closely unless you have unusual IR drop across a diode or something. So the voltages are usually going to track. But what happends is you see the difference in the current, on discharge current that it delivers, or else in the current it will accept on charge.

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NAPOLI: On discharge it could be depth of discharge.

BAER: Not usually, no. You know, they will try to seek the same voltage level. But the difference is going to be in your current usually.

LANDSAT/NIMBUS BATTERY DESIGN

- CONTRACTORS: SPACECRAFT - GENERAL ELECTRIC
  STORAGE MODULE - RCA
  CELL - GENERAL ELECTRIC

- CELL SIZE & TYPE: 4.5 AH NICKEL-CADMIUM (CYLINDRICAL)

- CELLS/BATTERY: 23 CELLS CONNECTED IN SERIES

- STORAGE MODULE: 7020 GMS (15.5 LBS) MAXIMUM

- BATTERIES/SPACECRAFT: 8

Figure 14
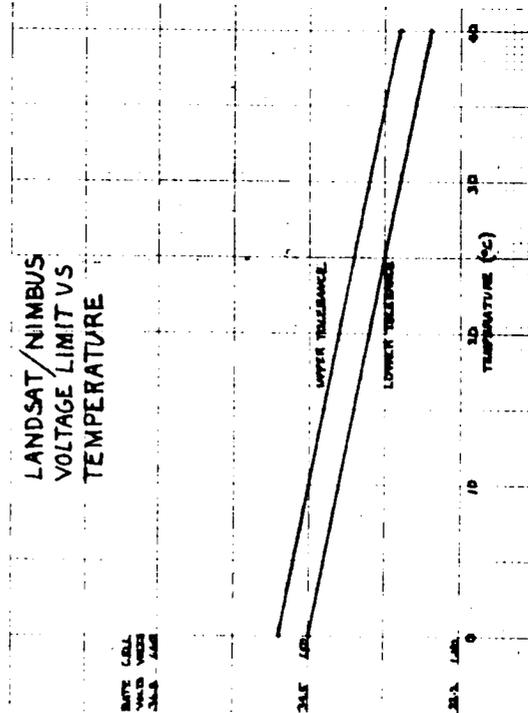
LANDSAT/NIMBUS CHARGE CONTROL & BATTERY PROTECTION

- CURRENT LIMIT: 1.1 AMPS EACH BATTERY

- CHARGE CONTROL: TEMPERATURE COMPENSATED VOLTAGE LIMIT AND
  USE OF AUXILIARY LOADS BY GROUND COMMAND

- TEMPERATURE CUT-OFF: TEMPERATURE OF 40°C SWITCHES BATTERY
  TO A .15 AMP TRICKLE CHARGE

- EACH BATTERY CAN BE REMOVED FROM MAIN BUS BY GROUND COMMAND

Figure 15

LANDSAT/NIMBUS
VOLTAGE LIMIT VS
TEMPERATURE

Figure 16

Functional Block Diagram, ERTS Power Subsystem
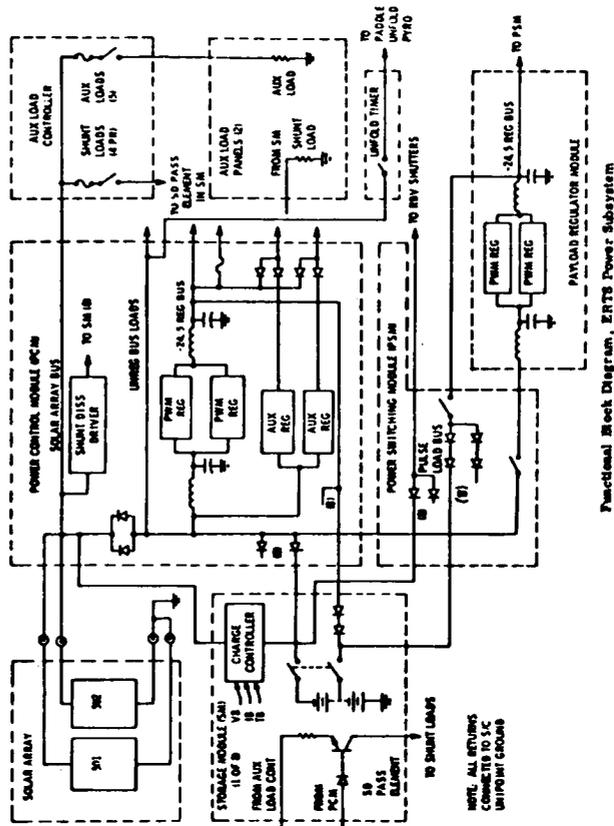
Figure 17

NIMBUS OPERATIONAL BATTERY

PROBLEMS AND SOLUTIONS

o THE NIMBUS SERIES OF SPACECRAFT WERE DESIGNED TO CARRY HIGHLY ADVANCED OCEANOGRAPHIC, METEOROLOGICAL AND EARTH-SENSING EXPERIMENTAL PAYLOADS TO INCREASE THE KNOWLEDGE OF EARTH'S ENVIRONMENT.

o DESIGN LIFE OF NIMBUS SPACECRAFT RANGED FROM 6 MOS TO 1 YEAR.

o CURRENT VERSION OF BATTERY MODULE DEVELOPED FOR USE ON NIMBUS 3.

o USED ON FOLLOWING NIMBUS SPACECRAFT

SPACECRAFT	LAUNCH DATA	CURRENT STATUS	YEARS OF OPERATION
NIMBUS 3	APRIL 14, 1969	TURNED OFF JAN. 22, 1972	2 3/4
NIMBUS 4	APRIL 8, 1970	PLACED IN HYBERNATION MODE 10/17/77	7 1/2
NIMBUS 5	DECEMBER 11, 1972	OPERATIONAL	5
NIMBUS 6	JUNE 12, 1975	OPERATIONAL	2 1/3

o NO BATTERIES ON NIMBUS 5 OR 6 TURNED OFF TO DATE

o NO BATTERY PROBLEM HAS AFFECTED MISSION OPERATIONS.

Figure 18

TYPICAL BATTERY OPERATIONS

o ORBITAL PERIOD = 107 MINUTES (34 NIGHT - 73 DAY)

o BATTERY TEMPERATURES DURING FIRST YEAR AVERAGED 20 - 24°C.

o SYSTEM BATTERY CAPACITY (RATED) = 2160 AMP. MIN. (8 BATS)

o DEPTH OF DISCHARGE WAS TYPICALLY 14-15 % (320 AM) INITIALLY AND DROPPED TO 4 TO 5 % AFTER 7 1/2 YEARS OF OPERATIONS (NIMBUS 4), - DEPLETED SEVERAL TIMES.

o MAXIMUM CHARGE VOLTAGES GENERALLY WERE -32.7 TO-33.0 VDC.

o END OF DISCHARGE VOLTAGES WERE GENERALLY CONSTANT THROUGHOUT FLIGHT DUE TO DECREASING DEPTHS OF DISCHARGE (-28.2 TO -28.7 VDC)

o EXPERIMENT LOADING MAXIMIZED TO S/C CAPABILITY.

o REGULATED BUS LOAD RELATIVELY CONSTANT THROUGHOUT ORBIT.

o THEREFORE CHARGE AND DISCHARGE CURRENTS WERE REASONABLY CONSTANT AT .5-.6 AMPS AND 1.1 AMPS PER BATTERY, RESPECTIVELY, DURING FIRST YEAR.

Figure 19

BATTERY PROBLEM

o BATTERY "MISMATCH" PROBLEM

o DIVERGENCE OF LOAD AND CHARGE SHARING PERCENTAGES.

o RISE IN C/D RATIO (AS HIGH AS 4.8:1)

o HIGHER TEMPERATURES (AS HIGH AS 43°C)

o WARM BATTERIES MORE SUSCEPTIBLE

o NIMBUS 4 - BATTERIES 3 AND 4 OK FOR 7 YRS.   S/C BEGAN PIROUETTING TWICE AN ORBIT.

o EXPOSED TO SUNLIGHT ENTIRE SAT DAY.

o BATTERY SPREAD INCREASED TO 18°C FROM 9-10°C.

o BATTERIES 3 AND 4 (28°C) BECAME MISMATCHED.

Figure 20

EXAMPLES OF NORMAL AND MISMATCHED BATTERIES

SAT. NIGHT (35 MIN)	(NORMAL)	(MISMATCHED)
BATTERY NO.	5	7
DISCHARGE IN AMP-MIN.	28.93	20.05
LOAD SHARING %	12.80	8.87
END OF NIGHT VOLTAGE	-26.23	-23.13
BATTERY TEMP IN °C	21.06	25.97
SAT. DAY (73 MIN)		
CHARGE IN AMP-MIN.	37.00	55.83
CHARGE SHARING %	11.64	17.57
MAX. CHARGE VOLTAGE	-32.26	-32.07
BATTERY TEMP	19.75	24.65
CHARGE/DISCHARGE RATIO	1.28:1	2.73:1

30 AM WASTED.

Figure 21

THE CHARGE CURRENT FOR BATTERY NO. 7 IS MUCH HIGHER THAN THE OTHER BATTERIES AND ACCOUNTS FOR THE HIGHER BATTERY TEMPERATURE AND WASTE OF OVER 30 AMP-MINUTES.

NOTE: THE DISCHARGE TLM IS SCALED ABOUT TWICE THE CHARGE TLM AND THE SATELLITE DAY PERIOD IS TWICE THE NIGHT PERIOD. THEREFORE, THE CURRENT SHOULD READ ABOUT THE SAME TLM READING.

Battery No. 7

Battery No. 3

Battery No. 2
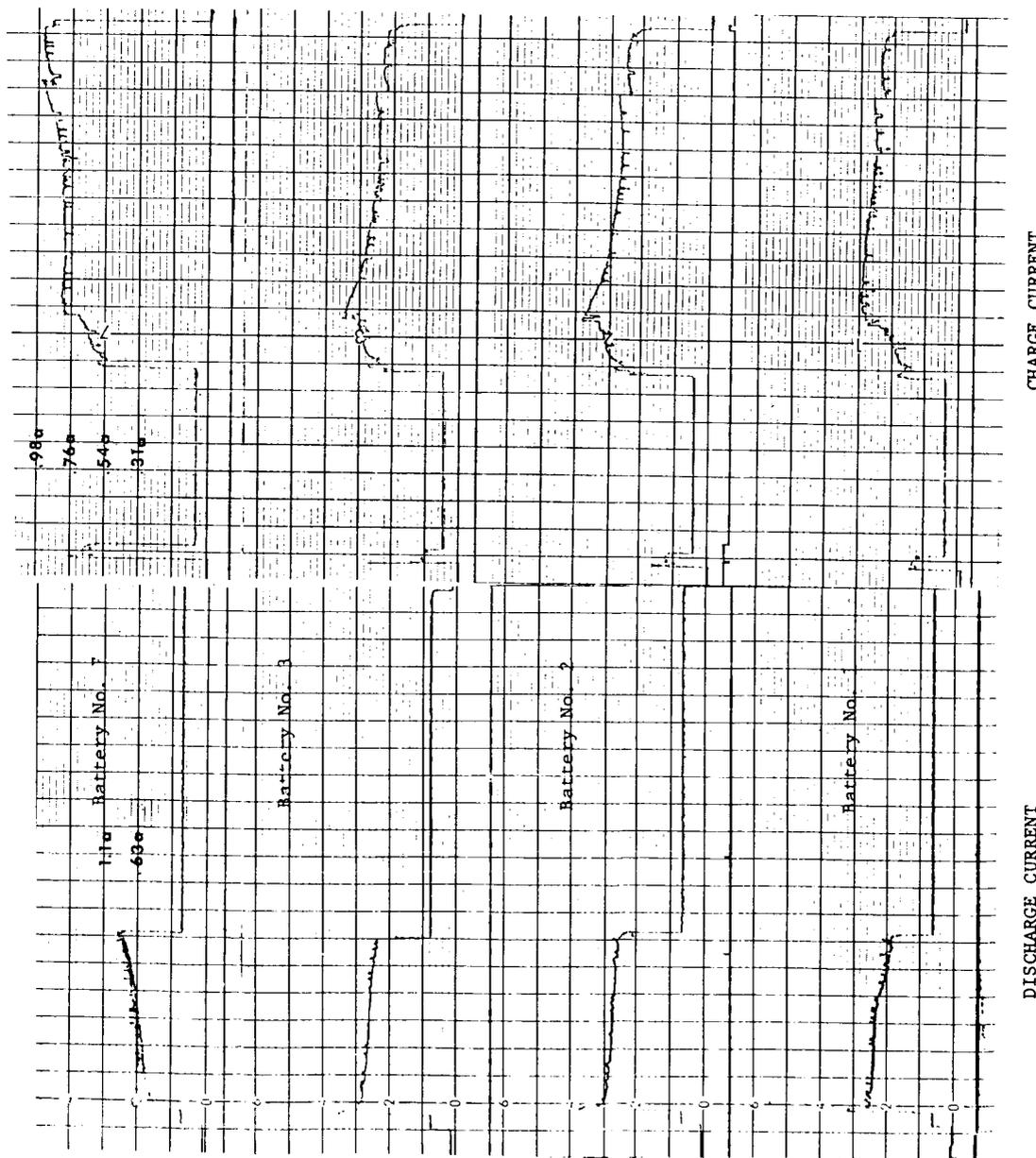
Battery No. 1

DISCHARGE CURRENT   NIMBUS 5   CHARGE CURRENT

Figure 22
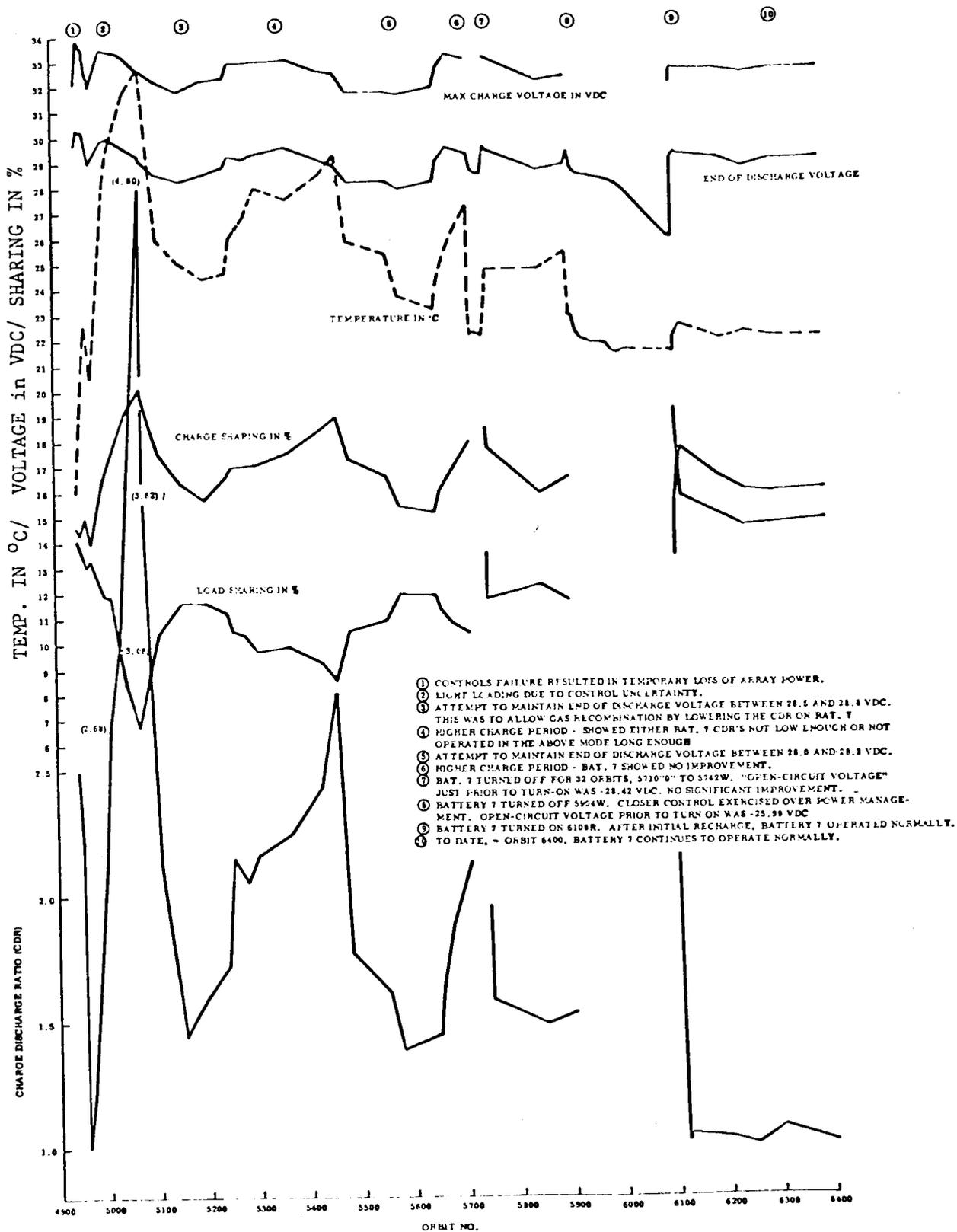
Figure 23. Battery No. 7 Performance

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o   TURN THE BATTERY OFF.

   o   WAIT UNTIL OPEN CIRCUIT VOLTAGE DROPS TO -26. VDC.

   o   SUCCESSFUL ON BATTERIES; 4,6,AND 7 ON NIMBUS 3.
                              3,4,6 AND 7 ON NIMBUS 4

   o   NEVER WORKED ON BATTERY 2 OF NIMBUS 4.

o   OPERATE SYSTEM AT LESS THAN FULL CHARGE

   o   SUCCESSFUL ON NIMBUS 5 AND 6, BUT REQUIRES MORE TIME.

Figure 24

LANDSAT

ALTITUDE   910 KM   CIRCULAR

GROUND SYNCHRONOUS — INITIALLY SUN SYNCHRONOUS

ORBIT PERIOD   103 MINUTES

72 MIN DAY   31 MIN NIGHT

SUN ANGLE — NOMINALLY 33° TO ORBIT PLANE

LANDSAT-1 LAUNCHED 7/23/72 ORBIT 27060 TODAY
                                (5.25 YEARS)

LANDSAT-2 LAUNCHED 1/22/75   ORBIT 14330 TODAY
                              (14330 YEARS)

BATTERIES HAVE NOT LIMITED MISSION OPERATION

Figure 25

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LANDSAT SIMPLIFIED POWER SYSTEM BLOCK DIAGRAM

Figure 26

		LANDSAT-1	LANDSAT-2
DOD	START	9 – 16 %	10.5 – 11 % (10 PEAK)
	Now	9.2 – 10.3 % (4)	10 – 11 % (10 PEAK)
TEMP	START	20.4° – 25.7°C	18 – 23 °C
	Now	18.7° – 26.6° (40.2°PEAK)	17.4 – 26.2° (30.4 PEAK)
C/D	START	1.06 – 1.17	1.05 – 1.08
	Now	1.15 – 1.33	1.17 – 1.25
SUN ANGLE	START	33°	36°
	Now	48°	42°
DAY/NITE	START	73/30	73/30
	Now	63/2.0	74.5/28.5
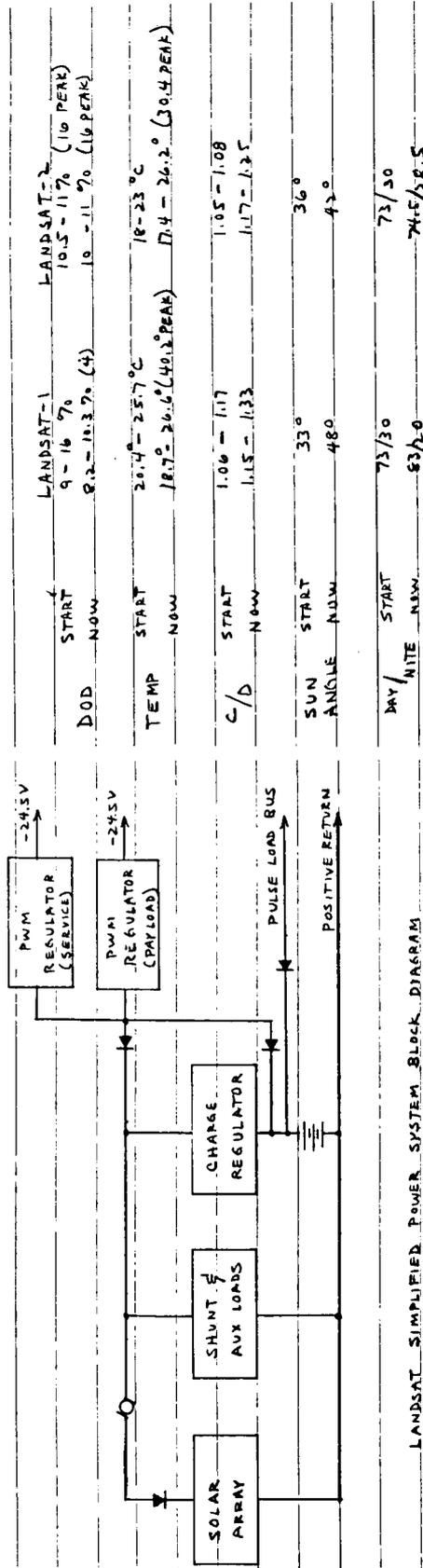
Figure 27

LANDSAT   RESTORATION   EXPERIENCE

LANDSAT-1	LANDSAT-2
BATT 5 OFF 4.5 YRS	BATT-1 4 CYCLES 1.7, 2.3, 2.7, 2.8 YRS
BATT 6 2 CYCLES 3.7, 4.0 YRS	BATT 2 1 CYCLE 2.5 YRS
OFF 4.7 YRS	BATT 5 1 CYCLE 2.1 YRS
BATT 7 OFF 5.2 YRS	BATT 6 10 CYCLES 1.0, 1.9, 2.0
BATT 8 OFF 3.1 YRS	2.2, 2.5, 2.6, 2.7, 2.75,
	2.8, 2.9 YRS
* TURN ON ANOMALY	BATT 7 2 CYCLES 2.7, 2.8 YRS
	BATT 8 1 CYCLE 2.7 YRS

Figure 28

ORBITING SOLAR OBSERVATORY
BATTERY AND POWER DESIGN

F. E. Ford
Goddard Space Flight Center
and
S. Bober
RCA

INTRODUCTION

FORD: The OSO-I represents a recent vintage satellite, or more recent design satellite. It represents the philosophy, I guess, of the early seventies.

(Figure 29)

Basically what I have provided here is a summary of the battery design. It is a 12 ampere hour G.E. cell, with 21 series connected cells packaged in two packs, 11 and 10 cell packs. There are also two batteries on the spacecraft. It had a design life of one year, and it is in a near earth orbit. Incidentally, if you haven't recognized it, all the discussions you have heard so far deal with satellites in near earth orbit. I believe the last three papers this morning will deal with the synchronous satellite. We designed for a 10 to 16 percent depth of discharge, a temperature range of 10 to 15 degrees C with a thermostat that would place the battery on open circuit. If the battery temperature ever exceeded 35 C, the charge control has eight commandable voltage versus temperature. I am going to put these up here because as the next gentleman talks to you he is going to be talking about voltage levels, and that represents the eight levels that are in the charger. And I believe there are two chargers. Right? One for each battery is that right? Yes, two chargers.

(Figure 30)

It has an undervoltage setting at 1.18 volts per cell. The spacecraft was launched in June of 1975, and at this time Stan Bober is going to talk to you about the performance of OSO-I and give you some insight into the operational modes that they have gone through. And I will leave the curve on the left for you to refer to as he talks about a voltage level because I don't think he will be talking about actual voltages per cell.

OPERATIONS

(Figure 31)

BOBER: I would like to begin by describing the OSO spacecraft itself before I go into the battery performance. You will notice that I have an OSO-8, and Mr. Ford was telling you about OSO-I. They are both the same except that when the spacecraft was being built it is given a letter designation for a model, and after it is launched it is numbered. This is OSO-8, the Orbiting Solar Observatory, eighth in the series. The rest of it is pretty much self-explained except that I would like to bring your attention to the number of orbits that we have completed as of yesterday, 13,240. That is almost the same number of cycles that the batteries have gone through.

The two sections of the spacecraft, the solar panel is called the sail, and the drum at the bottom of the sketch is called a wheel. The wheel rotates at approximately 6 rpm while the sail is stationary. The sail is actually on a shaft or an axle through the middle of the wheel, and it is driven in the opposite direction to the point where it is standing still and points at the sun. The two rectangular boxes are the solar observing telescope. One belongs to the University of Colorado, the other one to the Paris or French experimenter.

There are six other instruments or experimental instruments located within the wheel. The booms with the weights just provide additional mass for gyroscopic stability as the wheel rotates.

The spacecraft orbits around the earth at a 550 kilometer height, and it goes through spacecraft day and night. When it comes into the sunlight it is spacecraft day, and when it is eclipsed by the earth it is spacecraft night.

The length of the orbital period is 95.7 minutes. The day although variable is pretty well over 60 minutes. I will show you a graph of the day occurrence later.

Mr. Ford mentioned the two batteries are made up of two packs, one 11 cell and the other 10 cell. The 11 cell pack is mounted closer to the outside wall, the peripheral wall of the wheel. And the temperatures run somewhat cooler than the 10 pack, which is closer to this, within one of the sections of the wheel. Battery 1 is in section 3. Battery 2 is in section 9.

(Figure 32)

Our orbital operation is very much standard. With some differences as far as to the loading, the total behavior is repetitive. In this graph and in the next three the data are actual data taken from one orbit, 12,931, fairly recent, and you will see a little stepping on the graph. That is because the data are sampled at one minute intervals, and the currents, the telemetry readouts, or increments, are fairly fine. The voltage is a little coarser, and the temperature when we get to it will be large steps. That is because of the telemetry readout.

Here we show, starting during the spacecraft day of the charge cycle, and there is a drop in the current at the beginning of the graph. That is because we come to the end of the playback, tape recorder B ends its playback. And this required some 400 mils of current. But then we continue fairly steadily with some variation because the experimental instruments always varied their mode of operation; maybe a wave length change or something like that requires a little. Then we come into the spacecraft night or the discharge period, and the current as the voltages decrease, the preregulator draws more current. So the current is increased until we come to the next sunrise and repeat the cycle again.

(Figure 33)

There are also periods of time when some of the experiments turn off because they do come into the high radiation area for the South Atlantic anomaly area. But overall the operation is fairly standard.

Here we show the charge and the discharge currents of both batteries. You notice they are fairly identical. When the batteries are being charged the current is fairly high, and then it starts tapering off after the voltage clamp or the limiting takes place until it gets down to just a trickle rate or trickle current of about .32 amperes. Then we cross over to the discharge period, where we require about 3 amperes of current from each battery.

(Figure 34)

On the voltage profiles again very much alike.

(Figure 35)

As I mentioned earlier, the slight coarseness in the graph is because of the telemetry increment. Again, the charging cycle and maintaining the voltage at a predetermined level set by the charge control, we are operating since launch in level 2, which runs somewhere, oh, 30 point, I forget the exact figures, depending on the temperature. The charge control compensates for the temperature. As the temperature increases we do not push the battery too hard, and therefore we get a lower charge level.

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Then we come to the discharge cycle. The battery provides the operating power and repeat over and over again.

Temperature rise, where the great stepping comes in, I am showing the temperatures of the 10 and 11 cells. As I mentioned earlier the 11 cells are located closer to the outer wall of the wheel and they start cooler, but since they are 11 cells their operating range or temperature range is somewhat higher than those of the 10 cells. And I have intended to portray the actual or possibly the actual temperature curve as it most likely is.

(Figure 36)

I have stated earlier that the operating temperatures of the batteries will vary as the length of day or duration in sunlight of the spacecraft varies. This is the exact or graph with data taken from the predicts showing the length of day. Normally we are in the 60 to 62 minute range, but periodically we are extending upward to 71 minutes of sunlight for orbit. Those are just short duration, about five orbits, and then it starts decreasing again.

During these periods we modify the plan where our spin axes are maintained perpendicular to the sun normal. That is to minimize the temperature rise because if we go into positive pitch angle where the top of the sail leans toward the sun then we get a reflection from the sail onto the top of the drum, and the temperatures increase about degree of pitch forward leaning. So to keep the temperatures reasonable during these longer and hotter periods we keep spacecraft pitch angle at 0 degrees.

(Figure 37)

Now to show you what happens to the battery temperatures I have prepared a graph which covers the period from day 160 to 220, covering this high sunlight period.

This is battery 2 only. I didn't want to crowd it too badly, but both batteries behave pretty much the same. The temperatures are mainly effected by the duration in sunlight. But I show you here the pitch angle, ranging from 0 to 3 and 0 to minus 3. Each time we go into a positive angle the temperatures rise also, the peaks. When we drop into the negative regions it does not affect it as much. Things like heating the bottom of the spacecraft aren't as serious as the top of the spacecraft.

(Figure 38)

During the same period here is what the battery voltages look like. This is based on data taken from one orbit per day, and the computer extracts the minimum and maximum values. This is plotted for the same two month period as the warmest day where visible. You will notice that at this point the charge controller compensated for the temperature and did not allow the battery to charge up as high. Also because it is a longer day the terminal voltage at the end of the discharge cycle is higher. Both batteries behave pretty much the same way.

(Figure 39)

Now the next three graphs are also two-month periods based on one per day sampling, for a comparison of what they would look like in 75. You will note that the maximum voltage is around 29.94 volts on the average. When the days get longer it drops. The average minimum voltage is somewhere in the vicinity of 25.8. This is in 75, days 250 through 300.

(Figure 40)

In 76 the maximum voltage is pretty much the same. The minimum voltage dropped about .25 volts.

(Figure 41)

And again in 77, which is most recent, we have another drop.

I don't know if I attempt to put all three together and match them you will probably notice a difference in the levels at the bottom. The top appears to be charging pretty much to the same level, which is fine, speaks well for the charge control. The batteries are losing at the lower or the end-of-discharge cycle. And I am told that you can expect that also.

So, gentlemen, as you see, we in the OSO Operations Control Center are like the TV Maytag repairmen standing by and another tv ad says, "Thank you, Hughes Aircraft Corporation or Company for a well-designed power system."

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OSO-I VOLTAGE LIMITS

BATTERY VOLTAGE — VOLTS (21 Cells)

31.92 31.50 31.08 30.66 30.24 29.82 29.40 28.98 28.56 28.14

9 5 4 3 2 1 0 8

CELL VOLTAGE — VOLTS

1.52 1.50 1.48 1.46 1.44 1.42 1.40 1.38 1.36 1.34

0   10   20   30

TEMPERATURE — DEGREES C

Figure 30

OSO-I BATTERY DESIGN SUMMARY

• 12 AH GENERAL ELECTRIC NICKEL-CADMIUM CELLS

• 21 SERIES CONNECTED CELLS (11 CELL AND 10 CELL PACK)

• DESIGN LIFE   1 YEAR IN NEAR EARTH ORBIT
    10 TO 16 PERCENT DOD

• TEMPERATURE   10 TO 15 C, OPEN CIRCUIT @ 35 C

• CHARGE CONTROL   VOLTAGE VS. TEMPERATURE
    8 COMMANDABLE LEVELS

• TWO BATTERIES ON SPACECRAFT

• UNDERVOLTAGE @ 1.18 VOLTS/CELL

• SPACECRAFT LAUNCHED   JUNE '75

Figure 29

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OSO-8
OBSERVATORY LOAD CURRENT
ORBIT #12,931

AMPERES
6.5
6.0
5.5
5.0

CHARGE   DISCHARGE

1042 TAPE RECORDER B - END OF PLAYBACK
1130 S/C SUNSET,   NRL EXPERIMENT TURNED ON
1206 S/C SUNRISE,   NRL EXPERIMENT TURNED OFF

298/1040   1100   1120   1140   1200   1220
                  SET GMT

Figure 32

SPIN AXIS

ROTATION
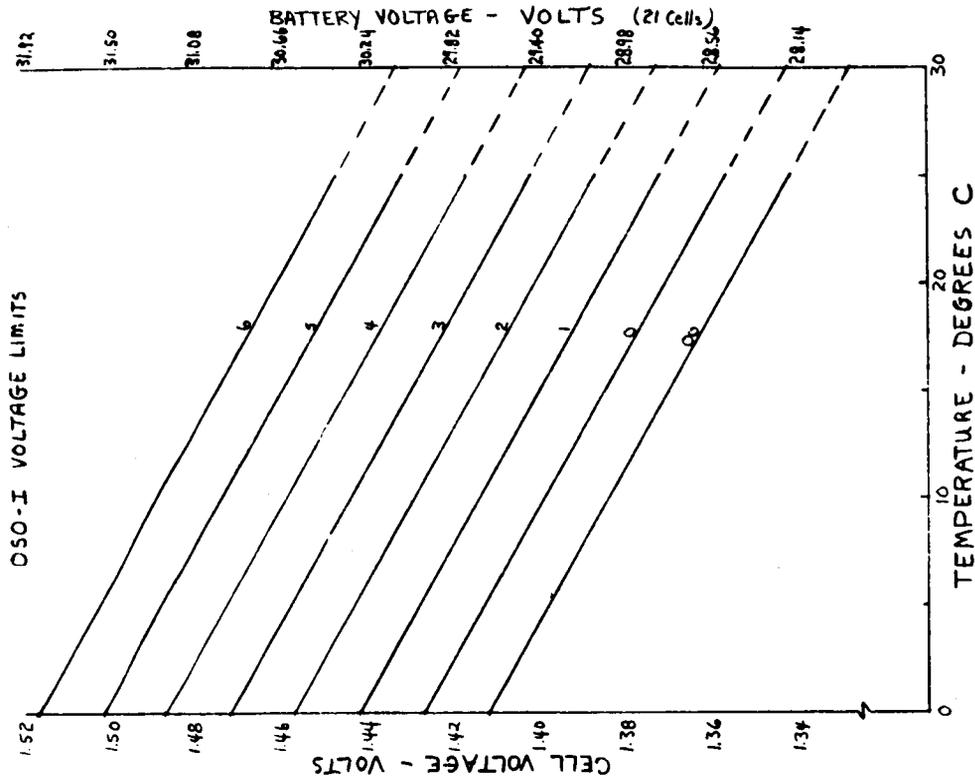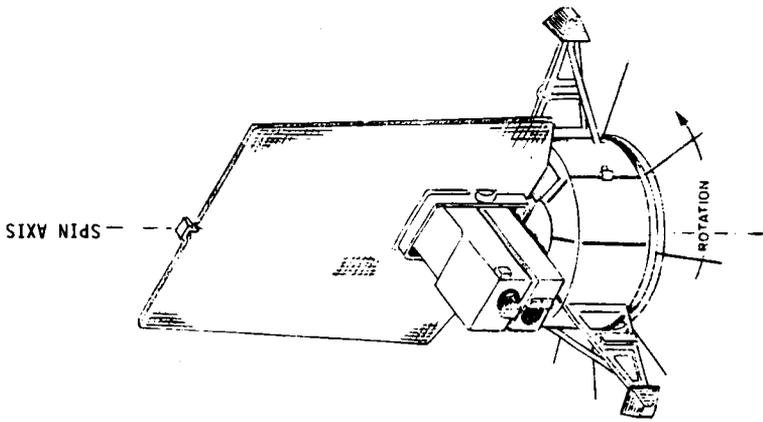
OSO-8

(ORBITING SOLAR OBSERVATORY, EIGHT IN THE OSO SERIES.

LAUNCHED 21 JUNE 1975 FROM ETR AT 1147Z.)

OSO-8 IS CURRENTLY IN ITS THIRD YEAR OF OPERATION.

ON 14 NOVEMBER 1977, OSO-8 COMPLETED 13240 ORBITS.

Figure 31

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OSO-8
BATTERY VOLTAGES
ORBIT # 12,951

BATTERY 1

DISCHARGE

CHARGE

BATTERY 2

30
29
28
27
26
25

VOLTS

30
29
28
27
26
25

898/1040   1100   1200   1400   1600   1800   1820
SET GMT

Figure 34

OSO-8
BATTERY "CHARGE-DISCHARGE"
CURRENTS
ORBIT # 12,931

BATTERY 1

DISCHARGE

CHARGE

BATTERY 2

4
3
2
1
0
-1
-2
-3
-4

AMPERES

4
3
2
1
0
-1
-2
-3
-4

898/1040   1100   1120   1140   1200   1220
SET GMT

Figure 33

50

OSO-8
DURATION IN SUNLIGHT
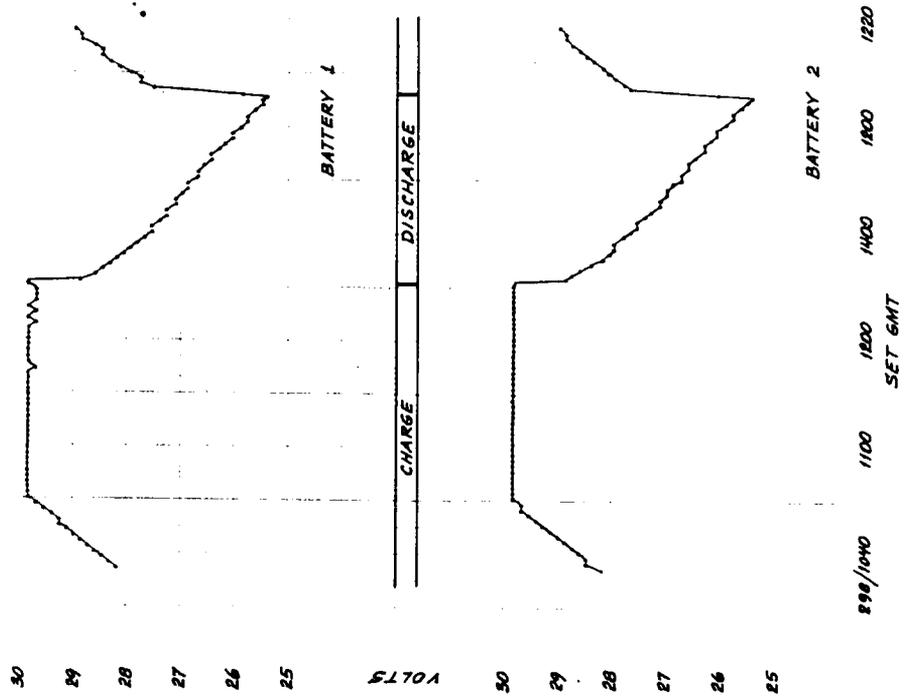
Figure 36

OSO-8
BATTERY TEMPERATURES
ORBIT #12,931

LEGEND:

BATTERY 1; 10 CELL Ⓑ   11 CELL Ⓓ
BATTERY 2; 10 CELL Ⓐ   11 CELL Ⓒ

Figure 35

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OSO-8
BATTERY 'MIN-MAX' DAILY
VOLTAGE LEVELS

BATTERY 1

BATTERY 2

VOLTS
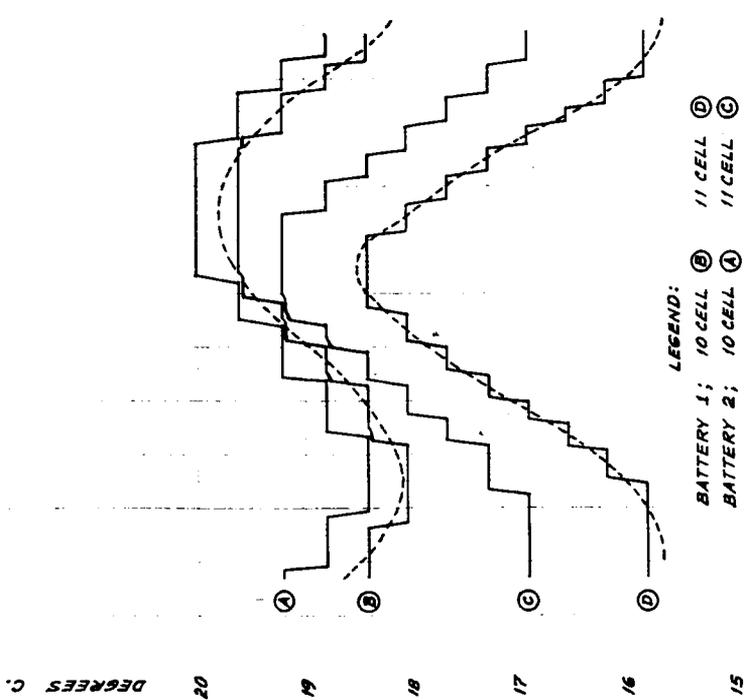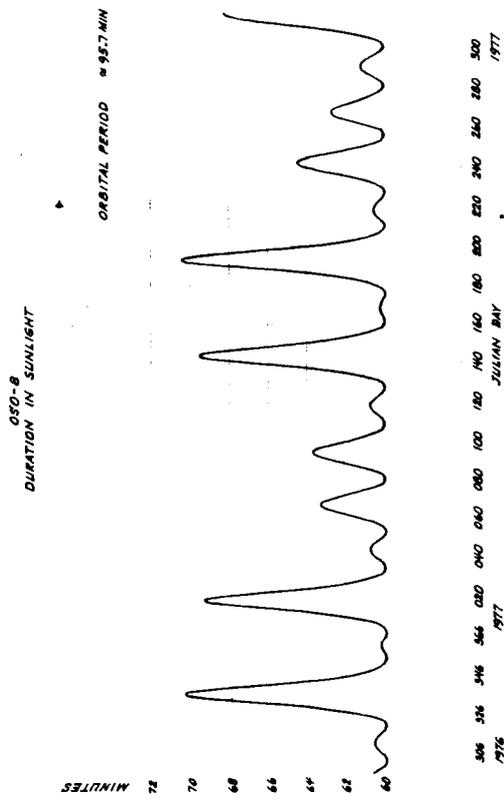
Figure 38

EFFECT OF S/C DURATION IN SUNLIGHT AND S/C PITCH ANGLE
ON BATTERY 2 TEMPERATURES

OSO-8

S/C DURATION
IN SUNLIGHT

10 CELL —— MAX Ⓐ
         MIN Ⓒ
11 CELL —— MAX Ⓑ
         MIN Ⓓ

S/C PITCH ANGLE

Figure 37

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OSO-8
BATTERY 'MIN-MAX' DAILY
VOLTAGE LEVELS
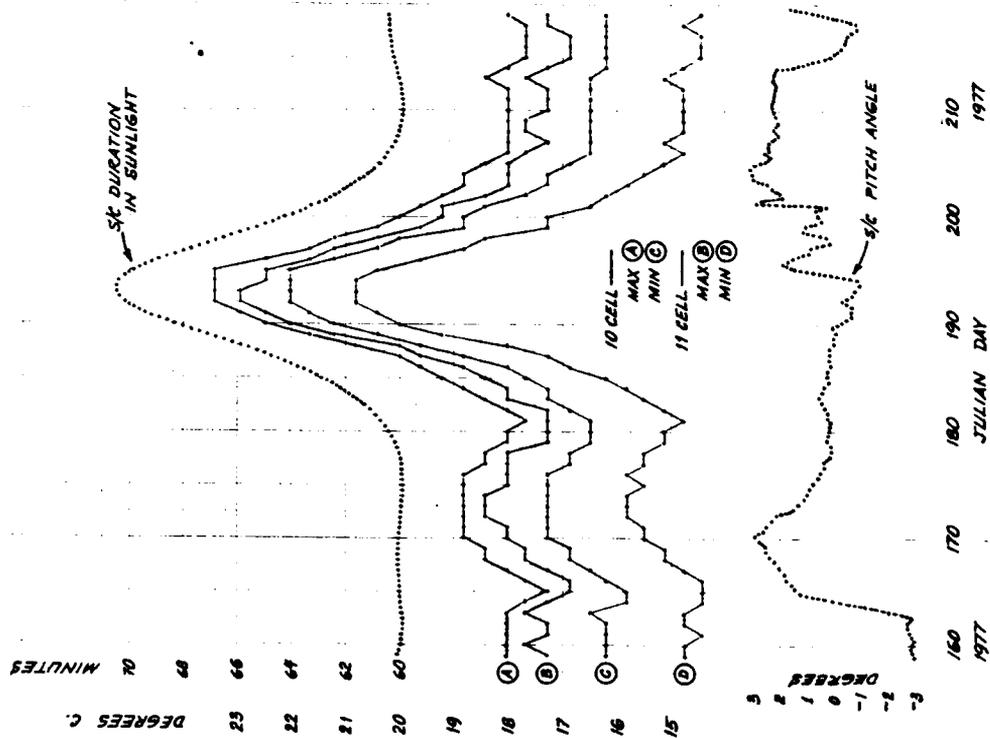
BATTERY 1

BATTERY 2

Figure 40

OSO-8
BATTERY 'MIN-MAX' DAILY
VOLTAGE LEVELS
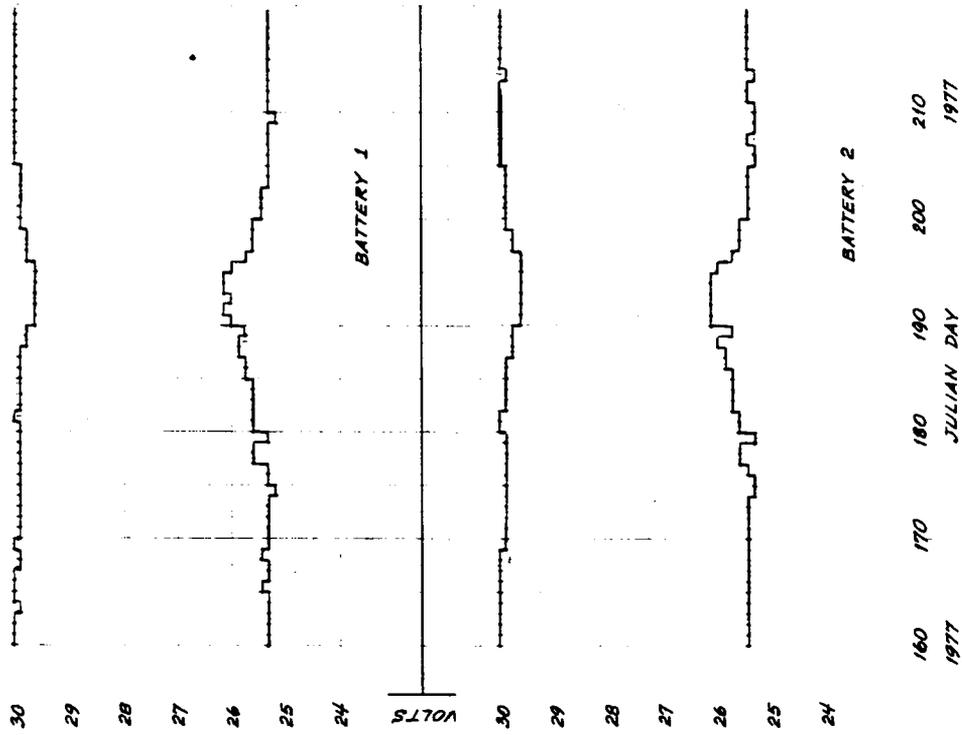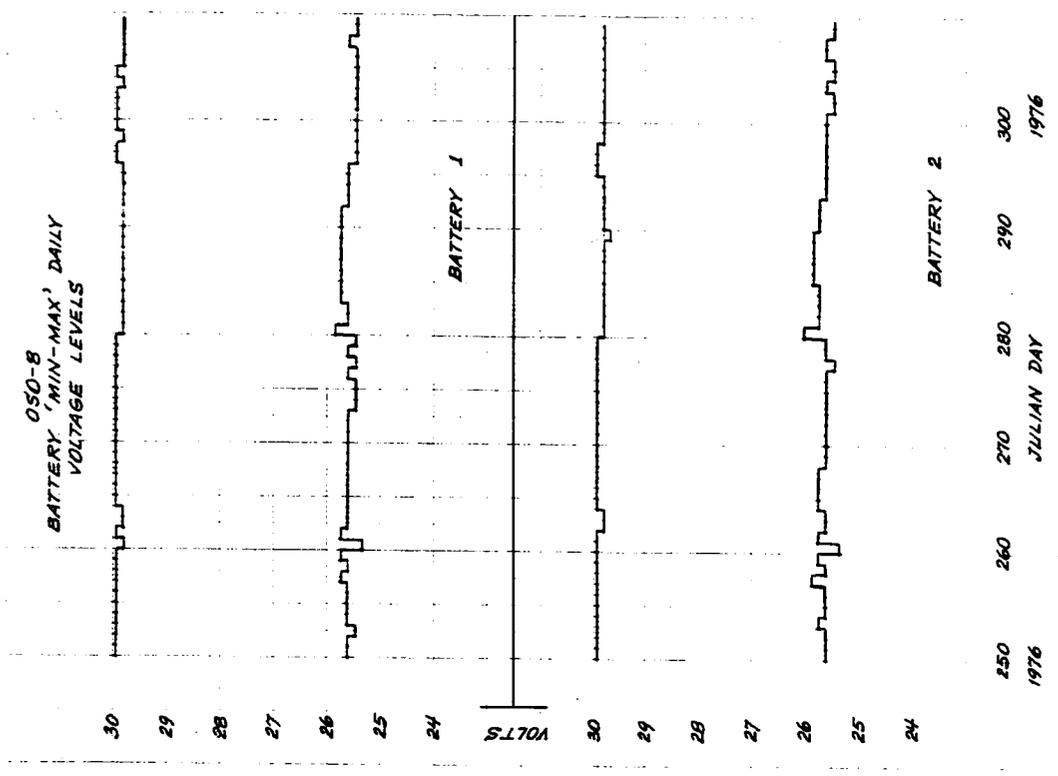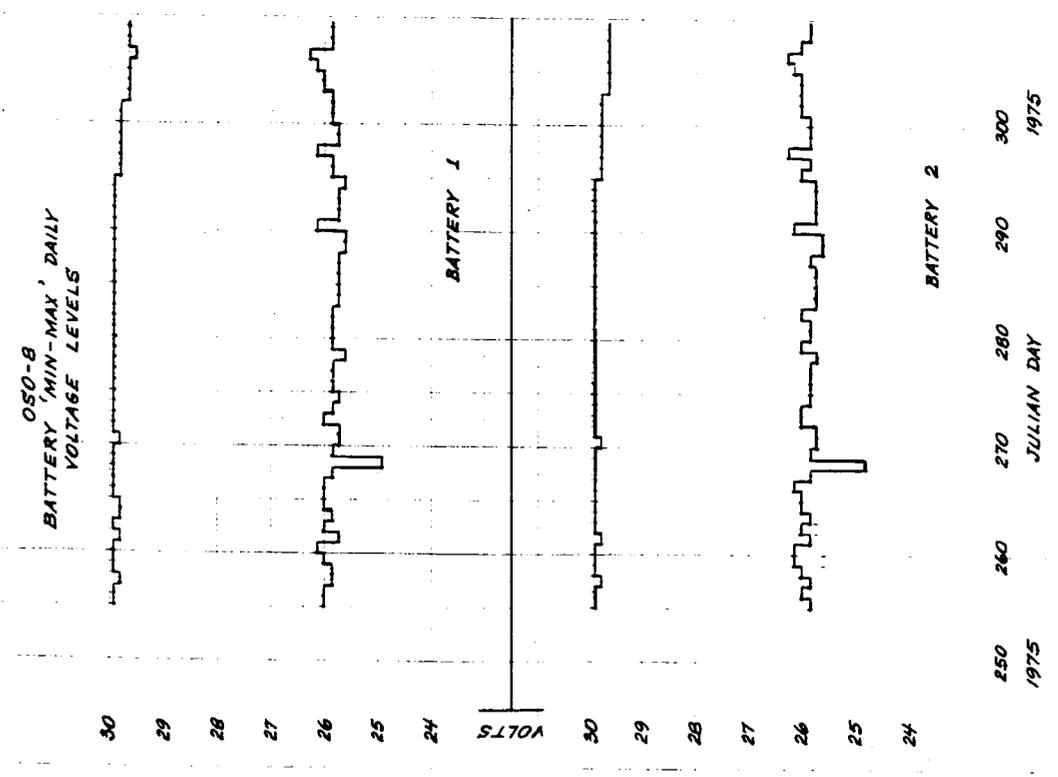
BATTERY 1

BATTERY 2

Figure 39

OSO-8
BATTERY 'MIN-MAX' DAILY
VOLTAGE LEVELS

BATTERY 1

BATTERY 2

Figure 41

54
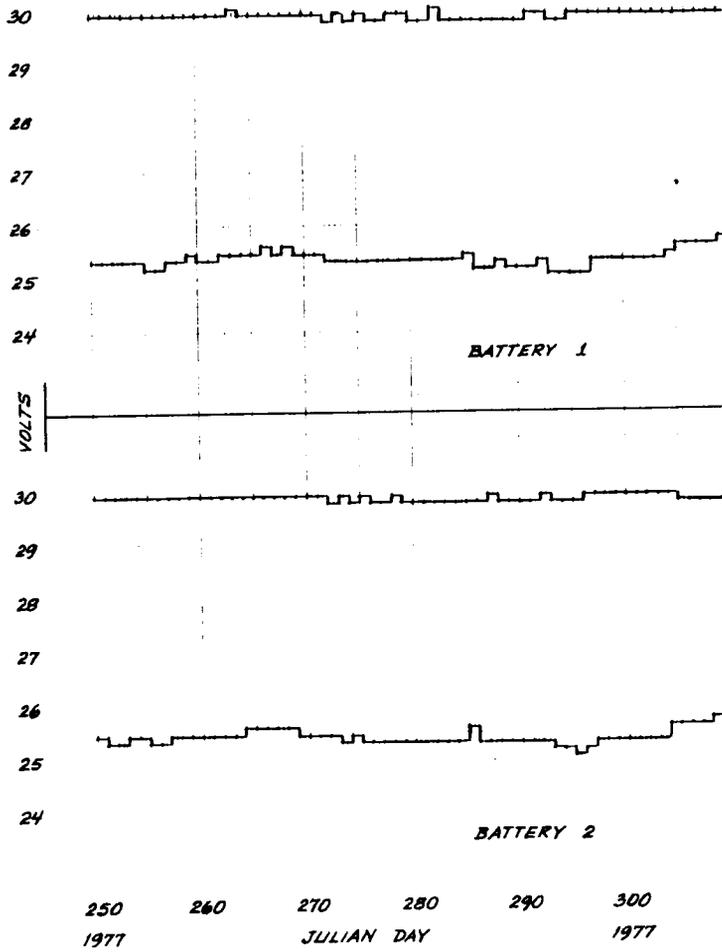
ORBITING ASTRONOMICAL OBSERVATORY
BATTERY AND POWER SYSTEM DESIGN

F. E. Ford
Goddard Space Flight Center

I would like to recognize the effort of Mr. Harry Wajgras of the OAO Control Center which provided me with all the data I am going to present to you this morning. Harry is with Grumman Aerospace and works here at Goddard, and he is the controller at the OAO-C spacecraft now.

As most of you know, OAO's series of spacecraft has a heritage back in 1962-63 as far as the conceptual design is concerned.

(Figure 42)

But we went through an evolution of designs, and what I am going to present to you today is the results of OAO-C, which in August exceeded five years of operational life. And at the conclusion of the data that I present for OAO-C I am going to give you a comparison with the differences that are even greater from OAO-A2, which also completed about five years. And I believe OAO-A2 was launched in 1968, December to be exact, and OAO-C was launched in August, 1972, I believe.

In summary, the battery design consists of three 20-ampere hour 22 series connected cells in the battery. This is in contrast to the OAO-A2 which had 21 series connected cells. There are three batteries per spacecraft. There is a unique packaging configuration which I will give you a little more detail on. Basically the three batteries are packaged in two mechanical assemblies. Each assembly contains 11 cells in each battery, and the two battery assemblies are isolated in a thermal base. They had a design life of one year in near earth orbit with a 15 to 20 percent depth of discharge. The temperature design range was 40 to 70 degrees F, and it had a 95 degree F thermostat which protected it from high temperature conditions. It has eight commandable levels that are temperature compensated, and the batteries are in parallel for charging. And they are also in parallel for discharging except they are decoupled by diodes. It has an undervoltage that is hardwired into the system at 26.4 volts, which turns out to be about 1.199 volts per cell. And as I said earlier, the spacecraft was launched in 1972.

(Figure 43)

This represents the different profiles of a battery assembly. There are two of these, and this is a pictorial view of the top, the bottom, and the side views. All I want to mention here is that this is the heat sync side. The battery does not have a heat sync mounted on it. The heat sync mounts to these that protrude to the cells here. And there are eleven cells. As you look around the battery you see battery 1, 2, and 3, eleven cells in each battery. And I repeat, two of these assemblies are mounted side by side in this spacecraft.

The reason I point this out is when I talk about battery temperature I talk about battery assembly temperature.

(Figure 44)

In order to fully comprehend the operational aspect this is a simplified block diagram of the power system, which consists of the 3 batteries connected in parallel. Notice you can disable a battery from charge or from the charge bus, but you cannot disable a battery from the discharge bus. The charge regulator has the V versus T characteristics in it. The system operates such that when you require the sun the shunt relay is closed, which is referred to as a shunt charge mode. When the battery voltage hits a present limit, this relay opens up, the charger comes in series and regulates the battery voltage as a function of temperature.

(Figure 45)

The eight levels that are used in OAO-C I put them up here because I will be referring to them later on as levels and not necessarily actually voltages, showing the curve design.

(Figure 46)

Now this is a summary of the operating characteristics that we have observed during 63 months, or as of November of this year, over 27,000 orbits. Typically the mode of operation they have used the BVLS level 1 and 2, -- refer to the right-hand screen -- for low array power, meaning that the system was somewhat energy starved for whatever reason, namely due to the experiment mode of operation or where they want to look in the celestial sphere. They have gone to level 3 or 4 essentially to enhance the recharge as well as available current that may be coming from the array. The typical discharge capacity per battery is 2.8 to 3.2 ampere hours. The maximum discharge opening the battery has been 4 ampere hours. Throughout the orbit life the average temperature has been about 50 degrees F. The variation has been from 46 to 52, and you see that the average is very close to the maximum, such that it says that is pretty close to where the battery has been operating for over five years.

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The recharge ratios, to the best I can determine, within the revolution of telemetry, what they have, and also up to orbit 21,000 they had what we call a SOCU, which is a state of charge unit. And a brief description of that: each battery had an ampere hour integrative. They monitor the current; they integrate it. And it had a readout of ampere hours, and it was set up so they could read the discharge ampere hours and the recharge ampere hours. The recharge ratio is up until orbit 21,000 and was determined through the SOCU. Also the SOCU was monitoring for the third electrode signals, of which they have had three. The most negative cell in each battery has a third electrode in it.

The system had a closed loop such that the SOCU could operate it, letting it charge up to voltage level 8 until they got a signal from the SOCU dependent on the ampere hour meter on the third electrode and it will switch it to level 1. This mode of operation was never used in orbit. It was used strictly as a monitoring device. The spacecraft flew on the fixed V versus T at levels indicated previously.

The battery current sharing throughout the life, as far as can be determined, is within the resolution of the telemetry. And I believe Harry told me that was like a tenth of an amp, that they could not distinguish anything less than that, and that they know that there has been no more change than a tenth of an amp between the battery current sharing over the five years.

The battery and the voltage setting, I mentioned earlier, the hardwire design was 26.4 volts. And I believe that comes out about 1.19, 1.2 volts per cell. Now notice that increments are reduced 23.3, and I guess that deserves somewhat of an explanation. This spacecraft flew one of the first On Board Computers, called the OBC. As a result, they were able to do a lot of things for real time monitoring. And when they were on the backside of the orbit you spend a majority of your life on a near earth orbit out of contact. The On Board Computer did a lot of looking and processing and monitoring of the conditions on the spacecraft. So, we knew before we launched that voltage was going to decay below the undervoltage, but knowing they had the ability to program the On Board Computer they decided they would let it run that way and then as they needed to lower that voltage on a real time basis. And that is what the reduction on an incremental basis is -- again, it is to 23.3. Now in a few minutes I will show you some discharge profiles to show you about how close they have been hitting to that, coming down to that voltage lately.

(Figure 47)

In talking this presentation over with Harry Wajgras, we realized that with 27,000 orbits you have a lot of data. So you have to be somewhat selective

in what you are going to present and what you are going to discuss. What we chose to put forth was not the early orbit characteristics but the more recent because that is really where the degradation has come to be observed.

What I have shown here is a comparison of the discharge, curves of OAO-C. Please note the scale. This is not 0 to 4.4. It is an extended scale, showing the last few minutes of contact with the satellite when they had real time data. The early orbit also had a tape recorder. As long as the tape recorder was going they could get any data they wanted. But, the tape recorder failed. I guess it was interesting to note there many things have failed before batteries do in a satellite. So all we have here is a comparison of the discharge voltage for orbit 13,590. We have also 10,420 and then a more recent one, 20,667. I said that the voltage I believe was like 23.3. You see, this was the closest they have been to that undervoltage. Recently they have made plans to drop that another increment.

But on this scale I plotted the volts per cell to show you that basically what they are doing or what it appears to be doing is reaching down into the lower plateau that we have observed in cycle test.

(Figure 48)

Here is a little more detail covering almost the entire history of the sunlight, starting with orbit 2,000 and then going to 17,000. I just want to point out that this gives you an indication that they have operated at level 1, level 2, and these were selected orbits pulled out. And the reason they are pulled out is that for practical purposes these orbits were pulled to be representative of repeated conditions. As you have seen earlier this morning, some satellites have very routine orbits. Once they get in a profile they stay there orbit after orbit after orbit. Others don't. And they only go into low profile or the power will vary from about 350 up to almost 500 watts, depending on what they are doing, the altitude, et cetera.

What I want to point out to you is that this represents the end of discharge voltage, degradation, that they have seen under normal conditions. Now the one I have shown you previously those orbits were typical of deep depth of discharge in the range of 4 ampere hours, not normal. Those were on the cases where they had to go down for some reason and pulled more capacity than they were doing on a normal basis.

Another reason for showing this to you is it also emphasizes the consistency in battery temperature. And this spacecraft probably has one of the most solid thermals on it as far as keeping that battery cool as any one we have

worked with in a long time. But I might also point out that this is being enhanced because we are not overcharging the battery a lot.

The other thing of interest here is that the OAO-A2 was the first time we flew third electrodes. Of course, they also flew on this mission. And I think I reported at a power sources symposium in 1972 of an anomaly of bird on third electrodes and how we got degradation, apparent loss in sensitivity in orbit. We are seeing the same loss of sensitivity in third electrode on the OAO-C. And what you are seeing here is a set of conditions over a larger performance where the recharge, as far as can be determined, is about the same each set of conditions, but with the same C to D ratio the end of life third electrode, overview, are decreasing. Now I won't go any further on that. I don't think it is germane here, but maybe later on tomorrow when we talk about cell degradation, cell characteristics, I think it would be worthwhile to pursue this and how this may be a manifestation of other things that are happening within the battery.

(Figure 49)

We put together a summary of the comparisons between OAO-C and A2. And why we do this, well, what we call the A2 we had some problems along with the satellite batteries before we really got to the five year period. While I said earlier the battery did perform for five years, they were finding certain constraining conditions of which they had to maintain in order to keep the battery within temperature range. As a result of that and other input, in the OAO-C design we expanded the voltage levels. And if you look back through the literature you will find some voltage levels published for OAO-A2. You will find out they don't have the same low levels here on a first load basis as the OAO-C does. What happened is we got more capability by going to a lower voltage level. I guess the main thing that drove this is that on A2 we found out after about two and a half or three years in the high sun time and you will remember the gentleman before me showed the high percent sun time, the low sun time where you had about 83 percent of the orbit in sun time at level 1, they could not control the overcharge current sufficient to keep the battery temperature down. In fact, near the end of the fourth year and in the early part of the fifth year before they shut off the spacecraft they found out to keep control of the overcharge during the high sun time at the end of that level 1 they used an A2, which was about equivalent to level 2 1/2 on this curve here to the best I can remember. They had to really smooth the spacecraft off of an unfavorable sun angle to get the level of power down. That was the only way they could keep the battery temperature.

The other factor that we attribute to the battery performance, longevity in a sense, is that the overcharge on A2 batteries there is no question in anyone's mind that they have been lower than what they were as far as the overcharge on

A2 or higher than OAO-C. Of course, part of that they operated at a higher temperature because of additional overcharge. And as pointed out previously both batteries exhibited a decrease in sensitivity of third electrodes. The depth of discharge of the OAO-C was running about 3 to 5 percent on the average higher than the depth of discharge of A2.

As a consequence of a number of items, which we don't fully understand all of them yet, the battery end of dark voltage on the OAO-C appeared to have degraded more in the same time period than the A2. Now you can say well the depth of discharge was a little greater. All these things tend to have a cumulative effect. And in my own estimation it is hard to single out any one thing, which I doubt if you ever could, to say this is why this happened.

Now I mentioned the A2 along about two and a half years exhibited signs, and this is documented in another paper that I presented of negative limited on charge. And I just put these factors up here not really to show what they mean as an area of concern to us, but we do know that one major difference explaining the cell production of the A2 batteries and the OAO-C was in a formation discharge, where that was done, and also we know that there was a significant difference in the way the precharge was set. And based on historical data we strongly suspect that the A2 cells of the cells used in A2 batteries had considerable more precharge than cells in OAO-C, which I think the number was 4.6 ampere hours. Each cell had an identical amount of precharge in the OAO-C. We don't know what that number was in the A2. All we know is from historical data that the process tended to lend itself to very high precharges under a certain set of conditions. Thank you.

DISCUSSION

GROSS: Boeing. Floyd, I don't understand the role the computer played in setting the undervoltage limit lower.

FORD: Okay, first, after about six months they disabled what I refer to as a hard line ERG function. In other words, they inhibited the electronics from doing anything if you got below the undervoltage setting they had designed for the spacecraft. Then they took the On Board Computer. Since all the telemetry information was available to it, they programmed it in a software package to look at battery voltage. And it had the capability to command a spacecraft independent of the ground controller. That is one of the things the computer could do. It flew the spacecraft. It could do a lot of things the ground controller could do. So what they did was they programmed the computer such that if they hit an undervoltage, on which they could set by ground then, that it would be the same thing basically as if they had hit an undervoltage with an electronic circuit.

And basically by the fact that it was a software package then instead of hardware they were able as the battery voltage degraded, you know, to ratchet down and to stay just under it throughout the five years.

RITTERMAN: TRW. I think you have two effects that seem to counteract each other. On your formation to a given ampere hour you intend to increase precharge, short, take the negative electrode all the way down to minus .2. On your venting of oxygen, and putting in a fixed number of ampere hours, you intend to decrease the precharge. Do you have any idea which it is, what magnitude, the charge is effecting?

FORD: Well, first of all, I am not sure I understood your premises from which you made your statement from.

RITTERMAN: I will say it again. You have a formation to a given ampere hours out but not to a negative voltage, negative electrode. So that formation tends to decrease the precharge. You leave more cadmium in the negative electrode.

FORD: You can, yes.

RITTERMAN: Then you were comparing two different methods. In one case you discharged negative down to minus .2 volts. The other case you just discharged to a given number of ampere hours.

FORD: Which was less than we would get out to minus .2.

RITTERMAN: That is right, and therefore you have more cadmium in your electrode.

FORD: In the former, yes.

RITTERMAN: Right. In the second case what you do is you vent oxygen, but you don't measure the oxygen that you vent. You simply charge to a certain ampere hour input. And in that case because of oxygen recombination your precharge is low. So you have two effects that tend to cancel each other. Yet your comment was that precharge was lower in the superior performing cells. Do you have any idea as to the magnitude?

FORD: You have got interacting effects.

RITTERMAN: Yes, and counteracting also.

FORD: Yes. Just because you deplete a negative doesn't mean you can't vent enough oxygen to control conditions to get the precharge back up. In the case of the OAO-C I believe the number was 4.6 is what you told me, right? 4.6 ampere hours of oxygen was vented from each cell after we had depleted the negative to between .2, minus .2 and minus .25. So, while I am comparing it with a condition where we depleted the negative less, went through a vented charge, of which I have seen negative cells that vented charge will in fact give you a lot more precharge than 4.6 ampere hours, I have seen it said it would give you less than 4.6 ampere hours.

I think the point I want to make here is that there was what I consider now a fairly significant difference in the production of the cells. And I know from the previous life of cells used for the OAO-B, we did measure fairly high amounts of precharge that we felt like was indicative of the amount of precharge that was in the A2 cells that flew on the earlier spacecraft. I am not sure I have answered your question.

RITTERMAN: Again, let me make the point that when you set the precharge venting, and you count ampere hours, the precharge that you measure, ampere hours, in actuality is less because oxygen recombines at atmospheric pressure. My point is the other factor when you discharge a cell a fixed number of ampere hours without going into complete exhaustion of the negative you leave precharge.

FORD: Yes. But one point that I think is very controversial, if you limit it at that point, what condition it would end later on when you reconstruct the cell and put it through testing, there is a lot of data that says you get different results, depending on time of day, the time of the year, the group of plates you are processing or what. There is a species of cadmium there that may or may not be readily available when the cell is assembled.

SEIGER: Yardney. When you describe the discharge to minus two-tenths of a volt that is with respect to what?

FORD: That was in the flooded plate test with respect to the positive.

SEIGER: The positive had exhausted. So you had a cell.

FORD: Right.

UCHIYAMA: Floyd, I wonder if you could put up your slide (Figure 47), where you had the discharge -- In that curve there, are you suggesting that you are seeing that the whole plateau on discharge? As I understand the curve

there, you seem to have taken out 3.2 ampere hours out of the total. What is that? About 40 percent?

FORD: It is about 20 ampere hour cell rated.

UCHIYAMA: Are you saying that you have a discharge that continues along there to final discharge and that this is a portion of that discharge curve?

FORD: On the life tests we did on the ground, yes, that is exactly what I am saying. We have never taken a satellite beyond this point to my knowledge.

UCHIYAMA: So if you have looked at the total discharge curve and flow charge to the end this is evidencing the --

FORD: Yes, that is what I am suggesting based on life tests.

GROSS: Boeing. Floyd, was there ever a need to open up that relay flowing to the individual batteries during the charge?

FORD: Somewhere in the neighborhood of over 11,000 cycles they were concerned about the voltage degradation. Incidentally I put the pencil there to show you 3 ampere hours with typical of what they were taking out. This is beyond the normal depth of discharge. And I think that over 10,000 is a situation where what they did in order to get this curve to orbit 10,420 is they disabled one battery so that the other two batteries would go to a deeper depth of discharge. And this is what they have got. They were more or less experimenting around to see if they in fact could see this thing stabilize out, as they did in several consecutive points showing a new regulating point on the battery voltage is what they were trying to find out. But they only did that over a period of about 100 to 200 orbits. Since that time I don't believe they have done it again. I will tell you why. They left that battery on open circuit for a while, and then they went back on. And the third electrode on that battery it took it about -- I think Harry told me -- 1,000 orbits before it got back to normal again. It really kind of worried them a little bit, because they weren't sure what happened. But, you know, the battery went on open circuit, it discharged down, and there is no charging for a few orbits. As it comes off the line because it is decoupled, it is going into further sort of depth of discharge. It was receiving no charge, so the third electrode was dormant for several orbits. And then they put it back on, and although the ampere hours as they built back up so that they were getting it recharged, the third electrode never indicated that it was recharging. In fact, it was erratic for several -- I think two or three hundred orbits following that.

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GROSS: If you were going to redesign that system would you charge and discharge the batteries in parallel the same way you have done here? Would you make some changes? If so, what changes?

FORD: Well, the alternative was sequential charge. I certainly wouldn't do that. Yeah, I guess we are satisfied that we have a viable system. We don't like the degradation we see, but the alternatives available to us in near earth orbit, alternatives meaning if you want to recondition, are not very attractive when you consider you have to take a battery off the line several days to do it. The answer to your question is yes, because basically the MMS system which will be talked about later on, I think tomorrow, and some tests we have done is similar to this system, if you had up to three batteries in parallel on charge. The main difference is that bypass relay that is around the charger is no longer there. That charger is in series with the batteries at all times.

I might point out that in contrast to what you heard this morning where you had I think eight batteries charging and discharging we had a much better thermal control on the batteries here. There is less than 3 to 4 degrees F between any of those batteries. The batteries are not, you know, spread around on a big platform on which you can get temperature spread. If you have to go to that type system, parallel charging is not that attractive, because the parallel charge you have got to assume you are at one of these points over here, on this curve, and you have got to assume one point for all batteries. The same is true on discharging.

Figure 43

OAO-C BATTERY DESIGN SUMMARY

- 20 AH NICKEL-CADMIUM CELLS (GULTON)

- 22 SERIES CONNECTED CELLS PER BATTERY

THREE BATTERIES PER SPACECRAFT

- TWO MECHANICAL ASSEMBLIES
- EACH ASSEMBLY CONTAINS 11 CELLS OF EACH BATTERY
- BOTH ASSEMBLIES LOCATED IN ISOLATED THERMAL BAY

OPERATING DESIGN LIFE	1 YEAR (NEAR EARTH)
	15 TO 20 PERCENT DOD
TEMPERATURE	40 TO 70 F RANGE
	95 F THERMOSTATS
CHARGE CONTROL	8 COMMANDABLE LEVELS
	TEMPERATURE COMPENSATED
	PARALLEL CHARGING
UNDERVOLTAGE	26.4 VOLTS 1.2 VOLTS/CELL
SPACECRAFT LAUNCHED	AUGUST 1972
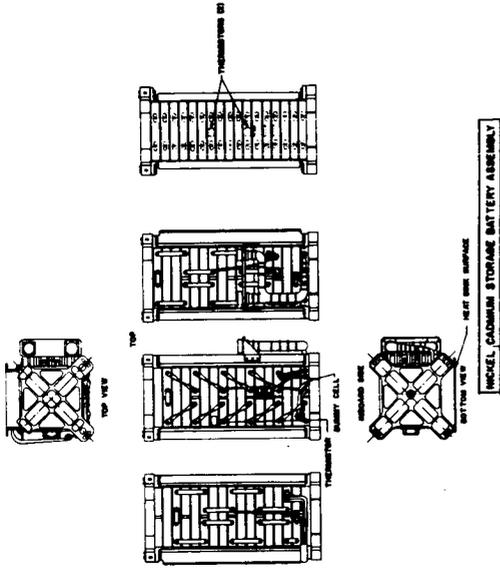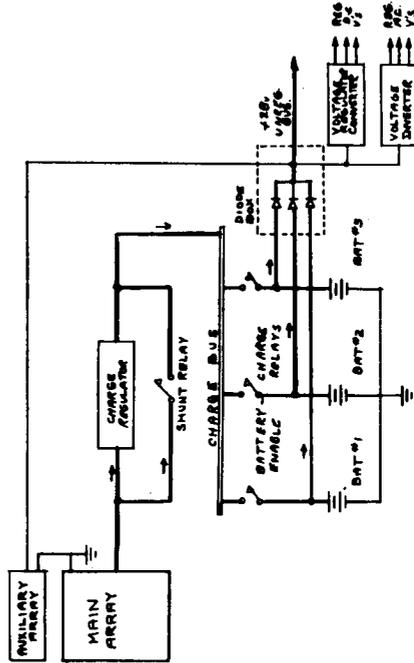
Figure 42

POWER FLOW
(FUNCTIONAL)

Figure 44

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OPERATING LIFE AS OF NOVEMBER 1977	63 MONTHS, 27,620 ORBITS
BVLS LEVELS USED	NORMAL OPERATION - 1 OR 2 LOW ARRAY POWER - 3 OR 4
TYPICAL DISCHARGE CAPACITY	2.8 TO 3.2 AH PER BATTERY 4.0 AH PEAK PER BATTERY
BATTERY TEMPERATURE	AVERAGE OF 50 F RANGE OF 46 TO 52 F
RECHARGE RATIO	TYPICALLY - 105% MINIMUM - 103%
BATTERY CURRENT SHARING	WITHIN RESOLUTION OF TELEMETRY
BUS UNDERVOLTAGE SETTING	FIRST SIX MONTHS - 26.4 VOLTS INCREMENTALLY REDUCED TO 23.3 VOLTS
SOCU FAILURE	21,050 ORBITS
SOLAR ARRAY DEGRADATION	APPROXIMATELY 20%
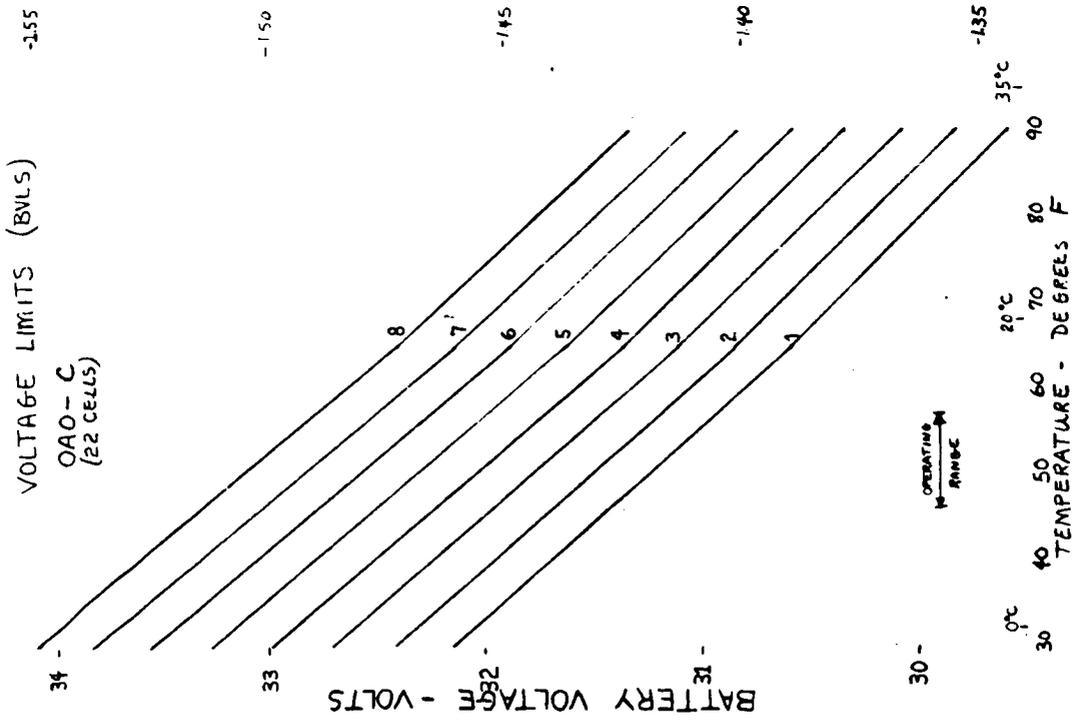
Figure 46

OAO-C END OF DARK VOLTAGES

Figure 47

VOLTAGE LIMITS (BVLS)
OAO-C
(22 CELLS)
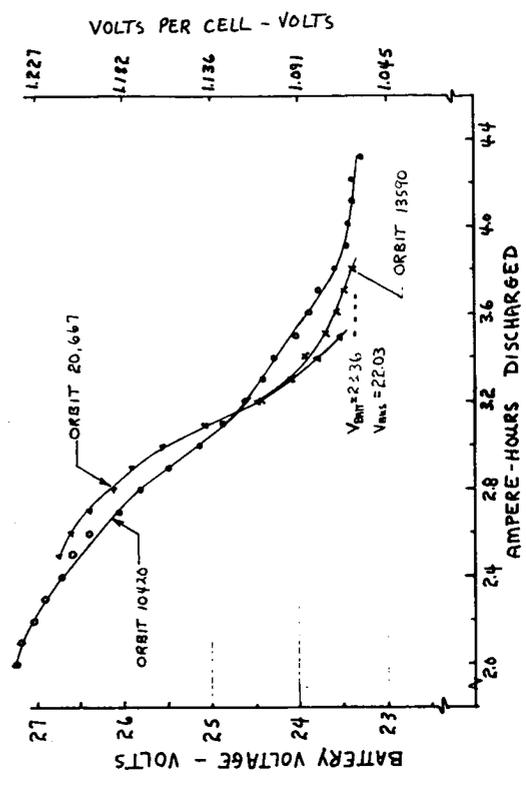
Figure 45

SUMMARY OF BATTERY PERFORMANCE

ORBIT	BVLS	BATT. VOLT. (EOD)	THIRD ELECTRODE (EOL)* #1 (MV)	#2 (MV)	#3 (MV)	S/C LOAD (WATTS)	BATT. TEMP °F (EOL) #1	#2
2037	1	26.69	223	223	221	479	48.8	47.4
3138	1	26.49	211	215	201	477	48.8	46.8
4500	1	26.22	201	207	183	439	47.3	45.7
5841	1	25.89	185	199	169	450	50.8	48.5
7310	1	25.22	191	195	171	456	49.8	47.4
8725	2	24.95	233	241	223	450	50.8	45.5
8769	2	25.09	231	239	225	451	50.8	48.5
11,475	2	25.09	131	153	229	449	51.3	48.9
17,613	2	24.56	197	205	213	441	50.3	48.1

* (EOL) END OF LIGHT

Figure 48

COMPARISON OF OAO-C WITH OAO A-2

- BVLS RANGE EXPANDED (LOWER LEVELS) FOR OAO-C
  -- LOWEST A-2 LEVELS NOT ADEQUATE TO LIMIT OVERCHARGE AFTER TWO YEARS

- OVERCHARGE OF A-2 BATTERIES HIGHER DURING LIFE

- A-2 BATTERIES OPERATED AT HIGHER TEMPERATURE DURING LIFE

- BOTH BATTERIES EXHIBITED DECREASE IN THIRD ELECTRODE SIGNAL

- DEPTH-OF-DISHCARGE FOR OAO-C GREATER THAN A-2

- BATTERY END-OF-DARK VOLTAGE DEGRADATION APPEARED GREATER FOR OAO-C

- A-2 BATTERIES EXHIBITED SYMPTOMS OF NEGATIVE LIMITING ON CHARGE

- KNOWN MANUFACTURING DIFFERENCES

	A-2	OAO-C
FORMATION DISCHARGE	NEGATIVES DISCHARGED FOR FIXED TIME	NEGATIVES DISCHARGED TO -.2 VOLTS
PRECHARGE	VENTED CHARGE FIXED TIME AND RATE	EACH CELL CHARGED AND MEASURED O_2 VENTED

Figure 49
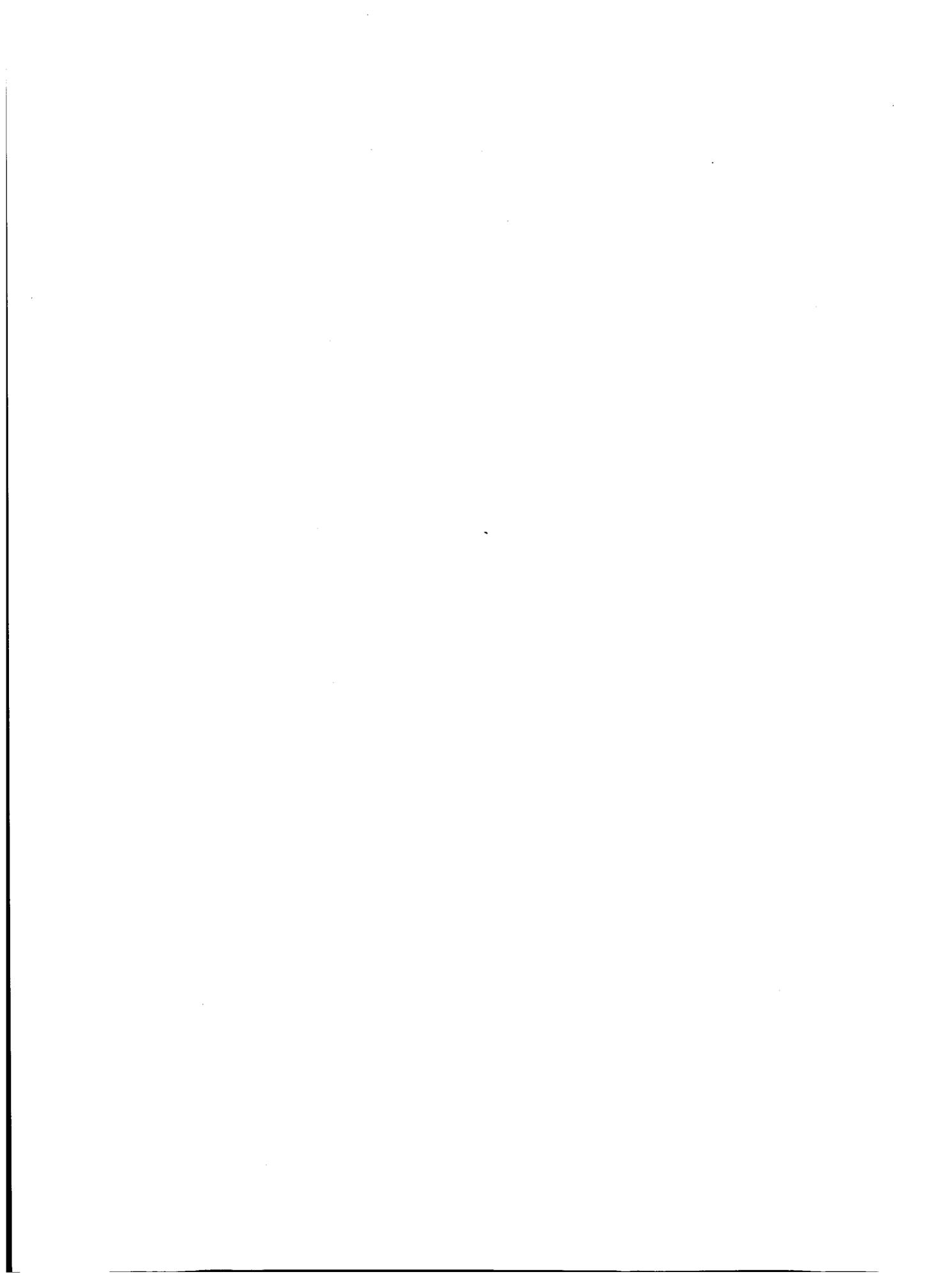
SYNCHRONOUS METEOROLOGICAL AND
GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES
BATTERY AND POWER SYSTEM DESIGN

D. A. Baer
Goddard Space Flight Center
and
W. J. Schedler
Ford Aerospace

INTRODUCTION

(Figure 50)

BAER: The prime contractor was Ford Aerospace, and they also built the battery. Eagle-Picher was the cell manufacturer. It was a three ampere hour nickel cadmium prismatic cell. The battery consisted of 20 cells connected in series. And I think the weight was typically about seven and a half pounds. There were two batteries per spacecraft.

(Figure 51)

The charge control was controlled basically from the ground. There were three ground commandable charge rates, C/13, C/20, and C/35. This is more typical of beginning of life. End of life they dropped off a little bit. The ground controller would select the charge rate based on battery voltage, temperature, and what use it was in, as to whether it was in Sun or whether it is in the eclipse. Also, there are the periods when there are loads on during the Sun periods. There is undervoltage of an average of 1 volt per cell, and these were in five cell groups. So if any one group dropped below 5 volts why then the battery would be taken off line. And one or both batteries could be placed on open circuit also by ground command.

(Figure 52)

I will just briefly run through this block diagram. The bus is a 29 volt bus, and during the sun periods it is maintained at 29.4 volts by clamping the lower part of the solar array with some shunt elements. I was going to briefly mention this area here is mostly control circuits for driving the shunt elements and also for the boost regulator. There is also charge control array. Actually there are two, one for each battery. And they are broken up into two different segments, and depending on which of these relays are thrown determines what

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your charge rate is. As you can see, like I said, there are two of them, one for each battery.

During discharge or dark, the batteries go through a boost regulator and boost the output up to 29.4 volts. About the only other pertinent item is that there is a battery undervoltage control that is located here. And there is also some overcurrent disconnects in the system.

OPERATIONS

SCHEDLER: I am from Ford Aerospace. However, I am assigned to NOAA - NESS locally here, real time engineering on the spacecraft.

I want to show some of the typical data on battery voltages and temperatures that the spacecraft see during a normal operational day.

(Figure 53)

We happened to pick a 302 here on SMS-2, and I have shown both batteries 1 and 2 to try and show you how closely or not so closely they track. In this particular case we see only voltage shown. There is one place you notice that is called satellite midnight. This is the time during the day when we have maximum load conditions relative to the sun, because this particular spacecraft has an opening in it which takes a proportion of the array during one part of the day. When your peak loads are occurring, when the visitor is taking a picture, you are also looking directly at the sun. So, as you look at some of these pictures you will see this effect, always off in that portion of the picture.

(Figure 54)

This is kind of the first available information on GOES-2 bird, which is the latest one that was launched. This is eclipse data, where we of course with the synchronous orbiting satellites don't have all these daily or orbital excursions and dipping into the battery. This happens two times out of the year for 30 or more days.

This is a day in the eclipse towards the middle of the eclipse period, where we got down to a 44 percent depth of discharge. The normal maximum depth of discharge is about 48 percent during the peak, the longest eclipse periods, which last somewhere around 72 minutes.

Some of the things that you will notice on here are the changes in temperature from batteries 1 to 2. There is almost 3 degrees difference in

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temperature. This also shows up on a normal operational day. If you just chop out the middle of discharge and recharge time and extend the lines across you will notice that they end up at about the same point. Some of these things we will talk about later on when we talk about eclipse problems.

(Figure 55)

One of the next things I want to talk about is, that one was more specifically in the area of delta T from batteries 1 to 2. Here we have a delta V problem. And you will see typically in this particular as it goes to one satellite that battery 1 tends to have overvoltage characteristics, whereas battery 2 doesn't. And those come from different cell lots. There is a difference there of maybe a volt and a half to maybe two volts. This is during the recharge of the battery. You will notice right in here we made a charge rate change. And the reason for this is we know historically with this bird that we couldn't leave it in the two-thirds charge rate during the recharge cycle after eclipse because it would exceed the voltage limits. So we make preplanned charge rate changes. Now this was this year, 1977. And the reason you see there are data missing in here is that we were time sharing, having to operate three birds instead of two, and we didn't have telemetry during that period of time.

(Figure 56)

This is the SMS-2 bird again, and we will see quite a dramatic overvoltage condition there, recharge up, or a smaller eclipse. And I don't know exactly what that depth of discharge was, but it looks like perhaps in the area of 12 to 15 percent.

In this particular case it wasn't expected seasonally that we were going to have to make this charge rate change, using the previous year's history. So we got surprised here, and the voltage went up over 30 volts, 30.143 volts. That is 1.5 volts per cell. The battery was at about 15 degrees at that time. The controllers did not catch this event. Presently we have a limit. I think it is about 30.05 volts, 15 degrees, not to exceed a half an hour. Then you are supposed to change the charge rate. But this one inadvertently was missed, and you can see right here when the charge rate was reduced it made a dramatic step down. And you can see what happened to the other battery, the one that seems to be much more stable.

One other point, they have had some play in this larger change. I also showed here the main bus current load profile during recharge. Normally this would have come up and stayed on here, but for some reason there was a load change made there so that you were recharging not with a full load on the system. That could have had some effect on that.

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(Figure 57)

This is a picture of what we sort of expected to see during that eclipse. This is a 15 percent depth of discharge. We didn't expect it to exceed the 30 volts. So, the controllers weren't alerted to expect that.

(Figure 58)

Here is, just to point out the voltage differential thing, another eclipse day where the voltage peaked at a much later time. It stayed well within the limits. Here we are really trying to point out the kind of nominal voltage differential from battery 1 to battery 2.

(Figure 59)

This is a comparison here, and I will see if I can get most of it on. I will get it up as high as I can here. This is a comparison of two years, 1976 and this year 1977. It addresses about a half a year, starting at day 124 through day about 324, which is kind of where we are currently at the latest data.

We can see here that we had to make some operational changes, which we hadn't done in previous years. This is the -- let us see. Which spacecraft is this? I will have to skip over which one it is. This is one of the spacecraft that this year we operated at the three-thirds charge rate, which is something that we hadn't expected to have to do.

If you will look at the solid line here, the solid line in all cases are 1976 data. Our trickle charge is 80 milliamps, about a C/35. Our two-thirds charge rate, also known as intermediate, is 150 milliamps. You can see here the effects of temperature and voltage increasing. By the way, these are minimum and maximum voltages and temperatures. So we can see here that the spread in voltage, min and max, closed as we went to the higher charge rate. The dip that we see over here is the autumnal eclipse period. On this particular spacecraft we have no way of increasing loads or doing any sort of reconditioning, although we do what we call a pseudo-reconditioning at the start of each eclipse period. Instead of decreasing the loads, with an anticipation of going into an eclipse, we leave them on. And you can see here the voltage decreasing down towards the very first part of the eclipse. The first couple of days when we expect the eclipse to be very short we don't bother to change loads. We just let it ride through.

Historically we have gotten improvement in the batteries. You can see that the voltage is increased then.

The dotted line is of some interest this year because of the three-thirds charge rate. Here we can see the effect of going to the three-thirds charge rate on the maximum voltage. The spread seems to increase relative to the previous year's operation. The minimum voltage is going lower. Now some of this can be the effect of the way the spacecraft is being operated in that the batteries are demanded more. But the one interesting thing to note is that after being in this three-thirds charge rate for about two months right here we seem to be somewhat lower than the previous year data. At this point here we changed back to the two-thirds. We saw a subsequent drop in maximum voltage, which is approaching a volt difference from the year previous.

We attempted to do as an experiment a reconditioning by turning on every available load that we had in the spacecraft. Unfortunately, that was only about 9 percent. You can see the effect, that the lower voltage started to come up, whereas the upper voltage limit remained the same.

Thin line you see here is when this spacecraft was placed in a standby mode when the GOES-2 was brought on line as the operational bird. The load dropped maybe 3 or 4 amps. Shortly thereafter we went to the one-third charge rate. The minimum voltage came up. The maximum voltage continued on down to where there was very little difference between the two. Well, one of the reasons is they really aren't being exercised. But I think the trend, though, that we are looking at and we were worried about was the decrease in the battery voltage down to under 27 volts. So we watched as we went into this last eclipse.

Here you can see this eclipse reconditioning cycle. And right away the voltage started to go back up. And after going through this eclipse the voltages, minimums and maximums, are now again tracking the previous year's data. However, keep in mind they are not really being used. Their voltage is back where it is expected to be.

I want to talk a little bit about the problems involved in having to do this operationally. Each eclipse year we have to make a plan for each particular bird as to how we are going to operate it when the charges have to be turned off or modified. Where can this be a problem? The problem is, number one, that extra commands are required. The geostationary birds, those birds take pictures. There is only about a ten minute period of inactivity each half hour, so any extra commands that we are asked to send are rather involved in the operation. When we are asked to change charge rates, they oftentimes like to have a real time engineer there when this happens because they feel they can't ask the controller to make these kinds of decisions. So this demands more time to look at things until we can decide at what time of the day should we change the charge rate so we don't go over.

On occasion we have had problems where the commands that are sent aren't executed exactly correctly. We have sometimes ended up in the three-thirds charge rate when we have wanted to be in the one-thirds charge rate.

With the controller having so many things to do and so many things to look at on his screen sometimes he doesn't catch this voltage creeping up and creeping up. So it is a dangerous situation operationally.

The other things that we would like to talk about then is operationally how could a battery behave better where it wouldn't have these kinds of problems. One of the obvious things is to have better control over the cell to cell variations or in this case battery to battery variation. As you can see, this battery 1 takes precedence over battery 2. So anything that we have to plan on we have to look at the worst case. Presently we have gotten around operational problems, but as solar array degrades normally in time we are going to have to start looking at maybe placing one battery on a different charge rate than the other. Things have become a lot more complex. And it is not -- because it is in eclipse time that we are having to do this. The eclipses change every day, starting off at just a few minutes and go down to 72 minutes. It means that you have real variable situation on your hands, not like the non-synchronous where you can kind of predict that it will do this each day. You can't do that, so it is kind of custom planning involved.

The other obvious thing there is having cells that are less susceptible to the overvoltage problem in the first place.

We have a couple of questions that operationally would be helpful to us. One is a study on which is better, many small dippings into the battery or several larger ones spaced days apart. As the spacecraft gets older we are going to start getting into batteries on a daily basis.

And the last thing is something that is probably available that we just don't have and that is a better V/T plots or something that would be easier to use at the control level. Right now we have like three charge rates, three temperatures, and three upper voltage limits that with time you are allowed to be in that. And some of the problems you have is what happens in one case, where you saw the large excursion, the operator looked at that and said, "Oh, it went up to over the limit, 30.1." It is not allowed to be in there for over a half an hour. So 20 minutes later it dipped down for one sample period and went back up. Now you get another half an hour. So, operationally we need a better plan on how to tell them what has to be done.

DISCUSSION

NAPOLI: RCA. I didn't understand some of the things you had on that one chart. Would you go back to the one where you had all those --

NAPOLI: The one where you showed the 1976, 1977 comparisons. (See Figure 59)

What I don't understand is on the upper curve you have autumnal eclipse. For some reason I see the voltage is going up during eclipse rather than going down. I don't understand that curve, the top two lines, the dotted and the solid lines.

SCHEDLER: That is a good question. I don't really know the answer.

NAPOLI: I believe that that looks like a 44 day, you know, cycle, but I don't understand the curve above that.

BAER: I think what happens sometimes here is that they use them at varying depths of discharge. And it depends what loads are on during the eclipse as to how much depth of discharge you are going to go to. Now, if you go through an eclipse where they don't take any pictures or they have a very light load, then you aren't going to go to as low a depth of discharge as you did the previous.

OBENSCHAIN: I think also, Walt, that the upper curve is during the daytime, the night voltage --

SCHEDLER: Yes.

OBENSCHAIN: Okay, you just change your charge rate for the most part from a one-third to a two-thirds you have got a higher charge rate, and you are also using your battery, recharging it. The bottom curve is the minimum voltage during the night, and the upper curve is at a higher charge rate during the daytime.

SCHEDLER: Yes, and when he says night he means eclipse.

NAPOLI: You have got the end of charge and you have got the end of discharge.

OBENSCHAIN: Exactly.

SCHEDLER: Right. I think another thing that we see here too is this overcharge peaking situation on one of the batteries that is going to give us this situation.

OBENSCHAIN: Where is the overcharge peaking on that? It looks like they are all staying at 29 volts.

SCHEDLER: You are right. I guess on this one it is. One of the reasons that might be is that some of those data may not be included in that curve.

SPARKS: TRW. I take it from your comments that if you had your choice as far as manual control from the ground you would vote against it.

SCHEDLER: Well, I hate to speak on an operational problem coming from a company that built the bird. Sometimes you might say that that would be true, a more automatic system would be better. I guess there are problems with both.

SPARKS: Do you find, you know, in trying to handle this thing manually that it is taking up an awful lot of your operational time?

SCHEDLER: To date it hasn't been; however, again, the reason it isn't is that we select some time during the day where we feel it is a good time to change the charge rate. Now as we get later in life where we will have to use more and more of the capacity of the battery and there is less array power to recharge it this is going to be more difficult and perhaps require controlling the batteries individually.

OBENSCHAIN: I would like to make one comment here. Walt, not to minimize the concern and the problems you are going to have downstream it seems to me that so far you have less problems, say, than Phil Brandt or the other people who have had to work on the near earth orbits. I mean, this doesn't seem to be an extraordinary amount of work to me because it changes once a day, the charge mechanism. Whereas, on a lot of near earth orbiting satellites you have to work at many, many. So, you know, I just do not see a problem here.

SCHEDLER: I would say that I wouldn't want to be in a near earth orbit and have to do every day manual control.

OBENSCHAIN: You wouldn't want it, and it is probably not desirable. But it happens, and I think it was presented here for two hours. Okay, so, you know, I just don't see how this is a big problem when you compare it with the people who have to work near earth orbit satellites and have to do it every day.

SCHEDLER: I agree.

SMS/GOES BATTERY DESIGN

- CONTRACTORS: SPACECRAFT & BATTERY - FORD AEROSPACE
  CELL - EAGLE PICHER

- CELL SIZE & TYPE: 3 AH NICKEL-CADMIUM (PRISMATIC)

- CELLS/BATTERY: 20 CELLS CONNECTED IN SERIES

- BATTERY WEIGHT: 3400 GMS (7.5 LBS)

- BATTERIES/SPACECRAFT: 2

Figure 50

SMS/GOES CHARGE CONTROL & BATTERY PROTECTION

- CHARGE CONTROL: THREE GROUND COMMANDABLE CHARGE
  RATES - C/13, C/20, C/35

- UNDER VOLTAGE: AVERAGE OF 1.0 V/CELL, SENSED IN 5 CELL GROUPS

- ONE OR BOTH BATTERIES MAY BE PLACED ON OPEN CIRCUIT BY
  GROUND COMMAND

Figure 51
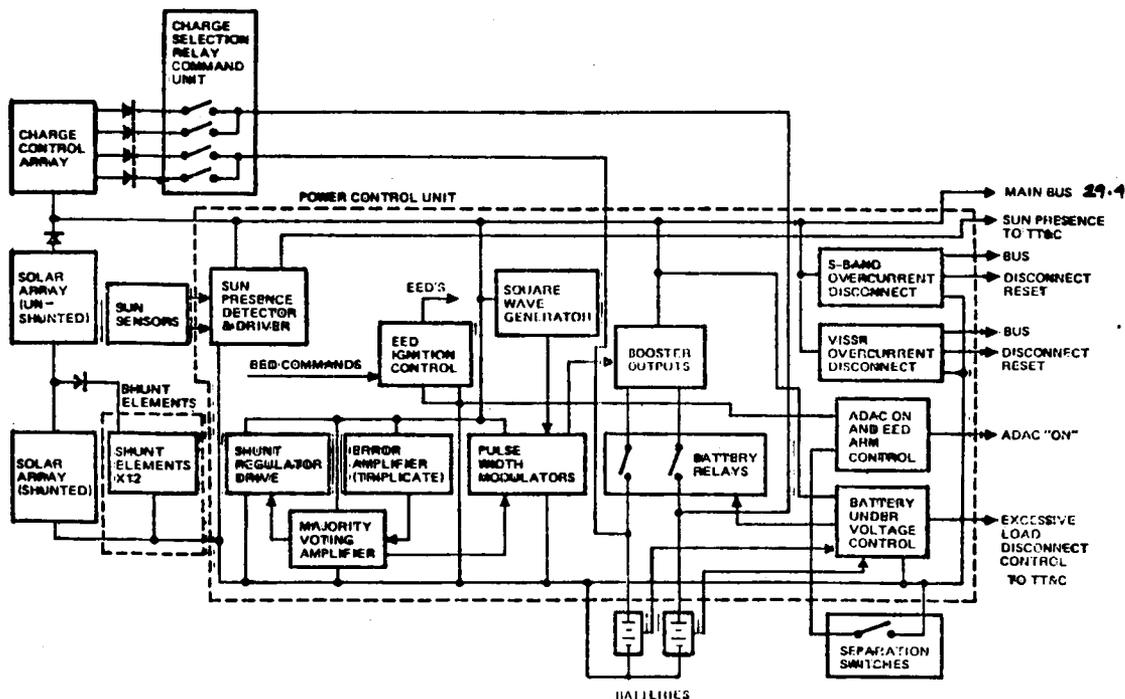
Figure 52. SMS/GOES Power Subsystem Block Diagram

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ECLIPSE OPERATION - BATTERY 1-2 TEMPERATURE DIFFERENTIAL

Figure 54

SMS-2 ECLIPSE RELATED CHARGE CYCLING TO PREVENT OVERVOLTAGE

Figure 56

NORMAL NON-ECLIPSE OPERATIONAL DAY

Figure 53

GOES-1 ECLIPSE RELATED CHARGE CYCLING TO PREVENT OVERVOLTAGE

Figure 55

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GOES-1 OPERATIONAL VOLTAGE DIFFERENTIALS

Figure 58

SMS-2 OPERATIONAL VOLTAGE DIFFERENTIALS

Figure 57

2 YEAR ECLIPSE COMPARISON
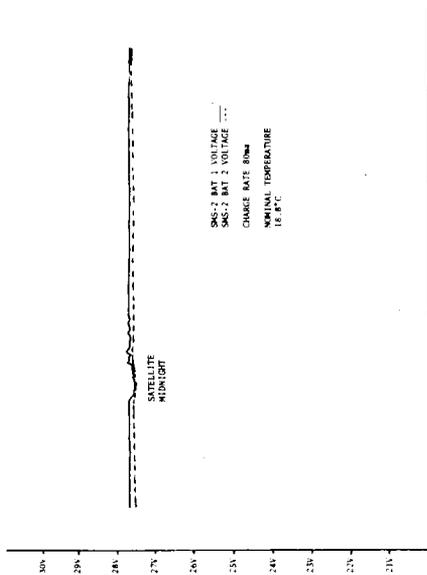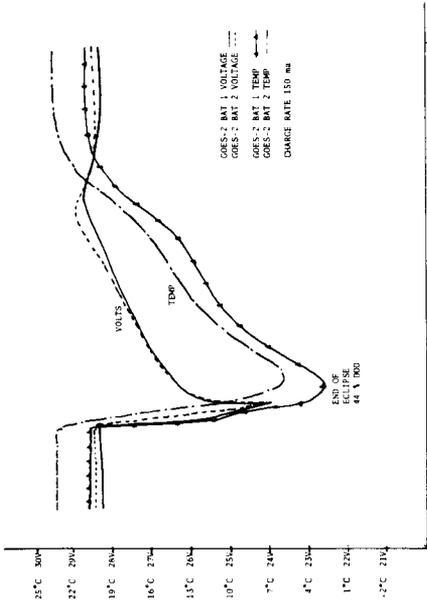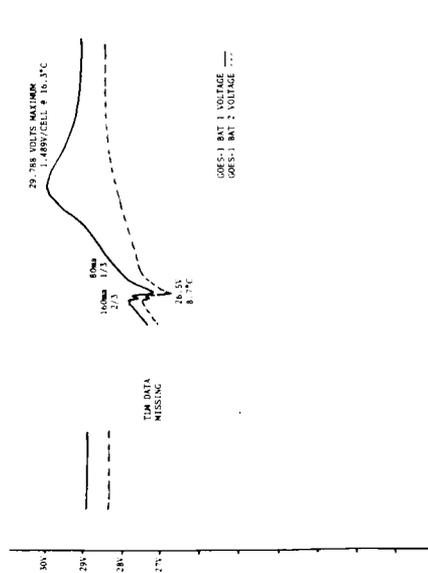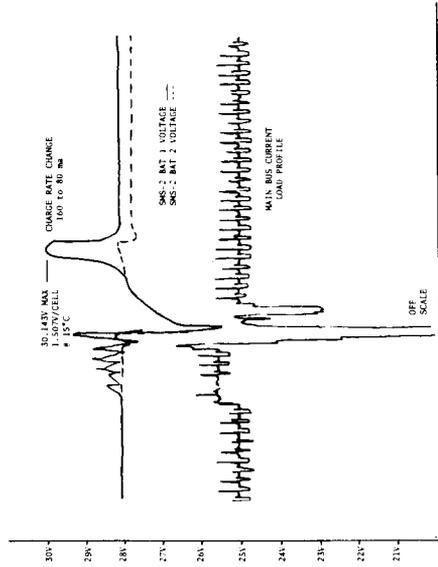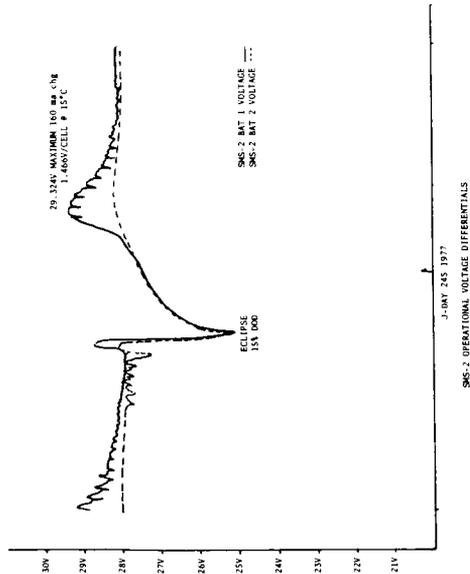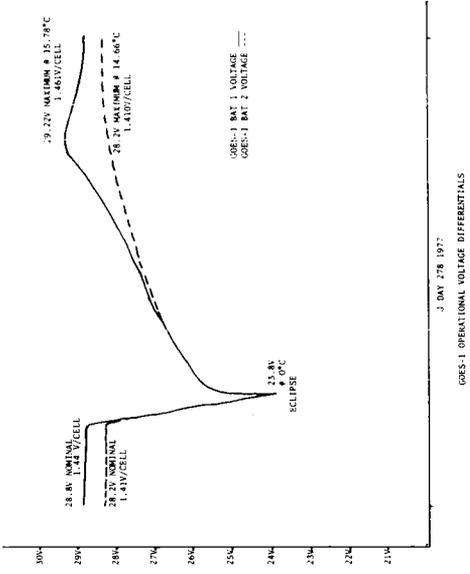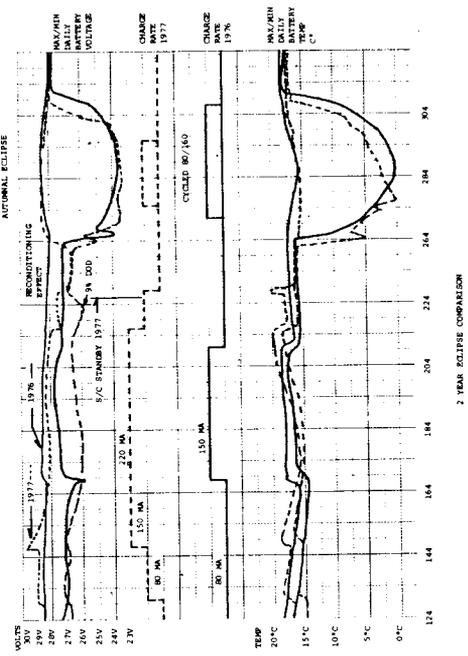
Figure 59

79

APPLICATIONS TECHNOLOGY SATELLITES
BATTERY AND POWER SYSTEM DESIGN

F. E. Ford
Goddard Space Flight Center
and
B. Bemis
Westinghouse

INTRODUCTION

(Figure 60)

FORD: A summary of the ATS battery design which is onboard the Applications Technology satellite (ATS) is provided here. The 15 ampere hour nickel cadmium cells were manufactured by Gulton, 19 series connected cells per battery, and there are two batteries in each spacecraft. The operating design life was two years in a synchronous orbit, and a maximum depth of discharge of 50 percent. The design temperature for the batteries in the spacecraft was 0 to 25 degrees C, and the charge control consisted of 1 volt versus temperature on a constant percentage voltage. Also, C/10 current limit, and a commandable trickle charge rate, using C/20 or C/60. The undervoltage was sent across a 9 cell and a 10 cell group, and it was set at one volt average per group on either group.

The spacecraft was launched in May of 1974 and not included in the design but old orbit requirements included the support of a site experiment which required for periods of about six months, I believe, two discharges each day. And these two discharges did not coincide with the eclipse mode, except to require that because the spacecraft load demanded more than the array could put out that the batteries had to go through approximately two cycles per day. And this was as of 5/76 there were over 337 cycles in this mode.

(Figure 61)

A picture of the battery, a photograph of the ATS battery, shows the construction. As I said earlier, there were two of these used in the spacecraft.

I will leave the V versus T at this point.

81

(Figure 62)

BEMIS: Early in the design phase of ATS-6 it was decided that instead of merely using the battery to support eclipse that they would be used to support experiment loads in excess of the solar array power.

(Figure 63)

And that is a history of what the solar arrays have done over the first two and a half years in orbit. That is about as predicted.

(Figure 64)

As time goes on the requirements on the batteries increase, or else we are going to have to start cutting off some experiments. Eventually we are going to have to start cutting off experiments anyway if we plan to keep the thing going.

This diagram shows the battery charge characteristics, battery voltage versus charge/discharge ratio. The taper charge comes in at about 95 percent state of charge at a C/60 rate. One of the problems that we have had with ATS-6 has been that at the C/60 rate we never reach full charge. So, we have had to command the standby charger into operation to attain a C/20 rate of charge to bring the batteries up to full charge.

Another of the problems that we have had on ATS-6 is that the location of the shunts to take the extra solar array power when the batteries are fully charged is such that they heat the battery up. Consequently, we have had to turn on an experimental load in order not to use the shunts during the hot temperature season.

(Figure 65)

We have got a couple of other curves here. These show battery capacity trends. There are three curves here that are NAD Crane curves on flight hardware, and I have two curves here. One is an in orbit eclipse curve, and this is a curve of the slight discharges. That is at 2.1 amp discharge, which is extended beyond the normal satellite, television program somewhere over India.

(Figure 66)

This is a little bit busy, and perhaps too many Xeroxes. But these are just the latest data -- in fact, they were just plotted yesterday I believe -- of the number seven eclipse. And one of the things that is of interest to us is that this number seven eclipse right along here seems to have a much steeper slope near the maximum discharge than these other ones did which were out fairly straight. And this is of concern to us. I don't know what has caused it, or what we can do about it.

So, the three problems that we are concerned about on an ATS are the battery degradation -- is there something that we can do to improve it, the fact that we have to command the C/20 rate in order to get back up to full charge, and the fact that we have to turn on an experiment load rather than using the shunt dissipators where they were designed to be used, in order to keep from heating up the batteries.

DISCUSSION

NAPOLI: RCA. We have a similar charge rate on our satellite, C/60. We never use that to return to charge. That should be a maintenance once the batteries have reached the charge. We just use it to maintain. We use it not to have any internal discharge. It is not really a means to return the charge to the battery. That may not be a problem --

BEMIS: Well, we use a C/10 rate as our normal charge rate. When we get to 95 percent state of charge we go into the C/60 rate automatically. That was part of the spacecraft design. Since that does not bring the battery up to full charge we are not commanding a C/20 rate by commanding the auxilliary charging.

FORD: Goddard. If you would clarify that, the way I understand it is C/10 is for the voltage limit. Then the current will cut back and maintain a voltage limit and it will taper down to C/60? Is that the mode? You indicated you got a bi-level C/10, C/60. It is really a C/10 taper to what you said is C/60.

BEMIS: I don't know. Could someone else comment on that? Bob Leone, can you comment?

LEONE: Yes, that is correct. It is not a step function. It is a gradual decrease from the C/10 to a C/60. And operationally what we do is when we taper down to the standby charge, C/20, and then we command it, we maintain that C/20.

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LACKNER: Canadian Defense Research. I would like to have a bit of clarification on your voltage limit on charge. Does this mean that if you are charging at C/10 once you hit 1, 4, and 5 at 0 or 1, 4, 2 you are never going to go above that voltage? You are going to just put on a taper current, is that right?

BEMIS: Yes.

LACKNER: Now, I have the impression that provided the voltage does not escalate so high that you should have a little bit of a voltage peak because the more overvoltage presents when you have the more effective charge you are getting into this, as long as you are not getting into gas evolution. So if you had it in 1, 4, 5 at 25°C, I think perhaps you could get a little bit more increment.

FORD: Goddard. It is a big system. They have what they have.

LACKNER: But why do they have what they have?

FORD: It was designed with the voltage, the undercurrent charge, the voltage, and then a voltage tapering. With the two level charge rates available to them by command, and I believe those two levels do not have a voltage limit -- current -- when they go to that mode of operation. So they do have the other mode, which is not restricted by the voltage.

BEMIS: That C/20 rate is a fixed rate.

SPEAKER: Well, when you go to C/20 can you go above your 1.45?

LEONE: No, we try not to overcharge.

FORD: Goddard. Can you comment on what the temperature of the two batteries has been running?

BEMIS: We are trying to maintain the battery temperature below 30 degrees. Actually we maintain it below 28 degrees. When the temperature gets up to 28 degrees we go ahead and turn on a transmitter just to take the power off the shunts and we use a transmitter for a shunt.

ATS BATTERY DESIGN SUMMARY

- 15 AMPERE-HOUR NICKEL-CADMIUM CELLS (GULTON)

- 19 SERIES CONNECTED CELLS · TWO BATTERIES PER SPACECRAFT

- OPERATING DESIGN LIFE - 2 YEARS (SYNCHRONOUS)
    - 50 PERCENT DOD MAXIMUM

- TEMPERATURE - 0-25°C DESIGN RANGE

- CHARGE CONTROL · VOLTAGE VS. TEMPERATURE (1 LEVEL)
    - C/10 CURRENT LIMIT
    - COMMANDABLE C/20 OR C/60 CHARGE RATE

- UNDERVOLTAGE - SENSE ACROSS 9 AND 10 CELL GROUPS
    - 1.0 VOLTS/CELL AVERAGE EITHER GROUP

- SPACECRAFT LAUNCHED - MAY 1974

- SPECIAL ON ORBIT REQUIREMENTS - SITE EXPERIMENT
    - TWO DISCHARGES EACH DAY
    - 30%, 43%
    - 337 CYCLES AS OF 5/76

Figure 60
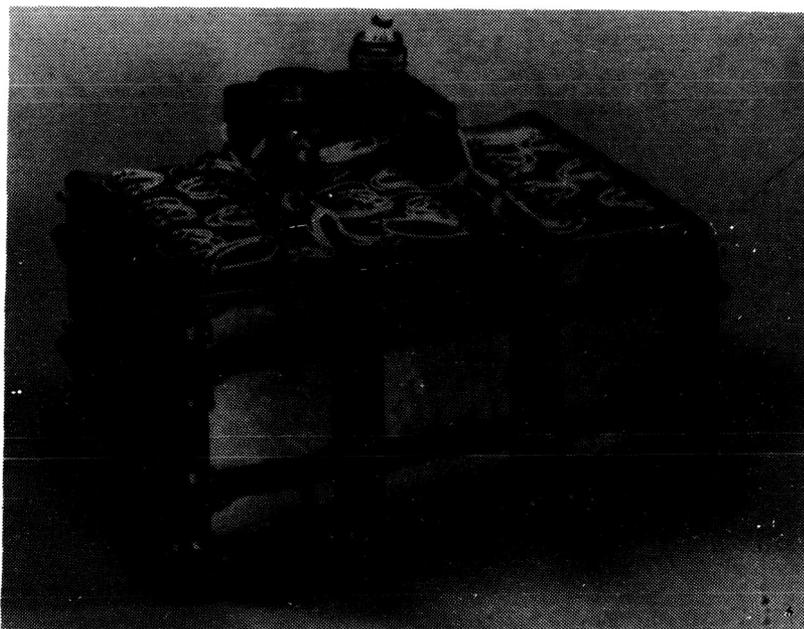
Figure 61
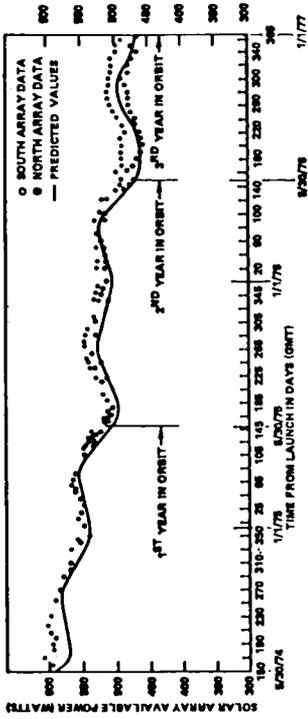
Figure 63
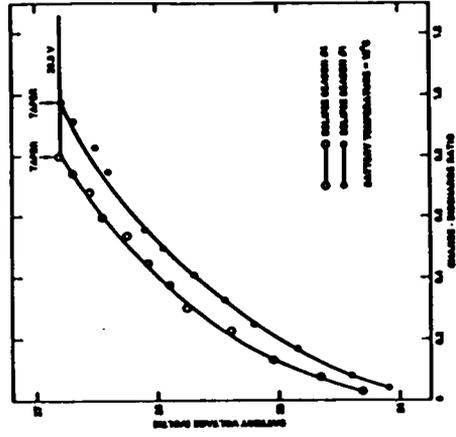
Figure 64

Figure 62

86
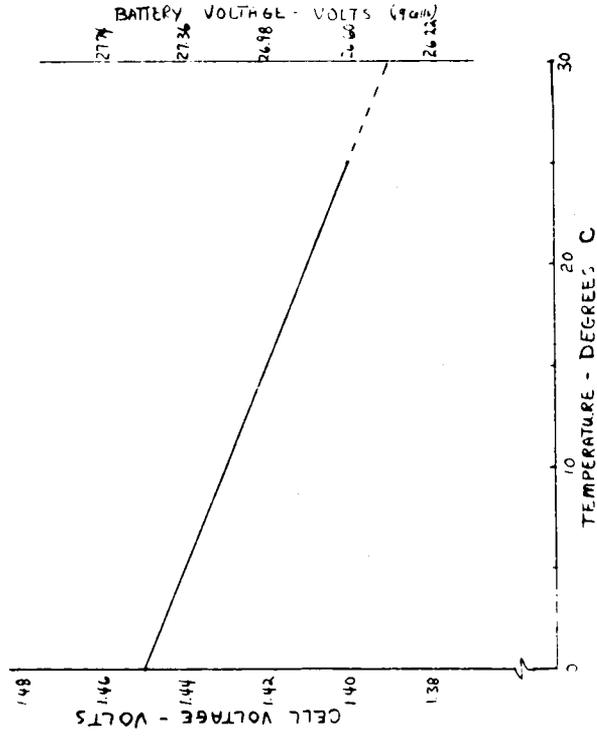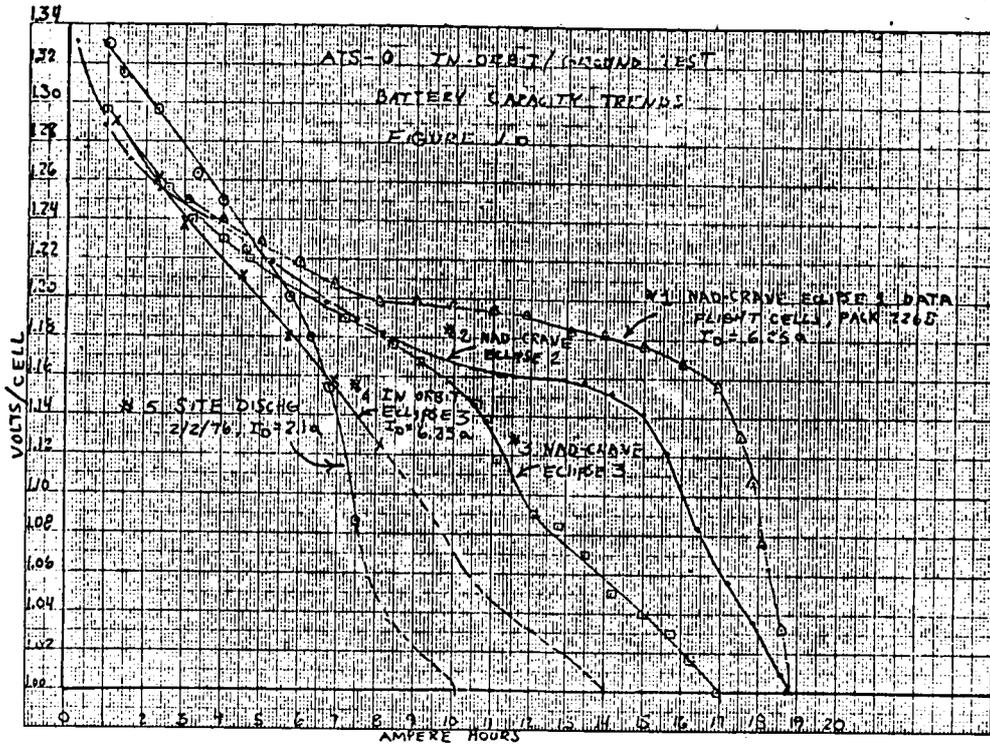
Figure 65

Figure 66

87
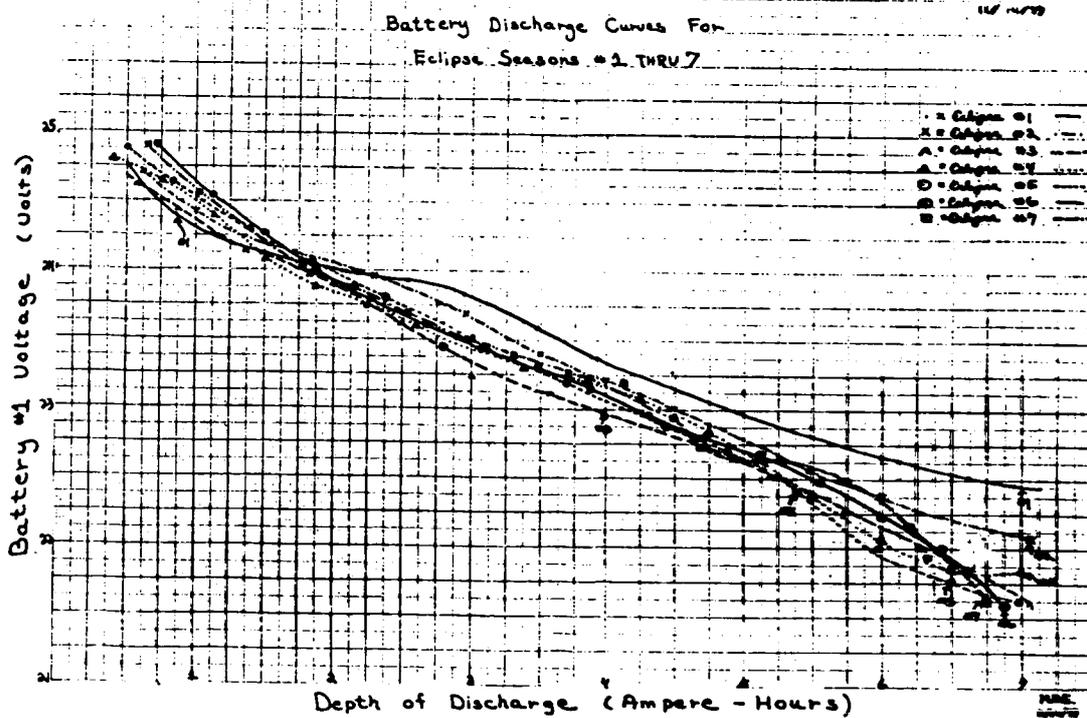
INTELSAT
BATTERY AND POWER SYSTEM DESIGN

J. Dunlop
Comsat
and
D. Cooper
Comsat

INTRODUCTION

DUNLOP: We are going to describe the in orbit data for the Intelsat
4 spacecraft.   The Intelsat 4 spacecraft have been in orbit, the longest one now,
for seven years.   So the data you are going to see in orbit are longer than any-
thing else you have seen so far this morning.   The Intelsat 4 F2 was launched in
January in 1971, and so in two months it will have completed seven years in or-
bit.   It has gone through 14 eclipse seasons.

On the battery the design of the Intelsat 4 battery, design life was for
ten years, with the operational lifetime of the satellite expected to be seven.   It
was approaching its operational lifetime design goal.   All of the subsystems in
that spacecraft were designed for 10 years.   It turns out that the batteries are --
and I repeat that, the batteries are -- probably the major, or at least one of the
major, subsystems that limits the lifetime of a synchronous satellite.

Now, before we are going to talk about the data, just by way of background
I want to briefly mention what cells they used.   That is very important to begin
with.   The cell that is being used in the spacecraft was designed 10 years ago.
As a matter of fact, it was designed right around the time of the first Goddard
conference.   It is an Intelsat 4 series, 15 ampere hour cell rated, G.E. cell.
It actually measures 20 ampere hours plus or minus one.   Almost every cell that
they have got from this will measure 20 ampere hours plus or minus one.   There
is some spread on it.

I have reported a number of times over the years results of electro-
chemical and chemical analysis on this cell as a result of laboratory tests that
have been run on a real time basis in our laboratory, and we have periodically
pulled cells from Intelsat 4 battery that has been on life test and reported data.
Hughes has done the same thing periodically on some of the work that they did.
So there is quite a bit of literature in both published data at other conferences
as well as this conference, describing the cell.

Basically I just reiterate some of the salient features. The negative-positive ratio measured electrochemically on this cell is about 1.7 to 1 when it is new. The negative electrode here will deliver -- you can measure 34 ampere hours in a flooded state new. That 34 ampere hours, roughly half of it is adjusted for overcharge and half of it is adjusted for precharge. So you have got roughly 6 or 7 ampere hours of overcharge protection, and 6 or 7 ampere hours of precharge. That is on the new cell.

They have 31 percent by weight KOH, 1 percent lithium hydroxide in this cell. The mild electrolyte in here is approximately 2.3 cc's per ampere hour. That is 2.2 to 2.3. That is fairly standard.

The nylon separator is normal, and the loading levels in these electrodes are very similar to the loading levels you will still find used in electrodes today.

The only thing probably that I would like to add is that the carbonate level that we measured in these cells when we first got them is a little higher than the carbonate level you are going to find today. It is about 5 grams of potassium hydroxide, roughly 10 percent by weight, 9 percent by weight of the electrolyte when they are new.

In the battery design it is very straightforward and simple. It is not too different than the one you saw where you use two batteries. And the batteries are made up of cells where we use 25 cells in series per battery. There is one battery per bus, so we use two separate bus systems. The way the battery is managed is that we use constant current charging with no voltage limits except as back up. We have three available charge rates at the beginning of life, C/12, C/24, and C/36. That is at the beginning of life. Those charge rates go down to something like about C/15, C/30, and C/45 at the end of life. Those charge rates are based upon -- the C rates are based on -- the 15 ampere hours rated capacity.

Now the batteries actually discharged, like every other battery, at a C/2 rate. And it is also a constant current discharge. It is around 7 1/2 amps design life. It varies, as you will see when the data are presented. That means it is discharged to about 60 percent on the longest eclipse day if you look at the rated capacity. It is only 43 percent of the measured capacity. Unfortunately, that difference between measured and rated needs to be stated because it is sometimes a confusing factor. Here, again, just to repeat that, it is 43 percent depth of discharge of measured and 60 percent depth of discharge of rated capacity.

Okay, and the battery operates in the temperature range of between about 3 degrees Centigrade up to about 17 degrees Centigrade normally.

The only other thing I would really like to mention is that the storage mode for this battery that was selected back about 10 years ago was open circuit charge stand, very low rate discharge. That is the storage mode, and we do a form of reconditioning.

OPERATIONS

COOPER: Okay, one of the things we are going to try to briefly go through here is the mission of course is Intelsat. We have 10 spacecraft we are using right now, five Intelsat 4's, which we will be talking about today.

(Figure 67)

Battery characteristics have already been covered by Jim Dunlop. The in orbit battery management, all the batteries now are in trickle storage mode except for two spacecraft which we have the lot 11's, which don't have overcharge protection. Those are on open circuit storage.

We do recondition the batteries once before each eclipse season, and we will go through some of that. We are going to show you the end of discharge voltage performance and some of the aging characteristics we have seen, some of what we consider failure characteristics, which are really not battery failures or spacecraft areas, just degradation of the battery over a period of time. And we will go on into the eclipse voltage profiles, some of the charge acceptance problems, loss of overcharge that we have seen, and some of the methods we have used to try to correct this.

(Figure 68)

This is the Intelsat 4 F2. We have battery voltage over here, a number of eclipse days, about 45 days for an eclipse season. The plots are only shown to the edges here because of the confusion that we generate if we try to plot the whole eclipse season. So what we are showing here is the third season, the fifth season, the seventh season, the ninth season, eleventh, thirteenth, and fourteenth.

The thirteenth and fourteenth the batteries were unloaded. They weren't carrying a full load. Up until about the eleventh season they were, which is a 7 amp load. So you can see that they have been dropping off. We have another chart that will show you what happened during these two seasons right here.

(Figure 69)

This is one of the other Intelsat 4 spacecraft. We are showing one battery here. The batteries are slightly different. We didn't try to do any comparison. Same scale, the voltage over here. We have 26 volts, about where we would like to go. 25 1/2 is about as low as we like to get. The same number of eclipse days. This is a whole eclipse plot here, 45 days, where the battery does come down. You get into about 69 to 70 minute eclipses during the plots you see here, the same as the 4 F2 type plot. This is season 1, 3, 5, 7, 9. We notice on season 11 the battery tends to trail off. In other words, you have the longest eclipse day here. The battery doesn't come back up when the eclipse days become shorter. This is the first sign we see of the battery having a problem. This season here the battery was when you turned off one TWT having an amp less load, a 6 amp load. And you can see what is happening to that battery. So whenever we see this we are pretty sure that the next season we are going to have a problem.

(Figure 70)

This I just threw in. It is not really what we are talking about. This is a 4F8, which only has been through six eclipse seasons. And it is a 4, 8 type battery, which doesn't have the same capacity or anything that we have talked about previously. It is not an Intelsat 4 type battery, a much heavier battery. So we do have much closer depth of discharge readings. What we are attempting to show here is that for one season we did not recondition the battery to see what effect reconditioning would have. So we have seasons 1 -- maybe if I can point these out a little closer -- 1, 2, 3, 4. 5 is down here, the season we did not recondition the battery prior to eclipse. And the sixth season you can see we are back up here. You can see this line. It is very close to the fourth season.

(Figure 71)

Here we are attempting to show last year's eclipse. This is the same -- the past two eclipses of the Intelsat 4 we had up here before. It is the eleventh and twelfth season with a little more detail. It is battery 1 and battery 2. The voltage scale is here for battery 1, battery 2. This is the eleventh season with the circles, and the twelfth season with the x's. You can see battery 1 the level was maintained, 6.3 amps for both seasons. And we can see that the battery is tending to drop off about eight-tenths of a volt. Battery 2 was running 6.8 amps with the circles, 5.9 amps. Like I say, after the longest eclipse season we noticed that fall-off, and the battery really doesn't recover very rapidly.

(Figure 72)

This is the Intelsat 4 F2, the one we really want to talk about, and this is the last, fourteenth eclipse season. And I needed to show you this because the other plot really doesn't tell the whole story.

We started out with this battery at a 5.5 amp load. We don't really use this spacecraft, so we wouldn't necessarily have to keep it loaded. We sort of wanted to see what it would do. Prior to this eclipse season we tried a deep discharge reconditioning. We went down to about 18 volts on the battery, and we are trying to see what would happen with a deep cycle reconditioning. We started out with 5.5 amps. We had to decrease the load here because we got down to 23 volt limit. The battery dropped way off in one eclipse day from here to here.

On this battery here we were continually changing the charge mechanism. We were using pulse charging. We will show you a chart of how we plot this battery. Every time we seem to change the way we charge it, which I will show you later, we did get some see-saw approach; however, the battery never came back up. We were operating at 6.4 amps up to this point, and then we are down to 5.3 and finally down to 4.3 to get it through the rest of the eclipse season. So we wound up with 6 transponders on that spacecraft, half a load.

(Figure 73)

This is a general overall picture of what is happening to the batteries. Can you see that? Down? Okay, what I want to show you is the eclipse seasons, first of all. This is through 14 seasons.

There are all the Intelsat 4 type batteries, and what we see is through about the sixth season we do fairly well. The ups and downs are because the loads do change from the different eclipse seasons, so it is not really a very true picture unless you look at the actual load on the battery. But in any case, as a general trend, when you are after the 14th season it tends to drop off rapidly.

(Figure 74)

To look at an actual eclipse, where we see what is happening, what is causing these low end of discharge voltages, this is the Intelsat 4, F4, battery 2. And this is a typical eclipse, and we tend to have a plateau and a second plateau, which brings us down to a little above 26 volts.

(Figure 75)

Here we see Intelsat 4 F2, which is the one that has been at 14 seasons, the bottom line again being 26. Both batteries are plotted here. Battery 1 is the top line here, and battery 2 the bottom, not that it makes much difference. But it is a comparison between the two batteries, slightly different loads, and you can see that the battery comes down and does tend to drop off right at the end of the eclipse period. However, when it gets down to here, it again levels off in that second plateau.

(Figures 76 and 77)

The eclipse lengths here are getting shorter by a considerable amount, and we can see that battery 1 now isn't dropping off. So, therefore, if you look at the plot each day you can see where the voltage jumps up. That is exactly what is happening.

So if you look at the difference between -- I don't know if I can line these up. Not very well. Well, let me just see if I can line the times up. The times are the same. The eclipses are getting shorter. I don't know if you can make it out here, but the battery here is stopping here. The other one is still dropping down, but it doesn't stay on a second plateau, so, if it wasn't for the second plateau which dropped down considerably. This is why the charge mechanisms we are using trying on a 42 battery 2 and battery 1 we have tried them, and this is at the low rate, four-tenths of an amp. Here we are going to a high rate, 1.2 amps, back to a low rate and back to a high rate. This is two hours of charge, one hour of charge, and this is the high rate charge for about 140 percent C to D.

None of these high charging or not charging or what-have-you seem to improve the battery performance after a period of time.

(Figure 78)

This is on the 4 F2. Jim mentioned that we normally open circuit storage or has open circuit storage in this spacecraft until the last year, 1976. This is right before we went to trickle charge storage, and it is a 20 day period of the battery just slowly decreasing, which is one of the reasons we decided to trickle charge storage.

(Figure 79)

This is after the thirteenth season. When we had seen that 42 battery was dropping off rapidly we thought we would try some deep reconditioning to see what would happen. So we went down really to 25 volts, which you don't really consider deep reconditioning, which is one volt per cell. And we only achieved about 6 ampere hours out of the battery of measured capacity by doing it this way. This is through a quarter amp discharge load.

This is an April reconditioned, two cycles, one right next to the other one, the first cycle. The second cycle we tend to get a little bit better. But you can see what is happening as the battery comes down.

A couple of months later we did the same thing again. We get a much smoother appearance. Now we tried this through four cycles, and it finally went down to 0. Each time we get an indicated capacity. However, when it came to the fourteenth eclipse season it didn't seem to help too much.

(Figure 80)

Okay, just a few more slides here since we are all getting hungry. This is a history of reconditioning, which is some measure of capacity. Over here we have the hours of discharge, and actually you can translate that into ampere hours. It is a quarter amp load. So I have two scales here, one is amps and one in ampere hours, or one of hours of discharge and one in ampere hours. In any case, battery 1 and battery 2, we were reconditioning the battery once prior to each eclipse season up until the end of 1973. And we went to once a month reconditioning, double cycle about that time.

One thing you might notice is the dots on here indicate the first cycle, the x's the second cycle. So, the second cycle we tend to, you know, change somewhat. Each eclipse season -- I don't know if you can see them marked here. These are the eclipse seasons through 10 eclipse seasons. You can see where we started reconditioning after the eclipse season the battery tends to drop down a little bit, indicating the eclipse season maybe does us some good.

(Figures 81 and 82)

This is an extension of that same plot, 76 through 77. And you can see that here is where we tried the four cycles. The one I showed you before is down here. As we reconditioned each time we finally got up to 60 hours of discharge.

Plot points are at 29 volts. It is pretty hard to plot these data since we were actually going down to 25 volts in some cases, so it is not a real indication of ampere hours. What we tried to do is maintain consistency and plot each time we got down to 29 volts.

(Figure 83)

Finally, this figure shows a list of some of our conclusions.

DISCUSSION

FORD: Goddard. Am I to understand that the reconditioning seen is down to an average of 1 volt per cell in the battery and not below that?

COOPER: On 42 that is what we went -- Well, on the deep discharge we went down to 18 volts, which is about eight-tenths of a volt per cell.

FORD: How many cells did you have in the battery?

COOPER: 25.

ELIASON: Ford. You say that the reconditioning did not help on the following cycles? Is that correct?

COOPER: The reconditioning, that is, the reconditioning prior to the fourteenth eclipse season and with this old a battery I don't think we can really truthfully say whether it helps or not.

ELIASON: So you saw no difference?

COOPER: Well, I think because we had to unload the spacecraft we really don't have enough data to show whether that reconditioning -- We feel that reconditioning on old batteries is really not going to help them too much. On newer batteries it does. I showed you we think it does.

SCHULMAN: TRW. Can you tell me why you included lithium in yours?

DUNLOP: It tends to allow better utilization of the cause of electrodes, quote, unquote, whether you believe that or not, supposedly improves the charge.

SCHULMAN: Did you find this to be the case?

DUNLOP: We think it probably causes -- First of all, this battery has been working in orbit for seven years, and I don't think the cellular mechanism that you are seeing here is related to the hydroxide. It may be more of a problem with the carbonate. In the laboratory we have experience. We have to run it for eight years, and at the end of eight years practically all the cells are performing as bad as the ones in orbit.

The capacity here is 5 ampere hours out of a 20 ampere hour cell, down to one volt per battery. The point is that you are really experiencing very poor ampere hour capacity to voltage. It turns out that in that reconditioning you may be able to take that almost to 18 volts at a low rate and able to take out quite a bit of capacity. As soon as you try to go back to C/2 rate the battery fell right apart in the fourteenth eclipse season. And the other point is up to the 11, 12 eclipse season they are going pretty good; up to about 5, 6 years they are doing pretty good. And then we start dropping off in voltage very rapidly, and I think that is not -- lithium hydroxide.

SCHULMAN: Let me ask you one last question. Do you still include lithium in the cells you are purchasing to date?

DUNLOP: The Intelsat 4 A cells do not have lithium hydroxide. There are arguments for and against using it.

BOGNER: JPL. When you quoted, I think 2.33 cc's was that on rated capacity?

DUNLOP: That is on measured.

BOGNER: Also, did you have any other additives in that cell?

RAMPEL: General Electric. I would like to add one more possible advantage to the lithium to a nickel-cadmium cell. There is some evidence that lithium retards cadmium migration.

NAPOLI: RCA. On the older batteries do you have to limit the operations you transpond during the eclipse as a result of this?

COOPER: As I have said before, we don't really use this spacecraft. So limiting the operation of transponders is not an operational problem. So, on this spacecraft obviously we normally operate 12 transponders. We were down to 6 to get through the eclipse season.

NAPOLI: You have a seven year, an eight year mission.

COOPER: Seven year mission, 10 year batteries.

NAPOLI: Is that seven year mission of 12 transponders?

WEBER: Comsat. 12 transponders for seven years. The satellites are carrying primary traffic. The older spacecraft is in a contingency mode where after the eleventh eclipse season they power them down without impacting the traffic.

NAPOLI: I am trying to get an answer to this. How are you able to meet a seven year mission operating 12 transponders seven years with the original battery?

WEBER: On the one that has completed seven years in orbit we are in the fourteenth eclipse season we are only in fact able to carry half the load, 6 transponders.

NAPOLI: Now the next question is at what year did you fail to meet the mission?

WEBER: Starting at about the eleventh eclipse, five and a half years to six years, we started reducing the load.

COOPER: Maybe I can go over these conclusions shown in Figure 83. We need to modify these a little bit.   They may be a little harsh.

We really haven't experienced any battery failures, such as hard shorts or any battery that, you know, we couldn't bring back, even though the capacity may be a little bit low.

We had accelerated degradation, not really premature.   It tends to accelerate after the sixth year.   It tended to drop off fairly rapidly.

All the charge management techniques we have tried to use doesn't seem to make any difference on the old batteries.   The new batteries we have managed to increase or decrease.   Well, we have been increasing the charge/discharge ratio.   Lately, we think we may be getting too much charge, heating the battery too much, and degrading the battery over a long period of time.   So we are tending to back-off of overcharging the battery.   We are using 130 percent C/D ratio on the 4 F4 you have seen, and about 120 to as much as 145, 160 on 4 F2 in certain periods of time.   But we don't really think that does anything except heat up the battery.

The overcharge therefore should probably be kept at a minimum.   Load reduction is one thing we may be looking into in order to maintain the battery lifetime up to seven years.

Reconditioning prior to eclipse we feel appears to improve the end of discharge voltage.   We don't really have the data we would like to have on this, and of course we will get into reconditioning later on.   Deep reconditioning, the same thing, we will get into it later on.   But with older batteries we don't feel that it really buys us anything.

KIPP: SAFT America.   Jim Dunlop, I believe you said that you had batteries on test in the laboratory which you were trying to compare to your batteries in the spacecraft.   And you also I think made a comment relative to carbonate increase during the lifetime.   Did you actually take cells and take them apart in the laboratory on life test and confirm that carbonate levels were increasing?   And what sort of numbers did you get?

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DUNLOP: In the life test in the laboratory we did remove one cell per year, sometimes two. We did plot the increase in the carbonate level, and it was almost a linear increase up through seven years. And it was independent of the storage mode, which you might expect. And we published something on this. The step we feel is the solubility of the nylon, not the electrochemical conversion of that soluble by-product -- carbonate. The carbonate level build up rate was about 1.1 something grams per year, which means that at the end of seven years we have roughly something like 10 grams of carbonate in that cell, and that is about 20 percent by way of the electrolyte. So, it is significant, but somewhere between 18 and 20 percent. And that is at the operating temperature that we ran. It turns out the operating temperature in the laboratory was about 4 degrees C higher or 5 degrees C higher on an average than in the spacecraft. That was simply because the temperature predictions that were used to start the test in the laboratory were slightly higher than in the orbit. This battery is running fairly cool in orbit.

INTELSAT IV F-2
BATTERY 2
END OF DISCHARGE VOLTAGE
14 ECLIPSE SEASONS

BATTERY VOLTS

ECLIPSE DAYS

Figure 68

INTELSAT IV BATTERIES - IN ORBIT EXPERIENCE

I   MISSION

II   BATTERY CHARACTERISTICS

III IN ORBIT BATTERY MANAGEMENT

     A. STORAGE MODE

     B. RECONDITIONING

     C. CHARGE TECHNIQUES

IV   PERFORMANCE

     A. END OF DISCHARGE VOLTAGE

     B. AGING CHARACTERISTICS

     C. FAILURE CHARACTERISTICS

         1. ECLIPSE VOLTAGE PROFILES

         2. CHARGE ACCEPTANCE

         3. LOSS OF OVERCHARGE

     D. EXTRAORDINARY CHARGE MANAGEMENT TECHNIQUES

         1. EXTENSIVE OVERCHARGE

         2. PULSE CHARGE AND CONTINUOUS "A" CHARGE

         3. DEEP RECONDITIONING

V   CONCLUSIONS
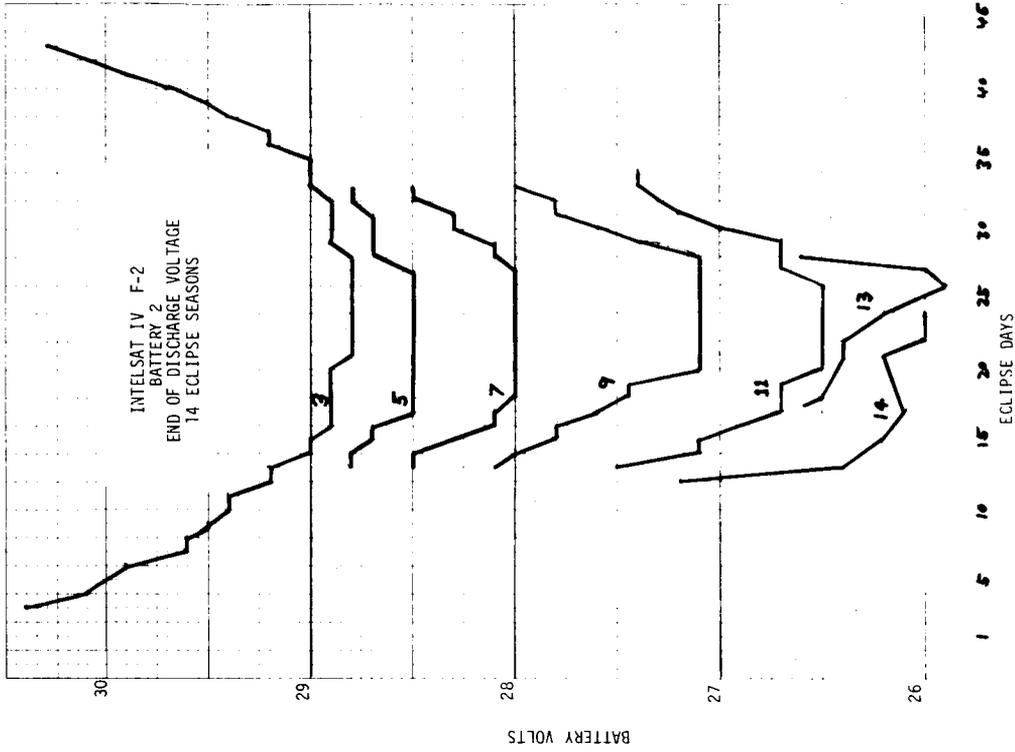
Figure 67
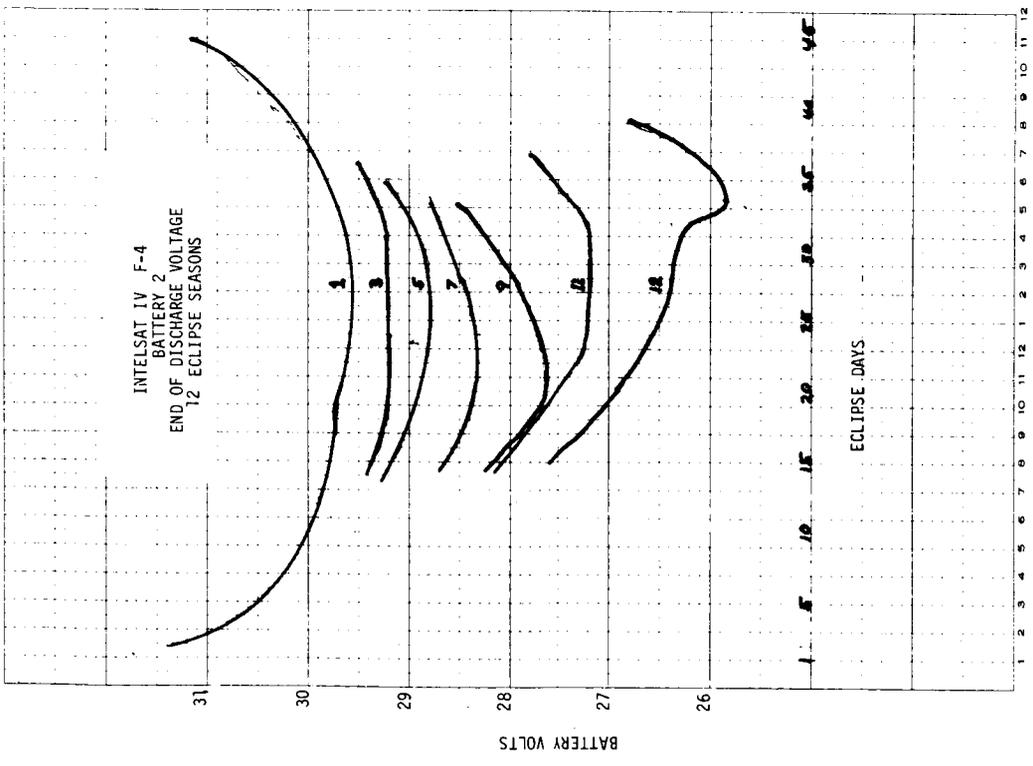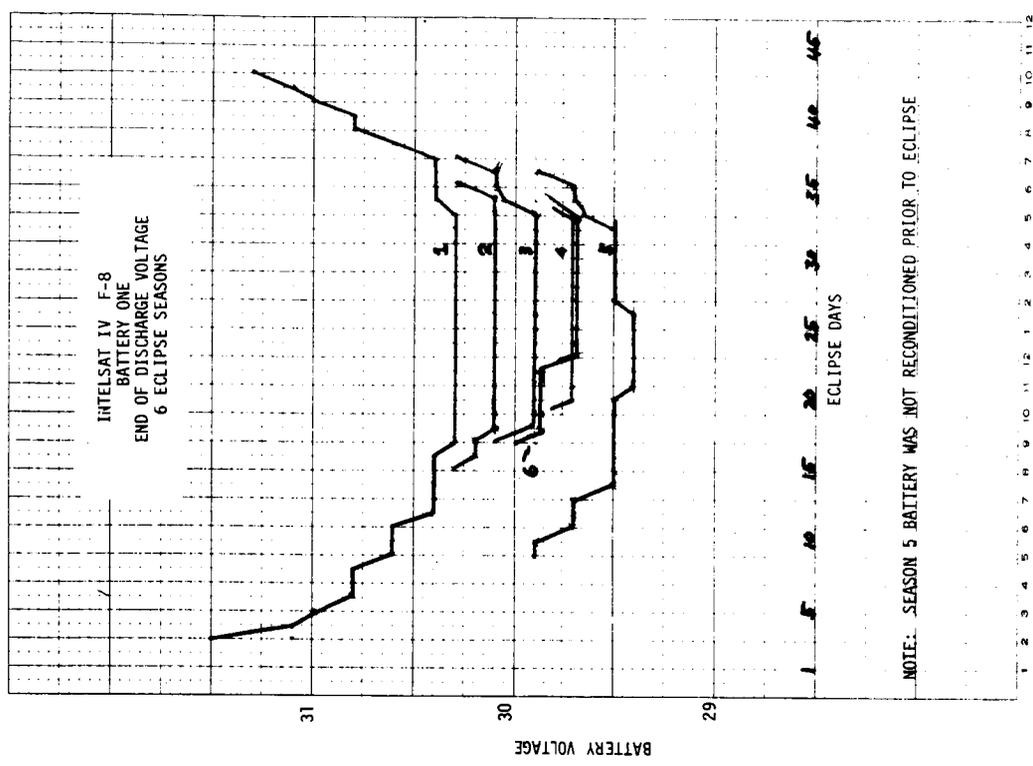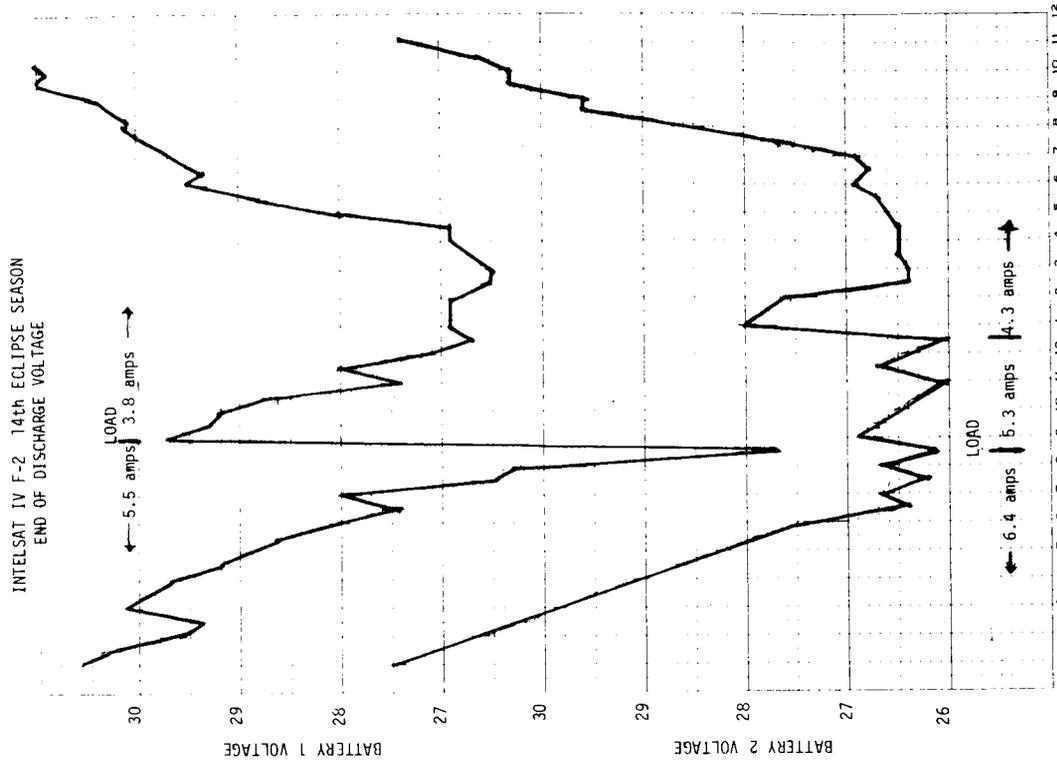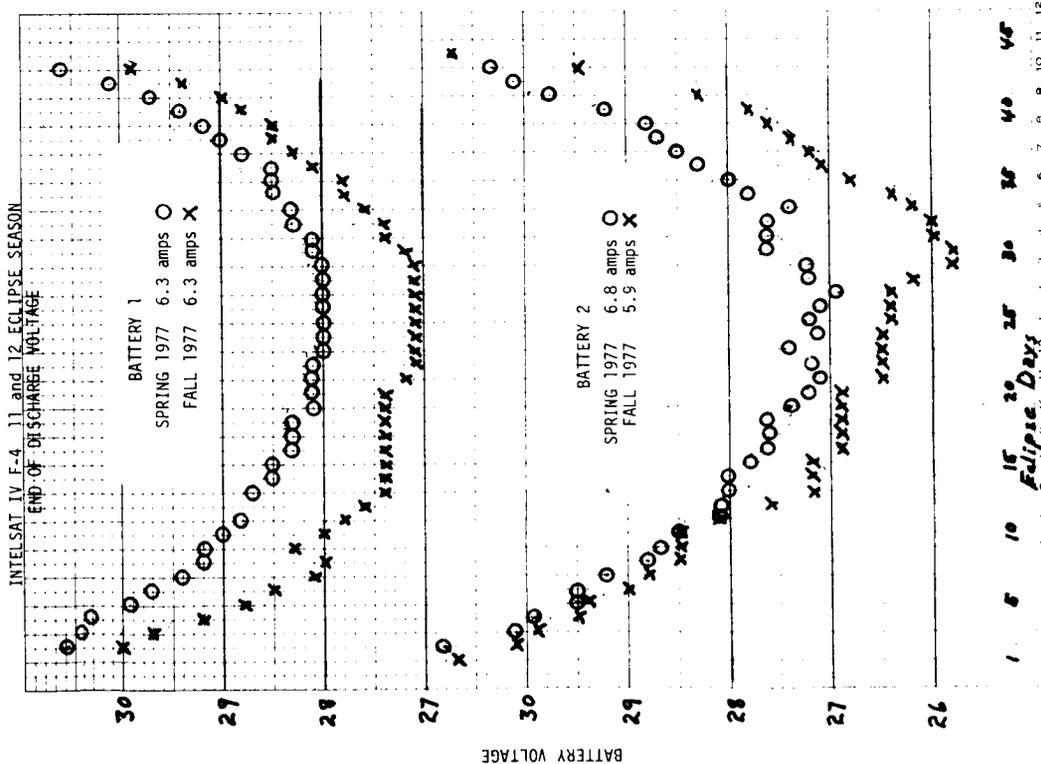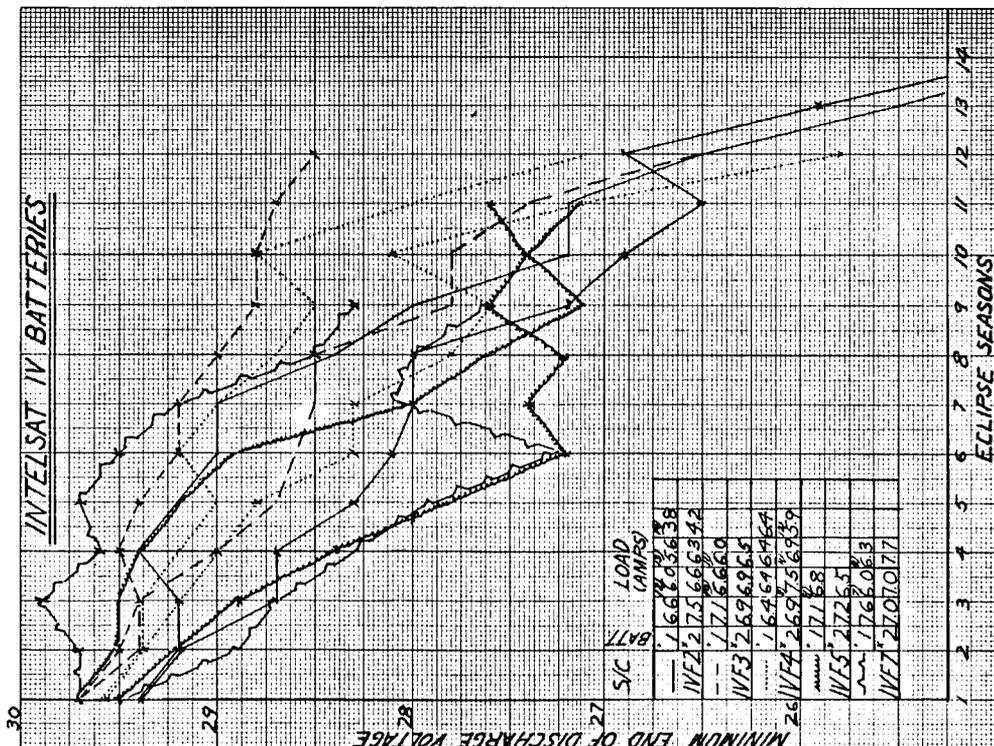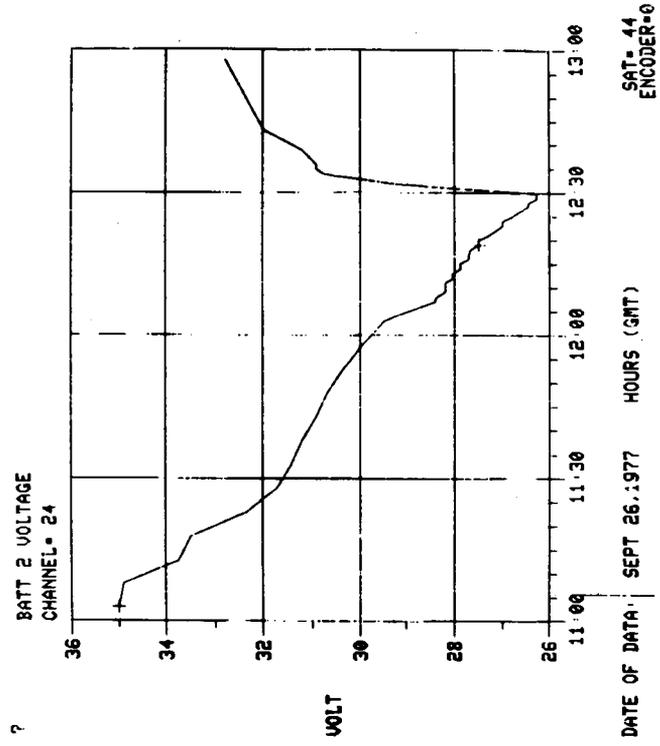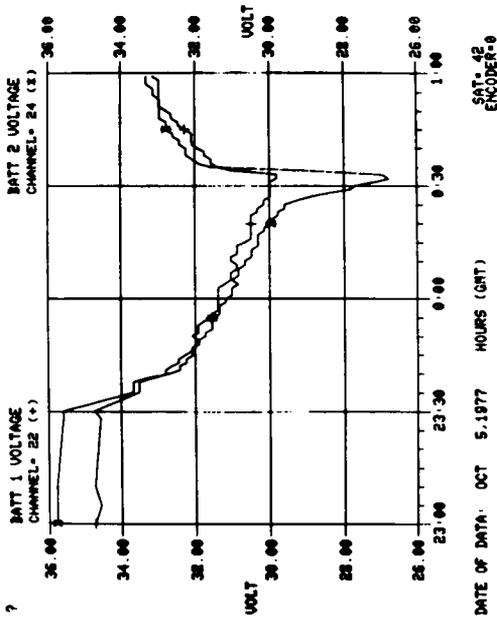
100

Figure 70

Figure 69

101

INTELSAT IV F-2 14th ECLIPSE SEASON
END OF DISCHARGE VOLTAGE

Figure 72

INTELSAT IV F-4 11 and 12 ECLIPSE SEASON
END OF DISCHARGE VOLTAGE

Figure 71

BATT 2 VOLTAGE
CHANNEL= 24

DATE OF DATA: SEPT 26,;977   HOURS (GMT)

SAT= 44
ENCODER=0

Figure 74

INTELSAT IV BATTERIES

MINIMUM END OF DISCHARGE VOLTAGE

ELIPSE SEASONS

Figure 73

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Figure 75

Figure 76

Figure 77

Figure 78

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Figure 80

Figure 79

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Launch: 23 August 1973

IS IV F-7

Hrs. of Discharge

● = 1st Cycle
X = 2nd Cycle

BATTERY 1

BATTERY 2
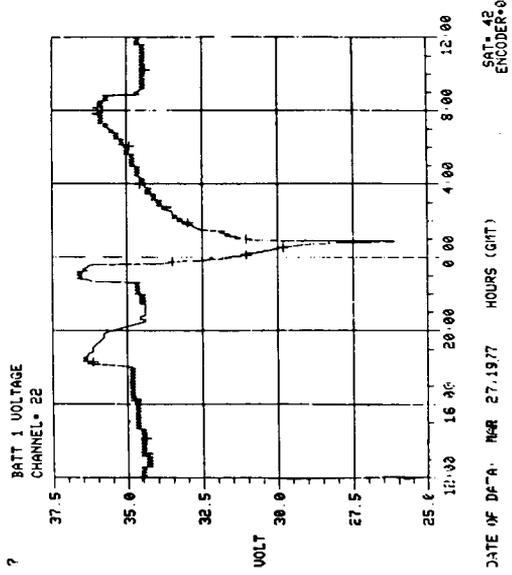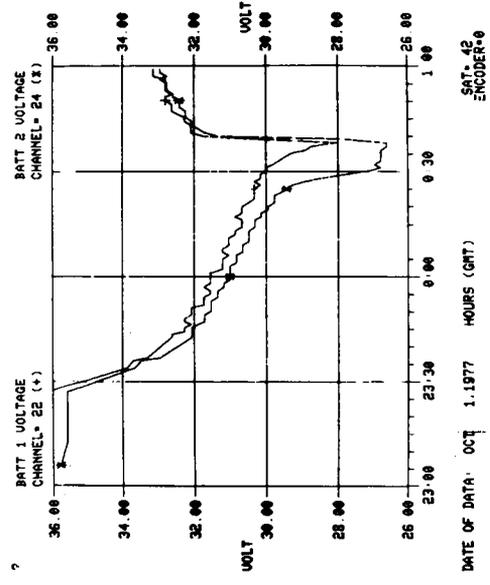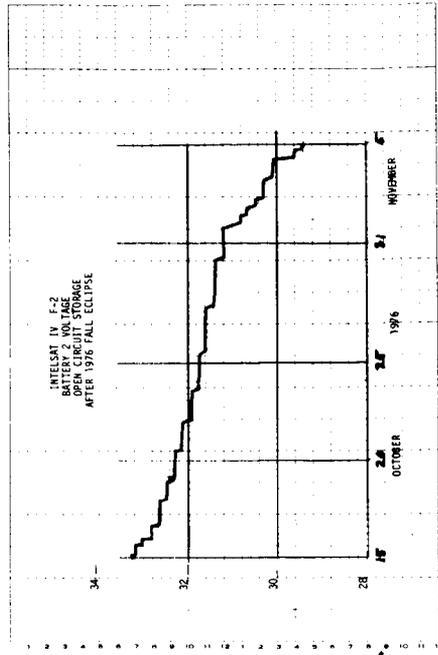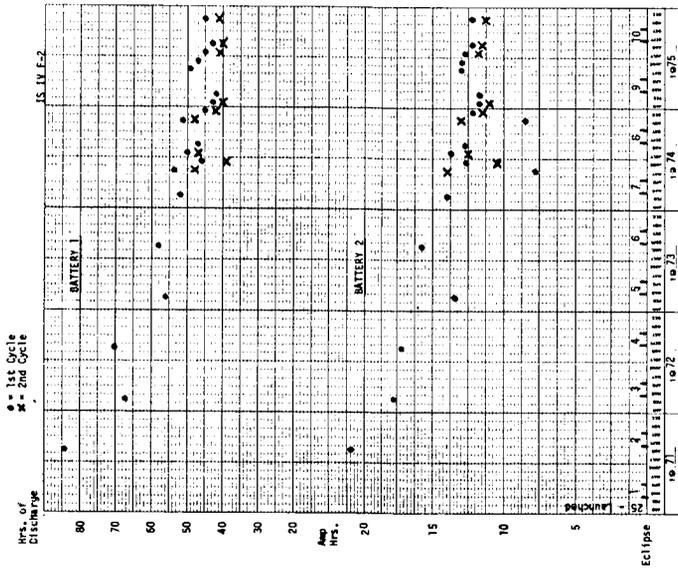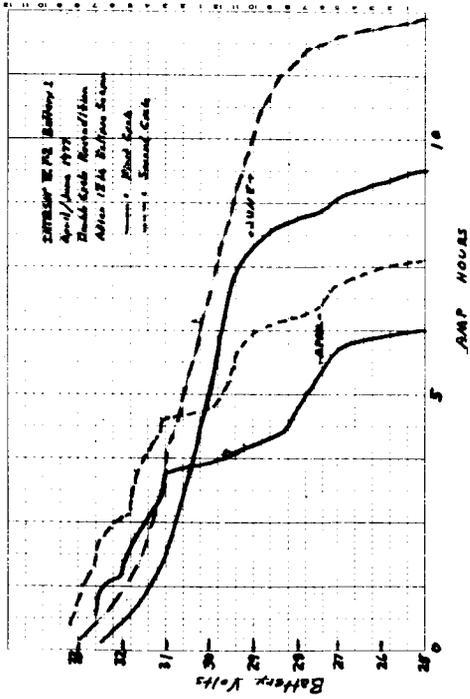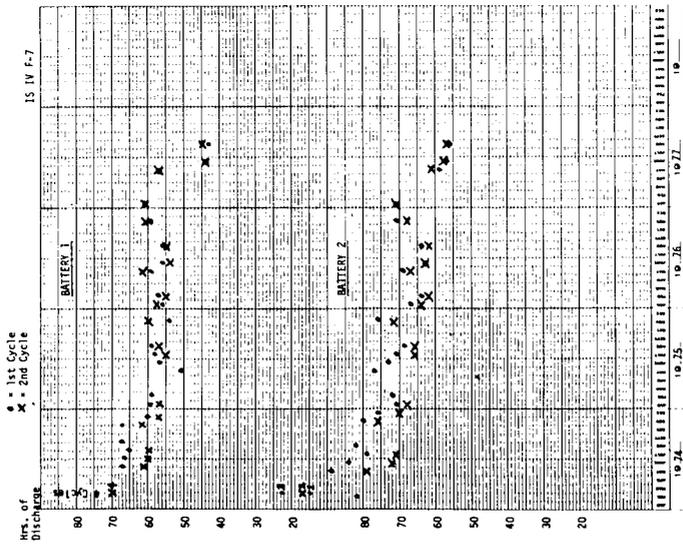
Figure 81

All plot points to 29.0 v.
Due to 1.0 v. drop, voltages attempted are not plotted.

IS IV F-2

44 Cycles
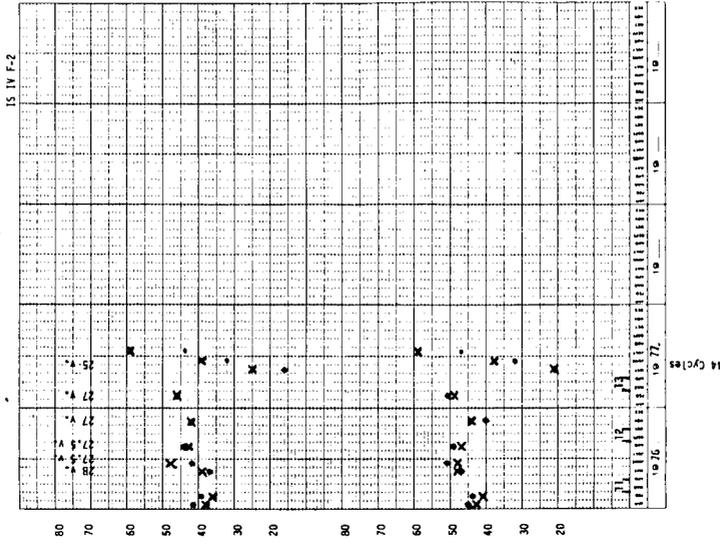
Figure 82

CONCLUSIONS

I   NO IN ORBIT FAILURE OR ANOMALIES SUCH AS SHORTS

II   PREMATURE DEGRADATION BEGINNING IN THE 6TH YEAR

III   EXTRAORDINARY CHARGE MANAGEMENT TECHNIQUES ARE
      RELATIVELY INEFFECTIVE

IV   OVERCHARGE SHOULD BE KEPT TO A MINIMUM

V   LOAD REDUCTION MAY BE A GOOD CHOICE IN ORDER TO
      PROLONG BATTERY LIFE

VI   RECONDITION PRIOR TO ECLIPSE IS NECESSARY TO
      MAINTAIN END-OF-DISCHARGE VOLTAGE

VII   DEEP RECONDITION .7 VOLTS/CELL DOES NOT BENEFIT
      OLDER BATTERIES

Figure 83

SESSION II

NASA OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY,
RESEARCH AND TECHNOLOGY PROGRAM

F. E. Ford, Chairman
Goddard Space Flight Center

NASA's OAST PROGRAM - AN OVERVIEW

L. Holcomb
NASA Headquarters

I would like to give you a brief overview of the NASA Office of Aeronautics and Space Technology (OAST), Research and Technology Program, and the area of batteries. I have taken just a portion of our space power program that relates directly to batteries and tried to include it here and grouped it in several key areas.

(Figure 84)

There are two areas that we are doing technology in the systems area that people have been talking about, and I would like to mention those at the end, which aren't included in here but do relate very closely to battery technology as it relates to the overall power system.

In general I have tried to split our program into four areas, and these areas are new. They are not new areas. There are new groupings. I have included the funding in 77 and in 78 and the manpower that NASA is putting, either direct manpower at NASA centers or JPL manpower. And I am talking about JPL programs.

The four areas, the first area is high energy density, long life batteries. And here we are talking about batteries which are basically secondary batteries that are currently used and in use in space today. And I have grouped together the nickel cadmium, the metal gas, nickel hydrogen, and silver hydrogen batteries, which have the potential of meeting these requirements and being within 5 to 10 watt hours per pound of each other ultimately and the goals that NASA has and the goals that the Air Force has ultimately for these technologies.

Our objective is to reduce the weight of batteries for missions where we are launch vehicle constrained, geosynchronous and deep space planetary missions, for instance, where battery weight is a very critical item. We think with the shuttle era that battery weight will probably be not as critical an item for low earth shuttle missions in the future, but it will continue to be a problem with geosynchronous missions.

We also feel that increasing the battery life is a very important goal. We heard about communications satellites today that are limited; as Mr. Dunlop

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stated, one primary limiter is the battery life. And we feel that simply increas-
ing the life of the battery for the same energy density has a great benefit for a
number of missions, particularly those where we can not get to the spacecraft
and maintain it. And those are the geosynchronous and planetary type missions
again.

To fill this need, NASA has put together an advanced nickel cadmium
program, battery program, aiming at doubling the energy density for life of
current state of the art nickel cadmium batteries. In addition to that we are
presently looking at metal gas batteries and evaluating these alternatives.

The second area that we are looking at is the low cost high capacity
battery application area. As we look at some very interesting application mis-
sions that are coming up in the early 80's, early to late 80's, we are looking
at very high power levels in space. And at the present cost of power in space
we can not afford to continue to pay these prices and still fill the shuttle up. In
order to perform these missions we must seek ways of reducing the cost, dras-
tically reducing the cost, of energy storage in space. And I am talking about
here missions that are looking for very large power levels in the multi-kilowatt
power range.

In another area I have grouped together very high energy density bat-
teries. We are looking at improving primary battery weights, reducing the
weights of these batteries, for Probe and Lander missions in the future, and
also looking at advanced technologies in what we might call new horizon type
technologies where we expect to have a very significant increase, like a five-
fold increase, in the energy density of batteries, which we feel that type of
technology may enable new missions that we have yet to even envision or plan
for.

And then finally we have an underlying electrochemical research and
technology program, which is evaluating the key elements of batteries as they
apply to not only batteries, but fuel cells -- separators, absorbers, and things
of that nature.

(Figure 85)

Now to go back through each of these items in a little bit more detail.
To start with the high energy density, long life battery program, our approach
as I mentioned before, has been to offer a coordinated program aimed at dou-
bling the energy density for life, current ni-cd batteries, through the develop-
ment of advanced cases and other components of the battery as well as trying
to optimize the design variables, the precharge, and other design variables in

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the battery, and also looking at operational techniques, things that we have been mentioning today -- reconditioning and various other electronic control.

To basically describe this program, JPL has just published a color pamphlet which goes in and explains our nickel cadmium battery program. And I have enough copies here. I would like to pass it around. It goes into the battery program in a little bit more detail than I will be getting into today. If you have any questions on it, please feel free to ask me or Aiji Uchiyama or Sam Bogner of JPL. There is one error on the energy density curve in there. The artist plotted some dashed lines where there should be dotted lines, so before you utilize that curve I would look at previous publications that report out that would clarify that error.

In addition to this nickel-cadmium battery program, we have evaluations going on in the metal gas battery area. And we feel that the proper approach for NASA at this point in time is to evaluate these metal gas alternatives while we concentrate on the nickel-cadmium battery program. And hopefully in two to three years from now we can make decisions on which battery type is desirable and applicable for a mission based on how close we come to meeting our objectives and how close the nickel hydrogen and silver hydrogen battery programs come to meeting their objectives.

Specifically accomplishments that we have had in the last year in the advanced high energy density, nickel cadmium battery program, we have established a detailed program plan that has been coordinated with Lewis Research Center, who is performing an important portion of this program in the area of the electrodes and separators. It is also being coordinated with Goddard Space Flight Center and with the Air Force materials laboratory and aeropropulsion laboratory, which are providing electrochemically deposited plates as a portion of this program.

We have completed reviews of the current literature on material ratio, precharge, electrochemical impregnation, and cadmium electrodes and state of the art cells. From these evaluations we feel that we have learned certain useful information that will help us design the battery in the future. We feel that additional information is needed in the material ratio and precharge area, and we will be conducting specific tests to gather more information in this area this year.

In addition, we have demonstrated the feasibility of lightweight graphite epoxy cases, and we will be fabricating a number of these cases this year and will go on to demonstrating them in full up batteries in subsequent years.

In the metal gas battery area we have procured a number of state of the art nickel hydrogen batteries for evaluation. I might mention that these batteries are really state of the art several years ago. We do not currently have any state of the art 1977 nickel hydrogen batteries presently procured. But we do plan to stay active and get the latest technology when it is available to be procured for evaluation.

In addition we have completed a preliminary research program on silver hydrogen batteries. I believe we have tested over 600 cycles on the silver hydrogen battery and a synchronous orbit type of duty cycle. We will continue this evaluation in the next few years.

(Figure 86)

In the low cost, high capacity battery area, really a new program, we have had no prior program in this area, at least within the last year or two. Our approach, at least one of the approaches we are looking at right now, is the development of a very large capacity toroidal nickel cadmium battery. We are looking at the possibility of developing a hundred, maybe even up to 2,000, ampere hour units for power applications that may go up into the hundreds of kilowatts eventually. I would say the hundred ampere hour size is probably sufficient for modest kilowatt power size.

Our goal here is to drastically reduce the cost of the aerospace nickel cadmium battery.

(Figure 87)

Very high energy density battery research, our approach is to demonstrate primary reserve actuated silver zinc battery technology for probe applications with wet life up to 90 days, energy densities in excess of 77 watt hours per kilogram. We are evaluating lithium primary and secondary batteries, and we do have a research effort continuing to explore the sulfur, thin, beta alumina solid electrolyte sodium sulfur system for operation at less than 150 degrees Centigrade.

Our accomplishments over the last year in the probe battery area we have completed a conceptual design of such a probe battery. And we have included analysis of gassing effects, how we would manage the electrolyte in such a system. And we have selected activation designs for such a system. In addition we are in the process of procuring primary and secondary lithium cells for evaluation. We have had in previous years evaluation of lithium cells going on in at least three NASA centers, and we are trying to make a more thorough evaluation this year.

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I am looking forward to the session we are having on Thursday in the lithium battery area to hear about some of the work that has been done in this area.

In the sodium sulfur system through a contract with Ford we have developed a method of fabricating thin beta alumina tubes. We have identified at least three solvents which appear to be feasible in such a system and will begin feasibility investigations of such a battery this year.

(Figure 88)

Finally, the electrochemical R and T area, I have chosen to put what we call accelerated nickel cadmium test program under electrochemical R and T. It could have been just as well grouped under nickel cadmium batteries, but I feel the technique once developed may be applicable to other battery systems. We will have a complete discussion on this as well as several of the other programs this afternoon.

Our objectives are to develop an accelerated test technique which will allow early diagnosis of the battery's life. As we develop new batteries we would like to know whether or not there are improvements over the current technology. We would like to know that quickly rather than having to wait 10 years to test and evaluate them.

We also would like to be able to provide accurate life prediction models for the spacecraft designers so that you will know how this system is going to behave in space and can design around it.

And then finally we are looking at ways of improving the performance and life of alkaline systems, both batteries and fuel cells through developing new stable separators and absorbers. Our accomplishments this year, we have completed or near completed at least 80 percent and maybe more. We will have an update this afternoon of the nickel cadmium batteries on test in the accelerated test program. Chemical analysis techniques have been developed. Analysis is underway and we have completed I believe through what we call starpoint cells, the central matrix portion of the accelerated test program cell. And statistical analysis techniques have been developed, regression analysis. And these are being evaluated and will continue to be evaluated of course as the data become available.

In the separator systems over quite a few years at the Lewis Research Center, inorganic separators, inorganic, organic separators, have been developed. They are under evaluation, silver zinc, nickel zinc, and nickel cadmium batteries. In addition, PBI separator is being investigated to replace asbestos

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and fuel cells and also as a separator -- as a potential separator -- in nickel cadmium batteries.

These are the program accomplishments we have had over the past year.

DISCUSSION

ROGERS: Hughes Aircraft. I take it you are not going to be sponsoring any work in metal gas systems other than from the evaluation of what already exists?

HOLCOMB: We do have some research that is currently going on in silver hydrogen metal gas system. We will be doing more than just evaluation. We will be building some -- and some lightweight cells in that area.

In the nickel hydrogen program we have no plans right now to duplicate any of the research in the Air Force. We do plan to work closely with the Air Force and watch the developments that come out of their program as well as the Comsat program.

HELLFRITZSCH: Consultant. You said toroidal design. Do you mean a toroid?

HOLCOMB: It looks like a jelly roll.

HELLFRITZSCH: Well, that is not a toroid.

HOLCOMB: It has a hole in the middle.

HELLFRITZSCH: A toroid is a ring. A jelly roll, okay.

HOLCOMB: It is a cylinder with a hole in the middle. It does not look like a donut.

NASA BATTERY R&T

	FY 77	FY 78
• HIGH ENERGY DENSITY/LONG LIFE	380 (4.6)	645 (5.7)
- REDUCE BATTERY WEIGHT FOR LAUNCH VEHICLE CONSTRAINED MISSIONS		
- INCREASE BATTERY LIFE FOR GEOSYNCHROMOUS OR PLANETARY MISSIONS WHERE REPLACEMENT IS NOT FEASIBLE		
- REDUCE REPLACEMENT FREQUENCY WHERE MAINTENANCE IS FEASIBLE		
• LOW COST, HIGH CAPACITY	0 (0)	128 (1.5)
- REDUCE COST FOR FUTURE HIGH POWER MISSIONS		
• VERY HIGH ENERGY DENSITY	289 (5.6)	258 (5.4)
- REDUCE PRIMARY BATTERY WEIGHT FOR PLANETARY PROBE MISSIONS		
- 5 X CURRENT NI CD BATTERY ENERGY DENSITY TO ENABLE NEW MISSION OBJECTIVES		
• ELECTROCHEMICAL R&T	753 (9)	624 (10.4)
- UNDERLYING SUPPORT OF BATTERY AND FUEL CELL OBJECTIVES		
TOTAL	1425 (19)	1655 (22)

Figure 84

LOW COST, HIGH CAPACITY BATTERIES

● APPROACH

- TOROIDAL NI CD CONSTRUCTION FOR LOW COST MULTI-KW-HR STORAGE

● ACCOMPLISHMENTS

- ESTABLISHED PLAN TO EVOLVE > 100 A-H CELLS AND ULTIMATELY > 2000 A-H UNITS

Figure 86

HIGH ENERGY DENSITY/LONG LIFE BATTERIES

● APPROACH

- COORDINATED PROGRAM TO DOUBLE ENERGY DENSITY OR LIFE OF CURRENT NI CD BATTERIES THROUGH DEVELOPMENT OF ADVANCED CASES, HEADERS, SEPARATORS, ELECTRODES AND PLAQUES AS WELL AS OPTIMIZATION OF DESIGN VARIABLES AND OPERATIONAL TECHNIQUES

- EVALUATE METAL-GAS ALTERNATIVES

● ACCOMPLISHMENTS

- ADVANCED HIGH ENERGY DENSITY/LONG LIFE NI CD BATTERIES

  -- ESTABLISHED PROGRAM PLAN

  -- COMPLETED REVIEW OF MATERIAL RATIO AND PRECHARGE, ELECTROCHEMICAL IMPREGNATION AND CADMIUM ELECTRODE IN SOA CELLS

  -- DEMONSTRATED FEASIBILITY OF LIGHTWEIGHT GRAPHITE EPOXY CASE AND HEADER

- METAL-GAS BATTERIES

  -- PROCURED SOA NI H CELLS FOR EVALUATION

  -- COMPLETED EVALUATION OF A AG-H RESEARCH CELL

Figure 85

VERY HIGH ENERGY DENSITY

● APPROACH

- DEMONSTRATE A VERY HIGH ENERGY DENSITY (> 77 WH/KG), LONG LIFE (90 DAYS WET LIFE) AG-ZN BATTERY

- EVALUATE LITHIUM PRIMARY AND SECONDARY BATTERIES

- EXPLORE DISSOLVED SULFUR, THIN BETA ALUMINA SOLID ELECTROLYTE, MOLTEN SODIUM (NA/S) SYSTEM AT < 150°C

● ACCOMPLISHMENTS

- PROBE BATTERIES

  - COMPLETED CONCEPTUAL DESIGN OF > 77 WH/KG, 90-DAY WET LIFE, REMOTE ACTIVATION AG-ZN BATTERY INCLUDING ANALYSIS OF GASSING, ELECTROLYTE MANAGEMENT MODELLING, AND ACTIVATION TECHNIQUE DESIGN

  - PROCURED SOA PRIMARY AND SECONDARY LITHIUM CELLS FOR EVALUATION

- DEVELOPED NEW EXTRUSION METHOD OF FABRICATING THIN WALL "BETA" ALUMINA TUBES, IDENTIFIED THREE SOLVENTS; FEASIBILITY INVESTIGATION IN A NA/S BATTERY

Figure 87

- **APPROACH**

    - DEVELOP IMPROVED BATTERY TEST TECHNIQUES AND LIFE MODELS:
        (1) ACCELERATED BATTERY TEST TECHNIQUE WHICH WILL ALLOW
            EARLY DIAGNOSIS OF BATTERY LIFE; AND

        (2) PROVIDE ACCURATE LIFE PREDICTION MODEL

    - IMPROVE LIFE OF ALKALINE SYSTEMS (BATTERIES AND FUEL CELLS) BY
      DEVELOPING NEW STABLE SEPARATOR SYSTEMS

- **ACCOMPLISHMENTS**

    - IMPROVED TEST TECHNIQUES AND MODELS:
        -- NI CD BATTERIES ON ACCELERATED TEST NEARING COMPLE-
           TION (80%)

        -- CHEMICAL ANALYSIS TECHNIQUES DEVELOPED; ANALYSIS OF
           FAILED CELLS UNDERWAY

        -- STATISTICAL ANALYSIS OF TEST AND CHEMICAL ANALYSIS
           DATA INITIATED

    - SEPARATOR SYSTEMS
        -- INORGANIC SEPARATORS DEVELOPED; UNDER EVALUATION IN
           AG ZN, NI ZN, AND NI CD CELLS

        -- POLYBENZIMIDAZOLE (PBI) BEING INVESTIGATED TO REPLACE
           ASBESTOS IN FUEL CELLS; AND AS SEPARATOR IN NI CD

Figure 88

EFFORT OF THE
JET PROPULSION LABORATORY

S. Bogner
Jet Propulsion Laboratory

(Figure 89)

The topic this afternoon is the NASA advanced nickel cadmium technology program.

(Figure 90)

Things we will try to cover here this afternoon are the goals that we set forth, program overview, talk a little bit about failure modes and mechanisms, factors of degradation, and some of the possible solutions to the degradation, and then start to look at some of the energy density considerations. How can we really decrease the weight? And, briefly go over the FY 77 accomplishments and our present status of the program and modifications to the program we made recently. Then we will look at the FY 78 milestones and then the total program schedule, which you all have now in front of you I believe. I won't have to say anything.

The viewgraph I had on the goals was missing. I will read them off here: to increase the absolute energy density from 33 to 35 watt hours per kilogram, increase the usable energy density from 20 to 44 watt hours per kilogram, and to increase the life reliability from 5 to 10 years. And we hope to have this technology ready for flights beginning mid 1980's.

(Figure 91)

Rather than to use words to try to describe the goals, this graph probably illustrates it better since the life of the battery may depend on how it is used.

This curve is based on a lot of the testing that has been done at Crane. I just plotted years rather than cycles versus energy density. So this is an average cell life as the test results come out of Crane. So if you put reliability numbers on that you would probably drop those down a little.

(Figure 92)

Here is kind of a pictorial of the total program, overview, This was made a couple of years ago on how we were looking at the program then, and it hasn't been changed that much. Now we were doing some work in pulsed charging. We had a coordination meeting with most of the NASA centers about a year ago, and Etheridge Paschal said that they had been looking at that at Huntsville and they decided it was too complicated to use on a spacecraft. And we have kind of dropped pulsed charging right now.

We also had a program on the negative limiting cell. Those cells were built and tested, and the concept didn't prove out quite like we would like for it. So we are not doing any further work in that area.

Then we come back here to the lightweight cell and battery technology, and we follow across here with several categories. We want to look at the plaques, case, seal, separator, and battery chassis design.

We come over here on the plaques. There is a possibility of using higher porosity plaque material, maybe even using plastic plaques, which you will hear a little more about from Dan Soltis, and possible new metals.

Then we come over to make the plates, and you can either use a sintered matrix to start with or possibly just use a pressed powered matrix in both the negative and positive electrodes.

Then under the case and seal, if you are considering using new materials and new metals for the cases and possibly going to thinner, stainless steel. Right now we have elected to look mostly at an epoxy graphite case. And more details will be given on that tomorrow.

Then we thought we had to do something with the separators. We were considering using possibly a modified polypropylene. We are even trying to modify nylon and new materials. And Dan Soltis will cover that a little bit later.

Then we also were looking at kind of state of the art cell technology, where we were looking at new electrochemical deposition processes. And we have cells on test now at Crane and at JPL, and I think some of the data on those cells will be presented by the people from Crane.

Then we also wanted to document as best we could from the flight battery programs, so at least we have kind of a base line to start with. And this meeting today has done some of that documentation.

(Figure 93)

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Over the years a lot of people have been doing failure mode analysis such as Comsat, Hughes, TRW and a lot of work at Crane. Generally what I consider the predominant mode from the life test is that in most cases the cells just lose capacity to a given voltage. And of course in addition to that sometimes you have cells short and some leak.

The observations then from the failure mode analysis is the positive plate usually swells 10 to 15 percent, the separator loses electrolyte, and you get a change in the size of the cadmium, cadmium hydroxide crystals. You also note cadmium migration both into the separator and also from the interior of the plate to the exterior of the plate. And a lot of times when you pull the cells apart and measure the capacity of the plates after they are out of the cell you will find that they have not really degraded that much. And also in this process the positive electrodes tend to pick up electrolyte, and of course the carbonate level increases with life.

(Figure 94)

Some of the factors of degradation are you have the positive plate swelling and deterioration. This compresses the separator and increases the internal resistance and you get some voltage degradation. Also it tends to absorb additional electrolyte, so you get changes in electrolyte distribution in the cell.

Overcharging is another factor in degradation. It increases the rate of positive plate degradation, raises the cell temperature, and of course accelerates the degradation of the cell and separator.

We have the negative plate material migration. The cadmium migrates from the interior of the electrode to the surface and also into the separator. Then you have the negative plate material, what I call or have coined a phrase here "cadmiation", where the cadmium hydroxide crystals grow and become inactive and also you get potassium carbonate contamination, which may accelerate that effect.

And then we are all familiar with nylon separator degradation, which produces carbonate and may upset the precharge setting in the cell.

(Figure 95)

So some of the possible solutions of the degradation modes are listed here. With the positive plate swelling it seems that the electrochemical deposition methods produce better electrodes that do not swell. And if we use properly sintered plaques and maybe optimum loading it would improve that situation.

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Or there is also a possibility of preswelling of the electrodes before they are put in the cells.

Overcharging, I think most of us are or can have proper charge control on a spacecraft and on our test programs, and also better temperature control will improve the life.

In the cadmium migration, I think we can reduce the carbonate level. That would help slow down the cadmium migration. Also optimized loading would be an improvement, and reducing the overcharge would help prevent that.

The cadmium crystal growth, periodic reconditioning and possibly additives such as indium have been reported to be effective. And proper charging or pulsed charging may have some effect on crystal growth.

Nylon separator degradation, if we can operate the cells at a reduced temperature it helps that tremendously or find a replacement separator, a replacement for it. I have just listed polypropylene as one. There are some others which Dan Soltis will talk about later.

(Figure 96)

Okay, getting into the energy density of the cell, we have a little curve here where this shows kind of the state of the art cell that we were talking about versus the theoretical energy density. So to get up to the area that we would like to get up to, around 55 watt hours per pound, we have to reduce the cell weight to around 450 grams somehow from about 900 grams now.

(Figure 97)

This chart shows where the weight for the components are in the cell, the active material, separator, case, header, and the grid and plaque. And this is our goal for 1981. It shows where we have to reduce the weights. We can't take too much active material out or we won't have a cell. Of course, this is all based on a 20 ampere hour cell.

So, the largest areas to reduce weight are the case and the header and the grid and the plaque.

(Figure 98)

Some of the items for the energy density improvements are reduction of the container weight, reduction of negative to positive ratio, reduction of

grid weight, use a high porosity nickel plaque, 85 to 90 percent porous, possibly increase loading levels, maybe use thicker electrodes, use sponge cadmium electrodes, pressed nickel electrodes, plastic sintered plaques, reduce separator thickness, reduce electrolyte volume.

(Figure 99)

The accomplishments during the FY 77 we held two NASA-Air Force coordination meetings. And we had most of the NASA centers and Air Force, Wright Patterson, come to these meetings.

Under the state of art assessment we had reports on design variables, which were precharge and material ratio. That was a contract we had with Boeing. Sid Gross prepared those. And also there was a report on the electrochemical deposition process. Prior to this we came out with a five volume index with abstracts of literature search. And we also had a report written on the cadmium electrode.

In the lightweight cell case we have been working on this in-house at JPL, and we think we have established the feasibility of using an epoxy graphite case that weighs about 30 grams compared to about 170 for standard stainless steel.

Then they have the accelerated test and analysis. That is approximately 80 percent complete, and a data analysis has been initiated. I guess you will hear more about that this afternoon.

Non-sintered electrodes have been tested, but they were tested in non-sealed cells. Lightweight plaques have been procured, and separator evaluation has been started by Lewis. They have selected two materials to look at.

(Figure 100)

Our status, Goddard Space Flight Center will not continue any further effort in the battery R and AD. However, they will consult with us technically on the program. The Air Force will provide no further funding in the accelerated test. They will consult technically with us on the program, and they will provide cells for evaluation from their manufacture and technology program on the electrochemical deposition process.

The OAST office and JPL and Lewis have gotten together and have written a program plan, and that is now being sent around for signature cycle.

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We just recently extended the schedule to the end of 1981, and we added a couple of tasks that we really didn't have initially in the plan. And that is battery chassis design, analysis and test, and operational and reconditioning techniques. And we want to procure some cells to check out these design variables, pre-charge and material ratio.

(Figure 101)

Milestones for FY 78 are the battery user's handbook, which Goddard is getting under contract with TRW. We would like to come out with a report on the Viking Orbiter battery program. We intend to establish a manufacturing technology for the epoxy graphite case so generate a vendor for those cases.

We expect to complete the accelerated tests, except for the normal packs, and we will have an interim report on the accelerated tests and a data analysis.

We want to procure non-sintered electrodes for sealed cells and determine the feasibility of plastic plaques, which can be nickel plated. And then we want to procure cells with new types of separators and procure cells with two unknown design variables, precharge and material ratio.

(Figure 102)

This is a pretty busy schedule. So, essentially during this time period up through FY 79 we will be looking at a lot of components. And then starting in FY 80 we will be going out for a procurement of our final design cells. And in each instance we are allowing just one year's time to test the cells. So the accelerated test has to come through for us in order to be able to properly evaluate the cells in a year's time and stay on schedule. Otherwise we would be stretching out.

DISCUSSION

DUNLOP: Comsat. I want to try and clear something up here. In previous presentation and this presentation I saw as an objective the following: reduce the weight or increase the energy density/increase life time. Are those one goal or two different goals?

BOGNER: You can look at them several different ways.

DUNLOP: Is that one goal or is that two goals? In other words, when

you put that slash in there does that mean one and the same or two different objectives?

BOGNER: And/or.

DUNLOP: That is the way it was stated, and/or.

BOGNER: Right.

DUNLOP: I would assume that means there are two different objectives.

BOGNER: One is to increase the energy density, and one is to increase the life.

DUNLOP: That is two different objectives.

BOGNER: We may not be able to do both at the same time. We may be able to, you know, compromise in between.

DUNLOP: Okay, now I see a program that you define in which you first list all the problems that you think exist in cells. And you point out in the next slide where you want to achieve the weight, the first goal, which is improvement in energy density. And I agree that there probably is a chance to reduce the can weight. But the other areas you can't correlate what you stated about your problems to what you stated about your objectives for reducing weight. For example, if you are going to optimize the loading level but minimize the swelling of the positive electrode you don't decrease the loading level. Those are contradictory statements that you made. If you are going to reduce the problem of drying out of the separator, you have got to increase the amount of electrolyte, et cetera, et cetera, et cetera.

I am really not trying to make an argument. I am just saying that typically if we look at nickel cadmium cells and we look at how we would go about trying to make it last longer our major objective is not to reduce the weight by the way. Our major objective is to try to make it last longer and from a communications satellite point of view. And to try and make it last longer generally what we see from the battery from the people we have talked to and the work that we do ourselves you don't necessarily come up with a lighter weight cell design. As a matter of fact, generally you almost end up going the other way to tell you the truth. To end up buying lifetime you tend to make the thing a little bit heavier rather than make it a little bit lighter.

I am just trying to clearly distinguish between these two different things.

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BOGNER: This one (Figure 96) presents an interesting point in that respect in that you are out here and you can add a lot of additional weight to the cell. But the curve is flattening off out here without, you know, really decreasing the energy density.

RITTERMAN: TRW. I want to answer one of your points you were talking about. Regarding the swelling of electrodes, we ran a program on how you loaded electrodes comparing electrochemically impregnated with vacuum impregnated. Now all the electrodes swelled to a degree, but the electrochemically impregnated was much more tolerant of a high loading level, 1.8 or 1.9 grams per cc employed. Swelling of the electrochemicals perhaps two or three percent as compared to 13 or 20 percent of the vacuum impregnated.

DUNLOP: True, and you will see a paper on that tomorrow. But typically electrodes that you would make today, you buy today commercially, has a loading level of 2.3, 2.1, 2.3, 2.4 grams per cc of active material. Typically electrochemically impregnated electrodes are between 1.6 or 1.8. Most of them are in the 1.6 or 1.7 range.

RITTERMAN: Well, I was able to produce a lightweight cell at a loading level of 1.8 grams per cc.

DUNLOP: Right, and that is lower than or that is conservative than most of the electrodes that you buy today.

RITTERMAN: Well, the same loading of a vacuum impregnated. You still get swelling. My point is that you can achieve the proper loading doing it electrochemically.

DUNLOP: We ran 4,000 SOCU's through SAFT electrodes. And we will present the data tomorrow. We took electrodes that had the same reducing loading, and we got the same results. We took electrodes that were overloaded, and they swelled.

I think your loading level of 1.8 is a reduced loading level is what I am saying.

RITTERMAN: No.

HOLCOMB: NASA Headquarters. I would like to make one clarification. In this program we may evolve two cell designs or three. And for reducing the weight we may end up with a cell that won't go more than a couple of years but will reduce the weight. On the other hand, to get the longer life, we may go

with a cell that has very little weight reduction or maybe even a little increase and doubles the total life. So we may have two cells evolve out of this.

RITTERMAN: I look upon the loading level as the ampere hours for C to D of electrolyte per gram of electrode. In that case we have been able to develop a high energy denstiy, high specific energy cell, using 1.8 grams per cc. And that is the important thing, not how many grams you have got into it, the fact that you were able to produce a high specific energy cell.

HAAS: Ford. We have done a little work on light weight battery within the last five years at Ford. And here I don't disagree with the base line you show, a 20 ampere hour cell, something like .88 kilograms. We have developed at Ford 20 ampere hour batteries that weigh about 575 grams, which is only maybe -- it can be accomplished with, say, a 60 L stainless can. Now I think Harvey Seiger's work on the electrochemical deposition, 20 ampere hour cell, by and large aside from some of the processes were probably to represent a good state of the art very reliable battery cell.

I think we have already gotten there. It is a matter of assembling the pieces and buying the product from a manufacturer. I don't believe that it is really necessary to shoot for some of these very, very exotic approaches. The design and the technology exists right now. The electrochemical process for the positive and the negative plaques wouldn't allow you to within the next year buy a cell exactly to the specifications. Chances are this is going to perform very well overall as we are hoping, the electrochemical --

BOGNER: Well, cells have been purchased and are under test that way. And we also are aware of the lightweight; and we are testing that, but there are problems.

HAAS: I really think we are there.

ROGERS: Hughes Aircraft. You indicated you were going to be working on, I assume, the inorganic gas impermeable separator that was developed by NASA in the program shown up there?

BOGNER: Yes.

ROGERS: I guess I am failing to see how that gas impermeable separator could possibly work in a sealed nickel cadmium.

BOGNER: Well, hold that question for Dan Soltis.

HENDEE: Telesat Canada. When I was looking at one of your problems it stated there was cadmium migration. Then on the second chart did you say one of the ways you alleviate cadmium migration was to reduce the amount of overcharge?

BOGNER: Yes.

HENDEE: Would you explain that?

BOGNER: Well, I think with the overcharge you raise the temperature of the cell up quite a bit, and the cadmium can become soluble and migrate over.

SEIGER: Cadmium hydroxide. Cadmium hydroxide dissolves over the electrolyte, not cadmium.

NASA ADVANCED Ni-Cd BATTERY TECHNOLOGY PROGRAM

AGENDA

- GOALS
- PROGRAM OVERVIEW
- FAILURE MODES & MECHANISMS
- FACTORS OF DEGRADATION
- POSSIBLE SOLUTIONS OF DEGRADATION
- ENERGY DENSITY CONSIDERATIONS
- FY77 ACCOMPLISHMENTS
- STATUS/MODIFICATIONS
- FY78 MILESTONES
- PROGRAM SCHEDULE

CONTROL AND ENERGY CONVERSION DIVISION

Figure 90

NASA ADVANCED
NICKEL–CADMIUM BATTERY
TECHNOLOGY PROGRAM

PREPARED FOR

NASA/GSFC BAS BATTERY WORKSHOP

S. Bogner

JET PROPULSION

Nov. 15--17, 1977

CONTROL AND ENERGY CONVERSION DIVISION

Figure 89

HIGH ENERGY DENSITY, LONG-LIFE Ni-Cd
BATTERY PROGRAM SCHEMATIC

CONTROL AND ENERGY CONVERSION DIVISION

Figure 92

NASA ADVANCED Ni-Cd BATTERY TECHNOLOGY PROGRAM
LIFE AS A FUNCTION OF USABLE ENERGY DENSITY
FOR PRESENT AND NEW TECHNOLOGY Ni-Cd CELLS
(ASSUMES OPTIMUM TEMP 0°-10°C)

STATE OF THE ART CELLS
NEW TECHNOLOGY CELLS

SYNCHRONOUS ORBIT

LOW EARTH ORBIT

AVE CELL LIFE, years

ENERGY DENSITY, Wh/Kg

CONTROL AND ENERGY CONVERSION DIVISION

Figure 91

FAILURE MODE/ANALYSIS

- PREDOMINANT MODE FROM LIFE TESTS
  - LOSS OF CAPACITY TO A GIVEN VOLTAGE
- OBSERVATIONS FROM FAILURE ANALYSIS
  - POSITIVE PLATE SWELLING 10-15%
  - SEPARATOR LOSES ELECTROLYTE
  - CADMIUM CRYSTAL SIZE INCREASES
  - CADMIUM MIGRATION TO EXTERIOR OF PLATE
  - ELECTRODE CAPACITY NOT APPRECIABLY DEGRADED
  - POSITIVE ELECTRODE GAINS ELECTROLYTE
  - $CO_3^=$ LEVELS INCREASE

CONTROL AND ENERGY CONVERSION DIVISION

Figure 93

FACTORS OF DEGRADATION

- POSITIVE PLATE SWELLING-DETERIORATION
  - COMPRESSES SEPARATOR AND INCREASES IR-VOLTAGE DEGRADATION
  - ABSORBS ADDITIONAL ELECTROLYTE – CHANGES ELECTROLYTE DISTR.
- OVERCHARGING
  - INCREASES RATE OF POSITIVE PLATE DEGRADATION
  - RAISES CELL TEMPERATURE; ACCELERATES DEGRADATION OF CELL
- NEGATIVE PLATE MATERIAL MIGRATION
  - Cd MIGRATES FROM INTERIOR OF ELECTRODE TO SURFACE
  - MAY BE DUE TO ELECTROPHORETIC EFFECT
- NEGATIVE PLATE MATERIAL "CADMIATION"
  - $Cd(OH)_2$ CRYSTAL GROWTH WHICH BECOMES INACTIVE
  - $K_2 CO_3$ CONTAMINATION MAY ACCELERATE EFFECT
- NYLON SEPARATOR DEGRADATION
  - PRODUCES CO_3 - CONTAMINATION
  - MAY UPSET PRECHARGE SETTING BY CONSUMING O_2

CONTROL AND ENERGY CONVERSION DIVISION

Figure 94

POSSIBLE SOLUTIONS OF DEGRADATION

- POSITIVE PLATE SWELLING
  - ELECTROCHEMICAL IMPREGNATION
  - PROPERLY SINTERED PLAQUES – OPTIMUM LOADING
  - PRESWELL PLATES
- OVERCHARGING
  - PROPER CHARGE CONTROL
  - PROPER TEMPERATURE CONTROL & OPERATION
- CADMIUM MIGRATION
  - REDUCE CO_3 - CONTAMINATION
  - OPTIMIZE LOADING
  - REDUCE OVERCHARGE
- CADMIUM CRYSTAL GROWTH "CADMIATION"
  - PERIODIC RECONDITIONING
  - ADDITIVES – INDIUM
  - PROPER CHARGING – PULSED CHARGING
- NYLON SEPARATOR DEGRADATION
  - PROPER TEMPERATURE CONTROL
  - FIND REPLACEMENT – POLYPROPYLENE

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Figure 95

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20 Ah CELL

0.88 Kg
33 Wh/Kg

0.53 Kg
55 Wh/Kg

FUEL
CADMIUM +
NICKEL
SEPARATOR
ELECTROLYTE
MISC
CASE AND HEADER
GRID AND PLAQUE

FLIGHT-PROVEN

1981 GOAL

WEIGHT, Kg

CONTROL AND ENERGY CONVERSION DIVISION

Figure 97

- REDUCTION OF CONTAINER WEIGHT
- REDUCTION OF NEG-TO-POS RATIO
- REDUCTION OF GRID WEIGHT
- HIGH POROSITY NICKEL PLAQUE, 85-90%
- INCREASE LOADING LEVEL
- USE THICKER ELECTRODES, 0.050-0.060 in.
- SPONGE Cd ELECTRODES
- PRESSED Ni ELECTRODES
- PLASTIC-SINTERED PLAQUES
- REDUCE SEPARATOR THICKNESS
- REDUCE ELECTROLYTE VOLUME

CONTROL AND ENERGY CONVERSION DIVISION

Figure 98

ENERGY DENSITY vs CELL WEIGHT

BASED ON 20 Ah CELL THAT YIELDS 24 Ah AND OPERATING VOLTAGE OF 1.20V

THEO. E.D. = 211.6 Wh/Kg (95.9 Wh/lb)

$$y = f(x)$$
$$f(x) = 1 - x$$
$$y = 1 - x$$

MAX E.D. BASED ON THEORETICAL MATERIAL WT AND CELL VOLTAGE OF 1.20 V

ACTUAL CELL

ENERGY DENSITY – Wh/Kg (Wh/lb)

CELL WEIGHT – Kg

Figure 96

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NASA ADVANCED NICKEL–CADMIUM BATTERY TECHNOLOGY PROGRAM
FY 77 ACCOMPLISHMENTS

TASKS	
NASA/AF COORDINATION	HELD TWO MEETINGS
S-0-T-A ASSESSMENT	REPORTS ON DESIGN VARIABLES & E.C.D. PROCESS
LIGHT WEIGHT CELL CASE	FEASIBILITY ESTABLISHED IN LAB
ACCEL TEST AND ANALYSIS	TEST 80% COMP - DATA ANALYSIS INITIATED
NON-SINTERED ELECTRODE	TESTED IN NON SEALED CELLS
LIGHTWEIGHT PLAQUES	PROCURED PLASTIC PLAQUE
SEPARATOR EVALUATION	SELECTED TWO MATERIALS I/O, PBI

CONTROL AND ENERGY CONVERSION DIVISION

Figure 99

NASA ADVANCED NICKEL–CADMIUM BATTERY TECHNOLOGY PROGRAM
STATUS

- GSFC
  - NO FURTHER EFFORT IN BATTERY R&AD
  - WILL CONSULT TECHNICALLY ON PROGRAM
- AF
  - NO FURTHER FUNDING IN ACCELERATED TEST
  - WILL CONSULT TECHNICALLY ON PROGRAM
  - WILL PROVIDE NASA CELLS FOR EVALUATION FROM THEIR MFG TECHNOLOGY PROGRAM ON ECD PROCESS
- OAST - JPL - LeRC
  - A FORMAL WRITTEN PROGRAM PLAN DRAFTED
- SCHEDULE
  - EXTENDED TO END OF 1981
- ADDED TASKS
  - BATTERY CHASIS DESIGN AND TEST
  - OPERATIONAL AND RECONDITIONING TECHNIQUES
  - DESIGN VARIABLES - PRECHARGE AND MATERIAL RATIO

CONTROL AND ENERGY CONVERSION DIVISION

Figure 100

NASA ADVANCED NICKEL–CADMIUM BATTERY TECHNOLOGY PROGRAM
FY 78 MILESTONES

- BATTERY USERS HANDBOOK
- VIKING ORBITER BATTERY PROGRAM
- MFG TECH FOR EPOXY/GRAPHITE CASE
- COMPLETE ACCELERATED TESTS (EXCEPT NORMAL PACKS)
- INTERIM REPORT ON A.T. AND DATA ANALYSIS
- PROCURE NON-SINTERED ELECTRODE SEALED CELLS
- DETERMINE FEASIBILITY OF PLASTIC PLAQUES
- PROCURE CELLS WITH NEW TYPES OF SEPARATORS
- PROCURE CELLS WITH TWO UNKNOWN DESIGN VARIABLES PRECHARGE AND MATERIAL RATIO

CONTROL AND ENERGY CONVERSION DIVISION

Figure 101

PROGRAM SCHEDULE

FY77 FY78 FY79 FY80 FY81 FY82

TASK*
1.0 NASA/AF COORDINATION
2.0 S-0-T-A ASSESSMENT
3.0 LIGHTWEIGHT CELL CASE
4.0 LeRC TASKS
4.1 NON-SINTERED ELECTRODE AND CELLS
4.2 LIGHTWEIGHT PLAQUES
4.3 SEPARATOR EVALUATION
4.4 BATTERY RECONDITIONING
5.0 ACCEL. TEST AND ANALYSIS (SAFT-EP-BELL TEL)
6.0 ADVANCE CELL PROCUREMENT AND TEST
7.0 BATTERY, PACKAGING DESIGN ANALYSIS AND TEST

1.1 NASA/AF COORDINATION MEETINGS
2.1 MATERIAL RATIO AND PRECHARGE RPT
2.2 ELECTROCHEMICAL IMPREGNATION RPT
2.3 BATTERY USERS HANDBOOK (GSFC)
3.1 CONTRACT INITIATED
3.2 PROGRAM REVIEW RPT
3.3 LIFE TEST RPT
3.4 INTERIM PROGRESS RPT-FEASIBILITY
3.5 START TEST ON EP AND BELL TEL CELLS
3.6 SOW FOR CASE VENDOR

4.3.1 MATERIAL PROCURED
4.3.2 SEALED CELLS DELIVERED
4.3.3 CELL TEST COMPLETE
4.4.1 CONTRACT INITIATED
4.4.3 RECONDITIONING METHODS DEFINED
5.1 START TEST ON EP AND BELL TEL CELLS
5.2 COMPLETE TESTS ON SAFT CELLS
5.3 INTERIM REPORT ON ACCELERATED TESTS-PREDICTION MODELS
5.4 FINAL REPORT ON ACCELERATED TESTS
6.1 ADVANCE CELL PROCUREMENT (DESIGN VARIABLES)
6.2 CELL DELIVERY AND START TEST
6.4 FINAL CELL TESTS COMPLETE
6.5 QUALIFICATION TESTS COMPLETE
7.2 PROTOTYPE TESTS COMPLETE

*UNLESS NOTED TASKS ARE PERFORMED BY JPL

Figure 102

LEWIS RESEARCH CENTER
PROGRAM

D. G. Soltis
Lewis Research Center

As part of the NASA lightweight program, the Lewis Research Center has a number of programs that we are looking at. We have been looking at them for different reasons to start out with, but this is an objective that is quite typical. And we thought in some of these areas let us give it a shot and see what happens.

Again, we have looked at a number of things, and we realize that maybe one cell shouldn't be considered for all of the applications that we do have. And some cell that might evolve here, as Lee said, would be good for one or two years and do the job that is necessary for us. So, maybe we have to look at Ni-Cd technology in a little bit different way. Let us design the cell for the application instead of taking one cell and using it for everything in the world.

(Figure 103)

As part of the lightweight program, our objective is to try to develop electrodes, separators, and the technology which will reduce the weight, extend or maintain the life characteristics of Ni-Cd dells. Extend the life, well, we think maybe separators could do that. Maybe absorbers can do that if in fact nylon does disintegrate and add carbon and things to the cell and cause decreased performance, deep discharge reconditioning. These things are all applicable to the cells that are now being made and used, and you don't have to change a cell much to put those things in or to control the cell with those things. I mean you start looking at lightweight electrodes. That is a pretty hairy subject in itself, but let us look at it. Let us see what we can do with the thing. We were looking at it for a different application, but it looked like we were able to get decent cycle life at 100 percent discharge at the C rate. It is not much good over that, but at the C rate or C/2 there are applications for that for a lower rate.

Lightweight substrates, again, this is something that might work and might not. The Japanese have tried it. They have got a little different application or a little different use, but we thought if you could plate a microporous plastic and electrochemically impregnate that you have got a lighter weight electrode and one that is probably pretty good. We have been able to come up with a lightweight plaque. This is just the substrate, but it has a grid embedded

in it. It is microporous, and it can be plated. What we haven't been able to do is the proper amount of plating and continuity through the plaque. But we think that there is a chance that you can do it.

Now let us take a look at what we are trying to do. This is the complete program and how we are going to do it, who is going to make the cells and where we are going to test it. We are not going to test it in our labs. We are going to have Crane test it.

The lightweight electrodes, Energy Research has been and is continuing to look at this. The positive plate has been made. It has been tested in nickel hydrogen cells. We do have them presently in vented nickel cadmium cells, and they are going to be placed in sealed nickel cadmium cells.

We hadn't looked at those cadmium electrodes, but as a result of our discussions we felt that we should give some attention to that. And they will take a little look at the cadmium. And here is where you might have a different cell that is designed specifically for an application using these electrodes.

Synchronous, we think we might be able to do it. Low earth orbit, we don't know. As I say, the lightweight substrate we are using a polyvinyl chloride microporous material, which is made by Amerace. The initial evaluation is being done in-house. We are sending materials out to be plated, and as yet they have been able to plate them but not to the extent of the thickness that we desire.

Separators, we are going to try the separator in a Ni-Cd cell. That statement was made that it was gas impermeable. I don't know if I believe that or not. Maybe the astropower one was, but we don't have the astropower separator any more. The separator that is used here has a different binder. It is a Creighton rubber binder. It is filled with inorganic material, some of which are soluble and leave. Some form gels.

The Amerace is a material that we tried in nickel zinc cell, and it is microporous. And it seemed to work quite well, so we are going to try it here too.

As far as absorbers are concerned, the PBI which Cellanese is producing started out as a separator for fuel cell. And what they want is high vol pressure. We want low vol pressure. But we can get both. And what we are trying to do is duplicate the pelon nylon in order to give us a comparable absorber which we can place in a cell and hopefully give us longer life, get to 10 or 12 years, and operating over a wider temperature range.

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In deep discharge reconditioning it looks like you might be able to help a battery extend its life by going to zero volts, and to do that you have got to be able to recombine hydrogen at a sufficient rate. And it looks like you can, and what we are going to do here is examine how it happens and why does it happen and then try to build in that feature into your electrodes so that it happens at a rate that will substantially increase the greater combination and keep your batteries in use more often or for a longer time.

So therefore, we will be testing these materials in SAFT cells, SAFT America cells, and be putting in the lightweight substrate, the separators, and the absorbers. And Energy Research will build cells using their electrodes. Then these cells will be tested at Crane, and the tests that we use will be some accelerated tests that were picked from the NASA program.

DISCUSSION

HOLLECK: EIC. I did not quite understand. What is the material of your absorber layers?

SOLTIS: PBI.

ROGERS: Hughes. My question relates do you have a program to study the bubble pressure characteristics where they pass gas, which is not quite the same thing?

SOLTIS: Yes.

ROGERS: Is that an on-going research program?

SOLTIS: Yes, Dr. Read at Lewis.

LIGHTWEIGHT Ni/Cd TECHNOLOGY

OBJECTIVE

TO DEVELOP ELECTRODES, SEPARATORS AND TECHNOLOGY WHICH WILL REDUCE THE WEIGHT AND EXTEND OR MAINTAIN THE LIFE CHARACTERISTICS OF Ni/Cd CELLS

APPROACH

- o LIGHTWEIGHT ELECTRODES
  - ENERGY RESEARCH CORPORATION
- o LIGHTWEIGHT SUBSTRATE
  - IN-HOUSE
  - AMERACE
- o SEPARATORS
  - IN-HOUSE
  - AMERACE
- o ABSORBERS
  - CELANESE
- o DEEP DISCHARGE RECONDITIONING
  - CONTRACT
- o TEST CELLS
  - ENERGY RESEARCH - SAFT
- o TESTING
  - NAD CRANE

Figure 103

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ACCELERATED TEST PROGRAM

F. E. Ford
Goddard Space Flight Center
and
J. Harkness
Naval Weapon Support Center

INTRODUCTION

FORD: At this time I would like to move more specifically into an element of this program, the accelerated test program, which comes in under this as a element to contribute to the overall program.

As most of you know, we do involve the accelerated testing or are trying to develop an accelerated test technique here at Goddard for a number of years. And this program was initiated when Tom Hennigan was here and was put into full operation under his guidance. I inherited the program from him and little did I know the magnitude of the problem that he had undertaken to solve until I got involved in this thing. And I can honestly say that three years ago and perhaps longer, four years ago, I was one of the non-believers. And it has taken the better part of two years, but today I am a believer because I think what you are going to see this afternoon looks like there is some substance there. And more than substance, it looks like there are some real tangible results coming out of this program.

I hope what you are about to get from different people that have been involved will shed some light on this. I might point out that the Air Force has been a very effective member of this effort. We have coordination meetings once a quarter, of which we meet at Crane, review the tests results, and have people from NASA centers and the Air Force. And they have been very helpful.

So without further discussion I would like to have Jim Harkness, who is the program director at Crane and in charge of the overall implementation of you might call it the hardware phase of the actual testing phase. Jim is going to give you an overview of the program, status report. From there we are going to go into the statistical analysis and get into various aspects of the modeling that has been done and the results that we have attained from this model. Jim?

NWSC ACCELERATED TEST

HARKNESS: Gentlemen, like he said, I want to warm you up with a

little background on the accelerated test, so you will kind of be excited for the statistical analysis results that Don Mains will present.

(Figure 104)

It is a combined effort of NASA and Wright-Patterson Air Force Base at the Air Force. And we do have quarterly meetings to discuss our progress and our problems we are having with the testing.

(Figure 105)

The objectives, let us start out on the accelerated test. Ideally the objectives of accelerated test would be if we could take a flight battery and run it through a very small amount of testing, which would not be detrimental to the life of the battery, and be able to predict the life of that battery under various operating conditions that we would use in a satellite. Ideally that would be the best objective of the test. Also to meet the objectives that you see listed here we could have various screening tests or maybe be able to predict the normal lifetime of a battery. Hopefully all the tests we would come up with would be non-destructive, although maybe we would have available a few cells that we could have destructive tests on, such as an accelerated type test, and still be able to predict a normal lifetime of the test. Like say there are a variety, maybe we could take a test or a battery, put it on lower operating conditions, and maybe just cycle it for say 300 near earth orbits and predict what the life of the battery would be.

(Figure 106)

Now these are the various parameters, factors, that the battery packs have been tested under at Crane. We have a total of 94 battery packs. In this eight of them are what we call storage packs, in which they would sit at various temperatures and were pulled out for chemical analysis whenever we had a cell failure occur in any of the accelerated test packs. We have 86 test packs that range from 5 cell to 8 cell packs.

The charge and discharge rates ranged from -- well, the charge rates ranged from 3 amps up to 48 amps, well, 24 amps on charge and ranged from 3 amps to 48 amps on discharge. Four of these packs are what we call the normal packs. There are two packs operating at 0 degrees C and two packs operating at 20 degrees C. The depth of discharge is 20 to 40 percent, and the percent recharge is fixed at 105 percent at both temperatures.

As of right now, we have eleven packs that are still operating, still

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performing, of this. The eleven are all at the 30 degree C temperature. This does not include the four normal packs. We had total of 517 cells to test, and as of now we still have 36 cells that comprise up the eleven packs at 30 degrees C that are still running. And this update is as of the first of November.

I would like to bring to your attention that the test status, the failure cycles of all these cells, the mode of failure, is included on a handout that is available over on the desk.

I would like to make a comment on the data that we have on accelerated tests. All our data is taken with an automatic data acquisition and control system. All the data is as records on mag tape. And we have a little interesting comment. Last June the individual that handles the data said that if we would take each record of data and put it on an IBM card and laid it side by side, as of June, that data would stretch for 10 miles, which is a lot of data.

Factors and Levels

	1*	2**	3***	4**	5*
A. Temperature °C (T)	20	30	40	50	60
B. Depth of Discharge (DOD)	20	40	60	80	100
C. Charge Rate (CR)	C/4	C/2	C	2C	4C
D. Discharge Rate (DR)	C/2	C	2C	4C	8C
E. Percent Charged (%C)	110	140	140	200	200
F. Concentration of KOH (% KOH)	22	26	30	34	38
G. Amount of KOH (cc)	17.5	18.5	19.5	20.5	21.5
H. Precharge (AH)	2.20	2.50	2.80	3.00	3.30

*Star Point Levels
**Factorial Levels
***Center Point Levels

ACCELERATED TEST PROGRAM

Figure 104

	Physical Design Parameters				
Concentration of KOH electrolyte Percent by weight	22.0	26.0	30.0	34.0	38.0
Volume of electrolyte, cc.	17.5	18.5	19.5	20.5	21.5
Negative precharge, AH	2.20	2.50	2.80	3.00	3.30

Figure 106

OBJECTIVE OF THE ACCELERATED TEST

1. Develop non-destructive test

2. Develop a simple screening test

3. Reduce test time (< 1%)

4. To determine degradation mechanism

Figure 105

STATISTICAL ANALYSIS

D. Mains
Naval Weapon Support Center

So sometimes we feel like we are under pressure to come up with the answer without having the whole story out. As Jim indicated, we still don't have all the cells in, but I think we have seen enough now that we can give some pretty good indications of where we are going.

(Figure 107)

The objectives of the statistical analysis, as we have looked at them, one is to develop a prediction technique that will reliably predict the life of a battery. And this is under various combinations of tests, under accelerated conditions, and hopefully would be extrapolatable back to normal conditions, because this is where everyone is going to be using the cells, the batteries. It is fine if we can predict life on accelerated level. This would still be a useful tool in being able to help us in investigations and that, but the ultimate is to be able to predict life on a normal use. The next thing is to use a minimum number of cycles to obtain such predictions.

Again, if we have to run it for its full life, then it is really not a prediction. The other is to reduce the total test in the matrix so that we can produce the failures and verify the predictions.

These things we are, I think, accomplishing, and we will give you some background on it and then show you some results.

(Figure 108)

To start out with, we have done quite a bit of investigation in a lot of different areas. I would like to start out by briefly summarizing some of the investigations that we have started.

First, is the polynomial coefficients. This was an approach where each charge/discharge cycle was analyzed. An equation was developed. It turned out that we could fit the curves almost perfectly with a quartic equation. Once you have these coefficients then you just line them up, run your analysis of that and be able to project into the future at any time what the cycle would look like. So you could set limits on your criteria and see at what cycle number that occurred. It didn't really work out.

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The coefficients gave us a random distribution as far as the types and numbers we came up with. The statisticians then looked at it and said, "Well, you need to do an orthogonal transformation on the data and on your coefficients and possibly that would solve it." We tried that. That still didn't give us really enough of a trend indicator to be useful.

So those two approaches we have sidelined them right now and are kind of waiting. It is still something that would be a possibility, but we are not spending much time or effort on it this time.

The next thing another one of the statisticians was looking at some of the data and said the voltage/current ratio at the beginning of discharge and at the end of charge might hold something significant.

We did some investigation of that. Again, we got good numbers, good information. But it still was not consistent enough to be able to show any kind of a prediction. We then moved into the regression analysis, and here we had two variations on it. The first one was looking at T sub i bar, delta T sub i bar. This is the time to discharge at a specific voltage level. A lot of the information was taken at a voltage level of 1.25 volts. We also then looked at voltage levels ranging anywhere from 1.3 all the way down to about a half a volt. This information didn't add anything to the regression analysis in the way of being able to predict individual cell performance.

The next thing was to look at the hysteresis loop, and this was analysis of the area between charge/discharge curve. If you take the discharge curve and fold the charge curve back on to it, look at the area between the two curves, this would give you some idea of the inherent difference or the hysteresis that is occurring from cycle to cycle.

With that information we again put it into the regression analysis. It also did not add anything that would allow us to predict individual cells. At the present time we are investigating the regression analysis on the eight parameters, and this is where most of our predictions we show today will be taken from. We are getting good correlations. We feel good control of this approach.

This allows us to determine the effects of the eight parameters and the average time to failure. Again, we added some additional variations to it. The first one was time on test. Instead of just using the depth of discharge, the charge/discharge rates and so forth, and then cycle number as the failure time, the idea was because these were running in different lengths -- the charge period is a little bit longer or a little bit shorter, depending on the depth of discharge, the amount of recharge, charge, and discharge rates -- that it might be that actual time on test is the more signigicant parameter.

After we ran this analysis it didn't really contribute anything additional to the regression, but it appeared that it was tied in with all the other parameters. And each time we used this, put it through the regression analysis, it either came in very, very late in the analysis or dropped out altogether.

At our last meeting at Crane two other items were brought up as possible additions. One of them was the depth of discharge percentage term, and this was suggested from two sources. Dr. Landers had one approach, and Dr. Pickett had another approach. These we have incorporated, and so far haven't seen anything of major significance to show that it would stay into the model. Again, it drops out pretty quickly.

The heat generated term was an attempt to look at the effects of temperature rather than just using the temperature itself. And this effect again was duplicated in other conditions. So at the moment this one has been sidelined.

(Figure 109)

So we are still at the point of looking at the regression analysis. And rather than just say we have got it and we will wait until the end, we are now looking at ways of improving and testing the regression model itself. These are some of the methods. One of them is to audit the data itself, checking on the levels of the five factors to see how they fit into it, create data files on these levels, and verify them and then to run homogeneity tests on the variance of the y's and print out the within pack variance.

Also, on the stepwise regression, is to use the linear, quadratic, and linear by linear terms in the factor to see if this will help improve our prediction, to select the F in and F out and tolerance to see what effect these have, and then to run the various regressions with certain factors in and with certain factors out to see how that will effect the ultimate prediction.

Then one should establish some criteria for what would be interpreted as a good model. You can see those there.

(Figure 110)

As a further step then is to use the ridge regression technique, which eliminates certain values of the x term to see how this again effects the regression equation, what it does to the stability or instability of the prediction.

And then you can use these methods then on the results to see just how

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good we can come up with a prediction model. By plotting the ridge results we can use these then to determine whether a particular value should be fixed in the regression, should be varied, should be eliminated completely. It might also indicate some other values that could be brought in.

Also, then, one could lack at the lack of fit, looking at areas that we don't have good fit. We feel that there may be certain regions in the test matrix that were beyond the expected operating levels, that were outside of the realm extrapolation, so that we can not get significant performance in those areas. And they may have to be eliminated.

There are some parameters that were picked we got little or any life, maybe 12 to 13 cycles. And based on that they just will not perform there. It may be that in trying to include this into the regression we have distorted it.

Then, finally, is to establish confidence bands along the y so that this then will give us the ultimate set of confidence bands for the y's that we pick.

(Figure 111)

With this background then we show you the regression equation that we have at the present time. This is included in the handout.

Below are each of the variables and their identifier. You can see the factors that have come in, how they effect. Some of them are the single unit. Other we have cross products. Some of them are the squared term.

The order here does not indicate the order they come in or the order of necessary significance they have. But this is the values that give most improvement or give us the best fit right now.

(Figure 112)

With that equation this is the type of predictions, and the handout has the predictions for all the packs that we now have in use. But to give you an idea of the type of results we are coming up with, you can see the predictions here, on pack 26N, on 49N, and on 42N. This one doesn't look too good. But this one and this one give us quite good results. We are still looking into the results, trying to find out why doesn't this one predict. Like I say, it may be that it is just outside of the realm of the overall approach. It may be a factor that just will not come in.

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This then after we have arrived at the equation then to test it we normally run it on the normal packs. Again these are the parameters, so the packs we are calling normal these are the ones that are down in the range of what would be considered normal use. The temperatures are room temperature and below. The depths of discharge are normal, low recharge values. Charge and discharge rates again are more consistent with flight use.

These are the cycle numbers that we have actually predicted. You might want to write down at the present time the four packs have completed the following number of cycles. This is as of the ninth of November. 83N had completed 14,197 cycles. 84N, 13,330. 85N, 14,517. And 86N, 13,501.

In addition to the results we have actually looked at on the matrix itself and on the regression analysis, we also have work that is being done to screen the manufacturer's data and the base line data to see if there is a way that we can detect and predict life possibly from that on individual cells. This is the one thing we still haven't been able to get a good handle on, and that is how do we identify those cells that seem to operate good and those that seem to operate bad. This is being done with some pattern recognition techniques.

Also we are developing now individual data packages on each of the packs as they complete test, which will include a summary of the manufacturer's data, base line data, the history of cycle performance, failure modes, and also postcycling and the chemical analysis. And these packages as they are completed will be available for anyone who is interested in looking at a particular approach on his own.

As was mentioned a couple of times before, we also are now adding some cells from JPL on the accelerated tests. We have 16 packs from SAFT American that are on, also some packs from Eagle-Picher. These will then be used as test packs or confirmation packs once we have the regression model developed.

On the chemical analysis to date we have completed 154 cells, or 27 that are in progress. And these are being included with the data packages as they are being developed. The results of the chemical analysis and some of the other prediction methods will be covered a little bit later.

DISCUSSION

HARKNESS: Crane. On your handouts, on your normal pack, your 83N and 86N, the wrong temperature is on your handout. 83N should be 0

degrees, and 86N is at 20 degrees. Now the accelerated packs that Don is referring to are on your handouts the N packs. Your other packs that Don was talking about as far as JPL are your X and Y packs. They are the SAFT cells.

MAINS: I think another thing too that is in the handout, near the back of it, is a summary of packs that were included in this regression, cells and so forth, if they were taken out or deleted, the reason for exclusion from this particular analysis.

HELLFRITZSCH: I have got several questions -- first of all, what is a pack? Is this a subset of a large number of cells all of the same type? I gather it is.

MAINS: Yes, the pack consists of five identical cells that are run under identical test primers.

HELLFRITZSCH: And then the object of this whole thing was to develop an accelerated test of life. And I gather by life you mean the cycle at which polarity will occur?

MAINS: Yes.

HELLFRITZSCH: Now wherein does the acceleration consist? In other words, you must have had some that failed at 20,000 cycles. I mean, you are trying to predict something to validate what you are going to use as the x's. You have got to have a y that you validate against.

FORD: Let me comment on that. Let us back up a minute because the accelerated test was to develop the data base to make a model. Okay? And the acceleration factors were built into it based on some work completed by the Air Force, like Bahelle; you know, several other companies were involved in it over a period of time. So the accelerated test itself is a means to an end, the end being the data base on which to develop these models from.

MAINS: I think maybe an answer though to your question the normal tests do approach that base that we will check the model against.

HELLFRITZSCH: But you have here predicted the cycle on which you expect the failure already.

MAINS: Right.

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HELLFRITZSCH: So you must have done what I was talking about.
But I am not clear how you did it.

MAINS: The way we arrived at these predictions here is we developed
a model that I had shown here on the regression.   Then based on that model
we plugged in the parameters for these particular packs and came up with these
predictions.

As I mentioned at the beginning, we don't have all the answers in that.
We are still missing a lot of our 30 degree operating tests at the 30 degree
temperature.   And I think when we get those results in this again will have some
impact on the model.   The model is not complete yet.

HELLFRITZSCH: No, but up in the middle you have got four cycles
on which four actually did fail I gather, up there, as part of this work.   They
are on the average where you would expect those treated that way, operated
that way, to fail.   And it is very good for that, if that is what it is.   So you
must have done the whole thing already, must have validated it.

MAINS: Well, we have gone through it several times.   Like I said,
this is the latest application of the regression analysis.

HELLFRITZSCH: The last question I have is you mentioned that for
goodness of fit or of regression, for example, for some of these packs you have
up there what percent of the variance, let us say, of those repeated alike is
accounted for by your regression equation?

MAINS: I don't have those numbers with me.   Like I say, these are
some of the things we have approached now.   We will be applying those as we
finish the model off.   We don't necessarily apply them each time, and I haven't
got it for this information for the information that is in your handout.   This is
one of the things we are working on now.   We will be applying it in the next
couple of months.

GROSS: Boeing.   If you are looking at the data in the packs below it
shows a relatively small sensitivity of predicted failure or lifetime to temper-
ature, whereas my recollection of the older Crane data was that temperature
was a much stronger factor.   Is everything else the same, or is there anything
else that is influencing this failure rate?   Or, is this a change of the sensitivity
of temperature in these cells?

MAINS: Well, like I mentioned before, temperature I think is one of
the prime factors, but we are missing one of the temperature blocks in a

significant way and that is the 30 degree. You remember the original matrix the 30 and 50 degree are the factorials, and that is where the largest number of tests were performed. And we are still missing eleven of those packs in that 30 degree. So the matrix isn't complete yet, and so we have developed a regression equation. It is lacking in that area. That is the one that right now is giving us apparently the longer life and I think will have a major impact on the final equation. This is the problem of looking at this part way through, before you get all the results in, because it is biased. I am sure of that.

FORD: That is the same question that we raised about six months ago at one of our meetings because of that prediction showing that the depth of discharge is not that different either but temperature -- and the fact is that this whole process is an iteration process, the regression. As you feed more data into it you update it and keep predicting.

Now, it is like a self feeding process because the numbers you predict there are based on the numbers that went into it from the accelerated packs. So obviously you hope to be able to predict those pretty good. But the proof of the pudding is when you take the accelerated and the base, feed into regression that you have refined and refined and refined and you just keep cycling it over and over and over, you can never stop, you know, if you want to carry it to the ultimate. But the proof of the pudding is when you can take data that were developed and not the accelerated test data, plug it into the accelerated test equation or the regression equation, and then make it predict. And this is what the test case is down here at the bottom. The rest of these are kind of like one feeds the other, because the cycle that is in the left column there or in fact went into the data base is predicting the cycle life of the cell.

HALPERT: Goddard. If I look at the regression equation, (Figure 111), the one thing that bothers me is that you have a constant that says 94,460. Obviously that is the number of cycles since the y there in that equation is the number of cycles. The constant is 94,460. If you look down at the third and fourth numbers, you see we have 3433 times 7. This value is the amount times KOH volume which is almost 20. It is 18 1/2 cc's, so you have almost a 60,000 number subtraction from that 90,000. And the next one down, precharge, is 3.000 times two and a half ampere hours of precharge for a total of 8,000 or so. So what I guess I am saying is the thing that bothers me is the insensitivity there of having a large constant and from that being subtracted a very large number that is dependent on the amount KOH, namely 60,000. So I just have to say a work of caution, that we look at this in light of all those big numbers that we are dealing with. There is some insensitivity.

MAINS: Right.

SCOTT: TRW. Would you please go down and give us the units of all those variables at the bottom?

FORD: Are you talking about that list?

SCOTT: Temperature, discharge rate.

MAINS: The units that would be used are degrees Centigrade. That would be percentage. Depth of discharge would be percent.

MCDERMOTT: It is a decimal point, and then 80 percent would be .8.

MAINS: Yes. The discharge rate is one-half or 1,2,4, the C rate. The charge is the same thing, the C rate, where C is the manufactured rate of capacity, and then the factor would be the number that would go against that. Precharge is a percentage again of -- a decimal point, yeah.

RITTERMAN: Is the rates -- are those in hours? What is the unit actually?

FORD: Let us let him go through, and then we will take questions. I think it will keep us going that way.

MAINS: The concentration is in percentage by weight, decimal. The amount is in cc's, and the precharge is ampere hours. This is a 6 ampere hour nickel cadmium cell, and the charge and discharge rates are like I say in the C rate normalized value.

RITTERMAN: What is the unit?

MAINS: It is a ratio. It is a dimensionless unit as we are using it right now.

HAAS: Ford. I guess eventually there will be some additional analysis in regard to the synchronous orbit, modeling. This is primarily now for a low earth orbit modeling for predicting life, or have I missed --

MAINS: Yes, this right now that is it.

HAAS: Is there some additional work planned for synchronous orbit modeling?

MAINS: I think once we get the base model then there is going to be all kinds of looking at, you know, how this can be refined and applied to other applications, not only nickel cadmium but other types of cells, synchronous as well.

PAYNE: Canadian Astronautics.   Particularly regarding that last question, is there any plan to model cells that are just being held at standby or are on trickle charge for a long period of time or open circuit?

MAINS: Not at the present time.

PAYNE: Can you make a comment on what type of a failure rate in that respect the cells being held --

MAINS: But we do have some cells that are on storage at the different temperatures, and their results will be incorporated.   Now most of those were put on there for control or analysis of the chemical analysis as opposed to identifying failure modes.

PAYNE: Would that be another area in the analysis?

MAINS: Not in the regression I don't believe because we are not really obtaining and looking for the failures at those conditions, so that particular part of it I guess we really weren't looking at extending it that far.   This again is still looking at a cycle performance under a near earth type of application.

MCDERMOTT: Coppin State College.   I would like to comment on one thing.   The cells that are on storage, say, at high temperatures, when you look at their failure, I think you will be able to feed back that information in for the cells that were at that high temperature also in the cycling regime.   We passed over at one point putting into the regression program a variable about simply time on test, and we said that it didn't help the regression.   I am still following up on that because I think that maybe it didn't help the regression for the wrong reasons.   So, I think we can take into account the storage cells, just the length of time it is on test as an important variable.   But we haven't gotten into the mechanics of how to get it into the regression.

MAURER: Bell Labs.   Since electrochemical process usually contains terms like reciprocals, exponentials, and logs, have you considered putting any of those in your model?

FORD: That is a good question.   You are leading into the next three papers.

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OBJECTIVES OF THE STATISTICAL ANALYSIS

1. DEVELOP A LIFE PREDICTION TECHNIQUE THAT WILL RELIABLY PREDICT THE LIFE OF A BATTERY.

2. USE A MINIMUM NUMBER OF CYCLES TO OBTAIN SUCH PREDICTIONS.

3. REDUCE TOTAL TEST TIME REQUIRED TO PRODUCE FAILURES TO VERIFY THE PREDICTIONS.

Figure 107

STATISTICAL ANALYSIS -- by Ralph Chipman, Statistician
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I. PREDICTION TECHNIQUES

A. Previously Investigated

   1. Polynominal Coefficients

   2. Orthogonal Polynominal Coefficients

   3. Voltage/Current

   4. Regression Analysis

       a) $\overline{T}$ and $\Delta \overline{Ti}$

       b) Hysteresis Loop

B. Current Under Investigation

   1. Regression Analysis

       a) 8 parameters

       b) Time on test

       c) DOD (%) terms

       d) Heat generated term

Figure 108

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Operating Procedure to Improve and Test
the Regression Model

1. Methods of auditing data

   A. Check the X-levels (5 levels per factor)

   B. Create data file of X-levels and verify

   C. Run homogeneity test on variances on y's and print out the within pack variance

2. Stepwise Regression

   A. Use all linear, quadratic, and linear by linear terms

   B. Select F_{in}, F_{out}, and Tolerance

   C. Run regression

3. Criteria for Good Models

   A. Usual $R^2 = \dfrac{SS \text{ due to regression}}{SS \text{ total}}$

   B. Adjusted $R^2 = \dfrac{MS \text{ due to regression}}{MS \text{ total}}$

   C. $Cp = \dfrac{SS \text{ (Due to regression)}}{\sigma^2 \text{ ("true" error MS)}} - (n-2p)$

   n = total number of observations
   p = number of x's in equation +1

Figure 109

4. Ridge regression

   A. Purpose: Ridge regression is used to eliminate those x's from a regression equation which exhibit instability.

   B. Method to use results
      Given x's have been discarded on basis of ridge plots
      i. one may use the remaining x's in a fixed regression
      ii. one may choose to put other x's in the model in addition to the remaining ones and do another ridge run

5. Lack of Fit

   A. If Lack of Fit is non-significant, plot residuals

   B. If Lack of Fit is significant
      i. Plot residuals and try transformations on x's in model.
      ii. Increase F_{in} and F_{out} and rerun regression.

6. Confidence bands on y

   A. Use confidence internal program to set confidence bands on y.

Figure 110

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REGRESSION EQUATION

STEP 23   21 VARIABLES $F_{IN} = 2$ $F_{OUT} = 1$

Variables in Final Model

94460		
-903.1	X_1	
-1114	X_2	
-3433	X_7	
+2023	X_8	X_1
-6.546	X_1	X_1
+3.206	X_1	X_2
+22.5	X_1	X_4
+44.16	X_1	X_7
+2.996	X_2	X_2
-1.824	X_2	X_3
+7.481	X_2	X_4
+.4717	X_2	X_5
-1.574	X_2	X_6
+21.69	X_2	X_7
-6.645	X_3	X_3
+4.895	X_3	X_4
-.4146	X_3	X_5
+12.72	X_3	X_6
+36.45	X_4	X_4
-4.187	X_4	X_5
-9.830	X_4	X_6
-323.6	X_4	X_8

VARIABLE IN REGRESSION

X_1	Temperature
X_2	Depth of Discharge
X_3	Discharge Rate
X_4	Charge Rate
X_5	Percent Charged
X_6	Concentration of KOH
X_7	Amount of KOH
X_8	Precharge

Figure 111

SAMPLE PREDICTIONS

	PACK 26N 30°C, 40% DOD	PACK 49N 50°C, 40% DOD	PACK 42N 50°C, 40% DOD
RECHARGE	140%	200%	200%
CHARGE RATE	12 AMP	12 AMP	3 AMP
DISCHARGE RATE	24 AMP	24 AMP	6 AMP

CYCLE FAILED	PREDICTED	CYCLE FAILED	PREDICTED	CYCLE FAILED	PREDICTED
12151		3946		827	
11067	11230	3764	3809	677	1740
11064		3057		953	
12096		3939		961	

NORMAL PACKS (NEAR EARTH ORBIT)

PACK	TEMP (°C)	DOD (%)	RECHARGE (%)	RATE (AMPS) CHG	RATE (AMPS) DISCH	PREDICTED FAILURE (CYCLE)
83N	0	40	105	2.52	5.0	13100
84N	20	20	105	1.26	2.5	21990
85N	0	20	105	1.26	2.5	24480
86N	20	40	105	2.52	5.0	12460

Figure 112

ANALYSIS OF VOLTAGE DATA

P. P. McDermott

Coppin State College

A lot of the questions that were raised in the last talk I want to address also in my presentation because they are problems that we have come in contact with over the last two years. We have really been struggling with them.

What I have been trying to do is to see how the various, those eight parameters, have been effecting the cell life, and trying as much as possible to isolate one parameter at a time and look at it in order to try to improve the regression model is possible by additional terms. We have the eight terms that are going into the regression analysis. There may be other terms which can go into it to help improve it. It is very difficult with regression analysis, if anybody has been into statistics, to when you are running a multiple correlation actually follow one variable at a time. In fact, the statistics of it tells you not to do that. But, anyway, I would like to put up here again the matrix and emphasize which of these levels we have discussed as the factorial cells and the starpoint cells.

(Figure 113)

The factorial cells, and this is terminology I will be using throughout so I really have to emphasize it again, are combinations of these two levels here, B and D. The starpoint, centerpoint, cells C are the centerpoint. That is, these packs would have these eight parameters. The starpoint cells would have one parameter from either column A or column E, and the other seven parameters from column C. So, this is one way of looking at one variable at a time is to look at the three packs, which constitute the centerpoint, and one variable out here and one variable out here. In other words, you can have three data points to examine one variable at a time.

(Figure 114)

So, if we looked at the failure times for the various eight parameters, what I have done is I have plotted them in such a way that you see three packs per graph, isolating out each variable at a time. You see that the variation in temperature, this is cycles versus temperature, 20 through 60 degrees, is fairly linear down. The variation, depth of discharge, we would expect. It starts high at the lower percent DOD and runs down to very few cycles at 100

percent DOD. Now this doesn't mean that a cell can't run at a 100 percent DOD, but it can't run that way at 40 degrees Centigrade and high charge and discharge rates.

The variation in charge rate and discharge rate I show that the range that was selected for the accelerated test matrix puts the centerpoint cell really in an optimum position, and the extremes are really considerably lower in cycle life. Now this is unusual. If you look at, say, discharge rate, you would expect that if you have a low discharge rate you are going to get more cycle life out of it. This is a question I have been trying to deal with. The variation in charge rate here is the low cycle life here was due to the fact that the cell wasn't charging up at the temperature that the cell was being run at. So you can understand that failure. It is hard to understand this failure for a low discharge rate.

It may have something to do with again something that we talked about in the last presentation, about the length of time that the cell is on test. If it is a low discharge rate that means that cell is going to be on test much longer than, say, the 2C discharge cell or the 8C discharge cell. So, I think we do have to look at time on test as one of the parameters to go into the regression. It hasn't worked yet, but I think there may be a problem with this which I will discuss later, why it didn't work.

(Figure 115)

Here are the other parameters. Variation in precharge did not have too dramatic an effect. The factorial cells would be right in here and here. So at least the factorial cells and the centerpoint cells, variation in precharge, would not have that much effect. Variation in KOH had some effect but not great. Variation in percent KOH had sort of a bell-shaped curve.

What this is telling us is that our matrix in a sense was linear in some of these variables, or at least monotonically increasing or decreasing. In other of the variables we were having from one side of the matrix to the other side going over a type of bell-shaped curve. When you are doing multiple regression this can cause problems if you are trying to correlate factors which are not changing linearly.

(Figure 116)

The multiple analysis, multiple regression analysis, goes something like this, to answer I think one question from the last presentation.

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The eight test parameters are put in as independent variables with squares and interactions among the eight test parameters. Now, remember when Don put that one up there, it had X_1, X_2, and so forth. It had X_1 times X_7, X_2 times X_7. These would be squares and interactions with the test parameters, which introduces non-linearity into the regression analysis, because you would get parabolic effects in here. Now this other parameter I put that in there because we are now generating from the eight parameters new parameters, which are combinations of the eight, which may be non-linear. This is to answer Maurer's question about whether you put in the parameter as is or maybe an exponential of it or a logarithmic function. And these we could test as other parameters. The input is, of course, of the independent variable versus the dependent variable, which would be cycles to failure. So you take the data within the accelerated matrix here plus the cycles to failure. You would compute the stepwise regression and calculate the coefficients. This is within the accelerated test matrix. Then, for output, you would take the parameters for the normal packs. These would be those four packs, 81 through 84, and try to predict failure for the normal pack.

Now, as Floyd said, we became concerned about six months ago. The temperature dependent was not showing up very strongly in the failure of the normal packs. So I tried to go back and see if maybe eliminating some of the variables or looking at how these variables might be changing we could introduce non-linearity into the regression, in other words, try to predict better the failure of the normal packs that would incorporate temperature.

(Figure 117)

What I did was a sort of first pass, to try to merge the existing data to eliminate some of those variables we saw in the first two slides, that is do not consider variation in KOH or variation in precharge as being that significant in predicting failure. As you noticed, some of the ones are relatively flat. And it may be that we are injecting too many variables into the regression program, and the regression program is sitting down and the variables are feeding with each other and not coming out with a good prediction. And this is something that you have to worry about in regression is colinearity among the variables. That is, several variables are trying to predict the same thing. They are competing with each other, and it is taking you really away from a good prediction. It is better to try to limit the number of variables going in so that they are as the statisticians call orthogonal. They are not relating to each other simultaneously.

So what I have done is reduced everything to DOD and temperature as the two main effects. I plotted them a certain way so that temperature is running

on the x axis, cycles to failure on the y, and then the lines are representative of the various depth of discharge. The enclosed circles would be the starpoint packs; and the squares, blacked in squares, would be factorial averages. In other words, I averaged together numbers of packs, in a sense averaging out the effect of KOH and such. The open circles are extrapolations from starpoint, centerpoint.

I found when I plotted them this way that if you connect those with percent DOD, granting that there are not many data points up here, they tend to give you a fan shaped plot, which it turns out if you take one temperature, say, 40 degrees, it is rising exponentially. In other words, if you drew a straight line through here and took the intercept with the cycles to failure, it would be an exponential function. So I could make an hypothesis of an equation, and empirical equation, because it is derived from the previous graph, as to cycles to failure as a function of temperature and depth of discharge.

(Figure 118)

And here depth of discharge is an exponential term. This is a linear term, but it is 70 minus the temperature at which the pack is being run. The way you get 70 is you see all those lines pass through 70 as an intercept.

Now these would be only packs that were run at the 140 percent recharge. I eliminated the 200 percent recharge because those packs seemed to be getting very spurious data for some reason that we haven't figured yet. But it doesn't seem to be a good accelerating factor. So I am taking now packs just at 140 percent recharge rate, and this would be 1 C charge and 2 C discharge. The averaging that I did was a normalization actually to 1 C and 2 C discharge.

This would be the predictions in cycles to failure for those normal packs here, which this would be pack 81 through 84. Now the normal packs are not de facto being run at 140 percent recharge and these charge and discharge rates, so just adding a factor of 30 percent or 50 percent, which I think in the long run we are going to have to do, brings these up considerably. But I was mainly interested in the spread between the failure times. And you see now temperature does have a more significant effect, 0 and 20 degrees here, fifteen and twenty thousand cycles, thirty-three thousand cycles and forty-six thousand. It also brought the cycles to failure up. The normal predictions right now are low. This is understandable since we don't have yet the 30 degree packs, the failures, which when put into the regression will probably raise the normal pack predictions.

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The motivation for this was to try to find terms which could now be put into the regression model. So we would take for example instead of injecting DOD straight into the regression analysis we would put the exponential term and possibly fit a constant here, try a couple of constants here, versus DOD, and see how this improves the prediction.

Now, I think Ralph Shipman out at Crane did put this factor in, and he said that instead of putting in DOD he put in this exponential term for DOD. And that factor and its interactions were the first six variables to go into the regression. So I feel that we are onto something that we can't simply stick in the variables as is. We are going to have to put in functions of the variables. And this may have to be somewhat of an empirical method, at least for the time being, because we don't understand the exact chemistry and physics of this cell.

I think Dr. Lander is going to come with another prediction equation in which temperature and DOD will be the main features.

We mentioned also in the last talk about another parameter which was heat generated. This is an example of getting a new variable into the regression that may combine some of those eight. Heat generated would be you take the exothermic part of the reaction for discharge and charge, and you try to calculate how this is going to effect the temperature within the pack. And this would relate a number of those eight variables which are discharge rate, depth of discharge, recharge, percent recharge, and charge rate. So you see it may be that we will have to go in and combine some of these variables and put them into regression rather than letting the regression sort it all out. The regression now has some problems with this multi-colinearity. It may be as battery scientists we will have to figure out how these variables really are effecting life, construct some functions, put them into the regression, and see how it makes the predictions. So this is one whole area of work that I have been involved in.

Another has to do with the tear down analysis of the cells after they have failed. There is a whole laboratory effort out there to take the packs, open them up, test for carbonate and electrochemical capacity, chemical capacity and so forth. The parameters that I have been looking at more closely are the plate thickness, plate weights, and how they relate to electrolyte and separator. This is one facet of the tear down analysis.

What I have found is that you can find fairly good correlations of plate thickness versus cycles.

(Figure 119)

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What this is is a correlation of the positive thickness versus cycles for the various packs, and this is unedited data so some of these correlations may not be too good. But at least on this one, positive thickness, you can see the R values here, which represents a correlation, is fairly high all along the line here.

What this means is, let me show it graphically.

(Figure 120)

If you take cycles and positive plate thickness, you will find as we would expect positive plate thickness is going to increase, where we get actually a fairly tight, for most of the packs, fairly tight fit. This is the first standard deviation from the average for the plate thickness.

Positive weight increases slightly for most of the packs, but sometimes it is slightly negative. But there is not a real big change in the positive weight. The negative weight decreases, and this is a variant in some packs. As you would get more cadmium migration, you would expect a loss of active material out of the negative plate, which actually does show up. The negative thickness versus cycles is fairly constant.

(Figure 121)

Now, one calculation that we made was to take IES (Inner Electrode Space) versus cycles. In other words, calculating, taking just the negative plate thickness, positive plate thickness, averaging it out, taking the can dimensions, subtracting it out, then versus cycles, we find some fairly good correlations, that the cycles to failure are correlating fairly well with the Inner Electrode Spacing. As the spacing goes down, then you are going to reach a certain point where the cell is going to fail.

This is looking at cell failure as almost a physical change within the Inner Electrode Spacing, which ends up squeezing the electrolyte out of the separator and causing failure.

(Figure 122)

Here is an analysis of the wet weight of the separator minus the dry weight. So this gives us an indication of the loss in electrolyte in the separator versus positive thickness. And here again we get some fairly good correlations. As the positive plate is growing, you would anticipate a loss in electrolyte in the separator. Some people have made an hypothesis that the electrolyte is sucked

out of the separator, but I think you can also make a case of being pushed out. The positive plate is growing and just eliminating the void space between the plates and therefore knocking the electrolyte out of the separator.

(Figure 123)

Here is wet weight versus dry weight, which would be again electrolyte weight versus the Inner Electrode Space. Here we have some 90 correlations, .9, which would indicate very high correlation.

(Figure 124)

In the last slide I found generally when the Inner Electrode Spacing gets down to 2 mils then the cell goes. The average grams of electrolyte, now this would be averaging a number of packs together, grams of electrolyte lost in the separator per thousand cycles versus mils of Inner Electrode Space loss per thousand cycles, meaning that we may ultimately be able to use it as a prediction technique, at least in those cells that have positive plates which grow at a fairly regular rate per cycle. That is, if you know that your ultimate limit is one or two microns, the cell is not going to go past that point in terms of Inner Electrode Spacing. I think once the nylon gets down to one micron it is almost solid nylon isn't it?

DISCUSSION

SEIGER: 2 mils?

MCDERMOTT: Yes, 2 mils. Once it reaches that point there is no space between the plates for electrolyte, and some got fairly close to that and were still operating, which surprised me.

So this is another aspect of the prediction in terms of simply a tear down analysis of the cell, the examination of components, and seeing the rate at which components are changing we may be able to predict when the ultimate life of the cell will be.

SEIGER: You have been measuring the thickness or the swelling of these electrodes after you have removed them from the cell.

MCDERMOTT: Yes.

SEIGER: We have observed that there are two kinds of thickening that we have kind of broken out, and we have called one a hard thickening because

it occurs in the cell and another one a relaxation or soft when you remove it from the cell. And that is probably why you could measure such thicknesses that you would have a solid sheet of nylon in there. And really you don't.

MCDERMOTT: I know. If you were measuring particular cells with a lot of cadmium migration, when you pull the cell apart then you are pulling some of the separator apart and you are actually measuring part of the Inner Electrode Space when you take that measurement. That is granted.

So I don't believe that it actually gets to 1 or 2 microns.

SEIGER: Not in the cell.

MCDERMOTT: -- mils in the cell. That is true. But when the measurement shows that it gets to that point, the cell will not operate. Now you may actually de facto have 3 mils of space or even 4 mils of space in there. In other words, you are finding that your measuring technique will tell you that when your measuring technique hits 2 mils it is going to fail. That is what I am saying. It is not an absolute, but your measuring technique is allowing you to predict failure.

SEIGER: There would be another interesting correlation that I would have liked to have seen you done or look at, and that is the wet weight or the electrolyte content of the negative electrode.

MCDERMOTT: Yes. I have found in other correlations that most of the electrolyte goes more than 50 percent of the electrolyte into the negative. Most people have said it is going into the positive, but I think more of it is going into the negative.

HELLFRITZSCH: A couple of questions again. These packs, are they the same kind of packs that Mr. Mains was talking about?

MCDERMOTT: This is the same test, yes.

HELLFRITZSCH: Well, now that was a homogeneous set of cells of some brand and dimensions and what not. How in that set of slides where you showed the correlation line, linear, betwixt cycles to failure, and plate thickness were you able to get so many different plate thicknesses out of a homogeneous bunch of cells?

MCDERMOTT: The plate thicknesses are within a certain range. But I was giving averages in standard deviations of the plate thicknesses.

HELLFRITZSCH: Could we see that slide?

MCDERMOTT: Yes. In other words, you are taking the 10 positive plates and the 11 negative plates. You are averaging them together and getting a standard deviation around the average, which tells you how tight the fit is around.

HELLFRITZSCH: But you are correlating plate thickness per se with cycles to failure.

MCDERMOTT: That is right.

HELLFRITZSCH: So the abscissa was plate thickness, and I will have to look at the numbers to see how much the variation was.

MCDERMOTT: Yes.

HELLFRITZSCH: It is a matter of a tenth of a mil in units, and I thought it would be something more like an eighteenth of an inch.

MCDERMOTT: The variation in plate thickness is given in Figure 120.

HELLFRITZSCH: I am just trying to understand exactly what you are doing.

HELLFRITZSCH: In other words, that was the variation you found in supposedly uniform manufacture of cells.

MCDERMOTT: No, this is after cycling. In other words, down here these are the original plates. They were within a certain narrow range, around 29 mils.

HELLFRITZSCH: Oh, so this is not cycles to failure.

MCDERMOTT: Yes, these are cycles to failure points along here. In other words, this cell which failed at a 1,000 cycles -- two of them in fact had failed at a 1,000 cycles.

HELLFRITZSCH: Had gotten that thick.

MCDERMOTT: Had gotten that thick. 38 mils.

HELLFRITZSCH: Alright. Okay. Now, the real question, when you get all through with this, this homogeneous set of batteries --

MCDERMOTT: They are not homogeneous by the way. They have three design variables in them which are different.

HELLFRITZSCH: Cell plate --

MCDERMOTT: No. Cell size and plates are all the same. KOH, okay.

MCDERMOTT: Capacity is the same, yes.

HELLFRITZSCH: I think I am beginning to understand wherein the acceleration is going to lie ultimately, namely that you are going to find that certain of these parameters predict cycles to failure for this brand, and that these tests are going to be limited to those that can be done in less than a year I heard somebody say hopefully earlier, because they didn't want to spend more than a year and then getting the data.

MCDERMOTT: Yes.

HELLFRITZSCH: You will determine what those parameters are for this new cell that you are trying to make a prediction about.

MCDERMOTT: There are several philosophies about how to approach it. The original one was to use this as a screening technique. You would take a lot of cells. You would have a certain test matrix. You would put it through 50 or 100 cycles, so it would not damage the cell and then predict life. I think that is foolish. You are never going to reach that. 100 cycles at accelerated rates can very definitely damage the cell.

You are cast then upon a sampling type technique. You take a lot of cells. You take 20 percent of them, say, and then you put them through an accelerated regime, through less than eight parameters. I would say you have got to stick to maybe two or three parameters DOD, temperature, but at an accelerated rate, 40 degrees C, 30 degrees C, and high depths of discharge. Then you actually build a regression equation out of that. If you get them from manufacturer B, you can take 20 cells, build your own regression equation, and make your own predictions.

I don't think you can use the regression coefficients generated on General Electric cells made after 1970.

HELLFRITZSCH: Nor the functions either. You are not even going to use the functions, each of the something times DOD.

MCDERMOTT: I think what the accelerated test program is going to do is select which variables are good accelerators, which variables make a consistent prediction, and which ranges of acceleration are valuable. See, we are not saying that you should take this regression equation from this test and make a direct application. I mean, you may want to, but I would be a little hesitant to do that. I would take a sampling of cells, build a new regression equation, and use those coefficients to predict the life of the normal cells.

GROSS: Boeing. Pat, did you determine that these cells are mostly negative limited during cycling?

MCDERMOTT: Not all of them. Some get negative limited. It really depends on the cycling parameters. There are a number of pressure failures in the starpoint cells, which I believe are negative limited. But there are a number of the factorial cells which are low voltage failures. They did not experience the pressure failure mode that the others did, so I would say those are not.

One problem we have had is the diversity of the type of failures that have occurred. There are three failure criteria: high pressure, low voltage, and shorting. And we may have to examine each of those failure modes separately in the regression program, taking only low voltage failures. I think right now we are only taking low voltage and shorts. Aren't we, Don?

MAINS: Yes.

MCDERMOTT: So we have eliminated the pressure failures. Now I incorporated some of the pressure failures in my work. But the regression program that they are running now did not include the pressure failures, which cuts down the number of packs that are going into the regression model. Yes?

SEIGER: I would like you to consider two cases. If you take a positive electrode that does not expand, or minimal expansion, significantly less than that, how would that impact cycle life -- your guess?

MCDERMOTT: Dramatically.

SEIGER: Similarly, you have noted the electrolyte redistribution into the negative. If one were to also solve that problem, what would then be the effect of these two changes on cycle life and what you have been doing?

MCDERMOTT: Well, you have answered your own question. It would increase it dramatically, so that is why you would have to go into taking, especially a new cell that exhibits a new technology, and setting up your own accelerated matrix and running it. Now I do think that you will still come back to DOD and temperature as the major accelerating factors.

SEIGER: I believe that entire program is even more valuable than you have been showing, that you can take these parameters and turn them around to help improve cycle life, et cetera, of the system.

MCDERMOTT: Yes, I would see one way of using this in terms of a manufacturing variable type analysis is to use DOD and temperature as your major accelerating factors, not percent overcharge and not varying the charge and discharge rates. In other words, you are taking those out as accelerating factors, having a high enough charge and discharge rate so that the cell is not limited in gaining charge, then taking your manufacturing variable and, say, plate loading, varying the plate loading. Run an accelerated test, accelerating the DOD and the temperature, and then see how the plate loading correlates with the accelerated failures.

Does that answer your question? I don't think -- we are not limiting ourselves to just these changes in manufacturing parameters.

LIM: Hughes. I have a comment and question about the actual measurement of the thickness. I think that if you measured the electrode for thickness or with the wet state; say, with the state of the electrode and with a certain pressure, I don't know what is the actual pressure in the cell, then you can eliminate the uncertainty that Dr. Seiger pointed out. And I wonder what is your actual technique of measuring the thickness.

MCDERMOTT: You will have to ask the gentleman from Crane.

MAINS: Crane. The thickness is measured with a one square inch measuring guide with a fixed weight on it. So all of them are weighed at the same weight. They are all weighed after they have been extracted and dried.

SCOTT: TRW. How were the two failure modes distributed? That is, what percentage of each are included in the cells that you performed the analysis on?

MCDERMOTT: Do you have any idea, Don? In terms of pressure versus low voltage?

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SCOTT: No, you said you included only low voltage and shorting. What percentage of each are you looking at?

MAINS: I would say the greatest percentage would be low voltage.   I don't have a real fixed number.

MCDERMOTT: Dr. Lander does, I think, don't you?

LANDER: Yes.   The shorted failures are less than 10 percent.

MATRIX OF TEST PARAMETERS FOR CELLS CYCLED
IN THE ACCELERATED TEST

TEST PARAMETERS	LEVEL OF EACH PARAMETER				
	A	B	C	D	E
1. TEMPERATURE (°C)	20	30	40	50	60
2. DEPTH OF DISCHARGE (%)	20	40	60	80	100
3. CHARGE RATE	C/4	C/2	C	2C	4C
4. DISCHARGE RATE	C/2	C	2C	4C	8C
5. PERCENT RECHARGED (%)	110	140	140	200	200
6. CONCENTRATION OF KOH (%)	22	26	30	34	38
7. AMOUNT OF KOH (cc)	17.5	18.5	19.5	20.5	21.5
8. PRECHARGE (Ah)	2.20	2.50	2.80	3.00	3.30

Figure 113

STARPOINT/CENTERPOINT
CYCLES TO FAILURE VS. PARAMETERS
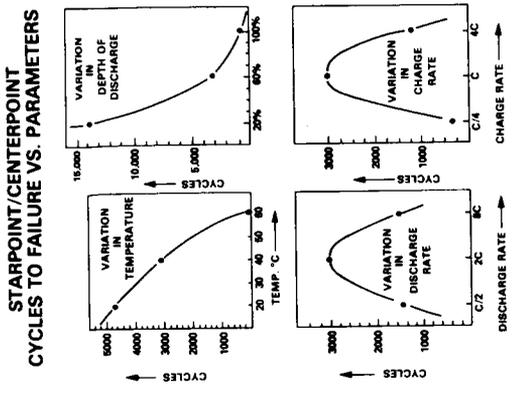
Figure 114

STARPOINT/CENTERPOINT CYCLES
TO FAILURE VS. PARAMETERS

Figure 115

REGRESSION ANALYSIS

1. INPUT — INDEPENDENT VARIABLES / DEPENDENT VARIABLE

A. EIGHT TEST PARAMETERS + B. SQUARES AND INTERACTIONS AMONG EIGHT TEST PARAMETERS + C. OTHER PARAMETERS = D. CYCLES TO FAILURE

2. COMPUTATION - STEPWISE MULTIPLE REGRESSION

3. OUTPUT

REGRESSION COEFFICIENTS CALCULATED FROM ACCELERATED TEST DATA × PARAMETERS FOR "NORMAL" PACKS = PREDICTED CYCLES TO FAILURE FOR "NORMAL" PACKS

Figure 116

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PACK 68   N= 8
POS TH VS. CYCLES
A= 30.970582   B= 3.06285E-03   R= 0.972018517

PACK 69   N= 6
POS TH VS. CYCLES
A= 29.29345879   B= 5.36680E-03   R= 0.989779082

PACK 70   N= 5
POS TH VS. CYCLES
A= 30.22199538   B= 3.76872E-03   R= 0.874283608

PACK 71   N= 8
POS TH VS. CYCLES
A= 29.96145635   B= 3.74666E-03   R= 0.828167334

PACK 72   N= 8
POS TH VS. CYCLES
A= 29.82762459   B= 5.88018E-03   R= 0.923659767

PACK 73   N= 4
POS TH VS. CYCLES
A= 32.21103282   B= 1.93010E-03   R= 0.999400971

PACK 74   N= 8
POS TH VS. CYCLES
A= 31.02406684   B= 3.13950E-03   R= 0.893585408

PACK 75   N= 7
POS TH VS. CYCLES
A= 27.23938916   B= 4.26392E-03   R= 0.903625106

PACK 77   N= 8
POS TH VS. CYCLES
A= 28.12936343   B= 6.45347E-03   R= 0.849756624

PACK 79   N= 7
POS TH VS. CYCLES
A= 32.55292193   B= 1.75773E-03   R= 0.920155727

PACK 80   N= 7
POS TH VS. CYCLES
A= 30.57807124   B= 2.80650E-03   R= 0.939359307

PACK 81   N= 4
POS TH VS. CYCLES
A= 33.99618984   B= 1.68901E-04   R= 0.079121712

Figure 119

CYCLES TO FAILURE VS.
TEMPERATURE (°C)
AT VARIOUS
DEPTHS-OF-DISCHARGE

Figure 117

I. EMPIRICAL EQUATION DERIVED FROM CYCLES-TO-FAILURE
VS.
TEMPERATURE GRAPH

FOR CELLS CYCLED AT 1C CHARGE, 2C DISCHARGE, 140% RECHARGE

$$\text{CYCLES TO FAILURE} = 1000 \times \left\{70 - \text{TEMP.}\atop (°C)\right\} \times e^{-\left\{0.038 \times \text{D.O.D.}\right\}}$$

II. PREDICTION OF NORMAL PACKS CYCLES-TO-FAILURE

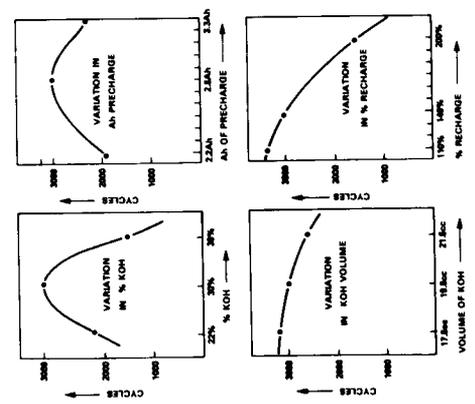| TEST CONDITIONS		AT 140% RC 1C CHARGE 2C DISCHARGE	FOR 105% RC AND LOWER CHARGE AND DISCHARGE RATES	
TEMP.	DOD		ADD 30%	ADD 50%
20°C	40%	10,000 CYCLES	13,000 CYCLES	15,000 CYCLES
0°C	40%	13,600 CYCLES	17,700 CYCLES	20,400 CYCLES
20°C	20%	22,500 CYCLES	29,250 CYCLES	33,750 CYCLES
0°C	20%	31,000 CYCLES	40,300 CYCLES	46,500 CYCLES

Figure 118

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Figure 120

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PACK 68   N= 8
I.E.S VS. CYCLES
A= 5.114737398   B=-4.05981E-03   R=-0.887733514

PACK 69   N= 6
I.E.S VS. CYCLES
A= 6.706388831   B=-3.47221E-03   R=-0.968876733

PACK 70   N= 5
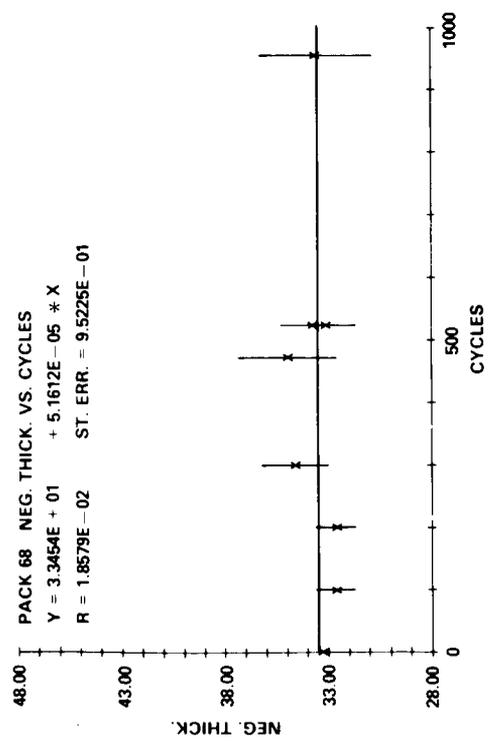I.E.S VS. CYCLES
A= 2.099484683   B=-8.18862E-04   R=-0.340644712

PACK 71   N= 8
I.E.S VS. CYCLES
A= 4.483394149   B=-1.48897E-03   R=-0.373696470

PACK 72   N= 8
I.E.S VS. CYCLES
A= 5.830487954   B=-3.04097E-03   R=-0.949251521

PACK 73   N= 4
I.E.S VS. CYCLES
A= 4.221379467   B=-1.02770E-03   R=-0.952251507

PACK 74   N= 8
I.E.S VS. CYCLES
A= 4.900749676   B=-1.40207E-03   R=-0.752711775

PACK 75   N= 7
I.E.S VS. CYCLES
A= 8.720542197   B=-2.86828E-03   R=-0.933802977

PACK 77   N= 3
I.E.S VS. CYCLES
A= 6.57384407   B=-3.43326E-03   R=-0.806610505

PACK 79   N= 7
I.E.S VS. CYCLES
A= 4.574537365   B=-9.45095E-04   R=-0.874944772

PACK 80   N= 7
I.E.S VS. CYCLES
A= 4.691950965   B=-1.23074E-03   R=-0.759505615

PACK 81   N= 4
I.E.S VS. CYCLES
A= 3.482434854   B=-4.77165E-05   R=-0.028565997

Figure 121

PACK 68
WET-DR VS. POS TH
A= 1.22531474   B=-0.02746300   R=-0.845230632

PACK 69
WET-DR VS. POS TH
A= 1.48399746   B=-0.034880002   R=-0.875000488

PACK 70
WET-DR VS. POS TH
A= 0.774658864   B=-0.016520537   R=-0.964457511

PACK 71
WET-DR VS. POS TH
A= 1.36668987   B=-0.034234658   R=-0.601679800

PACK 72
WET-DR VS. POS TH
A= 0.919226469   B=-0.016597149   R=-0.980136500

PACK 73
WET-DR VS. POS TH
A= 1.384396315   B=-0.031708502   R=-0.912303411

PACK 74
WET-DR VS. POS TH
A= 0.754699472   B=-0.011870464   R=-0.498737000

PACK 75
WET-DR VS. POS TH
A= 1.283067138   B=-0.029394203   R=-0.898743919

PACK 77
WET-DR VS. POS TH
A= 0.311357435   B=-2.68136E-03   R=-0.231577189

PACK 79
WET-DR VS. POS TH
A= 0.826443009   B=-0.018239080   R=-0.590527853

PACK 80
WET-DR VS. POS TH
A= 0.738364316   B=-0.011110150   R=-0.735437662

PACK 81
WET-DR VS. POS TH
A= 1.024337767   B=-0.019793152   R=-0.721886204

Figure 122

Figure 124

AVERAGE GRAMS OF ELECTROLYTE LOST IN A SEPARATOR PER 1000 CYCLES

MILS (0.001 IN.) OF INNER ELECTRODE SPACE LOST PER 1000 CYCLES

PACK 68
WET-DR VS. I.E.S
A= 0.086092565   B= 0.055613188   R= 0.941643555

PACK 69
WET-DR VS. I.E.S
A= 0.125381205   B= 0.049552649   R= 0.821596902

PACK 70
WET-DR VS. I.E.S
A= 0.183251764   B= 0.019786734   R= 0.644171017

PACK 71
WET-DR VS. I.E.S
A= 0.036460378   B= 0.052654156   R= 0.802149635

PACK 72
WET-DR VS. I.E.S
A= 0.234654497   B= 0.032971850   R= 0.979824306

PACK 73
WET-DR VS. I.E.S
A= 0.121482816   B= 0.056308175   R= 0.905336122

PACK 74
WET-DR VS. I.E.S
A= 0.243054986   B= 0.038555318   R= 0.680622123

PACK 75
WET-DR VS. I.E.S
A= 0.092991339   B= 0.046776240   R= 0.930989731

PACK 77
WET-DR VS. I.E.S
A= 0.200220035   B= 7.40360E-03   R= 0.358366592

PACK 79
WET-DR VS. I.E.S
A= 0.061444056   B= 0.039909270   R= 0.730660485

PACK 80
WET-DR VS. I.E.S
A= 0.291741953   B= 0.020642055   R= 0.741105474

PACK 81
WET-DR VS. I.E.S
A= 0.258385643   B= 0.025405723   R= 0.725049130

Figure 123

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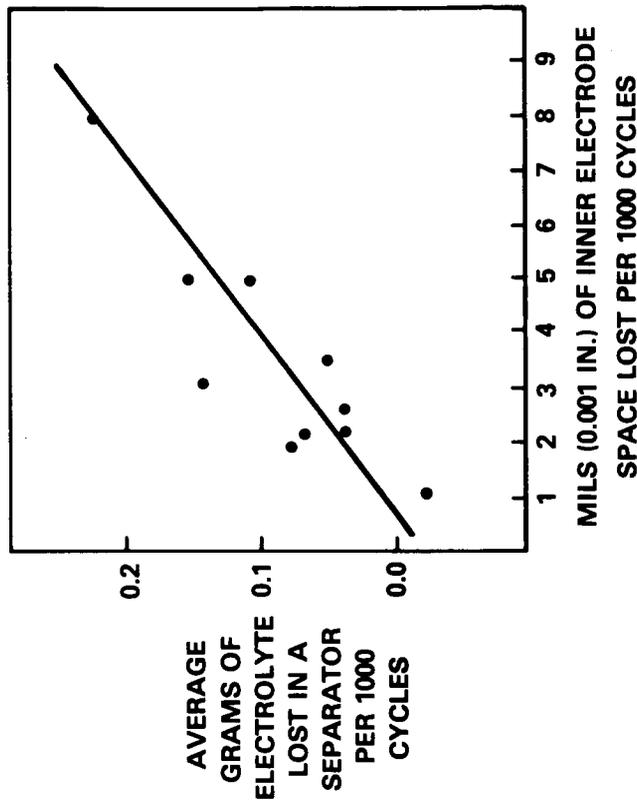
PREDICTION TECHNIQUE

J. Lander
Air Force Aero Propulsion Laboratory

Back in 1973 I derived this equation for the cycle life of ni-cd space cells, which relates the cycle life to a temperature function and a percent depth of discharge function.

(Figure 125)

In this equation this is T. It is obscured by the line going across there. Now M is a term which represents the degradation of capacity. It is a function of the number of cycles, and then the actual derivation I use that as a linear function.

The value 2 below the exponent derives from the old simple idea that a chemical reaction increases rate by doubling for each 10 degrees Centigrade. And of course instead of using Centigrade, I used Fahrenheit. That is why the denominator in the exponent is 18. And we did use an arbitrary value of M in order to test this out against the then existing data.

(Figure 126)

And in that process we changed the equation to fit the best data, which derived from a 1966 cell design, which was under test and producing information at that time at Crane.

Now the cycle life equation has changed somewhat. Instead of using 50 degrees as a base, we use now 68 degrees. That is in the numerator of the exponent. The value .1 corresponds to whatever temperature you use as a base line point in the numerator of the exponent. And now we find instead of doubling the degradation rate per 10 degrees Centigrade, we now get an increase of 1.5.

(Figure 127)

Now from these equations we can see that an average partial test of the equation can be made because the equation predicts linearity of cycle life as a function of the term 100 minus percent DOD all divided by percent DOD. Now the origin for the curve we have shown will lie upon the curve if for 100 percent DOD we use the actual capacity and not the nominal capacity.

(Figure 128)

Now when we make this test with the starpoint data which is available from the Crane program we find this. The cycle life is a function of 100 minus percent DOD divided by percent DOD. It is a linear function, and it goes through the origin if you use the actual capacity as 100 percent DOD. Now this data happens to be 40 percent Centigrade and 140 percent recharge, which was one of the conditions for starpoint.

(Figure 129)

Now there is another kind of a program, which is called the factorial design, which the previous people talked about, and it is producing cycle life data as a function of combinations of the variables, 40 and 8 percent, 80 percent DOD, and 50 and 30 degrees Centigrade. Now this data shows, and I have a question mark after "show", that cycle life doubles as temperature is decreased from 50 degrees to 30 degrees. And the reason for the question mark is that the data from this experiment is not complete. There are eight packs or eleven packs still cycling, and so it is not all that well defined.

However, using doubling as a function of temperature, then we can construct these curves based on the previous curve for 40 degrees.

(Figure 130)

The bottom curve in this is the previous curve we showed you, and the slope of the curve doubles as a function of each 20 degree decrease in temperature.

In the program we have also assumed that there are normal cells which are cycling under the conditions of 20 and 40 percent depth of discharge at 0 and 20 percent degrees Centigrade. Those depths of discharge are also based on a 6 ampere hour nominal depth. And if we recalculate that on the basis of the actual, original capacity of the cell, we can predict the lifetime of the normal packs for 40 percent of nominal here to be these values and for the 20 percent nominal to be these values.

(Figure 131)

And so on this basis we come out with this prediction of cycle life from the Figure 2 curve, for the temperatures and the depth of discharge, what you got for discharge is what you are concerned with.

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Now we have to bear in mind that these are for the condition of 140 percent discharge. And we have seen that the actual cycle life increases as percent recharge, I mean 140 percent recharge, and cycle life increases as percent recharge goes down.

(Figure 132)

And a year or so ago I viewed this curve for the effect of percent recharge on cycle life for the condition of 60 percent depth and 40 degrees C. Now you will notice that the shape of that curve is a little bit different from the one that Pat showed you. I don't really know why this is.

At any rate, looking at that curve, what we can say is that as you go down from 140 percent recharge to 105 percent regharge we can get a 39 percent increase in cycle life.

(Figure 133)

And based on that piece of information and I recalculate the predicted values for cycle life for normal packs to be these. Evidently I don't have to say, but there are large uncertainites involved in arriving at these predicted values. And we will await with great interest the final cycle life determination, from which we expect to refine them just like we do in the other approaches which have been made here today.

(Figure 134)

Using a little bit of simple arithmetic we can show that the equation for the Figure 126 curve is equation 3 and it shows the effect of doubling for 20 degree increments, 20 degrees C increments in changes of temperature. And that is equivalent to equation 4, when we use instead of doubling for 20 degrees we express the effect of decreasing temperature in 10 degree increments.

(Figure 135)

We can say another thing or two, and that is we can use, oh, equation 5 is the same as equation 4 in the last chart, only now it is expressed in degrees Fahrenheit. And we can compare it with equation 2, which was the cycle life equation for the best data in the 1966 design. And we can see from this that we have slid backwards in cycle life capability of space cells, maybe.

Now, we can ask the question how general might this equation be, assuming that it is anywhere near correct in the first place. Okay? What we

hope is that other designs will follow this kind of a general expression for cycle life and that we will see variations in the design arising from this term and this term.

Now at any rate I have got what looks like one of the very simplest of approaches to this problem and furthermore I predict the highest cycle life values.

MAY 1973 DERIVATION

Eq. 1 $\dfrac{\text{CYCLE LIFE}}{1000} = \dfrac{1}{M \times 2} \times \dfrac{\left(\dfrac{1 - 50}{18}\right) \times \dfrac{100 - \% \text{ DOD}}{\% \text{ DOD}}}{}$

T IN °F

M = 0.06 BASED ON AN ARBITRARY VALUE OF DEGRADATION
RATE - 3%/1000 CYCLES FOR CONDITION 50% DOD + 50°F.

Figure 125

MAY 1973

Eq. 1 MODIFIED TO FIT 1966 CELL DESIGN TEST RESULTS

Eq. $\dfrac{\text{CYCLE LIFE}}{1000} = \dfrac{1}{0.103 \times 1.5} \times \dfrac{\left(\dfrac{1 - 63}{18}\right)}{} \times \dfrac{100 - \% \text{ DOD}}{\% \text{ DOD}}$

Figure 126

PARTIAL TEST OF THE EQUATION

EQUATION PREDICTS LINEARITY OF
CYCLE LIFE AS A FUNCTION OF
(100 - % DOD)/% DOD

ORIGIN LIES ON CURVE IF 100% DOD IS
DEFINED AS ACTUAL CAPACITY
(I.E. NOT NOMINAL CAPACITY)

Figure 127

FIG. 1 CYCLE LIFE vs (100 - % DOD)/% DOD

STAR POINT DATA
FOR 40°C + 140% RECHARGE

$100\% = \dfrac{\% \text{ ·AH}}{\text{BASED ON ACTUAL CAPACITY}}$

(100 - % DOD)/% DOD.

Figure 128

FIG. 2 CYCLE LIFE vs (100 - % DOD)/% DOD

PARAMETER = T(°C)
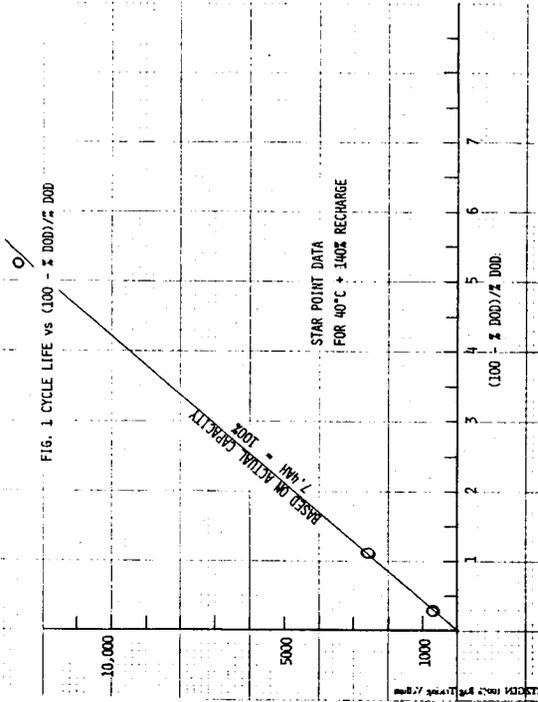
Figure 130

FACTORIAL DESIGN EXPERIMENT

DATA FOR: 40 ↓ 80% DOD @ 50 ↓ 30°C

SHOWS (?): CYCLE LIFE DOUBLES AS T

IS DECREASED FROM 50 TO 30°C

Figure 129
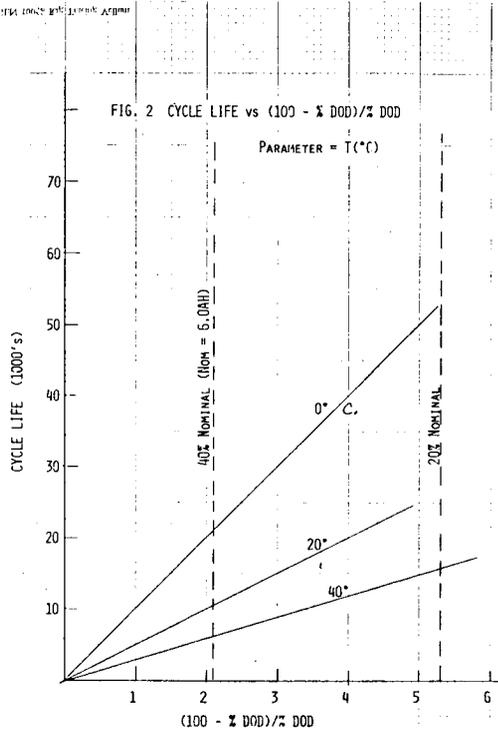
PREDICTED CYCLE LIFE
(FROM FIG. 2)

PACK#	T(°C)	% DOD(NOM. CAP.)	PRED. LIFE (140% RECHARGE)
83N	0	40	21,500
84N	20	20	26,000
85N	0	20	52,000
86N	20	40	10,500

Figure 131

PREDICTED CYCLE LIFE

(105% RECHARGE)
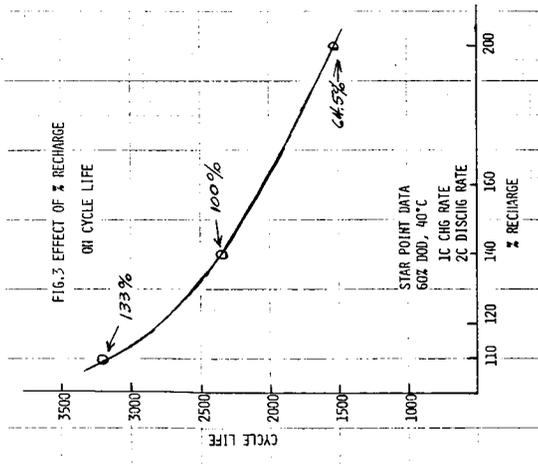
PACK#	PRED. LIFE (140%)	PRED. LIFE (105%)
83N	21,500 x 1.39	30,000
84N	26,000 x 1.39	36,000
85N	52,000 x 1.39	72,000
86N	10,500 x 1.39	14,500

Figure 133

FIG.3 EFFECT OF % RECHARGE
ON CYCLE LIFE

STAR POINT DATA
60% DOD, 40°C
1C CHG RATE
2C DISCHG RATE

Figure 132

EQUATION FOR FIG.2 CURVES

Eq. 3 $\dfrac{\text{CYCLE LIFE}}{1000} = \dfrac{1}{0.2 \times 2.0}^{\frac{(T-20)}{20}} \times \dfrac{100 - \%\,DOD}{\%\,DOD}$

Eq. 4 $\dfrac{\text{CYCLE LIFE}}{1000} = \dfrac{1}{0.2 \times 1.41}^{\frac{(T-20)}{10}} \times \dfrac{100 - \%\,DOD}{\%\,DOD}$

Figure 134

EQ. 4 EXPRESSED IN T(°F)

Eq. 5 $\dfrac{\text{CYCLE LIFE}}{1000} = \dfrac{1}{0.2 \times 1.41}^{\frac{(T-68)}{18}} \times \dfrac{100 - \%\,DOD}{\%\,DOD}$

Eq. 2 $\dfrac{\text{CYCLE LIFE}}{1000} = \dfrac{1}{0.103 \times 1.5}^{\frac{(T-68)}{18}} \times \dfrac{100 - \%\,DOD}{\%\,DOD}$

Figure 135

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CHARGE AND DISCHARGE PROFILE

P. P. McDermott
Coppin State College

This represents somewhat of a different approach to the prediction. It can be related back again to the prediction model, the regression analysis, through again these other parameters. If you take the eight parameters and the squares and the interaction of those parameters, this is sort of preset. In other words, you know what those parameters are when you go on test, and then you should at that point just predict everything from then on. You don't have to look at, say, the voltage and the pressure and so forth as you go on. At this point if you only use the eight parameters and the squares and the interactions of the eight you would only predict the failure time of the pack. You won't be able to discriminate between cells within the pack because all the information is about the packs' cycling parameters.

So we want to look at some possibly other parameters which could predict failures within the pack based on measurements that you were taking while they were cycling. Now Don Mains mentioned several approaches that were used and put aside, one of which was this T sub i bar, which is the time of discharge to 1.25 volts or 1.23 or 1.2. In other words, you measure the time it takes to get there, and that time is one of the variables. You put that into the regression analysis and see if you can predict life and variations of life within the pack itself.

(Figure 116)

Another that was mentioned was this hysteresis model, where you take the discharge curve and you take the charge curve. You superimpose them find the area between the two, and then use that area as one of the variables. This would measure somewhat the efficiency of the cell. If the charge voltage goes up higher or the discharge voltage goes down lower you would be measuring changes in the efficiency of the cell.

This one also ran into problems. I think both of those approaches the reason we were not coming up with really positive results is because the time to discharge to 1.25 volts is dependent on the discharge current. As you increase the current it is going to knock the voltage down a little, so that two perfectly good cells which show a different T sub i bar simply because their discharge rates are different.

So in an attempt to use the voltage curve, the discharge curve, or the voltage charge curve, we looked at some alternative methods. One that Don mentioned was to use a quartic fit. A quartic fit would by y equals a plus bx plus c, x squared, x cubed, and x fourth. So you would have coefficients for each of those terms. Then you would make that fit for cycle 1 and then make the fit for cycle 100, cycle 300, cycle 500, and see if you get variations in the coefficients. And then you go out to cycle of failure and see what the coefficient was out there and see if you can make some interrelationship there. The problem we found with this quartic equation was the coefficients were bouncing all over the place. That is, if you go from 100 to 300 to 500, you are finding that the coefficients are sinasoidal instead of either monotonically increasing or decreasing. You would really like to have a smooth function, which is either decreasing or increasing, so that you can extrapolate out to the failure cycle, and then say this is when the cell is going to fail.

(Figure 136)

So what Dr. Sommerfeldt and I did was to try to find an equation to fit the discharge curve, which would have terms in it that more closely matched the actual characteristics of the curve. See, when you are fitting with a quartic equation you could not identify really particular curves in that equation with shapes of the curve.

What we did after a number of hits and misses is to fit the curve, these are three discharge curves for pack 68, cell number 1. This would be the discharge curve at 36 cycles, the lower one, and then 171 and then 300. Okay. We fit it with two exponential terms plus a constant. So here would be the voltage plus the constant a plus b times e to the minus another constant c times time. See, time is along this scale here, and voltage is up this scale. So time variables would be all on this side, and voltage would be over here. Continuing, it is minus C T, minus d. There is another coefficient to be evaluated. E to the f, another coefficient to be evaluated. T minus tm. Now tm is the maximum time. That is, we had to actually make a first approximation as to what the fit would be, go down to 0 volts and say that is tm and then work backwards. So it is a relatively complicated computer process. Is is a non-linear fit, and Dr. Sommerfeldt did all this and I could not really go into describing how he did it.

But we found that we had to in a sense take first approximations, make the computations, readjust them, and make them again. You will notice that this term here, the "b e" to the minus "c t" would really be describing this exponential decay early in discharge. The "a" would be sort of the mean voltage over the whole discharge. The minus "d e to the f t minus t max" would be describing this portion of the discharge curve, the decaying exponential.

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Now you could say the physical relevance of this would be the first part of the discharge curve would be when those charges closest to the surface would be easily accessible so not very much over potential. Then as you go into the final discharge you are simply depleting the amount of protons in the positive crystal structure. So it is trying to relate in some way the physical discharge with the actual fitting equation.

Now when they tried the quartic equation the mathematicians out at Crane felt that the reason the coefficients were jumping all over the place was because they had non-orthogonal functions. The x and the x squared and the x cubed and the x to the fourth were not orthogonal, and therefore the coefficients were again relating, interrelating with each other. And that is why we were not getting smooth curves versus cycles. Here we are trying to separate the functions to identify actual physical shapes in the curve.

(Figure 137)

What I would like to now show are plots of the coefficients themselves, A, B, C, and D versus cycles. Now I am showing them for 68, pack 68, which is not one of our best ones. Pack 70, the data from that, is shown in an actual report which will be available tomorrow. So I am sort of showing the worst case analysis here and one of the better case analyses in the extra report. The extra report covers really pack 70, and the one I am covering today would be pack 68.

Here we see the first cycles here. It is as we would expect. It is not going to give us too much. But here is variable A versus cycles. So A was that constant term, and we find that that is not changing that much over the first 300 cycles. We are just doing this for the first 300. Coefficient B is decreasing. And if you started from this point, say, and we started doing regression lines instead of this type of plot you would find a fairly consistent downward trend for coefficient B versus cycles. Now here is coefficient C.

(Figure 138)

Here is coefficient D versus cycles, not very good as a predictor, and F. See, what we are looking at is trying to see if there are these coefficients which could be used ultimately to extrapolate out to failure cycle.

Now it turned out for this pack that the charge curve analysis was better in terms of what we think will ultimately be predictability. Again the computer fitting program is the same type except we have a minus before this coefficient and a plus in fromt of that coefficient because you are changing from a sigmoid going down to a sigmoid essentially going up.

(Figure 139)

We also have a problem estimating that T max because here is what the real charge curve looks like. Our model would actually fit it going off into infinity here, so we have to stop it somewhere where it changes direction. So the computer program takes the rise in the charge, the leveling off. Then, as it starts to rise again it stops when it stops becoming exponential. Now the physical thing going on here would be you are reaching the end of charge. The voltage is starting to rise. You are gassing. You consider that these additive effects would be exponential in nature. Then you stop when it stops becoming exponential.

(Figure 140)

Now, looking at the coefficients in only the first 300 cycles, index 4 was for the computer program, that the variable "t_m" actually gives one the best correlation versus cycles. T_m remember is the cut off point where you stop becoming exponential. So, here is index B, index A. Index C would not be a terribly good indicator for this particular pack.

(Figure 141)

And here are the other two variables. This would be coefficient D, which is jumping around a lot, and coefficient F, which is increasing. But at least the hopeful thing to us was the fact that the increases seem to be monotonic. They are not sinasoidal because once you go into an oscillating type thing you are not going to be able to use it for prediction. You have got something that is going to increase constantly out to failure. You may be able to use that rate of increase to predict the cycle failure.

At this stage we had not gone beyond 300 cycles because we had not gotten that data out of the Crane data yet. What we intend to do next summer is to take the cycles all the way to failure for many more packs and try to extrapolate these coefficients out to failure and see if when you change the cycling regime the coefficients still behave fairly consistently.

Now the importance I think for this type of approach is that you can in a sense throw out the accelerated test program if this works, because you simply take the voltage curve of the packs, cycle them under a certain regime, and watch the changes, which are relatively subtle, yet detectable through your computer program, and then predict failure. This allows us to move back, instead of using a sampling technique, back to the screening technique, which would ultimately be the best type of prediction. You could take a cell, cycle it under

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rather modest conditions, and be able to predict failure. Then you could screen out good cells and bad cells, and you wouldn't have to use a sampling technique, which ultimately depends on the statistics of your sample versus the cells that you are going to use for life.

It would also allow I think if you could measure cell voltage, say, up in the satellite, you could start to tell things about the degradation from afar rather than in sort of a laboratory bench type thing. So, it is trying to find a technique to measure cell health through its voltage, which can be sent to you from a few thousand miles away.

DISCUSSION

SEIGER: Yardney. Is that not similar? It seems reminiscent of the work that I believe the man was John Waite with code breaking techniques a number of years ago?

MCDERMOTT: What Waite was doing was this hysteresis type analysis, superimposing the discharge curve and the charge curve, superimposing them on each other, and taking the area and trying to use that as prediction. We have found, at least with the accelerated test data, it is not working out. In other words, we have done that. We have superimposed them on each other and tried to get consistent predictors out of it. And at this point we haven't done it. In other words, it bounces all over the place with the lifetime of the cell.

So, you are right. Something like this has been done. But it is not actually using the shape of the curve itself. It is using the total integral of the discharge over charge, or vice versa, charge over discharge.

HELLFRITZSCH: Just one suggestion, have you seen Shepard's work?

MCDERMOTT: No.

HELLFRITZSCH: Well, fitting discharge curves, he was amazingly accurate for both primary and secondary cells.

MCDERMOTT: Do you know what functions he used?

HELLFRITZSCH: He was at the Naval Research Lab. He is retired now. His papers are in the Journal of the Electrochemical Society.

MCDERMOTT: How far Back? Sixties?

HELLFRITZSCH: Oh, not over 20 years.

MCDERMOTT: Did he use exponentials like this?

HELLFRITZSCH: Yes.

MCDERMOTT: I will look it up.

HELLFRITZSCH: More recently, Gabano claims that a hyperbolic tangent function that Perregro and Mallory report in the literature is unusually good and fitting the discharge curve of a lithium copper sulfide cell.

MCDERMOTT: One reason that we were trying for exponentials was so that we could go into a more physical analysis of what is going on.   That is, if I use a hyperbolic tangent function, how do I relate that to the physics and the chemistry what is going on?   It is going to be little harder I think intuitively in trying to look at, say, a statistical analysis of the proton diffusion through the crystal structure of the positive plate, how I can relate that to an exponential function.

So, part of this not simply an empirical curve fitting for predictability, but it is also to relate it to the physics or chemistry of the discharge itself.   So that is one of the reasons we were choosing these functions over others.

HELLFRITZSCH: Incidental.

MCDERMOTT: They are incidental, yes.

(Laughter).

GROSS: Boeing. I might mention that Shepard's model is actually based on electrochemical modeling of the process.   So it is physical interpretation of what is happening rather than just the curves fitting.   And it probably would be useful.

PAYNE: Canadian Astronautics.   I have a slightly more general question.   In the first paper you presented you had an exponential dependence on depth of discharge.   Right after that we heard of a linear dependence of depth of discharge.   Could you comment on the reasons?

MCDERMOTT: Yes.   Dr. Lander is going to do that.

LANDER: They are not the same function.   One is depth of discharge, and the other one is the one I had up there.   And if you indeed use my equation to plot life as a function of depth of discharge you will see that there is a function like connection, somewhat exponential.

MCDERMOTT: One of the things I want to do is actually functionally take Dr. Lander's and mine and work through series expansions of exponentials and see if they are actually approximations of each other.

SCOTT: TRW. Do I gather that your modeling approach has evolved from the empirical to the physical, or are you essentially doing all these things at once and not clearly deciding which is better yet?

MCDERMOTT: As long as the empirical is working, we will do that. I am also interested in the physical interpretation.   So, I would say I am interested in the physical interpretation, but since it seems to fit the curve well and show coefficients which are fairly regular in their change with cycles then it is a two-headed approach.   If Floyd catches me it is the empirical.   If I am up at the college and somebody catches me then it is the physical approach.

SCOTT: A little earlier you showed examples of three packs, three predictions, two good and one not so good.   Is that all you can show us.   Are those the only three packs you have applied the data to?

MCDERMOTT: At this point we are trying to work the bugs out of the fitting and the coefficients.   It is not an easy thing to get at the data or cycles extending beyond 300 because right now there are, how many?   400 mag tapes out there of voltage data.   We have to go back and re-edit a lot of data in order to get it.   We are hoping to get more.   Our time just simply ran out.   We didn't have the data in time to apply it to more than a few packs.

SCOTT: I was referring to the previous regression equation that you showed us earlier today and the results of prediction for three packs.

MCDERMOTT: There was a prediction for the four normal packs.   Is that the ones you are talking about?

SCOTT: No because those don't have any failures yet.   I guess you were showing us three packs that had failed.

MCDERMOTT: Mains might have shown you that.

MAINS: Those three packs were just examples that I could put up there to show. In your package you have around 70 packs that were used. All the predictions were run on those. The three that were shown up here were just, you know, these are typical to give you an idea of what they are. If you look at your data package you will see all the other packs that we have also made predictions on. And there is, like I said, around 70 packs there.

FORD: Any more questions? Now this concludes accelerated test discussion or presentation, so if you were holding any questions regarding accelerated test now is the time to get them because we are moving on to another subject somewhat unrelated.

HELLFRITZSCH: I have a suggestion. You were talking about temperature. Within the last couple of months I have learned about a non-destructive test that the heart pacer battery people are using, and they are going bananas over it. I don't know what they are all going to find. But they are concerned with the life of the battery. If it were perfectly inert it wouldn't degrade. If it degraded in any way whatever, some chemical processes are going on. Those processes are exothermic, most of them, practically all of them. And so a simple thing that people are doing now with heart pacer batteries, and it could be done with any cell, is to deposit an open circuited cell in a microcalorimeter, which can resolve one microwatt. So any multiple of a microwatt can be measured as a constant evolution of heat. And, the interesting thing, open circuit, then you can put a load on it on the outside and measure out how much electrical work is being done through the resistor and separately measure the amount of heat that the cell is giving off internally which is not useful heat.

It opens up a vast opportunity. For example, heart pacer cells, the lithium iodine, which has to burn in to form lithium iodide, solid state, starts out at around 300 microwatts, and then about two months it goes down to about 4 microwatts. If it is a 1 ampere hour cell you can predict that in 10 years you will only lose, oh, 10 percent of the energy, just as one example of the kind of arithmetic you can do with this. So it is something to look for in the literature, and the heart pacer people are the only ones that have looked at it so far. But a number of battery companies are getting these devices. Catalyst research is going to look at their thermal batteries as well as their heart pacer cells. So, since you are looking for measures that I think are meaningful, physically meaningful too.

RAMPEL: General Electric. I am wondering to what extent the separator degradation and the 1,001 chemical products that are generated enter into the equations that we are coming up with today? For example, if we had

cells with an improved separator that does not generate any compounds, carbonate, or any other compounds, we are going to need a new equation. That is point number one. And another thing relative to percent DOD, I think it is probably pretty important to put that in current density perspective because you can get 100 percent DOD over a week's time or 100 percent DOD in 15-20 minutes. And I think the current density is the thing that has to be put into the equation as current density. Just some comments.

MCDERMOTT: In the regression analysis anything that is a multiplier of one of these variables it actually doesn't make any difference to the regression analysis. If you use, for example, depth of discharge as 80 or .8 it wouldn't make any difference. In other words, multipliers don't affect it. Things which would be non-linear functions would affect it. But a question came up before whether we use C, 2C, or whether we actually use amperes. It doesn't really affect the regression program. Current density, therefore, at least in the regression analysis, would not be a factor in terms of the mathematics because you are dividing by a constant.

SEIGER: Has anybody been looking at the instance of cells during the accelerated cycling? Has there been any variation?

FORD: I see Don Mains shaking his head negative, so I assume the answer to the question, internal resistance. Is that what I interpret?

MAINS: That is correct.

MCDERMOTT: There is one way of looking at it from the charge and the discharge curve. That was one of the outputs of this program which we hoped to do, to try to estimate. Gerry Halpert, I think suggested, that we may be able to estimate the change in voltage at the end of charge and the beginning of discharge and at least maybe get an approximation of the internal resistance that way.

We haven't done it yet, but it is a possibility.

SEIGER: Having electrodes swelling shouldn't have an impact upon the internal resistance as it changes the tortuosity and the porosity and the thickness of the separator.

FORD: Okay, one thing I would like to reiterate. I don't think it came out quite clearly. You are looking at cycles here. A cycle for one pack is different from a cycle for another one because you are not on the same time base. I think Pat made that point. But one cycle or one set of cells might be 30 minutes. But the complete charge/discharge for the high rates or another pack where you

are using lower rates the cycle may be in fact two or three hours. And Pat was trying I think earlier to imply that this is one of the things we got into discussion about two months ago on is not just looking at cycle life but looking at total hours in the environment, be it 40 degrees C or what. That is something we are still working on at this point.

RAMPEL: General Electric. I will mention one more contribution, hopefully a contribution. In relation to final equations work I think that the aspect ratio, height and width of the plate, and the plate stack, will or should play a factor I believe. You are working with 6 ampere hour cells right now of a certain aspect ratio, and I think that when you are going to look at other size cells the aspect ratio will play a part.

FORD: That may well be the case. Right now within the scope of this particular program we are limited to the 6. Now the other cells that were mentioned with JPL they were different size cells, and we really have not even looked at that data yet. So the burden of looking at all the data from these types that have been discussed this afternoon has been horrendous. As I said once before, I don't think it was at the last meeting, don't ever call up Crane and ask them to send you all their data on accelerated test because the box cars will pull up in your backyard and you will spend a few weeks unloading them.

CONSTANT - CURRENT
DISCHARGE
CIRCUIT
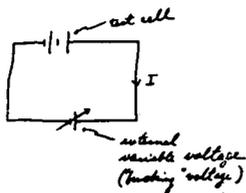
CONSTANT - CURRENT
(DISCHARGE)
VOLTAGE VS. TIME

MODEL
$v(t) = a + b e^{-ct} - d e^{f(t-t_1)}$

ex.
$v(t) = 1.13 + 0.15 e^{-0.05 t} - 0.19 e^{0.13(t-71)}$

QUARTIC
ex.
$v(t) = 1.27 - 5.7 \times 10^{-4} t - 7.2 \times 10^{-6} t^2 + 8.5 \times 10^{-6} t^3 - 1.5 \times 10^{-7} t^4$

Figure 136

Figure 137

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Figure 138

PACK 68   CELL 1

VOLTAGE VS. TIME

CYCLES: →

PACK 68, CELL 1, CYCLE 171.
MODEL (DOTTED) AND QUARTIC

$T_M = 102.3$
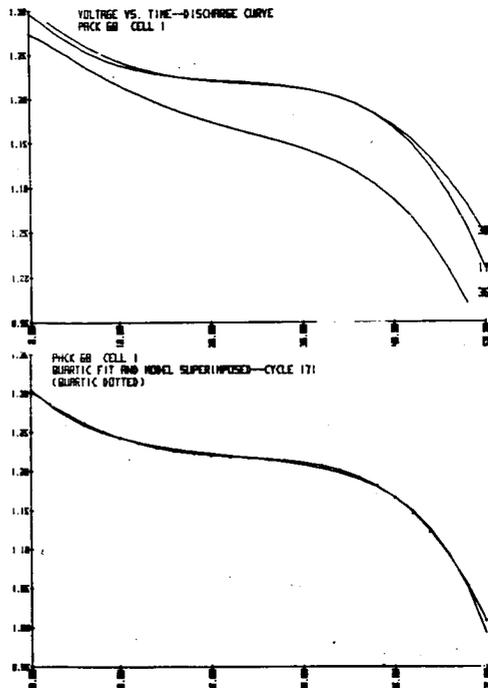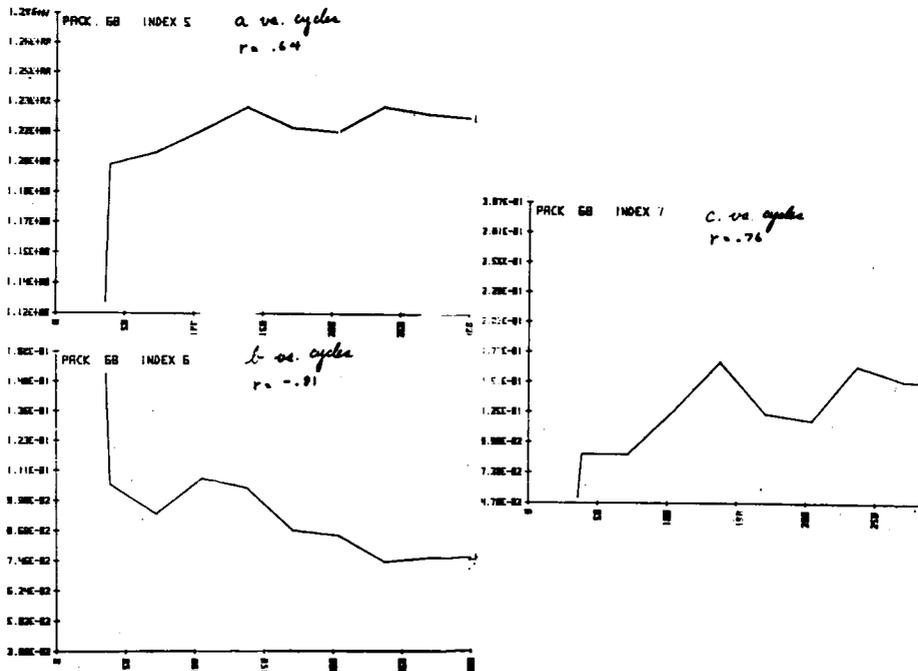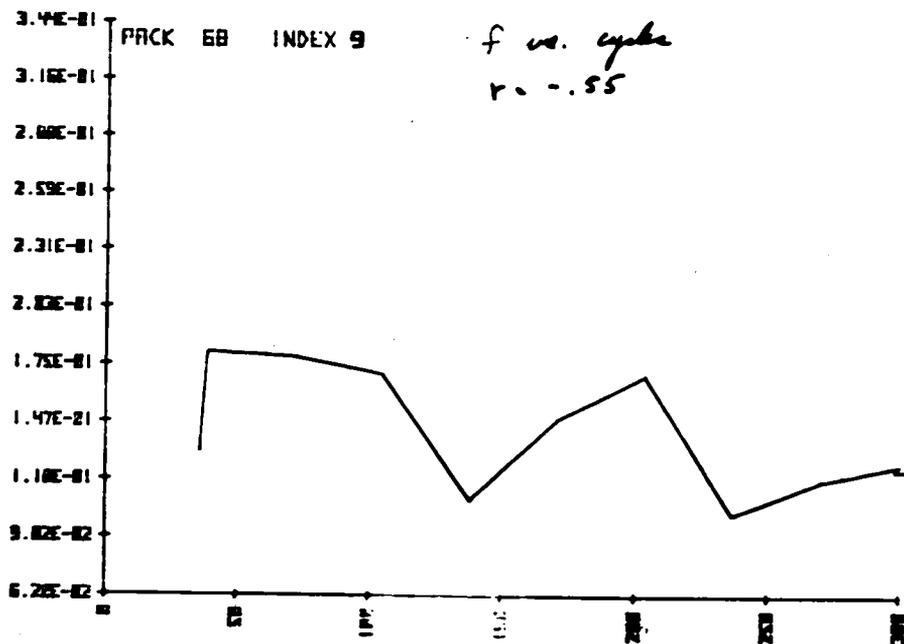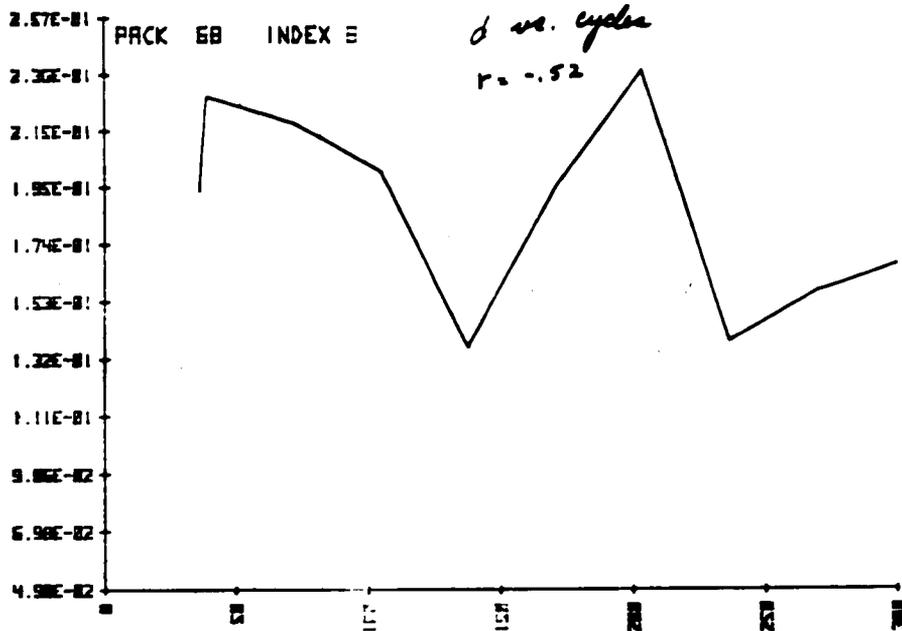
CONSTANT- CURRENT

CHARGE

CIRCUIT
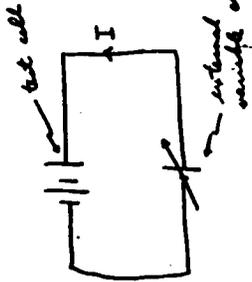
CONSTANT - CURRENT

CHARGE VS. TIME

MODEL

$v(t) = a - b e^{-ct} + d e^{f(t - t_m)}$

$v(t) = 1.39 - 0.12 e^{-0.05t} + 0.04 e^{0.03(t - 95)}$

QUARTIC

$v(t) = 1.27 + 5.52 \times 10^{-3} t - 1.05 \times 10^{-4} t^2 + 9.80 t^3$

Figure 139

193

Figure 140

194

Figure 141

195
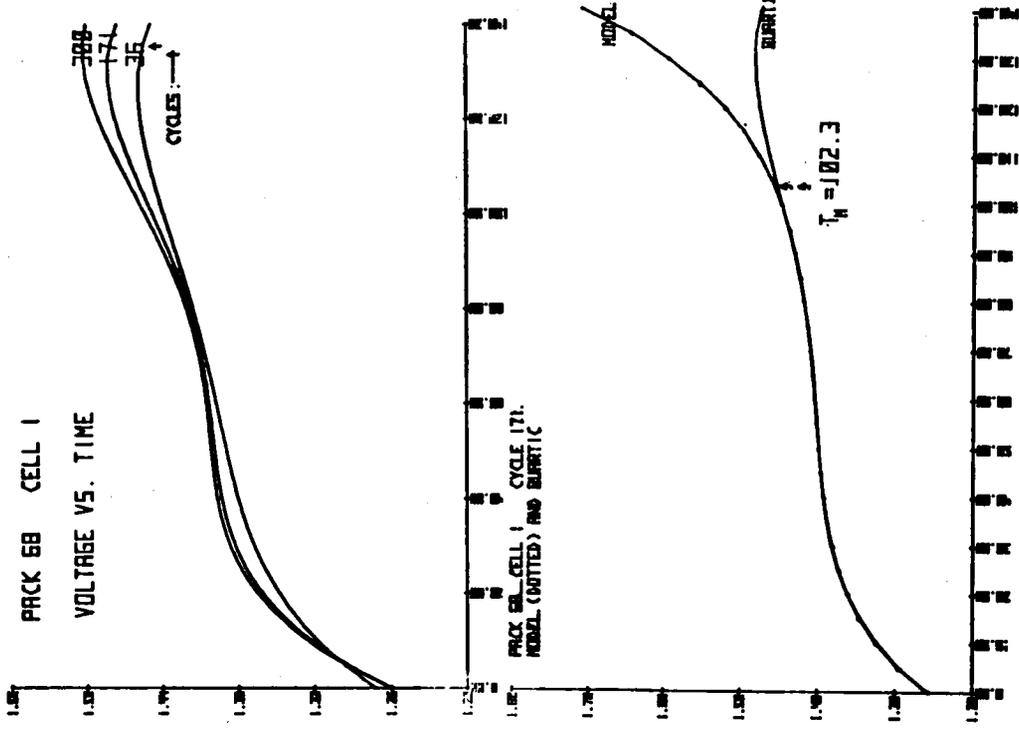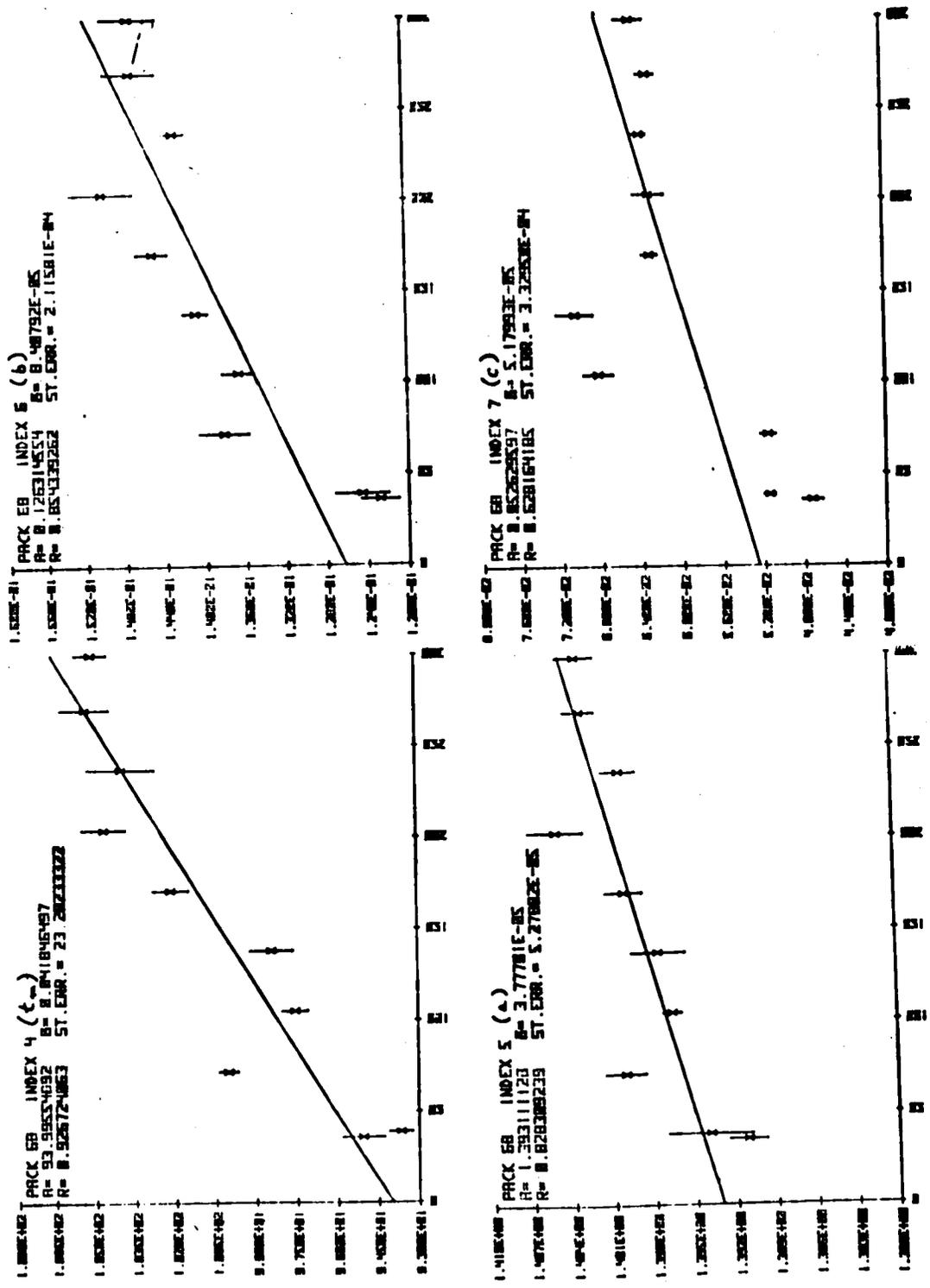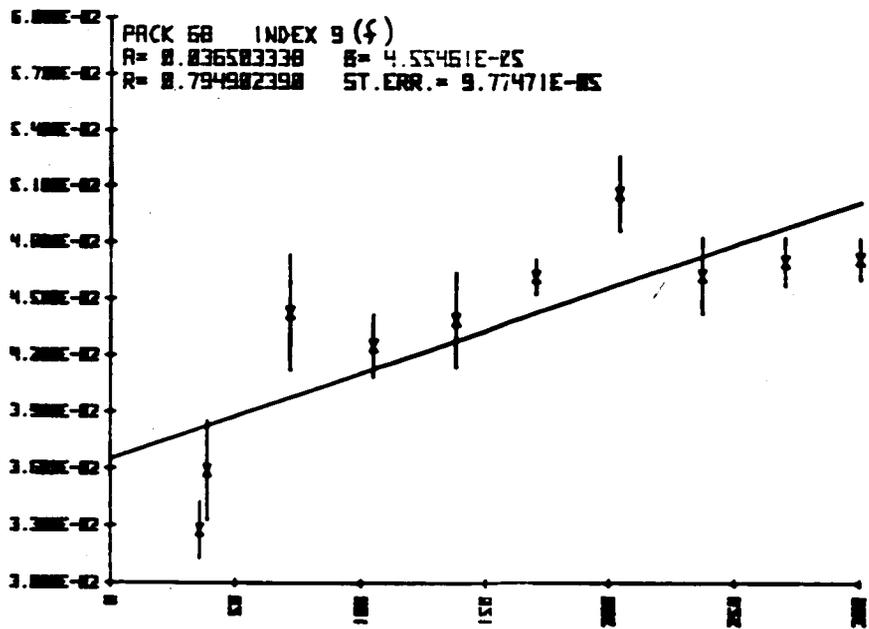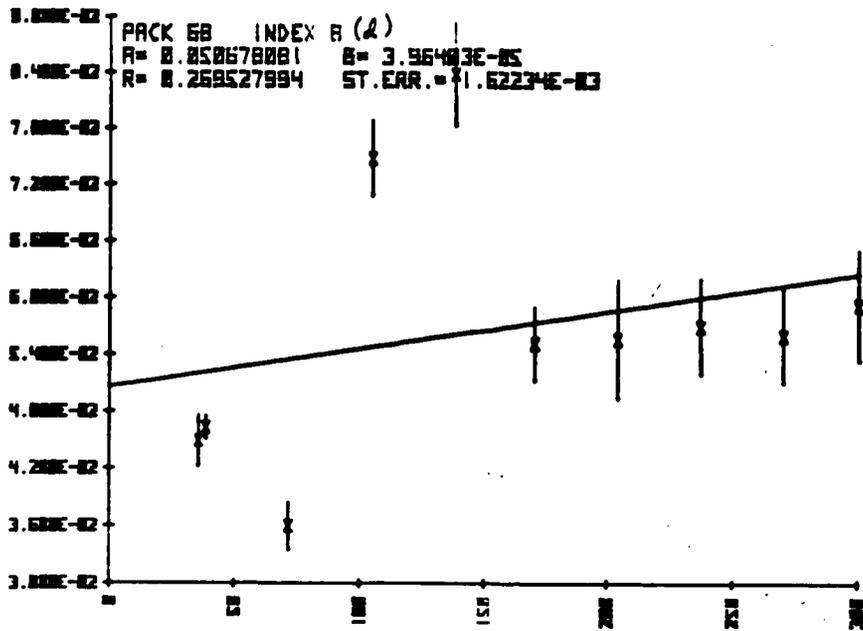
MULTIMISSION MODULAR SPACECRAFT
PARALLEL BATTERY TESTS

C. Palandati
Goddard Space Flight Center

This is an engineering evaluation of the Multimission Modular Space-craft (MMS) power supply.

(Figure 142)

The spacecraft has one charger with eight commandable voltage versus temperature levels.

On this other viewgraph you see all eight levels, based on the average cell voltage rather than the actual battery voltages.

(Figure 143)

The battery capacities would be standard 20 ampere hours or 50 ampere hour design. There can be a total number of three batteries in parallel. The orbit regime is 100 minutes, 36 shadow, 64 sunlight. The nominal depth of discharge for each battery used would be 25 percent of rated capacity. This particular test used two 12 ampere hour batteries for simulation.

(Figure 144)

This is actually one of the test batteries used. There were 22 cells. There were 12 ampere hour G.E. cells. Cell number 22 and 12 had pressure transducers for this test. We also took temperature measurements of cell number 16 in about four different locations, one at the top of the cell which I will later refer to.

The thermal design is based on an IUE spacecraft battery. This is going to be flown in the next several months.

(Figure 145)

This is a simplified block diagram of the power system exerciser we used during the test. We used a power supply for charging the batteries. We also used a power supply to force discharge the batteries at a constant current. Each battery had a diode in series which was shorted out. This is also a normal

condition for the actual batteries in the spacecraft. There was a shunt in the leg for each battery and also one in the series for the power supplies to measure total current to and from the chargers. The purpose of the diode is actually to be capable of disabling the charger, and this will possibly take place during ground testing and also possibly during abnormal flight conditions. As far as the abnormal flight conditions, I think we have heard enough about that this morning. This may take place. All you have to do is just move the short across the diode, and at this point current can not flow from the charger back into the battery. During discharge, though, this battery still can supply power to the load. So the diode is in series. The power balance between the two batteries will not be shared evenly.

(Figure 146)

One of the first tests we performed was an evaluation of the charger voltage levels versus temperature, determined by the batteries charge to discharge ratios. The voltages of each level, again, are based on the average cell voltages for the 22 cell battery.

The C to D ratios of both batteries are similar at levels 3, 5, and 6. They started to diverge at level 7. And they increased as temperature increased, the divergence increased and also the C to D ratios increased. At charger level 3 the C to D ratios were marginal. They were less than 1. And they were exceedingly high during level 7. At level 5 this was the only level capable of recharging both batteries at a moderate percent recharge throughout the entire temperature range, moderate being 1 to approximately 1.12.

(Figure 147)

The normal operating temperature for the batteries is 10 degrees Centigrade plus or minus 10 degrees. What we did here was keep the ambient battery of temperature of A at 10 degrees, and we varied the temperature of battery B plus or minus 10 degrees with respect to the A battery. And we measured the C to D ratios.

At level 3 both batteries' C to D ratios were less than 1. At level 5, B battery ratios were less than 1 several times. Again, at level 7 we saw exceedingly high C to D ratios for both batteries. Level 6 the C to D ratios appear to be moderate, within a range of 1.0 to 1.1.

(Figure 148)

One of the specifications in the spacecraft is that the impedance to the power cable for each battery should be less than 150 milliohms. But there is no requirement that says that the impedance for both battery cables has to be matched or balanced. The purpose of this test was to see whether there would be any significant difference in the load sharing should the impedance of both battery cables vary.

Prior to starting the test, we definitely matched the impedance from both cables, and they averaged out to be approximately 94 milliohms. This it with a zero percent imbalance. And as you can see at this particular condition, the capacity for both batteries was similar. The C to D ratios were similar.

For the next five steps we increased the impedance 10 milliohms each step, which came out to be 10.8 percent, based on the 94 milliohms we started with. During the last step we increased the impedance of the cable an additional 54 percent. And as you can see, the battery with the least impedance, the A battery, definitely receives a substantial increase in the power output. Throughout the entire test though the C to D ratios did not change for either battery.

(Figure 149)

This is the actual plot with the 0 percent imbalance where the data was presented in the previous table. Both batteries were operating at level 5 and 10 degrees Centigrade. The charge currents, as you can see, are similar throughout the entire discharge. The battery voltage throughout the entire recharge is similar. Battery current during recharge for both batteries are also similar. And again there are the C to D ratios. This is also typical. We saw this particular type of a plot throughout the entire test, and we have run over 5,000 orbits periodically at these particular levels and they have not changed that much.

(Figure 150)

In this particular plot what we are trying to simulate here is the A battery with 22 cells and the B battery with one shorted cell, which is a condition which possibly will happen after many months of operation. This is the third orbit that these two batteries were operating under this condition. And as you can see, the battery voltages, both batteries, are fairly close at the start of charge, the reason for this being on the previous orbit B battery was severely overcharged. The C to D ratio on B battery was 2.18. The actual 21 cell voltages were approximately one and a half volts per cell.

As you can see here, there is only about a 300 millivolt difference between the battery voltages at the start. There is a substantial difference in

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battery current. The battery with the shorted cell is less than 3 amps, with the other battery supplying over 7 amps. At the end of the 36 minute orbit the currents start to come together, but A battery is still delivering more that B battery. The total action of ampere hour capacity range from the A battery without the shorted cell is 3.67 ampere hours, where B battery delivered approximately 2.4 ampere hours during the 36 minutes.

On recharge you see that A battery is taking a normal recharge. Due to the fact that the depth of discharge was much greater for the A battery, it takes much more current until both batteries start to limit. The A battery voltage stayed stable. B battery, on the other hand, the voltage was gradually decreasing during the last 45 minutes of the charge. The cell voltages at this point were approaching one and a half volts.

Also, as you see, as the battery voltages decreased on B battery, current is going up. It is getting higher and higher. We are measuring the pressure of the one cell in the B battery on up to 82 pounds by the end of charge. The higher cell voltage measured at that point for that particular battery was 1.507 volts, whereas the normal battery with the 22 cells was 1.445. We also measured, as I mentioned earlier, the cell temperature of number 16, the top of the cell. This particular cell was up to 13.5 degrees Centigrade under normal conditions with a 22 cell battery. Towards the end of charge we saw the cell voltages being similar to the ambient temperature. But we were having -- thermal runaway taking place. It was at this point we decided to stop this particular test at this voltage level and lower the voltage level to level 3.

(Figure 151)

At voltage level 3 with the one cell still being shorted in battery B we ran 53 continuous orbits with no problems. This plot is the plot of orbit number 29. As you see, the cell pressures are down. At the 82 pounds, the other condition, it is now down to 25 pounds.

The C to D ratio where it had been 2.22 it is now down to 1.18 for that battery. And like I said, we did run 53 orbits and we saw no appreciable change at orbit number 53 as compared to what we you seeing here at orbit number 29.

(Figure 152)

What we did here is we were trying to simulate one of these abnormal flight conditions where one of the batteries might have to be disabled from the charger and possibly run in this condition for several orbits.

We always disabled the charger to the B battery. The charger on A battery was always enabled. The first condition we went for three orbits with the charger being disabled. And during the fourth orbit towards the end of discharge we then enabled the charger to B battery. Prior to enabling the charger A battery was delivering 7.4 amps; B battery was delivering 2.6 amps. A battery had delivered 5.29 ampere hours during that particular orbit. The cumulative discharge capacity from B battery through the first three orbits and also into the fourth orbit was 5.22 ampere hours. So, if you look at the depth of discharge at this point for both batteries they are similar.

The instant we enabled the charger both batteries delivered 5 amps. This should have been in this column right here. The second test condition is where we disabled the charger for four orbits, and then we enabled the charger at the start of charge during the fifth orbit.

Prior to enabling the charger on the B battery, A battery was receiving the complete 12 amps from the battery charger. B battery was receiving 0 current. The total drain just prior to this was a negative 5.48 ampere hours out of A battery. The cumulative capacity discharge, we are up to four orbits here and during the fifth orbit, for B battery was minus 5.7. Again, if you look at the depth of discharge for both batteries they are fairly similar.

The instant we enabled the charger to B battery the current to B battery went to 14.4 amps. This was an actual measurement taken. Since the battery charger can only deliver 12 amps, it is assumed that A battery was supplying 2.4 amps at this point as an instantaneous current rate. The third condition was where we disabled the battery charger for three orbits and enabled the battery charger at the end of charge during the fourth orbit. In this particular instant, just prior to enabling the charger, the A battery was receiving seven-tenths of an amp. It was at the very end of charge, so therefore it was just about fully charged.

I put down here greater than 12 ampere hours. Previous capacity tests show that these batteries were capable of delivering 14.5 ampere hours. So we have a good feel that it was definitely over 12. Where we are we don't know for certain.

Prior to enabling the charger again B battery was receiving no current. When I look at the capacity, while the B battery had not been charged during the four orbits here, the total accumulative discharge was 5.17 ampere hours. A battery at this point is probably somewhere in the area of 14.5 ampere hours. There is definitely a large capacity imbalance between the two batteries. The instant we enabled the charger we saw a current spike of 25 amps going into B

battery. Since the charger can again only deliver 12 of those amps it is going to be assumed then the other 13 amperes had to come from A battery.

We ran a third condition, which was a worst case condition. And that is where we created a complete capacity imbalance between the two batteries. What we did was we removed the A battery from the system and we discharged the B battery at 6 amps for two hours to a 100 percent depth of discharge based on a rated capacity. We then put the A battery back in the circuit and started charging it until it was fully recharged. At that point we enabled the charger to B battery, and again we say a current spike of 25 amps, which was similar in both cases.

(Figure 153)

To date we have run over fifty-four to fifty-five hundred cycles. What you are seeing here is the discharge voltage profile for both batteries at 10 degrees Centigrade with a charger voltage level 5. On the left-hand side is the battery voltage, and over here is the corresponding average cell voltages for that particular battery based on a 22 cell battery.

As you can see, at approximately 1,000 orbits we had hit a plateau voltage, and we stayed at this plateau. At approximately 3,600 orbits we reached a second plateau. We had planned to run a capacity test at approximately orbit 5,000, with the idea of giving you people some more information as to what the battery capacities were after 5,000 orbits. When we looked at this profile we decided not to run the capacity test because it looked like we are starting to come down to another level.

DISCUSSION

SPEAKER: General Electric. On the shorted cell how did you short out the cell?

PALANDATI: I should have mentioned that. What took place there was we went to 16 orbits with a 1 ohm. At that point we introduced a half ohm short for one orbit, and then and only then did we place the hard short across the cell. At the end of the orbit we had the half ohm load the highest cell pressure was approximately one atmosphere. The C to D ratios between the two batteries, A battery C to D ratio was 1.11, B's was approximately 1.00. The first orbit that we ran with the shorted cell condition, the C to D ratio for B battery went up to 2.62. The cell pressure went from approximately one atmosphere up to 52 to 59 psia. At the second orbit of this condition the C to D ratio

of B battery decreased some; it was down to 2.18. And the cell pressure at the end was approximately 74 pounds. The pressure was deinitely going up each orbit.

FORD: Right after you saw the hard short it was that cell that was physically out of the pack.

SCOTT: TRW. How long did those high current transients last?

PALANDATI: You are talking in milliseconds. Because pulses were measured with a scope with a memory tracer, they were like I said milliseconds.

NAPOLI: RCA. What were the discharge rates on that last curve that you showed?

PALANDATI: The discharge rates were again 25 percent depth of discharge.

NAPOLI: Rates?

PALANDATI: If you look at both batteries, and both batteries basically do share the same load, so therefore the charge rate is 6 amps going into each battery, C/2. The discharge, total discharge coming from both batteries, was 10 amps. They both shared the load fairly evenly, which is approximately C/2.2 to 2.4.

NAPOLI: About 5 amps, 5 amps each?

PALANDATI: 5 amps each, right.

BAER: Goddard. On your next to the last table (Figure 152) you had up there you showed the capacity out of battery A and battery B being the same in most cases. Battery B was off line, at least off the charge line. Let us take your first line. You say battery B was disabled for three orbits.

PALANDATI: Yes.

BAER: Yet the capacity out of battery A was 5.29 ampere hours. The capacity out of battery B was 5.22. And I am not sure how you accomplished that.

PALANDATI: This battery is always delivering some power at the diode in series. It will never receive the recharge with the diode in series.

FORD: He said the accumulative discharge over those orbits was down to that depletion. That is a depletion capacity, not cyclic depth. It has to follow that if one battery cycle could be for depth since your diode is coupled to the other battery it is going to follow that down to some smaller difference through the diode drop.

BAER: Okay. Since battery A was recharged on that diode.

PALANDATI: Basically at this point both batteries are at a similar depth of discharge, and therefore we don't accelerate, maybe a little. In fact, there is no variation at this particular point when we introduce the charge and go into discharge.

BETZ: Naval Research. How many consecutive cycles do you use to establish your C/D ratio?

PALANDATI: Okay, where we look at the C to D ratios a minimum, and we were changing temperatures from day to day. Where we have a battery A sitting at 10 degrees C and then we varied the temperature of battery B, we had a minimum of 14 cycles.

BETZ: So at the end of 14 cycles you could conceivably still be at 98 percent C/D ratio. That means that the state of charge would be back down to 70 percent or something like that?

PALANDATI: Let me put it this way. Within the first three to four orbits the battery C to D stabilized and didn't change.

BETZ: Within 3 to 4 orbits you stabilized?

PALANDATI: Yes.

CLARK: Grumman. I guess it was about 1966 or so that we first put together that OAO system, doing batteries in parallel, and started asking the same kind of questions you are concerned about. What happens when the engineering tests we ran at that time pretty much duplicated what you are showing up here? We shorted out one cell, two cells, enabled disabled batteries, and induced some pretty dramatic changes, differences, from the way batteries are operating. But the very comforting fact is that the system is stable. It always stabilized out. There was nothing that we could induce that indicated the system was going to blow up in between ground contacts.

And I think in the MMS you are going to have an on board computer that should be able to monitor the kind of changes that you are looking at here. And you will find that something is happening in the system.

PALANDATI: Well, again, this is one of the reasons for having the various voltage levels, such as when you short a cell. There is no way I believe that we could possibly live after we were at voltage level 5.

CLARK: I think the tests show you that you can live there long enough.

PALANDATI: Oh, yes. We would not tolerate just one or two voltages, no.

WESTROM: Goddard. When you mentioned your temperatures you were getting into thermal runaway condition in one earlier. You were at 10 degrees C for the normal plate temperature, and you said that, I guess cell 16 or something, you got a three degree temperature variation?

PALANDATI: Yes, well, what actually happened each orbit you could see that particular cell's temperature get higher and higher.

WESTROM: But were you suggesting that was a three degree variation?

PALANDATI: No, I am saying this was just another data point that confirmed or explained what was taking place between a high cell voltage, the high pressure. This was just one other data point that we could look at and say, "Yes, we have a varying condition here." I believe they went hand in hand.

FORD: Yeah, let me emphasize that the thermal condition here was ideal, not what you encounter on the spacecraft where it is very hard to duplicate on a laboratory basis any thermal design you would get on the spacecraft. So, rather than get off and on distortions of that, we ideally set up a thermal condition so we would control the environment of a battery as a unit. And all that indicates is that battery was dissipating a lot more because it was being held in the same thermal experience. But temperature was rising. Hence we felt that dissipation was up considerable in that.

I guess one comment I would like to make regarding this test, and I guess the big surprise I got out of it, was in this unbalance and state of charge and how you really interpret that data and what it can mean to you in designing parallel systems.

Bear in mind we talked about the impedance in each battery loop, and that was like 90 milliohms. So that means that with any two batteries you have double that, 180 milliohms total. And basically what it boils down to when you wonder what happened and the question always come up in the spacecraft environment what happens if two batteries that demonstrate the charge are running together? I am going to well contact on the relay, invariably that is the answer. In a lot of cases that is the correct answer.

But what this data suggests is there is an optimum amount of resistance to put in those leads. Granted, you pay a penalty for it if you go too high in losses in the system. But if you put in enough resistance you build in self-protection for circulating current due to conditions created here.

Now what surprised me was that with this configuration we only got a maximum, about 25 amps a piece. You know, that was the peak observed under transient conditions. Steady state was much less than that. So with that as a guideline it says when you look at the system, particularly with parallel batteries, you should try to look at not just minimizing, which you want to do, but there is an optimum which you should achieve. And basically what you are concerned is the impedance between two batteries divided into the delta D between the batteries. Now when you throw a 25 amp load on a 12 ampere hour battery and you shove 25 amps into a 12 ampere hour battery you don't have a delta D between them that is different for very long. They come together, and that is what this test proved.

PALANDATI: I mentioned the highest going into battery B at the end of charge was 1.507. This was not the same at the 82 pounds pressure. This particular cell had no pressure transducer. We don't have any idea what this particular cell's in general pressure was, or any of the 20 other cells in that particular battery, other than the two pressure transducers. And that was again one of the reasons why we stopped right there on that.

ENGINEERING EVALUATION

OF

MMS POWER SUPPLY

o BATTERY CHARGING — ONE CHARGER WITH 8 COMMANDABLE
                      VOLTAGE VS. TEMPERATURE LEVELS

o BATTERY CAPACITY — STANDARD 20 Ah or 50 Ah DESIGN

o NUMBER OF BATTERIES IN PARALLEL — UP TO THREE

o ORBIT REGIME — 100 MINUTES (36 SHADOW, 64 SUNLIGHT)

o NOMINAL DOD — 25% of RATED CAPACITY

o TEST USED TWO — 12 Ah BATTERIES FOR SIMULATION

Figure 142

VOLTAGE/TEMPERATURE CHARACTERISTICS
FOR MULTIPLE LEVEL NICKEL-CADMIUM
BATTERY CHARGER

REFERENCE POINT

Level #8 1.580 ± .019V at 0°C
Slope -2.33 ± .20mV/°C
Separation between levels .020 ± .002V
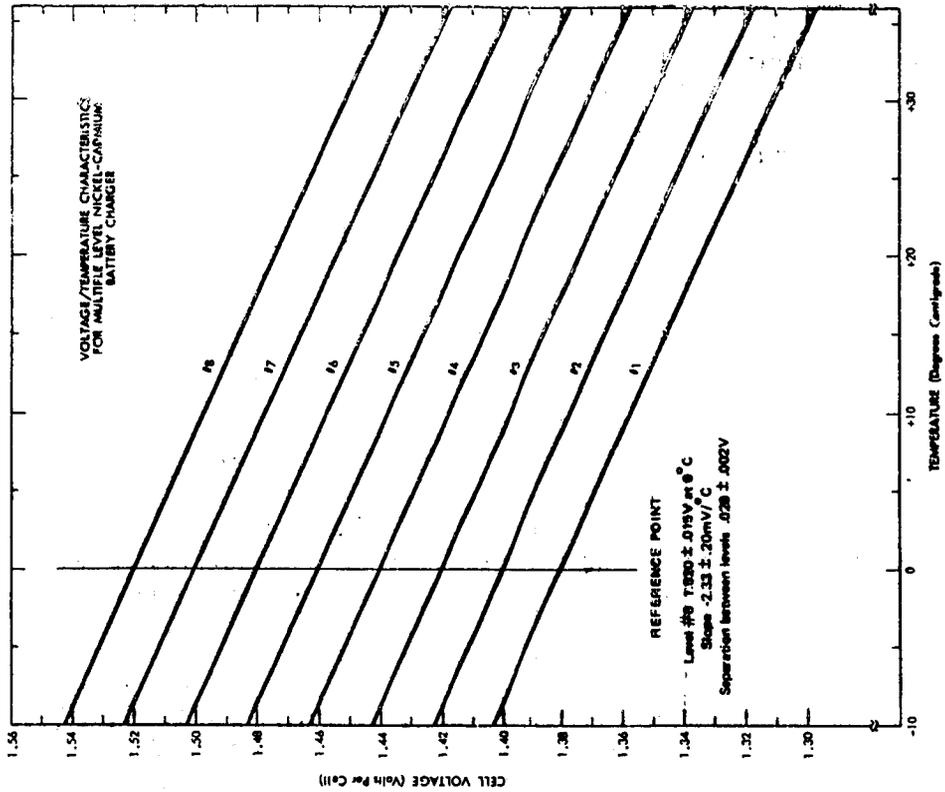
Cell Voltage Limit versus Temperature

Figure 143

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SIMPLIFIED BLOCK DIAGRAM— POWER SYSTEM EXERCISER
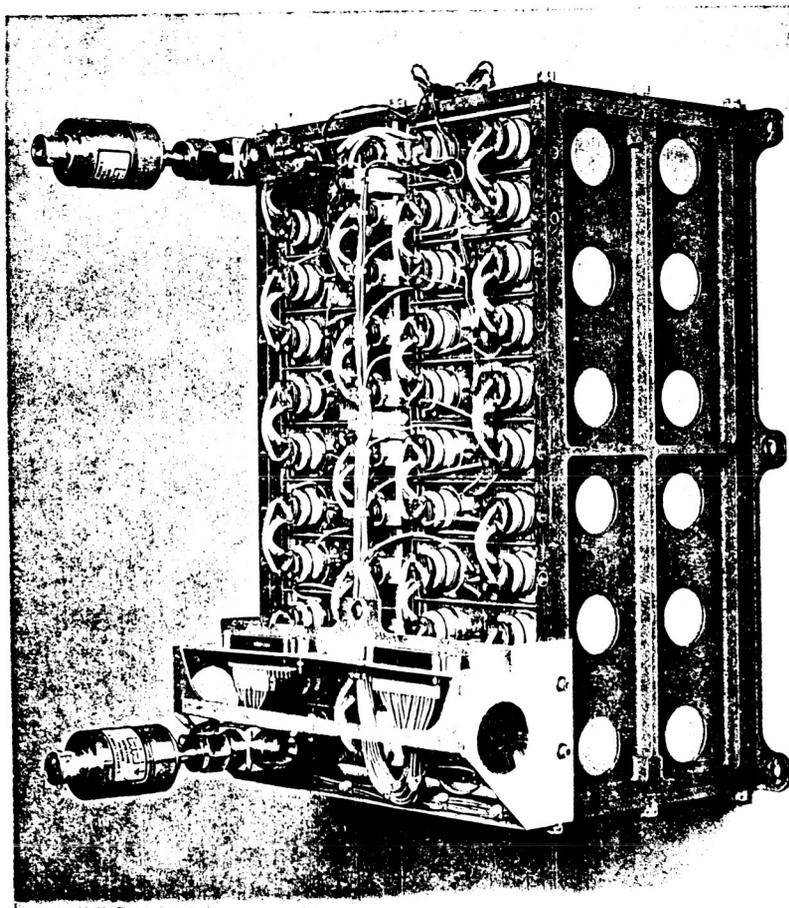
Figure 145

PARALLEL BATTERY TEST

CAPACITY: 12Ah

WEIGHT: 13.47KG.

DIMENSION: 26.52Cm X 21.18Cm X 15.72Cm

Figure 144

BATTERY "A"		BATTERY "B"	
TEMP. °C	C/D RATIO	C/D RATIO	TEMP °C
	CHARGER LEVEL "3" (1.397 V/Cell)		
	.98	.98	20
	.99	.98	15
	.98	.98	10
	.98	.97	5
	.99	.98	0
	CHARGER LEVEL "5" (1.437 V/Cell)		
	1.04	1.12	20
	1.01	1.01	15
	1.00	.99	10
	1.01	.99	5
	1.02	.99	0
	CHARGER LEVEL "6" (1.457 V/Cell)		
	1.03	1.10	20
	1.05	1.09	15
	1.09	1.08	10
		1.03	
	1.07	1.00	0
	CHARGER LEVEL "7" (1.477 V/Cell)		
	1.10	1.33	20
	1.16	1.24	15
	1.18	1.15	10
	1.23	1.10	5
	1.26	1.05	0

Figure 147

CHARGER LEVEL

G.E. 12.0 Ah CELLS

25% DEPTH OF DISCHARGE

$I_C = 12.0a.$ $I_D = 10.0a.$

100 MINUTE ORBIT (36 minute shadow)

LEVEL 7
1.50-1.454 V/Cell

LEVEL 6
1.48-1.434 V/Cell

LEVEL 5
1.46-1.414 V/Cell

LEVEL 3
1.42-1.374 V/Cell

TEMPERATURE °C

CHARGE TO DISCHARGE RATIO (C/D)

Figure 146

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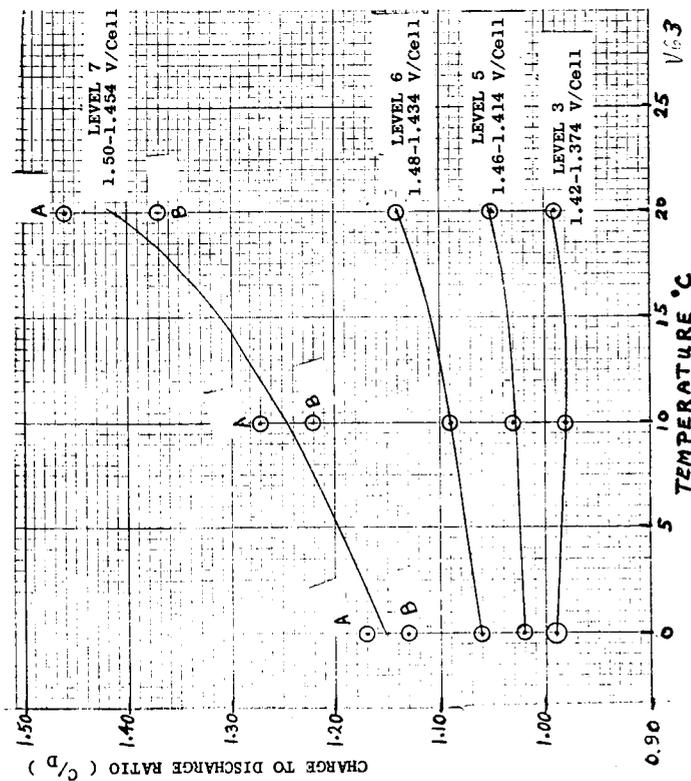
Figure 149

Figure 151

% IMPEDANCE IMBALANCE	BATTERY A Ah Out	C/D	BATTERY B Ah Out	C/D
0 *	2.98	1.04	3.03	1.02
10.8	3.02	1.04	3.00	1.03
21.9	3.06	1.05	2.96	1.02
32.5	3.10	1.05	2.91	1.03
43.3	3.14	1.04	2.88	1.03
54.1	3.19	1.04	2.83	1.02
108.0	3.38	1.04	2.63	1.02

* At 0% IMBALANCE THE IMPEDANCE
BETWEEN THE BATTERIES AND THE CHARGER
IS AS FOLLOWS: BATTERY A   94.0 milliohms
                 BATTERY B   93.4 milliohms
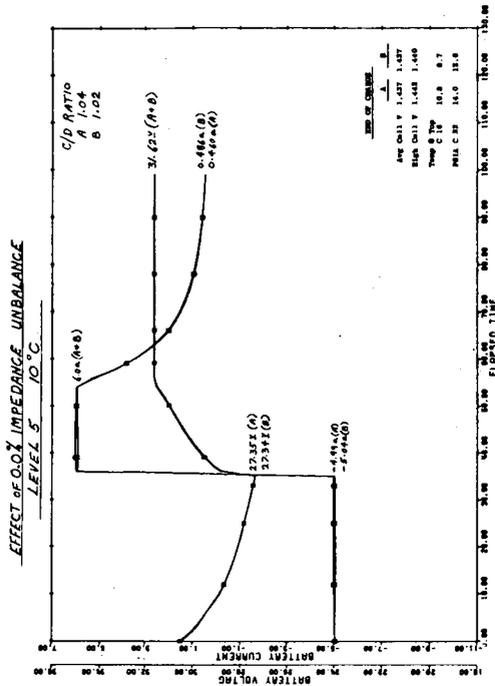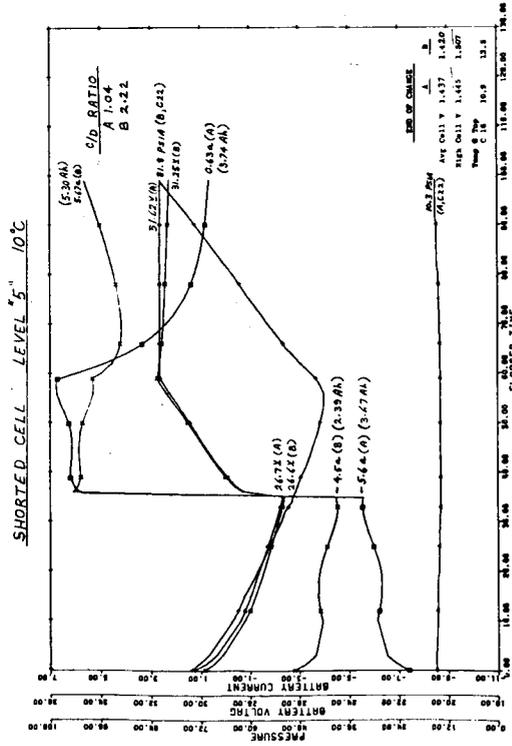
Figure 148
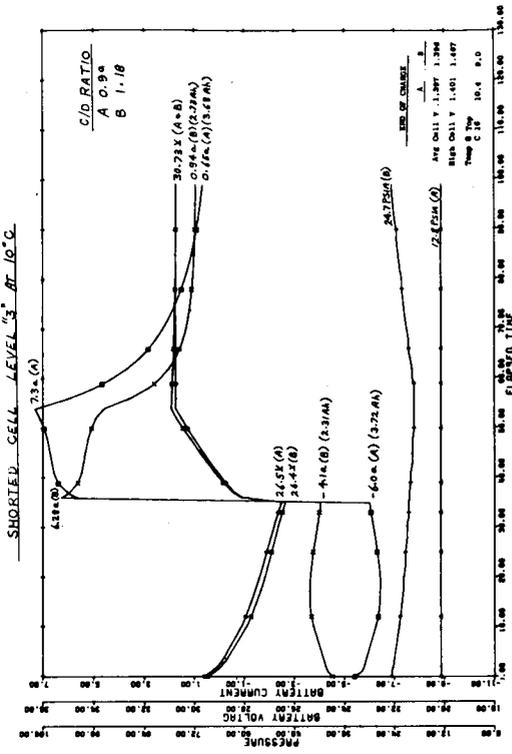
Figure 150

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EFFECT OF DISABLED CHARGER

CHARGER TO BATTERY "B" STATUS	BATTERY "A"		BATTERY "B"	
	I (AMPS)	A HR	I (AMPS)	A HR
DISABLE FOR 3 ORBITS	-7.40	-5.29	-2.6	-5.22
ENABLE AT END OF DISCHARGE DURING 4th ORBIT	-5.00	-5.00		
DISABLE FOR 4 ORBITS	12.00	-5.48	0.00	-5.70
ENABLE AT START OF CHARGE DURING 5th ORBIT	-2.40 *		14.40	
DISABLE FOR 3 ORBITS	0.70	>12.00	0.00	-5.17
ENABLE AT END OF CHARGE DURING 4th ORBIT	-13.00 *		25.00	

EFFECT OF CAPACITY UNBALANCE

DISCHARGED "B" BATTERY			6.00	-12.00
CHARGED "A" BATTERY	0.57	>12.00		
ENABLED "B" BATTERY	-13.00 *		25.00	

Figure 152
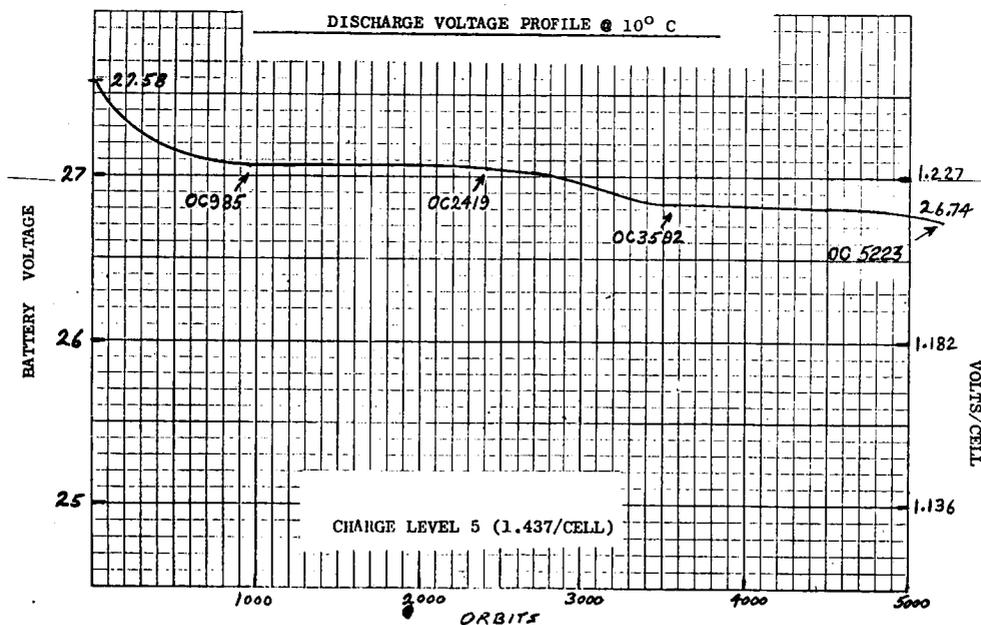
Figure 153

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SYNCHRONOUS METEOROLOGICAL AND GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES OPERATIONAL EXPERIENCE

R. J. Haas
Ford Aerospace

(Figure 154)

The mode of operation that is of interest here is a solar array battery load-sharing mode. Now, this is a situation where the battery is loaded for a fraction of a second and then charged for, let's say, half a second, so the cycle is a 100-millisecond load, followed by a 500-millisecond charge. So the pulse charge is this; but the purpose of the experiment was to evaluate the charge efficiency and the state of charge.

On the Synchronous Meteorological and Geostationary Operational Environmental Satellites (SMS/GOES), battery cells, these are three amp hour cells, over a temperature range of 10 to 25 degrees C. We have there, as you see, charge rates that vary from a trickle to a full charge rate. And then on the right, in the columns, is a C/D ratio, or the inverse of a C/D ratio, which is shown at 98 percent or down to 60. That is the inverse of the normal C/D ratio.

The numbers under those columns, then, and in the column, are milliamps and discharge current for the 100 millisecond period.

(Figure 155)

Explaining just a little bit how the experiment was run, each test was a cycle period of a week, in terms of this duty cycle. The cells were fully charged, reconditioned, a capacity check made, and then started off with a full charge. The C/D ratio, then, associated with the charging rate, a 2/3 charge rate or a 1/3, that is the intermediate or the trickle.

We have two types of cells there. One, the SMS type cell, is a number of cells that were life-tested for about five years of equivalent synchronous orbit cycling, so they would be representative of the efficiency and state of charge characteristics of a battery cell after a lot of cycling, which may be typical of the end of life. The GOES cells, on the other hand, were new cells, and you can see that there is a trend for the newer cells having a capacity, a state of charge, that is somewhat higher.

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I would point out here, again, the charge efficiency is the reciprocal of a C/D ratio; and so for a charge efficiency in the order of 90 percent, the capacity is maintained around four amp hours, which incidentally is the full capacity although some cells after a week of cycling in this mode have a reduced capacity, particularly for the 95 percent charge efficiency.

(Figure 156)

This is more of the same series of testing. Again, we show the difference between a cell that has been cycled about five years of synchronous orbit cycling as compared to a new cell. The GOES cells are performing well with regard to the capacity retention in this load-sharing mode, and particularly for a C/D ratio in the order of 1.1 or less.

(Figure 157)

For each one of the slides, we have a different temperature. This is a 25 degrees C temperature for these tests, with varying charge rates. In this case, again, there is a difference between the new and old cells.

(Figure 158)

Here we have a wider range on the C/D ratio, going from 1.67 for the lower assumed charge efficiency down to about a 1.1 or 90 percent assuming the charge efficiency. This is at a lower temperature, now; this is at 10 degrees C; and there is, again, the difference in charge efficiency and state of charge for the older cell, the SMS type cell.

(Figure 159) and 160)

This is a summary, then, of the temperatures and the charge rates for this special load-sharing test. And I think the interesting thing we have seen here is that the state of charge is less for the lower temperature. At 10 degrees C, we show a lower state of charge than for 20 or 25 degrees C for the new cell; also, we see that the C/D ratio is important and will definitely cause a reduction in state of charge for a charge efficiency of greater than 90 percent. As a matter of fact, there is a drop-off at the lower temperature, even back around 80 percent.

This information, incidentally, may be useful for a transfer orbit calculation for energy balance, calculations for transfer orbit synchronous orbit application, where during the solstices and/or some other equinoxes, then, there is a requirement for pulse-load discharge and charging of the batteries.

And our analysis of this data is basically a battery that can be operated in a pulse-load mode for a period of time, at least several months, without an immediate degradation in capacity or voltage characteristics.

The state of charge of the battery, though, is definitely going to be reduced from the nominal or the actual capacity, and you would expect, for a 90 percent charge efficiency situation, the capacity may be reduced by about 25 percent. So I think this will allow us, particularly for, as I mentioned, a transfer orbit energy balance, missions where there is a limited solar array capability in a spin mode, this will hopefully provide some insight.

Table 6-9. Special Battery Cell Characterization Test Conditions

Cond. No.	Temp (°C)	Charge Rate	I_{chg} (mA)	(I_{disch}) (mA) (%)				
				N_B = 98%	N_B = 90%	N_B = 85%	N_B = 80%	N_B = 60%
1	25	EOL Trickle Charge	71	–	320	–	–	–
2	25	EOL Intermediate Charge	121	–	545	–	484	–
3	25	BOL Intermediate Charge	140	–	630	–	560	–
4	25	BOL Full Charge	210	1029	945	–	840	–
5	20	BOL Full Charge	210	–	945	–	–	630
6	10	BOL Full Charge	210	–	945	–	840	630
7	25	EOL Intermediate (Life Test)	121	–	–	515	–	–

(1) $N_B = \dfrac{I_{disch} \cdot T_{disch}}{I_{chg} \cdot T_{chg}}$

(2) $I_{disch} = \dfrac{V_B \cdot D}{pwr}$

where

I_{disch} = Pulsed battery discharge current in milliamps for a time period of T_{disch} in seconds (100 ms).

I_{chg} = Pulsed battery charge current in milliamps for a time period of T_{chg} in seconds (500 ms).

N_B = Forced battery recharge efficiency; equal to Q_{out}/Q_{in}

V_B = Battery (20 cell) voltage; assumed equal to 27 V.

D = Discharge pulse duty cycle equal to 100 ms/ 600 ms = 1/6.

Figure 154
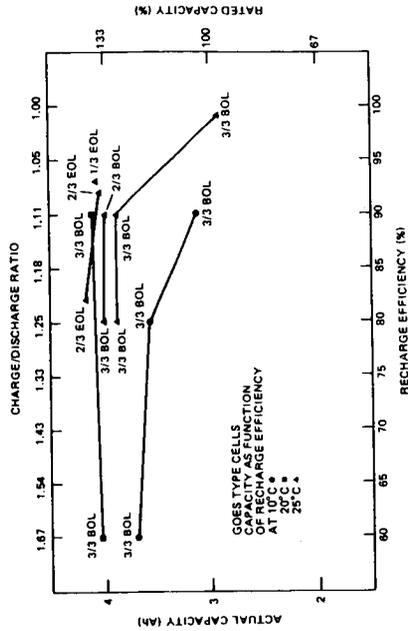
GOES Cell Load-Sharing Capacity Characteristics at 10, 20 and 25<0>C

Figure 155
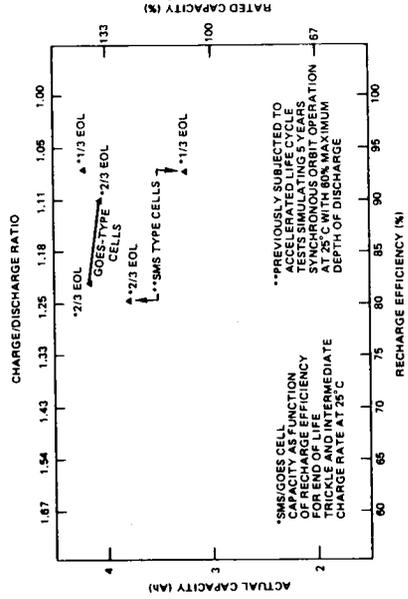
SMS/GOES Cell Load-Sharing Capacity Characteristics at 25<0>C (Intermediate and Trickle Charge Rate)

Figure 156

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SMS/GOES Cell Load-Sharing Capacity

Characteristics at 20<o>C (Full Charge
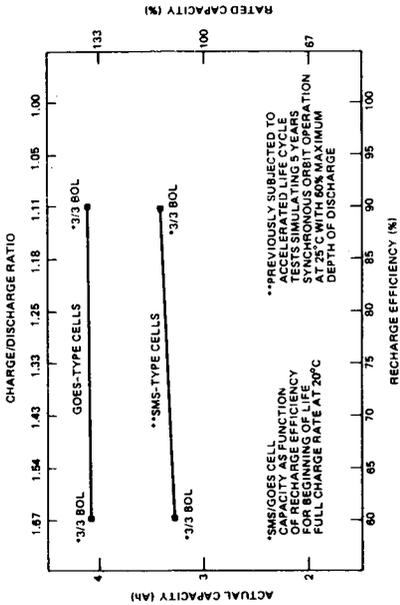
Rate)

Figure 158

SMS/GOES Cell Load-Sharing Capacity

Characteristics at 25<o>C (Intermediate

Charge Rate)

Figure 160

SMS/GOES Cell Load-Sharing Capacity

Characteristics at 25<o>C (Full Charge
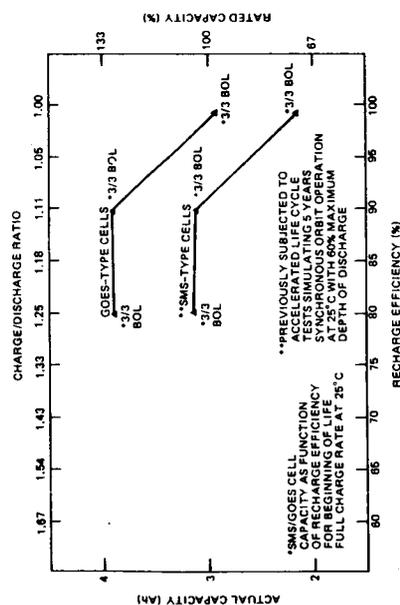
Rate)
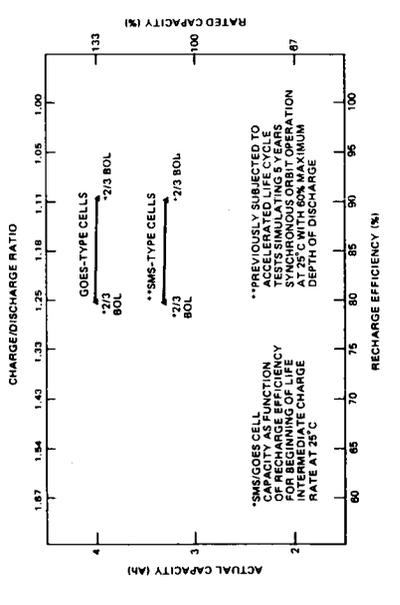
Figure 157

SMS/GOES Cell Load-Sharing Capacity

Characteristics at 10<o>C (Full

Charge Rate)

Figure 159

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LONG-TERM STORAGE EFFECTS-UP-DATE

W. Scott
TRW Defense and Space Systems Group

Last year at this meeting, I described the results to date of a three-year program to find out what the possible effects might be of storing batteries over a period of a number of years prior to their use in a synchronous orbit application. At that time, we had completed the first phase of the program, consisting of life testing, using an accelerated test program, life testing a battery and doing tear-down analysis on cells after having stored the battery for a period of three years with the cells shorted and at a temperature on the order of five to 10 degrees Centigrade.

At that time, I indicated that the electrical testing consisted of performing a sequence of 10 simulated eclipse seasons, which would be the equivalent in cycling of five years in synchronous equatorial orbit, with the result that we saw very little degradation in the minimum end-of-discharge voltage during eclipse seasons and the results of the tear-down analysis indicated that there was very little change in the physical and chemical conditions of the cell compared with what they looked like, what similar cells looked like, at the beginning of the three-year storage period.

So at that time we have concluded that there was essentially no appreciable effect that would impact using batteries stored in this way, from this type of storage, extended over a three-year period.

Since that time, we have extended the program for an additional year. We tested another battery from the same batch that had been stored for four years with the cells shorted, doing the same thing; performing an accelerated life test and doing tear-down analysis. And basically all I can say, really, is that with one exception, which I will mention in a minute, we have seen no further change that is significant from the three year test and analysis point. The physical and chemical conditions of the cells are essentially identical to those that we obtained after three years of storage, and the electrical life test results were essentially identical.

I might mention that the life test is carried out with a reconditioning cycle performed between each simulated eclipse season. This particular form of reconditioning involves discharging at a moderate rate down to the order of 0.9 volts per cell. This is the particular method that happens to be implemented on the spacecraft for which this test program is being carried out; it is an existing ongoing hardware program.

The one exception that we did find was in the determination of the un-charged excess negative in the cells. These are 24-ampere-hour cells made by General Electric. Last year, in carrying out this analysis, we obtained a value for excess uncharged negative on the order of three to six ampere-hours, in this size cell. This year, we obtained negative numbers for uncharged excess negative; and some of the other values, for example, for total electrochemically active negative and the other factors that go into the calculation of uncharged excess negative, using the method that is given in the NASA 74-15000 specifi-cation, were also somewhat different from what we got the year before.

I want to indicate that for a long time, we have been concerned with the variability that we have obtained using the test method as described; but we have as yet not had the rather distrubing results from that test that we got on this last analysis of the cells, where essentially all the results were negative.

So that is basically all that I have to say about the results of the storage test so far, except to say that test is nearing its completion right now, with the evaluation of the effect of a fifth year of shorted storage, and so far, we are in the middle of the electrical test. We have not yet done a third round of teardown analysis; but the electrical test performance is still very good. It is hardly any different from what we saw the last two years, so it looks like, at least for the particular kind of application that we are talking about here which, by the way, involves approximately a 55 percent maximum depth of discharge during the deepest eclipse seasons from the accelerated life test, that there seems to be very little concern with up to five years of storage, when you store the cells shorted and at a fairly low temperature.

As a result of the strange result that we obtained for determination of uncharged excess negative, we have started to look into another way of measuring this parameter; and I want to describe the results that we have obtained so far later on this afternoon. But that concludes what I have to say right now.

DISCUSSION

NAPOLI: RCA. Let's take a hypothetical situation, where your program manager came to you and said, "What if we have to launch a spacecraft as a replacement, and we don't have available new available batteries, but we do have batteries that have been stored for four years, according to your storage method." What recommendation would you give him in terms of using those batteries to achieve a seven or eight-year mission?

SCOTT: Seven or eight years in orbit?

NAPOLI: Using four-year-old batteries that have been in storage for four years.

SCOTT: Well, first of all, the particular applications that we are concerned with on this hardware program have associated with them a three-year mission requirement. I maybe should have mentioned that. Although we are testing to with five years of equivalent cycling, the program requirement is for three years.

Granted, you would have to factor in, when you get into starting to talk about five years to seven years, you have to add in other factors. Right now, if one could know that you could operate at a reasonably low temperature, nothing above 20 degrees Centigrade, and could have the right kind of reconditioning implemented, in orbit, I would not hesitate to go ahead and recommend using stored batteries.

NAPOLI: For a five-year mission?

SCOTT: For five years.

NAPOLI: Where do you draw the line on the number of years, then?

SCOTT: Well, I don't think I could generalize on that.

NAPOLI: When you said "right conditioning," do you mean down to 0.9 volts per cell?

SCOTT: Well, I think we will probably get into what is right and what is wrong before we get through this morning in talking about it, because there is an infinite number of ways to recondition. Most of them may not do anything for you. It depends upon the condition of the cells and other operating parameters; but what I mean by "the right kind of conditioning" is a reconditioning that works.

SCOTT: That is all I can say right now.

HENDEE: Telesat. Could you briefly describe the pre-storage history of these cells?

SCOTT: Well, yes. There are two aspects of that. It so happens that even though we now strongly recommend that batteries that would be stored for possible use in flight do not get used prior to that for integration testing or general spacecraft testing, it so happens that these particular batteries that we are using for this study program did indeed go through just that sort of usage

for a period of eight to 10 months before they were shorted down and put into storage. And still they are behaving very well, at this point in time.

But I would say that certainly we would not recommend that that occur in the future, and our present policies are such that we would not me. It just so happened that these were the only batteries that were made available to us for use in this particular study program.

But I would say that certainly they should go into storage immediately following battery assembly and battery acceptance tests, and that should be the end of it as far as their usage is concerned.

But it doesn't look like the particular usage, for this application, is that sensitive to a certain amount of testing prior to storage.

MARTIN: Canadial Astronautics. I wonder if you could give us an idea of how temperature of the storage affects the performance itself.

SCOTT: Well, frankly, I don't really know. We have not done any controlled tests of that kind. However, my gut feeling is that if you treat the cells properly prior to storage, and you store them shorted, essentially, all their storage life they are stored shorted, that I don't really believe that it is going to make much difference over a range of 10 or 20 degrees what the storage temperature is, between maybe zero and 20 degrees Centigrade.

Of course, the only thing that theoretically is going to be different from I know of, well, there are of course several processes that are temperature-dependent that could go on there, but I looked at a few cells that had been stored at room temperature for several years, and they don't look any different from the cells that I see that have been stored at zero degrees, shorted, for a few years. But I don't have any, you know, complete comparative test statement.

GASTON: RCA. Well, you mentioned you had a little degradation, and you mentioned cadmium analysis. Do you have some quantitative data, and will they be published in the future?

SCOTT: Well, I am sorry I don't have the actual data here to show you. It looks almost exactly like the data that we got last year, that appears in last year's publication.

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STORAGE EFFECTS ON CELLS

J. Harkness
Naval Weapons Support Center

It is a pleasure to follow Will Scott's presentation, since our results are essentially going to show what he said, that the shorted condition is the best way to store cells. And our temperatures that we stored these were control temperatures of about 22 to 23 degrees C.

This information was first presented by Floyd Ford in 1972 here at the workshop, and then I made an update on this in the 1975 workshop. And again, this is an update.

The type of cells are Gulton 20-amp-hour OAO type cells. The various modes that we tested were the integration type mode, the trickle charge, the discharge shorted and the discharged OCV. Every six months, we reconditioned the cells and performed approximately two weeks of tests; therefore, in each year of storage, the cells receive about a month of testing.

The tests include three capacity checks, two zero-degree overcharge tests and what we call "internal short" tests, in which the cells are shunted for 16 hours, the shunts removed and allowed to stand on local circuit recovery for 24 hours.

The integration pack was discontinued after three years, and I will not really go into that any more, since we all came to the conclusion that the flight batteries should not be the integration battery. The trickle charge and the shorted packs were discontinued after five years of tests; this was set up as a five-year test.

The discharged OCB test has completed three years of tests, and this is because this test was started a couple of years after the initial tests, and the discharged OCB cells are not from the same lot of cells that the old three-packs were from.

(Figure 161)

Quickly, we will go back through the graphs I have. These are the results of the capacity checks. As you can see, this has been presented, and we will move on to the last part.

(Figure 162)

Looking at the shorted and the C-over-40 trickly charge, you can see
that the capacity has held up rather well under shorted conditions, whereas in
the trickle charge you can see it as dropping off. This is times in minutes, and
you can see at the 60 months, or at five years, we were running 146 on the first
capacity check and 145 on the second one. To go back right at the beginning on
the pre-storage, here you can see that it was the same capacity of what we ini-
tially started with. Over on the C-over-40 trickle charge, you can see that they
were in line; they went up and then they increased around 18 months. So as the
conclusion of the capacity tests, it looks like the discharge shorted condition
is the best.

(Figure 163)

This is the trickle charge, and naturally since we came up with that
the shorted condition was best, I don't have the graph on the results of the shorted
condition, but I do on the trickle charge. As you can see, the initial 18-months
capacity check, the first one, and the third one was here and it has dropped off,
which is what the graph had shown, on the five years, at the 60.

(Figure 164)

This is the results of the open circuit test, what we called the "internal
short test." This again was presented, this part.

(Figure 165)

And this is the last part of the five years. As you can see on the C-over-
40 trickle charge, we have gotten down to where one cell did not recover at all.
Throughout the test, the shorted condition always recovered above the 1.20.
You will notice over here that in the three-year test on the discharged OCB
condition, that they are all below the 1.20.

(Figure 166)

This is the zero degrees overcharge test. This again was presented
before, except on the discharged OCB condition, we did run into problems at
the 30th month, where it was discontinued from that portion of the test because
of high pressure. The only limit we had during this test was pressure; and 75
psig is where we discontinue the tests.

The test is essentially we put them into zero degrees, we stabilize them for four hours, and then we discharge them for five minutes at 6 amps. They then go on a constant charge of C over 20 for five hours; and the only limit, again, is high pressure. As you can see, at the 30 months, high pressure was observed on the first test of the discharged OCB condition. The second test, the cell voltages were all above 1.6, but the pressure had not reached the limit yet.

(Figure 167)

Toward the five-year mark, you will notice that in the shorted condition, we essentially had no problems throughout any of these tests, on the zero degree tests, whereas on the C-over-40 trickly charge, we reached the high pressure limits.

(Figure 168)

This is just for information. Again, this is the integration pack. It was presented. I just kept this graph in here so all the information would be together. As you can see, it was discontinued after three years, and you can see how your peaks during the zero-degree overcharge test, how they came up to where finally here, we never got up to another plateau because the pressure took us off test.

(Figure 169)

HARKNESS: This is a discharge in short. As you can see, we had no problems. You can see the various peaks, and we still had maintained essentially the same voltage plateau, with about 20 millivolts difference, a little higher at the end of five years.

(Figure 170)

HARKNESS: The C-over-40. You can see the peaks kept coming up; your prior to storage, your 18 months, and then here is your 48 months. This is the 60 months; it got right here. It wasn't even allowed to go up for it, because pressure again stopped the test.

(Figure 171)

HARKNESS: Here is your discharged OCB. Prior to storage, 12 months, 18 months, and then the last one, which was three years, is up here and it got knocked off because of high pressure.

As you can see, the best condition is the shorted condition. The old thing in the trickle charge pack, between every two weeks of testing, which was between every six months, toward the end of the five years the pack was running at about 70 psig pressure prior, or at the end of the storage mode, the end of trickle charge before we started testing, so the pressure did increase on this pack.

The analysis data is not available at this time. It is at Crane and also, I think the last cell that we pulled out in the discharged OCB condition was sent back to Goddard for them to run some tests. But this is available at Crane. Hopefully, in two years, when we are finally done with this test, and I make the final updating we will get this information and put it all together and wrap it up.

DISCUSSION

SEIGER: Yardney. Have you been performing any tear-down tests?

HARKNESS: Yes. That is what I said earlier.

SEIGER: Okay. What have you been observing with the teardown? Anything on the negatives; apparent thickening of the negatives?

HARKNESS: I don't think so. Not in the short.

SEIGER: Good. What about trickle?

HARKNESS: Well, I think we saw just a little increase in the trickle. I will say that I think after 48 months we pulled the cell out in the shorted condition and in the trickle-charged condition, and as far as visual analysis, the shorted condition almost looked like a new cell, meaning it was gray, as compared to the other, which appeared white or cloudy on the surface. Okay; I am talking about the separator, okay? And you saw much more migration and that on the seal before you --

SEIGER: On the trickle you always had more migration.

HARKNESS: Yes.

FORD: Goddard. Would you clarify that last point there? I didn't understand what you said, between the trickle and the shorted, on the migration.

HARKNESS: I saw more evidence of migration on the trickle than I did on the shorted.

LACKNER: Defense Research, Canada. I just wanted a clarification on your test. You said that you took out the cells every six months, and did a check on them?

HARKNESS: Yes, sir.

LACKNER: Now, was that on a sampling basis, so that when you said you had a three-year-old cell, it was actually in storage for three years, or it had only been in storage for six months?

HARKNESS: No. There were five cells in each pack, and every six months, all five cells went through the test.

LACKNER: Oh, I see. So that actually it was only six-month intervals up to three years?

HARNKESS: Yes. Now, I think Dr. Scott has had them in storage for three years continuous. Isn't this right, Dr. Scott?

SCOTT: Affirmative.

HARKNESS: Okay. We pulled all of them out every six months; all the cells of that pack were reconditioned. Yes, sir?

FORD: Ford, Goddard. That brings me to the question I wanted to ask Will, since we were still on storage. There are two philosophies, now, I have heard from different places and administrators. One is, periodically, you pull a flight battery out, you condition it, you look at it, evaluate it, and put it back in storage. The other thought is you don't do anything after you have run it through the acceptance tests. You accept it as a valid flight unit, put it in storage, and leave it there until you are ready to fly, when you just pull it out and check it out again.

Now, of the two, for long term, let's say if you had to go a five-year period, and periodically went to six-month intervals, or one-year intervals, what do you think would be the most desirable alternative?

SCOTT: Originally, we were nervous about storage, and we took batteries out and cycled them a little bit every six months, and we still do that on some programs. But the changes that we have been seeing are so slow, at least with anything we can detect, that now we feel that that is much too frequently.

And I don't really know whether there is any real need to electrically cycle them at all, at any particular intervals. But the only thing I would do would be to maybe check, make a leak check or an impedance check, or some very benign sorts of checks just to make sure, you know, that the rats haven't gotten in and got the wires over a period of years. But otherwise, I don't see any basic need for electrically checking them.

HARKNESS: I agree with Will.

SPARKS: TRW. As Will mentioned, we have looked at this periodically to see what we should do. It turns out that when you look at it from just the battery point of view, I would have to agree with Will. However, when you put on the program pack, you know, they get a little uncomfortable just leaving the batteries there unattended for years and years and years. And we have on occasion, on the six-months checks, found other defects: The packaging leaks, supposedly disappeared; we have had like a switch failure, and a leak showed up after some time; these types of things.

So from a program point of view, they don't like to really leave that hardware sit there a long time unattended. So you really do need some kind of methodology (?) for periodic inspection, which is perhaps a function inspection.

ROGERS: Hughes Aircraft. I noticed you stored at 22 to 23 Centigrade, is that correct?

HARKNESS: Yes.

ROGERS: Whereas Will was talking about I believe five to 10, was it? It would seem if you were going to put something in storage, you would want to cool it as much as possible, and I would question the validity of your results applied to a rather different temperature.

I mean, I am not saying what you got isn't what you got, at 22 degrees. But if you go to five degrees, cadmium migration, for example, I would expect to be much reduced. I wouldn't know how to apply those results to a lower temperature, or even implications.

HARKNESS: Well, if you are going to believe what I said, then you have to believe what Will Scott said, and he already gave you the same type of information, that stored at from five to 10, you are not seeing any electrical differences. Was this right, Will?

SCOTT: Yes; that is correct.

HARKNESS: So, you know, why wouldn't you think that the results, I mean you could apply my results to the lower temperatures?

ROGERS: I don't remember Will talking about trickle charge, or maybe I missed that.

HARKNESS: No, he didn't. He just talked about shorted. But I am saying that at 25 degrees C, or 20 degrees C, that we got essentially the same type of results that he did.

SCOTT: I think maybe the point is you did see a difference in certain test responses between trickle charging and shorted storage?

HARKNESS: Oh, yes.

SCOTT: And maybe those differences would be different if they were both done at a low temperature.

HARKNESS: Well, yes. This is true, But I -- Yes; Ford?

FORD: Goddard. Let me comment on that; let me put the whole test in perspective. I believe it started in 1971; and at that time, we were trying to answer a very fundamental question that we were having problems with project people putting batteries in spacecraft, and we weren't trying to determine the optimum storage conditions under all sets of parameters.

What we were trying to find out is, given the environment which is on a spacecraft, what option do we have to us to maintain that battery as healthy, in a state of health as high, as we possibly can?

So obviously, we don't have the option to put a spacecraft at 15 or 10 degrees C or five degrees C. We have to stay with whatever they are going to offer us. But the things you saw here were things that we felt like were realistic: Trickle charge, discharge open circuit, you know, random use as we simulated, and of course, the discharge shorted for some finite periods.

So we didn't try to answer the whole question. We were directed particularly at what happens in a spacecraft environment during this integration mode, and what options are available to us. And I think the type of data that we have see, like Will has presented, is more or less complementing. In very low temperatures, you would probably get even better results than what we are getting on these tests at 0.5.

THIERFELDER: General Electric. Willard, do you have any comparison between the discharge open circuit and the discharged shorted for the low temperature?

SCOTT: No. I don't have that.

SEIGER: How about storage trickle-reverse? Anybody try that?

MAURER: I would like to say a word of caution about the results on the shorted storage and the testing following shorted storage. On the trickle-charged batteries, presumably you have nylon separator decomposing in the electrolyte over the several years of the tests; and the mechanism of that aging phenomenon is that the separator decomposes in the electrolyte, and then the decomposition products migrate to the positive electrode and they are electrochemically oxidized; and it is that oxidation, that in turn charges the negative electrode. This takes place throughout the trickle-charge period, and tends to charge up the negative.

And we have shown that the electrochemical oxidation step is a fast step, relative to the nylon decomposition, but it is not a very fast step. It is relatively slow, in terms of chemical reactions; so that on the shorted storage test, presumably you have nylon degradation going on all that time, but it won't have any effect on the electrochemistry of the cell when you start testing it immediately. The negative will still be back at its former state of charge, and it will have no reason to come back in and charge it up.

So you will have to wait until all those decomposition products have been oxidized on the positive, and get the negative charge. Now, that may take some period of time. I don't know how long, but if you could -- it could take a year of operation before the negative reaches the state of charge it should be for that amount of nylon degradation.

So you might possibly fool yourselves into thinking that the voltages are all right, after a short-term test.

LIM: Hughes. We have studied the nylon separator degradation, and we got a little bit different result. I guess it was published about two years ago, in the workshop meeting. And the nylon separator degradation will occur whether you trickle-charge it or short it. And the separator degradation product will be accumulated and oxidation of that process takes only a matter of days, rather than years.

RITTERMAN: TRW. Dr. Seigers' point about reverse trickle, I have some experience in that. And we ran some cells in reverse for about a month, C over 400, 24-ampere-hour cells; and we found on a subsequest charging that we had an additive capacity; of course, this is not the long-term storage, but it is an interesting point.

HARKNESS: I would like to ask a question on that. Was that a constant C-over-40 discharge, or 400?

RITTERMAN: 400.

HARKNESS: C over 400 for how long?

RITTERMAN: About a month.

HARKNESS: About a month. That was constant, unbroken?

RITTERMAN: Unbroken.

HARKNESS: What were your voltages?

RITTERMAN: The voltage was maintained at minus 0.2.

HARKNESS: 0.2. How about your pressure?

RITTERMAN: Pressure was for the most part allowed in storage.

HARKNESS: How old were the cells?

RITTERMAN: They were essentially new cells.

HARKNESS: New cells; yes.

WADHAM: Telesat. We have had basically the opposite results to you on some cells that we have had on storage. We had one model cell of which one part was used on an in-orbit spacecraft, where we have been doing long-term simulations. The other lot were on the spacecraft for about a year, were put in cold storage shorted, and after we had held onto them about two years, I think it was; and they were put into an eclipse simulation, and also some were sent to Jim Dunlop for analysis.

We found the amount of precharge increase on those cells was identical to the precharge increase on the old cells which had been cycled; and also we

found that after a very short period of time in that eclipse simulation, those cells failed, whereas the ones in orbit are still working. The ones in the simulation failed; and we ran into overcharge problems. Do you have any comment on that?

HARKNESS: It may mean you can measure capacity but you can't charge them in an open regime.

FORD: Goddard. But you mentioned what I consider a key factor. You said they were in the spacecraft for about 10 months.

MAURER: About a year; something like that.

FORD: And I think if there is one thing I am convinced of, I know I said this two years ago, if you want to make batteries fail, leave them open circuit in a random condition; and six months is enough to really have catastrophic effect over a long period. I mean, three months is even too long. And we are constantly in that battle with project managers to keep them off the spacecraft. And yet, you know, you go to them with this type of data, and they look at it and say, "So what?" But when you say, "Yes, we did it 10 months or 12 months, and then we had a failure," These are the type of things we need to convince bull-headed project managers that they do have a problem when they go this way. So I think that is a very important point, which you can't overlook.

HENDEE: Telesat. That was precisely why I asked Will Scott what the previous history was on the storage cells. The other thing I wanted to ask you was what type of cells were you using? Did you have things such as silver in your cells? Anything unusual?

SCOTT: Yes; the cells, I believe, I will have to double-check that; I believe they had silver in them. Otherwise, they were, you know, a standard, what I consider a fairly standard type of General Electric cell design.

HELLFRITZSCH: I think here we have an excellent opportunity to have an accelerated test. I mentioned the microcalorimeter yesterday. If you are wanting to measure rate of degradation, if any degradation is going on while the cell is standing open circuit or shorted or whatever, it will show up as heat.

I told you yesterday that the resolution is one microwatt. That means if it were degrading, that it is generating heat at that rate, it will take a million years for roughly ampere-hour, if it were operating at one volt. If it were degrading at 10 microwatts, it would be one-tenth of a million years. That will give you some idea of the sensitivity, how exactly you can measure the peak

given off when one rice grain germinates, about 15 microwatts. The Bureau of Standards has done measurements of that kind.

So there you have got a very sensitive thing. It takes about two hours to insert the speciman and have it stabilized and measure this rate, and it is certianly not destructive. You can measure this on a sample or on individual cells; find out which one is going faster than the others.

Now, when you have a suspicion that the heat is not coming from electrochemical discharge, the nylon separators that react, well, that, too, will show up exothermically. And then you can do a little experiment. Forget about the battery. Just put some nylon together with the electrolyte that you have and put it in a little test tube and put that in the microcalorimeter, and see at what rate heat is being generated due to that. So it is excellent, and in two hours you can find out, I don't know how many cycles you want; you know, whether you want to test this every six months or every so many years or whenever. I have said the heart pacer people are going overboard. I don't think they are going overboard at all. I think we have here one of the first nondestructive tests, which I deposited 20 years ago because I was being paid to come up with brilliant ideas like this.

HOLCOMB: NASA Headquarters. Yesterday, in the talk about synchronous spacecraft and the orbital operation of them, what is used in them, the trickle-charge storage, and I don't know that much about everybody's applications, the data on ground storage, it appears, and there is a lot of controversy, that shorted storage is superior to trickle storage.

And I am wondering why we haven't yet heard anything about using this operation, or maybe we have, in synchronous spacecraft.

THIERFELDER: G.E. Well, the big difference is that in space it is in a charged condition, and on the ground, in a discharged condition, and that makes all the difference in the world, whether those batteries are charged or discharged.

HOLCOMB: Well, I mean could you simulate that in space by discharging them?

THIERFELDER: Well, that has been proposed, but nobody wants to fly with a discharged battery on board.

NAPOLI: RCA. I think one of the answers here is that you never know when you are going to need those batteries on an operational spacecraft; and then

you go into a lost pitch or lost lock mode, and you don't have a ray, you know, you could have a catastrophic problem on the spacecraft, too.

SPARKS: TRW. I think the answer to your question is that we have been. It turns out it is feasible and it works in orbit; and we have flown it that way for about five years. The secret to it, though, is that you have to have battery redundancy in the system, so that one battery is always up to support the bus. But we have, on several spacecraft, flown on the hot side of the space-craft with the batteries stored shorted. And these have been taken down in the manner we have been talking about later, where we effectively do a deep recon-ditioning, and I can go into that a little bit later. But I think the mode has been tried in space. It does work and it has been satisfactory.

DUNLOP: Comsat. First of all, when you make a statement that it is "better," it is not clear that it is better. This goes way back to Bell Labs. I asked Bell Labs that question seven years ago, and they told me they had got trickle-charging in -- we had those nickel-cadmium batteries on live tests, we were going to test four for eight years on real time. And the negative electrodes that were trickle-charged looked very good after eight years of real-time trickle charge operation.

If you would like to see that data, we have presented it at some of these meeting. The utilization that was left gives us still about 70 percent, 68 to 70 percent. We don't really see any advantage whatsoever to the shorted mode at this point.

NAVAL WEAPONS SUPPORT CENTER CRANE
OAO STORAGE TEST
10 AMPERE DISCHARGE TO 0.5 VOLTS

	INTEGRATION 215A		DISCHARGED-OCV 215B		SHORTED 216A		C/40 TRICKLE 217A	
	COND. CYCLE	TAPER CHG.	COND. CYCLE	TAPER CHG.	COND. CYCLE	TAPER CHG.	COND CYCLE	TAPER CHG.
	MINUTES		PRE-STORAGE				MINUTES	
C1	146		151		144		142	
C2	146		151		146		143	
C3	148		153		145	140	148	
C4	151		149	151	146		144	
C5	145	144	164		147		140	140
	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG
	6 MONTHS							
C1								
C2	132						146	
C3			151	149	144	138		
C4								
C5		141						144
	12 MONTHS							
C1		*	*					
C2								
C3	133	148			138	139		
C4			145	139				
C5							154	150
	18 MONTHS							
C1			*	*				
C2								
C3			165	152	138	136		
C4								
C5	120	147					167	150
	24 MONTHS							
C1	141		*	*	*	*	*	*
C2	*	*			140	135		
C3			165	153			162	144
C4								
C5		143						
	30 MONTHS							
C1			*	*			*	*
C2	*				*	*		
C3			168	153	142	142		
C4		120					164	
C5	105	120						150

Figure 161

	INTERGRATION 215A		DISCHARGED-OCV 215B		SHORTED 216A		C/40 TRICKLE 217A	
	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG
				36 MONTHS				
C1		110	*	*		*	*	*
C2	*	*			*			
C3					137			
C4			166	147				
C5	82					143	163	147
				42 MONTHS				
C1	PACK				*	*	*	*
C2	DISCONTINUED				*	*	*	*
C3					132			
C4								
C5						142	160	150
				48 MONTHS				
C1					*	*	*	*
C2					*	*	*	*
C3					*	*	*	*
C4					151			
C5						135	161	138
				54 MONTHS				
C1					*	*	*	*
C2					*	*	*	*
C3					*	*	*	*
C4					146			
C5						145	157	150
				60 MONTHS				
C1					*	*	*	*
C2					*	*	*	*
C3					*	*	*	*
C4								130
C5					146	145	145	

PACKS-216A & 217A Discontinued

*CELL REMOVED FOR ANALYSIS

Figure 162

OAO STORAGE TEST
PACK 217A C/20 TRICKLE CHARGE
VOLTAGE PROFILE FOR 10 AMPERE (C/2) DISCHARGE
TEMPERATURE--25°C

Figure 163

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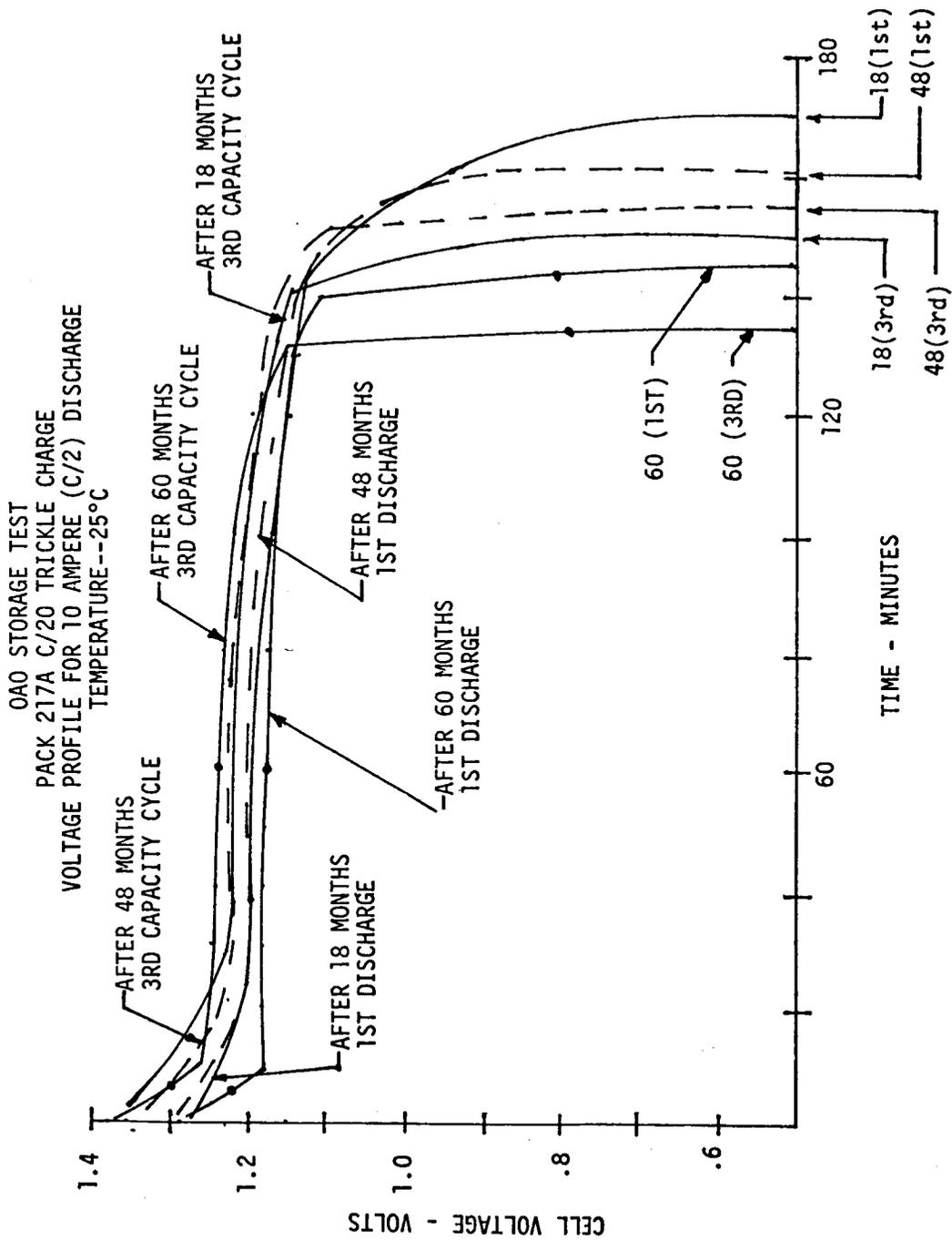
NAVAL WEAPONS SUPPORT CENTER, CRANE
OAO STORAGE TEST
OPEN CIRCUIT VOLTAGE RECOVERY

	INTERGRATION 215A	DISCHARGED-OCV 215B	SHORTED 216A	C/40 TRICKLE 217A
	PRE-STORAGE (1)			
C1	1.161	1.237	1.140	1.152
C2	1.167	1.246	1.150	1.158
C3	1.179	1.239	1.187	1.192
C4	1.179	1.242	1.187	1.143
C5	1.173	1.236	1.136	1.128
	6 MONTHS			
C1	1.184	1.207	1.202	1.182
C2	1.177	1.207	1.202	1.179
C3	1.169	1.207	1.217	1.174
C4	1.171	1.219	1.215	1.183
C5	1.190	1.207	1.204	1.185
	12 MONTHS			
C1	1.145	*	1.201	1.207
C2	1.168	1.200	1.206	1.202
C3	1.153	1.197	1.219	1.204
C4	1.147	1.209	1.221	1.204
C5	1.147	1.198	1.203	1.203
	18 MONTHS			
C1	1.156	*	1.202	1.128
C2	1.145	1.192	1.212	1.130
C3	1.147	1.189	1.226	1.117
C4	1.158	1.204	1.223	1.133
C5	1.157	1.194	1.206	1.129
	24 MONTHS			
C1	.227	*	1.247	1.144
C2	*	1.180	*	1.142
C3	1.152	1.177	1.237	1.148
C4	1.149	1.197	1.235	1.142
C5	−.003	1.184	1.210	1.142
	30 MONTHS			
C1	1.166	*	1.201	1.136
C2	*	1.175	*	*.
C3	1.158	1.170	1.229	1.133
C4	1.159	1.190	1.228	1.136
C5	1.169	1.186	1.208	1.129

Figure 164

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	INTERGRATION 215A	DISCHARGED-OCV 215B	SHORTED 216A	C/40 TRICKLE 217A
36 MONTHS				
C1	0.00	*	1.213	1.135
C2	*	1.190	*	*
C3	1.172	1.186	1.240	1.162
C4	1.171	1.194	1.232	1.153
C5	0.002	1.191	1.219	1.147
42 MONTHS				
C1	PACK		*	*
C2	DISCONTINUED		*	*
C3			1.215	1.168
C4			1.204	1.141
C5			1.170	1.132
48 MONTHS				
C1			*	*
C2			*	*
C3			*	*
C4			1.213	1.145
C5			1.209	1.140
54 MONTHS				
C1			*	*
C2			*	*
C3			*	*
C4			1.213	1.153
C5			1.217	-.002
60 MONTHS				
C1			*	*
C2			*	*
C3			*	*
C4			1.206	NO DATA
C5			1.214	NO DATA

NOTE (1) Prestorage test conducted following initial conditioning cycle-all cells had previously exhibit voltages 1.18 volts when tested by manufacturer.
*Cell removed from test

Figure 165

NAVAL WEAPONS SUPPORT CENTER
OAO STORAGE TEST
OVERCHARGE VOLTAGE @ 0°C - C/20 FOR 5 HRS

	INTERGRATION 215A		DISCHARGED-OCV 215B		SHORTED 216A		C/40 TRICKLE 217A	
	1ST	2ND	1ST	2ND	1ST	2ND	1ST	2ND
				PRE-STORAGE				
C1	1.509		1.539	1.510	1.503		1.501	
C2	1.503		1.549	1.515	1.504		1.504	
C3	1.503		1.553	1.515	1.503		1.504	
C4	1.505		1.545	1.517	1.502		1.502	
C5	1.501		1.542	1.515	1.508		1.501	
				6 MONTHS				
C1	HV>	HP>	1.491	1.538	1.511	1.543	1.488	1.492
C2	1.560	75.0	1.492	1.550	1.515	1.553	1.486	1.489
C3	2 HR.	2 HR.	1.491	1.555	1.509	1.553	1.502	1.504
C4			1.514	1.558	1.505	1.556	1.492	1.490
C5	31 MIN.	15 MIN.	1.489	1.558	1.515	1.552	1.493	1.491
				12 MONTHS				
C1	HP>	1.555	*	*	1.513	1.505	1.510	1.492
C2	75.0	1.526	1.548	1.534	1.519	1.509	1.504	1.493
C3	1 HR.	1.523	1.555	1.538	1.513	1.509	1.516	1.498
C4		1.527	1.555	1.526	1.517	1.509	1.504	1.492
C5		1.543	1.548	1.530	1.511	1.509	1.509	1.492
				18 MONTHS				
C1	HP>	HP>	*	*	1.522	1.506	1.507	1.499
C2		75.0	1.584	1.544	1.524	1.511	1.502	1.499
C3	75.0		1.598	1.593	1.520	1.510	1.519	1.504
C4	AT START	2 HR.	1.586	1.557	1.518	1.500	1.519	1.498
C5	OF TEST	30 MIN.	1.571	1.557	1.522	1.507	1.504	1.498
				24 MONTHS				
C1	HP	HP	*	*	1.532	1.518	1.518	1.508
C2	75.0	75.0	1.577	1.524	*	*	*	*
C3			1.595	1.550	1.525	1.516	1.529	1.509
C4	45 MIN.	30 MIN.	1.588	1.523	1.525	1.516	1.507	1.506
C5			1.571	1.516	1.528	1.515	1.515	1.506
				30 MONTHS				
C1	HP>	HP	*	*	1.526	1.516	1.524	1.508
C2	75.0	75.0	HP	1.620	*	*	*	*
C3	AT START		75.0	1.623	1.524	1.519	1.544	1.512
C4	OF TEST	45 MIN.	4HR.	1.623	1.522	1.518	1.514	1.509
C5			50 MIN.	1.611	1.522	1.516	1.521	1.508
			CELLS> 1.60V					

(1) HV=High Cell Voltage> 1.560
HP=High Cell Pressure> 75.0 PSIG
*Cell Removed From Test

Figure 166

OVERCHARGE VOLTAGE @ 0°C - C/20 FOR 5 HRS.--CONT.

	INTERGRATION 215A		DISCHARGE-OCV 215B		SHORTED 216A		C/40 TRICKLE 217A	
	1ST	2ND	1ST	2ND	1ST	2ND	1ST	2ND
36 MONTHS								
C1	1.503	HP	*	*	1.530	1.530	1.530	1.524
C2	*	75.0	HP>	HP>	*	*	*	*
C3	1.582		75.0	75.0	1.528	1.529	1.576	1.525
C4	1.582	1 HR.	2 HR.	1 HR.	1.531	1.529	1.526	1.521
C5	1.448	10 MIN.	30 MIN. CELLS> 1.62V	CELLS> 1.61V	1.528	1.530	1.536	1.524
42 MONTHS								
C1	PACK DISCONTINUED				*	*	*	*
C2					*	*	*	*
C3					1.528	1.546	HP>	1.545
C4					1.520	1.548	75.0	1.523
C5					1.535	1.551	1 HR. 28 MIN.	1.528
48 MONTHS								
C1					*	*	*	*
C2					*	*	*	*
C3					*	*	*	*
C4					1.528	1.518	HP>	1.520
C5					1.524	1.520	75.0 15 MIN.	1.532
54 MONTHS								
C1					*	*	*	*
C2					*	*	*	*
C3					*	*	*	*
C4					1.538	1.526	HP>75.0	1.521
C5					1.531	1.525	2 HR. 15 MIN.	1.607
60 MONTHS								
C1					*	*	*	*
C2					*	*	*	*
C3					*	*	*	*
C4					1.537	1.535	HP>75.0	HP>75.0
C5					1.532	1.534	3 HR 40 MIN.	45 MIN.

Figure 167

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OAO STORAGE TEST
OVERCHARGE VOLTAGE AT 0°C
C/20 CHARGE
PACK 216A - DISCHARGED & SHORTED

Figure 169

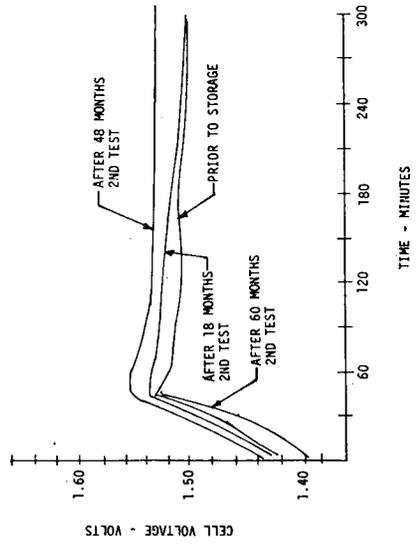OAO STORAGE TEST
OVERCHARGE TEST AT 0°C
C/20 CHARGE
PACK 215A - INTEGRATION

Figure 168

OAO STORAGE TEST
OVERCHARGE VOLTAGE AT 0°C
PACK 215B - DISCHARGED OCV
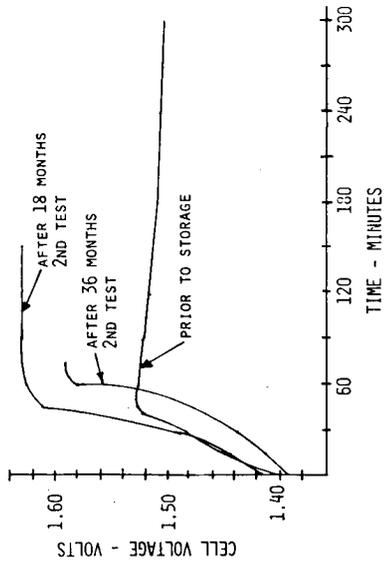
Figure 171

OAO STORAGE TESTS
OVERCHARGE VOLTAGE AT 0°C
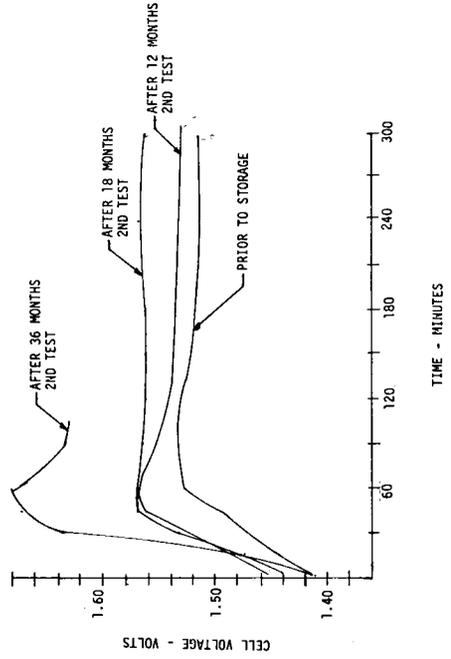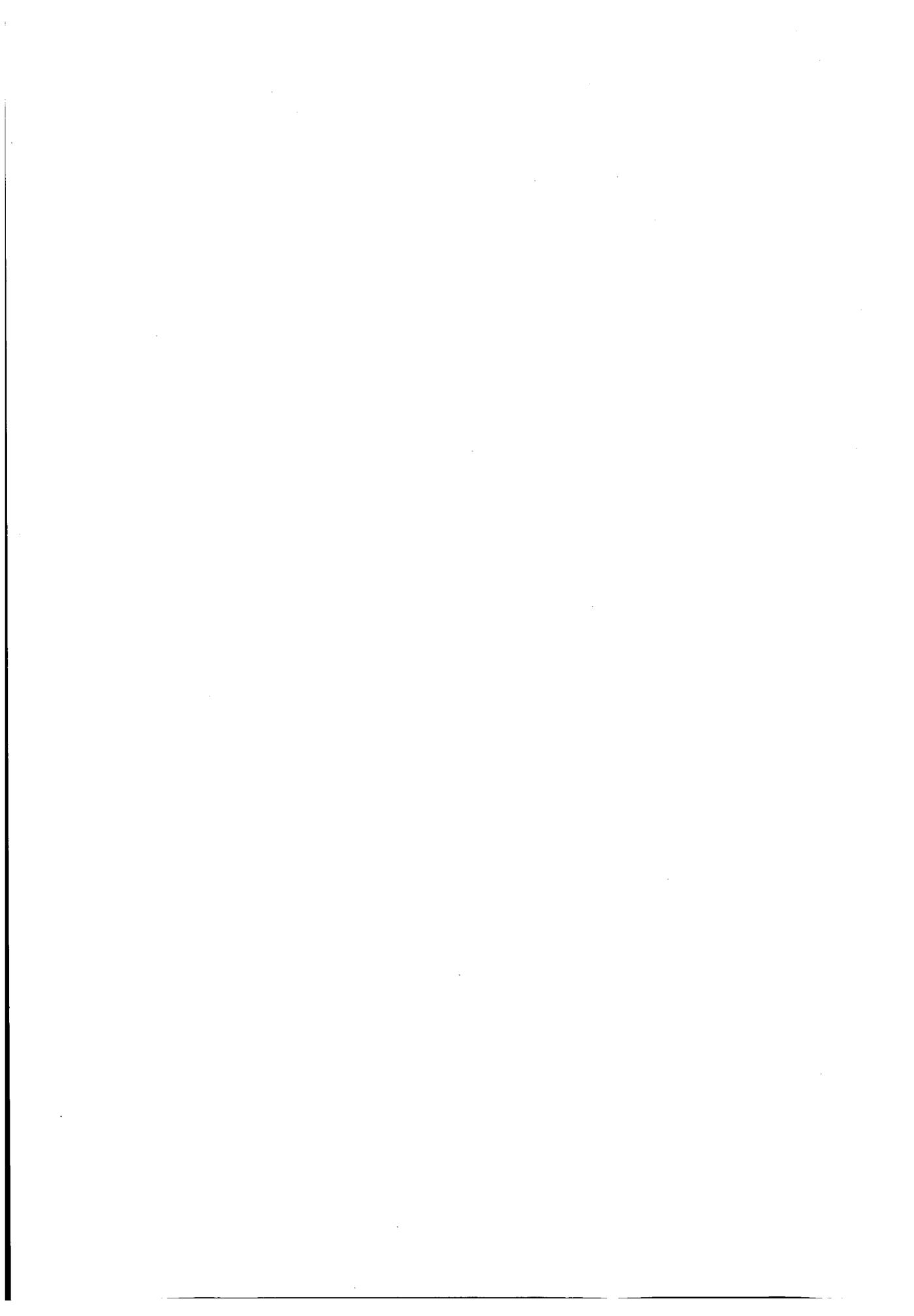C/20 CHARGE
PACK 217A - C/40 TRICKLE CHARGE

Figure 170

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SESSION III

CELL/BATTERY TEST EXPERIENCE

G. Halpert, Chairman
Goddard Space Flight Center

PERFORMANCE OF BATTERY RECONDITIONING ON THE COMMUNICATIONS TECHNOLOGY SATELLITE

J. Lackner
Defense Research Establishment, Canada

First of all, I would like to acknowledge the many interesting discussions and technical assistance that were provided by Floyd Ford and Bill Webster of Goddard, Vic Gore, CRC, and Guy Rampel of G.E. on this program.

Now today, I would like to present some real life data on the flight performance and reconditioning program on the Communications Technology Satellite. CTS is an experimental, geosynchronous satellite that was launched the 17th of January, 1976, as part of a joint U.S.-Canadian program between the Communications Research Center, Department of Communications, and NASA Lewis Research Center. It is a two year mission; its two years will be up on the 17th of January, '78.

Description of the batteries: There are two 24-cell nominal 5 amp-hour nicad batteries on board. The essential cell characteristics are G.E. manufacture bought to CRC spec EQ04-01 and EQ04-02. We feel it isn't enough to say that it is a standard G.E. cell. Polypropylene separator is qualified to our CRC spec; low carboante, less than 5 percent; low precharge; and enhanced high temperature design.

The operational characteristics: The two batteries are operated in parallel with isolating diodes in between and permanently connected to the house-keeping buses. During the non-eclipse season there is a common diode rail drain which gives a depth of discharge of 12-1/2 percent on each battery if shared equally, or 25 percent DOD on one battery if only one battery shares the CDR. The circuits are set up in such a way that the highest-voltage battery supplies the load, which means that you may not get equal sharing all the time.

The recharge can be at C over 10 or C over 20 to a 1.4 charge/discharge ratio; and recharge is terminated either when a computed 1.4 charge/discharge ratio is reached, or a charge voltage peak is reached.

During the eclipse season the power drain is a maximum of 60 percent DOD on each battery during maximum eclipse day. In the "worst case" condition, one battery may have to supply 85 percent DOD in the temperature range minus-5 C to plus-40 C.

The spacecraft operates at a design temperature of 25 C with a passive thermal control. It is a three-axis stabilized spacecraft, not a spinner. During summer solstice, Battery "A" temperature varied between 18 degrees C to 28 degrees C. Battery "B" temperature varied between 23 C to 33 C. During the winter solstice both batteries operate between plus-2 C to plus-12 C. Battery heaters are available in case of extreme low temperatures.

Reconditioning: We chose a reconditioning program to maintain our batteries because we were operating in a non-ideal mode, namely, 25 degree ambient, continuous low rate discharge of approximately C over 100 on one battery or C over 200 if the CDR shared equally on both batteries. Now, also, either battery could experience several hours of open circuit stand each day. Reconditioning is done just before and after each eclipse season; and reconditioning is done on one battery at a time with the other battery kept fully charged.

We chose a reconditioning rate of C over 3, using a fixed resistor of 18 ohms which is placed over the whole battery. The C over 3 discharge rate approximates our eclipse load so we get an accurate characterization of the battery capacity available for the eclipse season. Operationally, the C over 3 discharge allows us to complete our discharge in 2-1/2 to 3 hours; and the whole discharge-charge recondition cycle takes approximately 20 hours, so there is a minimum of disruption to spacecraft operations.

We felt that the low rate recondition discharge, although safer from a reversal standpoint, would not be as efficient in reducing any large crystals which may have been generated due to prolonged low rate discharge in the non-eclipse season. The low rate discharge would also tie up spacecraft operations for a longer time. Operators do not like this.

Ideally, reconditioning discharge should be at a high rate to one volt per cell and then at a low rate down to at least 0.6 volts per cell, with individual cell control. That is our opinion. Weight limitations, plus the short mission life, precluded our adoption of the ideal recondition mode.

Observations: After one and 3/4 years of operation and four eclipse seasons, we have been able to maintain over 80 percent capacity on battery A to our operating cutoff of 26.2 volts and 100 percent to 21.6, which works out to be 0.9 volt per cell.

Battery B has caused some concern because it is operating in a higher temperature range, but it is still giving over 50 percent capacity to our cutoff voltage.

Now the benefits of reconditioning, as we see it, are improved voltage and capacity; recovery of under-utilized plate material and balancing of cells; retarding the drying out of the cells by driving some of the electrolyte bound up by the plates back into the separator; and characterization of the battery capacity before an eclipse season so that efficient spacecraft load management can be exercised during the eclipse.

Drawbacks: The dangers of reconditioning are cell reversal and possible gas pressure build up on reversal; shorted cells may occur due to driving more active, more negative material into the separators during discharge; and stressing of the cells due to deep discharging.

Extended overcharge: We have observed that once the cells have faded in between recondition cycles, that extended charging, that is, charging more than the 1.4 charge/discharge ratio, will give you a little improvement. It will give a little bit of improvement. However, extended overcharging alone, without any cycling in between, will not recover faded capacity. You have to exercise the nickel-cadmium cell.

This can be observed from a lowering of the end-of-charge voltage and end-of-discharge voltage as the time between recondition is extended. Once reconditioned, the cell voltages on the end of discharge and the end of charge are definitely improved, whereas extended charging alone does not give the same treatment.

In the second year of operation, it was noted, particularly on Battery B, which operated at a warmer ambient, that the self-discharged increased during low rate discharge, that is on a common diodraft and open circuit stand from approximately 4 milliamps per hour to about 50 milliamps per hour. This caused a requirement for an extended overcharge, before you hit your peak end-of-charge voltage.

Some people yesterday were alluding to the fact that batteries were requiring longer charges, and I think it is because possibly a self-discharge mechanism is increasing.

The charge efficiency tended to decrease with age and time in between reconditioning, requiring up to a 200 percent charge-to-discharge ratio to reach the peak voltage, whereas after recondition, the charge efficiency returned back to about 1.3 or 1.5.

We have done some cell reversal tests. Okay. We conducted some tests on our simulated eclipse cycler to determine the effects of deep discharge

and cell reversal. Our simulated eclipse cycler has been operating some eight months prior to launch, and follows the same operational mode as the CTS spacecraft in orbit, but it is on the ground where we can observe it.

Pressure gauges were fitted to two cells. One cell had been operating for over 28 months. The other cell was an uncycled cell.

(Figure 172)

The upper curve here is an uncycled cell that had been kept in cold storage for 28 months, discharged and shorted, in cold storage at zero degrees Centigrade. Both cells were fully charged and run in reversal on a forced discharge at C over two. On reversal, the new cell dropped, in fact the new cell followed a classical electrochemical curve of dropping to minus 0.2. Within three minutes it generated a pressure of 1 psi per minute, which was hydrogen until the precharge was wiped off. It then dropped to minus 1.6 and generated hydrogen and oxygen.

The older cell dropped a bit more gradually, instead of a sharp drop, to minus 0.2, stayed constant, and we kept it on reversal for 2 hours and 38 minutes at C over two. It did not generate any noticeable amount of gas, about 5 psi at the most, and after those 2 hours and 38 minutes, it shorted out and stayed shorted out.

Now, the new cell, on recharge, came back over for a little while, and then came back and has acted normally. It has recovered its original capacity and has been operating without any problems on the simulated eclipse cycler since August of this year.

Cell reversal can cause problems to a new cell discharged at a high rate. However, the danger of gas pressure buildup is minimized as the cell ages and if the discharge rate is kept low. In older cells, the benefits of reconditioning with deep discharge have to be weighed against the possibility of shorts.

What we are saying here is, we are obviously not advocating high rate discharge down to zero; and I mentioned earlier the ideal mode was to take it high rate to one and then low rate down to at least half a volt and below, with individual cell control.

Now, our guidelines to the recondition mode, and I do feed we need a definition for "recondition." Just saying that you have "reconditioned," and that recondition is a benefit, is like saying "polypropylene is good." We have used polypropylene for 10 years, and all this while it works well; people have used it for two weeks and it has failed. So you have to specify it.

Now, the recondition mode, if it is to be considered, then certain guidelines should be followed to gain maximum benefits.

One good recondition at a high rate discharge down to one volt and below is better than several reconditions that are higher in end-of-discharge voltage at a low rate of discharge.

Some of the rates of discharge for recondition are so low that you are actually forming large crystals, which you are trying to avoid; and you are doing it to a high cut-off voltage, which is giving you a double indemnity. And if you find out that reconditioning is "no good" it is obvious why. Discharge at a high rate down to one volt; okay. Individual cell control.

After completion of the recondition discharge, the battery should be put on charge immediately.

(Figure 173)

Recondition may not be necessary for a new cell during the first year of operation. Curves one and two; you see, this simulated eclipse cycle was put into operation in April of '75. So during the eclipse season, the 17th of February to the 13th of April, there is hardly any significant degradation, so you may not need it in the first year of operation. But it does become necessary as the battery ages; and the benefit of reconditioning may last for a shorter length of time as the battery ages, therefore requiring more frequent and thorough recondition cycles.

The initial recharge should be at a low rate of C over 20 for the first few hours and then at a high rate until completion of charge. The reason for this is that when you have discharged a battery down to zero or to a low voltage, you have dried it out. You don't want to put a high rate of chrage onto a dry, high-resistant battery. You want to charge it at a slow rate and then give it the benefit of a high-rate charge.

If a second recondition discharge is considered, it should be done immediately after the end of the first recondition discharge.

(Figure 174)

Now we have a couple of points here. On the simulated eclipse cycler, it was obvious that we were degrading in capacity. This is normally a five amp-hour battery. Okay, one month after the fourth eclipse season, we got Curve One. We are down to about, oh, 55 percent capacity. So we said, okay, we will give a second recondition two days later.

The benefit really wasn't very much. So we said, "Okay, give it an extended charge." If you give it an extended charge, you get a little higher voltage, but really not very much. So we then discharged it all the way down to zero with individual cell control; and when that discharge was completed, put it immediately onto charge, C over 20 to start with, and then C over 10, and complete that. Now, when you do that you get a dramatic difference.

What is happening is that you have reactivated some material. If you put it on charge immediately after, you are going to be able to drive some of that electrolyte from the plates into that reactivated material and make use of it. If you wait several days, it is going to be useless.

(Figure 175)

Now, that was the simulator; this is the flight bird, Battery B, which has been giving us a hard time. We have run across the same thing; we have some problems with managers taking the battery down low. We found out we had, perhaps, a shorted cell, because we had a little bit of a hook, here. So we charged it one day, waited another day, and we got a slight improvement. Then a week later it had degraded.

So we said, we were going to have to "bite the bullet" and discharge it down and charge it immediately thereafter, which we did, and we got an enhanced improvement. So what you are doing is you may well be overcoming your so-called "soft shorts."

Battery maintenance technique: When considering the advisability of reconditioning or maintaining the battery on continuous charge, one has to take into account the battery design and the overall spacecraft power conditioning design.

Every electrochemical system will try to degrade to its rest potential, and eventually into an irreversible state. Therefore, it is essential either to stop the degradation process from starting or, at periodic intervals, to recondition the battery and try to return it to a high state of charge.

It may well be possible to operate programs without reconditioning, if the batteries can be maintained in full charge and now allowed to degrade or be subjected to open circuit, low rate discharge, high temperature, or inefficient charging.

Trickle charging can be beneficial in maintaining capacity, but continuous overcharge can cause problems on the long term, five years, unless the cells

are specifically designed to accommodate continuous overcharge. Continuous overcharge can swell the positive, degrade the nylon, generate oxidation degradation products such as carbonates and reduce overcharge protection.

Now it is recognized that certain dangers exist in any reconditioning program. However, if they are recognized and catered to, then definite benefits can be obtained, especially when operating under non-ideal operations.

To quote a noted medical expert, Dr. Hans Selye, in his book, "Stress Without Distress," we feel that an efficient reconditioning can provide beneficial stress without distress.

DISCUSSION

SEIGER: Yardney. I have three questions I would like you to comment on. It appeared that you have a ratio of 1.3 to one, according to the discharge curve of the new cell.

LACKNER: 1.3 to one what?

SEIGER: Negative to positive.

LACKNER: No.

SEIGER: That is what it appeared like on the three and 1/4 hours to two and 1/2 hours. The second question: Do you have anti-polar mass to explain the low voltage on the recharge of the new cell? And thirdly, in the cell that refused to go below two-tenths of a volt, the old cell, was the positive swollen in that?

LACKNER: Let's try the last one first, because that is the first one I remember.

LACKNER: We took one of the cells out of our simulated eclipse cycler at about 24 months, and had a tear-down analysis of it. The positive had swollen, yes.

SEIGER: How many mils?

LACKNER: Oh, I can't recall exactly, but it was larger than it was before. Not sufficient to short it. The separators had dried out somewhat, and there was a fair bit of cadmium migration; but operating at a high temperature,

low rate discharge, open-circuit stand is not the way to go, and that accounts for a lot of it. The fact that we have been able to survive, I think, is due to the reconditioning. Now, what was the other?

SEIGER: Anti-polar matter, or could it have been cadmium migrating to the positive? There was a "hole" in the recharge of the new cell for a significant period of time. Is that anti-polar matter? Is that hydrogen that is adsorbed on the positive? Could it have been cadmium that migrated over to the positive? Any explanation for the hole?

LACKNER: There possibly is some anti-polar mass. There is anti-polar mass in all batteries. I would have to refer that question to the battery manufacturer, if he would care to answer it. I think there possibly is some.

SEIGER: And the third one was the ratio, or the apparent ratio.

LACKNER: The design ratio was 1.5 to one. We had hoped to get around 1.7 to one, because we have always advocated a very high negative-to-positive ratio. There were weight limitations, and everybody said, "For a two-year mission, don't give us a hard time," so we ended up with 1.5 to one. The manufacturer could have given us more had we given him a bit more weight tolerance.

SEIGER: Well, then, did that represent the loss of capacity, the fact that it measured out on a discharge of 1.3 to one?

LACKNER: It looks that way.

FORD: Goddard. Joe, I think a point of clarification. You did not fully charge that cell and try to charge the negative up before you did that?

LACKNER: Yes.

FORD: You did? And you only got that much out.

LACKNER: No. That is a standard electrolyte system. It is identical to all the other cells that had been on storage. Let's see; it is a nominally five amp-hour battery. We qualified them. They gave us around five and a half to 5.8 amp-hours; after the 28 months in storage, when that was fully discharged, it gave us 6.2 amp hours.

FORD: Were you trying to measure the precharge on that test? Or were you trying to measure the total excess negative on that test?

LACKNER: What I was trying to point out on that test was the effect of driving a cell into reversal. Everybody seems to take the effect you get with a new cell, saying that you are going to generate gases; and we have observed in the past that you don't generate gases with old cells. So to make a valid test, we put a new cell in with an old cell, and ran them both at the same time. They were both fully charged.

FORD: All right. Fully charged in the sense of a sealed cell? You did not vent the cell when you charged it to get the excess negative charged up, too. That is what I am trying to arrive at.

LACKNER: Oh. No.

FORD: Okay.

RITTERMAN: TRW. I was going to make the same point that Floyd made; that unless the cell were vented, you could not fully charge the negative electrode to its full capability. What you were measuring there was the precharge versus the capacity of the positive.

LACKNER: Okay.

RITTERMAN: So 1.3 to one seems reasonable.

LACKNER: Okay. Let's define our terms; fully charged, we are asking for a nominal five amp-hour battery. In actual fact, we are getting around five and a half. We have a certain precharge in there, we have certain overcharge protection. When we get six amp hours, 6.2 amp hours out of it, as far as we are concerned, that is as fully charged as that battery, as you want to get in that state of a sealed cell. So it is not possible to vent a sealed cell.

RITTERMAN: That is my point exactly; that you could not get 1.5 to one on discharge unless you were to vent that sealed cell on charge and get the negative capacity all the way up. Once the cell is sealed, it has some discharge reserve; so then the 1.3 to one is reasonable.

LACKNER: We have had it to 1.5 to one in some of our qualification tests. Why this one, after storage, came out to 1.3 instead of 1.5, I cannot explain.

WADHAM: Telesat, Canada. You made a statement that the high-rate reconditioning, you felt, was far more beneficial than a low rate. And I realize, of course, that that communications satellite, except when Joe Napoli is here,

ran at a fairly low rate, averaging, for example, was about 0.13 amps on a nine amp-hour cell, which is about C over 40 or C over 50.

Bearing in mind that at these rates, you can discharge more of the active materials at a given voltage, because it is a low rate, I have got to see positive evidence to show the fact that a high rate is, in the long term, more beneficial.

LACKNER: Let's get two things straight. One: In qualifying a nominal capacity, you usually refer to a particular rate, and in spacecraft batteries it is C over five, or C over two. Your nominal capacity is established at C over two.

If you discharge at a lower rate, you are going to get more capacity than if you discharge at a higher rate. There is no argument there. The point is, if you discharge at a low rate, you are going to affect the crystallography of the battery into large, inactive crystals, whereas if you discharge at a high rate, you discourage that. And I think I would have to turn this over to Dean Maurer, who could go into the whole electrochemistry of it.

WADHAM: Yes, but my question was, do you have actually any evidence on the long-term, on actual clinical experience, that this is in fact the case.

LACKNER: Yes. We have also had about 15 to 20 years experience with nickel-cadmium aircraft batteries that have gone through a variety of uses: High rate charging, high rate discharging, and just sitting on the aircraft. And you definitely have to institute a reconditioning program with high rate discharge to recover them.

NAPOLI: RCA. I never got to understand what was it you brought your cell down to.

LACKNER: Last year, when we gave the presentation, we showed that we had a constraint to bringing it down to one volt per cell. We had built in the operational mode to bring it down to at least 0.8. As of last October, we convinced our operators that, yes, you have to go below one volt; and I think I pointed out last year the benefits we got from going to below one volt. So we take it down to 0.8.

We feel that if we take it down at the high rate, we don't have to go to as low a level as if you take it down at a low rate.

DUNLOP: I want to make one comment here.   I am not sure that all batteries are going to behave the same; but in the ones that we have tested from G.E., it was reported yesterday in orbit, and you see the same thing in the laboratory, if you discharge those cells, once they get to be five, six, seven years old, you discharge them at a high rate like a C over two rate, then the cell goes below one volt and in the case we showed here, it was a 20 ampere-hour cell originally, we got to one volt and we took three and a half ampere-hours out of it.   We got to zero volts when we took about five or six ampere-hours out of it at high rates.

Now, at a very low rate, that is with the resistor class, we were able to take out 18 ampere hours on this cell; and this is typical of what we see in the laboratory as well as what we see in orbit.   You can't take a cell that is seven or eight years old and discharge it at a high rate, if you have been in a synchronous orbit, and expect to get the capacity out of it.   And in order to get the reconditioning effect in that case, it has been necessary for us in the laboratory, as well as in space, to go to a low rate discharge to really remove a significant amount of capacity without at the same time --

If we ran it down at the C over two rate, and continue to discharge it in the laboratory, we have blown cells up in that fashion, because you will give it a hydrogen rate sufficient for it.

LACKNER: Now, what I mentioned earlier was to get the best of both worlds, take it at the high rate down to one volt, then at the lower rate below one volt.

DUNLOP: Well, we don't have any argument with that; and I think that was really Peter Wadham's question.

LACKNER: Yes.

HALPERT: Let's just have one more, Steve, and then we will get some coffee.

GASTON: RCA.   I would just like to rephrase the question before, on the anti-polar matter.   I mean, ask it directly.   Are there any silver additives in those cells?

LACKNER: Could you refer that question to Guy Rampel?

RAMPEL: General Electric.   There is silver on the negatives and there is cadmium in the positives.

FORD: Goddard. How much electrolyte did you have in this design? Did you comment on that?
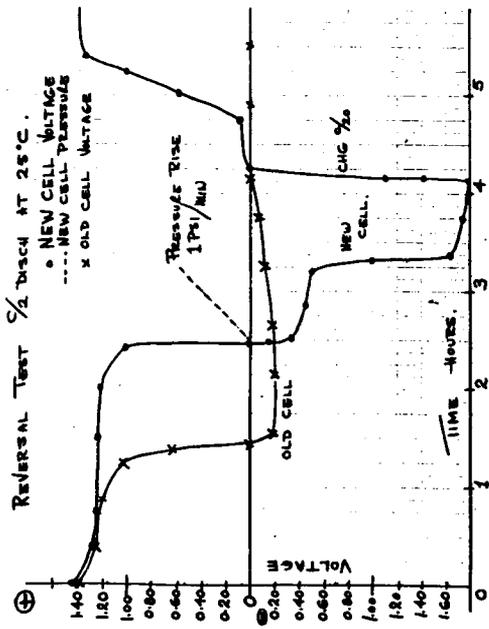
LACKNER: It was approximately 2.3 to 2.5 cc's per amp-hour. We have a polypropylene separator.
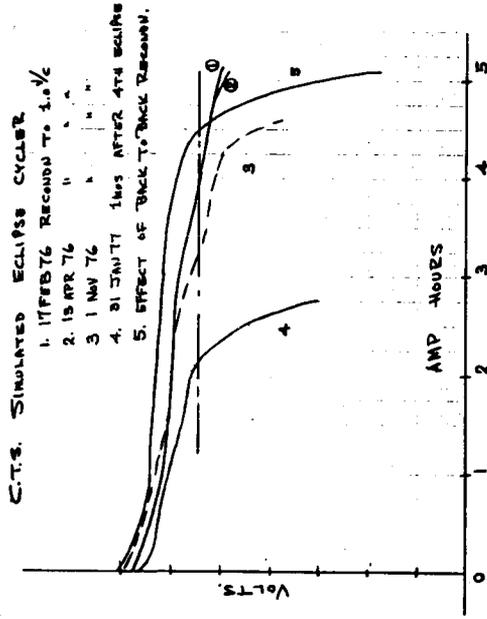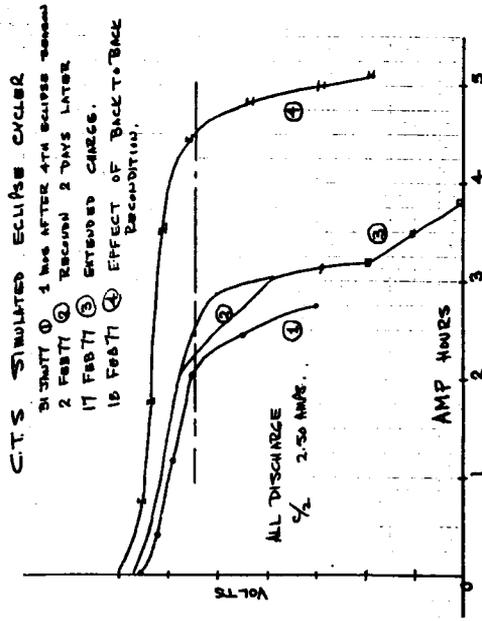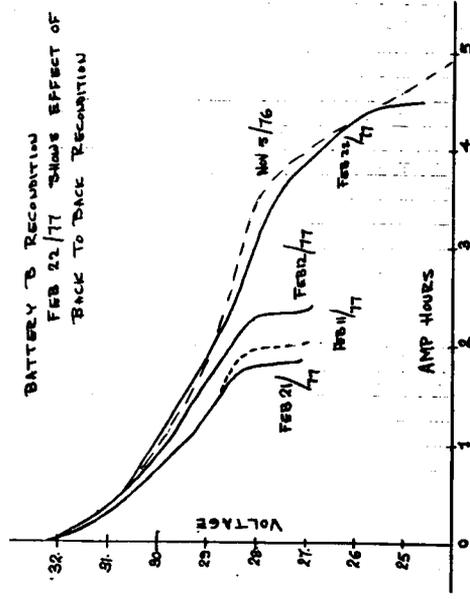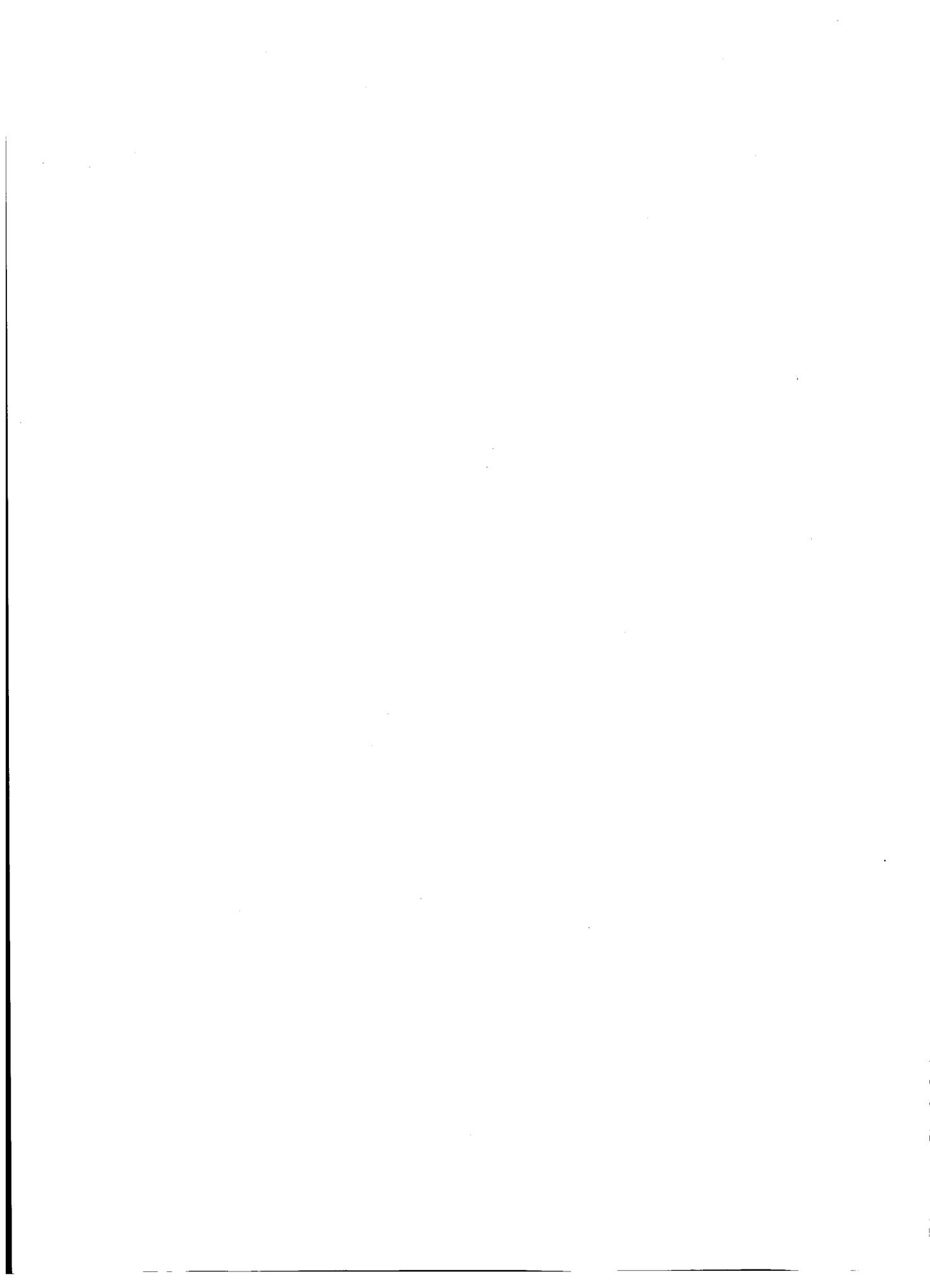
Figure 172

Figure 173

Figure 174

Figure 175

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BATTERY LIFE TEST USING RECONDITIONING

R.H. Sparks
TRW

I will be giving a discussion on nickel-cad battery life tests using reconditioning and some comparative tests not using reconditioning. My discussion will be aimed at the application part of the testing. Paul Ritterman will be following me with a discussion of the internal cell behavior during reversal, during some of these tests.

The goals of our program have been to get an increased utilization out of the nickel-cad system in geosynchronous orbit. We have actually tried to push the depth of discharge operations up around 80 to 85 percent depth of discharge; and our intent with the reconditioning program was to extend this type of utilization out towards a 10-year life and attune the voltage regulation.

Now, I should comment before I go too much further, so that I don't forget later on: Reconditioning per se, you know, is not a cure-all for everything. If you have got a bad cell, you have got a bad cell; we won't fix it with reconditioning, so we should all understand that before we go too much farther.

Futhermore, if you have lost your overcharge protection, and you are unable to fully recharge the cells, reconditioning will also buy you very little, from what we have seen.

(Figure 176)

Now, the work we are doing. As I mentioned, we have got test programs going on with no reconditioning. We have partial discharge reconditioning under evaluation and in orbit, where we discharge to approximately one volt per cell, usually about nine-tenths of a volt per cell, at a nominal 40-hour rate. We also have evaluated and tested for two-step type reconditioning, whereby you discharge to one volt at normal load rates, and then you go with about a 40-hour rate and discharge again to one volt, or nine-tenths of a volt.

In addition, we have what we call "deep discharge reconditioning," where we discharge the battery into a resistor for three to five days until the battery voltage is below one volt. This is usually done at no higher rate than C-over-60, and usually somewhere around C/80 or C/100. It varies from cell design to cell design.

We also have done reconditioning where we discharged battery cells into individual resistors for two to three days until all the cells have less than one-tenth of a volt.

(Figure 177)

To set the stage for why we got involved in our reconditioning work, we have some flight data and some test data for the early designs, which we were developing around '70, '71, '72, where most of the systems used three batteries, one redundant; normal design was 40 percent depth of discharge. The flight data which came back early, compared with the life test data, which was not reconditioned, we had a gradual degradation in the end-of-discharge voltage in the deepest eclipses versus season number, two seasons per year, which pretty well correlated with early flight experience.

However, we also had some batteries in orbit on which we were doing the so-called "single" reconditioning and "double" reconditioning to one volt or nine-tenths of a volt per cell; and that did improve our voltage regulation characteristics in flight.

(Figure 178)

About 1973 or 1974, we started going to deeper depths of discharge. We had designs working at 65 percent of rated capacity, 75 percent, 85 percent of rated capacity. So we started accelerated tests to determine how operation at 75 percent depth of discharge would work for five-year missions. Will Scott has already mentioned the other life testing which we have done following storage, and that was at 55 percent depth of discharge.

We ran 50 ampere hour real-time tests at 80 to 85 percent depth of discharge, which Scott has previously reported on, which showed that a single deep redonditioning recovered capacity after it was badly degraded. The same thing happened in 50 ampere hour accelerated life tests operating at the same depths of discharge.

(Figure 179)

Now the life test that I will be talking mostly about today uses this profile, the eclipse time in minutes, peaking out at 72 minutes, 45 cycles per eclipse season. This is the conventional geosynchronous type of eclipse profile.

(Figure 180)

The life test which we have operating has been going on for over 48 months. The early part of the test was run at 63 percent depth of discharge for the first five seasons, and that simulates an early life array and an early life operating condition for this particular spacecraft we were working on. The charge rate, this was a 24-ampere-hour General Electric cell, was around C over 12. The temperature during charge was profiled to simulate what happens in the spacecraft during charging.

As you charge, early in the charge, you go down near 7 degrees Centigrade. Near the end of charge, the temperature gradually rises towards 15 Centigrade; and then discharge was also profiled to go up to 21 to 26 Centigrade.

We started the life test in two ways; I will show you the graph in a minute: One without any reconditioning at all, and one using the so-called "shallow" or "soft" reconditioning to one volt per cell. At season 6, which is about three years, 2-1/2 years, actually, we switched to 75 percent depth of discharge and we lowered the charge rate to simulate array degradation and held the same temperatures.

Over the lifetime of the tests, then, you will see, as I report today, that we varied the temperature to determine sensitivity to temperature. We varied the charge rates to determine the sensitivity to charge rates; and we also went to deep low-rate reconditioning following season 13.

(Figure 181)

This plot shows a 12-cell battery voltage. We actually tested 13 cells; a cell with pressure gauge, a pressure transducer, was in series with this, which Paul will talk about later; but we monitored the 12-cell voltage, which is half of a battery pack, on this test and on this test.

The upper curve was the one that we used the soft reconditioning; the lower curve with the circles, we did not use any reconditioning. And you can see, I have a pointer here, as we started out with and without reconditioning, there was very little difference between the performance for 2-1/2 years, at 63 percent depth. When we switched to 75 percent depth, without reconditioning we degraded very rapidly towards our under-voltage limit, which in this case would be around 12 volts.

We had the same experience as reported on two of the other papers. We increased the overcharge, tried playing "charging games," and we could not recover the performance, other than very temporary conditions, by changing the charge mode. Now, we did find that by using the soft reconditioning to around

nine-tenths of a volt, we did extend the capability of the system in terms of its cycle performance out to between six and seven years of equivalent cycle life, and again, we got into an under-voltage condition. That is what forced us to look at deep reconditioning.

At the time we went to deep reconditioning; by the way, the rate on this was approximately the 40-hour rate. When we went to deep reconditioning, we changed this, then, to the C-over-60 rate sized at about approximately one volt per cell. Since that time, it has been running prior to every eclipse season, using that type of reconditioning. As you can see, we have maintained the voltage stable for 40 seasons, which is equivalent to a 20-year cycle life; not 20 years real time, necessarily.

(Figure 182)

Looking at the capacity behavior of the system, when we were doing those cycles, we plotted the reconditioning discharge capacity, using the soft reconditioning to one volt. This particular capacity, then, degraded with time and gradually approached the usable capacity, the capacity that we were trying to use from the battery.

We switched at season 13 to deep reconditioning and recovered a little of the capacity, and a lot of the voltage regulation, but by the next season, we had also recovered a lot of the capacity. We changed the temperature to 10 to 18 degrees Centigrade, accidentally, at this time and the capacity degraded a little bit. We went back to 7 to 15 C, and again, the capacity continued to recover and to remain stable.

We again modified the temperature to determine the sensivity of the system to our prediction tolerances, and again, you see a drop in capacity at the lower temperature and some change in the voltage characteristics, but a minor change.

After season 36, we reduced the charge rate to C over 20, and the temperature came back down to 7 to 15 Centigrade on charge, and the capacity jumped markedly. Now out here, we also show, the triangles show the capacity to one volt a full load rate following reconditioning. These were reconditioning capacities here, low rate capacities to one volt. The triangles show that indeed, even the high rate capacity is maintained.

Now, the circled stars, or starred circles, show the capacity following the eclipse season, prior to reconditioning at the higher discharge rate. And it shows coming out of the season, and in this case we had rated capacity at about

a C/15 charge rate, under the conditions we were operating at, and we recovered an awful lot of capacity with reconditioning, although we had lost quite a bit in the season.

At the lower charge rate, this data shows a similar type of behavior, but not quite as drastic a decay in the eclipse season. We don't fully understand that.

(Figure 183)

To give you an idea of what the discharge voltage characteristics look like, this is season 36; a 220-watt discharge on a 12-cell battery. Just following reconditioning, and we measured the discharge capacity of the cells at 27.3 ampere hours at the 220-watt rate, which is roughly a C/2 rate; then at the middle of the eclipse season, in the deepest eclipses, the voltage had degraded to this type of a characteristic.

The interesting thing that happens is, going on out of the season, and that intrigued me by what Jim reported yesterday, going out through the season, we got a further drastic decay in the characteristic of the voltage, which says that if you weren't reconditioning, you were really starting here the next season, or approximately at this point, which would account for some of the marked degredation we have seen in voltage characteristics.

Why this is happening, we still don't understand; but it does say that our power system models have to be modified a little bit.

(Figure 184)

Another interesting piece of behavior of the cell groups: I show the voltage balance at the end of discharge here; and we have comparable behavior at the end of charge, without using reconditioning, with the soft reconditioning, and then with the deep reconditioning. You can see without reconditioning, the cells started to diverge quite markedly. Here we are seeing a 50-millivolt unbalance. With a shallow reconditioning, we also started to diverge just before we went to the deep reconditioning. After we went to the reconditioning and got everything stabilized, by the time we were at season 36 to 29, at the end of the 75 percent depth of discharge, the cells are balanced to within 6 to 7 millivolts.

That is a lot of cycles for it remaining that well-balanced. It turns out on charge they were also very well-balanced; so that we can apparently modify the behavior of the cell adequately to make them all operate alike.

Now, we are continuing this test. We have implemented deep reconditioning in some of the spacecraft designs that we have, or the capability to do it in all of them. We have used this technique to take batteries down in orbit and store them, solstice, as I mentioned previously.

The advantage of doing that, we can't say that it helps the life a great deal because we trickle-charge at C over 100 or C/80, which is also a great amount, but it does reduce the operating temperature of the battery in orbit, and this is what we have been after when we do that. I guess that is the presentation I have for now.

DISCUSSION

GASTON: RCA. You mentioned during the deep discharge, you go to less than a tenth of a volt per cell. Do you discharge on a battery basis, or on a cell basis? Could some cells possibly reverse?

SPARKS: We discharge on a battery basis. Cells do reverse, and we have had no problem with that, for many seasons. We do get a small amount of hydrogen pressure building up, and it gradually decays back to zero pressure, and Paul will discuss that at more length.

GASTON: Do you have any silver additives in those cells?

SPARKS: Yes, we do.

HAAS: Ford. I was just wondering; the number of seasons, you mentioned the 40 seasons; what is the nature of the cycle that you are doing? It sounds like a tremendous amount of testing.

SPARKS: Well, okay. The test has been going on for four years real time. The early part of the tests, where you use a C over 12 charge rate, operates so that you run cycles required to meet the deepest eclipse at recharge with about an hour of trickle charge following that recharge; so roughly a 13-hour duty cycle, per cycle. As your charge rates decay down to C over 20, we are operating on about a 20-hour cycle. We use five days between the seasons for reconditioning, for measuring capacities; so we are time-accelerated, but we have not accelerated any charge rates or any discharge rates. We have maintained those at the same densities that we use in flight.

HALPERT: And the schedule shows five days between one season and another season.

SPARKS: Right. And the reason we have dropped the time in between the seasons on trickle charge is that the trickle charge rate we are using is very low; it is around C over 100; and we do try to keep the temperature very low in the solstice season wherever we can, now, in our designs.

BAER: Goddard. Do you attribute this improvement in performance to be due to the short points, the redistribution, run by the reconditioning?

SPARKS: I would have to guess. Don't ask me if we really know. We suspect there is some electrolyte movement in the cell when we do this; but we also have seen, you know, drastic changes in the behavior of both the positive and actually especially in the negative, but in the positive electrode when we do deep reconditioning.

At season 13, which was the first season we did the deep reconditioning, we had a plateau voltage at the low discharge rate of around two-tenths or three-tenths of a volt for hours and hours and hours, well below the eight-tenths of a volt we were talking about in some of the other discussions.

Now since we have gone to deep reconditioning, we haven't seen any plateau voltages in those regions. In other words, the temperatures rise up towards 20 Centigrade or so, we have seen plateaus like we have talked about, you know, up around eight-tenths of a volt; very small ones, but we have seen them.

PARK: Battery Development. I just wasn't quite clear on the rate of discharge in the deep reconditioning; the C-rate.

SPARKS: Okay. It varies from cell design to cell design. You have to determine it for each cell. For this particular life test, on a G.E. 24-ampere-hour cell, we sized that life test for approximately C over 60 to one volt per cell, average, okay.

PARK: For reconditioning?

SPARKS: Right; we set that, we use a resistor; so you set the resistor at C/60, based on a battery voltage average of one volt per cell.

BELLOS: Air Force. On the deep discharge to a tenth of a volt, did you worry about cell reversal; and if so, any problem?

SPARKS: Early in the game, we worried a whole lot. That is why I mentioned that the discharge rate varies from cell design to cell design. Paul

will report on it; but in a kind of a summary capsule, what we find is that you have to stay below that C-over-60 rate, and in many cells, you have to go to the C/100 rate or so. So you are looking at a three- to five-day discharge in geosynchronous orbit. That is not an operational problem, particularly; but it is a long time to, you know, sit around and wait.

WADHAM: Telesat. Can you explain why the voltages in the test set-up were lower than the ones you were seeing in orbit? Are they in curves which prevented that?

SPARKS: They are actually pretty close. This set is a little higher than the test, the upper curve is; and the lower curve was slightly below it, and we think that this is a result from -- we are operating at a little bit higher temperature in orbit, and the temperature profile is a little different than we had expected. So we got slight shift downward in the orbital contitions.

MAURER: Bell Labs. In the series of tests that Joe Lackner was describing, his cells were very dry when they were aged, and so he had to put them back on the charge immediately after the short-down to get them to come back at all. Do you have any experience with the length of time you leave it shorted down? I think this all has to be put into perspective with Will Scott's data, which says that shorted storage is the way to go, for long term.

SPARKS: Yes. I guess that question has a lot of different answers, depending on where we are in the operations. Basically, once we short them down in the spacecraft, we come back, we have stayed shorted down the whole solstice season, which is 3 or 3-1/2 months; but we come back on charge in the trickle mode. Number one, if you came back full charge, you would collapse the whole bus, and we can't do that. And you do see a very slow recovery, you know, when you come in at those low-trickle rates. But we have had no problem in coming back out from these types of conditions. It takes a little while for the voltage to recover, but we haven't had a problem with it. I don't know if that addresses your question.

FORD: Goddard. Let me be more specific. Have you seen any evidence, I think your data showed like 40 accelerated eclipse seasons; have you seen any evidence in charging of peaking early in the charges as the cells come up and go positive, peaking and then decaying and then going through the normal charge profile. Have you seen any evidence of that in these cells?

SPARKS: No. Not in this group of cells. One thing I should comment on: The charge control system we are using for this test is a voltage cutoff system, a temperature-compensated voltage cutoff system. And we recharge to a fixed voltage, based on that curve, and then we trip it into trickle charge.

The recharge ratios that we are running are very low, so we really don't drive the cells on into overcharge in the mode that you have been talking about earlier. Our recharge ratios are running around, the deepest eclipse is about 1.12 to 1.15, very low. In the shallower eclipses, as you would expect, the recharge rates are a little higher. And so we really haven't forced this voltage peaking and that characteristic.

We haven't seen, since we have gone into deep reconditioning, we haven't seen a shift; you know, an early rise in the voltage characteristics on this test, up through four years.

GASTON: RCA. Just one comment: When you talk about reconditioning, you have got to keep in mind cells which have nylon separators and cells which have polypropylene separators. They might have a little different characteristic.

SPARKS: Absolutely.

GASTON: You might need a little more care to recondition them.

SPARKS: Yes. These are nylon separators.

TRW

NICKEL-CADMIUM BATTERY LIFE TESTS USING RECONDITIONING

TYPES OF RECONDITIONING BEING EVALUATED

o NO RECONDITIONING

o PARTIAL DISCHARGE RECONDITIONING

   o DISCHARGE TO ~1.0 VOLT PER CELL AT NORMAL 40 HOUR RATE NOMINAL

   o DISCHARGE TO ~1.0 VOLT PER CELL AT NORMAL LOAD RATES FOLLOWED BY EXTENDED DISCHARGE TO ~1.0 VOLT PER CELL AT NOMINAL 40 HOUR RATE.

o DEEP DISCHARGE RECONDITIONING (DDR)

   o DISCHARGE BATTERY INTO A RESISTOR FOR 3 TO 5 DAYS UNTIL TOTAL BATTERY VOLTAGE IS BELOW 1.0 VOLT

   o DISCHARGE BATTERY CELLS INTO INDIVIDUAL RESISTORS FOR 2 TO 3 DAYS UNTIL ALL CELLS ARE LESS THAN 0.1 VOLT.

Figure 176

TRW
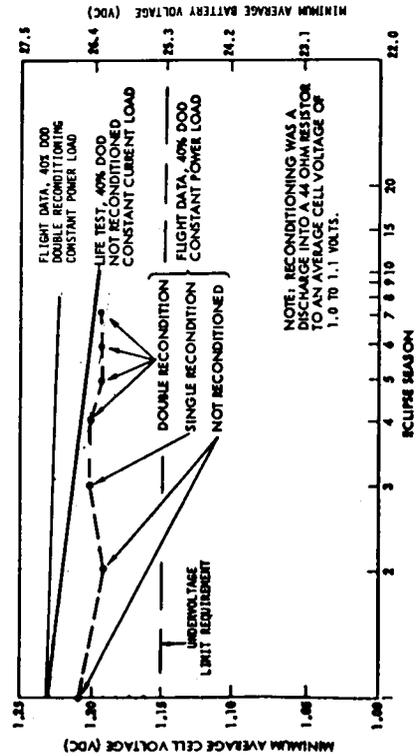
NICKEL-CADMIUM BATTERY LIFE TESTS USING RECONDITIONING

BATTERIES BEING TESTED

o 24 Ah TIME ACCELERATED — 75% DOD GEOSYNCHRONOUS SIMULATION

o 24 Ah TIME ACCELERATED — 55% DOD GEOSYNCHRONOUS SIMULATION FOLLOWING 4, 5 AND 6 YEARS STORAGE

o 50 Ah REAL TIME — 80-85% DOD GEOSYNCHRONOUS SIMULATION (PREVIOUSLY REPORTED TEST RESULTS BY M. R. SCOTT)

o 50 Ah TIME ACCELERATED — 80-85% DOD GEOSYNCHRONOUS SIMULATION (PREVIOUSLY REPORTED TEST RESULTS BY M. R. SCOTT)

Figure 177

TRW

BATTERY FLIGHT PERFORMANCE WITH AND WITHOUT RECONDITIONING DISCHARGES TO ~1 VOLT/CELL

Figure 178

TRW

TYPICAL GEOSYNCHRONOUS ORBIT ECLIPSE DURATION PROFILE

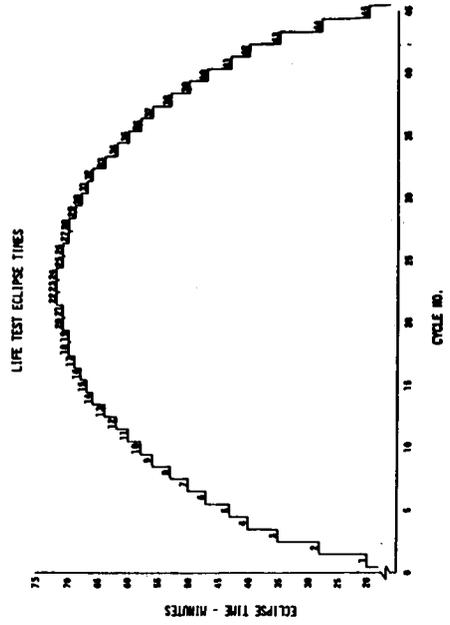LIFE TEST ECLIPSE TIMES

Figure 179

TABLE OF LONG TERM LIFE TEST VARIABLES

SEASON	DEPTH OF DISCHARGE	CHARGE RATE	CHARGE TEMPERATURE	DISCHARGE TEMPERATURE	TYPE OF RECONDITIONING
1 - 5	63%	2.0A	7 - 15°C	21 - 26°C	SHALLOW-2 STAGE
6 - 12	75%	1.6A	7 - 15°C	21 - 26°C	SHALLOW-2 STAGE
13 - 14	75%	1.6A	7 - 15°C	21 - 26°C	DEEP-LOW RATE
15	75%	1.6A	10 - 18°C	24 - 29°C	DEEP-LOW RATE
16 - 19	75%	2.0A	10 - 18°C	24 - 29°C	DEEP-LOW RATE
20 - 29	75%	2.0A	7 - 15°C	21 - 26°C	DEEP-LOW RATE
30 - 32	75%	2.0A	10 - 18°C	24 - 29°C	DEEP-LOW RATE
33 - 35	75%	1.6	10 - 18°C	24 - 29°C	DEEP-LOW RATE
36	75%	1.6	7 - 15°C	21 - 26°C	DEEP-LOW RATE
37 - 40	75%	1.2	7 - 15°C	21 - 26°C	DEEP-LOW RATE

Figure 180

Figure 181

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Figure 183

Figure 182

Figure 184

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THE CHARACTERISTICS OF SEALED
NICKEL-CADMIUM CELLS DURING VOLTAGE REVERSAL

P. F. Ritterman
TRW

The first part of the talk is going to concentrate on a mechanism which allows us to reverse cells. And specific tests were made on various new and old cells; specifically 12-ampere-hour size and 24-ampere-hour size.

(Figure 185)

When a battery is reconditioned to zero volts, some of its cells, obviously, are driven into voltage reversal by cells of the battery that have greater capacity. Now, we have tested a total of 25 nickel-cadmium cells, both new and extensively cycled, and they have been subjected to voltage reversal at discharge rates ranging from C over 200 to C/12. And these tests, the result of these tests, has been a hypothesis of a hydrogen recombination theory and a determination of a safe reconditioning resistor for each particular cell.

(Figure 186)

The general results of the rests have been: Hydrogen is the only gas generated, in all cases, meaning that the cells are positive-limiting. The pressure rise is always below the theoretical rate, based on the agglomerate equivalent of hydrogen gas.

The pressure reaches an equilibrium for the low over-discharge rates; and the cell voltage stays at between minus 0.1 and minus 0.2 volts, no matter how long we over-discharge.

(Figure 187)

This figure shows a plot of ampere hours of over-discharge versus the pressure increase during that over-discharge. And also shown is the theoretical rate of pressure rises; that is to say, if there were no hydrogen recombination, then the pressure rise for the 12 and 24 ampere hour cell would be as shown over here.

The particular rates that I plotted represent the highest rate at which we got equilibrium of below 40 psia; and you can see that for the 24-ampere-hour cell, we could over-discharge at C over 60, and maintain equilibrium

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pressure of 30 psia. For the two 12-ampere-hour cells, although the pressure is higher, the equilibrium pressure is higher for the new 12-ampere-hour cells, we did get an equilibrium at 100 milliamps.

I want to make another point with regard to Steve Gaston's question. The 24-ampere-hour cell does have silver in the negative. The 12-ampere-hour cells do not; so the rate is enhanced somewhat by the silver, but you can have a hydrogen recombination, which I will talk about later, without having silver in the negative.

(Figure 188)

Previous curves showed a dynamic equilibrium situation. Here is a static equilibrium, a static condition where no current is passing through the cell, and where the negative and positive electrode are essentially at the same potential. The positive electrode is at the potential of the negative; no current flows, and you have got a resistor across the terminal and you have an excess negative capacity. And we filled these cells with hydrogen and let them decay, these are typical curves, at 20 degrees and 30 degrees.

And the rate of reaction, as you can see from this, is doubled when you go from 20 degrees to 30 degrees. I would say the rate of pressure decay, which is the rate of reaction.

(Figure 189)

I was interested to examine state of charge; and although not shown here, at a fully charged state, the hydrogen recombination on open circuit is almost negligible. At a 50 percent state of charge, it is somewhat increased; and at zero percent state of charge, based on the positive capacity, we have about three times, or twice; twice the rate we have at 50 percent.

(Figure 190)

From these results the following mechanism was postulated: When the positive capacity exhausts, hydrogen is generated at the positive electrode; and in the meantime, the negative capacity is still present, and was simply discharging cadmium to form cadmium hydroxide.

The gas generated, obviously, is directly proportional to the over-discharge time. Some of that hydrogen gas migrates over to the negative electrode, where it is adsorbed onto the sintered nickel sites of that negative electrode. Hydrogen is removed from the nickel sites by reaction with

hydroxide at the potential of the cadmium, cadmium hydroxide electrode. So first you adsorb hydrogen, then you remove it; and at the same time, the cadmium hydroxide is reduced chemically back to cadmium, using the electrons generated in reaction 4.

And the net reaction, summing up 3, 4, and 5, is that cadmium hydroxide reacts with hydrogen to charge it and form cadmium plus water.

So in the recombination we have, hydrogen not only removes some of the gas, but it results in a charging of the negative electrode. When the rate of hydrogen generation equals the rate of hydrogen recombination, you have an equilibrium situation, and constant pressure results. The cell can be over-discharged in this case indefinitely without a change of pressure or state of charge of the negative.

(Figure 191)

Although it is not evidenced in the figures, I did do some calculations and found out that the hydrogen recombination during over-discharge, when current is passing, exceeds the open-circuit rates by an order of magnitude. And some of the reasons to explain this are, one, that during over-discharge, the polarization of the cadmium electrode is away from hydrogen evolution; so it tends to favor, it is more anodic, it tends to favor the recombination of hydrogen, whereas in open circuit, the cadmium electrode is at its maximum potential compared to when it is over-discharged.

There is a constant replenishment of reactants by the over-discharge. And finally, and I think this is probably the key to it, people have reported a disappearing electrolyte phenomenon during over-discharge. This was reported, I think, by Dr. Seiger on a vented cell, plastic case; but when he took it into reverse, the electrolyte seemed to essentially vanish. And I would say that this phenomenon, in sealed cells, results in the decrease of this diffusion path. The hydrogen has to diffuse through the electrolyte; and under the diffusion path is lowered, hence the reaction rate is increased.

(Figure 192)

Now, these are the cells that Dick Sparks was talking about. We have added a 13th cell. This particular experiment is run at about 10 degrees, between 7 and 15; and since we are over-discharging at a low rate, we are discharging at very low rates and we have a 40-ohm resistor, I assume the cell temperature is around 10 degrees when this happens.

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We start this off with the battery pack fully charged; then on cell number 13, we hook up a one-ohm resistor, which we remove after four hours. All we are doing is, we are prejudicing the one cell to go into reversal by taking out four ampere-hours more than the other cells in the battery. And obviously, this cell is pushed into reverse by the other cells.

(Figure 193)

And this is typically what happens. This is again after the 35th season, reconditioning. I plot here voltage versus ampere hours of discharge, and I start out when cell number 13 is just about exhausted. And as you can see from the curve, the cell is positive-limiting. The negative electrode gives a little blitch, but then it essentially flattens out; so we establish that it is a positive-limiting cell, and this was the case in each of the instances that we ran this experiment.

(Figure 194)

Now, essentially placing the same ampere hour discharge period, we plotted pressure; we had a transducer on the cell, versus the discharge current, which is shown over here. Not versus the discharge current; versus ampere hours of discharge. And we plotted the discharge current versus ampere hours of discharge; and we see that the discharge current drops as the other cells become less and less charged and the voltage goes down; and cell number 13 is driven into reversal at lower and lower over-discharge rates.

From this data, and from the philomic equivalent of hydrogen gassing, I can take my pressure data and the over-discharge current, and calculate my recombination current. Obviously, when the pressure change is zero, the re-combination current equals the over-discharge current, which is this point over here, and you can see that the slope over here is essentially zero.

And the interesting point is here that as the over-discharge current drops, the recombination current exceeds it, and the pressure begins to go down.

(Figure 195)

Here is why I wanted to use that other projector. This is the same data, but now I show what the theoretical hydrogen gas pressure would be if there were no recombination. It would go up to about 200 pounds.

(Figure 196)

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I have shown a linearity between the hydrogen pressure recombination rate in a static condition and now with this particular data, I was able to make some plots in a dynamic condition.

I have to point out that in that particular experiment, the cell that we put the pressure gauge on was not evacuated, so we had about 10 pounds of nitrogen throughout the entire test. I subtracted that 10 pounds of nitrogen, and then I plotted the hydrogen pressure versus the recombination rate. And going up as the pressure is rising; this is based on the data that I showed in the previous figure, as the pressure is ascending, the linearity cannot be seen too clearly, because there are other effects; there are the electrolyte layers, that form an equilibrium condition.

But as you are descending in pressure, there is a direct linearity. If I extrapolate the curve back to zero, it does indeed go through zero. You have a zero hydrogen pressure and you have a zero recombination rate, in a dynamic situation.

DISCUSSION

HALPERT: I would like to add that on your scale, of pressures, the units are kilonewtons per square meter. One atmosphere is approximately equivalent to 100 kilonewtons/m^2.

ROGERS: Hughes Aircraft. If you calculate the potential for that reaction, though, production of cadmium hydroxide and hydrogen and a catalyte by nickel, which I assume is what you are doing, does it really come out that you can plate out cadmium? It would seem to me that cadmium is too high above in the electromotive series, isn't it?

RITTERMAN: No, it is not; it is thermodynamically quite feasible. The hydrogen evolution exceeds the negative voltage of cadmium hydroxide. You can check that out.

SEIGER: By 19 millivolts.

RITTERMAN: By 19 millivolts, Dr. Seiger tells me.

ROGERS: A whole 19 millivolts?

RITTERMAN: Well, we don't have a great rate, there. But don't forget, Howard, that when you are discharging a cell, that potential is much lower than 19 millivolts. It exceeds it by perhaps 100 or 200 millivolts then.

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O'SULLIVAN: Bell Labs. Could you tell us more about the composition of the positive and negative electrodes in the cells?

RITTERMAN: These particular ones are the standard composition: Vacuum-impregnated pos and neg, presumably some small amount of anti-polar mass, loading factor I guess about 1.8, 1.6 or 1.8 for the pos; that is granted for cc void; 1.9 to 2 for the neg.

O'SULLIVAN: There is no silver in the negatives?

RITTERMAN: There is silver in the negative for the 24-ampere-hour cell. For this particular experiment that I described, yes; there is a small amount of silver in the negative. It is the same set of cells that Dick discussed.

SEIGER: Yardney. I would like to add a comment on Paul's work; that if you took a cell and hooked a platinum electrode up to the negative electrode, and then pressurized the cell to about 50 pounds, you will get a fantastically high recombination rate, and furthermore, you can put a little galvanometer in that circuit and show that the current that flows through is proportional to the pressure and decrease.

RITTERMAN: You are thinking on that. That shows that platinum is a better hydrogen catalyst than nickel.

LIM: Hughes. Do you have an explanation why the cycled cell has faster recombination, in terms of your mechanism?

RITTERMAN: Yes; I just explained that. Shall we show that slide again? (See Figure 195.)

RITTERMAN: Is this what you mean when we put current on, over-discharge current tests, for the cells. One, the potential between hydrogen recombination and the cadmium potential is greater; so it favors the hydrogen recombination more. Second, you continually replenish your reactants when you are passing an over-discharge current; and three, I think most important, is the disappearing electrolyte phenomenon.

CLARKE: Grumman. One of your last graphs up there showed an expected recombination rate proportional to the pressure of hydrogen. Wouldn't that lead you to expect a tapering pressure decrease with time on cells that are left on open circuit?

RITTERMAN: This is precisely what we do have.

CLARKE: Didn't you have a linear decay with time?

RITTERMAN: This is an elaborated plot. As you can see, I didn't mention the log, but you can see 10, 50, 100.

SEIGER: Yardney. On one of your early slides, where you showed the steady-state pressure, you had a 12-ampere-hour cell that was new that equilibrated at a higher pressure than the aged one; one that was heavily cycled. Could you comment on that? Could it possibly be the swelling of the positives and changing the inter-electrode spacing?

RITTERMAN: I don't have a reason; so if you would care to comment on your theories?

SEIGER: Oh, I was just wondering if it could possibly be due to the change of the inter-electrode spacing.

RITTERMAN: Conceivably.

SUIKES: I was going to ask the same question; why the difference between the new and the old?

FORD: Goddard. Well, do you think the amount of cadmium migration and the degree of cadmium buildup in the substrata would affect the results of this?

RITTERMAN: You are suggesting a possible shorting effect. We have not seen any shorts throughout these particular tests and during the cycling of our 13-cell battery pack.

HALPERT: Were you asking about cadmium in the negative possibly being the mechanism for that hydrogen combination?

FORD: I was asking about the cadmium migration in general; would it affect the results? In other words, the more migration, would you expect better recombination?

RITTERMAN: No; it would not. I think if the migration were very severe, and you were to over-discharge the cell at a high rate, conceivably, shorts might occur, although we did not see shorts in any of our work.

HALPERT: But how much cadmium migration did you see in those cells?

RITTERMAN: I did not open up the cells.

GASTON: RCA.   During this test, did you determine how well the anti-polar matter formed in the positive electrodes, how efficient it was, or did it do its job, or do you have some estimate on that?

RITTERMAN: How well, in the case of a cell being positive-limiting, did the cadmium perform on subsequent charge; is that what you were asking.

GASTON: No.   I just, before you went into reversal, you went into that stage where the anti-polar matter is supposed to protect it, give you some reversal protection.

RITTERMAN: Yes.   There is a very slight effect.

GASTON: Very slight.

RITTERMAN: Almost negligible.

GASTON: It is not worthwhile having it there if it doesn't do the job. When in fact they put it in there on purpose, and just if it doesn't do the job, whey put it there?

RITTERMAN: I don't know if that is the complete reason that they put cadmium in the positive; perhaps Guy could comment on that.

GASTON: Maybe somebody else would like to comment on that.

PARK: Battery Development.   Were these new cells?

RITTERMAN: I showed some of the early results, some of the early results in the talk, where I had some new 12-ampere-hour cells and some new 24-ampere-hour cells.

PARK: And what about old cells?   Have you studied them in the same way?

RITTERMAN: Yes.   Also in that same group; we had, and you can consider the cells where we did the reconditioning as old cells, we had at the time of that experiment, we had 35 seasons on those cells.

PARK: Did they short out or did they behave any differently?   I mean, the old cells.

RITTERMAN: They did not short out.   No; I showed the data.

RITTERMAN: This was the particular case after 35 seasons, when we did our reconditioning; and all of these cells were still operative, and they are now in their 40th season, and they are doing fine.   Their 41st.

MAURER: Bell Labs.   Have you looked at the varying amount of electrolyte in the cells?

RITTERMAN: No, I have not; but I plan to.

- WHEN A BATTERY IS RECONDITIONED TO ZERO VOLTS SOME OF ITS CELLS ARE DRIVEN INTO VOLTAGE REVERSAL BY CELLS OF GREATER CAPACITY

- A TOTAL OF 25 NiCd CELLS (BOTH NEW AND EXTENSIVELY CYCLED) HAVE SEPARATELY BEEN SUBJECTED TO VOLTAGE REVERSAL AT OVERDISCHARGE RATES RANGING FROM C/200 TO C/12

- THESE TESTS HAVE RESULTED IN DETERMINATION OF A "SAFE" RECONDITIONING RESISTOR FOR EACH SIZE CELL TESTED AND THE CONCEPT OF HYDROGEN RECOMBINATION

Figure 185. Effects of Reconditioning

- ONLY HYDROGEN GAS IS GENERATED

- PRESSURE RISE BELOW THEORETICAL RATE

- PRESSURE REACHES EQUILBRIUM VALUE FOR LOWER OVERDISCHARGE RATES

- CELL VOLTAGE STAYS AT -0.1 TO -0.2 VOLTS

Figure 186. Characteristics of Ni-Cd Cells During Voltage Reversal at Low Overdischarge Rates
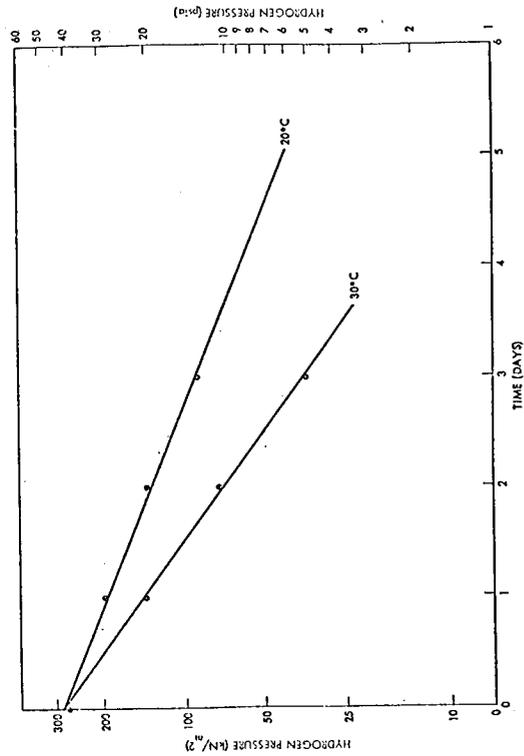
Figure 188. Hydrogen Pressure Decay-Effect of Temperature (Cell Terminals Connected through Resistor)

Figure 187. Hydrogen Pressure Increase During Overdischarge

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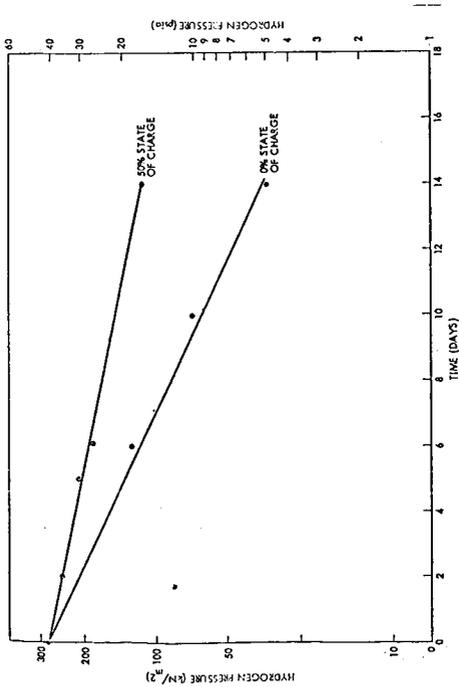
Figure 189. Hydrogen Pressure Decay— Effect of State of Charge (Open Circuit Stand)

- WHEN THE POSITIVE ELECTRODE HAS EXHAUSTED ITS CAPACITY, HYDROGEN GAS IS GENERATED WITHIN THE CELL AT THE POSITIVE ELECTRODE

  (1) $2 H_2O + 2OH^- + H_2$

  AND WHILE NEGATIVE ELECTRODE IS DISCHARGING

  (2) $Cd + 2OH^- \rightarrow Cd(OH)_2$

- THE GAS GENERATED IS DIRECTLY PROPORTIONAL TO THE OVERDISCHARGE CURRENT

- SOME OF THE HYDROGEN GAS MIGRATES OVER TO THE NEGATIVE ELECTRODE WHERE IT IS ADSORBED ON THE SINTERED NICKEL SITES

  (3) $H_2 + Ni \rightarrow 2H(Ni)$

- HYDROGEN IS REMOVED FROM THE NICKEL SITES BY REACTION WITH HYDROXIDE AT THE POTENTIAL OF THE $Cd/Cd(OH)_2$ ELECTRODE

  (4) $2 H(Ni) + 2 OH^- \rightarrow 2 H_2O + 2 e^-$

  WHILE $Cd(OH)_2$ IS REDUCED TO Cd

  (5) $Cd(OH)_2 + 2e^- \rightarrow Cd + 2 OH^-$

  FOR A NET REACTION OF (3) + (4) + (5)

  (6) $Cd(OH)_2 + H_2 \rightarrow Cd + 2 H_2O$

- THE RECOMBINATION OF HYDROGEN NOT ONLY REMOVES THE GAS, BUT ALSO RESULTS IN "CHARGING" OF THE NEGATIVE ELECTRODE

- WHEN THE RATE OF HYDROGEN GENERATION EQUALS ITS RATE OF RECOMBINATION, EQUILIBRIUM IS REACHED AND THE CELL CAN BE OVERDISCHARGED INDEFINITELY WITHOUT CHANGE OF PRESSURE OR STATE OF CHARGE

Figure 190. Hydrogen Recombination Mechanism

- HYDROGEN RECOMBINATION RATES DURING OVERDISCHARGE EXCEED OPEN CIRCUIT RATES BY AN ORDER OF MAGNITUDE DUE TO

  - POLARIZATION OF CADMIUM ELECTRODE TO A MORE ANODIC POTENTIAL FAVORS RECOMBINATION OF HYDROGEN

  - REPLENISHMENT OF REACTANTS BY OVERDISCHARGE

  - "DISAPPEARING" ELECTROLYTE PHENOMENA DURING OVERDISCHARGE DECREASES LENGTH OF DIFFUSION PATH

Figure 191. Hydrogen Recombination Rates; Overdischarge Vs Open Circuit

Figure 192. Reconditioning Experiment 13 Cell-24-Ah Battery Pack at 10°C

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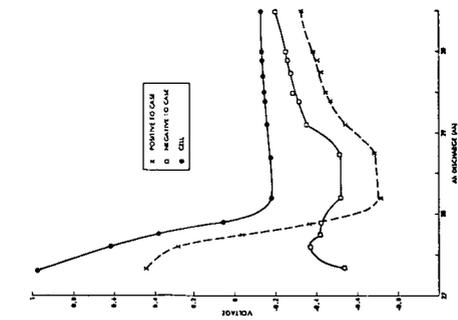
Figure 193. Cell, Positive and Negative Electrode Voltage During Reversal When Reconditioning a 13 Cell-24-Ah Battery Pack Through a 40 Ω Resistor

Figure 194. Theoretical Hydrogen Gas Pressure If There Were No Recombination

Figure 195. Pressure, Discharge Current and Recombination Current During Voltage Reversal When Reconditioning a 13 Cell-24-Ah Battery Pack Through a 40 Ω Resistor
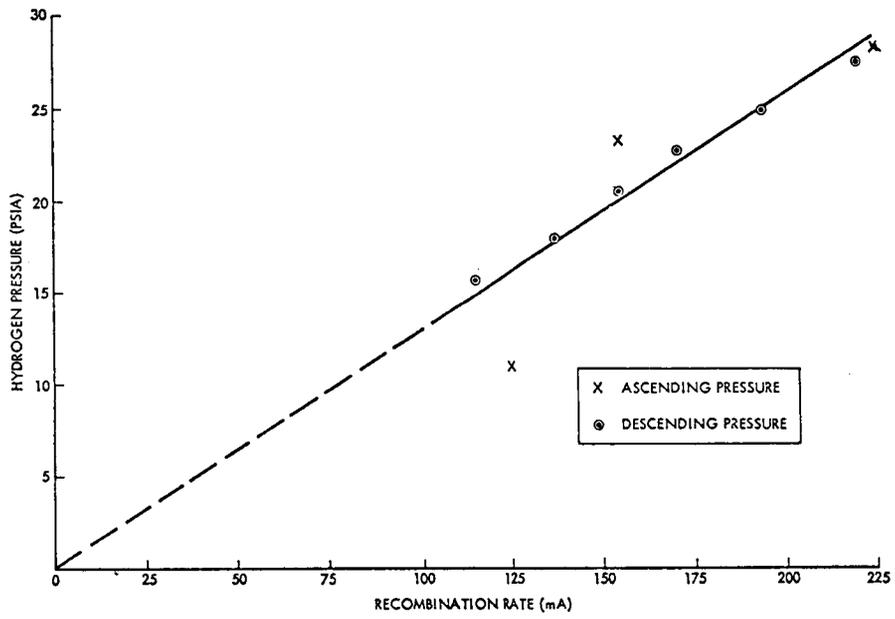
Figure 196.   Effect of Hydrogen Pressure on Recombination Rate
              During Overdischarge
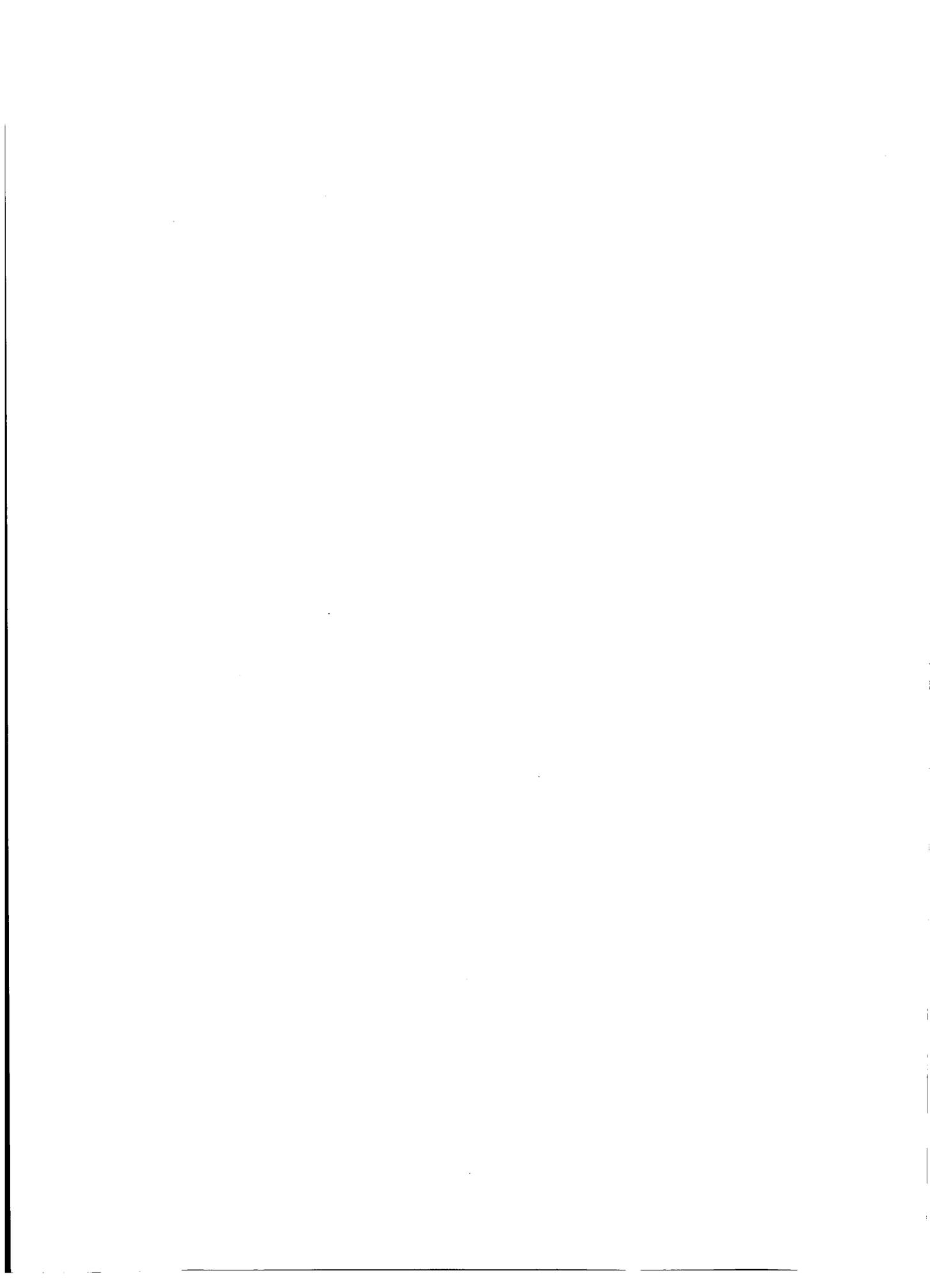
EFFECTS OF CELL REVERSAL
DURING FLIGHT TESTING

J. Harkness
Naval Weapon Support Center

My talk is essentially on cell reversal during flight. Approximately about a year ago, we had various practice in on tests for, say, three to eight years; and our failure criteria was that they reach .5 volts during discharge, on a regular flight cycle. And as our standard tactic is, any time that this happens, we always call the NASA project technical monitor and let him know that this is happening. Well about this time, I said a year ago, the technical monitor on this pack was Floyd Ford, and he suggested that we lower our limit, consider that the cell has failed, but lower the limit and see what happens if we just let it reverse during the discharge.

And then before I could say anything, he would ask, "Did we have a pressure gauge on it to where we could watch if the pressure would start to rise?" Well, on some I would say, "Yes, we do," and he said, "Oka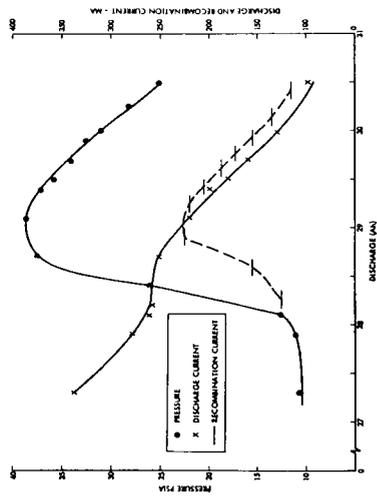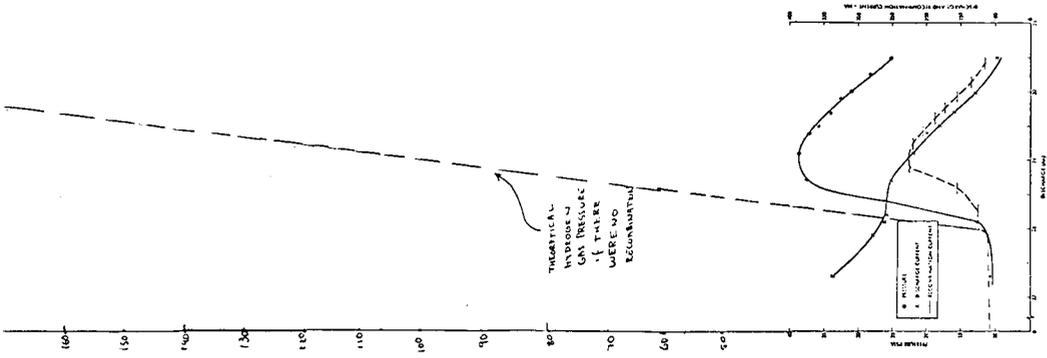y, fine." And on a couple I said, "No, we don't," and he said, "Well let's do it anyway," you know, so we would go ahead.

And I can say that we do have some interesting phenomena happening.

(Figure 197)

The first pack I would like to look at is Pack 58-D. As you can see, they are a group of six ampere-hours; they began life-cycling in January, 1969. They are a 25 percent DOD; the discharge rate is C over two, and they are at 20 degrees C.

Now, we had five cells in the pack. One cell was pulled out early, just to do an analysis. It was sent to Goddard for an analysis; they had not failed. It was pulled out early in life.

Another cell that was not shown here failed, I believe, around 35,000 cycles, and that was at .5 volts, and we just took it out of the circuit. And then the other cells that failed after that were when Floyd said, "Let's let them reverse."

As you can see, cells 3 and 4, you have your failure there at .5 volts. We let them go on and they finally shorted out at the cycle shown. Cell 1,

failure occurred at 40,000 cycles. You get about 5,800 cycles per year; so what have we got, about six? Six and a half; or something. Anyway, they have been cycling, that cell has been reversing for a year. As of the 31st of October it had 46,000 cycles on it.

Now, as you go along, you can see that these are the end-of-discharge voltages at various cycle times. Now, the recharge, you can tell that the pack charges at a constant current to a voltage limit, so we are only talking about one cell. The voltage limit is 1.44 volts. The cell comes up, it does reach .44 volts, the current tapers off, and then we have determined the percent recharge. As you can see just lately we have gotten down to 82 and 83 percent recharge.

Now, these packs were set up on a capacity check scheduled every year, and the last capacity check we ran was at 40,916 cycles. Just before that, here, you see we were running 102 percent; the cycle before the capacity check.

At the capacity check, the ampere hours after one volt were .87 to .50; it was .99 and to zero volts with 1.12.

Now as the pack began reversing, there has been kind of a gradual trend to where it reverses sooner and sooner during the discharge period, but we let it complete 30 minutes of having discharge forced through it. These discharges are not with a resistor. They are forced discharges with a power supply.

(Figure 198)

The next pack was Pack 75-E, on a 60 percent DOD. It is a 24-hour orbit, where it gets a 3.6 amp discharge for one hour every day. They are G.E. six-ampere-hours; they have a nickel-braze seal, and as far as I know, they do not have silver in the plates. They began life cycling in 1971.

On the data, we determined that failure was on cycle 1210. Now, they get 365 cycles a year. The pack started to reverse after about 3.3 years of cycling, and finally shorted out after 5.9 years of cycling; therefore, it was reversing every cycle for approximately 2.6 years.

To back up, on that first pack we showed, that cell did not have a pressure assembly. We have gone out. It is still cycling. We have seen no bulging of the cell. We have checked it for leaks, and we have detected no leaks. This cell has a pressure gauge assembly.

As you can see, we are essentially operating in a vacuum; 13 to 15 psia at the end of discharge. We checked the assembly because we thought possibly maybe we had a leak and this caused an early failure, but we have not been able to determine any leak in the cell. The cell, when it was shorted out, was sent back to Goddard, and Ford, at the end of the presentation, may make a comment on the analysis. I believe his one comment was that it was completely dried out.

(Figure 199)

Again, the same pack, which is a graph of the data that was just shown, where failure occurred, your end of discharge, and then finally where it shorted out.

(Figure 200)

The next packs we had are AE type cells. They are six ampere hour G.E.; they operated for approximately three years before we discontinued the packs. I believe the packs were discontinued because of lack of project funds. Was this right?

HALPERT: Yes, that was the reason.

HARKNESS: They had completed three years of cycling, near-earth orbit, approximately 15 to 20 percent DOD. The three temperatures were zero, 10 and 20 degrees C. Following discontinuance, we ran a number of special tests, the last of which was we would charge the cells at C over 10 for 24 hours at room ambient temperature, which was about 23 degrees C; we would take them down -- well, we would give them a capacity check, C over two capacity check following this, and then we would pick one cell out of each pack, discharge it to minus one volt.

We would relieve the pressure during the discharge if it ever reached 85 psig. When the cells reached minus one volt, we would then want to take a gas sample; so we did this.

The pack of 2-H, which was the zero degree C pack, looked like a new cell. In other words, it came down and went into reversal. The ampere hours out of that one cell was 7.02, and the total ampere hours out to the end of discharge was 9.5 ampere hours; so when you subtract the two, you get about 2.3 ampere hours from 0.75 to minus 1.4 volts.

Now, during this time, we had to relieve the pressure three times at 85 psig. We took the gas sample. We got 94 percent hydrogen, 1 percent oxygen, and 2 percent nitrogen.

The next pack was at 10 degrees C. The maximum reversal voltage we got was minus 0.2 volts. The ampere hours out of this cell, to 0.75 volts, was 7.35. The ampere hours out total, to the end of discharge, were 13.9; so we essentially discharged it for two hours at the C/2 rate, and the maximum voltage was minus 0.2, and then it started to go back towards zero, so at that time we shut off the test; we stopped the discharge.

The pressure was vented twice during this time; but the cell again never would go to minus one volt. The gas sample, when we finally stopped, was 96 percent hydrogen, one percent oxygen, and about 3 percent nitrogen.

Now, pack 2-G was at 20 degrees C. It also would not go to minus one volt. We also, during this time, did not have to relieve the pressure at any time. The maximum pressure rose from 13 to 25 psig; in other words, it stabilized and stayed at 25 for a good hour. The maximum reversal voltage was minus 0.26 volts, and when we stopped the test, it was minus 0.14 volts. The ampere hours out to 0.75 were 7.3; and the ampere hours out to the end of discharge were 17.2, so that is about a total of 10 ampere hours at the C over two rate that we discharged the cell; then we stopped it.

It looks like, from these results, which we all know, that the degradation at zero degrees is much less than at any other. So it brings out, we are talking about reconditioning at the low rates and that, it brings up an interesting question: How long in life, at a certain temperature, could we just run it down at the C/2 rate and make it a quick discharge? How long did we have to operate the cell during life cycling to where we would not have a pressure problem?

We also, on a synchronous orbit type test, we had a couple of cells that failed. These were G.E. six ampere hours, the earlier cells that we ever put on synchronous orbit. This was at a temperature of 25 degrees C, 40 percent DOD; we had a cell reverse or fail at the beginning of the 16th shadow period, and it reversed for two days before it finally just shorted out. And the time on test for it was about 8.2 years. Another cell at zero degrees C with 80 percent DOD, it failed at the beginning of shadow number 11, and four days afterward it shorted out, after letting it reverse. The total time on test for it was about five years.

DISCUSSION

HALPERT: Are there any questions or comments? There is something wrong. I will ask one question. On your first figure, it looked like you had two volts on there, for the end of charge.

HARKNESS: Yes, sir, that is true.

HALPERT: It was two volts?

HARKNESS: Yes.

HALPERT: Would you put that figure on again for me? (See Figure 198)

HARKNESS: Just before it got down to shorting out, these are true cell voltages for that. That was measured -- well, we got it by the computer, and we kind of thought, you know, "That is a little weird," and we did measure it by hand during the discharge; went out and checked it in the chamber, and it did get to those values. Ford, did you want to make a comment on the analysis?

FORD: Well, we just got the cell open last week. It was interesting, because when we pulled it open the cell was extremely dry; and what surprised me about this cell is the separated material visually looked to be in pretty good condition. What really had deteriorated considerably was the positive plates. They were like, around the edges, you could see the substrate all the way around each plate; but bear in mind, this is in a 24-hour orbit, where we are discharging at 60 percent, and I think we talked about this about three years ago, some of the effects we had seen on high-rate discharges on the positive plates.

But we are continuing the analysis, and we hopefully next year will be able to present the results of that.

MAURER: Do you have any indication of why the short occurred? Is it active material in the separator?

HARKNESS: Which short?

MAURER: The short that occurs after reversal.

HARKNESS: I have not seen that cell. The only ones that are still cycling are the first three. Those two that have shorted are still in the pack, okay; and we just removed them electrically. We kind of figures, where the other one happened; it is going to short real quick and we would take the whole pack out. That was a year ago.

FORD: Goddard. In the cell that we have opened here, we didn't see any evidence of the short. There was nothing we can look that said,

physically, here is a short. Now, that is in contrast to where we have open cells that have shorted early in their life, and when you find burned separators, you know, evidence of high heat. But bear in mind, this cell really had no energy in it to dissipate when it shorted anyway. But I suspect it was, from what I looked at, I would not attribute it to cadmium migration. I would attribute it more or less to the positive plate's state of deterioration.

PACK 58D - Gulton, 6AH, Auxiliary Electrode
25% DOD, 20°C, 1.5-hr Orbit
Began Life-Cycling January 1969

CYCLE

Cell	Failure (.5 volts)	Shorted
1	40,393	NA
3	38,241	40,329
4	37,726	38,150

NA - Not applicable, still cycling, has completed 46,506 life-
cycle as of 31 Oct 1977.

EOD Voltage and Percent Recharge
(CELL 1)

Cycle	EOD (volts)	Recharge (%)
39,893	.99	108.2
40,393	.50	106.0
40,915	-.15	102.5
42,878	-.06	102.7
45,612	-.06	82.0
46,403	-.06	83.0

NOTE: (1) No swelling of cell case.

(2) Results of capacity test, cycle 40,916: AH_{out}
to 1.0V(.87), to 0.5V(.99), to 0.0V(1.12)

Figure 197

PACK 75E - GE, 6AH, Nickle-Braze Seal
(CELL 1) 60% DOD, 10°C, 24-hr Orbit
Began Life-Cycling March 1971

CELL VOLTS

Life-Cycles	EOD	EOC
719	1.15	1.460
902	1.10	1.467
930		1.462
946		1.453
989	1.00	1.443
1180	.94	1.427
1210	.50	1.396 - Failure
1215	-.11	1.396
1229	-.19	1.394
1247	-.20	1.380
1277	-.10	1.378
1396	-.07	1.360
1492	-.15	1.377
1599	-.10	1.381
1655	-.13	1.392
1683	-.13	1.410
1824	-.12	1.429
2005	-.25	1.424
2034	-1.71	1.400
2098	-1.80	1.388
2170	-2.43	.630
2178	SHORTED 14 Sep 1977	

NOTE: Cell pressure ranged from 13 to 15 PSIA at EOD while cell was
reversing.

Figure 198

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PACK 75E - GE, 6AH, Nickle-Braze Seal
(CELL 1) 60% DOD, 10°C, 24-hr Orbi
Began life-Cycling March 971
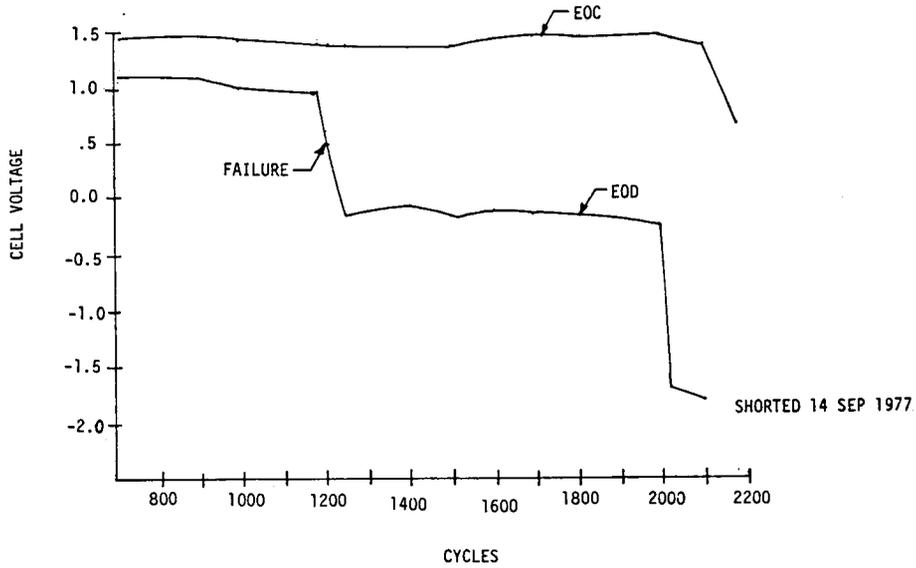
NOTE: Cell pressure ranged from 13 to 15 PSIA at EOD while cell was reversing.

Figure 199

Pack 2F, GE, 6AH, Project: AE-C&D
15-20% DOD, 10°C, 1.5-hr Orbit
Began Life-Cycling 11 Dec 1973
Discontinued 22 Sep 1977, 17734 Life-Cycles
AHout to .75 Volts was 7.35
AHtotal to EOD (-.152) was 13.9
Maximum Reversal Voltage was -.202
Pressure Vented Twice at 85 PSIG
Gas Sample: 96.5 H_2, 1.0 O_2, 2.5 N_z

Pack 2G, GE, 6AH, Project: AE-C&D
15-20% DOD, 20°C, 1.5-hr Orbit
Began Life-Cycling 11 Dec 1973
Discontinued 26 Sep 1977, 17637 Life-Cycles
AHout to .75 Volts was 7.34
AHtotal to EOD (-.143) was 17.2
Maximum Reversal Voltage was -.261
Pressure Rose from 13 PSIG (.75 Volts) to 25 PSIG (EOD)
Gas Sample: 58.0 H_2, 9.0 O_2, 4.5 N_z

Pack 2H, GE, 6AH, Project: AE-C&D
15-20% DOD, 0°C, 1.5-hr Orbit
Began Life-Cycling 11 Dec 1973
Discontinued 26 Sep 1977, 17168 Life-Cycles
AHout to .75 Volts was 7.02
AHtotal to EOD (-1.393 Volts) was 9.5
Pressure Vented Three Times at 85 PSIG
Gas Sample: 94.5 H_2, 1.2 O_2, 2.0 N_z

Plots are of Cell 1 in Each Pack

Discharge Rate of C/2 (3.0A) was performed

following a C/10 charge for 24 hours at 25°C.

Figure 200

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RECONDITIONING ON SATCOM

J. Napoli
RCA American Communications

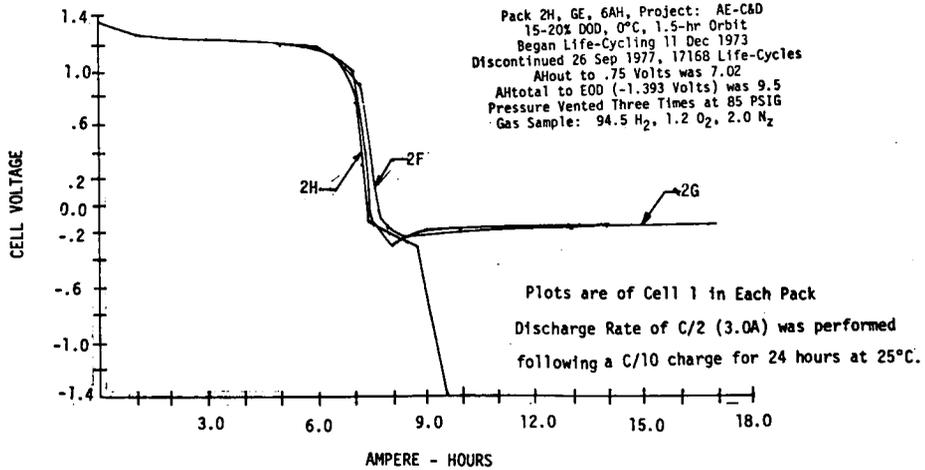Just a little history on the RCA SATCOM satellites. We have presently two operational satellites. They are at geostationary altitudes. We have one which is deisgnated the F-1, and it is operating for 23 months and has seen four eclipse periods and four deep-reconditioning cycles. We have the F-2, which is operating for 18 months and has seen three and a half eclipse periods, and it has seen three reconditioning cycles. We say three and a half eclipse seasons; we launched it into the middle of the eclipse, you know, hence the half eclipse season.

The F-1 power system does see a true synchronous orbit cycle regime, whereas the F-2 sees a 24-hour orbit with a daily DOD of 28 percent in addition to the synchronous orbit. We presented some data last year where we showed some of the effects of reconditioning on F-2. We showed some of the reconditioning that we performed, and we continue plotting this and we are going to show you some of the curves that we have here today.

(Figure 201)

Basically, again, the characteristics are a repeat of what we have in the last year's record: The 12-ampere-hour nameplate cells with an actual capacity of 14 ampere hours. We have Teflonated negatives; they are prismatic cell cases. We have a single positive isolated terminal, and we have 22 cells per battery. The spacecraft actually have three batteries. We don't have any backup batteries; they are all being used operationally.

(Figure 202)

These are the battery operating characteristics. We have a maximum depth of discharge during the peak eclipse periods of 58 percent. That is of rated. It would be, I guess, approximately 52 percent of actual. As we mentioned before, the F-2 spacecraft has a daily depth of discharge of 28 percent at one time; that is once a day. And we have various charge rates that we have available on the spacecraft. There is the C over 10, which has a DT taper when we reach the voltage clamp, or the function of temperature. We also have the C/20 and we have a C/60 for our solstice maintenance charge.

The operating temperatures average between 2.5 to 15 degrees C. We do have peaks at times, right after the vernal, the eclipse periods, just before going into solstice and I guess right into solstice, we do have peaks where we go up to about 25 degrees C. But on the average, the yearly average is between 2-1/2 to 15 degrees C.

We do recondition the batteries and the cells at the cell level; unlike what you have heard here earlier today, we do have individual shorting resistors, one-ohm resistors, that we do place across each cell approximately about a week prior to going into the eclipse period. We do bring these cells down to 0.09 volts per cell. We don't have individual cell monitoring capabilities. We do monitor the terminal voltage on the battery.

(Figure 203)

I believe I may have shown this last year. This was the first reconditioning that we performed on the F-1 spacecraft as part of the operational check-out of the spacecraft, which happened to coincide with about a month or so before entering the eclipse season.

You can see that we take the cell down to two volts per battery pack, or battery terminal voltage; and it takes approximately 23 hours to get there. Using this 23 hours, we use it as a baseline for comparing this to subsequent reconditioning periods to see how much time it takes us to get down to that same level, and I guess we use it as a means of checking capacity as the spacecraft goes on.

Right after we get down to two volts, we remove the shorting resistors from the cell. Immediately the cell pops up, the terminal voltage of the battery pops up to about 16 volts, at which time we then place the C over 10 charge rate on it, which then brings it right up to about 28, as you see right there, to about 28 volts, a little bit over 28 volts, I guess. And we continue charging until we feel that the battery is fully charged.

The criteria that we use for determining when the batteries are fully charged are time and temperature; or actually, it is the other way around, temperature and time. We closely monitor the battery temperatures on strip chart recorders, and when we start to go into overcharge, we see a corresponding increase in temperature on the battery, and we feel that is the time to take them off or put them into the flow charge.

So this is the reconditioning deep discharge for the F-1 spacecraft. It happens to be battery number 2, in this case.

(Figure 204)

A comparison, four eclipse seasons later; this was taken during the autumnal equinox reconditioning period. You will notice that we have a little bit more than 24 hours to the two-volt termination voltage. And the problem I have here is that we do have some time data gaps from one control center because of either ranging or because of other things that are going on at the station, so I have to get the data from the other station, and sometimes trying to piece all these things together to come out with one integral time, I may have exceeded it by about an hour or two.

It looks like we do still get out to 24 hours to get down to that level, at least 24 hours, which compares with about 23 hours from the first reconditioning deep discharge. This is also the F-1 spacecraft again, here. I could superimpose these, but the only problem here is that there are two different kinds of plots.

(Figure 205)

This particular reconditioning, and I think this is also in the record from last year, is on the F-2 spacecraft. You can see as we deep discharge, what happens is that the battery temperature starts to rise. And we have a temperature criteria where we discontinue the deep discharging if we reach 25 degrees C.

So if you will notice, we have a rise in voltage here all of a sudden as the batteries are deep discharging. What we have done here is we have taken them off deep discharge because of the temperature; as you can see, the temperature gets up to 25 degrees C. We take them off. And it turns out that during the autumnal reconditioning periods, we have more discontinuities in deep discharge because of the temperatures reaching 25 degrees C more frequently, because of the way the sun angle is in relation to the battery panel. And that is one of the reasons why it was hard to measure the actual ampere hours taken out from that previous chart, because we do have places where we have to take the batteries off for several hours and then put them back on, and about a couple of hours later we have to take them off again, and put them on; and that happened about three to four times. So it is hard to piece all the data together. We are still going through this.

(Figure 206)

Pretty much of this is a repeat of last year, except with the deep discharges this year. This is the end-of-discharge battery voltage for the 44-day

eclipse season during the 1976 vernal equinox. Actually, this is our first equinox, our first eclipse period, for the F-1 spacecraft.

And the average low peak end-of-discharge voltage, which is the average of these voltages down here, was 26.55 volts. This was eclipse season number one.

(Figure 207)

On the same spacecraft, four eclipse seasons later, the average of these voltages down here was 26.3 volts. This represents approximately about a 1.4 or 1.5 percent degradation.

(Figure 208)

On the F-2 spacecraft, which has, as I mentioned before, somewhat different operating characteristics, the average low peak end-of-discharge voltage here was approximately 26.1 volts. We see this to be somewhat less than the F-1, but it is also within the calibration accuracies of the telemetry systems and differences that could exist between the two spacecraft.

In addition to that, the average load here happens to be 13.5 amps, and in the case of F-1, it happens to be 13.1; so there is a somewhat higher load on F-2, which is contributing to the lower end-of-discharge voltage. And again, the other differences; I don't feel that all that all the differences are recognized there, but I do think that it is within the resolution of the telemetry system, it is hard to really find out why we have such a small difference, anyway.

(Figure 209)

This again, if you look in last year's workshop record, this is a plot of the end-of-discharge voltage that we get during the 24-hour discharge on the 24-hour orbit that we see with the F-2 spacecraft. This is where we go down to between 20 and 30 percent DOD daily. And what I have plotted here is, this is a day of the year, Julian day of the year; I have plotted what the end-of-discharge voltages are. Now, this is in the record, and in fact, in the record, I have compressed the data. I have more days out here, but to try to show it at this conference, at this workshop, it would have been too unwieldy to present this. So what I have done with it, I have compressed this plot to bring us up to the time period that we are operating presently, and this is what the data looks like.

(Figure 210)

This is the beginning of life, and this is months of life into the space-
craft versus the end-of-discharge voltage. Now, when we started out on the F-2
spacecraft, we did not recondition the batteries prior to launching the spacecraft.
So at this point here, as you notice, we reached an end-of-discharge voltage
prior to the first reconditioning which is approximately, I guess, 27.2.

When we reconditioned, the recovery voltage took us up to about here;
and the effects of reconditioning, and I define the effects of reconditioning as
how long it takes us to get down to the pre-reconditioning level, or how long
does it take us to get down to 27.2 volts again, and that comes out to about
this point here, which is three months after we reconditioned.

Prior to going into the second eclipse season, we reconditioned again
here. Now you will notice that the end-of-discharge voltage is slightly less.
From a plot standpoint, it seems a little severe, but this is a very expanded
scale. We actually have one volt between here and here, so we are really
looking at very small changes.

The end-of-discharge voltage, prior to reconditioning in this case
was about 27, just over 27 volts. When we reconditioned, we did not recover
to the same level that we recovered last time. However, the effects of recon-
ditioning again, until we got down to the 27.2 volts, was again three months.

The last pre-reconditioning voltage brought us down to here. When
we recovered, we recovered the voltage up to where we were last time. We
are still looking at this. We are not too concerned about it. Some of the things
that we have, at least I have, a problem with is trying to keep the variables
from changing on the spacecraft; and the variables are namely the loads that
affect the kinds of parameters that we are trying to measure in an operational
spacecraft that we have. I have often been accused of just launching a satellite
to test the batteries; and I have a problem trying to get all the data I want, con-
trolling all the variables on a spacecraft.

They have been switching telemetry transmitters. We have two beacons
on the spacecraft, and sometimes they change philosophies and say, "Let's
turn two of them on during the eclipse season," and so there are other things
going on on the spacecraft, too. So again, I am not too concerned about this.
It isn't that severe. It is interesting to note that we do come back to the same
recovery level that we did during the second season reconditioning.

DISCUSSION

BETZ: Naval Research. On your F-2 satellite, that does not see the eclipse season in the typical synchronous in addition to this 28 percent, or does it?

NAPOLI: It sees the eclipse seasons in addition to the daily 28 percent depth of discharge.

BETZ: With that one, do you recondition the batteries sequentially?

NAPOLI: We recondition the batteries sequentially a week prior to, maybe about a week and a half; it takes a good week, a good six days, to recondition three batteries on a spacecraft. It takes approximately 24 hours to bring them down to two volts per battery pack, but that is not including the time we have to tinker with them because of the temperature on it, so sometimes it takes as much as 36 hours to get them down to two volts per battery.

WADHAM: Telesat. In your reconditioning curves there, you were saying that it took you on, I think it was the last discharge, it took you something like 24 hours to get down to 0.2 volts because there was that much difference in the capacity. I didn't think that it covered very much area. What was your actual difference in capacity, for that, say to one volt; what were you getting?

NAPOLI: We can look at that. Again, one of the problems here is that a lot of this data has to be replotted. They are on two different scales. If I can just put this one on again. (See Figure 205)

NAPOLI: I guess to get to the knee of the curve here, if you want to define this as a knee, it took us approximately, 12, about 16 hours; and to get to the knee here, we have three here; is that about the same? Is that approximately 15 hours? We only have to, about 11, and about 14 hours.

Again, I tend to believe more than the other data. The problem is again that I was trying to piece together the times where we didn't have telemetry and I had to get it from a second station. It turns out that there are calibration errors that are inherent in the second station; and trying to piece it all together, I have some reason not to fully believe the second plot that I showed here, fully believe the fact that these points are really accurate. I will look into this further to try to get a more accurate plot.

But the times are approximately between 23 and 25 hours to get down to the two volts per battery. Again, I had this operational problem trying to get the people to do what I want them to.

FORD: Goddard. If I interpret your data right, you are saying that you are not seeing a drop-off in capacity, based on the reconditioning data.

NAPOLI: That is correct.

FORD: And the only thing you are doing is reconditioning to enhance the discharge voltage as you showed by your slide.

NAPOLI: Well, we are trying to enhance the capacity as well as discharge voltage. It turns out that right now we haven't seen any degradation in capacity. We are getting some recovery voltage. The only means we really have for measuring the recovery voltage is on this daily discharge of the F-2 spacecraft. Otherwise, I don't know how we can do this.

Well, we could on F-1, since we have the three-spacecraft. But if you look, I have done this; I have done this at one time to get a comparison between F-1 and F-2, and that is on the plot that I presented last year. I also have plotted it here to get a comparison between F-1 and F-2, and I showed the F-1 point, here.

In order to get this point on F-1, since it is a three-axis spacecraft, all I have to do is turn the arrays around and go through a 28 percent DOD on the F-1 spacecraft.

These data points that I have here, the squares, the triangle, and the asterisk, is the F-1 plot, are F-1 parameters.

(Figure 210)

NAPOLI: And you can see that they compare pretty close to what the F-2 are. They are just running slightly higher; and the F-1, again, does not see any 24-hour orbit. So the only means I have to measure what the recovery voltage is is during this kind of activity, and as I showed it on the monthly plot, it does last about three months before we get down to where we were originally, prior to reconditioning.

FORD: At this point, can you interpret the data to say you have seen a loss of capacity, or you only just see a degradation in voltage?

NAPOLI: No. Let me restate that. We have not seen a loss of capacity as the data is being interpreted right now. In fact, if I clip it the way the data is just literally presented here, it looks like I have an increase in capacity because of the time, but I don't believe those extra two hours out there. I think that is just a data collection problem.

MARTIN: Canadian Astronautics. I was wondering if you had any analysis of how the reliability of your switching components affects the over-all switching liability. Could you comment?

NAPOLI: That is a good question. Of course, we recognize that we have the potential of losing a whole battery if we can't take the batteries off of deep discharge, or if one of the contacts that goes across the cells doesn't make contact, and we could therefore force that cell into reversal.

But I think there is a trade-off on risks. The risks are that you want to try to use reconditioning to attain an eight-year mission, which is our design mission, but the reliability numbers have been generated, and it turns out that the relay that we have been using has had a history of problems. I think that some people are being more conservative. I think the Canadians are being more conservative here with Telesat; and they are actually going through the same type of reconditioning system on their ANEC-B (?) that they are putting into -- I guess power relays, Peter, is that what they are using?

WADHAM: I think we are having series relays.

NAPOLI: Series on them?

WADHAM: I think they are putting a series relay of contacts so if one shorts out, it doesn't short out the cell. I don't know whether you have that system.

NAPOLI: No. Actually we have, just one relay that handles four cells in the battery, each.

WADHAM: I think we have the same basically, but we have a series of contacts so that the worst that can happen is a contact will stay open, and I think you will find that they will go into reversal. We only have two cells in effect in a series in that condition, so if one shorts out, the other cell will go into reversal.

NAPOLI: But not the whole pack will go into reversal.

300

WADHAM: Not in that case, no; not if just one relay contact goes out.

Steve Gaston is with RCA Astro Electronics. They are the contractors for the SATCOM spacecraft, and I am with RCA American Communications, and we are the end users and operators of the spacecraft.

GASTON: Two separate divisions. We are also building ANEC NB. First I would like to comment on the SATCOM. It is the first time that individual cell sensors have been used up in orbit, and we did double the number of relays for adding three-four reliability.

Figure 203

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 201

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
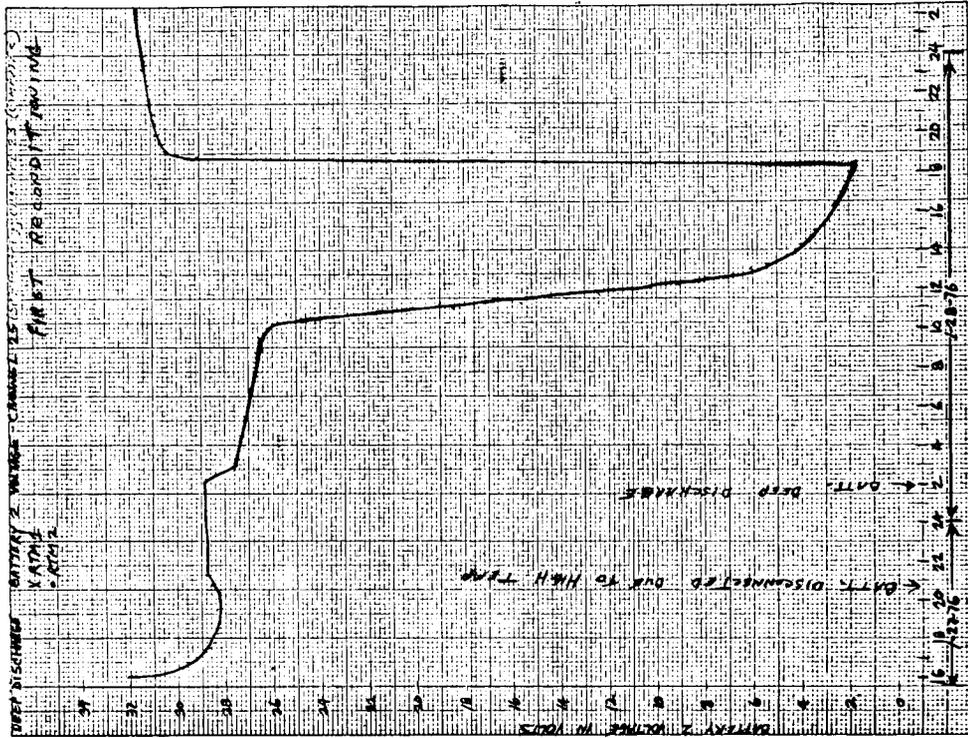
○ RECONDITIONING AT CELL LEVEL TWICE YEARLY
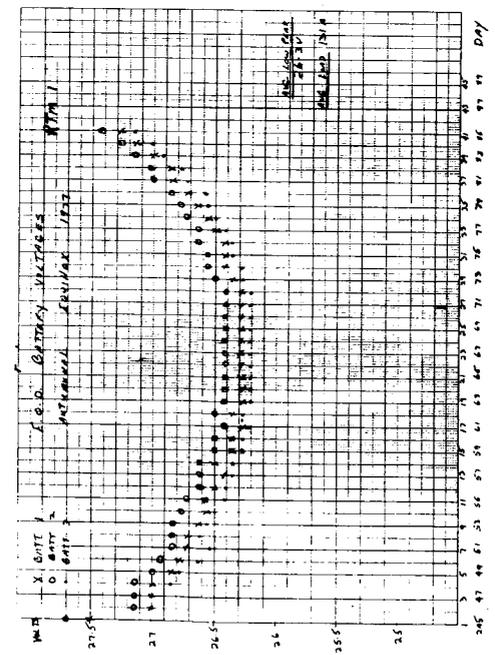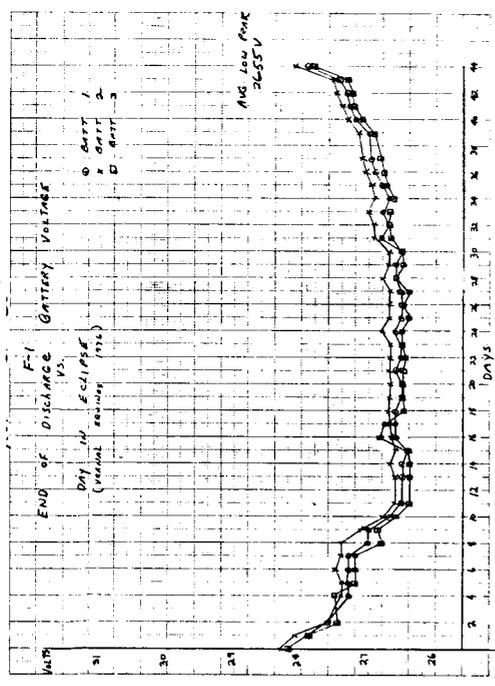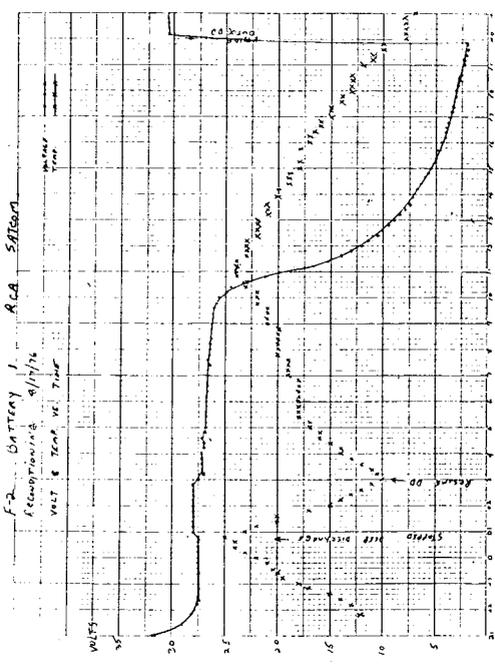
Figure 202

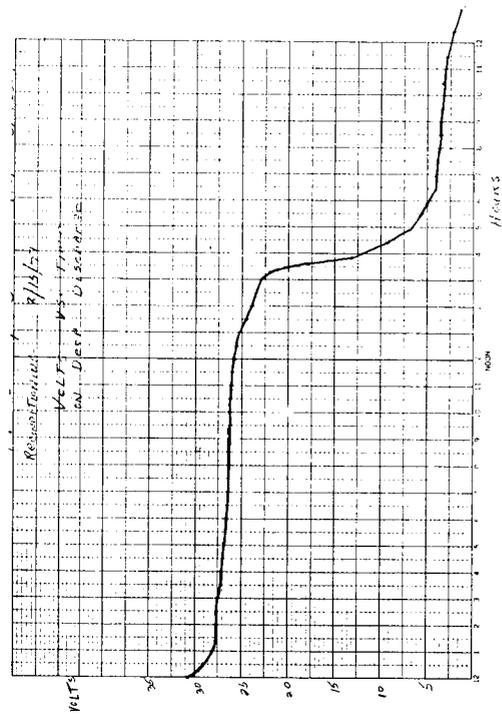302

Figure 205
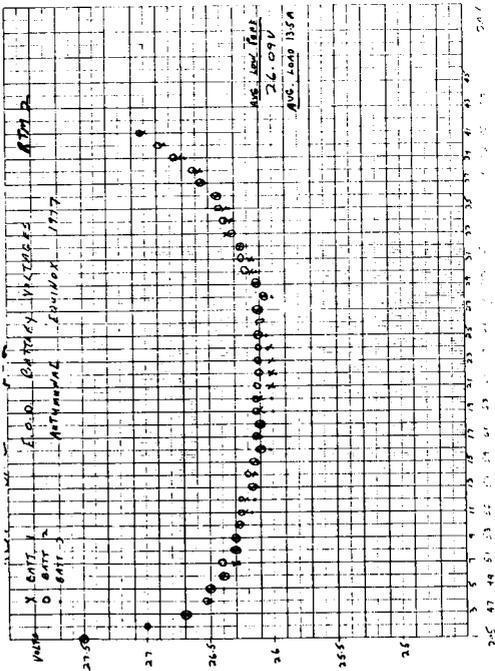
Figure 207

Figure 204

Figure 206

303
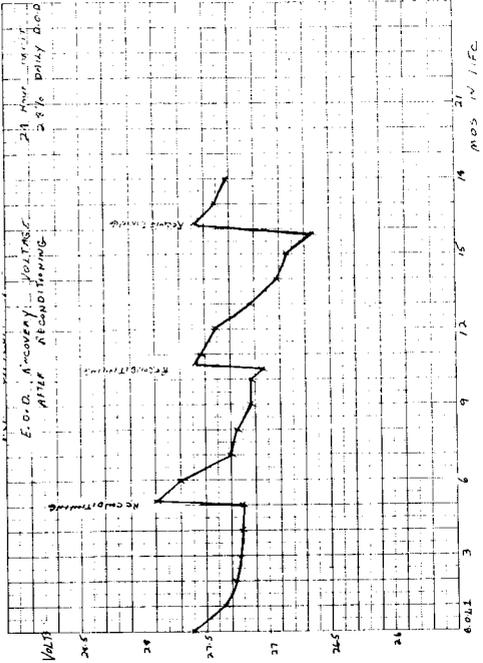
Figure 209

Figure 210

Figure 208

304
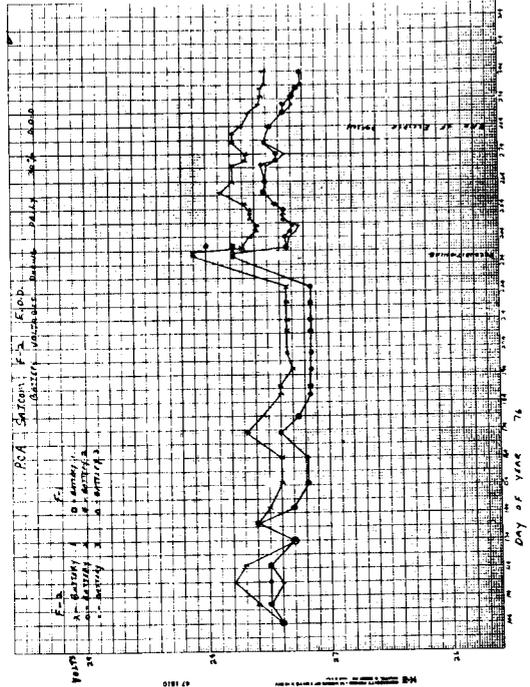
RECONDITIONING EXPERIENCE AT
MARSHALL SPACE FLIGHT CENTER

L. Paschal
Marshall Space Flight Center

I plan to cover the reconditioning effort that the Marshall Space Flight Center has been involved in since approximately 1973. This effort started as a result of the problems that were encountered on the Skylab. I will show the background information, the development of a reconditioning circuit, and the test results that we have had to date.

(Figure 211)

This first chart shows a typical capacity degradation on a battery. This is a 24-cell battery that was tested in the thermal chamber at 20 degrees C, 200 watts, or about seven amps discharge current. The particular battery is based on, and all the ones that we are going to talk about that we have used in the tests, are based on a 20 ampere hour G.E. cell which had a bed electrode and a recombination electrode.

Now, as you see, we had a degradation of wet capacity, which is normal, down to this point here; then at about 2,500 cycles we performed a reconditioning.

Now at that time the way we were doing reconditioning was to discharge the battery down at a 10-amp rate to approximately one volt on the first cell; then we reduced the current and continued to discharge to about half a volt on the first cell. Then as the cells dropped below this value, we would pull them off on open circuit, and then as they all got down to that point, we would put a resistor across the cell and continue to discharge the individual cells to two-tenths of a volt, and at that point we shorted each cell individually.

Now, obviously, this type of a system required individual cell monitoring and the capability of putting resistors across each cell as they dropped down to the proper value, and then later, of shorting the cells. And to do this inside a spacecraft would result in a highly complicated system and probably cost-prohibitive.

But anyway, up until the time of the launch of Skylab, this was the type of reconditioning that we were performing; and we held the short, in this case, something like 72 hours or more; a minimum of 72 hours. And in this particular figure, I show that we recovered approximately to the same level of capacity that

we had initially, and again decayed on about the same order of magnitude with cyclic life.

Now, the cycle in this case involved 58 minutes of sunlight, or charge period, and 36 minutes of discharge.

(Figure 212)

With the launch of the Skylab, we lost some of our heat protection system, lost one wing, and were unable to defer the second wing on the airlock system. Later, we were able to deploy that one wing that we did not lose on the airlock system. But prior to the astronauts going up and providing additional thermal control and deploying the array, the ATM system provided the entire spacecraft load.

Now, we talked of the thermal shield being lost. It was necessary to off-point the spacecraft such that the crew compartment was protected against the high heat that would have resulted if it had remained with the ATM array pointed directly at the sun. This meant that the batteries operated at between 15 and 30 degrees C, and were operated at near energy balance.

After the astronauts went on board, the wing on the AM system was deployed, and we then, at that point, obtained some help from the airlock system and almost near-normal operation was restored.

However, the initial operation, after the end of the initial operation proir to the deployment of the one AM wing, there was some degradation in the ATM systems, and this was apparent because of the under-voltage limit of 26.4 volts. There were several batteries that hit this limit and were open-circuited; and as a result, it was determined that the actual capacity we had was not up around 20 ampere hours, as we expected in that time frame, but something like eight to 12 ampere hours.

So we started a test on two batteries in the thermal vacuum chamber to simulate the conditions that we would experience on ATM, and we had like, oh, 3,000 cycles at the launch of the Skylab. So we went to the test chambers and started trying to re-establish, operate the system in the same manner as the Skylab.

As you can see in here, we had a normal degradation period down to here. At this point, we degraded it, very similar to what occurred in the actual operation of Skylab. Unfortunately, we do not have any reconditioning capability; well, let's put it another way. We didn't have the type of reconditioning that we needed to bring the capacity back up.

The most we could do was to take individual batteries down to 26.4 volts, or approximately 1.1 volts per cell. This gave us a slight voltage recovery which lasted a very short period of time.

So as a result of these problems, we started in developing a reconditioning circuit that could help in providing a recovery in capacity. I will remove this figure temporarily and show you that circuit.

(Figure 213)

This is a typical reconditioning circuit that has been developed by the Marshall Space Flight Center, and a patent has been applied for this. It is a fairly simple approach. It involves a DC to DC converter, a current sensing device, and the capability of switching several size reconditioners into a circuit. Also, across each cell, there is a full rectifier, a full bridge rectifier.

Now in operation, during a discharge of the battery, if we had a low cell voltage, the reconditioning system would hold that voltage up and allow us to continue to discharge on the system. When the cell is good, the voltage is up above one volt, of course, the diodes are back, or reversed biased, and the current drawn out of the system here is very low. The system has a standby power thrown at about one watt.

As the voltage drops on a cell to, say, seven-tenths of a volt, the circuit starts picking up the load and helps hold the overall battery voltage up.

With the hot-carry diodes, of course, the circuit would pick up something like five-tenths of a volt.

Going back to the second chart, it shows the effect that we had in reconditioning. We continued the operation of the two test batteries in the temperature chamber after the ATM Skylab mission, and somewhere about 8,000 cycles, we were able to breadboard and put the reconditioning circuits into operation. And the way this thing worked, we discharged at the normal ATM rate of about seven amps to the 26.4 volts, and at that time we switched the system off the normal load bus and picked up the reconditioning circuit.

The reconditioning resistors are rated at five ohms or 15 ohms and 26 ohms. We continued to discharge, and as we got down to a low cell voltage, the reconditioning circuits started picking up on the load to hold the cells in reasonable proximity to each other.

We discharged down to approximately two-tenths of a volt, and we hold the system at that point. It takes something like three to four days to completely discharge the battery and the individual cells. Following that, we give a C over 20 charge rate for several hours, then we return the battery to the normal flight charge system.

As you can see, following the first reconditioning attempt, we came up to something considerably below, well, 24 ampere hours as compared to 26 initially; and the reconditioning system was repeated.

At this first one, the time that we held the battery down, or all the cells down to two-tenths of a volt, was less than the optimum value, something like 24 hours. The second time we held it down for a longer period of time, and as you see, it almost recovered the full capacity.

Since this initial attempt to recondition, we have continued to operate this battery, and as you see, its capacity has recovered in each case, continued to come up, and we have something like 27,000 cycles on the system and it is still operating. I might add that there were two batteries on the line. The first battery was reconditioned. The second battery was allowed to run something like nearly 18,000 cycles and then it was reconditioned, and it performed in a similar manner.

(Figure 214)

At around 14,000 cycles, we started noting that there was one cell that apparently was weaker than the other cells in the battery, and the voltage started dropping down considerably below the normal cell voltages on discharge. The normal cell is cell number 12; the weak cell is cell 23. So you see, this drifted along in this manner there for oh, 3,000 cycles, and after the fourth reconditioning cycle on that battery, that cell recovered, and it is operating fairly close to the average pack cell voltage and we, as you see, have something on the order of 27,000 cycles today.

(Figure 215)

One other thing that we have. At about cycle 26,475, we noted that we had what appeared to be a cell short, and the cycle prior to that, 26,473, we had this type of a voltage curve on that cell. The battery voltage as shown on this side over here showed a normal voltage curve that we have experienced for that type of a cell system.

We note on the next curve, at 26,475, on the battery voltage, there is very little to indicate that we were getting into trouble. There is a little bit of a change in here, but with telemetered data, we most likely would miss this point here.

But anyway, as the cell attempted to go down, the reconditioning circuit was holding on, and came in and picked up the voltage on that particular cell and held the system up. If we had shorted, we would have gone down below zero, in this manner here, the way we had predicted. However, the actual voltage was held up in this manner here.

Two cycles later, at 26,477, we see another picture of this; and we kept the reconditioning circuit energized and continued to cycle, and at 26,480, you will note, we recovered back to this original curve on the cell.

So what we have shown here, what I have endeavored to point out, is that we have a reconditioning circuit that can be put in, packaged in something like 350 cubic centimeters or the equivalent space of two 20-ampere-hour cells, equivalent volume. It can be very reliably used in a spacecraft, and in some systems, like the power module, can go a long way towards helping to reduce the amount of maintenance that we need, or the frequency of maintenance.

We got a dividend, as I tried to show you on the curves: First, that we were able to recondition and recover capacity and voltage; second, if we have a shorted cell, we have the capability of holding up that voltage. If we are cycling and there is a weak cell, the reconditioning circuit comes in and supplies it and holds the voltage up.

(Figure 213)

We have a current sensor here, and of course, through this we can detect that we have indeed picked up a cell or are helping a cell from the system and through this, we can take whatever action is necessary in flight by changing the voltage limits or what-have-you.

DISCUSSION

FORD: Goddard. Would you elaborate a little bit more on what the capability is of that circuit to hold the cell's voltage, even though that cell is being discharged, say, at C/2 or C/4? Will it hold a positive voltage at those rates going through that cell?

PASCHAL: That circuit will hold the voltage up; well, it was being discharged at the time that it was being held up at seven amps; so that voltage was held up at a pretty good load, to run a good load.

FORD: The circuit will supply that seven amps that the cell can't supply, will supply it to the load?

PASCHAL: Yes. That is correct.

HOLCOMB: NASA Headquarters. Have you compared the reliability of this system with one similar, the one RCA has proposed? Have you done a reliability comparison?

PASCHAL: We have not run a reliability study on the system; but the one, we feel that we should be very reliable here. We do not have any relays or anything of this sort across the cells, or individual resistors or this sort. We are using basically diodes which are relatively, well, I would say real reliable. But yes; we still need to run a reliability study on it.

I don't have the numbers, but from the looks of the electronics and the components in there, we feel that it is a very reliable circuit; and we feel that it would be well worth considering.

NAPOLI: RCA. On the question of reliability again, on the individual cell contacts, there is one thing we have to realize here. We are only using these relays twice a year, so that the kinds of duty cycle that they see are relatively small, compared to what they have been rated for. And of course, there is always that one chance that they won't, you know. I guess that we see very small duty cycles, and if you have to use them 14 times in a seven-year mission, I don't think it is that severe.

MARTIN: Canadian Astronautics. Did you say that the diodes you used were hot carrier diodes?

PASCHAL: I am not sure which diodes, of course, that depends on the individual design, but we are not using hot carrier diodes on this particular one.

MARTIN: Do you know if there are hot carrier diodes in the spacecraft?

PASCHAL: Yes, they are available. We have ordered some.

MARTIN: Are they space-qualified, though?

PASCHAL: I don't know. I think Roy Lanier, who is the electronics man at Marshall, can give you more data on the actual diodes that he has got. I meant to get that data and I didn't get it when I left Marshall.

There is a report that gives a more detailed description of the circuit and the test information, and this is a NASA technical note, TN-D-8508. The title is "A Nickel-Cadmium Battery Reconditioning Circuit."
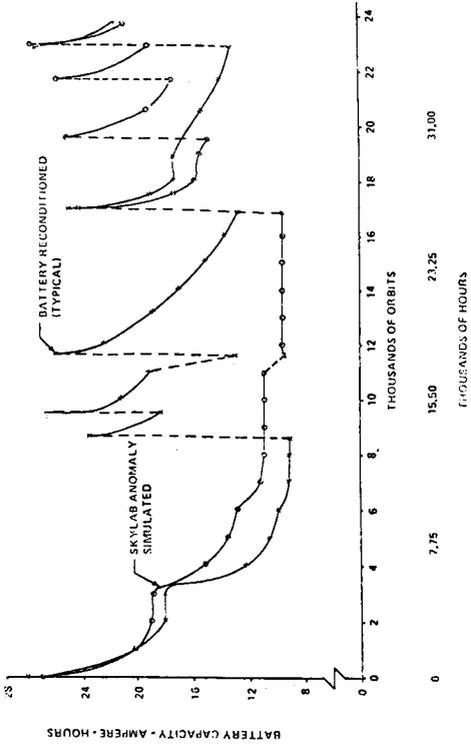
Figure 212

Figure 211

Figure 213

312
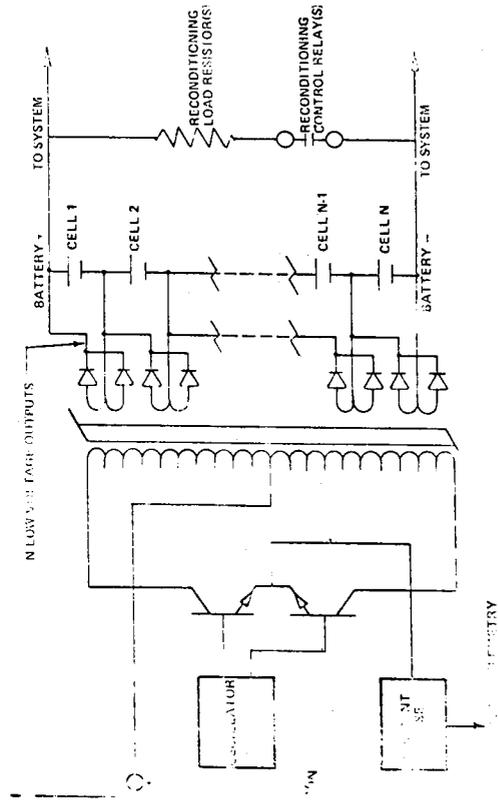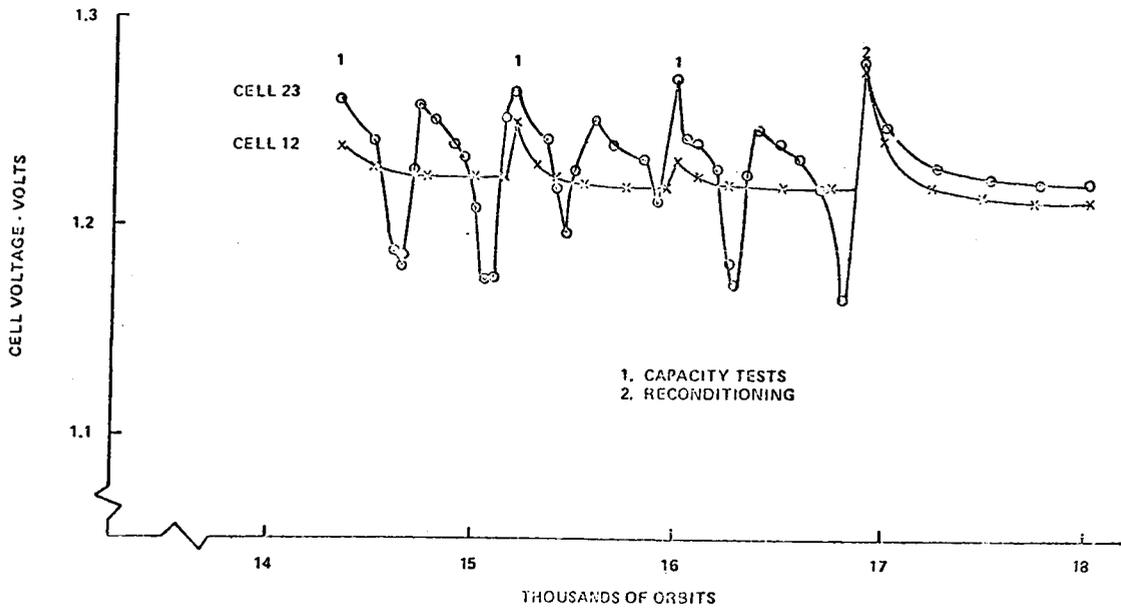
Figure 214

Figure 215

313
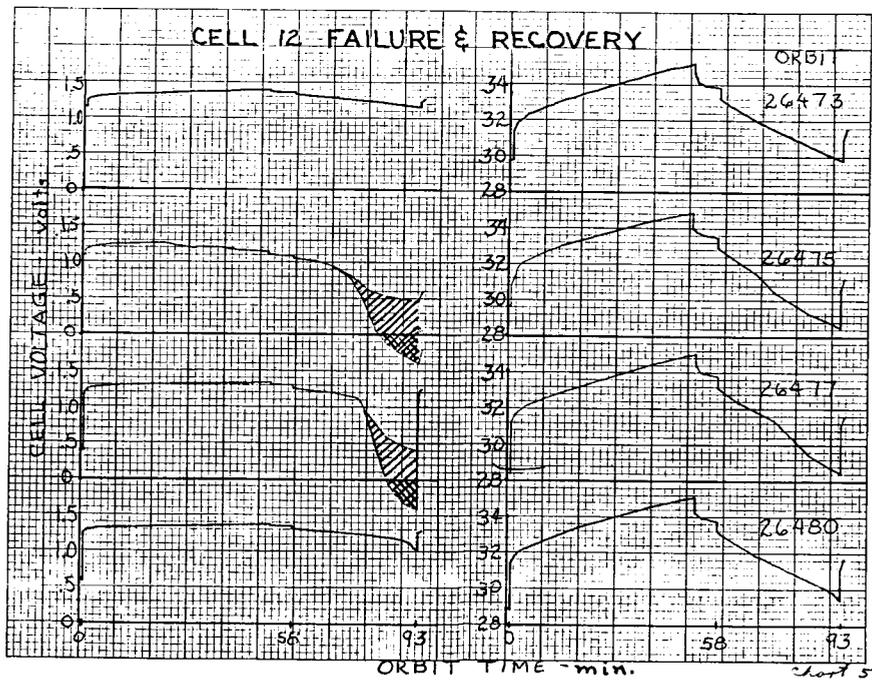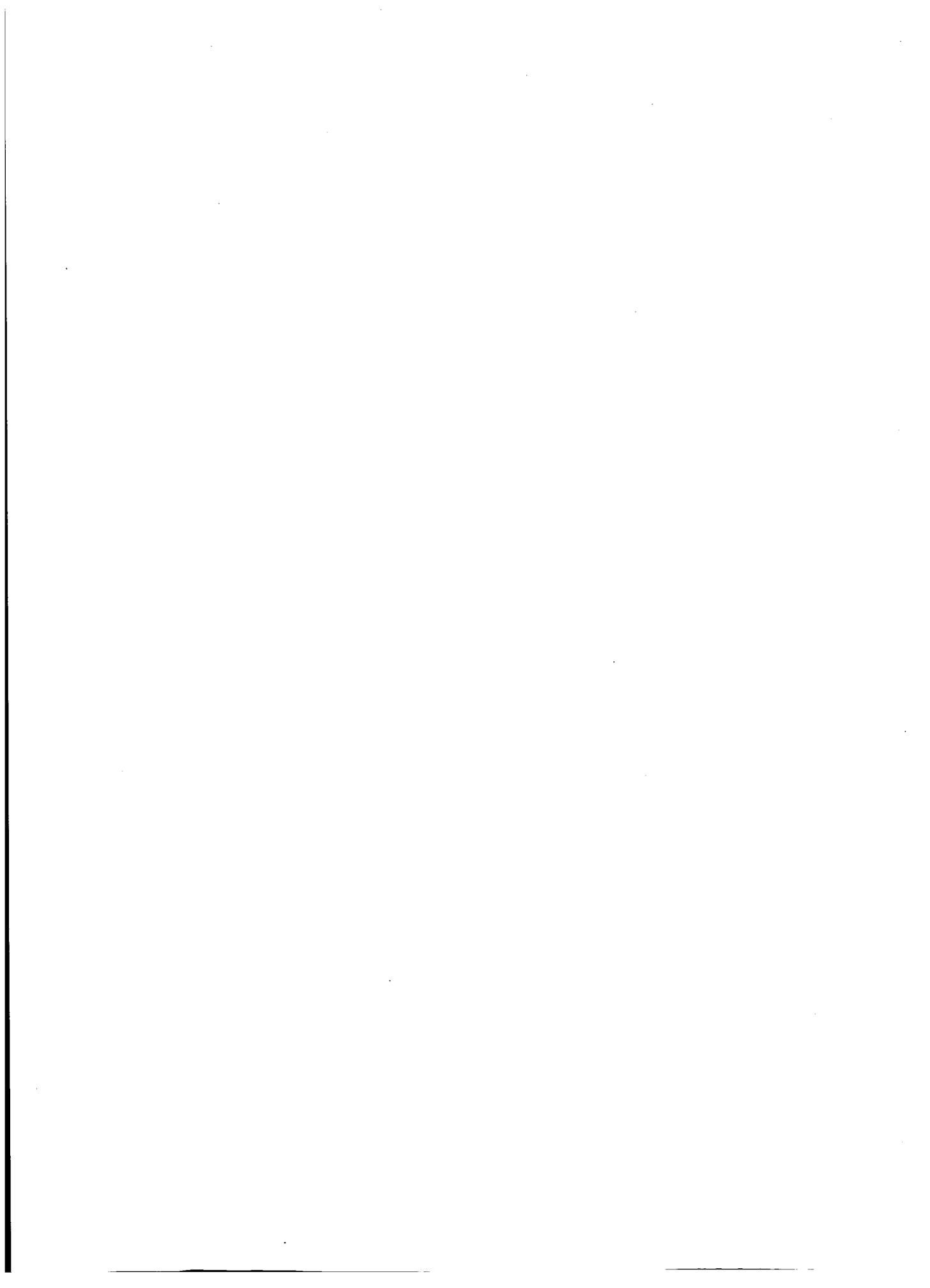
EFFECTS OF PERIODIC
DISCHARGES

F. E. Ford
Goddard Space Flight Center

First of all, my topic is not totally on reconditioning. It deals with the effects of periodic discharges, or periodic capacity checks, and the effects they have on the cycle life, and the performance of the cells during the cycle life.

And with that background, some time back, as the result of either constructive criticism or otherwise on the Crane program, people raised the point that "Well, in fact, you are reconditioning your cells every time you do a capacity check."

And it was a valid observation, because in the synchronous orbit, we do in fact, or we did at one time, discharge every cell at the peak of the eclipse; and in the near-earth orbit cycling, we did in fact do a capacity check on every cell in every cycle, every 88 days.

I guess that came about about 1972 or '73, and we started looking at the data, and some interesting observations come out. As a result of that, we took that job on a number of programs, set up capacity discharges in a matrix form, and one of the matrices, which I am going to show you today, deals with a five-cell pack when we discharge two of the five cells every six months and then at the end of two years, we discharge three cells down to determine capacity. One cell has not been discharged for two years. And of course the remaining two cells do not receive a discharge until we get some appreciable life on the cell.

In this particular test that I have where we were also looking at the effects, or trying to determine the effects, of Teflonation on the negative, and which we have been evaluating and are now flying on a couple of programs. The cells I will be talking about in one group I will refer to as the "conventional group," which means they went through the process, as you would normally process cells, in the time frame of about 1972 to '73. The second group will be processed identically except they did have the negatives treated with Level 2 Teflon treatment.

And of course, the other thing I want to talk about is the effects of the voltage plateau that we have discussed many times at the workshop and elsewhere, particularly on the OAO presentations where we have talked about the redistribution of voltage with time, and also the capacity fall-off with time.

315

As a matter of background, I would like to just briefly touch on the cell design. Basically, it is a G.E. 20-ampere-hour cell. The new cell capacity at Crane on the initial evaluation test was approximately 28 ampere hours at room temperature, again indicative of the actual capacity that the 20-ampere-hour cells that G.E. was making in that time frame would give you.

And also, the conventional cells have 69 cc's of electrolyte, which I think we calculate depending on rated actual to about 3.4 cc's per rated or about 2.4 actual, depending on which way you go. And likewise, you can do the same calculations for the Teflonage, which have 79 cc's electrolytes, or an additional 10 cc's that was put into the cell because of the Teflon, apparently, from the data we have seen here; you get more electrolyte into the cell.

And of course in the final part of this test, which I want to show you today, we have some of the cells that have come off the test. We want to do a tear-down analysis to find out just how effective is the Teflon treatment for cadmium migration.

Now, in near-earth orbit, we are concerned with cadmium migration, because it is our belief that all other things considered, that ultimately that causes a failure in near-earth orbit. In other words, you get enough electrolyte in the cell, you get good loading, you get good build and good quality in the production, and you get the best cells you can build, ultimately they are going to wear out due to cadmium migration, based on what we have seen in the earth orbit.

And I will not present the data today on cadmium migration in these cells, because we have not completed the analysis. We are in the process of doing that now.

(Figure 216)

The first viewgraph I will show you is pack numbers 1T at Crane. This data can be obtained from the pack history as well as the annual report. It shows a summary over 24 months. The right-hand column shows the cycles that the cells had been through at that time, and the left-hand column shows the incremental months that we had completed.

And the initial capacity, what I call "pre-life" of these cells at the C/2 rate, and incidentally, all these capacities are determined at the cycling rate. So if I show you one at 40 percent depth, that means we have discharged those cells, at 16 amps, not 10 amps, as would be the case in the 25 percent depth.

Well, what I show is that initially, we start off with 28-1/2 ampere hours. This is the conventional pack; and I am not going to try to depict a comparison except in one case between a conventional and a Teflonated pack, because in the two-year time frame we have not seen, on the electrical data, what I consider any significant difference in the performance of the cells on cycling.

Now, I emphasize that the electrical data was in the two-year time frame. But basically what you see here is that we did see, after six months, a slight increase in capacity. We have seen this before, at the shallow depths, meaning 15 to 25 percent; and then after 24 months or 11,000 cycles, we find out that the C-1 cell indeed has higher capacity than the two cells that have been discharged every six months.

Looking at the 24-month period, I will show you what those discharge profiles look like.

(Figure 217)

What you see at the top of the screen is the pre-life test, indicative of the voltage of all five cells. Now, if these plots look a little peculiar, it is because they were done by computer, and a computer has its own mind about where it puts certain data points. The only place that this data may be a little skewed is right in here because of the way the computer handles the data and the lack of data points at which to work with.

The important thing I want to show, is the fact that you indeed start off with a very healthy discharge voltage. This voltage plateau here, is one of the cells that had completed 24 months of cycling but had been capacity-checked every six months.

The lower voltage is a cell that had completed 24 months of cycling, but this was the first capacity check that it received. We did in fact measure the capacity on each cell to nine-tenths of a volt, and I will show you a summary of that later on. Typically a large percent of the capacity is in the range of about 1.05 volts per cell. So I guess you conclude that from periodic discharges, you do get some enhancement of discharge voltage. I think that is pretty straight-forward.

What I have shown you here is a pack at 25 percent depth of discharge and 25 degrees C. I am going to show you the next pack (see Figure 218). First a summary of the capacities, because this pack had been cycled at zero degrees C and 40 percent. Again the capacity on this table is the capacity where the first cell reading is below one volt.

The important thing here is that, we are seeing at 40 percent a tremendous drop-off. Now, I would like to point out a couple of things here.

In six months at the higher depth of discharge, we did not see that slight increase in capacity. That I mentioned at the 25 percent depth. And I think you could go back to some data in the literature at OAO; we showed that at 15 percent depth, we in some cases got 15 or 20 percent capacity increase to one volt within the first year of cycling, and then we started seeing a drop-off in capacity. For reasons I don't understand but I think it might become a little clearer if you look at the voltage profile, we are seeing an appreciable degradation in the capacity to one volt.

(Figure 219)

But what is significant here, I think, is to look at this curve, and see how the capacity has redistributed itself. In fact, you can see that the plateau on this curve is below one volt but above nine-tenths of a volt.

Now, let me put that in perspective. From a 15-percent depth of discharge in long-term near-earth cycling (and all this is referring to near-earth cycling) we see the onset of a double plateau and we see, as you observe the cycle life, a buildup in the amount of capacity at the lower plateau.

So what I am showing you here is that that plateau voltage can definitely be, related to depth of discharge. The higher the depth of discharge, the lower voltage you get the capacity. Or you can get the capacity out, but you can't get it at the same voltage level, so the plateau voltage that we see is definitely a function of the depth of discharge.

Now, I would like to show you a comparison of the 25% and the 40% voltage curves.

(Figures 217 and 219)

The bottom curve, is the one for 40 percent depth at zero degrees C. The next curve up is at 25 percent depth, at 20 degrees C, exactly the same number of cycles.

Now, one of the things that Goddard has been interested in doing for some time is increasing the battery utilization in a spacecraft; in other words, you can get improvement in energy density in two ways: You can improve the total energy density, or if you can use more of what is there and get a good cycle life.

Well, what this has demonstrated is that then you find that capacity is a function primarily of depth of discharge, I think temperature plays a part but in this case, I am not trying to compare temperature simply because the matrix did not include that.

(Figure 220)

To further illustrate the effects of this fall-off in capacity, I have summarized it here in this chart. This is a summary of all four packs. They have completed two years.

What is interesting is to look at the depth of discharge and look at the capacity that you get out of the cell. In the case, between a 40 percent depth, the first reading here on the left-hand side of the slant is the one volt, and then if you allow it to go down to nine-tenths of a volt, this is the reading. You almost double your capacity, simply by redefining an undervoltage cut-off, in this case.

We contrast that with the shallow cycling at 25 percent; we see a similar phenomenon, but nothing as great as we see at the lower voltage.

Now, I am sure someone is saying, "Well, what is the practical limit of the lower voltage on a spacecraft?" And I am not suggesting nine-tenths of a volt is. I am presenting this data for a twofold purpose.

One is that it has been our experience in other test programs, as well as this, that the degradation mode that we have seen in the near-earth orbits and also in some 24-hour orbit cycling that the older a cell gets, the more rate-dependent the capacity becomes. This is an inherent characteristic of cell aging. For some reason, they become more and more rate-dependent with cycle life.

Now the thing that we found of interest this morning, I think, when we looked at some of the reconditioning, and also the question, is if you can get rated capacity or new capacity out of a cell after six years at a low rate, can you really get it, even though you recondition, can you get it at the high rate? And I don't know that the question was answered this morning in the reconditioning session. If you really have a C/2 discharge rate that you want to support a load during the next eclipse, and you have demonstrated, you get capacity at the low rate. Can you, in fact, get the capacity at the high rate? I don't know if that has been clearly demonstrated yet.

One other point I want to make concerning the double plateau and also concerning reconditioning: During this morning's presentations, we heard about reconditioning, I think, from five or six different people; probably six different

cell designs, and about the only real commonality I could stand up here and claim that I know is that they are all NI-cds. Now, once you accept that premise and start looking at the variation in design, and how these designs may effect the reconditioning results it's no wonder the data is contradictory. You should know the cell design, and you should know what you are reconditioning.

Well, in order to bring back a point on the floor, I think I made it two years ago, and I would like to put it forth just to refresh your memory. One of the things we have been looking at and trying to evaluate for some time is the effects of electrolyte in a cell. If you get more electrolyte in a cell, can you improve the life? Can you improve the capacity performance, and can you improve the voltage performance?

(Figure 221)

The answer to the first question, I think, is if you can get more, and I am not sure how much more is needed; the numbers we are shooting for right now and are getting in some specific designs are like 4 cc's per rated ampere hour, I think you can get that, there is no question in my mind, you can improve the life of a cell.

On the second point, can you improve the voltage characteristics with more electrolyte, we have not seen any evidence, with the cell that we have life-tested and cycled in-house at Goddard, by increasing the electrolyte, that we are going to appreciably affect the voltage degradation that we are seeing. I do believe very firmly that the more electrolyte you have in a cell, the longer it is going to be before you see the collapse of this capacity curve to one volt.

And I think that is the whole objective: To keep the capacity curve up, as far as performance of the battery, and then if you can get a cell that you can do that without reconditioning, you can also, with reconditioning, certainly enhance that voltage characteristic. That is all I have.

DISCUSSION

SCOTT: TRW. I wonder whether we have become mesmerized with one volt per cell. True, it is a good place to stop for a good cell; but, you know, the more data I see, the more I wonder whether it has, really, any significance beyond a cell in new and good condition. And I think some of your data generally tends to indicate that. But of course you have to put the spacecraft undervoltage somewhere.

And that leads me to another observation, and that is that from what you have seen and what you have said, it looks like one might be able to prolong the useful life in a spacecraft if you had, perish the thought, a variable under-voltage limit, as well as your variable charge voltage limit.

The reason that I say that is because I don't think that it is safe and practical to use an under-voltage limit very much lower than one volt per cell, if even that low, on a new battery; because we have found, and I am sure other people have, that if you discharge a multicell down to close to one volt per cell, you are going to start reversing cells, because of the normal range of capacity and minimum unbalance that you can get in a practical battery.

So you should start with that under-voltage fairly high; and I would like to see it start at 1.1 volts. Then you would have an even greater margin of safety on a new battery. But then you would like to be able to lower it, as you cycle the battery, and as the normal voltage curves degrade.

THIERFELDER: General Electric. Well, what you say is true, Ron, that we have boost regulators in all our spacecraft, and we can go down to one volt or lower. But as you take the voltage down, we have constant power loads, so the amperes have to go up; so then we need more ampere hours. So we don't really profit very much by going to the lower voltages.

SCOTT: If you have some of these low plateaus, your voltage is going to be pretty flat down there at 0.9 volts, and you are not going to really see that much of an increase in current at the end of discharge. It is only when the voltage is rolling off rapidly at the end of discharge that you run into that kind of trouble on it.

HALPERT: You made the comment about starting at one volt or even 1.1: When do you start reconditioning? Do you start after six months, or do you start after the first year? Should you let it go three or four years before you do it? Is it good for everybody?

FORD: In regard to Will Scott's comment, yes; we have the same experience. On a new battery you want that under-voltage as high as you possibly can get it; you have got to look at an orbit number meaning 20 or 22 cells in series, because it is almost impossible, if not certainly impractical, to get ideal, you know, every cell tracking.

There is more than one way to do this, though, and of course the GOES satellite, that Ron talked about earlier had an under-voltage system that went to groups of five cells. So they looked at five-cell groups in a 20-cell battery,

and they used that in whichever detector of five was first; that let you go to one-volt average.

But the thing I would like to see us address, and we have the people here that I think have a lot of insight into it, is, as battery people, what do we know that we can do enhance the characteristics with life that we don't get all this degradation other than reconditioning? I mean that sincerely. We recognize that reconditioning enhances the voltage characteristics. What is the mechanism? Is it the negative electrode and the crystal growth that is taking place in there? Is it redistribution of electrolytes? Dryness?

You see, one of the things we pointed out, I guess last year or two years ago, when we started talking about the increase in electrolyte and the cell we were building for IUE, one of the things that really amazed us was when we got up to about 4 cc's per ampere hour of electrolyte in that 12-ampere-hour cell that we built, we found out that we were getting, at least on the intial perform-ance, the capacity at 35°C was as good, if not slightly better, than the capacity at 20. And if you look back through all the literature that has been published, we have always accepted the fact that an aerospace cell is a starved cell, and you have to take a compromise in capacity at high temperature.

Well, what is not clear to me is: How does the amount of the electrolyte affect the capacity of a cell at 35 degrees C? And in fact, if we put more elec-trolyte in a cell and can get good performance at 35, or enhance the performance at 35, maybe what we are just seeing is that with life, and these drop-offs in capacity at lower temperatures, is the manifestation of all these things building up with the cycle of the cell so that the cell is becoming more critically starved as you cycle it simply because it doesn't have enough to start with.

Now, I am going to directly say that I recognize that increasing the electrolyte isn't the solution to all our problems. I think it is a solution right now to helping maintain the most healthy possible capacity you can get in the cell throughout the life. Certainly it compromises, I think how you get that electrolyte in there is another factor altogether.

But it is our firm experience that with the electrolyte increase, increase in the quantity, we still get voltage degradation on discharge. And we don't know how to solve that problem. I think it is something we should be looking at.

DUNLOP: COMSAT. I would like to comment based on the results of the data that was presented by our people yesterday, from a battery design system point of view.

When you design a battery subsystem for a synchronous satellite, the first thing you have to do in designing the subsystem is define the behavior of your subsystem. So assuming, then, that you try and do that, then you try then from a control center point of view, you try and make the thing last as long as you can, based on the design constraints that you are given.

In our case, we saw a performance that was acceptable for us based on the design that we were using up through five or six years. After that point in time, we started seeing a problem with the performance of the battery that didn't meet the design goals that were established for the battery. And so what happened in reality was that we reduced the load on the spacecraft so that we wouldn't fail the spacecraft during eclipse operations. We cut back the loads.

We tried the discharge reconditioning; and we found that at a very low rate, we could take out of those batteries 18 ampere hours of capacity. That is at a rate that is down to something like C over 40, 30 to 40. If we tried that same discharge at a C/2 rate, which is the rate we have to operate in, in the spacecraft, we can only get something like about 3-1/2 ampere hours of capacity out of that battery before we go below one volt; actually, before we go below about eight-tenths of a volt per cell.

We found that in life-testing of cells in the laboratory, they served and behaved very much like they did in orbit. And then after we got out to about seven or eight years, that the cells' capacity may be about five ampere hours.

Actually, the cells have more capacity than that if you take the plates out and flood them. So the probability is, that it is a problem with the electrolyte management and whatever the other, all the total characteristics are in the plate.

If you are going to talk about it, you have got to sort of divide this problem up between cell design, the spacecraft design, and the operations center, as far as a communications satellite goes. I think that there are a couple of points that I would like to make.

From a control center point of view, flexibility is the key thing. The individual has to have the capability, if he wants to make the thing last for seven to 10 years, of having a lot of flexibility, because we have changed our mode of operation practically on the data from each eclipse season, we are changing our mode of operation these days, to try and extend the lifetime of the battery.

But it also points up the need for a better battery design. Now, that is the key point for this meeting: We need a better battery design, whether it is a nickel-hydrogen or a nickel-cadmium. We need a better battery design,

and there are ways that a battery can be designed better. It just isn't throwing in more electrolyte or something else.

One more comment I would like to make along that line. If we are going to get a better battery design, we are going to have to put the money out to the battery manufacturer to get him the support he needs to design a better battery. And I don't think I see that really going on in the kind of discussions that I am hearing at this meeting. I don't see really the kind of work that needs to be done on the part of anybody in supporting the industry to really go out and try and make a battery that is a better battery from a lifetime point of view for a synchronous satellite.

I saw a presentation yesterday that says, "We are going to make a lightweight battery." And I know from our work in our laboratory that that lightweight battery design isn't going to extend the lifetime, for a synchronous application.

ROGERS: Hughes Aircraft. I would like to make a comment on the electrolyte starvation theory or comment that you making, that in some work with a nickel-hydrogen cell with an asbestos separator, which in low-earth orbit went roughly a thousand cycles, that you could get the cell to work almost like new again by either letting it sit a little while, or by refilling it with electrolyte; but that that state that it was working well again wouldn't last very long.

And I guess what I am suggesting is that there were changes, in this case in the asbestos, in relation to the nickel electrode, because the hydrogen electrode was working fine, that were electrolyte starvation, but didn't relate to the amount of electrolyte in the cell; that something had happened to the separator, we think, that caused the problem. But you wouldn't have gained anything by putting more electrolyte in there.

FORD: Since you mentioned separators, I would like to make a comment along those lines. No one, including myself, denies the scientific argument for polypropylene. It is known to be more stable; to have the potential of a longer-life ni-cad.

However, I have yet to see cycle life test data where cells built with polypropylene and cells built with nylon, polypropylene cells will not outlast the nylon cell in a cycle life test, in a real environment. I am an engineer. I don't dispute the scientist when he says, "Polypropylene is more stable." What I do dispute is the compromises that I think I have to make today in the initial cell parameters to put the polypropylene in there. Now, until we learn how to build a better cell, starting from the day one, I don't think that polypropylene is going to buy us that much in a ni-cad. In fact, there is evidence that it is

going to be less than what we can get. The only real application I have ever seen for polypropylene, I think, was JPL in the Viking lander. They had two sterilized batteries; and we all know you don't sterilize nylon separators.

I think one of the things that needs to be done is a harder look at the cell components, particularly at the plates. Maybe this electrochemical impregnation that we are talking about may be a solution to a lot of our problems. I am going to put Figure 222 up here that I have had for four years. I have never shown it before.

FORD: But it goes back to when we started looking at what we call the IUE prototype cells, which I have talked about in recent workshops, or the last three or four workshops; and in looking at this program, we were concerned about the stability of the negative electrode. And we asked the manufacturer to do a test for us, and they did.

I think Guy Rampel probably remembers this. I know he looked at it. Basically, what we were interested in, if you took a cell and went through the normal process to clean the negative during formation, reassemble the cell, and then just cycle it, what happened to capacity? Could you get a feeling for the negative fading, if you cycled a cell in that condition?

The cell had not been precharged. And in this case, that is exactly what was done. In 24 cycles, the capacity of the cell dropped off from what you see, the initial, just slightly above 12, to about 9-1/2 ampere hours. Now, what the whole mechanism of precharge is all about is to raise that capacity back up beyond that point. And there is also data in the literature from the contractor we had back in '69 that was really looking at third electrode or recombination electrode cells, but there is also data that says the stability of negative electrodes will vary from lot to lot. And I think this is an area that we really have to look at.

I am convinced that my problem, right now, with the cell design I can get, with the 4 cc's per ampere hour of electrolyte in it, on a rated basis, is in fact the negative electrode. Until I can get a more stable negative electrode, I have a constraint on me as far as the life I can expect out of a ni-cad. And until I learn how to solve that problem, I don't know how to push that life, when you say seven, 10 or 15 years, I don't know how to push it beyond the next stage.

RAMPEL: General Electric. You can add a little bit more electrolyte to cells if you change the overcharge requirements and specifications. Some time back, it was very important to attain C over 10 at room temperature and C over 20 at zero degrees, because of precharge and overcharge balance considerations.

Today, though, I think that is pretty well under control; and we could gain a significant increase in the amount of electrolyte we could add to cells if the overcharge rates were decreased. There is no real reason to be able to overcharge continuously that I am aware of; perhaps 200 percent, or C over 15, or C/20 would be sufficient. And in that case, we could add much more electrolyte to cells.

HARSCH: Eagle-Picher. I would like to follow that same line. You have made a plea for a better cell and Jim Dunlop for a better battery; yet as manufacturers, there is a very fine balance of these designs, and they are all based on C over 10 overcharge. It doesn't allow you any room to move, in electrolyte, separators, precharges, any part of that design.

I don't really feel like that requirement is that hard and fast; and if it is, maybe the systems people should be looking for a different control mechanism. Is 1.52 volts at zero degrees realistic? What is wrong with 1.53 or 1.54, if it allows you to put in several more cc's of electrolyte, and extend the life or improve the voltage?

I think as manufacturers, we are all trying to do that, but we get a lot of opposition from the users in changing anything because of a set of requirements that we have been using for years and may or may not be realistic, including the pressure. We set it at 50 psi or 60 psi, yet that cell design, seal or weld, won't rupture to about 1,200 psi. So why pick 50 psi? Why not 100? Why not 150, if you can put in 4 or even 5 cc's per ampere hour of electrolyte? I think those are the things that you people, as users, need to consider so that we as manufacturers have a little more flexibility in how we can design a cell.

SPARKS: TRW. I think one of the things that should be brought out is that we see the voltage degradation mechanism and then we see the life-limiting function, they aren't necessarily the same function, from a system point of view. We can add extra cells in the system and take care of the low voltage problem, generally as long as we know about it early in the game.

The thing that is bothering me is that we have changed the electrolyte in the system, and we really haven't helped this voltage regulation problem; and I haven't heard any data reported that suggests that we try to characterize the source of that degradation, or what it is sensitive to.

I know some of the work we have done shows that it is very sensitive to temperature, as far as the rate of onset of voltage degradation. Why? That is the question. Adding more electrolyte in the cell hasn't really curtailed that, so it suggests that flooding the cell isn't the magic answer at all.

The early thing that showed up in some of the early work on that life test was that the negative electrode was polarizing very, very early, in a non-normal manner, giving us a real low plateau voltage. And again, the rate of onset of that seems to be a function of temperature.

Willard Scott's tests on the 2 KW program, which he ran at the cell level and reported previously, show that at zero Centigrade, the rate of voltage degradation was very, very low, when indeed you kept the cells at zero. But as soon as you got up to higher temperatures, the rate of onset of voltage degradation was very high. So I am not at all certain that we have truly characterized where that mechanism is occurring, and more work needs to be done in that area.

SEIGER: Yardney. I think this morning that we have been hearing that there are possibly three different things that are going on, and we can't pin them down as to what electrical phenomena they are causing.

One is the instability of the positive electrode, the way it has been swelling. This in turn causes a change in the inter-electrode spacing, and presses the electrolyte around and makes that slosh around.

We also heard that there is a separator degradation with nylon that has been affecting the precharge in the cell. It has been increasing the precharge, through the mechanism that Dr. Maurer described this morning; and we also have heard that cadmium is actually migrating outside the area where the sinter exists, and is sitting on the surface of the negative electrode.

Now, if we remember way back, it has been demonstrated that the oxygen is recombining on active sites on that negative electrode, and we are covering that with cadmium hydroxide, then we are affecting the recombination rate; so that a new cell and an old cell will recombine differently.

It would also be interesting in the nickel-hydrogen; they have changed the separator and they have changed the negative electrode, and they have been cycling, I think there is a discharge in many cycles, and it would be very interesting to hear what they have to say about the positive electrode.

MAURER: Bell Labs. I had a couple of comments. One, you were asking for some data on polypropylene versus nylon. Our major use of it is reserve, so our cells are on long-term overcharge; but we have had commercial nickel-cadmium batteries, the standard cylindrical design, and in telephone service, telephone-pole-mounted equipment, the nylon cells last typically one to two years in the field, and the polypropylenes are lasting three to five years. If they are sealed completely, they will undoubtedly go over five years.

The other comment was along the lines that Guy and Bill were talking about, design parameter relief to improve the cell performance. Another area would be to provide some relief on the weight or volume of the cell so that you could load your electrodes to a lower level, increase the porosity of the plates, and then you could increase the amount of the electrolyte.

Our cells that we make in house typically have five to six cc's per ampere hour, and work, still work in a vaccum at C/10.

DUNLOP: In response to that comment by Dr. Seiger on nickel-hydrogen, if you cycle a nickel-hydrogen cell for several thousand cycles, and you are using a, well, let's take an electrochemically impregnated electrode that doesn't swell. Up to at least 1,000 cycles you don't see any change in the physical characteristics.

That electrode, if you keep the electrolyte in the cell, you will not see any appreciable voltage degradation at all. And there is strong evidence from the nickel-hydrogen work that this plateau that you see is a result of the cadmium electrode, not of the positive electrode.

There is a second thing that you do see in nickel-hydrogen. There are really about three different designs of nickel-hydrogen these days, with different electrolyte management concepts. But if you take a polypropylene separator in a nickel-hydrogen cell, for example, you will generally see that the voltage will drop off in the cell, will drop below one volt, at a cycling rate of 80 percent DOD and about 600 to 1,000 cycles. That has been reported in the literature.

And that fall-off was shown to be the problems of the wettability of the polypropylene separator. If you deal with nylon or asbestos, the cycling life goes on longer, but there is a trend for an impedance, what appears to be a slight drop, a straight line, more of a straight-line drop-off in voltage.

If you maintain the electrolyte in the separator you don't see any drop-off in voltage with cycling, with an electrochemically impregnated positive electrode.

ROGERS: Hughes Aircraft. I would hate to disagree with Jim Dunlop but I am afraid I will have to. In some of our earlier work, these were Eagle-Picher cells with chemically impregnated plates, which is a difference, and asbestos separators, this was an 80 percent depth of discharge in a low-earth orbit, after roughly, I think, 400 or 500 cycles, we did see some voltage degradation of the plateau type you are referring to. It wasn't anywhere near that extreme. And this was removed, for the most part, by a couple of capacity tests,

essentially reconditioning; which would imply that, well, it would have to be the positive electrode. The negatives can't do that.

So apparently we have seen that effect, that it was due to the positive and not an electrolyte distribution. Of course, I am not sure. But these were chemically impregnated. I have not seen that effect with electrochemically impregnated, which isn't to say that it doesn't happen, however.

RITTERMAN: TRW. Did the electrochemically impregnated positives give you any sort of degradation to begin with? You say that you did not see it in electrochemically, this reconditioning effect?

ROGERS: In 3,000 cycles at 80 percent depth of discharge in low-earth orbit, we have not seen that kind of degradation. But that is only one test.

FORD: Would you qualify "that kind of degradation"?

ROGERS: The voltage plateau, where you are going along at a pre-flight level of, say, 1.2 volts or 1.15, and then it drops down to about one. I haven't seen that. The only comparative plateau we have seen is through the oxygen, which gives lower voltage.

SEIGER: Yardney. As I have been sitting here today and yesterday, I started to make a little list of differences that we have been seeing in cells. There are differences in grids; some have iron that is nickel-plated, some with nickel screen, some with perforated grids. There are really differences in the nickel powder that is used: There is type 287, 255, there are some from over-seas. They are made by loose powder techniques, slurry techniques, some have proforma; they are made to various thicknesses, to various porosities. They are loaded to different levels. They have different methods of loading, and the amounts.

There are differences in the way putting the electrolyte into the cell, the amounts and how we get it in. There are differences in interelectrode spacing. There are differences in ratios of negative to positive, and then in the balance of them, in setting the precharge. The separators: Nylon, polypropylene; in the nickel-hydrogen, we hear of asbestos, and there are others in that. Silver in the negatives, cadmium in the positives, cobalt in the positives, Teflon around the negatives, lithium in the electrolyte, and the concentration of electrolyte.

And I must say that I am surprised that there is so much agreement in how the cells behave on reconditioning, and not more disagreement.

GASTON: RCA. I have one comment about it. If it were a solution to add more electrolyte to the cells, I am a little bit disturbed. After 15 years of technology and the study in space, I will have to go back to my full-time people and tell them I need more weight. Now, weight is still a problem, in many applications; weight is still ballast. So if that is the only solution, for me it is a somewhat embarrassing solution.

SCOTT: TRW. I think that even though that may be the only immediate solution, or the best one that we can come up with immediately, it may be sort of a "crowbar" solution, because I suspect that the final distribution of electrolyte in a cell is determined by certain partition functions between the separator and the plates. And all that you are going to do, by putting more electrolyte in the cell, is end up with a little more electrolyte in the separator, and a lot more electrolyte in the plates.

And I don't know what exactly that is going to do to the oxygen recombination and all of the other things that are a function of the level of electrolyte in the plates.

LACKNER: Defense Research, Canada. I don't doubt that putting in extra electrolyte will help you. However, after 15 years of experience with aircraft batteries which use a flooded, vented system, you are still required to recondition them at periodic intervals because they have degradation loads. They do lose capacity. They do have so-called "memory effects."

So there are other things like utilization factors. Having very little depth of discharge doesn't stress it, but it sure as heck does not expectisize it. The point is, it may only give you a little benefit, not the whole profit.

SEIGER: To address myself to Steve Gaston, if you use a positive electrode, such as the electrochemical, which has higher utilization, you can couple that with the same capacity. Just make the change in the positive electrode and get your extra electrolyte, and I would like to caution people on how that electrolyte is put in and distributed.

There will be a paper, I don't know when it is going to be published, in the Journal of the Electrochemical Society. It has been accepted, oh, about four or five months ago.

GASTON: Harvey, I am aware of this, the progress was made. I was just a little bit overdramatizing it, to say about the increase in the weight, because weight is still, in many applications, a problem. It is possible it will increase the weight to a certain extent, if we can't place the weight someplace

else, but I would much rather have a higher depth of discharge for the same weight, or I have more power for the same weight, rather than going the other way, increasing the weight for the same power.

FORD: Let's back up a minute. Nowhere do I imply, I don't think, that the extra electrolyte is the cure of all evils, just like I don't believe that reconditioning is the cure of all evils, either. It is one of many steps we have got to take; and what we have tried to demonstrate to you is that there is a degree of starvation which you can't exceed. If you do, you have no cell to start with.

Now, once you have got that amount of electrolyte for whatever life you need, and I don't know what that is, except based on the empirical data I have a gut feel, for, you know, certain performance characteristics; once you have got that amount, I am not saying another 10 cc's or 6 cc's or 8 cc's per amp hour is going to do any better for you. All I am saying is, that is the first step.

The second step, now, is, we have identified one of the degradation functions, the second step is how to improve the electrodes. What do about this cell that won't, okay, to get that voltage from the case? Reconditioning is one way on that. If there is something more fundamental that can be done, though, through the development or through additives, and I hate to suggest that; but there have got to be ways to attack the problem other than just from the external, what I call the "engineering approach" to the problem.

ROGERS: Hughes Aircraft. Are you in a position to fund some fundamental work on finding out what the phenomenon is?

FORD: I think if you saw that viewgraph yesterday, you would know the answer to that, because the funding we have this year from the headquarters, and I won't go into the reasons why, but it is zero. So the answer to your question is a definite "No."

ROGERS: It was a rhetorical question.

FORD: If NASA were in a position to fund something like that, I would think if there was a good, viable program that could be put together, I think you could present it to the right people, and yes, I think there would be funds made available, if you have got something that has good potential.

SCHULMAN: TRW. I just noticed that graph you just had on the screen and you are showing amounts of less than 3 cc's per ampere hour. Now, what you have recommended is as many as four cc's per ampere hour. Let me just state that on the program on which I am presently working, that would be 2,800

grams additional weight. That is a lot of additional weight, and very few program managers will put with anything like that, regardless of what the apogee is.

FORD: I will give you the fact that it costs you weight to do that. All I can do is raise the point that if that, by chance, will get you from seven years to 10 years without a cell fader, how much is that worth? And I will bet we can't answer that here, either.

WEBER: COMSAT. Most of the data in testing described seems to aim at extending the capacity or the battery life at a given capacity or a given discharge rate. And I was wondering if there was any testing that is going on where the flexibility of this to operate, say, at a C over 4 rate, discharge rate, for a period of two to three years, and then go to a C/2 rate; has anybody done any testing to see what the long-term effects are?

FORD: I don't know where any data exists. The Crane tests usually are over a fixed regime unless a particular satellite program has a need to go through some change in orbit plane or change in orbit parameter; but specifically, that doesn't change the load very much; it may change it over time. But, no; I am not aware of any. I throw it open to the floor. Are there any other comments or discussion?

HOLCOMB: NASA Headquarters. You know, I hear a lot of different approaches in the battery here. We are talking about reconditioning, whether or not that is what we want to do; whether or not we want to change the battery design. When we talked about battery design changes, I have heard at least 50 different things in the last 20 minutes here; and we talk about, you know, how willing we are to fund all of these changes.

And I think anybody that adds up all of these changes, without putting some prioritization or critiquing that realizes that NASA couldn't afford, the Air Force couldn't afford, COMSAT couldn't afford, to go after all of these approaches; so I think, you know, we have to look at those which have the best payoff.

And this initial discussion was aimed at reconditioning and I would like to back up for minute, now; because I think it started out talking about reconditioning and we have gone back into the cell. And I think maybe that brings a very fundamental question out, which I would like to find out, and that is: As far as reconditioning is concerned, are the gains that we get out of it worth going in and trying to understand it better, or should we concentrate on trying to work with cell design, and really use this only in a last-ditch sort of operation?

And I don't think anybody answered that today. I don't think anybody conclusively said that reconditioning is as good. Floyd Ford presented some data that indicates that reconditioning actually, for a fixed voltage, the capacity of the cell is damaged by reconditioning; at least I think, you know, that was what your data indicated, that some of those cells, if you picked nine-tenths of a volt and operate at nine-tenths of a volt, that taking the reconditioning periodically decreased the capacity of the cells somehow. I am not sure if I interpreted that right.

Anyway, I would like to open it up: Is reconditioning something that we should be doing, and really trying to understand? Or should we be worrying about the cell?

SPARKS: TRW. The answer to your question, I think, from the system point of view today, is that the key thing we have to deal with is how to get the most utilization that we can out of the system we have, for as long as we can get it. And the leverage that you get at the spacecraft design level, with the capability we have of putting a spacecraft especially into synchronous orbit, is very, very large with increased utilization.

The difference on a battery system between, let's say 75 depth of discharge and 50 percent depth of discharge is around 50 or 60 pounds in typical geosynchronous spacecraft; sometimes larger. That is an awfully large leverage. So for the short-term, reconditioning has a big payoff for us, if it can be made to work reliably.

For the long run, I think there your mechanism study is important, because you really need to understand what to change, before you start trying to change all kinds of things. And I think here, the electrolyte problem was identified previously as one potential problem area. It has helped the capacity situation; and with the cell rating that Seiger made of all the things we are doing in cells, I think what came out of the whole thing was they still all operate the same. They still all degrade in voltage. So we really don't understand that mechanism.

So to kind of summarize it, the near-term solution, as I see it, is to try to get the utilization from reconditioning; for the long-term, then try and fix the problem.

MAURER: Bell Labs. You might combine some of these to some extent and just do a fundamental study of the reconditioning mechanism, and find out what you are doing in the reconditioning. It might then tell you how to design the cell properly.

SPARKS: I will vote for that.

MAURER: But here today, after how many years of these workshops, we are still arguing over whether the plateau change is due to the positive or the negative electrode. That is not very far along on understanding, I don't think.

I would like to comment on one of the questions or comments that has been made on reconditioning techniques. There is a law in the aerospace industry, I think, that says that you want to minimize overcharge to minimize the degradation rates of the cell. I just want to put that in a little broader perspective.

That is true when you are talking about the amount of overcharge in a fairly low percent, 100 percent, up to 100 percent at the very high rates. There you promote the movement of negative material into the separator and so on.

But much of our work is continuous overcharge, and not cyclical and we have taken batteries apart that have been in the field on C over 20 overcharge at temperatures, on an individual battery, that ranged from zero Centigrade up to probably 60 Centigrade from winter to summer, taken them apart and you find absolutely nothing in the separator, except electrolyte, of course; but there is no movement of negative material at all, under those conditions. So overcharge per se is not what makes the cadmium move. It is some of these other things.

So when you consider reconditioning techniques, you ought to not limit yourself to "no overcharge," or minimizing overcharge; but perhaps the overcharge rate, if it is low enough, will not promote this problem.

Also, we have some of our cells on test at 80 degrees Centigrade at C over 10 overcharge; and the cells have gone 240 days, which if you used the activation energies that come out of these stress aging tests, that would extrapolate to 20 years of service. But after 240 days, taking those cells apart, there is no negative material in the separators. They are still clean.

KIPP: SAFT America. An interesting thought comes to mind when I hear the discussion going on, and that is, talking about reconditioning and weight. A question that probably someone like Decker or someone else involved in power system design could answer is: How much weight have you added to your system to accommodate reconditioning of the battery? Or to ask it another way, how much weight could you add to the battery if you didn't have to put in the weight for the reconditioning?

SPARKS: TRW. It depends on the mission. If you are talking about a geosynchronous orbit mission, the weight you add to put in reconditioning in the system is probably a third of a pound.

KIPP: For the whole system?

FORD: Zero. It is already there.

SPARKS: It is already there. Most of it is already there. You are adding a couple of small resistors and a cable harness, and a relay.

For a low-earth orbit, if you are trying to use reconditioning like was shown in Etheridge's paper, there, you are adding a more substantial amount of weight. You are trying to handle the load. When you try to protect the battery and handle the load, you are adding a severe weight constraint. But just for straight reconditioning, if you are trying to go down to a low voltage and allowing reversal, for instance, you have very, very little penalty.

KIPP: We have had two concepts talked about. One is taking the battery down to a certain end voltage, and allowing some cell reversal, and also one where you take individual cells down. Are we talking about the same weight?

NAPOLI: RCA. I can answer the question about bringing the cells down to a zero volt condition. The circuitry, basically, is just the individual shorting resistors that are across each cell and become part of the battery configuration; and then the relays, which are miniature relays with two-amp contacts, are also mounted on the battery.

I can give you a feeling for weight, here. We have, for example, on the SATCOM spacecraft, three batteries. Each battery assembly, with the reconditioning circuit, weighs 27 pounds, with the total reconditioning circuit. Of that weight, about 23 pounds are the cells. The rest is into mounting and plates and clamps, the whole thing together. So I think of that seven pound difference, or not actually seven; of the five-pound or four-pound difference, I think about maybe a pound, probably, or less than a pound is the total reconditioning circuit.

GASTON: Five or six tenths of a pound.

NAPOLI: So we are not really losing much in terms of spacecraft weight.

DUNLOP: I thought his was a very good comment about the difference between working on cells, batteries, and operations such as reconditioning. It

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seems to me when I see what we are doing, and I hear what NASA is doing and TRW and everybody else, reconditioning definitely gives you a voltage improvement when you do it. The question remains as to whether or not it is going to extend the cyclic life of the battery, and from an operational point of view, whether it is really going to provide a benefit to us; from an operational point of view, whether it is going to give us any better lifetime, and whether it will keep those transponders on for another year or two before we have to start shunting and backing the load.

And that is the real question; and I think the proper answer to that is, we don't know yet. And I think the point there is that there is a lot of work going on. It has been going on for about three years or more, and it will probably take another two or three years before we can really decide whether or not we have really, truly seen that reconditioning extends, or doesn't extend, the lifetime of the battery.

And I think that is one very important program to carry on, but in addition to that, I think it is equally important to look to the cell design improvements.

GASTON: RCA. I think one thing we know right now. If we keep the batteries cool, we get a longer cycling life; so I would say one thing to shoot for is good thermal design to keep the batteries cool. I mean, if they are around zero degrees C, or maybe zero to 10, operating most of the time in that temperature, I think it is pretty well established, I don't think anybody can argue here, we can prolong life more than if they operate in a higher temperature.

SPARKS: TRW. One thing I should point out, when we talk about going to the lower temperature operation versus other types of operation. As you push the temperature down, the penalty you pay at the spacecraft level for design complexity is becoming extremely large. If you push the temperature down to around 10 Centigrade or so, somewhere in that region, you know, the penalty is not too severe. But when you start pushing it to zero Centigrade and in that region, the penalty really is getting severe, in terms of thermal control systems complexity, and ground control complexity in operating the spacecraft. So we have to be a little cautious about overreacting to the low temperature extreme.

GASTON: RCA. I disagree a little bit on that. I think it is not quite as severe. I think it can be done; and it has been done in many of these programs.

FORD: Yes. I think it depends on the spacecraft design a lot. Most spacecraft just don't lend themselves to low temperature operations. For instance, the spinners operate as a, they are apt to stabilize (?), so, yes; I think

each spacecraft, particularly, the thermal design may be even in fact more unique than the battery design.

PASCHAL: Marshall Space Flight Center. In looking at the hardware that we have put in the breadboard of our reconditioning circuit, I don't see a real substantial increase in weight. Yes, there is some weight addition when you add a reconditioning system to the battery, but the ones that I presented a little while ago before lunch, there, are not too heavy from a weight standpoint. So I don't believe it is too excessive a penalty to pay, and as a using center, of course, we have to take the hardware that is available.

Of course, ideally, yes, we would like to go back and look into the cell, and redesign the cell, this sort of thing. But where you don't have the dollars to do that, and I think we are talking possibly of substantial dollars and substantial periods of time, what do you do to get the life that you need in the most economical manner?

I think it depends on how you operate the system; and reconditioning, as outlined, is one tool. Now whether that is the best way to go, there is some question. But that particular circuit does offer advantages of reconditioning. It offers advantages of holding up a weak cell; and here again, there is a problem of matching the cell characteristics, of determining whether you have got a weak cell or not. How much do you expend to match the cells to make sure that they perform on the same level; that they all discharge and charge at the same voltage level? So I think we have to consider that the added weight, where there is no cell redesign, is just one way of achieving a longer life and holding your system up.

FORD: Let's take about two more quick comments and questions, then I think we are going to move on. Gerry told me I had to summarize, and I am not sure how you summarize what has been said.

HOLCOMB: NASA Headquarters. I just wanted to ask Etheridge Paschal Paschal a question. On the 25-kilowatt panel how many pounds or kilograms of batteries are there, and what would there be, to give an example of what the reconditioning weight would be for that.

PASCHAL: In the 25-pack module, in the 25-kilowatt power module, we are talking of somewhere like 12 to 16 batteries, depending on what the final depth of discharge and operating temperatures are. And the batteries are something on the order of, oh, 170 pounds; we are talking of 16 batteries up to almost 11,000 pounds.

HOLCOMB: It is a different ball game than the rest of them.

PASCHAL: Yes.   So the weight of reconditioning carries forward when you look at that type of figure.

WEBER: COMSAT.   One of the things, the cost involving adding your reconditioning circuits, it may only be a half a pound or pound of weight in the power subsystem; but you need housekeeping telemetry, a command system, additional wiring on it; so a lot of these things were considered for Intelsat V, and the impact of adding a half a pound to the battery resulted in several pounds for the spacecraft and had to be traded off on its utilization.

PASCHAL: In the system I presented this morning, I see one added telemetry measurement, and that is on this current sensor, within the reconditioning network.   So there is a little additional instrumentation, but here again, I think that the weight we are talking about it is far in the background.

HOLCOMB: This has to do with this whole area, and I was going to mention this yesterday.   We have another program that is not in the battery area per se, but it does relate directly to the battery area.   We are trying to develop what is called an automated power system management capability on a spacecraft.

It basically consists of a dedicated computer for the power system with microprocessors for each of the major subsystems, including microprocessors for a battery subsystem, which would be fed to various sensors and would do all of these functions, plus it would record the visual data from the sensors and could be coded so you would send it out and minimize the number of channels.

It gets into the operational problem we had yesterday, you were talking about having to have "babysitters" all day long, watching the batteries.   So I think there are design approaches to the power system that can make reconditioning, integrate it, say, into a power system management capability like this, to be beneficial.   And it can also attack the operational problems, the cost of having people around all and every day, watching; so there are system approaches that can be taken that can help integrate this problem, and we are working on that in another side of the house.

FORD: In summary I think from what I have heard so far, there is no cure-all.   Just like we have many cell designs, we have many approaches to how to live with those cell designs, including reconditioning as one method.   And within that category, it seems like we have talked about three or possibly four different methods of reconditioning or techniques of reconditioning.

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It wasn't inherently clear to me that one offers a superior advantage over the other. I think that is still a controversial question that we will probably discuss again next year, if we have this topic matter, and it seems to be a favorite among the group.

CAPACITY MEASUREMENT SUMMARY

GE 20 AMPERE-HOUR CELLS
PACK 1 I - CRANE

| | AMPERE - HOURS | | | | | |
	C-1	C-2	C-3	C-4	C-5	CYCLES
PRE-LIFE	-	-	-	-	28.5	
6 MONTH	-	-	-	29.6	29.6	29/5
12	-	-	-	26.4	26.4	5806
18	-	-	-	NO DATA		8765
24	27.1	-	-	23.5	23.9	11,443

(CONVENTIONAL)

NOTES:
(1) CONVENTIONAL DESIGN
(2) 25% DOD, 20°C
(3) AMPERE HOURS TO FIRST READING BELOW 1.0 VOLTS

Figure 216

CAPACITY MEASUREMENT SUMMARY

GE 20 AMPERE-HOUR CELLS
PACK 1 H - CRANE

| | AMPERE-HOURS | | | | | |
	C-1	C-2	C-3	C-4	C-5	CYCLES
PRE-LIFE	-	-	-	26.3		
6 MONTH	-	-	-	23.6	25.5	2912
12	-	-	-	17.3	19.3	5726
18	-	-	-	NO DATA		8746
24	15.5	-	-	16.7	19.3	11695

TEFLON DESIGN

NOTES:
(1) TEFLON DESIGN
(2) 40% DOD, 0°C
(3) AMPERE-HOURS TO FIRST READING BELOW 1.0 VOLTS

Figure 218

DISCHARGE VOLTAGE PROFILE
GE 20 AMPERE-HOUR Ni-Cd CELLS
CONVENTIONAL DESIGN
PACK 1 I

PRE-LIFE TEST

11,443 CYCLES
6 MONTH CAPACITY
DISCHARGES

11,443 CYCLES
2 YRS. CONTINUOUS
CYCLING

TEST CONDITIONS: 90 MIN. CYCLE (34 D - 60 C)
20° TEMPERATURE
25% DEPTH-OF-DISCHARGE (C/2 RATE)
1.480 V/CELL LIMIT
10 A CHARGE CURRENT LIMIT
105 TO 110 C/D RATIO

CELL VOLTAGE - VOLTS

CAPACITY - AMPERE HOURS
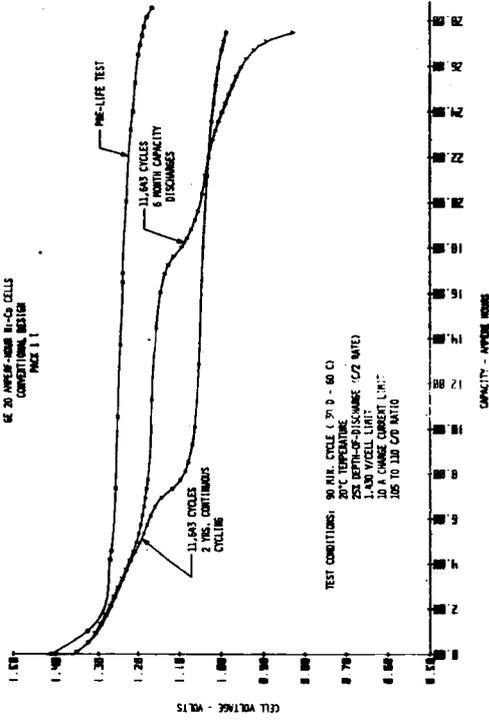
Figure 217

DISCHARGE VOLTAGE PROFILE
GE 20 AMPERE-HOUR Ni-Cd CELLS
CONVENTIONAL DESIGN
PACK 1 J

PRE-LIFE TEST

11,679 CYCLES
6 MONTH CAPACITY
DISCHARGES

11,679 CYCLES
2 YRS. CONTINUOUS
CYCLING

TEST CONDITIONS: 90 MIN. CYCLE (34 D - 60 C)
0° TEMPERATURE
40% DEPTH-OF-DISCHARGE
1.490 V/CELL LIMIT
16 A CHARGE CURRENT LIMIT
102 TO 105 C/D RATIO

CELL VOLTAGE - VOLTS
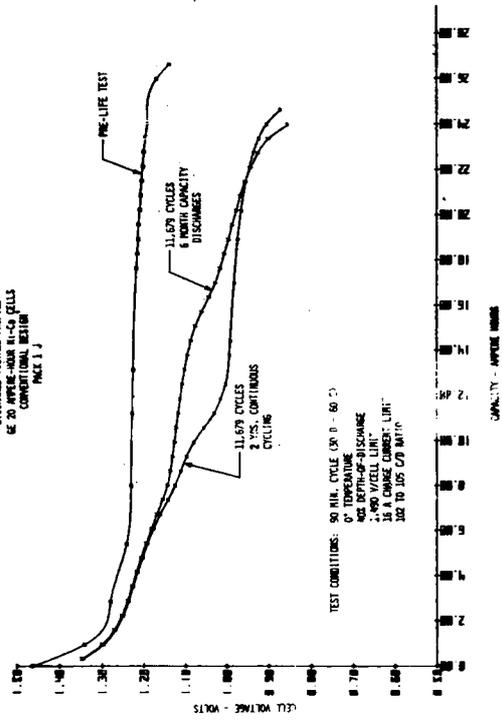
CAPACITY - AMPERE HOURS

Figure 219

AMPERE-HOUR CHARACTERISTICS AFTER TWO YEARS

GE 20 AMPERE-HOUR Ni-Cd CELLS
90 MINUTE CYCLE

PACK NO (CRANE)	DOD %	TEMP. °C	AMPERE-HOURS TO 1.0/0.9 VOLTS					CELL DESIGN
			C-1	C-4	C-5			
1H	40	0	14.8/25.1	16.8/25.5	19.3/25.1			TEFLON
1J	40	0	12.5/24.0	20.2/24.6	18.2/23.4			CONVENTIONAL
1I	25	20	26.7/29.2	23.5/26.3	23.9/24.7			CONVENTIONAL
1G	25	20	DATA NOT RECORDED					TEFLON

NOTES:
(1) PACK 1H AND 1J DISCHARGED AT 16.0 AMPS.
(2) PACK 1I AND 1G DISCHARGED AT 10.0 AMPS
(3) TEFLON DESIGN HAS 79 CC OF KOH, CONVENTIONAL DESIGN HAS 69 CC OF KOH

Figure 220

GULTON 6 Ah NICKEL CADMIUM CELL
VOLTAGE AND CAPACITY CHARACTERISTICS
AFTER 5051 CYCLES
DISCHARGE RATE - 3.0 AMPERES
TEMPERATURE - 20°C

CYCLE PARAMETERS
TEMPERATURE - 20°C
DEPTH OF DISCHARGE - 25%
CHARGE CURRENT LIMIT - 3 AMPS
VOLTAGE LIMIT - 1.417 PER CELL
CYCLE TIME - 90 MINUTES

Figure 221

CAPACITY DECREASE IN 12 AMPERE-HOUR
CELLS CYCLED PRIOR TO PRECHARGE
IUE PROTOTYPE CELLS

TEST CONDITIONS
TEMPERATURE — ROOM AMBIENT
CHARGE — C/10 FOR 16 HOURS
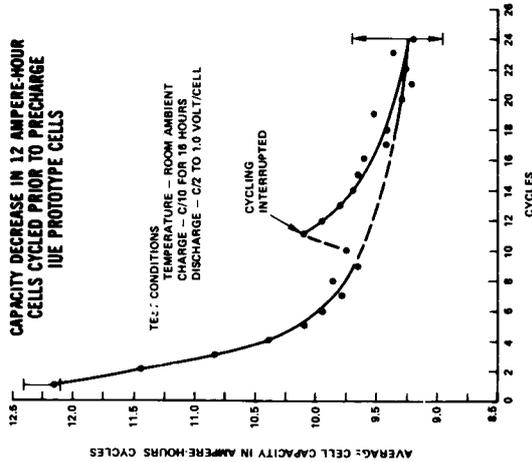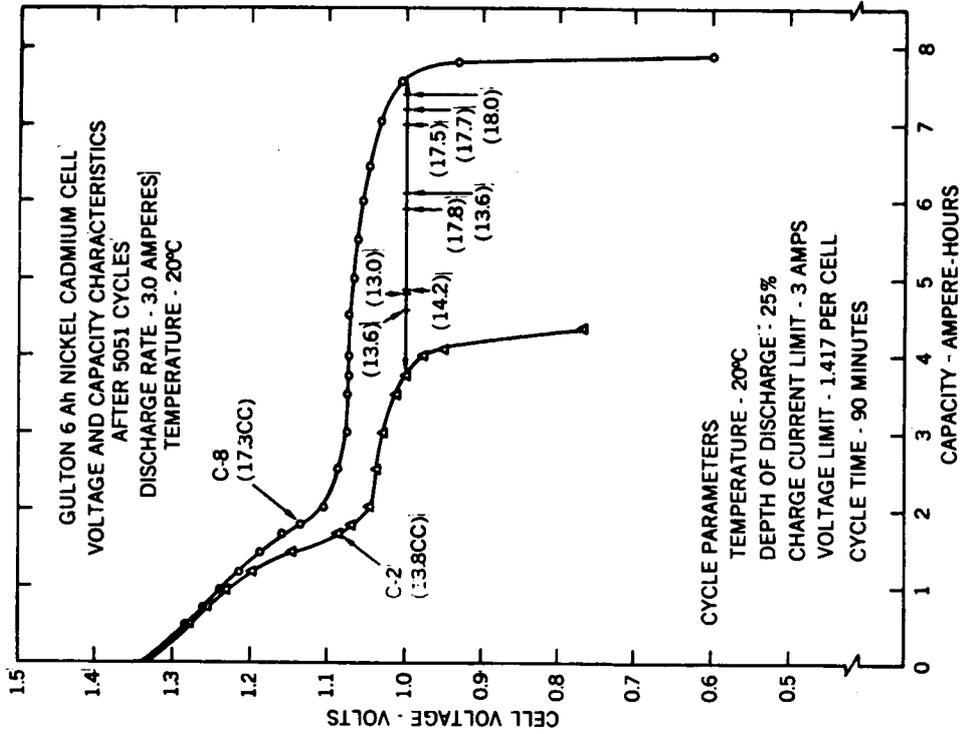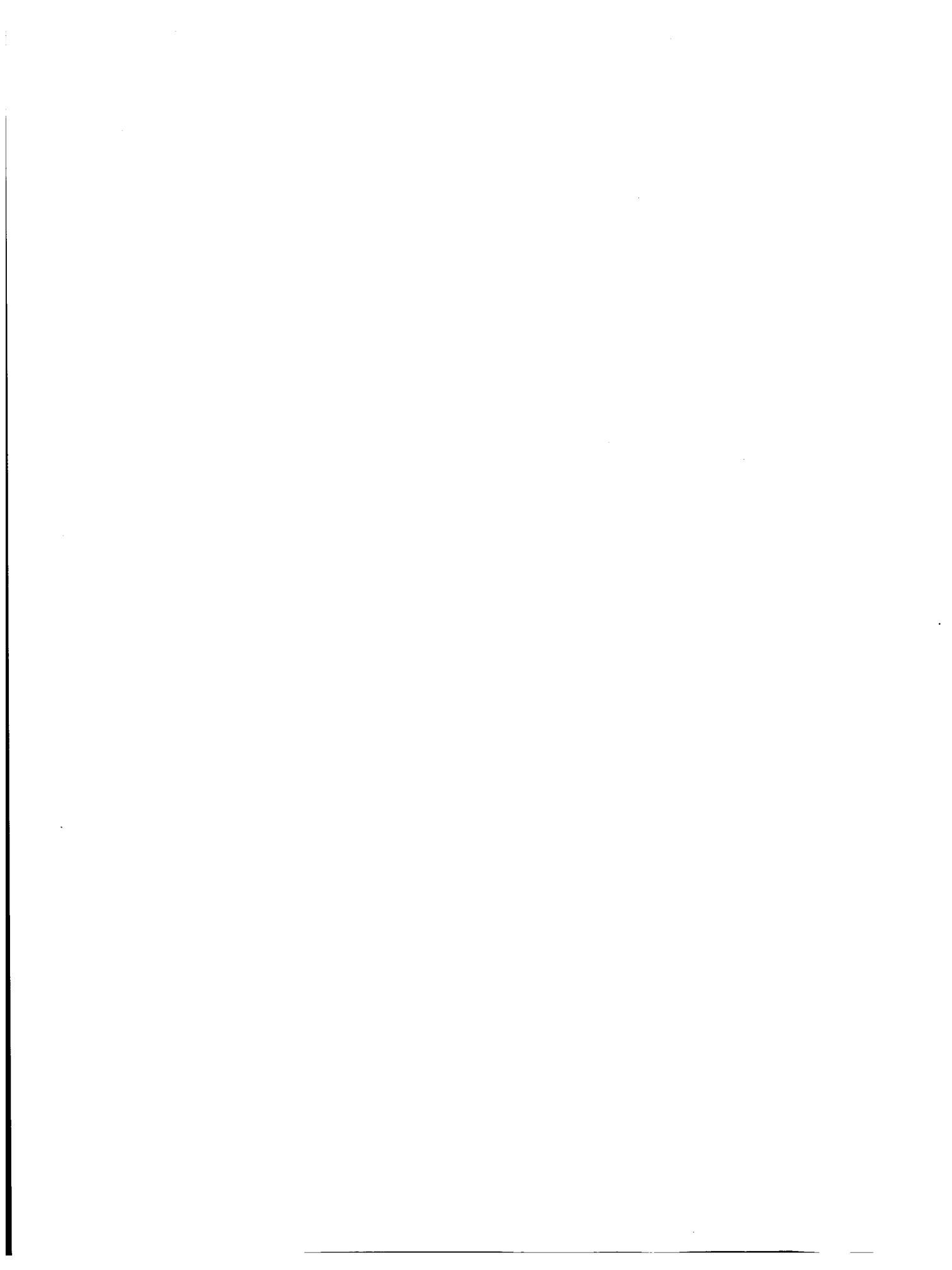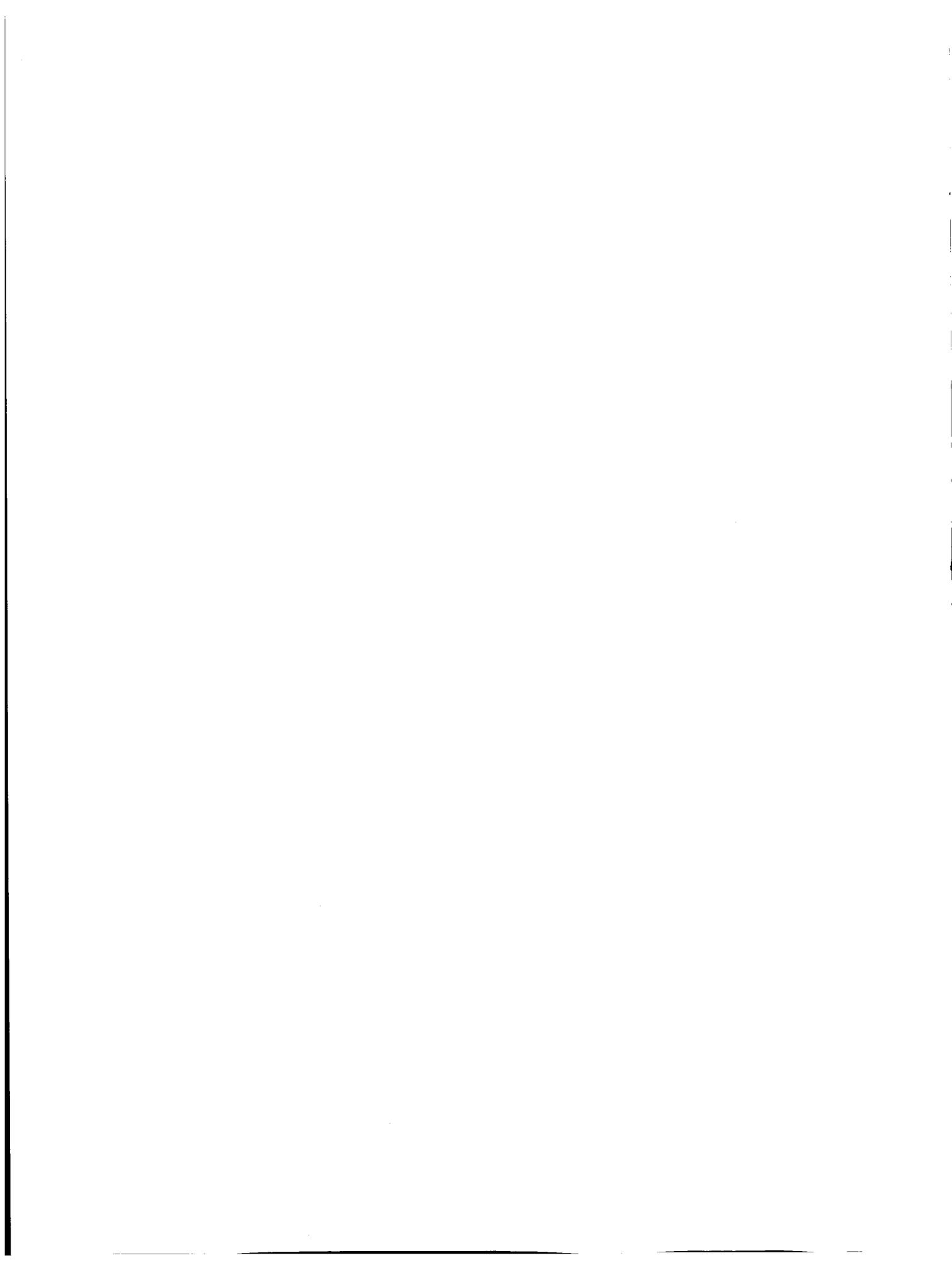DISCHARGE — C/2 TO 1.0 VOLT/CELL

CYCLING
INTERRUPTED

Figure 222

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SESSION IV

COMPONENTS AND MATERIALS

J. Lander, Chairman
Air Force Aero Propulsion Laboratory

DETERMINATION OF OVERCHARGE
PROTECTION

W. R. Scott
TRW Defense and Space Systems Group

Before I get into the main thing I want to talk about, I would like to show you a graph that is the plot of the data for separator, nylon separator degradation and the function of temperature, as determined by Lim and published in several different places.

And the reason I want to show this, one reason is, that I don't think I have seen this particular plot in this fashion.

(Figure 223)

Namely, on a semi-log curve, as a straight line of time required for 10 percent hydrolysis of nylon six separator, the solid line is a plot of the data published from the publications available, using, I guess, what appears to be the latest activation energy value obtained for this reaction as far as I am aware. Maybe there is some better data available.

The only reason I really want to show this is to indicate the rather extreme temperature sensitivity of this function. Granted, it is true that at 25 degrees it appears that there is 10 percent hydrolysis in about 7.6 years, which, if converted, if all hydrolysis products are converted 100 percent into a change in the pre-charge level of the cell, that would mean that you would have in the usual distribution of precharge and overcharge protection in a General Electric cell, you would have essentially no overcharge protection left.

However, all I want you to do is follow this line down here, maybe down to 10 degrees or even 5 degrees, and here notice you are up to something like 75 or 76 years. And even for a change in temperature of five or 10 degrees, let's say 10 degrees, down to 15, you are at a time for 10 percent hydrolysis of 20-some odd years.

So in talking about the disadvantages of nylon separator material in this regard, really, all that is required to extend the failure mechanism due to nylon degradation by this mechanism almost indefinitely, relative to conceivable missions as things stand today, is to reduce the average operating temperature by 10 or 15 degrees.

So because of this, I don't feel like the nylon separators are essentially doomed, as far as use even in long-term missions, because for various other reasons, it is very advantageous to reduce the average battery operating temperature, and that is going to reduce the rate of nylon hydrolysis drastically.

Furthermore, as I indicated, this line is a "worst case" line. It assumes as far as its possible impact on the cell behavior is concerned, it assumes 100 percent of the hydrolysis products are converted into charging the negative electrode. This degree of conversion has not been demonstrated. If one assumes that only 25 percent of the amount of separator hydrolyzed at any point in time is actually converted into a change in the negative state of charge, then we are up, say, on this dashed line, for example. And there, of course, the life of the cell with respect to changing the negative state of charge is prolonged accordingly.

So I thought that just taking a look at this might present a kind of an orientation with respect to the temperature effect that we needed, for a little better perspective on where we are with nylon separators.

Now, this morning I mentioned that we had made a determination of uncharged excess negative, or actually, electrochemically active uncharged excess negative, which is sometimes referred to as "overcharge protection," in some cells that had been stored shorted for four years and then subjected to a life test, and had gotten negative results; that is, the calculated value for excess uncharged negative, using the procedure prescribed, gave us numbers that ranged from minus one to minus four ampere hours in a 24-ampere-hour cell.

Without going into the details of why this may have occurred, or all the extenuating circumstances, we decided to try to apply a different method altogether for measurement of excess uncharged negative, which is a method that Jim Dunlop has mentioned several times in the past which he has tried a couple of times at COMSAT. And it involves simply charging up the cell, venting the cell when it becomes fully charged, and continuing to overcharge and vent gas, analyzing the gas as a function of time, and looking at the amount of hydrogen involved and looking at the cell voltage as oxygen and/or hydrogen is evolved from the cell.

And by doing this process, one simply is further charging the negative; and when you presumably get to the end of the electrochemically active, or chargeable, negative reserve, the cell will start to generate hydrogen, and that is the end of the useful excess capacity of the negative electrode.

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There are some questions as far as interpretation of this kind of data which I don't want to dwell on at the moment. I am not really sure exactly how best to interpret the data. I just wanted to show you what some of the data looks like for information and comment.

(Figure 224)

First of all, we did this kind of venting and overcharging on two cells that had been stored, that were fairly new cells, at least relatively uncycled cells, that had been stored shorted directly after our incoming receiving and acceptance testing, and had been on the shorted stand at a fairly cool temperature for a couple of years, and then we simply took them out and reconditioned them and went ahead and charged them up.

And the results of those two cells are shown here; call them Cell "A" and Cell "B". They are otherwise identical cells. They just have a little bit different characteristics.

At the top is shown the cell voltage during the vented charge. The center plot is a plot of the volume percent of hydrogen in the gas, as it was vented from the cell. We analyzed the gas continuously by passing it through a thermo-conductivity bridge, and where the output was balanced against the oxygen gas on the other side of the bridge, and it was calibrated in terms of volume percent hydrogen and oxygen.

The bottom plots are the percent of the ampere-hours of oxygen vented as a function of the total ampere-hours charged in the cell, which is shown along the bottom axis. That is, the cells were recombining oxygen all during this vented charge, so that only a fraction of the total amount of oxygen generated by the charge actually leaves the cell. And this bottom plot shows that fraction as a percent, the oxygen vented, versus the total amount of ampere hours that was passed through the cell.

So what this shows is that first of all, we charged these cells up; these results were all done at 15 degrees C, as indicated here. We charged the cells up at a C over 15 rate, 1.6 amperes, and when we charged them up with approximately a 125 percent recharge, and then started the venting.

And at the beginning, first of all, you can see from the hydrogen plot that the gas was essentially pure oxygen initially, as you would expect, or you would hope. And the amount of oxygen vented as a function of the total theoretical amount that was regenerated by the charge current was a little over 10 percent.

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And then as the charging and venting continued, that percentage dropped down and sort of leveled off at about 5 percent. This means that out here, approximately 95 percent of the oxygen gas actually being generated in the cell was being recombined, and only 5 percent was being vented. The venting was being done at essentially atmospheric pressure, just a few inches of water pressure above one atmosphere.

The second set of curves shows that until you get out here somewhere between eight and 10 ampere hours of oxygen removed from the cell, therefore, of the change in state of charge of the negative, that there was essentially very little hydrogen in the gas, and then it gradually started to increase out here, and these are just the two different cells, with a little bit of spread between them.

The question, the thing is, that with 95 percent of the total oxygen gas being recombined, this indictaes that within the cell, at this point, for example, although the percentage of hydrogen in the effluent gas was only about 1 percent, you have to divide that by 20 to get the actual fraction of the total charge current that was going into hydrogen within the cell, because the hydrogen was being concentrated by the fact that most of the oxygen is recombined; so that the actual rate of hydrogen evolution at this point is still extremely small.

And actually, even when you get up to 10 percent, that means that the actual rate, relative amount of hydrogen and oxygen, the relative amount of hydrogen is only about a half a percent of the total charge current, up to this point. This is what I mean by the fact that these results have to be interpreted in some arbitrary fashion.

The question is: When are we at the end of overcharge protection? Is a half a percent of hydrogen in the oxygen being generated in the cell a dangerous condition? Should we consider that the end of the useful overcharge? I don't know exactly. Maybe someone would like to comment on this. I do have a couple of other pieces of data to show you that might help in that regard.

But now, in addition to hydrogen generation, there is another, possibly more important, consideration, and that is the cell voltage. If you have a system designed to operate with a certain end-of-charge voltage, note that the charge voltage is pretty constant until you get out here to about the same place where the hydrogen percentage starts to increase. And then that voltage starts to increase.

And in one cell, the increase was very gradual and very slight. In the other cell, it was considerably more rapid out here; so that possibly, somewhere out here one could say from an end-of-charge voltage standpoint that you had

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reached the end of the useful overcharge protection available as far as your particular application is concerned.

All of these numbers are probably also a function of the operating temperature and of the charge current used. So that it just makes the point which I believe Dean Maurer has made a couple of times in the past, that the effective overcharge protection is a function of all of these variables, and isn't any single number for any particular application.

Now, you might say, well, okay; there is the voltage of the cell in a vented condition. What has that got to do with the real world, and a sealed cell? I have a partial answer to that. By the way, this work is still continuing, so these represent just interim results, here.

(Figure 225)

At one point, we closed up cell B. This doesn't say so, but this is after six ampere hours had been vented, in terms of oxygen, from cell B; and what we did was close the vent, go back to a low trickle-charge rate for a while, noted that the voltage and the pressure decreased down to fairly normal values, even after having vented six ampere hours of oxygen. So then after we had attained a steady state under those trickle charge conditions, again at 15 degrees over here, then we again put, increased the current back up to 1.6 amps, and followed the voltage and the pressure for a period of eight hours. This was under sealed conditions.

And this is what happened. The voltage peaks out at almost 1.53 volts, and then gradually declines and levels out at about 1.51 volts. The pressure gradually builds up; it looks like it is starting to level out here. This is absolute pressure, by the way, not gauge pressure.

Now, in this particular application, we don't ever overcharge the cell at this rate for this length of time. We are always in trickle charge long before we get to this degree of overcharge, of course; and the cells are not vented in this way, but I think the interesting thing is that except for the voltage characteristic, which goes well above -- Well, this particular battery has a 1.5 volt per cell upper limit; so obviously it is going to -- And the current is tapered as soon as the battery voltage reached that limit as an average, so obviously, it is probably never going to get to see anything close to 1.6 amps at this state of charge.

But still, as a sort of an extreme condition, we thought we would take a look and see what the pressure and voltage would do under these conditions.

This is where the hydrogen percentage and the voltage start to take off, as I showed you on that previous graph. I am not sure how to interpret that either, yet. But it is one more piece of data.

(Figure 226)

Now in addition to that, I will show you one more. These are voltage versus current plots. The lower dashed line is a plot of the voltage versus current for these 24 ampere hour cells before any gas was vented from the cells; that is, when they were essentially as we started out in this experiment; and you can see that slope there.

Now the curve with the squares is a similar plot, up to four amps in this case, from one of the two cells that I have just talked to you about, which are essentially new as far as cycle life is concerned. After venting six ampere hours of oxygen you can see the change in slope.

Now we are starting to work on cells, as I mentioned, that have been stored four years and then have been put through a life test. Unfortunately, I didn't make a plot of the voltage versus oxygen vented on those cells; it got left off of that other plot. But what happened on those cells is that the voltage began to increase very rapidly as soon as those cells started to vent; and by the time that we had vented four ampere hours from those cycled and stored cells, we were up to about 1.6 volts, and we decided to stop there, arbitrarily.

At that point in time, interestingly enough, all the way up to that voltage the gas was pure oxygen; no measurable hydrogen. And at that point, then, we sealed up the cell and did a voltage-versus-current stand and that is the data plotted in the solid squared. It goes on up off the chart up here to 1.6 volts at four amps. It is almost a very good straight line, linear with current, whereas these others are all sort of logarithmic with current.

I am not quite sure what is really happening, why that should be a straight line. It looks like just a high internal resistance, but the cell otherwise behaves fairly normally, or at least behaves quite normally. It had completed 10 eclipse seasons of accelerated life test behaving electrically in a very fine manner. So this is the range of voltage versus current in overcharge that we get as a function of the amount of oxygen vented, and therefore the amount of shift in precharge level that we have introduced into these cells.

As I say, we are still experimenting with the cycled cell. We are still going to be doing more of this work with the new cells, in trying to understand exactly what we have got here; and we are trying to determine whether this is

basically a better method to determine uncharged excess negative than the method involving a prior discharge, recharge, and then further discharge, such as described in the NASA spec.

It is true that this method is quite slow. It usually takes on the order of two or three days of charging in order not to have to push the cell too hard, and not have to force any premature hydrogen evolution. If you have that much time, then it might be a worthwhile method, at least to check the other method of determining uncharged excess negative.

DISCUSSION

SEIGER: Yardney. Two questions. When you have that cell recombining about 90 percent of the oxygen, did the cell start to warm up? Were you able to determine a thermal effect due to the recombination of that 95 percent oxygen, during the overcharge? That is one question. The other: We see from your data that you have a hydrogen evolution and an oxygen recombination occurring at the negative electrode at a common potential. Did you also look to see whether there was a third process, the charging of cadmium, so that we can have three electrochemical processes occurring at one potential?

SCOTT: First of all, we had no way of measuring any thermal effects under this setup. We didn't really plan to, and the setup just didn't lend itself to that sort of thing. Certainly, I guess, I had occasion to put my finger on the cells occasionally, and of course, they were on a 15-degree heavy-duty base plate, solid aluminum, and the thermal mass was so much that I don't think, you know, you couldn't have ever been able to feel it, anyhow. You say the second question is do we know whether the cadmium was charging?

SEIGER: Simultaneously with the oxygen consumption and the hydrogen evolution; did you have three processes occurring at one single potential?

SCOTT: Well, maybe I don't quite get the gist of your question, but I don't see how we could be venting oxygen and not charging cadmium. Are you talking about mechanistically, or what?

SEIGER: No. We have observed this at a zinc electrode, that you can have three processes occurring at one single potential. You can't have, as you showed there, an oxygen consumption, a hydrogen evolution, and then you can calculate from the residual current that you are still charging that zinc oxide into zinc. I said in the zinc system, we spotted that, and I was wondering if you saw a similar case in the cadmium.

SCOTT: Well, we had no way of independently measuring the state of charge of the cadmium plate coat.

DUNLOP: Just a quick comment. Your basic data implies that those three processes were going on, because the percentage of the hydrogen kept increasing, and the assumption is that you are going to continue, you have got oxygen recombination, but you are continuing to charge the cadmium electrode a little bit more, until eventually all, if you keep this going, I think Will would probably say if you kept this going, pretty soon hydrogen increasing and no longer charging, and essentially you have only got two processes; hydrogen evolution and oxygen and nothing else.

SCOTT: The farthest we went was to about 50 percent hydrogen in the evolved gas, which means at that point I think it was like less than 5 percent of the total charge current going into hydrogen in the cell. And the voltage was so high at that point that, you know, we didn't feel it was worth continuing.

ELIASON: Ford. Have you been able to interpret the results to the extent of what the answer should be, on your uncharged negative? Have you run a comparison?

SCOTT: Well, we have not; the only comparison data that we have right now is this data that we got negative numbers on, that I told you about, which indicates that that test method is not working very well for us. On the one cycled cell that I showed you data for here, it gave us four ampere hours to 1.6 volts. Now granted, that is a lot of voltage; I mean, you can't really utilize that. Probably it was more like one or two ampere hours to 1.55 volts, I would say. So maybe that indicates that at least there is that much utilizable, or at least chargeable negative excess in that cell, whereas in another cell from that same battery, with the same history, we got negative results with the other analysis procedure. So there is quite a discrepancy.

LIM: Hughes. I would like to make a couple of comments about the data that you quoted from our nylon studies. The data on the viewgraph is the correct up-to-date data, but I would like to point out that is the data for 34 percent KOH, and the rate is somewhat different, which I am going to talk about later; and it appears to me that there is a little bit of confusion about the rate of the oxidation of the hydrolysis product.

We postulated a six-step oxidation mechanism, and we could confirm up to the first four steps. And there is some evidence that it goes all the way down to carbonate, and starting from a 6-amino-caproid (?) to carbonate, from some of the people's data.

And we observed that the first four steps were quite fast; it was a matter of days. And I believe that is not the rate-limiting step at all; so your postulation of a 25 percent oxidation, I think, is not realistic postulation of actual data, I mean, of actual operating conditions of the battery.

SCOTT: I would like to see some of that data. I have not seen it; so that was simply a gimmick to indicate what the shift in the conclusions would be if, indeed, only 25 percent of the actual amount that was hydrolyzed initially truly ended up, at the end of this long chain of degradation and conversion to negative pre-charge occurred -- You know, there are a lot of assumptions, I still think, in that chain of events. And it just indicates the possible range of uncertainty that we are talking about.
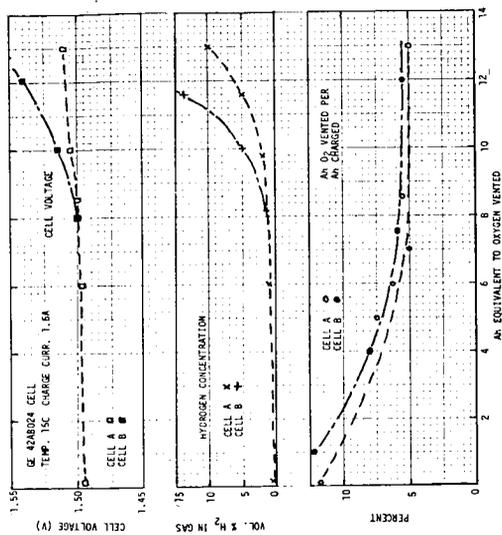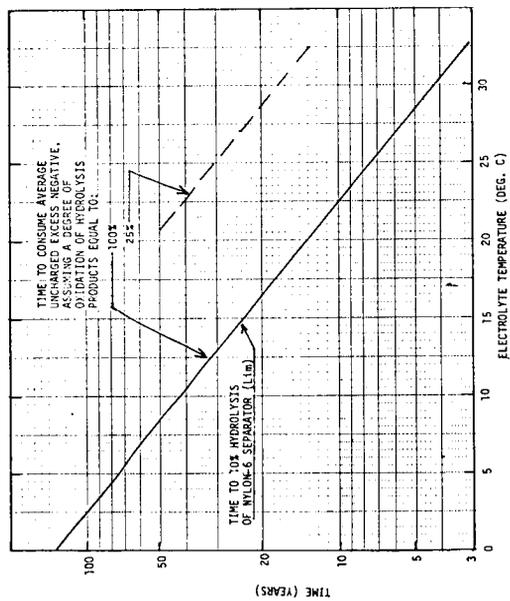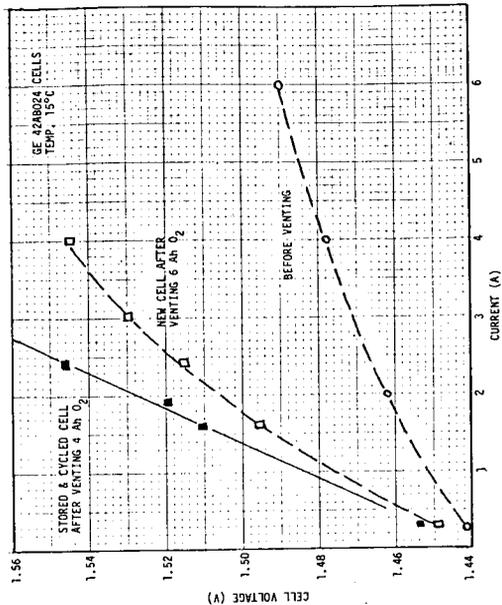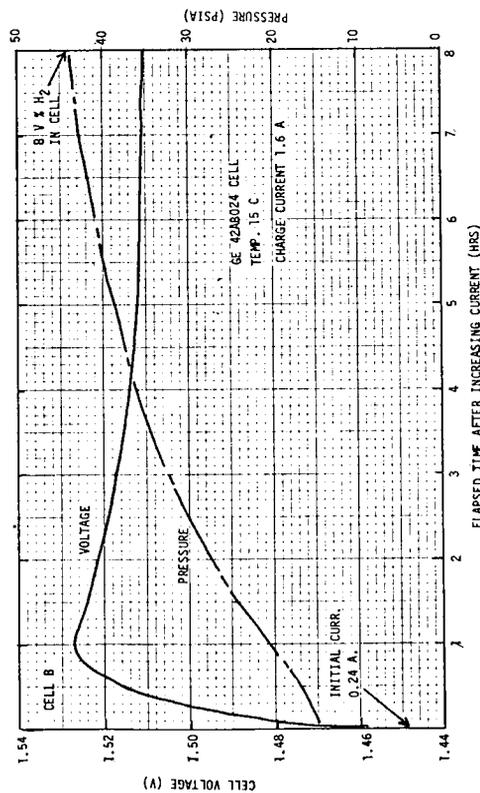
Figure 224

Figure 226

Figure 223

Figure 225

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CERAMIC/METAL SEALS

A. M. Bredbenner
Ceramaseal, Inc.

It almost seems a little inappropriate for me to be standing up here talking about ceramic or metal seals for aerospace batteries, when that is probably one of the least things you have to worry about these days, but maybe a little change of pace might be interesting at this point.

My memory goes back to the early '60s, the mid-60s, when the ceramic to metal seal was required for aerospace batteries and a search was on, and it so happened that Ceramaseal had a tailor-made process which would fit right into ceramic to metal seals which would hold up in the alkaline environment of a nickel-cad battery system. It was a silver braze alloy, silver-copper braze alloy, using an active metal process which was alloyed with titanium, and tests indicated that it would hold up well.

And then these batteries got moving along for several years or so, into the early '70s; I remember Intelsat IV pretty vividly, where I think our seals got involved in the batteries.

And then as this progressed along, the problem of silver migration came along; so how to get rid of silver in the system and improve the battery, especially going to a longer life of batteries; and so another tailor made braze system, the nickel braze system, nickel-titanium system, came along which G.E. had developed and had patented, and Ceramaseal made a quick exit from the aerospace battery business, and we haven't been there probably since 1973 or 1974.

Then more development came along in battery systems. The electric car was being developed; and along came the lithium metal sulfide battery, and the need for a hermetic seal to seal off the battery. When they came to Ceramaseal for suggestions, well, we said there is the nickel-titanium system and several other people who have some systems that are apparently working very well, why don't you try them? And they said, "They don't work. What can you offer?"

At the time, the only thing they had that worked was kind of a "crunch" deal of boron nitrite squeezed down against the center electrode and the outer casing, which worked very well. It had a leak rate of somewhere around 10^{-5} atmospheres cc's per second of helium, but they wanted something better.

So after thinking about it a while, and not knowing of any braze system that we could really offer, we decided to try a mechanical seal ourselves.

The presentation that I am going to give you, then, is something that we have offered to solve this problem. It is a mechanical seal, but it could possibly find applications in aerospace batteries, so that is why we are here today to present it.

As you know, the lithium-metal sulfide battery system operates around 450 degrees Centigrade. The electrolyte is a molten solid lithium-potassium chloride; and so the seal system required there has to withstand this environment.

(Figure 227)

The seal system consists essentially of a ceramic, which is item number 16, and two metal sleeves, item 14 and item 24. Now, this assembly can be put together as it is shown there with the conductor assembly all put together, consisting of items 24, 26, and the conductor, 28. It can be brazed or welded together; and that assembly is then pressed onto the ceramic.

Or the other sleeve, item 14, can be preassembled to the cell cover, item 10, and then this assembly is just simply pressed together. You see the ceramic consists of two tapered areas on each end leading to a corner on which the ceramic and metal seal is effected. There is an interference bit between the parts, and as they are pressed together, you will notice area "P" there is a malleable coating which is put on the metal part, so that when you press it together, this malleable coating presses over the corner and produces a hermetic seal.

The metal part is just pressed slightly beyond the corner there; and you can get leak-tight seals in the area of one times 10^{-9} atmospheric cc's per second of helium. There are a lot of advantages to this seal, because you have a ceramic; you can work with any variety of ceramics. Thermal expansions aren't as critical as they normally are in other ceramic-to-metal seals, and the thing is pretty simple to put together.

(Figure 228)

In this older figure I just indicated a little bit on how you go about designing this type of seal. The metal part that you are pressing onto the ceramic should be of a metal that, when you press it together, you don't exceed the yield strength of the material; you want the thing to be on there within its elastic limits, so it can cycle back and forth and not begin to leak.

Now, just a simple stress formula: If you figure stress equals the strain in inches per inch times the modulus of elasticity of the material, and in our particular case we worked with about 5,000 of an inch per inch of strain. So if you multiply that times the modulus of elasticity of a typical material, which is 30 times 10^6, you see you need a material with a tensile strength or a yield strength in the area of 150,000 psi.

Now, since you are putting that type of strain on the metal part, you need a ceramic with a compressive strength exceeding that or, as I indicated here, say, over 300,000 pai; 95 percent alumina or beryllia or any ceramic that you can come up with that has a compressive strength in that range would be acceptable, and could be used.

The metal thickness that is required here varies by some constant times the cube root of the diameter. Now, "K", this constant, would vary with the ceramic strength, where the wall thickness for this ceramic was the actual ceramic compressive strength. Typical values of K for alumina are about .05.

The maximum use temperature, and as you recall, we talked about the lithium-metal sulfide battery had to operate at 450 degrees Centigrade; so we press this metal part on there, and we have a residual stress of about 5/1000 of an inch per inch. So as this heats up and the metal part moves away, we need to maintain at least a residual strain of 2/1000 of an inch per inch. So if you figure your expansion of ceramic versus your expansion of the metal part, you can calculate where you are going to be, what temperature you can go to and still maintain this strength.

And under item 5 here, I have listed a couple of typical materials that have very high yield strengths that might be considered. There is a whole raft of them, and this is just a small number that I picked out.

That first material there, 17-4 pH stainless steel, has a typical composition of 17 percent chrome, 4 percent nickel, 4 percent copper, and the balance is iron; and that has a heat-treated yield strength of 185,000 psi. Inconel X-750 has 15 percent chrome, 76.75 percent iron, 2.5 titanium, .85 columbium, 0.7 manganese, and 0.8 aluminum. Now, that is a little lower, 120,000 psi; and in this particular case, I would work with a little less strain, something down around 3/1000 of an inch per inch, or maybe four, to effect that seal.

AM-350 stainless steel has a chrome percentage of 17 percent; nickel, 4; molybdenum, 3; and iron is the balance, and that has a typical yield strength of 173,000 psi.

One typical unit, then, that we have put together and tested is using 99-1/2 percent beryllium oxide, 17-4 pH stainless steel, and the malleable coating that we used -- Well, we have used a number of them. Copper is one, silver is another, gold can be another. In the case of the lithium-metal sulfide battery, we even used moly-disulfide, and it worked.

The particular combination of metal used was 17-4 pH stainless steel. We used copper as the metal coating and 99-1/2 percent beryllia as the ceramic; and we pressed that together and then put heating tapes around it, heated it up to 450 degrees Centigrade, and leak-tested it at that temperature. And we maintained a leak rate of better than one times 10^{-9} atmospheric cc's per second of helium.

The major problem that is encountered in the lithium-metal sulfide system; the materials appear compatible and there is no problem, except that there is a problem of stress corrosion due to the high strain on these parts. In the silver cadmium cell it is particularly bad. If you were in an alkaline situation, the problem wouldn't be there. Heating an acid or a nautral system of chloride salts, stress corrosion is a real problem. So a coating is sometimes required over the metal part which will protect against stress corrosion, if the particular material that you are choosing is subject to stress corrosion that you are working with.

DISCUSSION

ROGERS: Hughes Aircraft. If I understand that seal correctly, you have a center conductor of a high-strength alloy, which are notoriously bad conductors. Now how do you apply such a seal to a high-current battery for lower temperature use?

BREDBENNER: That center conductor wasn't sealed to the ceramic; it just passed through. The seal was effected on the outside of the taper, where the tubular part on the outside pressed down over and made contact there. The center conductor just passed through there.

ROGERS: So you could use something like nickel.

BREDBENNER: You can use anything you want. In the lithium-metal sulfide system, it was molybdenum.

GASTON: RCA. Are there any limitations on the size of diameter of the center conductors; that is to say, is there a critical size for a small diameter or for a large diameter; what is the present size you are making right now?

BREDBENNER: One that we made had a one-inch diameter; the center conductor was a quarter of an inch.

DESIGN CRITERIA

(1) Metal part yield strength cannot be exceeded.
    Normal interference of .005"/in.

$$S = \epsilon E$$

ϵ = Strain (in/in)
E = Modulus of Elasticity
S_c = Hoop Stress psi

$$S_c = (.005)(30 \times 10^6)$$

$$S_c = 150,000 \text{ psi}$$

(2) Ceramic compressive strength 300,000 psi or greater.
    95% or greater Alumina or Beryllia.

(3) Metal thickness (t_m)

$$t_m = K \; D^{1/3} \quad \text{where } D = \text{Ceramic O.D.}$$

    K varies with Ceramic Strength

(4) Max Use Temp. -- Residual Strain of .002"/in.

(5) Typical Metal Components

Material	Composition	Heat Treat Yield Strength, PSI
17-4 PH S.S.	Cr-17 Ni-4 Cu-4 Fe-Bal	185,000
Inconel X-750	Cr-15 Fe-6.75 Ti-2.5 Cb-0.85 Mn-0.7 Al-0.8	120,000
AM-350 S.S.	Cr-17 Ni-4 Mo-3 Fe-Bal	173,000

Figure 228

FIG. 2

FIG. 1

Figure 227

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EVALUATION OF POSITIVE
PLATES WITH VARIOUS
LOADING LEVELS

G. Van Ommering
Comsat Laboratories

The title of this talk may be a little bit misleading. I am not going to talk only about electrode expansion. There is quite a number of other degradation modes in nickel electrodes that we have been looking at over the past few years.

When we started a few years ago, we began to investigate failure mechanisms of nickel-hydrogen cells. Jim Dunlop mentioned this earlier: One of the typical failure modes we used to see was that a cell that was being cycled, with a separator like polyporpylene or nylon, develops a high impedance after some few hundred or a thousand cycles and dries out, low voltage, and it fails. So you had a pretty good idea that the problems had to do with an electrolyte redistribution, and we started a program with Buckner Appelby at Marc SC in France to investigate what exactly was going on. So he did quite a bit of work on various kinds of nickel electrodes, primarily SAFT type electrodes, which, of course, are very similar to G.E. types which most of us here work with in ni-cads.

One of the variations he put in there was that he looked at several loading levels. He looked at electrodes at normal loading levels, electrodes with about 84 percent of normal loading levels, and electrodes at 69 percent of the normal loading levels.

Now, more recently, we have been looking also at electrochemically impregnated electrodes, which were made for the NTS-2 flight program by Bell Labs, or by Eagle-Picher using the Bell Labs process. And we essentially have been running those electrodes the same way as Dr. Appelby does with his SAFT electrodes. We wanted to get a good comparison of the two types of electrodes, as well as what the effect of loading on them was.

I have a lot of data here on those four types of electrodes, the three SAFT electrodes at different loading levels, and the EI electrode. And in addition, in some of the figures, I will be showing data on nickel-cadmium tests that we have been doing, and some other nickel-hydrogen tests that we had at Comsat to compare them, to see what the effects of overcharge, total cycling rate, et cetera, were.

(Figure 229)

On this first figure I have just shown the four main electrode types. The EI is the Eagle-Picher made Bell Labs type. The other three SAFT types are shown below; "CI" means "chemical impregnation." It doesn't show too much. I guess that probably the most interesting thing to note here is that the EI electrode has about the same amount of nickel hydroxide as that 69 percent CI electrode; so it is a nice straight comparison there in impregnation method. It is about the same loading level.

In actual grams per cc void of nickel hydroxide, those lowest loaded electrodes come to about 1.2, and then in addition to that, there is some water hydration and cobalt. The 100 percent CI electrodes run at about 1.85 or something around that, nickel hydroxide, grams per cc void. So these are the four main ones that we were comparing.

I guess the last column is kind of interesting, because it shows something that I guess most people know, that the EI electrodes show very good utilization, and this is based on capacity measured in the cell; so that is not a flooded measurement, but it is in the cell. You can see that the EI electrode with a considerably lower rate than the CI electrode, even the fully loaded ones, shows better capacity right at the start, and it is considerably higher.

(Figure 230)

We will take a look at the expansion. There is a lot of data on this plot, here. The first three curves to look at are this one, this one, and this one. Those three curves are for the fully-loaded SAFT type electrode, the 64 percent loaded SAFT type electrode, and the 69 percent loaded, respectively. And you can see very clearly that the loading level has a very, very strong effect on the rate of expansion in a cycle which is fairly severe.

This was a three-hour cycle, 1.2 hour discharge, 1.8 hour charge, at a C over 2 rate for both the charge and discharge. So it is 60 percent depth, and there is about 50 percent overcharge at a high rate. That is quite severe.

The next thing to notice is that the EI electrode, which is this curve. It is very close to the 69 percent loaded electrode. That seems to indicate that loading level is one of the determining factors of expansion; that the impregnation method isn't nearly as important there as the loading level.

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Some of the other data here we will look at quickly. That short little curve in the corner is for Intelsat IV and Telesat nickel-cadmium cells, and the real-time tests, both at Comsat and at Telesat. You will see that even though they are run with a lot less overcharge on a relatively mild cycle compared to what we were doing with the other electrodes, they are expanding much more rapidly. It will be very interesting to see what happens once you get to that 2,000 cycles with that type of electrode.

But even with the milder cycling mode, we are developing more thickness there, and a lot of the reason might very well be that those electrodes are operating in a much more starved condition than the electrodes in nickel-hydrogen cells, which normally run fairly wet. So whatever is at the root of the expansion is apparently more severe in a starved system.

One other line to look at is this one here. That is for exactly the same electrodes that this curve is for, but this was at about one-half the cycling rate, with considerable less overcharge. So you can also see that the overcharge, the amount of overcharge, has a very strong effect on expansion. I guess I should anticipate the comment that Dr. Seiger is going to make after the talk, that there is no such thing as expanding an electrode by 125 percent in the cell. It just has no place to go; and this, of course, goes back to his "hard" and "soft" expansion.

In the cell, you will find a bit of expansion, and as soon as you take it apart and measure the electrode, the thing just relaxes. What this curve is, however, is still a measure of the kind of stress you build up in the stack. This electrode really wants to expand, but it can't, and it builds up a sort of equilibrium against the separator, and will tend to squeeze electrolyte out of that, and also some problems associated with that. Now, that is all for expansion.

(Figure 231)

One of the other things that Dr. Appleby found, and which we have been looking at for most other electrodes that we work with ever since, is the changes in the porosity distribution in the electrode. This is just an example, there.

There are two sets of curves, here: One for the fully-loaded SAFT type electrodes, and one for the 69 percent loaded electrodes. You can see that for the new electrode, here at zero cycles, we find a tremendous increase in pore volume, which is plotted on the line axis; after 1,888 cycles, the pore volume has increased dramatically. And of course, a lot of that is simply due to the expansion; you are adding more void volume to the electrode.

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The most interesting thing, though, is that most of this pore volume increase occurs at very small pore radii. We are looking at about a 1,000-angstrom pore radius here. And it seems that most of this new volume that we are getting is in these very small radii. You can also see in this figure that that phenomenon doesn't occur quite as rapidly for the low-loaded electrodes as compared to the standard-type electrodes which everybody today is using for ni-cads; or almost everybody.

Now, this development of a lot of micropore volume is going to have consequences for the electrolyte distribution in the cell. These micropores, of course, can take up an awful lot of electrolyte simply by capillary action; and there is just no way that that electrolyte can ever return to the separator. It is just going to be tied up and it will lead to the cells drying out and eventually failing, due to low discharge voltages.

(Figure 232)

I have got the same kind of curve for the EI electrodes, and you can see that they behave a little better than the other ones, but the mechanism seems to be a basic one. It is something that occurs in every type of electrode. The EI electrode, after 4,000 cycles, has a total pore volume of about .15 cc's per gram of electrode. The 69 percent loaded electrode, chemically impregnated, after 4,400 cycles, is considerably higher at that point.

So the EI electrodes behave somewhat similarly to the low-loaded electrodes; and again, the loading level seems to be a major determining factor in this pore volume development.

(Figure 233)

I will quickly display a figure that shows we have actually measured what happens with these cells when that pore volume starts building up. This shows the percent of total electrolyte in the positive electrode and in the separators for cells that have been cycled up to 3,000 cycles here.

These two curves are for cells with nylon. You can see there is a considerable decrease in the amount of electrolyte in the separator, at this point. In the positive electrode, you find an increase in the amount of electrolyte. Cells with asbestos show the same sort of thing, and I guess Dr. Rogers mentioned something like that, that there is a redistribution in cells with asbestos separators.

We have also measured, or Dr. Appleby has measured, the porosity changes in the asbestos after cycling. And he concluded that the asbestos is

fairly stable, and that it is really the positive electrode which is changing and drawing electrolyte out of the separators; so that the separator can't be blamed for that. It is purely the positive electrode.

(Figure 234)

Now, a few figures to summarize that porosity data, and throwing in the data for Intelsat and Telesat also; that is the little curve in the corner here.

Again, you can see that with cycling, this is the micropore volume that is building up considerably for the 100 percent CI electrodes, the 84 percent, and 69 percent CI electrodes. The EI electrodes are fairly similar to the 69 percent CI. Intelsat IV and Telesat seem to follow this same general trend, but since there were so few cycles on them at that point, it was very hard to say what is going to happen. The best guess you could probably make at this point is that they would follow, eventually, the curve for the 100 percent CI electrodes, and at something like 1,000 or 1,500 cycles, you may begin to run into real electrolyte redistribution problems.

We can skip the same kind of curve for total pore volume, because that doesn't show very much.

(Figure 235)

One other thing to be looked at was corrosion of electrodes that we cycle under these fairly harsh conditions. And shown in this figure, it expresses the change in weight percent of nickel sinter in those electrodes in relation to cycles. That, of course, is very sensitive to how you run the test. If you give a lot of overcharge to these cells, it will corrode considerably faster. I just want to use this to show that there does not seem to be any significant difference between electrodes at different loading levels or different impregnation levels. Everything seems to corrode at about the same rate.

(Figure 236)

One other thing that we have looked at is the change in capacity of the electrodes; and here it is really very easy to see that the EI electrode is definitely superior to all the conventionally-impregnated types, regardless of what the loading level is.

This here shows the in-cell capacity in milliampere hours per gram of electrode; and you can see very clearly that the EI electrode is way above any of the CI electrodes. It is also very interesting to see that an under-loaded

chemically-impregnated electrode, or vacuum-impregnated electrode, behaves a lot better than a heavily loaded standard SAFT or G.E. type electrode.

There has always been a tendency of cramming more material in if you want more capacity, but it seems very clear that the thing to really do is to underload the electrodes somewhat, by which you can extend the life considerably. And obviously, the best thing to do, if you are going to underload it, is to do it by electrochemical impregnation.

Also, we have been looking at electrodes with the electron microprobe, SEM, to see if you can correlate some of the changes that we measure in thickness and microporosity with something we might be able to see inside the electrodes.

What we show here is one of these Eagle-Picher made Bell type electrochemically-impregnated electrodes when they are new, and I hope it is clear enough for everybody. Probably you have seen things like this before.

(Figure 237)

The very bright areas are the metallic nickel, and you can see it is a relatively uniform sinter. The gray areas right around the bright areas are the nickel hydroxide, and the deep black areas are just voids in the plate. If you look at this new electrode, you can see there is very good distribution of active material in this plate.

(Figure 238)

Now, if you look at the next figure, we can see what it looks like after 1,000 cycles. It looks like all the active material is gone, but it is there, and if you could see this better, you would see that the material has lost some of its initial good distribution. It has moved to some of the void areas in the plate, and actually there seems to be a tendency for it to move towards the surface. It is probably clearer on the next figure, which is a picture of an electrode after a little over 2,000 cycles.

(Figure 239)

And here, you can probably begin to see that there is quite a concentration of active material near the surface, especially in the right side of the figure, which is the side on which the separator was, in this electrode.

(Figure 240)

Now, the next three figures show surface views of those electrodes. This is the new one. You can see there are nice little globules of nickel hydroxide; it looks very nicely distributed.

(Figure 241)

The next figure shows that after 1,000 cycles, not much change, that the blobs of nickel hydroxide seem to have grown a little bit, but it gets very dramatic in the last figure where you can see that active material is really accumulating near the surface, and it looks actually like it might be blocking some of it off. Also, when you look at this type of material, this sort of almost a gel-type form, you can imagine that a material like this might have an awful lot of very small pores, a lot of micropores; and while it moves towards the surface of the electrode, it leaves some fairly large voids inside the electrode itself.

(Figure 242)

So by looking at these figures, you can really see that there is a sort of polarization of pore sizes. You begin with a fairly uniform distribution, and after 2,000 cycles, and of course it gets worse still after that, you have a very, very large number of very small pores, and a relatively small number of very large pores, and that those medium sizes are not really changing very much and probably decreasing somewhat in number.

So this kind of process will eventually lead to electrodes or cells drying out due to, number one, the absorption of electrolyte in the micropores and, number two, the fact that the surface is progressively being blocked; the material becomes less and less utilizable, because it is in such large blobs, as it were.

Now, EI electrodes show this as well as the CI electrodes. It seems to be not particularly accelerated for CI electrodes; so again, it looks like the cycling mode is the determining factor in how fast this sort of migration or movement of active material occurs.

DISCUSSION

RITTERMAN: TRW. Perhaps you mentioned it, but I missed it: What was the mode of cycling? That is, were these cycled as nickel-hydrogen cells, as nickel-cadmium cells?

VAN OMMERING: Well, the four electrodes or the four main types, let's say; those were cycled as nickel-hydrogen cells, some of those at marked SC by Dr. Appleby and some of those by us.

RITTERMAN: Right.

VAN OMMERING: So those are all nickel-hydrogen cells in our cycle.

RITTERMAN: That would explain the sort of excessive expansion, because in the nickel-hydrogen cell, you are more loosely held than you would be in the cadmium.

VAN OMMERING: Yes.

RITTERMAN: Do either Dr. Appleby or you have any figures in regard to similar tests done on these plates when they were nickel-cadmium cells?

VAN OMMERING: Well, I showed in that expansion curve (see Figure 230), at the far right inset; you can see that the thickness there is increasing more rapidly than any of the other electrodes.

RITTERMAN: The only thing is, though, that in nickel-cadmium, usually, what I am used to, most of the swelling occurs real early, and tapers off.

VAN OMMERING: There is no way of telling what is going to happen here when we extend this for 4,000 cycles; but just on the basis of what we see here, the best conclusion I could reach here would be that it follows this, because it is the same type of electrode, essentially.

RITTERMAN: Another question. You have only one level of impregnation on the EI; that is at 1.2 per gram for cc void. Have you the intention of trying it at a high loading to see how that would compare? If you just have one level, you can't really say in what direction EI would go if it were impregnated to a greater extent.

VAN OMMERING: I think that if you would use EI electrodes with heavier loading levels, you would see something very similar to what we see here for a CI electrode. That is, there is going to be somewhat more expansion. It may be delayed a bit, initially, but it is not going to be significantly different.

I think we have a pretty good idea that the levels that we work at are just about optimum. In the last Intelsat programs, Dr. Seiger at Yardney did a comparison between EI electrodes with two loading levels; and he also looked at the two porosities on the sinter. And his conclusions were that the lower loading level, if you looked at it, which was relatively close to what we had here on these Bell type electrodes, was optimum for several reasons.

In terms of energy density, that seems to be optimum, and it gives extremely little expansion.

RITTERMAN: I ran 10 years life simulation of geosynchronous orbit with EI electrodes that were made by Dr. Seiger, when he was at Heliotech. And based on the weight gain, the loading was 1.9 grams per cc void, and the swelling was minimal, but, of course, these were in nickel-cadmium cells where the interelectrode was held rigid.

HALPERT: I have two questions. One relates to that figure. You say the expansion from the point at which the manufacturer puts it in the cell or from the point which you exceeded after some cycling?

VAN OMMERING: That is something that I kind of purposely left out to avoid confusion, but I guess it generated the confusion. For practically all the electrodes that you see here, the thickness was measured when we received the electrodes, and build cells with it, and that is what the data is based on.

The only exception there is the 100 percent CI electrode that was run in the nickel-hydrogen cell at the high rate. And that one thickened quite a bit in formation. It started out, well, I guess it thickened about 20 percent during formation; and that 20 percent is not added in here. So if you would add that to the curves, it would start out really here, and wind up almost off the figure.

HALPERT: So that is the percentage of dry weight.

VAN OMMERING: Yes. That is right.

HALPERT: The second question I had relates to the impregnation level. You listed 100 percent versus something reduced, I don't see what the percent was. Can you say something about what the 100 percent was and what the other one was, in terms of the loading of it?

VAN OMMERING: It depends on exactly what you take into account there. If you do it purely on nickel hydroxide, which you measure by chemical analysis, I think it comes to something like 1.8 grams per cc void.

HALPERT: That is the 100 percent?

VAN OMMERING: For the 100 percent; but you have to add to that cobalt and water hydration; so altogether it winds up something like 2.1, or whatever.

DUNLOP: I think the electrochemically-impregnated ones per cell are about 1.6.

VAN OMMERING: Yes; but that again includes water and hydration.

DUNLOP: I know; but the 1.2 number is really confusing. The actual number, in terms of grams of active material per cc weight volume, is about 1.6 to 1.7. And if you don't take out the weight of hydration, the weight of hydration is about 6 or 7 percent of the total, around 6 or 7 percent of that.

VAN OMMERING: Well, there is a slight difference between lot one and lot two, here.

DUNLOP: The other point to make is, as far as these expansions go, on the SAFT, which is for Telesat and Intelsat IV, those electrodes were measured after we received them. And those expansions that you see there are the expansions that did occur in those cells as a function of time. It is also important to point out that those things occurred over a four or five-year period, because it takes five years 500 cycles in a simulator, so the time difference, while the cycle difference is the same, the time difference here for the nickel-cad data is quite different and it may have an impact on the expansion as well.

ROGERS: Hughes Aircraft. In looking at the figures you showed, the microphotographs, it would seem that the migration of the active material toward the surface, where it gets into a larger "lump", if you want to call it that, would seem to be kind of permanent. Is that, do you think that might be reversible in some manner, with a full reconditioning or something?

VAN OMMERING: No, I don't really see any mechanism by which it could return. I can't really even see a very good mechanism by which it goes out in the first place.

ROGERS: Would you repeat the cycling mode, please.

VAN OMMERING: It was a three-hour cycle at 1.2 hours of discharge, 1.8 hours charge; and everything was done at a C/2 rate; that is real capacity, measured capacity on cycle one.

HALPERT: I didn't get the answer to what was the reduced loading on the chemical impregnation. You gave me the full loading at one point; 1.8, you said?

VAN OMMERING: That is just nickel hydroxide. It is about 2.1 on the total weight gain.

HALPERT: And that is on 100 percent. What about the reduced rate?

VAN OMMERING: Well, that 84 percent is simply based on weight gain, so whatever that comes out to be. I don't know the exact amount.
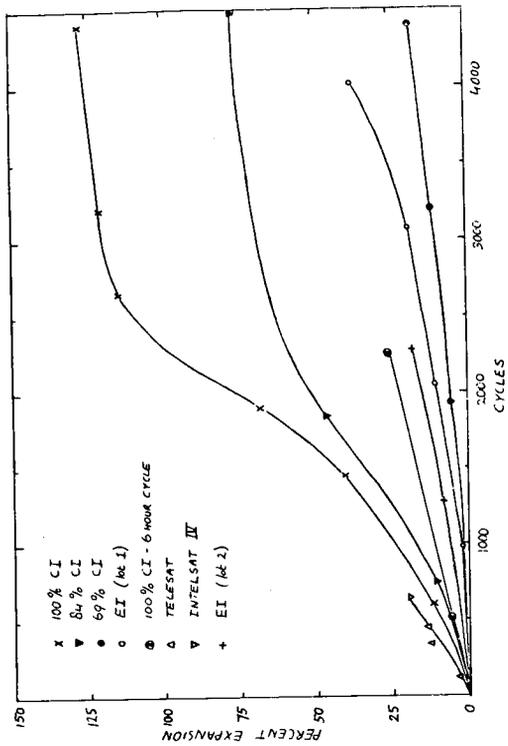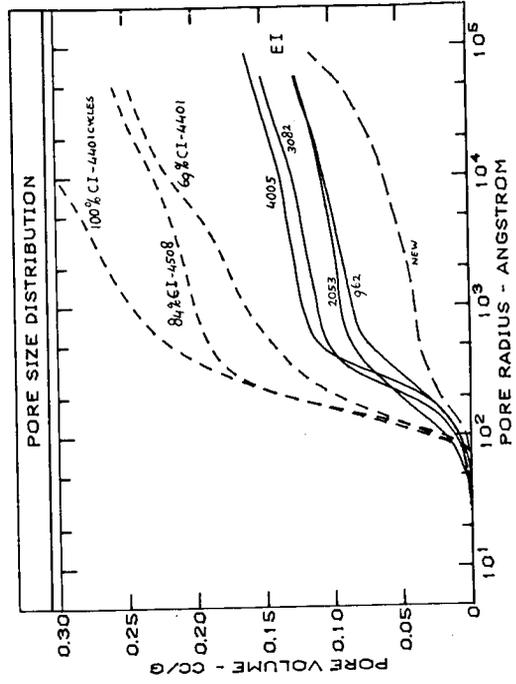
Figure 230

Figure 232

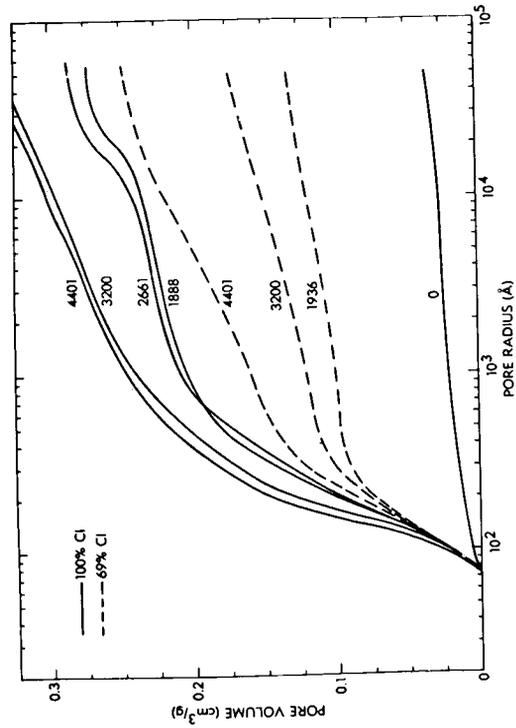| ELECTRODE	PLATE WEIGHT (g)	Ni(OH)$_2$ w/o	Ni SUPPORT w/o	IN-CELL CAPACITY (Ah)	Ah/g
EI	12.0	30.1	62.6	1.27	.106
100%CI	14.80	39.3	53.6	1.25	.084
84%CI	13.70	35.6	57.9	1.28	.093
69%CI	12.67	31.7	62.6	1.10	.087

Figure 229

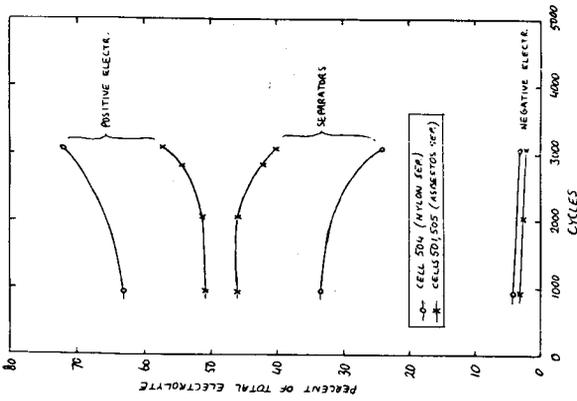Figure 231

Figure 234

Figure 236

Figure 233

Figure 235

373
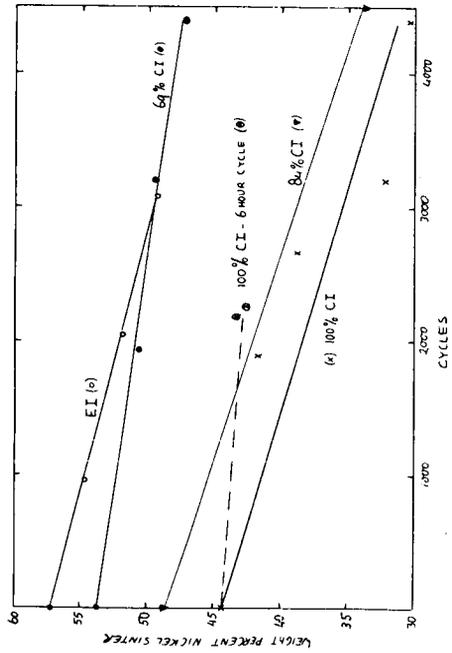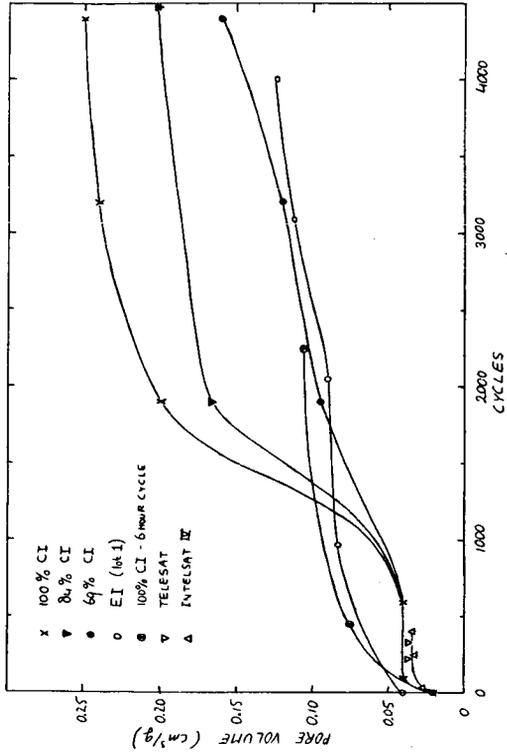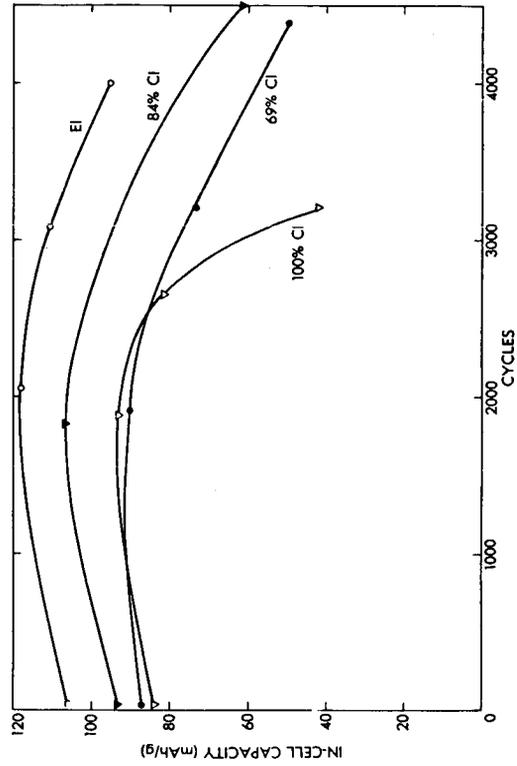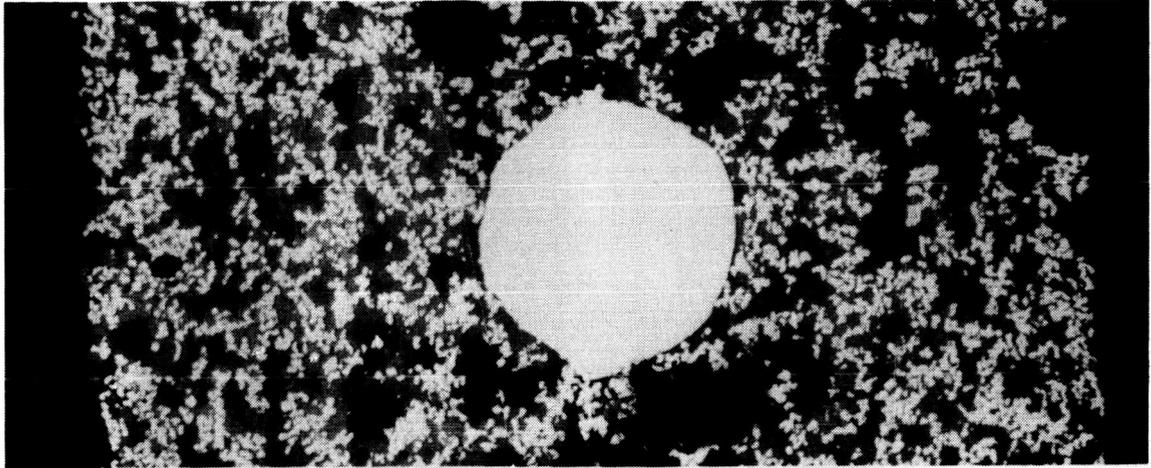
E.I. ELECTRODE NEW
├──────┤ 40 μm
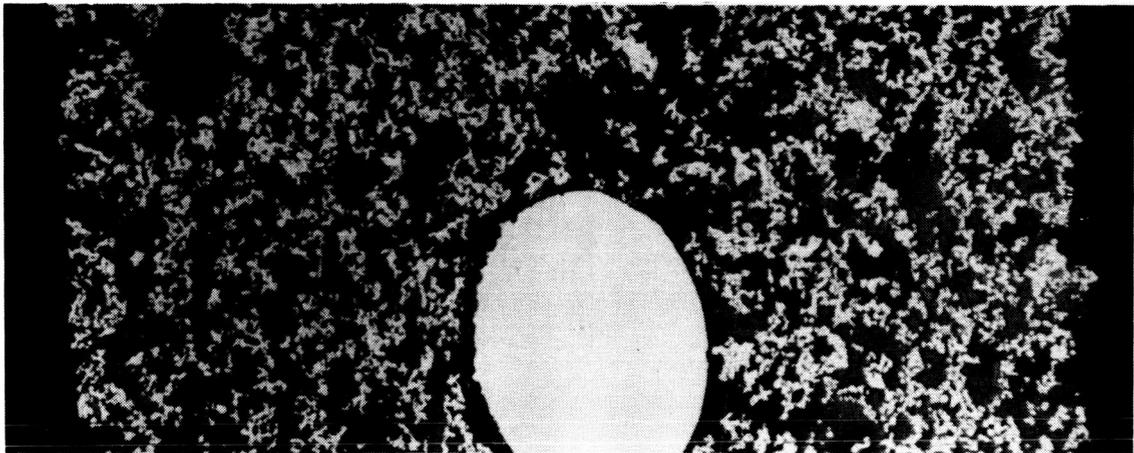
Figure 237

E. I. ELECTRODE 962 CYCLES
├──────┤ 40 μm

Figure 238

374

E.I. ELECTRODE 2053 CYCLES
├────┤ 40 μm

Figure 239

E.I. ELECTRODE NEW
├────┤ 10 μm

Figure 240

E.I. ELECTRODE 2053 CYCLES

10 μm

Figure 242

E. I. ELECTRODE 962 CYCLES

10 μm

Figure 241

ANALYSIS OF AEROSPACE
NI-CAD BATTERY CELLS

R. R. Eliason
Ford Aerospace and Comm. Corp.

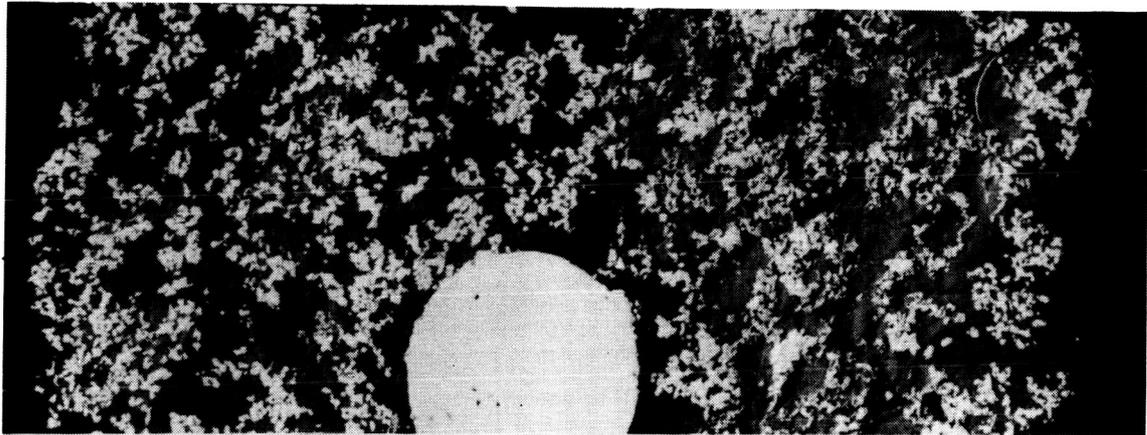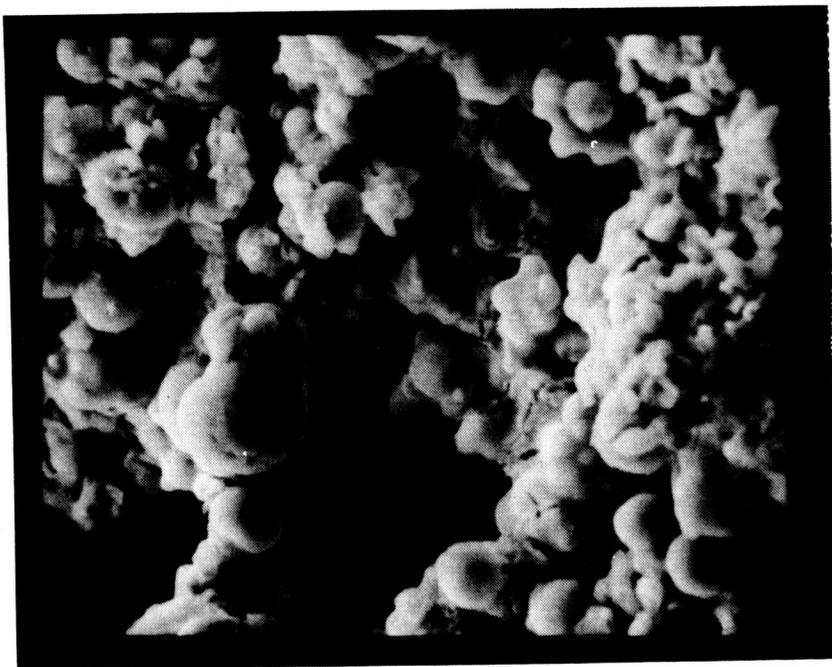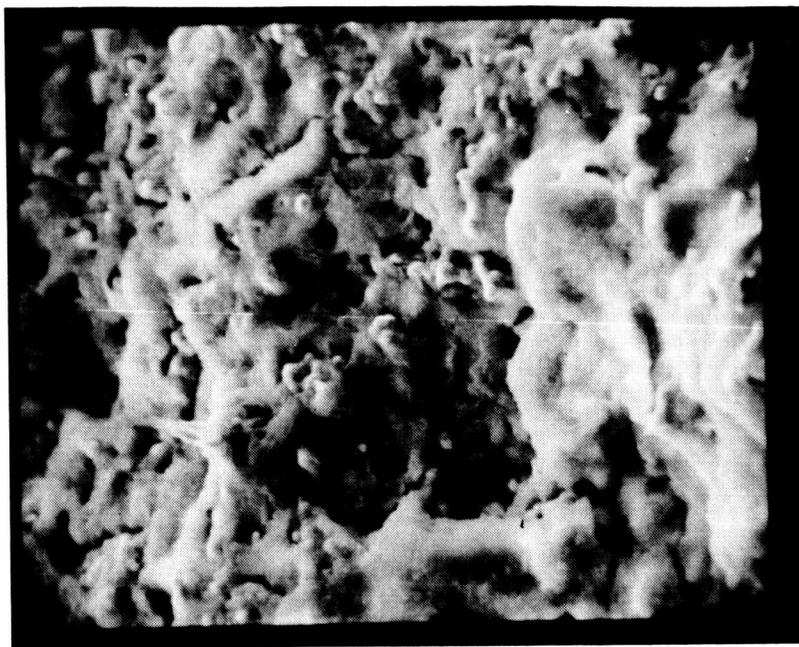First, I would like to show you the block diagram of how we go about analyzing nickel-cadmium aerospaced cells; and then I would like to get into more specifically one area.

(Figure 243)

But first of all, we record the data, go through the physcial measurements of the cell, do the electrical normalization; that includes reconditioning, cycles; and then we go into the usual precharge measurements, cell disassembly, packaging, and then into the analysis.

We do the extraction of the negative plates and the positive plates, the separtors, analysis of the electrolyte; and then we get into the other varied analysis: Atomic absorption spectroscopy in analyzing for the different components, emission spectrographic analysis of all other components, the four components; the electrolyte, nickel electrodes, cadmium electrodes, and the separators; SEM plate metallographic analysis, insoluble carbonates; up in here we do the soluble carbonates; analysis for NO_x, nitrates, also separator molecular weight analysis, and also the micro and macroporosity of the electrodes.

Today, basically what we want to look at is SEM and metallographic analysis, as related to cadmium migration.

(Figure 244)

We have had a lot of people talking about cadmium migration, so I thought I would finally show you what it is and show you a little bit more about it, and people won't be quite so afraid of it, hopefully.

First of all, I would like to define cadmium migration, show you examples of it, show the effects of cadmium migration, some of the causes of cadmium migration, and some methods of reducing cadmium migration.

(Figure 245)

Let's start in by defining it strictly as cadmium or cadmium hydroxide that has diffused or migrated beyond the surface of the electrode. That includes cadmium in the electrolyte, cadmium in the separator, cadmium beyond the surface of the cadmium electrode, and cadmium in the nickel electrode, as shown here; cadmium in the separators, the nickel electrode, the electrolyte, and cadmium that has migrated beyond the surface of the cadmium electrode.

(Figure 246)

First of all, I don't know how many of you have observed cad migration' in cells, and a lot of you have. These are cells that are taken apart. This is a basically a new cell, or clean cell. You can see the separator. It is very clean. It was analyzed, found to contain approximately 10.5 milligrams per bag. This was about a 10 amp hour cell.

Here we can look over here, and you see a little bit of discoloration on the cadmium electrode, and the matching pattern up on the nylon separator, and you see we have a higher content of cadmium in the nylon separator.

Then we get into a heavy cadmium migration, where you are looking at 400 to 500 milligrams per separator. Then we have another condition that we refer to as separator adhesion to the cadmium electrode. This is where the separator is actually embedded in the surface of the cadmium electrode.

(Figure 247)

To start out as a comparison, let's look at a new cadmium electrode. You see, this is one that has never been in a cell. This is a typical G.E. electrode. Over here we have the SEM on the surface, approximately 200 x of the cadmium electrode; then we have the potted cross section, metallographic cross section, approximately 340.

The white spots are the nickel plaque material in the electrode. The gray spots, as you see; that is your cadmium, cadmium hydroxide. Now, you see the black areas, which sometimes are referred to as "voids," or not necessarily voids, but sometimes are actually what we refer to as "pull-out." In other words, in milligraphic cross-sectioning, you get a condition when you are grinding the sample where pieces of it, because the material is very fragile, will pull out and leave a void there, So you have to be careful in your definition of this, and it is difficult to know whether that is really pull-out, or it is a void in the electrode.

So this is a new cadmium electrode that has never been in a cell.

(Figure 248)

Now, let's look at a cell that has undergone typical acceptance testing. Here again is the SEM on the surface of the electrode. There you start to see the cadmium, cadmium hydroxide crystals on the surface. This one had approximately 80 cycles on it.

The metallographic cross section shows, here is your surface of your electrode, all in through here, and you see just up on the surface small cadmium hydroxide crystals. Incidentally, this is an error; this decimal point should be over. The cadmium crystals are approximately a half a mill above the surface of the electrode.

(Figure 249)

Now, let's look at some, what we refer to as "medium," cadmium migration. Here you see the separator or the nylon strands embedded in the surface of the electrode, in the large cadmium crystals. Again, this is 200 X SEM surface, compared to the metallographic cross section; and here you see this is the surface of the cadmium electrode, in through here. You see that we have in this cross-section, we have cadmium approximately 1-1/2 to two mills above the surface of the cadmium electrode; and again, the separator is embedded, parts of the nylon separator, embedded in the cadmium-cadmium hydroxide.

Now, let's take a look at some heavy cadmium migration.

(Figure 250)

Again, you see the nylon separator embedded in the surface of the electrode, in the SEM picture, and over here, we see approximately 3 to 4 mills of cadmium that has migrated beyond the surface of the electrode, and again, the nylon strands throughout the surface.

Let's just classify it basically, and say, light cadmium migration is roughly one mill, medium cadmium migration is one to two, and heavy cadmium migration runs from three to four and up.

(Figure 251)

Now, what does cadmium migration in situ look like, in a cell, where you have the nickel electrode, the cadmium electrade, and the separator? We

cross-sectioned some of those, also. Here you see that the cadmium has migrated approximately 50 percent of the way through the separator; the same here, approximately four to five mills.

This cell was still operating. It was a 15-amp-hour cell and gave 19 amp hours capacity. So even though we had 50 percent migration of cadmium through the separator, the cell was still operable.

(Figure 252)

What does the cadmium look like in just the separator? Suppose you cross-section the separator? Here are some pictures at approximately 200 or 250 X. This is the surface of the nylon separator that was next to the cadmium electrode, and you can see the cadmium, the gray material, all in through here; and again, it migrated approximately halfway through the separator. These, again, had approximately 400 to 500 milligrams per bag. That is a nylon separator.

(Figure 253)

Now let's take up what are the methods of reducing cadmium migration? One method, as we know, is to put the cells. Now, this is not for storage of cells, but this is during flight to store the cells, of course, on trickle charge. Well, this was a test that was approximately five years; it was a real-time test. We ran cells on open circuit stand, and cells on trickle-charge.

This is the open circuit stand after approximately five years. Here again, the SEM of the surface of the cadmium electrode; we see the nylon separator material, large cadmium crystals. Again, here is the electrode surface, and we see approximately three to four mils of cadmium migration beyond the surface.

(Figure 254)

Now, let's compare that to the trickle-charge mode. Again, this cell is the same; after five years of operation. You can see the vast difference. difference. These again are approximately the same magnifications on the SEM and also on the metallographic cross-section.

Here is your electrode surface, and you see you have approximately one mil of cadmium that has migrated above the surface of the cadmium electrode.

(Figure 255)

Now, for just a comparison of the surface, just looking at the surface of the two electrodes, you see the crystal size also. Here we have 2,000 X and 2,000 there; you can see you have very large crystals over in the cell that was in an open-circuit stand versus the one that was on trickle charge. You have very fine crystals. This is a little piece of the nylon separator there that has some degradation on it.

Dr. McDermott has a very good paper out on cadmium migration. One of the mechanisms that everyone is considering at this time is carbonate. What is the effect of carbonate on cadmium migration? Well, one of the interesting things was that this cell, that was on trickle charge, had approximately 238 to 240 grams per liter of soluble carbonate, and the one on trickle charge had approximately the same; I think it was about 240 grams per liter of soluble carbonate.

So while the carbonate may be a mechanism that produces cadmium migration, it is not the predominant mechanism, evidently, because we have the same carbonate content, roughly, in both cells, and yet we have extensive cadmium migration in the cell. And again, as I say, these cells still produced 19 ampere hours with this type of cadmium migration.

(Figure 256)

What else can we do to reduce cadmium migration? One of the things, of course, you can do is utilization of TFE on the cadmium electrodes. This is a test that was run on one cell. First of all, it was 550 cycles, approximately a 90-minute orbit, 50 percent DOD, 40 degrees C. One was the control, approximately 162 milligrams per separator of cadmium. This had a level one TFE; at that time, they were using different levels of TFE to see what controls, what effect, it would have on it. And as see, we reduced it approximately a third. This had approximately 53 milligrams per bag; whereas, when you go up to TFE second level, again you have reduced it approximately in half, and so on up the scale.

(Figure 257)

I believe Gerry Halpert will recognize this. Also, the solubility of cadmium hydroxide in the electrolyte is a function, as you see, of the concentration. In other words, here is your solubility of cadmium hydroxide here. You see as you go down lower in concentration, you have lower solubility of cadmium hydroxide in the electrolyte.

So basically, the four methods of reducing cadmium migration are: One, the lower temperature; two, trickle charging; three, Teflonated cadmium electrodes; and also lower concentrations of electrolyte.

(Figure 258)

So the conclusion that we have come to so far is that cadmium migration is a normal aging mechanism associated with the rate of degredation of quality of the cell. It can be accelerated or reduced by varying the stress factors on the cell.

DISCUSSION

SCOTT: TRW. What was the prior history of the cells that you showed us, the pictures after open-circuit stand? What was their condition, do you know what they looked like under the same scanning electron microscope situation before they went on open-circuit stand? Were they clean? Were they free of that sort of thing? In other words, are you saying that the open-circuit stand, per se, produces the conditions that you saw?

ELIASON: As I understand your question, it is: "Did we analyze the cells five years ago, before we started the test?" Is that correct?

SCOTT: Essentially, yes.

ELIASON: No, we did not. We are assuming that after the five year test, we just compared the two new cells, as we have compared it with the new cells, this is what we would expect a new cell to look like. No, we did not analyze these cells at that time to compare them; but I assume that we did not have extensive cadmium migration in brand-new cells. I have never seen any like that.

LIM: Hughes. I would like to offer you a speculation there that may be explaining this factor. During the trickle charge, you are passing the current which reduces the cadmium plus-2 which is in solution to cadmium zero; so near the electrode, that reduces the cadmium concentration; while on the open-circuit stand, you don't pass current. It is off; the concentration will be determined by solubility. I don't know whether it makes sense to you, though.

ELIASON: Yes. This is what I had more or less postulated, too. That was very good.

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ROGERS: Hughes Aircraft. You didn't say whether your open-circuit stand, or the trickle for that matter, was at a constant temperature or not. This could make a difference, because you would expect, since there is a very large temperature coefficient in solubility, that the cadmium hydroxide would dissolve as a complex in the battery and then reprecipitate each time it cycled which might affect the rate.

ELIASON: Right. That was at room temperature.

ROGERS: The room kept constant, or just at the room temperature?

ELIASON: No. Just room temperature, at that time.

McDERMOTT: Another factor in the trickle charge may be the fact that you are constantly evolving hydrogen, which is agitating the environment and may be interrupting the precipitation of the cadmium in the separator area.

FORD: Goddard. I have two questions for you. The first one: The figure you had that showed the large crystals on the open circuit and the very small ones on trickle-charge; could you put it back up there?

ELIASON: Yes.

(Figure 255)

FORD: What caught my attention is that here in the viewgraph, you showed what appeared to be nice cadmium crystals, but the crystals in the left-hand figure are not really crystals, in a sense; they are wafers from crystals.

ELIASON: Right.

FORD: This is the same type of crystals we see in near-earth cycling, you know, 25 or 30 percent, we see at this depth. I was wondering if you had explored into what causes these crystals to assume this shape, and then, is it possible that once they are in this shape they are no longer available, because, you know, to fit back into the reaction of the cell as far as normal discharge. That was the first question I had.

ELIASON: No; we really have not investigated that. I will tell you what I have seen on that, Floyd; I didn't bring it with me, unfortunately, but I have seen the large crystals, we have done metallographic cross-section of the large crystals, and then put them on a SEM and then E-dash, the energy dispersive X-ray analysis; and you can actually see and detect cadmium, not cadmium

hydroxide but cadmium, in the middle of the crystal; and this is a totally discharged cell, for once. So the cadmium is tied up in the bigger, larger crystals.

But the platelets; yes, we see a lot of the platelets. They look a little bit different here, in this comparison. These are both, of course, at 2,000 X. But in the other ones, where I was comparing them with the metallographic cross-section, they were about 300 to 400 X, so they looked a little bit smaller.

DUNLOP: Comsat. In the last, I think, two or three battery workshops here, we have reported, showed, pictures very similar to this on the life testing of the Intelsat IV. In answer to one question; I think it was Dr. Scott's: We did take cells and look at them each year, twice a year. And the phenomenon you are describing shows up as a function of time and is aggravated by time.

And there does seem to be a difference, by the way, if you have a cell in which your electrode has a silver catalyst and if your electrode does not have a silver catalyst. Our data shows that if you have a silver catalyst, at least for the first two or three years, the migration rate of the cadmium from the cadmium electrode over to the positive electrode, is increased by a factor of between four and six, with the silver catalyst. And that cadmium migrates all the way from the negative over to the positive electrode and shows up with the positive, with the trickle charge storage mode, by the way.

The other thing that we have observed when we see the large crystals grown with the open-circuit stand is that we have cross-sectioned those electrodes and divided them up into 12 different sections. Some, you see larger crystals in certain sections than you do in others. Where you find the large crystals formed, it is true that it is more difficult to utilize that material. The utilization of the material where you have your large crystals drops down to less than 50 percent, very often; whereas if you have a cell which is trickle-charged and you maintain this other type of crystal structure, your utilization will stay up to about 70 percent.

MAURER: Bell Labs. There was a paper by Opinocha in the '60s that describes the formation of these crystals on cycling; and I think he correlated that the slower the discharge rate and the higher the temperature, the larger the crystals; you could make them grow bigger and could make them grow smaller;

There is evidence that the active surface of those hexagonal platelets is the outside edge, that the material dissolves from the outside edge, not from the flat face; so that they are intrinsically less active than the small crystals.

INVESTIGATION OF CADMIUM MIGRATION IN SEALED Ni-Cd BATTERY CELLS

I   Define cadmium migration and examples

II Effects of cadmium migration

III Some causes of cadmium migration

IV Methods of reducing cadmium migration

Figure 244

NICKEL-CADMIUM CELL ANALYSIS
Standard Procedure

Figure 243

DEFINITION OF CADMIUM MIGRATION

Cadmium or cadmium hydroxide that has

diffused or migrated beyond the surface of

the cadmium electrode

Figure 245

DEGREES OF CADMIUM MIGRATION

CLEAN
10.5 mg / BAG NYLON SEPARATOR
CADMIUM ELECTRODE

LIGHT CADMIUM MIGRATION (LCM)
66.9 mg / BAG NYLON SEPARATOR
CADMIUM ELECTRODE

HEAVY CADMIUM MIGRATION (HCM)
467.6 mg / BAG NYLON SEPARATOR
CADMIUM ELECTRODE

SEPARATOR ADHESION TO CADMIUM (SAC)
10.8 mg / BAG NYLON SEPARATOR
CADMIUM ELECTRODE

Figure 246

NEW CADMIUM ELECTRODES

SEM

METALLOGRAPHY

POTTED AND CROSS-SECTIONED AT 90°

NO CADMIUM CRYSTALS ON ELECTRODE SURFACE (200 X)

NO CADMIUM MIGRATION BEYOND ELECTRODE SURFACE (340 X)

Figure 247

LIGHT CADMIUM MIGRATION

SEM

METALLOGRAPHY

POTTED AND CROSS-SECTIONED AT 90°

CADMIUM - CADMIUM HYDROXIDE CRYSTALS ON CRYSTALS ON SURFACE ARE APPROXIMATELY ELECTRODE SURFACE (200 X). CELL COMPLETED 0.005 INCHES ABOVE SURFACE (340 X) ACCEPTANCE TESTING (~ 80 CYCLES)

Figure 248

MEDIUM CADMIUM MIGRATION

SEM

METALLOGRAPHY

POTTED AND CROSS-SECTIONED AT 90°

CADMIUM ELECTRODE SURFACE WITH NYLON SEPARATOR MATERIAL IMBEDDED IN MIGRATED CADMIUM HYDROXIDE CRYSTALS (200 X)

CADMIUM HAS MIGRATED APPROXIMATELY 1.5 TO 2 MILS BEYOND ELECTRODE SURFACE (340 X)

Figure 249

HEAVY CADMIUM MIGRATION

SEM

METALLOGRAPHY

POTTED AND CROSS-SECTIONED AT 90°

NYLON IMBEDDED IN MIGRATED CADMIUM HYDROXIDE CRYSTALS AND PLATELETS (200 X)

CADMIUM - CADMIUM HYDROXIDE HAS MIGRATED ≈ 3 TO 4 MILS BEYOND ELECTRODE SURFACE (250 X)

Figure 250

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CADMIUM MIGRATION IN SITU

METALLOGRAPHY NICKEL ELECTRODE, NYLON SEPARATOR, AND CADMIUM ELECTRODE (COMPRESSED TO 6 IN-LB) POTTED AND CROSS-SECTIONED AT 90°

ELECTRODE SPACING - 4.5 MILS (630 X)

METALLOGRAPHY NICKEL ELECTRODE, NYLON SEPARATOR, AND CADMIUM ELECTRODE (COMPRESSED TO 6 IN-LB) POTTED AND CROSS-SECTIONED AT 90°

CADMIUM MIGRATION HAS PENETRATED ~ 50% (THROUGH SEPARATOR (630 X)

Figure 251

SEM PHOTOGRAPHS OF CROSS-SECTION OF NYLON SEPARATOR 6 SHOWING HEAVY CADMIUM MIGRATION

TYPICAL PENETRATION OF CD-CD (OH)₂
APPROXIMATELY 50% 460 MG CD/BAG

CROSS-SECTION (250 X)

APPROXIMATELY 50% PENETRATION
460 MG CD/BAG

CROSS-SECTION (200 X)

Figure 252

CHARGED OPEN CIRCUIT STAND VS TRICKLE CHARGE STAND

SEM
CADMIUM ELECTRODE SURFACE
(CHARGED OPEN CIRCUIT STAND)
5 YR

LARGE CADMIUM HYDROXIDE PLATELETS AND NYLON SEPARATOR MATERIAL (500X)

METALLOGRAPHY CADMIUM ELECTRODE
POTTED AND CROSS-SECTIONED AT 90°
(CHARGED, OPEN CIRCUIT STAND) 5 YR

CADMIUM HAS MIGRATED APPROXIMATELY 3 TO 4 MILS BEYOND ELECTRODE SURFACE INTO NYLON SEPARATOR (312 X)

Figure 253

CHARGE OPEN CIRCUIT STAND VS TRICKLE CHARGE STAND

SEM
CADMIUM ELECTRODE SURFACE
(TRICKLE CHARGE STAND) 5 YR

SURFACE IMPRESSIONS OF NYLON SEPARATOR AND SMALL CADMIUM - CADMIUM HYDROXIDE CRYSTALS (500 X)

METALLOGRAPHY
CADMIUM ELECTRODE
POTTED AND CROSS-SECTIONED AT 90°
(TRICKLE CHARGE STAND) 5 YR

ALL CADMIUM MIGRATION ≤ 0.001 INCHES BEYOND ELECTRODE SURFACE

Figure 254

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EFFECT OF TFE UPON CAD MIGRATION.
550 CYCLES, 90 MINUTE ORBIT, 50% DOD, 40°C

CONTROL
162.2 Me/BAG

TFE 1.
53.5 Me/BAG

TFE 2.
22.7 Me/BAG

TFE 3.
5.45 Me/BAG

TFE 4.
0.65 Me/BAG

Figure 256

CADMIUM MIGRATION IN
SEALED Ni-Cd BATTERY CELLS

CHARGED OPEN CIRCUIT STAND VS
TRICKLE CHARGE

SEM
CADMIUM ELECTRODE SURFACE
(CHARGED OPEN CIRCUIT STAND)
5 YR

SEM
CADMIUM ELECTRODE SURFACE
(TRICKLE CHARGE STAND)
5 YR

LARGE CADMIUM HYDROXIDE PLATELETS AND
NYLON SEPARATOR STRANDS (2000 X)

TYPICAL CADMIUM HYDROXIDE CRYSTALS
ON ELECTRODE SURFACE (2000 X)

Figure 255

V Conclusion

Cadmium migration is a normal aging

mechanism associated with the rate of

degradation of quality of a cell. It can be

accelerated or reduced by varying the stress

factors of the Ni-Cd cells

Figure 258

APPENDIX

PROPERTIES OF KOH SOLUTIONS

% KOH	Density gms/ml 21.1°C	Baume 15.6°	gms KOH/ Liter	Moles/ Liter	Molal	Viscosity Centipoise	Conductivity Mhos/cm	Equivalent* Conductance	O₂ Solubility CC/L	O₂ Diffusivity D × 10⁶ cm²/sec	H₂ Solubility CC/L	Solubility Cd(OH)₂ M/L × 10⁶
						(3)	(4)	(4)	(5)	(6)	(7)	(8)
20	1.187	23.1	237.80	4.238	4.456	1.48	4970	117	6.3	100	4.6	75
22	1.206	25.1	265.98	4.740	5.027	1.58	5160	108	4.9	90	4.0	80
24	1.227	27.1	295.20	5.261	5.629	1.70	5320	100	4.0	80	3.4	90
26	1.247	29.0	325.00	5.792	6.263	1.84	5420	92	3.6	73	2.8	1.05
28	1.268	30.9	365.88	6.342	6.932	1.98	5420	84	2.7	67	2.3	1.25
30	1.289	32.8	387.60	6.906	7.639	2.14	5400	76	2.2	61	2.0	1.38
31	1.300	33.7	403.00	7.182	8.007	2.24	5360	73	2.0	56	1.9	1.43
32	1.310	34.6	420.16	7.488	8.388	2.32	5310	70	1.8	50	1.6	1.50
34	1.330	36.3	453.56	8.083	9.182	2.52	5210	63	1.3	44	1.3	1.70
36	1.354	38.1	488.16	8.700	10.026	2.72	5030	57	1.1	39	1.7	2.30
38	1.376	39.8	523.64	9.332	10.924	3.04	4800	51	0.9	35	1.0	2.95

*Equiv. conductance is conductivity in mho/cm divided by gm equiv/cc

(3) J. Cooper & A. Fleischer
Battery Separator Screening
Methods Appendix

(4) N. A. Lange — Handbook of
Chemistry
10th Ed. p. 1208

(5) G. Geffecken — Z Phys Chem
71, 47 (1910)

(6) Extrapolated from K. E. Gubbins
& R. D. Walker
JECS 112 469 (1965)

(7) P. Reutschi and R. F. Amlic
J Phys Chem 70 718 (1966)

(8) D. E. Ryan, J. R. Dean, and
R. M. Cassidy
Canad. J. Chem. 43 999 (1965)

Figure 257

388

NYLON SEPARATORS

H. S. Lim
Hughes Research Laboratory

My talk is going to be about nylon separators. This is a part of our effort to study the separator and develop a new separator. We have described the previous work on the nylon separator two years ago, in this battery workshop. This is going to be updating work of that separator study.

I would like to start with reviewing some of the previous conclusions that we had drawn, for those of you who are not familiar with our work.

(Figure 259)

Well, this is the main conclusion we had reached previously. By the way, the experimental tactic we have used is that we have put the piece of nylon separator, which is the Pellon 2505, and the material is nylon-6, in the KOH solution, which is a flooded condition, and heated it to various high temperatures, that is from 60 to 110 degrees C; and after a certain amount of reaction, we take out the separator and dry it out and weigh the separator to measure the weight decrease, and analyze the molecular weight and analyze the chemical analysis to determine the decomposition product.

And previously, we reached the conclusion that nylon hydrolyzes in KOH solution with an activation energy of 19.8 kilocalories per mole in 34 percent KOH.

And when we extrapolate the data to 25 degrees, it corresponds to about 7.6 years for a 10 percent degradation of nylon, and the hydrolysis product is irreversibly oxidized in the battery, in the battery operating condition, to reduce the overcharge protection and the 10 percent decomposition of nylon is approximately enough to consume all the overcharge protection in the space battery, to ruin this battery, literally.

(Figure 260)

I would like to talk about four different items. One is the effect of KOH concentration on the hydrolysis rate. We realize that 34 percent is not really actual concentration in the space batteries; and the effect of oxygen on the nylon degradation, in comparison of the extrapolated value of the hydrolysis rate with the actual rate at 35 degrees C, and analysis of nylon separator from old batteries.

389

(Figure 261)

I guess that one question probably all of you might ask is whether that extrapolation method is valid or not, so I would like to answer that question first. Previously, we had reached 19.8 kilocalories per mole in 34 percent KOH making an activation energy plot from 60 to 110 degrees; and this is the least square line of that plot, and we just simply added the 35 degree point, which indicated it agrees very well. So we think that the extrapolation method is valid.

(Figure 262)

The next item is the effect of KOH concentration on the nylon degradation. The relative rate is plotted against the KOH concentration, and we have observed a rather unexpected result, here. If we decrease the concentration from 34 percent further down, the degradation rate actually increases, rather than decreases, and it gives a maximum of about 16 percent KOH, and then decreases. And if we look at the literature mechanism for amide hydrolysis, Nylon is a polyamide, this is supposed to be proportional; the rate is supposed to be proportional to the KOH concentration, more accurately, the activity of OH. And the activity of OH actually increases this way; it goes up almost exponentially.

First the activated correction, because the decrease is from unity a little bit, and it catches up around the one-molar concentration and goes up. According to that rate, you would predict this kind of a rate; so this a very unexpected factor. We have some speculations, but I am not going to discuss all that here.

And another question you might address is, this is at 100 degrees; and if we go down to, say, 25 degrees or 20 degrees, what would happen? Would this relative be valid? Or would it give a different relative rate? One way of finding out is to determine the activation energy at different KOH concentrations, and extrapolate that value to, say, 25 or whatever temperature you want, and compare it.

(Figure 263)

This is an activation energy plot at two different concentrations, and this is a least square line in 34 percent here; and we have three points for 16 percent KOH, which is the maximum point of the rate, and it is approximately proportional, but I am not sure whether it is valid or not to get the least square plot out of this three points, but if we do that, the activation energy comes out to about 18.9 kilocalories per mole, which is somewhat smaller.

Another thing I would like to point out is the ratio of this point and this point. If this is one, this is 1.5; 50 percent higher, this point. So if you draw the line this way, the 50 percdnt would carry over all the way down, but if we do the least square line like this, a little bit slower slope, and if you calculate it for 25 degrees value, for example, the ratio would be one to two: 100 percent faster in 16 percent KOH.

That is approximately the idea; so that is what I pointed out earlier, when Dr. Scott presented our data, because at lower KOH concentrations; well, let's say a 26 percent; I believe that is the average KOH concentration in a new space battery in the charged state.

(Figure 264)

The next item is the effect of the oxygen on the nylon degradation. Previously, we were shown data that the nylon degradation could be a little bit faster in the presence of oxygen. That was data at 100 degrees; I believe that was three years ago. So at that time we couldn't make a conclusion whether the oxygen is involved in the nylon degradation reaction, directly or not; so we reproduce the data in a little bit more careful manner, and this is the data. Well, actually, the result is negative. We couldn't make it any different.

The reason why we drove it at three different temperatures is that the solubility of oxygen is very much dependent, the general gas, is very much dependent on temperature. As you go lower, the temperature, the solubility, increases drastically. So if you have any difference in weight, that means the direct oxidation is important; that would be much more pronounced at lower temperature. Even at 35 degrees, we didn't see very much difference; I believe this is an experimental error of some kind.

So we have to conclude that if there is any direct oxidation of nylon, the rate should be negligible compared to the hydrolysis rate.

(Figure 265)

And we have analyzed some of the separator from old batteries in order to compare with the predicted value from our extrapolated data. And in order to do that the quantity we are interested in is the weight decrease. But from older battery separators, we cannot directly measure the weight decrease. That is one reason; and another is the molecular weight measurement which is much more sensitive; the error in the weight decrease measurement, or in the weight decrease is a very small percentage, one to say five percent, or one to 10 percent is very high.

So I would to show you the relationship between molecular weight decrease. We have shown that empirically, the weight plot, if we plot the log over molecular weight versus time, it gives a straight line during the reaction. And another relationship is the weight decrease to two-thirds as plotted against time; it gives another empirical straight line.

So from those relationships, we would expect that molecular weight, the log of molecular weight, would be proportional to weight decrease to two-thirds, which turned out to be valid in this weight decrease range. And this is approximately the scatter of the molecular weight versus the weight decrease; so we analyzed the separators from all the batteries, and estimated the weight decrease from this relationship.

(Figure 266)

I hate to draw any conclusion from this data, because we have a very limited number. We have only four batteries tested or analyzed, the separators from four batteries and the initial condition was not certain and the operation condition was not exactly describable. Anyway, the two batteries were 2-1/2 years old, and the other batteries were six years old; and the initial separator molecular weight was 27,000.

After 2-1/2 years, and six years, we get this value when we estimate the weight loss from this value, it came out about this, 5.627 in 2-1/2 years and approximately 9.5 to 11 percent in six years. And the extrapolated value, the estimated value by extrapolation of the data, from 34 percent, the experiment, is 3.6 percent or 6.5.

And as I pointed out earlier, the most likely concentration of KOH in the actual battery is 26 percent or lower. And I think this discrepancy is due to the concentration effect.

(Figure 267)

Finally, I would like to summarize what I have said. The nylon hydrolysis rate increases as KOH concentration is decreased from 34 percent, giving a maximum rate at about 16 percent. Separator hydrolysis is confirmed by molecular weight decrease in age of the batteries, and the reaction of nylon with molecular oxygen is probably negligible, compared to hydrolysis, and the extrapolated rate value from the high temperature experiment correlates very well with experimental values at 35 degrees.

DISCUSSION

DUNLOP: Is that the average molecular weight that you were using, when you talked about the molecular weight? Was that the average molecular weight?

LIM: This is the viscosity average molecular weight.

DUNLOP: Was this your permeation, or how did you measure that?

LIM: We dissolve it in formic acid and measure the viscosity at different dilutions, and we can correlate to viscosity average molecular weight.

ELIASON: Then the hydrolysis, if I am correct, then the hydrolysis is still the weight-limiting step of the reaction; is that correct?

LIM: Yes.

McDERMOTT: Coppin State. I think in your last paper you were speculating about glass transition of nylon would have any effect on this. So your 35 degree mark is now saying that it does not seem to have an effect on the rate of hydrolysis?

LIM: Right. The glass transition of nylon textile in the literature varies from I believe from 40 to 52 degrees up, depending on which paper you look at. And when we measure by DSC of this Pellon 2505, and the literature value is for the bulk nylon textile material, and this is fibrous material, and with a different treatment. So you should expect the value would be different here, and actually you would expect it to be lower.

I believe that value is somewhere around 37 degrees. That is a dry value; and the glass transition temperature, when it is wet or it is moist, the literature seems to indicate that it is usually lower then. And we were trying to measure the glass transition in the KOH wet state; and we didn't observe any glass transition down to something like 12 degrees. I am not sure about this value; probably 15 or 12 or around that. And below that, we are not even sure whether there is a glass transition; but there is some conflict as to what occurs conflict as to what occurs

So we believe that down to at least safely 15 degrees C, probably the extrapolation would be valid.

McDERMOTT: Are there other factors besides oxygen which could accelerate this? We found in the accelerated test cells tremendous amounts of carbonate, which I believe are coming from the separator, degradation of the separator. And I tried to plot some of your hydrolysis, and it seems like the cells are getting more carbonate, even, than you would anticipate at a particular temperature from the time on test and the hydrolysis of the nylon. Is there anything beyond temperature and oxygen which could accelerate the breakdown of the nylon? For example, ions in the separator area, cadmium buildup, things like that.

LIM: Well, I can only tell you what we have tried. We have tried nickel oxide there, in connection with the oxidation, and we didn't see any catalytic activity for nickel oxide there. And I had a private conversation with Dr. Will Scott; and he seems to observe a lot different values, in some cases. It is not exactly comparable conditions. So there is some indication that the quality of the nylon separator is somewhat different from batch to batch, but I cannot say any more than that.

MAURER: Bell Labs. I think we have to be careful in comparing the cell lifetimes from the molecular weight analysis. What we are dealing with here is a very complex chain reaction. If you have a hydrolysis chain, and then certain of those products are probably electrochemically oxidized on the positive electrode, maybe not all of them, and so the net overall activation energy of the process may be rather different in the cell than it is on just the molecular weight of the separator.

In fact, the activation energy that I measured, where I measured the time it took to fully charge the negative electrode in the cell, the activation energy for that was around 14 or 15 kilocalories, quite a lot lower than what you are getting from the molecular weight studies; and some work at G.E. that hasn't been published agreed with the 15 kilocalories.

Now what that would do to the high temperature data is that it would extrapolate to a much shorter lifetime at room temperature if you had a lower activation rate. So the fact that people are finding a lot more carbonate than you would expect from a 20 kilocalorie would agree with that. The extrapolation should be on a shorter activation energy.

LIM: Well, let me make a comment on your last comment there. I am aware of the activation energy you have got from cell experiment. I understand that was the whole cell heated up, and the rate was taken by the 50 percent failure; is that correct?

MAURER: When 50 percent of the cells had fully charged their negative.

LIM: Right; and I don't know how directly comparable to that data are our data. Our data are purely just the nylon separator. And on the first part of your comment there, or question; we described that rate, the oxidation rate, in a previous paper. What I am simply assuming here is the hydrolysis is the weight-determining step, and after the nylon is hydrolyzed to 6-amino-caproid then oxidation takes place, and that oxidation rate is much faster. It is a matter of several days, rather than a matter of several years, here.

MAURER: Well, you are breaking up the nylon chain from a very long molecule into smaller and smaller pieces. Any one of those pieces could be oxidized, and now not available for further hydrolysis.

LIM: Well, our evidence here shows the negative to that. We didn't observe any direct oxidation. The data that I presented here covers the question that you raise there.

MAURER: I am talking about direct electrochemical oxidation.

LIM: Direct electrochemical oxidation. The reason we tried this, is actually in the oxidation case, we added some nickel oxide inside. We were trying to oxidize 6-amino-caproate at the electrode, and at the glassy carbon electrode, we didn't see any oxidation by cyclical chemistry. Maybe the rate was too small, or something. But when we used nickel oxide electrode, the oxidation is visible in cyclical chemistry. That means the rate is quite fast.

So that shows the nickel could be catalyzing the electrochemical reaction. And molecular oxygen has more than enough chemical potential to oxidize 6-amino-caproate and if there is a nickel oxide catalyst there, I think you would have to go to similar things. The electrode, that is why we added nickel oxide, but still we didn't observe anything; any effect.

PREVIOUS STUDIES

6826-1

- PELLON 2505 (NYLON 6) HYDROLYZES IN KOH SOLUTIONS. (E_a = 19.8 Kcal/mole IN 34% KOH)

- EXTRAPOLATED RATE:

  TAKES 7.6 YEARS FOR 10% DEGRADATION AT 25 °C

- HYDROLYSIS PRODUCT IS IRREVERSIBLY OXIDIZED IN BATTERY OPERATION CONDITION TO REDUCE OVERCHARGE PROTECTION. (10% HYDROLYSIS WILL RUIN BATTERY).

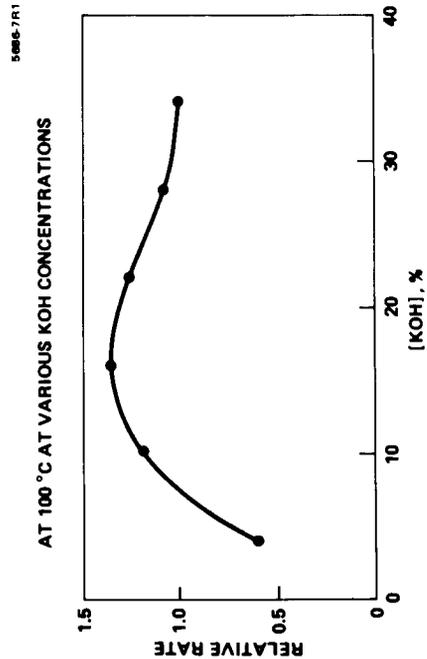Figure 259

RELATIVE RATES OF HYDROLYSIS OF NYLON 6

AT 100 °C AT VARIOUS KOH CONCENTRATIONS

Figure 261

TODAY'S TOPICS

6826-2

- EFFECT OF KOH CONCENTRATIONS ON THE HYDROLYSIS RATE OF NYLON

- EFFECT OF OXYGEN ON NYLON DEGRADATION

- COMPARISON OF EXTRAPOLATED VALUE OF HYDROLYSIS RATE WITH ACTUAL VALUE AT 35 °C

- ANALYSIS OF NYLON SEPARATORS FROM OLD BATTERIES

Figure 260

RATE OF MOLECULAR WEIGHT DECREASE

Figure 262

EFFECT OF
OXYGEN ON NYLON
SEPARATOR
DEGRADATION

Figure 264

● IN VACUUM
□ IN 1 atm OXYGEN

AT 100°C

AT 70°C

AT 35°C

TIME, days

TIME, days

TIME, months

WEIGHT DECREASE, %

A PLOT OF
MOLECULAR
WEIGHT vs WEIGHT
DECREASE

Figure 265

*CORRECTED FOR ZERO POINT VALUE

MOLECULAR WEIGHT

(% WEIGHT DECREASE*)$^{2/3}$

ACTIVATION
ENERGY PLOT FOR
RATE OF NYLON 6
HYDROLYSIS

Figure 263

E_a = 19.8 Kcal/mole

IN 16% KOH

IN 34% KOH

1/T x 10^3,(°K)$^{-1}$

*DEFINED AS THE INVERSE OF THE
TIME FOR 10% WEIGHT INCREASE

RATE OF HYDROLYSIS*, day^{-1}

397
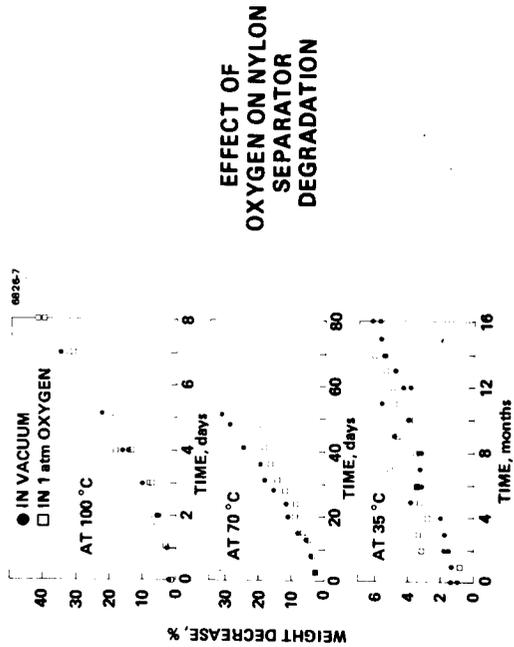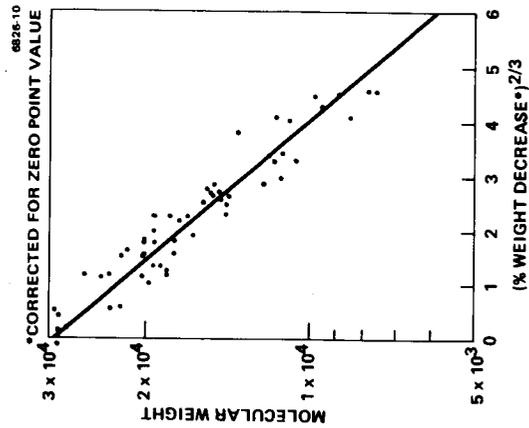
NYLON SEPARATORS FROM
AGED BATTERIES

BATTERY	INITIAL MOLECULAR WEIGHT	AGE	MOLECULAR WEIGHT	ESTIMATED WEIGHT LOSS*	EXTRAPOLATED VALUE OF WEIGHT LOSS IN 34% KOH AT 25°
A	2.7×10^4	2.5 yr	1.36×10^4	~ 5.6%	3.6%
B	2.7×10^4	2.5 yr	1.13×10^4	~ 7%	3.6%
C†	UNKNOWN	6 yr	0.84×10^4	9.5 ~ 10.5%**	6.5%
D††	UNKNOWN	6 yr	0.78×10^4	10 ~ 11%**	6.5%

* FROM MOLECULAR WEIGHT CHANGE

** ASSUMING INITIAL MOLECULAR WEIGHT TO BE $(2.7 \sim 3.1) \times 10^4$

† OPEN CIRCUIT

†† TRICKLE CHARGED (FAILED)

Figure 266

SUMMARY

- NYLON HYDROLYSIS RATES INCREASE AS THE KOH CONCENTRATION IS DECREASED FROM 34% GIVING A MAXIMUM RATE AT ABOUT 16%

- SEPARATOR HYDROLYSIS IS CONFIRMED BY MOLECULAR WEIGHT DECREASED IN AGED BATTERIES

- REACTION OF NYLON WITH MOLECULAR OXYGEN IS NEGLIGIBLE COMPARED TO HYDROLYSIS

- EXTRAPOLATED RATE VALUE FROM HIGH TEMPERATURE EXPERIMENT AGREE WELL WITH 35 °C EXPERIMENTAL RESULTS

Figure 267

PROPERTIES OF NICKEL-CADMIUM SEPARATORS

J. Lee
RAI Research Corporation

My talk this afternoon is about the properties of 2291 used as a separator in nickel-cadmium and silver-zinc batteries. 2291 is the radiation-grafted separator manufactured by us, and it is now being used in military vented nickel-cadmium aircraft batteries.

This is possible because the separator can gain about three to four fold increase in service life, and also does not have the thermal runaway problem associated with cellophane. See the first figure.

(Figure 268)

I will quickly describe the part of the grafting process, where we make our separator. We start with a polyethylene resin which is extruded to one mil and six-tenths. This is cross-linked by beta radiation into a three-dimensional structure, and then grafted with methacrylic acid with gamma radiation and then which is converted into a cell form and then quality-controlled into different specifications.

Next, I am going to talk about the properties of the separator. As a separator manufacturer, we test the properties into four groups. First, there are the physical properties. Second, we have the diffusional properties. Third, we have the stability properties; and lastly, the electrical properties.

In the physical properties, we have thickness measurement, moisture content, exchange capacity, and tensile strength. See the next figure.

(Figure 269)

This shows the thickness measurement of 10 square feet of separator, which gives a mean thickness of about 1.23 mils, plus a center division of about 0.09 mil. So we manufacture our separator 1.2 mil plus or minus the thickness, about 0.3 mil thick.

(Figure 270)

Moisture content of the separator is perhaps the important factor that determines the swelling in the separator and ion exchange equilibrium. We have

hydrated fixed charge ion groups in the separator. You have the mobile cations around the separator, and also we have free water. The high amount of moisture is important, not only in terms of wet outline in the cell, but also in handling and in the electrical resistance of the separator. As you see, in the first column, when the moisture content goes pretty low, let's say about 0.1 percent, the electrical resistance shoots up rapidly, as compared to, let's say, at a 4 percent moisture level, from 36 to 4,000 milliamps per square inch.

The next is ion exchange capacity is one of the characteristics of ion exchange separators. In our separator, this means the number of carbocylic groups which is capable of exchanging cations, which is usually expressed in mil equivalent per gram of dry film. Since this is the number of free acid groups in the separator, it should be a direct function of the same graph in a separator. See the next figure.

(Figure 271)

This figure shows the exchange capacity of the separator as a function of percent per hour. It is approximately linear up to about 60 percent, and our specification is about 3, plus or minus 0.6, mil equivalent per gram.

Lastly, in this group is the tensile property. Since the separator has to wrap around the electrodes and had to withstand mechanical handling shocks, vibrations, in the field, the tensile strength is a good indicator of the mechanical properties.

(Figure 272)

This shows the tensile strength of the raw material, the cross-linked material, and the finished product, which all have over 1,000 psi as our specification. In the next group of properties, the diffusional properties, we have electrolyte diffusion, we have some other ion diffusion properties. And the permeability of the separator to the ions in the electrolyte is a necessary requisite for the proper functioning of the cell.

The electrolyte diffusion rate reflects somehow on the membrane structure of the separator, the pore size, and the porosity. Ideally, you would expect the separator to pass freely the ions of the electrolyte, but to restrict the ion passage of other ions that are found in the electrode and in other components. This has never been found. To some degree, we could restrict the passage of other ions. See the next figure.

(Figure 273)

400

This figure shows the fluxed profile of the diffusion of 30 percent KOH across the membrane, as a function of time. And in the next figure, we summarize the flux properties of the separator.

(Figure 274)

You see they are all on one times 10^{-3} mole per square inch per minute, compared to cellophane. They are about the same. However, with respect to the restriction of other ions, see the next figure.

(Figure 275)

For instance, the zinc cation diffusion across the membrane, in the case of cellophane, we have about 10^{-6} moles per square inch per minute. In 2291-40/30, we are talking about 10^{-7}, so there is one order of magnitude difference, and there is some degree of restriction of the passage.

In the next group, we have the stability properties of the separators. We studied the oxidation stability, the thermal stability, and also the dimensional stability of the separators. The oxygen stability was evaluated with the use of oxygen of silver oxides and silver dioxide. This test gives us two kinds of information. First, it gives you the rate of metallic silver pickup onto the membrane, which if the accumulation is large enough, will shut off the cell. Second, it provides some kind of a measure of degradation that is due to the effect of the oxygen, silver oxide.

(Figure 276)

This figure shows the rate of silver pickup onto the membrane as a function of time at 100 degrees C. For the 2291 series, 40/20, 40/20E, the rate of pickup of silver line is approximately linear with time, and it is much smaller than PuDo, which is a cellophane. The next figure shows the time to total degradation of the separator.

(Figure 277)

As you see, PuDo, cellophane, degrades completely in from eight to 16 hours, whereas there are practically no observable effects on the 2291 separator in 24 hours. The thermal stability of the separator is studied by keeping the separator in 145 degrees C for seven days and 14 days, and we study the weight loss of separator and also the electrical resistance.

401

I will briefly describe the result. For the 2291 separator, it shows that we lost about 4 to 9 percent in 14 days at 145 degrees C. For the cellophane, it is completely dissolved, and there is no more separator after the test.

The dimensional stability of the separator is measured by the percent change of the linear dimensions in the electrolyte. The electrolyte shows the 2291 has a change of about 5 to 6 percent in width and about 4 to 5 percent in length, and very little change in thickness. The last group of properties I am going to describe is electrical properties. We measure the AC and DC resistance of the separator at low temperature, and also some cycle life data. The electrical resistance is perhaps the most valuable measurement in the development of a separator. If we find out the resistance is too high, we usually can forget about the other tests.

(Figure 278)

This figure shows the comparison of the AC and DC resistance of the separator at 40 percent across it. Usually the DC resistance is about two or three times lower than the AC resistance. We know that the temperature decreases the resistance of the electrolyte increases, and so does the separator.

(Figure 279)

This figure shows the electrical resistance of 2291 from 20 degrees C to minus 30 degrees C, from 20 percent KOH to 40 percent KOH. In general, the total resistance of a cell is largely due to the electrolyte; but if we look at minus 30 degrees C, the 40 percent column, the first column, has a resistance of about 610 milliamps per square inch; for 2291 40/30, it has already gone up to 537, and for 40/60 separators, this is even larger than the electrolyte.

(Figure 280)

This next figure shows the effect of temperature on the electrical resistance of a separator in a fixed 30 percent caustic. As you see, below minus 20 degrees C, the resistance rises very rapidly.

(Figure 281)

The next figure shows the effect of KOH concentration on the resistance of the separator at minus 30 degrees C, and about 35 percent caustic; and the resistance also rises rapidly. We have come up with a table whereby you can calculate the resistance of a separator at a given temperature and a given concentration, within the ranges we studied.

402

(Figure 282)

The next figure shows a regressional analysis of our results. The "R" is the resistance in milliamps per square inch. The temperature is given in Kelvin, and "C" is the concentration of the KOH given in weight-percent. And K_1, K_2, K_3 are the numerical coefficients. This is approximately good up to 25 percent accuracy, and it further shows that the effect of temperature is much more pronounced than the effect due to the electrolyte.

Lastly, the ultimate test for a separator is in a cycle life. And we as a separator manufacturer do not have the cycle life data on nickel-cadmium batteries. The people who are interested may have the papers published by Dr. Lander. But we do have some silvox, silver-oxide-zinc data.

(Figure 283)

The last figure shows the relationship of cycle life at 40 percent depth of discharge as a function of a percent graft in a separator. You see at the very low percent graft and very high percent grant, the cycle life is a little bit poorer. And somewhere in between there is an optimum, around 40 to 60 percent graft.

And if we recall the ion exchange capacity curves and maybe the electrical resistance curve, the properties are better the higher the percent graft. But if you look at the zinc cation diffusion or some other property, the properties are better the lower the percent graft. And somehow a compromise is made; and the 2291 is such a compromise.

We offer for low drain, long shelf life, we have the 40/60 series, 40/100 series; and for high rate, moderate life, we have the 40/30 and 40/20 series.

LANDER: I would just like to remark that we have some experimental aircraft batteries flying in the A-7 aircraft. Now, these have been flying for three years now with not one single cell replacement in an aircraft which had been a high user of replacement cells made with cellophane.

Thickness Measurement of Grafted Membranes

Thickness Mills	d^a	d^2	Thickness Mills	d	d^2
1.30	0.07	0.0049	1.15	0.08	0.0064
1.30	0.07	0.0049	1.15	0.08	0.0064
1.38	0.15	0.0225	1.15	0.08	0.0064
1.38	0.15	0.0225	1.15	0.08	0.0064
1.30	0.07	0.0049	1.25	0.02	0.0004
1.25	0.02	0.0004	1.30	0.07	0.0049
1.25	0.02	0.0004	1.35	0.12	0.0144
1.15	0.08	0.0064	1.35	0.12	0.0144
1.20	0.03	0.0009	1.30	0.07	0.0049
1.15	0.08	0.0064	1.31	0.08	0.0064
1.38	0.15	0.0225	1.35	0.12	0.0144
1.35	0.12	0.0144	1.20	0.03	0.0009
1.35	0.12	0.0144	1.10	0.13	0.0169
1.35	0.12	0.0144	1.15	0.08	0.0064
1.35	0.12	0.0144	1.10	0.13	0.0169
1.28	0.05	0.0025	1.30	0.07	0.0049
1.38	0.15	0.0225	1.15	0.08	0.0064
1.25	0.02	0.0004	1.15	0.08	0.0064
1.23	0.00	0.0000	1.35	0.12	0.0144
1.28	0.05	0.0025	1.15	0.08	0.0064
1.20	0.03	0.0009	1.21	0.02	0.0004
1.30	0.07	0.0049	1.20	0.03	0.0009
1.25	0.02	0.0004	1.20	0.03	0.0009
1.20	0.03	0.0009	1.20	0.03	0.0009

Total 63.83 3.84 0.3786

a. d is the absolute value

means = $\frac{63.83}{52}$ = 1.23 mil

= $\pm \frac{3.84}{52}$ = $\pm$ 0.07 mil

= $\pm \frac{0.378}{51}$ = $\pm$ 0.09 mil

Figure 269

Figure 268

RELATIONSHIP BETWEEN HEAT TREATMENT,
MOISTURE CONTENT & A.C. RESISTANCE AT 40% KOH

CODE NUMBER	HEAT TREATED		HEAT TREATED LEFT OPEN 72 HOURS		NO HEAT TREATED	
	% H_2O IN FILM	R	% H_2O IN FILM	R	% H_2O IN FILM	R
1010-46-7	1.05%	200 mr-in^2	3.17%	122 mr-in^2	4.4%	35 mr-in^2
1010-46-9	0.45%	500	3.94%	103	4.80%	32
1010-46-10	0.34%	2500	3.60%	165	4.9%	28
1010-46-12	0.15%	4000	3.26%	133	4.3%	36
1010-46-8	1.22%	150	3.11%	95	5.2%	35

Figure 270

404

TENSILE PROPERTIES OF MEMBRANES

MEMBRANE	CROSSLINKING	% GRAFT	TENSILE AT BREAK
L.D. Polyethylene	0	0	3269 psi
	0	0	3370
	0	0	3020
	0	0	3050
			3120
L.D. Polyethylene	90 Mrad	0	3528 psi
	90	0	3491
	90	0	3637
	90	0	3332
	90	0	3990
P-2291	90 Mrad	40-50%	3370 psi
	90	40-50%	3775
	90	40-50%	3196
	90	40-50%	4061
	90	40-50%	3725

Figure 272

Acid Form
Sample dried at 65°C for 16 hrs.
Equilibrate in dessicator 3 days.
Convert in KOH 4 hours. Titrate with HCl.
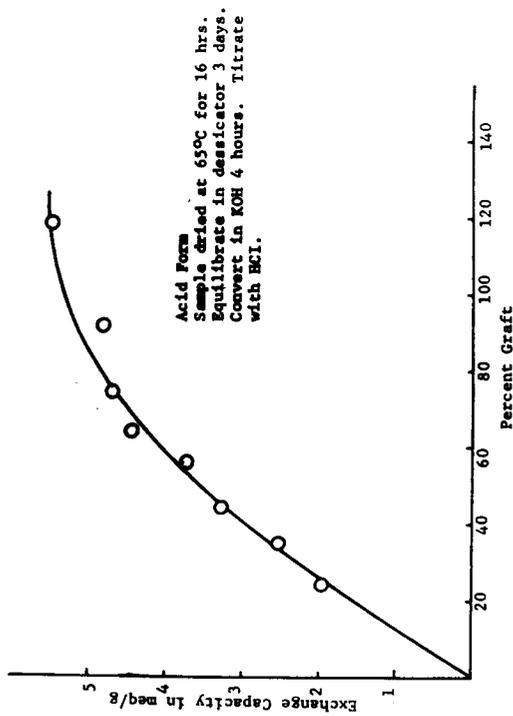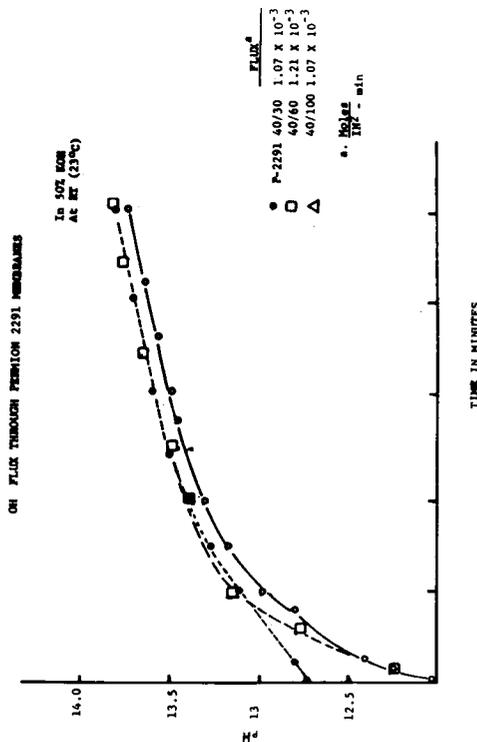
Figure 271

Electrolyte Diffusion across Permion Separators 30%KOH at 23°C

Separator	Flux
PUDO 193	1.2×10^{-3} moles/in^2-min
2291 40/20	1.5×10^{-3}
2291 40/30	1.6×10^{-3}
2291 40/60	1.1×10^{-3}

Figure 274

OH FLUX THROUGH PERMION 2291 MEMBRANES

In 50% KOH At RT (23°C)

		Flux^a
●	P-2291 40/30	1.07×10^{-3}
□	40/60	1.21×10^{-3}
△	40/100	1.07×10^{-3}

a. Moles/in^2 - min

TIME IN MINUTES

Figure 273

Zincate ion Diffusion across Permion separators. 45%KOH saturated
with 1M.ZnO at 23°C

Separator	Flux
PUDO 193	4.6 x 10^{-6} mole/in^2-min.
2291 40/20	1.4 x 10^{-6}
2291 40/30	8.8 x 10^{-7}
2291 40/60	2.0 x 10^{-7}
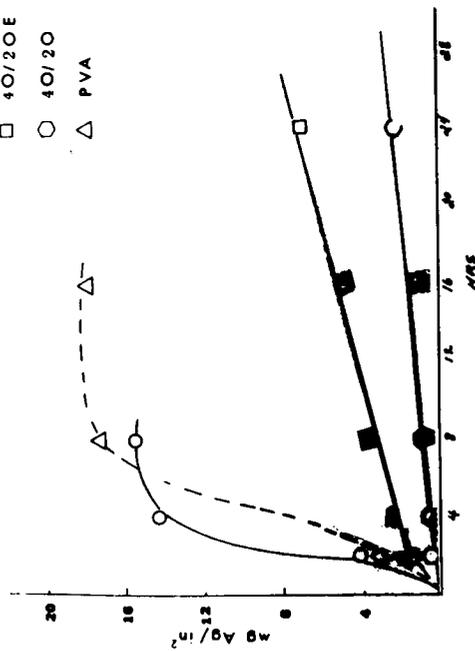
Figure 275

Figure 276

DEGRADATION OF SEPARATORS IN 30% KOH
SATURATED WITH SILVER OXIDE AT 100°C

SEPARATOR	TIME TO DEGRADATION	ACCUMULATION METALLIC SILVER I
PUDO 193	8 to 16 Hours	Dissolved
Monsil PVA	24 Hours	Dissolved
E-2291 40/20	No observable attack in 24 hours	7.1mg/in^2
P-2291 40/20	"	2.3mg/in^2
P-2291 40/30	"	1.4mg/in^2
P-2291 40/60	"	2.0mg/in^2
E-6001	"	3.0mg/in^2
P-6001	"	4.5mg/in^2
Celgard 3401	No observed attack but appears non-wettable	7.6mg/in^2

Figure 277

Figure 278

CODE NUMBER	D.C. RESISTANCE	A.C. RESISTANCE
WP-20-1-T1	20 mr-in²	36 mr-in²
WP-20-1-B3	40	90
WP-20-2-T2	16	37
WP-20-2-T3	16	55
WP-20-2-B4	13	45
WP-20-2-B2	12	30
WP-20-1-B1	25	65
WP-20-1-B2	33	55
WP-20-1-T3	38	68
WP-20-2-B3	26	48

Figure 278

Figure 279

Temp.	Pudo 193 (mΩ-in²)	E6001	6001	E40/20	40/20	40/30	40/60	Celgard 3401	Monsil PVA	Cell Constant
20°C	7	15	22	11	16	34	48	17	12	265
10°C	13	21	31	18	27	54	78	19	19	300
0°C	17	30	46	30	35	83	116	25	24	333
-10°C	26	58	77	40	55	126	197	31	45	370
-20°C	41	88	127	53	114	254	387	41	76	445
-30°C	71	179	297	111	240	537	962	67	188	610
20°C	8	7	13	11	17	32	38	11(89)	12	263
10°C	9	8	18	13	24	43	56	13(121)	18	277
0°C	17	12	22	19	33	62	75	23(159)	39	299
-10°C	21	21	36	29	54	100	121	34(204)	43	337
-20°C	42	23	47	31	96	181	264	36(292)	76	405
-30°C		39	94	65	173	338	471	47(451)	143	525
20°C	5	8	15	8	13	27	33	10(215)	17	256
10°C	6	13	22	13	17	35	43	14(258)	19	268
0°C	8	17	28	17	25	52	66	21(295)	22	287
-10°C	12	22	40	24	38	82	107	19(453)	28	323
-20°C	18	30	55	32	58	140	174	36(533)	53	375
-30°C	28	52	104	47	108			49(782)	97	458
20°C	5	6	11	8	12	31	34	10(66)	8	254
10°C	7	7	13	9	16	31	34	14(74)	16	268
0°C	9	9	20	13	23	43		20(92)	17	289
-10°C	13	13	26	18	38	97		26(122)	20	312
-20°C	14	20	35	24	43			26(171)	23	358
-30°C		28	58	41	87			30(254)		432
20°C	4 (Broke)	7	11	10	11			8(113)	3	255
10°C	Broke	10	13	14	16			9(152)	4	267
0°C	Broke	12	25	17	21			17(209)	6	287
-10°C	Broke	17	35	25	32			17(251)	7	309
-20°C	Broke		57		48			26(319)	12	345
-30°C		33						31(443)	Broke	416

Sample washed in water and soaked 48 hours before measurements.

Figure 279

Figure 280

O PUDO
□ 6001E
O 6001
△ 40/30
O 40/60

Figure 281

O PUDO
□ 40/20E
O 40/20
△ 40/30
O 40/60

407
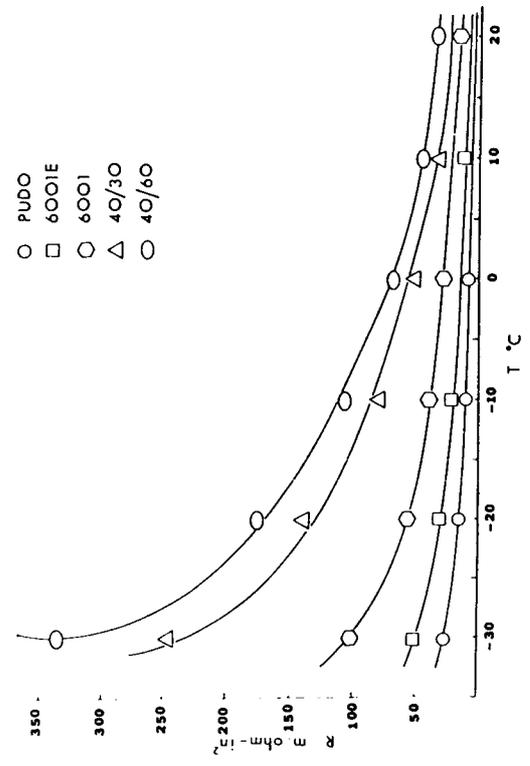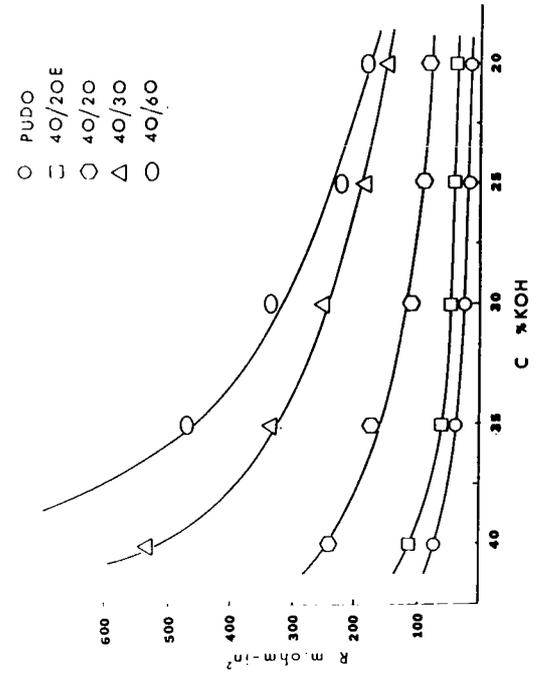
REGRESSION ANALYSIS OF SEPARATOR RESISTANCE
AS A FUNCTION OF TEMPERATURE
AND KOH CONCENTRATION

$$\ln R = K_1 + K_2 \frac{1}{T} + K_3 C$$

SEPARATOR	K_1	K_2	K_3	Variance
PUDO 193	-7.82	2199	6.67	0.038
P-2291 40/20	-9.80	3280	3.85	0.026
E-2291 40/20	-7.93	2615	3.89	0.026
P-2291 40/30	-9.80	3416	4.46	0.023
P-2291 40/60	-10.09	3458	5.63	0.027
P-6001	-8.97	2623	6.79	0.076
E-6001	-8.89	2851	5.70	0.053

Figure 282

Figure 283

408
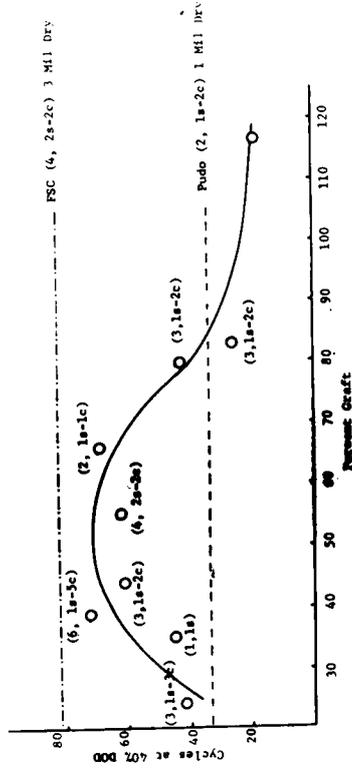
CELL CASES FOR DISCUS III

H. Thierfelder
General Electric Space Division

The title for this presentation may be titled, "Cell Cases for Discus III, "
or DSCS III, and "DSCS" stands for the Defense Satellite Communications System. "

The General Electric Space Division is currently building eight batteries
for the Defense Satellite Communications System, and during the initial study
and the design phase, well, we found, like many others, that the power require-
ments were continually going up, but they kind of froze the weight budget. So
we had to meet this challenge; actually, we had to do some redesign on the pro-
posed battery. And what we finally came up with was a battery that had 17 per-
cent higher capacity, but had the same weight as the original battery.

Now, just one of the many things that we did was to replace the 19-mil
stainless steel cell cases with 12 mil stainless steel call cases. So I wanted
to share with you what experience we have had on that during the past six months
or so.

(Figure 284)

What you see here, I will describe the three different cases you see. On
your left-hand side is the 12-mil stainless steel case for the cell. The dimensions
are about four inches wide, 4-1/2 inches high, and one inch thick. The side walls
are 12-mil 304-L stainless; the bottom is 19-mil 304-L stainless. And one
other change with this case is that it is a welded case, but the weld is not at the
corner. The weld is down the center of one of the narrow edges.

The thing in the middle there is what we call a "retainer," and that is made
of 60-61 aluminum, and it is dip-brazed. Now, the dip-brazing makes it possible
to make that retainer with tolerances as close as plus or minus five mils, and
the corners are perfectly square. And one of the problems in this type of assembly
is the tolerances on the cell case and the tolerance on the retainer.

What you see on your right, there, then is the assembly of the stainless
steel case and the aluminum retainer. And they are electrically separated by
15 mils of potting compound. Actually, we are using two different types of com-
pound in there, and with the tolerances, the thickness can vary from 10 mils to
20 mils, except at the bottom, where you have actually 20 mils to 30 mils on
the bottom side of it.

The one other thing I would like to explain is that the 12-mil case is new, but the assembly that you see here is something that we have been using for quite a number of years already, the only difference being that we are using it with 19-mil cases. And later, I will show you some of the batteries we have built with this same concept; although they are not the same size, they have the assembly of an aluminum retainer with the stainless steel case.

One other thing is that one reason we originally got into this aluminum retainer going around five sides of a cell was that back in the late 1960s, I think the Air Force sponsored a very extensive test program at Battelle. And one of the major conclusions of that test program was that although the nickel-cadmium cell temperature is very important, even more important is the gradient across the cell. Now, I haven't heard much discussion about this recently, but that was one of the main considerations in going to the retainer around all five sides of the cell, so we can withdraw the heat from every side except the cover, of course.

In this way, we do reduce the gradients across the cell in all directions, to the best of our ability.

(Figure 285)

The assembled cell, which now in this case has the cover on it, the cover which we are using for the DSCS program, and that is a 19-mil-thick cover and the G.E. ceramic seal: One of the first things that we did, of course, with especially the customer's concern about the use of the 12-mil can, was to run some pressure tests.

(Figure 286)

So one of the first things, as I said, that we did was to run a pressure test. And this one, without any restraint on it, was pressurized to 180 pounds per square inch. The black area you see there is not a hole in the case; the case is not ruptured. That is part of the potting compound that is adhering to the stainless steel, whereas in other portions the potting compound is adhering to the aluminum.

In this figure you can see the dip-brazed construction of the aluminum retainer. It is sort of a tongue-in-groove assembly; and actually, the retainer had opened at about 135 pounds per square inch. Now, of course, again, there was no restraint on this cell at all. It was free; no side plates or clamp on it.

(Figure 287)

410

This is the same thing, merely looking down from the top of the cell; at 180 pounds pressure, this is what the assembly looked like.

(Figure 288)

We then put the cell back on the pressure test, and we ran the pressure up until the cell ruptured. And the case ruptured at 480 pounds per square inch; and you can see, actually, the break or the tear is immediately below the weld of the cover to the case. The weld itself is not broken, but the metal immediately adjacent to the weld is torn.

(Figure 289)

This is the same thing from the top. One other thing you can see here is that the fill tube blew out at the same time as the weld ruptured; and this actually happened at the same instant. I think when the metal tore out, it distorted the cover, which then caused the fill tube to fly out.

When the cell ruptured, that was the only thing that we did hear. This was inside of a steel box and the ping was the fill tube hitting the wall of the box.

(Figure 290)

We ran a number of other tests. And on the cover, it may be very difficult for you to see, probably, on here. There are two cells clamped together with the retainer here, and the cell with the pressure gauge on it has two braces welded to the cover and the one on the front has a single brace.

What we found was in the initial testing, before we ever did the burst test, was that the cover had a slight bulge when the pressure went up to 100 pounds per square inch. In fact at 120 pounds, we had like a 60-mil bulge in the center and a slight distortion of the ceramic seals. So we went into a program to determine a method of reinforcing the cover; and what we came up with and what we are using is two braces, which are not shown here because, they are like the one on the cell with the pressure gauge. There is a brace on each side, but it is a somewhat narrower brace, and it is a lightweight brace because it had holes in it, lightening holes in it.

And with this reinforcement, there is no distortion at all in the cover, up to 100 pounds per square inch.

The other test that was run here and is demonstrated by this figure is that we clamped two of the cells together, and then we drilled a hole in the clamp and a hole in the one wall. And we pressurized that back cell while the front cell was at atmospheric pressure.

What we were concerned about here was the deflection of the wall, when we have a difference in cell pressures. In other words, when we construct a battery and cell number "A", in the back, would have a pressure maybe of 25 pounds per square inch, and cell number "B" in the front might have zero pressure, or the one might be 35 and the other 10. So what we did here was bring up the pressure of the back cell in five-pound increments between five and 25, and measure with an indicator gauge through the hole what deflection of the wall, which is now a combination of 12-mil steel and 40-mil aluminum, another 40 mils of aluminum, and another 12 mils of steel; and what we found here was that with this design, at 25 pounds difference in pressure, the wall moved 34 mils; but when the pressure was released, the wall actually went back to within one mil of what it was.

Now, of course, we were concerned about this, because of the difference it could cause in the interelectrode spacing of the cell which had the lower pressure. In other words, if the wall would move a significant amount, you could significantly reduce the interelectrode spacing on the one cell. And for a mission that has 10 years' life, we wanted to make sure that this would not be a problem. And with the design that we have, we do not feel that it will be.

(Figure 291)

I mentioned at the beginning that we have used the same design on other spacecraft; and this was probably the first flight battery that we built. It was with four ampere hour cells. You see the cell on the left-hand side. In the center you see the retainer, which in this case has sort of like wings on there, but extensions to the bottom. So this is to increase the radiating surface of the bottom of the battery. All these batteries that we are using on synchronous orbit are fastened to the outside of the spacecraft, or through a wall in the bulkhead of the spacecraft.

So in this case, this is a BSE, broadcast satellite experiment, cell; and I will show you the battery next. But the battery is mounted through a hole in the wall, and the bottom of the battery radiates directly to space. So the fins, the aluminum fins, on there are all lined up and there is an aluminized Teflon, or tape, on there which then serves as a radiator, and no additional radiator plate is added to this particular battery.

412

(Figure 292)

This is the four-ampere-hour BSE battery; and you see that some of these cells did not have fins because they interfere with the mounting lugs. This is a 16-cell battery. All of our current programs use 16-cell batteries, and we have a boost regulator to boost the voltage up to the 28-volt spacecraft bus. The DSCS battery actually will look very, very similar to this. It will have 16 cells in one line, the same as this; and the advantage, of course, of the single line is that we do have slightly lower weight for a battery with 16 cells in one line than having two lines of eight cells; and also, again, it reduces temperature gradients, because all the cells are in the same position. There is not an "inside" and "outside" of any one cell.

(Figure 293)

This is a battery for the LOBOS positioning system, for which we have built 21 of these and shipped them to Rockwell for their spacecraft. And this has the same design; that is, these are 15-ampere-hour cells. Each cell is in an aluminum retainer; the retainers are then just pressed together with the end plates.

One other advantage to this is on the one side you will see on the top the heater strip. The heater is bonded directly to the cell retainers; and then underneath there, you see three thermostats. And of course, in this case it was eight cells in a line, 16 cells total.

Another interesting point was, you see six mounting holes at the top. This battery is mounted on the outer bulkhead of the spacecraft, actually; it is not inside the spacecraft at all, and it mounts with the six mounting points, and then the radiator plate is attached to the bottom end, and that radiates directly to space.

DISCUSSION

GASTON: RCA. What is the capacity of the DSCS III battery nowadays?

THIERFELDER: It is rated at 35 ampere hours.

FORD: Goddard. You mentioned in the early part of your presentation going to this packaging concept, I believe, where you put the cell, or weight, and you use a like 12-mil can; but you didn't mention the weight of the cell when you got through versus what you had used in the 22 or 28-mil can. Do you have a comparison?

413

THIERFELDER: Well, there is no real point in comparing cell weights. We are comparing the total battery weight. And all the previous have these retainers that, of course, vary with the size of the cell. The one on DSCS is a 40-mil; the one on GPS was a 32-mil; the one on the BSE is 20-mil. And we could have gone down to less than that, but you can't fabricate it very well, when you get less than 20 mils. But we are not looking at cell weight; we are looking at total battery weight.

FORD: Would you comment on approximate number of pounds or whatever the savings was that you can accomplish by going to the thinner cells and using the clamping technique?

THIERFELDER: Well, the only number I can give you is the number I gave at the beginning. We had kept the same weight of the battery, which was 47 pounds, and we have increased from 30 ampere hours to 35 ampere hours, for the same weight. But there are many other changes besides the cell case; that is not the only change.

HALPERT: How did you change from 30 to 35? Did you add extra active material, or did you make the cell differently?

THIERFELDER: No; it is a different cell, a different design cell entirely, than what we originally had regarded.

HAAS: For me, the cell turns out, is the Intelsat V 35-ampere hour cell, the weight savings is actually to the cover and the can is approximately, 70 grams total; that would include the smaller seal size, and the reduced thickness. So 70 grams out of 1,050 is 7 percent.
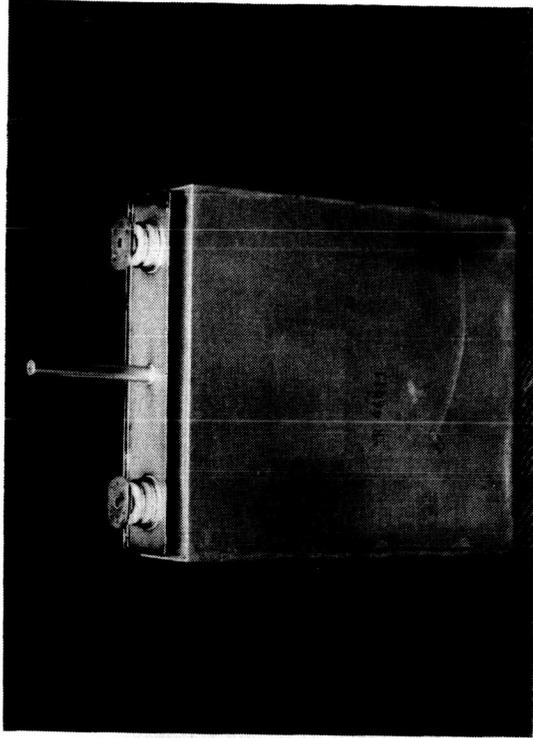
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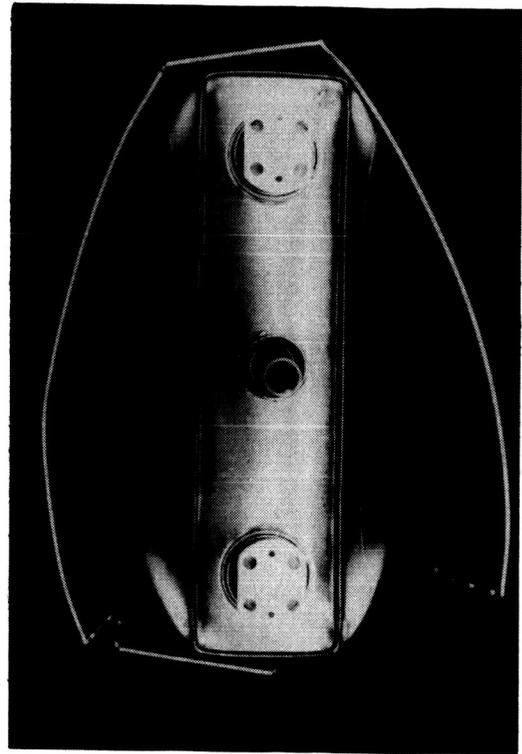
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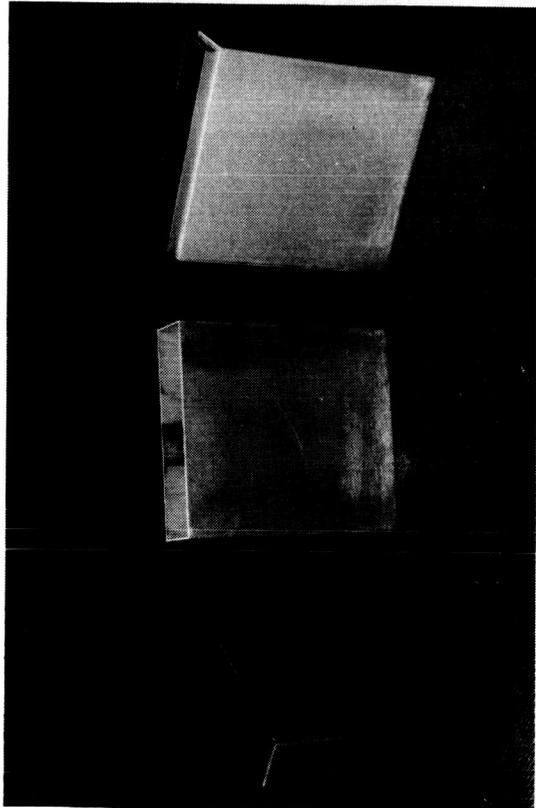
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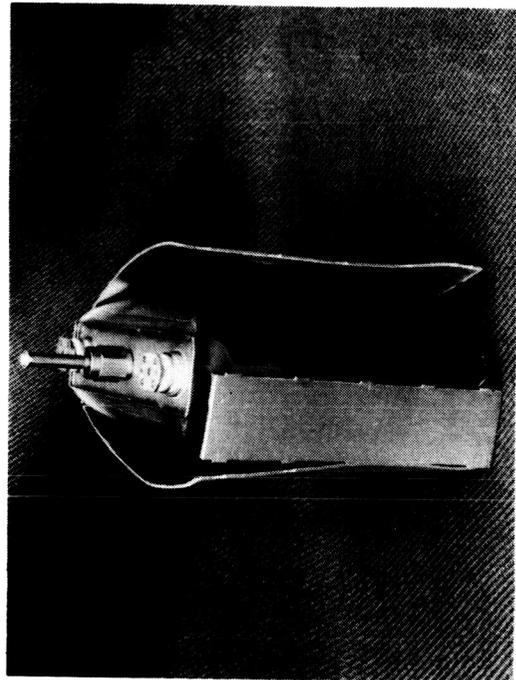
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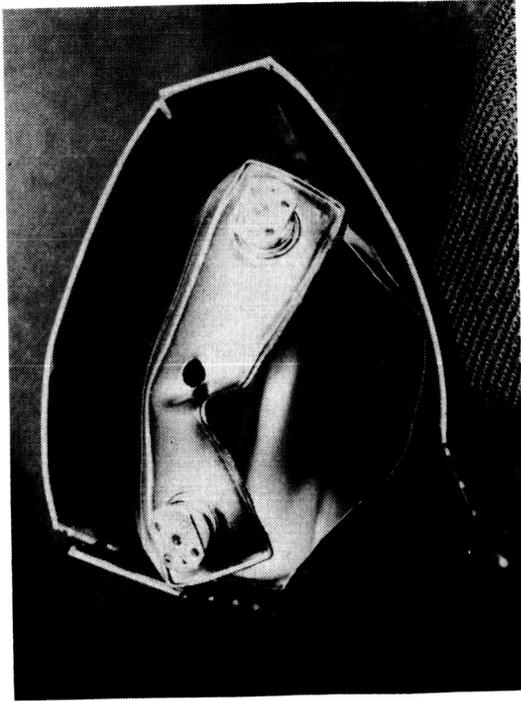
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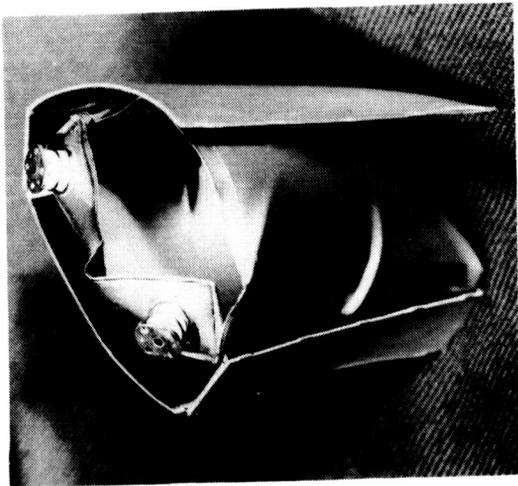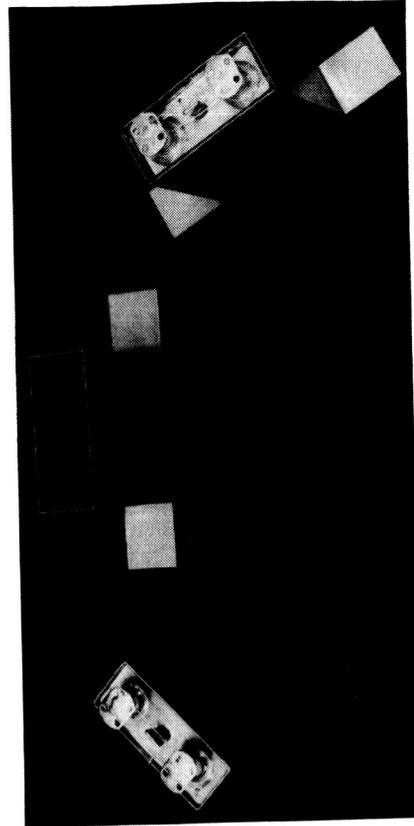
Figure 291

Figure 288

Figure 290

416
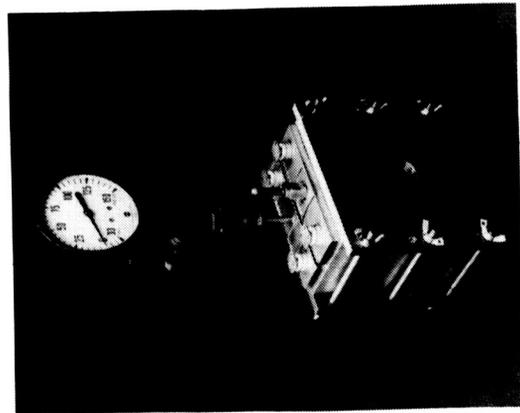
Figure 292

Figure 293

417
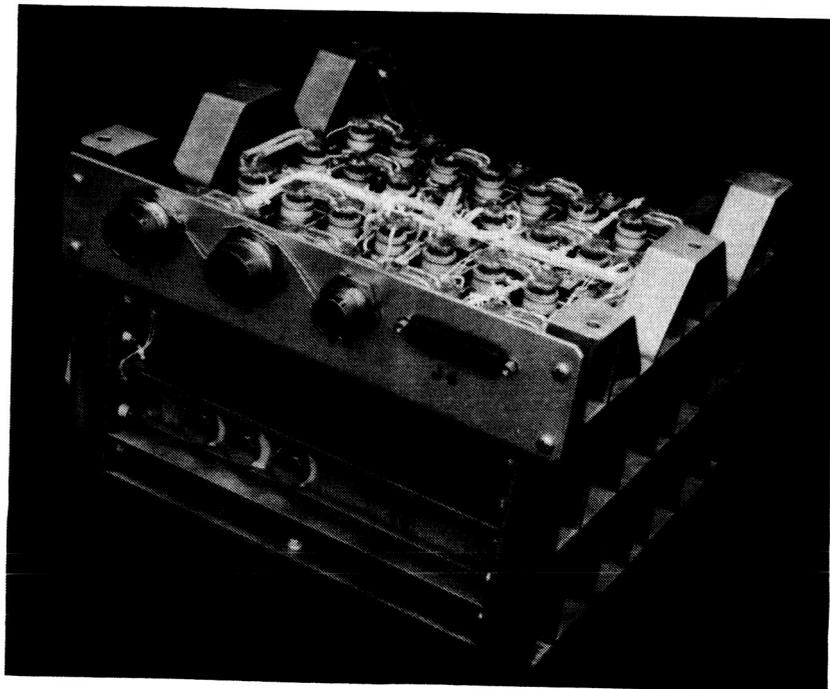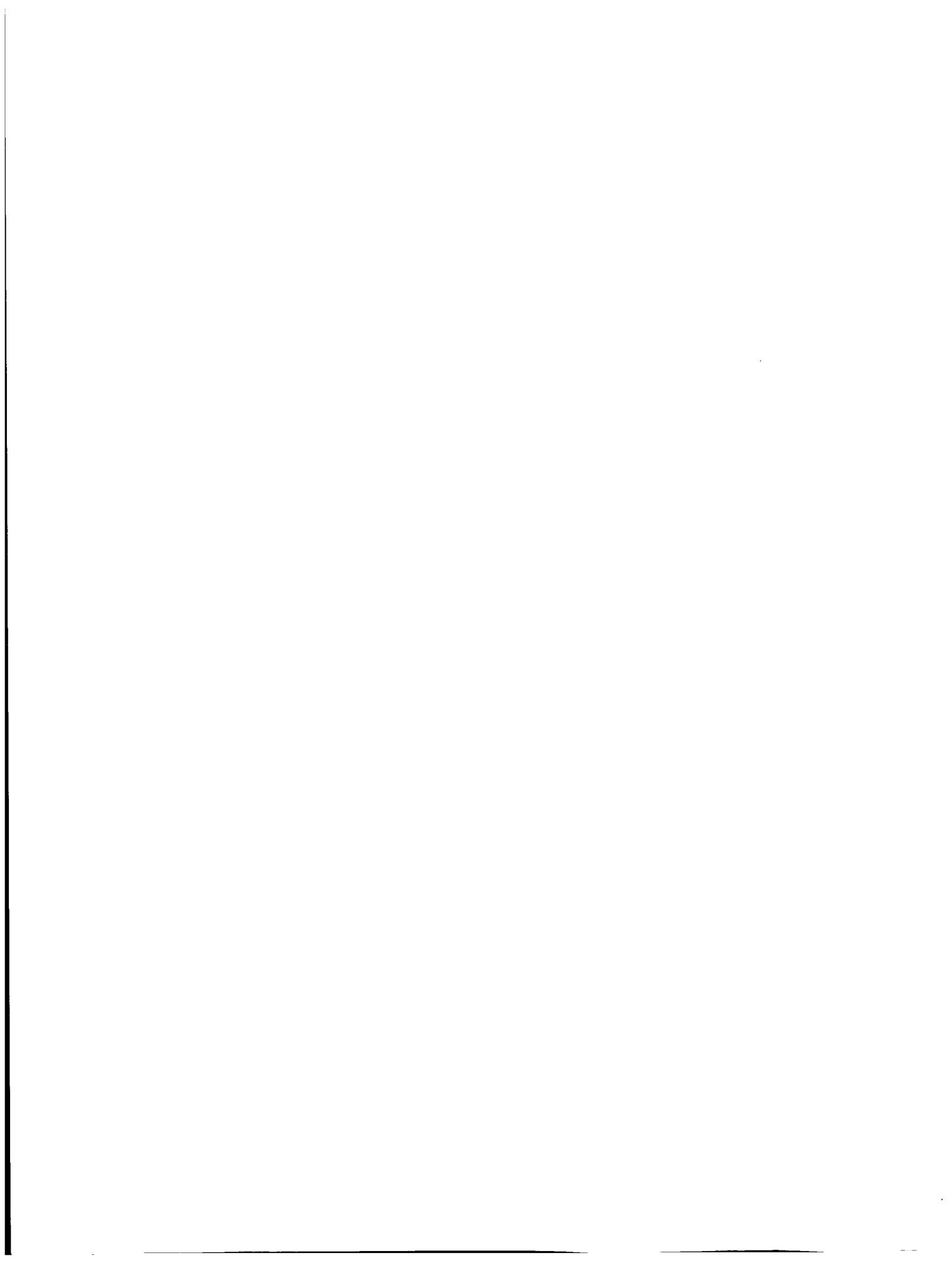
EPOXY GRAPHITE CELL CASES

S. Bogner
Jet Propulsion Laboratory

I am going to talk about the graphite epoxy cell case and header.

When we first decided to look at weight reduction in the area of cases, we knew people that were going to thinner metal cases; and this just shows a chart of some other possibilities of using other materials, compared to the graphite epoxy.

(Figure 294)

This is one of the major numbers that you look at is the density pounds per cubic inch versus the ultimate tensile strength, here, in KSI. And you can see that the graphite epoxy is a pretty strong material. And one of the reasons that the stainless steel case does make a good case is because of its yield in elongation, which allows it to expand and form a ball that can hold the pressures; and that isn't the case with the epoxy graphite, because it has none; no elongation.

(Figure 295)

Some of the things we considered in going into, or looking at, the graphite epoxy case were the gas permeability, KOH compatibility, pressure and structural dynamic integrity, and the fiber orientation and fabrication process; cover-to-case sealing, terminal installation and sealing, reproducibility, exposed to the extractable materials that might influence the electrochemical portion of the cell, and electrical conductivity between the terminals.

(Figure 296)

On this program we developed some tooling, and this kind of shows part of the tooling to make the case. We have a female mold, and then the center portion here is an RTV bladder; and then that is pressurized when the epoxy graphite is put on and it is compression-molded there.

(Figure 297)

This shows another shot of it. See Figure 298. This shows the final configuration of the wraps of the epoxy graphite layer, showing, I think, eight layers of material with a zero-90 degree wrap.

(Figure 299)

This shows a couple of completed cases. The material that is used is a 2-1/2-mil material.

(Figure 300)

This is the tooling that was developed to mold the cover.

(Figure 301)

And it is molded from a chopped fiber material.

(Figure 302)

Some of the initial testing we did was to cut some of the cases that we molded into strips, and we glued stainless steel strips on the end to form tensile bars.

(Figure 303)

Now, those strips; we coated some of them with epoxy and some of them were left uncoated, and then they were placed in 30 percent KOH at 150 degrees F for seven days, and then they were given a tensile test, and you can see the results. And from these results, we concluded that the potassium hydroxide was not attacking the material during that period of time.

The material that was used for attaching the case to the header and also used in the tensile test was a 3-MEC-2216, and they also experimented with some other materials; and another one that was found to be good was Crest 363.

(Figures 304 and 305)

Now another thing we were concerned about was sealing of the terminal to the header, and what we ended up with is a compression seal with epoxy around it; and this doesn't really show a good photograph of the seal. But we ran some tests in 30 percent KOH at 150 degrees F with these three covers in the pictures with 100 psi pressure, psig pressure, behind them for 95 days, and we didn't get any leakage around the terminals, though you see some leakage came out around the edge of the fixture.

(Figure 306)

Some of the experiments we did on the cases, and this is some of the later ones, after a lot of initial work, was that we built 15 cases with eight plies of 2.5-mil prepeg, and that should be zero-90 degree wrap, rather than zero-19. And the cases, then, had headers sealed into them, and then we placed them between platens to hold the broad sides of the base, and they were bursting at 100 to 240 psig, and it was estimated that these things should be capable of holding about 300 psi.

The mechanical engineer looked at it, and he was saying that the sides were deforming because we didn't have any plates in the cases, and we were getting those high-beam stresses fed into the edges, so that the edges were cracking. So in the next one, we built six cases, two with eight layers, two with 10 layers, and two with 11 layers of the material, and we placed an aluminum block inside the case to simulate the plates. And you can see, the burst values then did go up. So we decided that we would stay with the eight-layer material.

The question was asked, "Well, what pressure do the cells really operate at?" And the number I gave them was about 70 psig because that was the pressure limit, usually, on the acceptance test. So the men who rate that say they have to go four times that, so that is 280 pounds.

(Figure 307)

So in the next experiment, we built 29 cases, eight plies of zero to 90 degree layer, and we ran them initially through a 15 psi pressure test and found that six failed the initial leak test. Then we placed them in a proof pressure test at 280 psig, and three failed that test. Then we took them on up to the burst pressure, and 13 of the cell cases burst between 290 and 420 psig.

Four of them failed at the case-to-cover seal, and the rest failed at the edge, corner, or bottom of the case.

(Figure 308)

We also tested two of them with helium leak tests. One of the cases passed 1 times 10^{-8} standard cc's of helium, and the other one was down around four; but we think that we have at least established that the feasibility has been proven that you can build these cases.

The case weight and the header is about 25 percent of the stainless steel cases and headers, based on a 20-ampere-hour cell that uses around a 21- or 22-mil stainless steel case. This particular case weighs about 30 grams, and

the header that we are working with now is about 30 grams; so we have not really tried to decrease the weight in the header, and I think we can take another 10 grams out of the header, so we would end up with a total of 50 grams for a 20-ampere-hour sized case.

There is probably going to be a problem area in the case-to-cover seal, so the additional work that we want to do is to be able to go out and develop a supplier and establish a production capability, and find out what the reliability of these cases are in a kind of a semiproduction run, versus building them in the laboratory. And then we still want to work on optimization of the header terminals.

REPRESENTATIVE PROPERTIES

	S.S. 304L	Annealed Titanium	Zircalloy II	4130 Steel	Inconel 718	G/E
Density (lb/in³)	0.29	0.16	0.24	0.28	0.30	0.06
UTS (ksi)	75	140	60	90	180	100
Modulus (ksi x 10⁶)	29	16	14	29	30	12
Yield (ksi)	25	130	45	70	150	100
Elongation (%)	45	10	37	10	15	1

Figure 294

GRAPHITE EPOXY CELL CASE AND HEADER
TECHNICAL PROBLEMS CONSIDERED

- GAS PERMEABILITY
- KOH COMPATIBILITY
- PRESSURE AND STRUCTURAL DYNAMIC INTEGRITY
- FIBER ORIENTATION AND FABRICATION PROCESS
- COVER TO CASE SEALING
- TERMINAL INSTALLATION AND SEALING
- REPRODUCIBILITY AND RELIABILITY
- EXTROCABLE MATERIALS TO INFLUENCE CELL
- ELECTRICAL CONDUCTIVITY BETWEEN TERMINALS

Figure 295
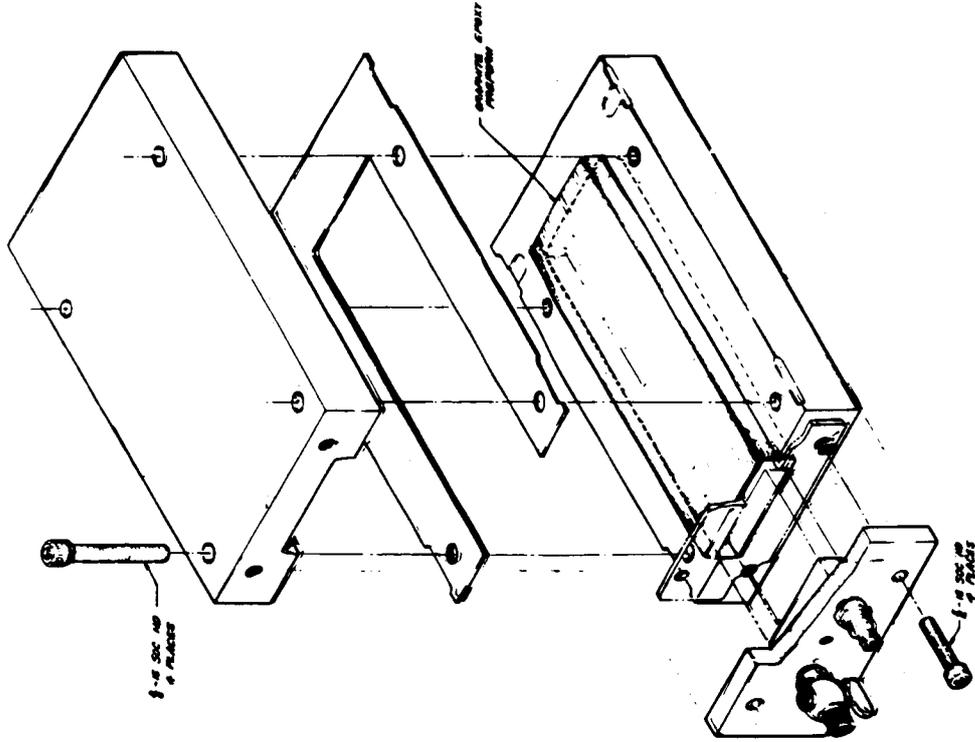
Figure 296
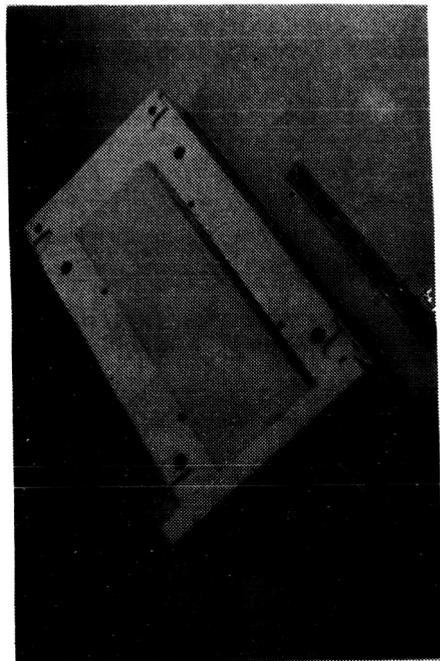
Figure 298

Figure 297

Figure 299

424
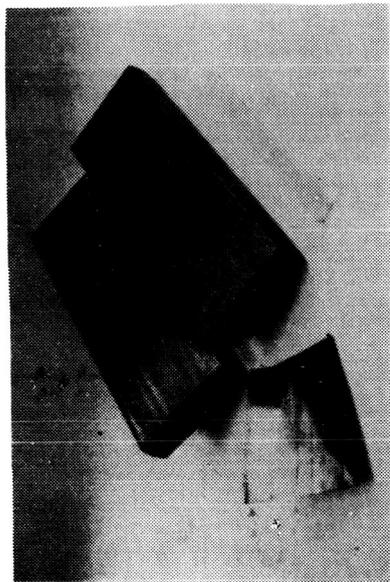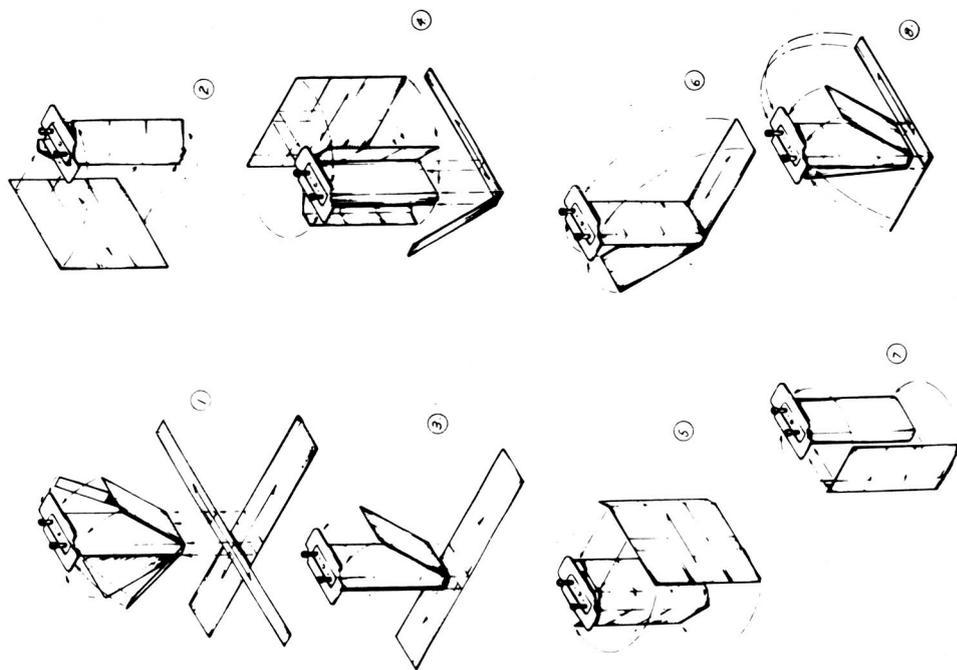
Figure 301

Figure 300

ION RESISTANCE

No.	Tensile Strength	Deviation	
3	74.0	±4	Exposed Uncoated Specimens
2	87.0	±5	Uncoated Control
3	?	±10	Exposed Coated Specimens
2	?	±0	Coated Control

Figure 302

Figure 304

GRAPHITE EPOXY CELL CASE AND HEADER
PRELIMINARY TESTS

- 15 CASES 8 PLIES 2.5 MIL PREPEG
  0°/19° WRAP

- BURST AT 100 - 245 PSIG

- SIDES DEFORMED HIGHBEAMS STRESSES FED INTO
  EDGES

- 6 CASES 8 - 10 - 11 PLIES

- 5 PACER PUT INSIDE CASES

- BURST VALUES 300 - 400 - 525 PSIG

Figure 306

Type 304 Stainless Steel

GLE

← 0.5" →
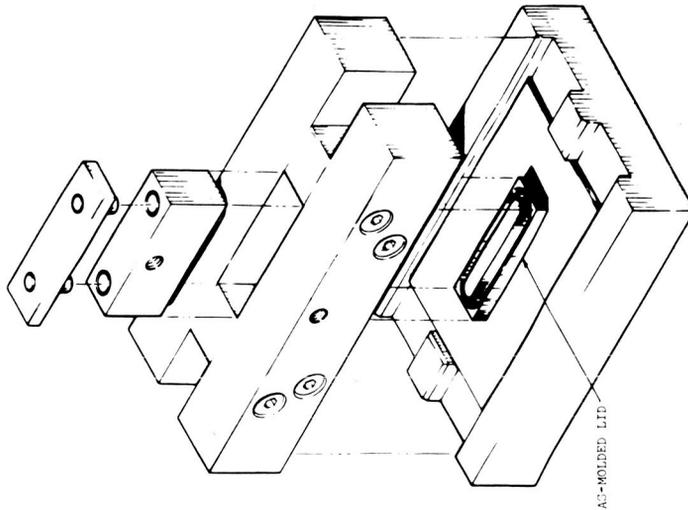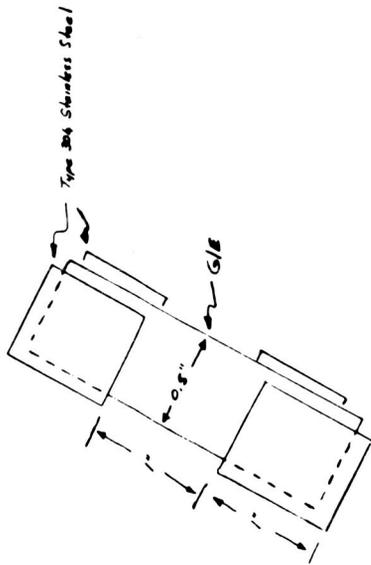
TENSILE SPECIMENS

Figure 303

Figure 305

426

GRAPHITE EPOXY CELL CASE AND HEADER
FINAL TESTS

_____

- 29 CASES BUILT 8 PLIES 0° - 90° LAYUP

- 6 FAILED INITIAL LEAK TESTS

- 3 FAILED PROFF PRESSURE AT 280 PSIG

- 13 BURST TEST   290 - 420 PSIG

    - 4 FAILED AT CASE TO COVER SEAL

    - REST FAILED EDGE - CORNER - BOTTOM

Figure 307

GRAPHITE EPOXY CELL CASE AND HEADER
CONCLUSION

_____

- FEASIBILITY HAS BEEN PROVEN

- WEIGHT 25% OF SS CASES AND HEADERS
  (20 AH CELL)

- PROBLEM AREA CASE TO COVER SEAL

- ADDITIONAL WORK REQUIRED

    - DEVELOPE SUPPLIER

    - ESTABLISH PRODUCTION RELIABILITY

    - OPTIMIZE HEADER AND TERMINALS

Figure 308

427
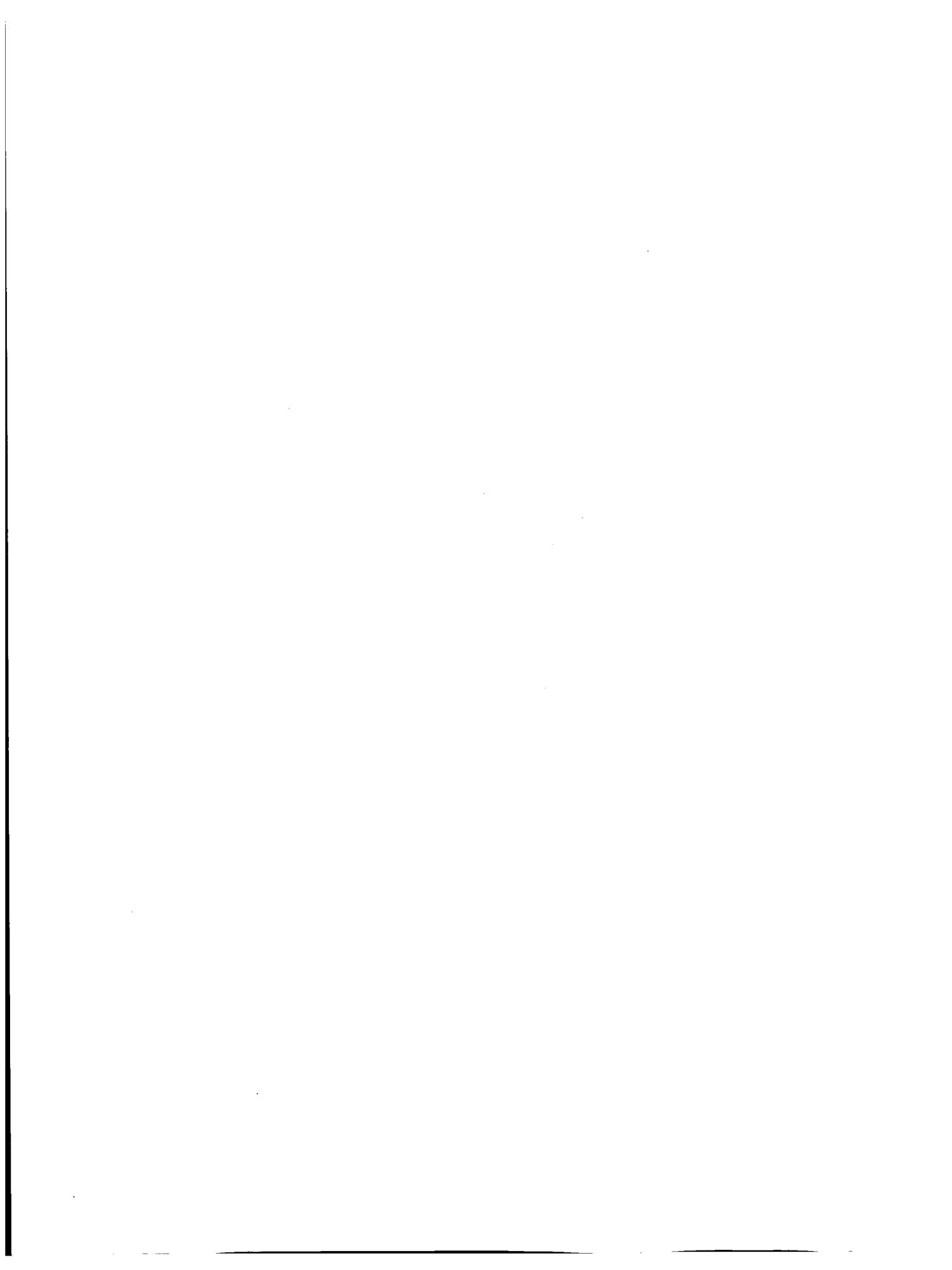
SESSION V

LARGE BATTERY SYSTEMS

G. Halpert, Chairman
Goddard Space Flight Center
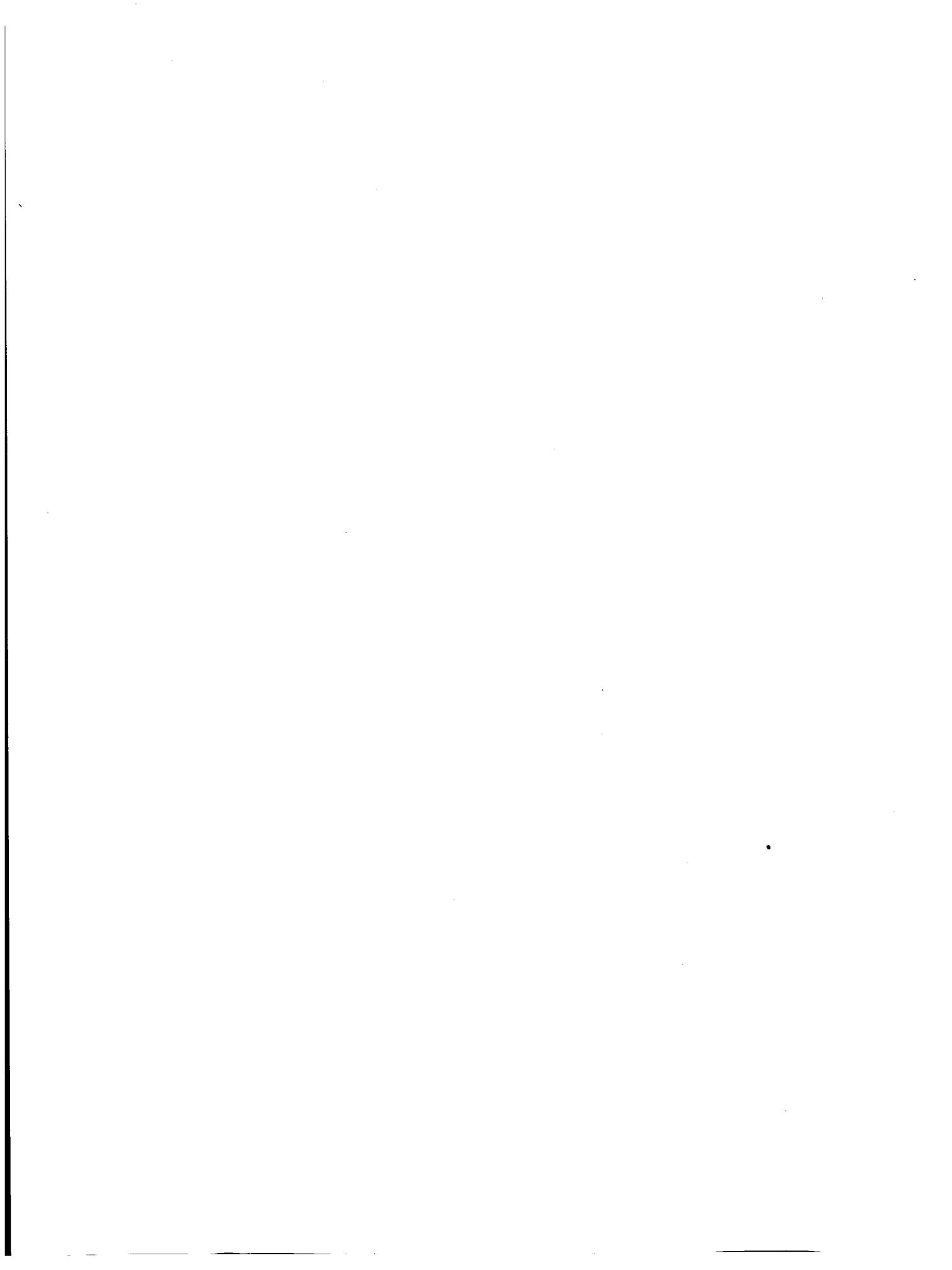
THE STANDARD 20 AH CELL,
A STATUS REPORT

G. Halpert
Goddard Space Flight Center

Contracts to produce standard 20 AH nickel-cadmium cells meeting a capacity requirement of 24± 2 AH and an envelope requirement listed in NASA/ GSFC specification S-711-17 have been placed with four manufacturers. The cells were to be produced in such a manner so as to meet the intent of the GSFC 74-15000 nickel-cadmium cell specification. The electrical test requirements appearing in the cell specification (para 6.4.2) were to be met in the sequence listed. Among the requirements were 10 burn in cycles 24°C, 0.°C, and 35°C capacity tests, charge efficiency tests and precharge verification tests.

From this program, 54 cells were to be manufactured by each of the companies involved; 24 of which were to be sent to McDonnell-Douglas in St. Louis to be placed in a battery which would be later termed a "Standard 20 ampere hour battery." The other 30 were to be sent to the Naval Weapons Support Center at Crane for qualification testing.

The results at this time are the following. General Electric delivered 54 cells in April of 1977. Their cells have completed initial evaluation tests at Crane and are now undergoing some cycle testing there. In addition, the 24 cells have been sent to McDonnell-Douglas and they have been incorporated in a battery pack, which is being qualified to the S711-17 specification. Maurice Zollner from McDonnell-Douglas will talk about that in the next paper.

The other three manufacturers are still involved in building cells. Our first cells shipped from Eagle-Picher had some problems. They were high in voltage and pressure at the end of the last cycle and their precharge had grown to proportions that were beyond the requirements. They are rebuilding cells for us at this present time.

With regard to the cells SAFT America, the capacities were low, the pressures were also high, and they too are manufacturing new cells to meet the requirements.

With regard to electric cells, at the moment we have a problem mostly in mechanical, but there are some electrical factors to be considered. We have to remember that these cells are manufactured by the electro-chemical

impregnation technique and we are not as familiar with the operation of these cells as we have been with those produced by chemical impregnation. However, this is a flight hardware contract. We will have to deal with the mechanical problems.

I want to make sure that I make it clear that all of the manufacturers were extremely cooperative in working with us to try to achieve the requirements of producing a standard cell, but there were some differences between this program and previous programs.

In addition to the unusual electrical test requirements no rework was allowed. The idea of this program was to produce a manufacturing control document describing the entire process and build a cell to that process without changing, and without any on-line engineering. This, evidently, became a bit of a problem.

At the present time, we are still planning to evaluate the cells from the three manufacturers when they are received.

We have samples from each of the manufacturers now and they will undergo vibration tests which are the qualification test in the 74-15000 document. We have made some changes in the spec because of vibration levels of the cells when they were vibrated in the battery frame that is being tested as a standard battery. I will list these for the record so we know what levels we are talking about.

(Figure 309)

As you can see, there are considerable levels in random and considerable also in sine. These levels reflect the overall requirements that a 20-ampere hour cell would receive in any one of the NASA spacecraft. That is why they encompass significantly large test levels.

The random level has been reduced from 43 GRMS down to 36 because of engineering tests that were done at McDonnell-Douglas. Even though we have dropped the levels, as you see, they are still considerable.

There will be two cells from each manufacturer vibration tested at Crane. Internal inspection will be made upon completion of that vibration. In addition, Crane will test four near earth orbit packs at 10, 20, and 30 degrees centigrade; at 25 and 40 percent depth of discharge; and one synchronous pack at 60 percent depth of discharge.

General performance tests will be performed on each manufacturer's cells and chemical analysis will also be done on the cells. The effort at Crane is just getting started.

DISCUSSION

HOLCOMB: NASA Headquarters. A couple of questions on the specification because I guess I am not that familiar with what you went through in establishing it.

Yesterday we heard from some of the cell manufacturers that we may be over specifying the cell requirement. I am wondering, in terms of NASA missions, have you looked at two things; one, whether or not, for instance, these vibration levels can be relieved or whether they are driving the cell design; and two, whether there are any other of the cell requirements that are in the standard specification that could be relaxed after going back and viewing the various missions?

HALPERT: With regard to vibration, the answer is that an environmental committee, Committee on Environmental Procedures, has looked at all the NASA requirements for any possible mission in which a 20 ampere hour battery be flown. These levels are their recommendation.

Now these are scaled a little bit differently because these are cell level. The committee considered the component level which in this case is the battery level. But these measurements were taken from the battery vibration test and that is why they are considered to be relevant in terms of what the cells actually do see in that battery. The battery is being given a pretty good shake, too, as you can imagine.

There are several project engineers who have said to us, "You are driving the requirements because of the vigorous vibration levels". In their particular case the requirement is in 9 g's, not 20, or 30, the only answer is that this is a standard piece of hardware and the Standards Environmental Committee say, "These are the levels you will vibrate to, " and so unless we get relief from them saying that there will be new levels, we don't have any choice in the matter.

With regard to tests, there is a very relevant question that was brought up by two of the manufacturers yesterday. We are performing the same tests that have been done for many years. The tests involve three capacity measurements; at 10, 35, and 24 degrees centigrade. At 0 degree, we are running at

C/20 for 72 hours, which is a moderately low rate, and we haven't had any failures at that level. The manufacturers were asked to design a cell to meet the voltage, temperature and pressure requirements.

The position that we took with regard to this was, "You are designing the cell, we are going to buy the cell from you, we would like you to tell us how you are going to build it, and write it down." That is all we want to do. We did have some arguments about how to do that. It was their cell, and they would have to meet the requirements. If we dictated how they were going to do that, of course we would have to end up buying it. So we did look to them for advice but the requirement still stood as to what they would have to meet in terms of the capacity measurements, voltage and pressure limits.

Right now we don't know another way of saying you have a good cell or a bad cell, and yet, when we operate this way, we find some problems. So for the long term, at the moment, this is the only way we can go. Unless we find that the results from the accelerated test program tell us something about how we should operate for the long term, and then we may change some of those requirements.

PALANDATI: NASA, Goddard. The levels are these mainly at more or less a flight level or are these mainly on a design level which is usually one and a half times the flight level?

HALPERT: A qualification level which is one and a half times the flight level. Now the qual battery will also be exercised to those levels. The flight battery will be done to lower levels. But we are qualifying the cell now to meet the quality levels.

RECOMMENDED DESIGN QUALIFICATION VIBRATION REQUIREMENTS
FOR STANDARD NICKEL-CADMIUM BATTERY CELLS

(a) **Sinusoidal Levels**

Axis	Frequency (Hz)	Level	Sweep Rate
All	5-34	1.27 cm (da)	
	34-200	±30 g	2 oct/min
	200-2000	±9 g	

(b) Random Levels

Axis	Frequency (Hz)	Level	Grms	Duration
All	15	.023 g^2/Hz		
	15-30	+15 dB/oct		
	30-100	.700 g^2/Hz	36.4	2 min/axis
	100-120	+6 dB/oct		
	120-1000	1.0 g^2/Hz		
	1000-2000	-9 dB/oct		

Figure 309
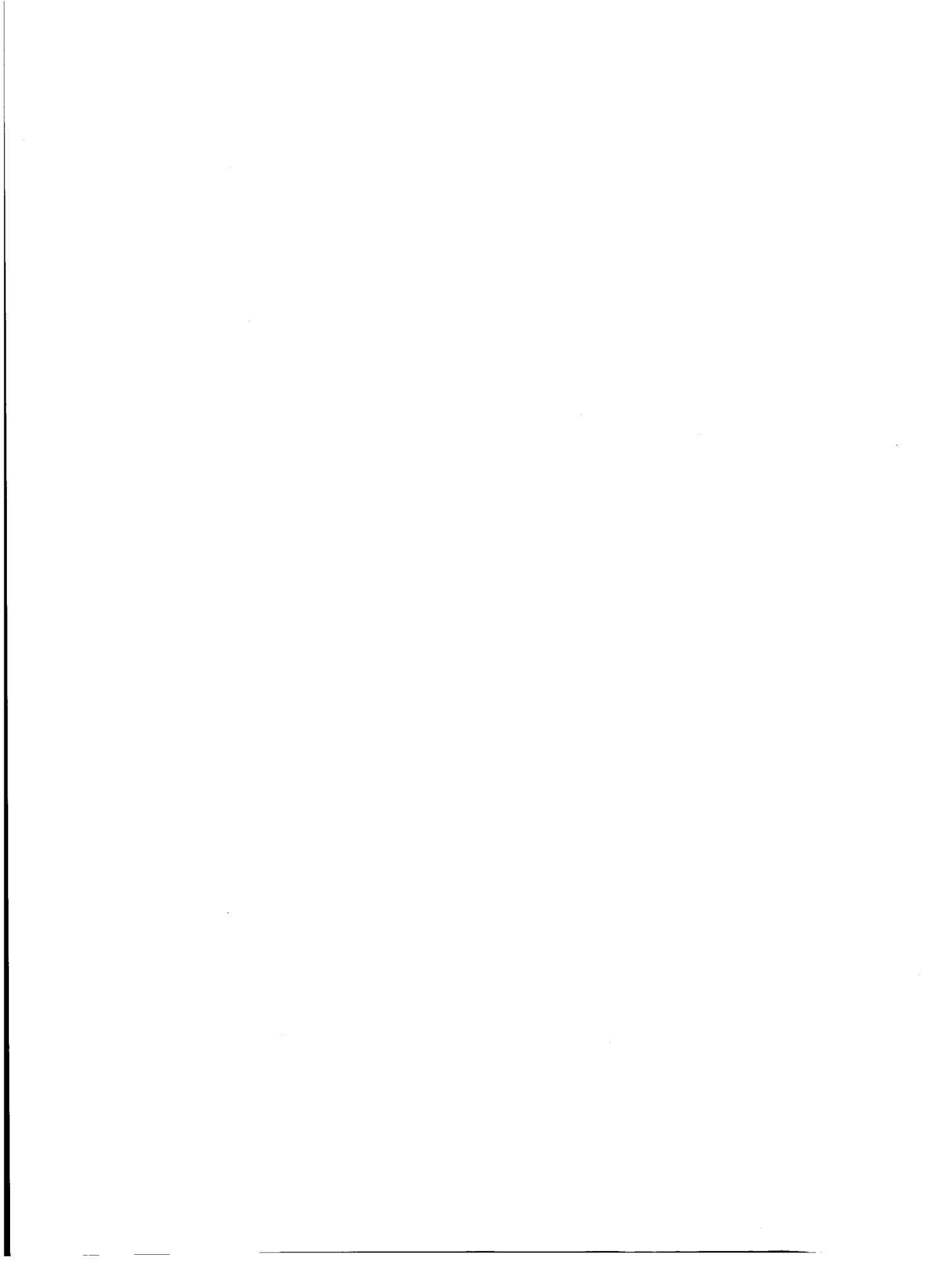
THE STANDARD 20 AH BATTERY

M. Zollner
McDonnell-Douglas Astronautics Co.

The modular power system, which is the first intended use for the NASA standard battery, is basically a four foot by four foot by eighteen inch box which can handle a complement of three 20 ampere hour batteries or later on the intended use is for three 50 ampere hour batteries to be the full complement.

The system is designed to be used as a plug on component on a multi mission modular spacecraft. It has as a design point a basically 1250 watt orbital average load. The way it breaks up in a near earth orbit it would be somewhere around 1,000 watts for everything except 10 minutes, and during any 10 minute period it may go up to a peak of a 3,000 watt load.

The battery that we are talking about here the 24 cells that Gerry was talking about which were sent to McDonnell-Douglas.

(Figure 310)

To take a quick look at what some of the criteria are to store electrical energy. Some of the features of the battery package, it is basically a tension bolt and machined in plate design, potting and fiberglass insulation wrapped around each cell, 22 series connected cells. One of them, the most negative, signal electrode.

Some of the features I guess that we could talk about are the covers and cases and electrolytes and all these different features are all of the same manufacturer's lot. There is a very close matching done to the cells, not only in terms of the 22 cells in the battery, but also in terms of which 11 cells go with the other 11 cells to be matched up so that when we measure differential voltages on half of the battery, we can expect to have a very close value there also.

(Figure 311)

A couple more features of it. The capacities that we are expected to obtain; 90 percent, the average cell capacity for 24°C, 90 percent of the actual battery capacity of 19°C, and 85 percent of the actual 25 degree battery capacity at zero discharge voltage for 50 percent DOD new battery is in the vicinity expected or predicted of 26.4 volts.

It is expected to be able to withstand a peak load at 50 percent DOD of a 3C rate or 60 amps for five minutes and still have a terminal voltage in excess of 24.2 volts.

(Figure 312)

The connectors on the the battery are MIL-C-38999 Series One. It is expected to not exceed the thermal requirements on it; that is a 3°C delta temperature in the plains parallel to the base of the battery, and a 5°C delta T in plains perpendicular to the battery base. We will talk a little about some of the development testing that we did to try to ascertain whether or not the design accommodates that particular requirement.

The battery has over temperature protection, a thermostatic switch that operates at a 35°C plus or minus 1.7°C in order to shut down charge conditions. The battery remains on the bus for discharge at all times.

It has temperature sensors, platinum sensor, which is utilized by another standard component, the power regulator unit which is being built by Gulton. I guess some of the features of this power regulator unit might be brought to mind now.

It has the potentiality for eight different voltage temperature curves which are ground selectable or possibly selectable by on-board computers. The platinum thermistor is the sensor for that power regulator unit. The other three thermistors are utilized for telemetry and hard line information. The overall radiation concerns, the average surface emittance, and shall be greater than 0.84. It actually turns out that measurements that we made are somewhere in the vicinity of 0.91.

(Figure 313)

What does it look like? Basically this is a figure showing the major components of the 20 ampere hour battery; 22 cells, two strings of 11. In between each group of two cells there is a T-shaped thermal fin for thermal control. The machined end plate, four tension rods. You see one there. There is actually four; two in the center and two at the edges of the top. The tension members at the bottom are utilized in a double roll, not only to provide tension but also to provide a mounting feature for the battery. In addition, to continue with the mounting features, there are two tie downs provided at each end plate.

One of the features of this battery that I think should be pointed out, possibly from the point of looking at it in terms of structural analysis may not

be the best way to design a battery you might think. But let's remember that this battery's structure is to be standard and it is to be of such a nature that it can accommodate cells from four different manufacturers. Even though Gerry calls his cells standard, one thing that isn't quite as standard as you might like is the fact that each of the cells thicknesses vary. In fact, depending on the four cell manufacturers, you can end up with a battery that is as much as three-quarters of an inch longer or shorter than another battery. So the sandwich technique here has primarily been selected because of the fact that the cells actually can be larger and smaller in the thickness range and we need some way to accommodate all of that without producing a separate set of hardware for each particular cell manufacturer.

(Figure 314)

Now to continue with how the thing is put together. These particular pictures show the 24 cells which were delivered from NASA and from General Electric. The first picture shows the cell as we see. The first phase of its build up to the battery is to encase the cell in a room temperature vulcanizing silicon and glass fiber wrap. This wrap is approximately four mils all around, top, all five sides except for the top cover of the cell.

The thing you see up there on the top is a protective cover for the terminal cases during the bonding procedures. The other two pictures merely show the cells in the other directions.

The next step after each of the 22 cells have been wrapped in this manner is to produce sub-assemblies where four packs and three thermal fins are bonded together. This particular assembly shows the two phases of that process. The blue strip up and down the center here is merely laboratory instrumentation and some rather colorful blue epoxy that lends a little something to the picture.

These particular pictures are the build up of the qualification battery which at present should be pretty close to beginning its initial conditioning. That is why the particular instrumentation shows up. As I will describe a little bit later, it is pretty heavily instrumented.

(Figure 315)

After as many as you can make of those four packs are made, the battery's final step is to be bonded into an assembly that looks something like this. The bags up here on the top are just protection for the thermal couple pliers which are very fragile. The black coating on the metal parts of the battery is Chem Glaze Z306, which meets the radiation requirements.

(Figure 316)

The final step for the battery is to be wired. When it is wired and completed, it looks something like this. The wiring is MIL-W-81381 Capton and the intercell connections consist of three 12 gauge wires which is the basic intercell connection.

(Figure 317)

With its attached ground support equipment, the battery looks something like this. It has a protective cover on the bottom. The thermal control in the modular power subsystem is basically a passive radiator. The surface at the bottom of the battery then becomes highly critical as far as dissipation of heat. The requirements for the battery base flatness are 10,000ths TIR. Once you attain that kind of TIR, the heavy base plate there is merely to protect the battery in handling.

(Figure 318)

Now of course, you have seen a picture of it. Somebody probably thinks it looks pretty big, well let's take a look at some of the physical parameters. As I mentioned, due to the fact that four different cell manufacturers are involved in the potential battery, then there are a couple of things that are determined by which cells are actually selected. One we talked about was the length and the other, of course, is the weight.

These particular parameters represent the maximum end values that you might expect and the maximum length of the battery, 13.3 all the way down to 12.8. Of course, the weight, somewhere between 52.5 and 45.3 pounds. The other two dimensions, width and height, remain constant. The height here refers to the height to the top of the connectors in the picture shown previously.

(Figure 319)

I mentioned before that we had done some development testing. No one likes to proceed to qual testing and get these surprises. So there are a few things that we have done already, even though standard cells were not available at the time we began this testing.

In order to determine whether or not the structural design was adequate, we performed vibration and shock, and as a sidelight of this particular endeavor, we were able to furnish Gerry with some information about what the standard cells might be expected to experience.

440

We also made some thermal tests of which I will describe a little bit more in detail a little later, which I think are somewhat unusual. We performed some electrical tests where we checked for the performance of capacities and so forth and whether or not we were able to reach the particular charge, the discharge, the predicted values that Gerry Halpert told us we should.

One thing I might point out there is that I mentioned that the cells were not available at the particular time that this testing began, and as a result, we were forced to make two different batteries. The first was made out of some doorstop cells that SAFT American was kind enough to provide to us. The second, which was planned to undergo electrical and thermal tests, was made also from some cells that SAFT was making. These cells were, we felt, highly representative of the standard cell. I think Gerry concurred. They had a few problems, but basically they would have been everything that they had intended them to be, they would have been standard cells. So that is at least, we feel, representative of the electrical performance that the standard cells will display.

(Figure 320)

To take a look at the structural vibration levels, Gerry said the battery gets a pretty good ride. It certainly does. It takes a strong heart to stand around close to it when it is vibrating. Basically, the battery was subjected to several different levels. This represents the most severe. With few exceptions, it came through it with satisfactory results.

I am not mechanically inclined, but for any of those of you who are, I guess that is sufficient time and you can take note of that.

(Figure 321)

As I said, we made two different batteries. One of the mechanical test, this is a picture of the mechanical test battery. As you can see there, it is slightly different than the qual battery. Vibration proved to us that we needed to tie down some of the end plates which this battery does not have, and also the connector bracket, which at this time is made out of sheet metal configuration. On the qual batteries, you saw it was a hogged out bracket.

The cells as I said before, were of the door stop variety, that is why the unevenness of heights there. There were actually 11 of one kind and 11 of the other. Both sizes and heights were identical in width so they fulfilled our requirements adequately.

(Figure 322)

441

With respect to thermal testing, of course the main purpose of thermal testing was to evaluate the adequacy of the thermal fin and its design. I mentioned before that I think the test was a little bit unusual. Normally, the electrical side of the house gets to determine what happens to the battery. For once, we let the thermal dynamicists have their way. So they came up with a little bit different test.

Just to mention briefly the test set up: we didn't want to go through the expense of a thermal vacuum chamber, so we were to design the test apparatus so that we might minimize the boundary effects and try to minimize the heat storage in the battery, which, since the battery mass is so large and the available mass of the active cold plate on which it was mounted is also very large, it is very difficult to keep the heat storage effects from masking the heat transfer effects.

So basically the battery was mounted on an active cold plate which was mounted with a heater, auxillary heater, inside a styrofoam box, rather a large box, that was then filled with insulating pellets. The system was operated very near ambient temperature to minimize the boundary condition. Prior to the installation of the battery onto the cold plate, the cold plate had been calibrated at several different points in order to provide an available, measurable, constant cooling source much similar to the base plate radiator of the modular power subsystem on which the battery is first intended to operate.

After the calibration was run at several different levels, then by adjusting the power, which was very easily measured, to the auxillary heater, we were able to obtain several different constant values for heat removal.

(Figure 323)

To take a quick look at the instantaneous power balance equation, ignoring the effects of the boundaries, the bracketed term is the term of interest and, of course, the battery and battery mount heat storage rate is a very difficult term to measure and that is the one we attempted to zero or at least if not zero, to have a very small and calculable in order to obtain the term on the left hand side of the bracket. The heater power rate, of course, was easily measured. And, as I said, the coolant heat removal rate was also calibrated before we began the test.

We made three separate runs at different power levels. The way these runs were operated basically was to continue the overcharge of the battery at a constant current rate in order to put in a well defined exact amount of electrical energy.

Watching the temperatures until they stabilized at a particular gradient, top to bottom of the battery, we then switched over to a discharge mode which has been predicted to match that particular amount of waste heat generation that the battery had previously undergone during the overcharge condition. If we guessed right, we saw no difference in the delta T top to bottom of the battery as the battery continued to discharge in order to eliminate the cyclic condition that you always see with batteries.

It took a couple of tries at it, but of course, each time we got smarter and smarter, and we used the artillery method and bracketed this thing down until we found out exactly what discharge rate matched exactly what battery heat dissipation rate.

(Figure 324)

To look briefly at the results of the test, we found that the battery's tolerance, the orbital average waste heat, is 35 watts. To compare that with what the battery is expected to experience, the value for a 90 minute orbit, 30 percent DOD, is 25.2 watts. So we have got 9.8 watts of excess available for transience that occurs during cycling.

The horizontal differential was found to be only 0.75°C. Thus we felt that due to the fact that 5°C being a top to bottom differential allowable, and 3°C being the horizontal differential available, that the terminal fin design was adequate to perform the job.

We did find that in respect to horizontal differential, the battery acts as a giant heat capacitor and it helps remove effects that appear on the base plate radiator itself in order to balance them out and equalize them. We also were able, due to the accuracy at which the temperatures were obtained, to effect a value for the thermal resistance of the base interface where the battery sits on the radiator surface.

This surface was coated with ekotherm PC4 and we had assumed the rate of something like 100 BTU's per feet, whatever those terms are. As it turned out, it came out around 300, which is pretty close to what the specified values that the heat sinc compound people predict.

The battery waste heat was found to be, depending on which level the run was, somewhere in the range of 18 to 21 percent. It varied. This is slightly on a pessimistic side of the predicted values, but as I said before, there is nothing really you can hang your hat on here because these were representatives of the standard cells, and not standard cells themselves, so we may find a little bit different results there.

(Figure 325)

I don't have a great deal of electrical performance data as most of this testing has been done very recently. I just didn't have time with the qual tests and everything beginning to get all the data reduced so that I can present something to you.

I did, however, go over there last Monday and with my handy dandy calculator whipped out a few points so that we could get an idea of whether these charts of the discharge ratios that have been predicted are anywhere near what I think we might get.

I mentioned before, the power regulator unit has the capability of charging the battery at eight different voltage temperature levels. I believe the present system now is somewhere for 10 percent DOD should be a level 5 precharge; 25, level 6; and 40 percent DOD, level 7.

At the time that we were running these tests, that wasn't what was predicted. We, as a result, then didn't pick some precise points that might be clearly compared with those that we presently predict. However, I might point out also that the cycling is slightly different on this particular test data. We ran a 35/55 minute cycle instead of 30/60, whichever effect that might have.

To briefly look at the results here, at a zero degree Z condition, with the battery discharge 29.5 percent, very close to 30 percent DOD, the maximum, that is peak to peak spread, of cell voltages was 4 millivolts. This is a worse case condition throughout the cycle. That is quite a bit better than what we have previously seen, and it apparently is very highly repeatable. At cycle after cycle, the value was the same within a tenth of a millivolt. Incidentally, all these conditions seem to be highly repeatable.

The charge limit for this particular base was 32.9 volts, which was level 7. It is kind of in between; 25 percent DOD would be level 6 and 40 percent DOD would be level 7. The design goal C/D ratio was 1.03 to 1.06 and it actually came out 1.04 five times in a row.

Taking a quick look at the other two values, at 20° C we ran a 12 percent DOD and 29.5 percent DOD. Once again, delta T's are highly repeatable between the cells; 2.4 and 4.2, 4.6 millivolts. In two different charge levels, level 5 and level 7, we did get some disparity here between the predicted values and the actual values, but once again, this is only, like I say, representative and I don't know if we can get upset at this particular point.

I did want to mention that we are presently beginning construction of the 50 ampere hour big brother or big sister, whichever you prefer, for this particular battery, which is basically designed structurally the same way.

DISCUSSION

BETZ: Naval Research, a comment and a couple of questions. In that last eclipse thing there, if you did have five minutes more charge, you would have a higher C/D ratio?

ZOLLNER: Yes.

BETZ: So that is one thing that does vary as the orbital parameters change around. My question is, with that type of battery, I have had some experience with these separate elements, and after vibration, I would like to know how your base plate held up to the 10 mil TIR, your total indicated reading?

ZOLLNER: Slightly better, about 2 mils.

BETZ: Better by 2 mils? And that was the one you had tied down all over the place? Or I should say, the ones with the bolts in the end plates or not?

ZOLLNER: Yes.

BETZ: With the bolts in the end plates?

ZOLLNER: Right.

THIERFELDER: G.E.. On the termal results you showed the horizontal temperature grading but you didn't show the vertical, what was the vertical?

ZOLLNER: It was 3.6°C.

GANDEL: Lockheed. What 50 ampere hour cell are you using for your set up?

ZOLLNER: At the present, I believe the cell is going to be G.E.. We are kind of right in the middle of that particular thing.

PALANDATI: Goddard. The data I presented the other day was on the 12 ampere hour battery. The orbital regime there was a 100 minute orbital regime with a 64 minute charge and our C/D ratios definitely were higher for

the various levels and I definitely believe the nine minutes difference in the charge time made an appreciable difference in the C/D ratios.

o FUNCTION

  -STORE ELECTRICAL ENERGY FOR USE DURING ECLIPSE AND
   PERIODS OF PEAK LOAD

o DESIGN FEATURES

  -TENSION BOLT AND MACHINED ALUMINUM END PLATE FRAME
  -THERMAL FIN TO CONDUCT HEAT TO BASE
  -POTTING AND INSULATION
  -HERMETICALLY SEALED NICKEL-CADMIUM PRISMATIC CELLS
    o 22 SERIES CONNECTED CELLS INCLUDING ONE SIGNAL
      ELECTRODE CELL MOST NEGATIVE IN STRING
  -CELLS IN SINGLE BATTERY CONTAIN PLATES, SEPARATOR,
   COVERS, CASES AND ELECTROLYTE FROM SAME MANUFACTURER'S LOT
  -CELLS IN A SINGLE BATTERY MATCHED IN CAPACITY TO
   WITHIN ±3.0% OF THE 24°C AND 0°C CAPACITIES WHEN
   TESTED BY CELL MANUFACTURER
  -CELL VOLTAGES OF A SINGLE BATTERY WITHIN
    o ±.004 VOLTS AT END OF 24°C CHARGE
    o ±.008 VOLTS AT END OF 0°C CHARGE

Figure 310

STANDARD 20 A.H. BATTERY

o CONNECTOR: MIL-C-38999 SERIES 1

o THERMAL GRADIENTS
  -MAXIMUM 3°C IN BATTERY PARALLEL TO BASE
  -MAXIMUM 5°C IN BATTERY PERPENDICULAR TO BASE

o OVERTEMPERATURE PROTECTION
  -THERMOSTATIC SWITCH TERMINATES CHARGE AT +35° ± 1.7°C

o TEMPERATURE SENSORS
  -ONE PLATINUM TEMPERATURE TRANSDUCER
  -THREE THERMISTORS

o RADIATION
  -AVERAGE SURFACE EMITTANCE, EXCEPT MOUNTING SURFACE,
   TO BE GREATER THAN 0.8u

Figure 312

STANDARD 20 A.H. BATTERY

o CAPACITY

  -RATED 20 AMPERE HOUR (CELL RATING)
  -@ 24°C 90% AVERAGE CELL CAPACITY MINIMUM
  -@ 10°C 90% OF THE ACTUAL 24°C BATTERY CAPACITY
  -@ 0°C 85% OF THE ACTUAL 24°C BATTERY CAPACITY

o DISCHARGE VOLTAGE 26.4 VOLTS NOMINAL

o PEAK LOAD AT 50% DOD
  -3 C RATE FOR 5 MINUTES AT 24°C
  -24.2 VOLTS MINIMUM

Figure 311

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20 A. H. BATTERY MECHANICAL/STRUCTURAL DESIGN
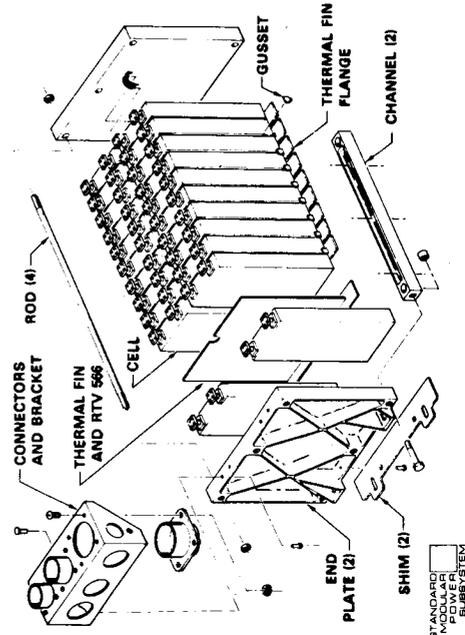
CONNECTORS AND BRACKET — ROD (4) — THERMAL FIN AND RTV 566 — CELL — GUSSET — THERMAL FIN FLANGE — CHANNEL (2) — END PLATE (2) — SHIM (2) — STANDARD MODULAR POWER SUBSYSTEM

Figure 313

Figure 315

Figure 317

Figure 314

Figure 316

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DEVELOPMENT TESTING

1. STRUCTURAL   - VIBRATION AND SHOCK

2. THERMAL   - TEMPERATURE GRADIENTS
                  WASTE HEATS

3. ELECTRICAL   - PERFORMANCE
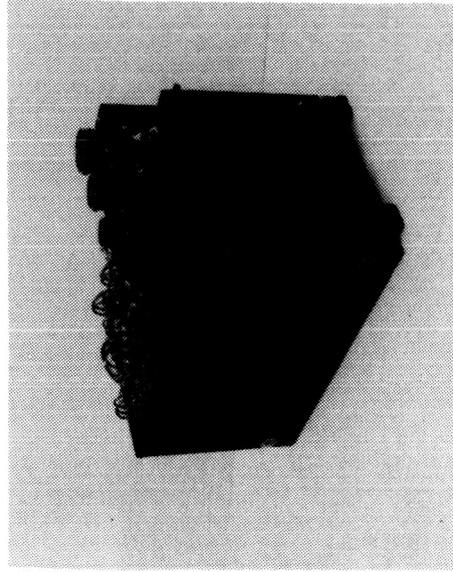   CYCLING & ELECTRICAL STABILITY
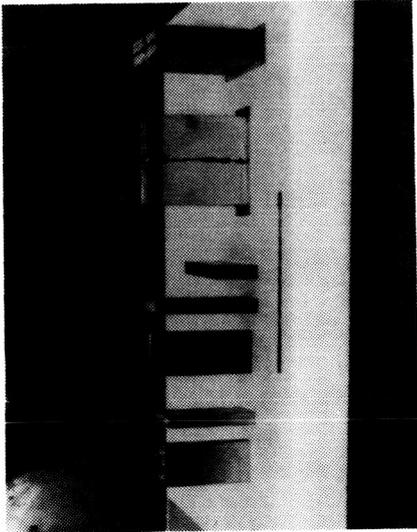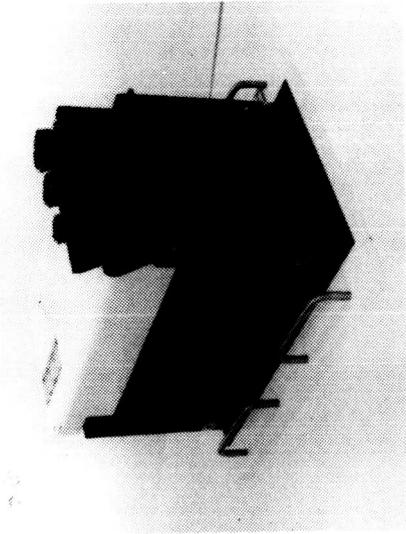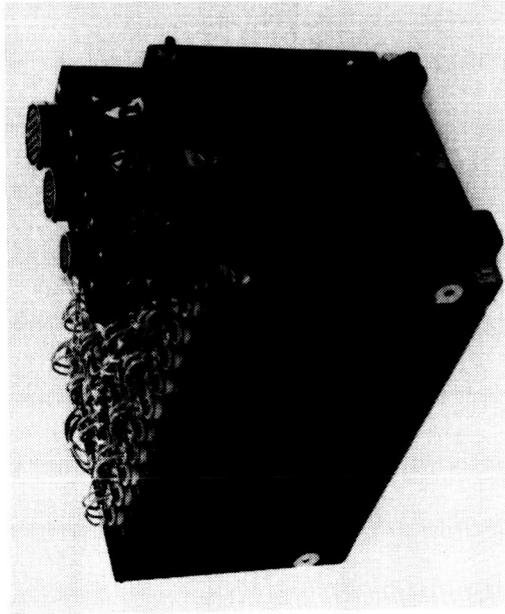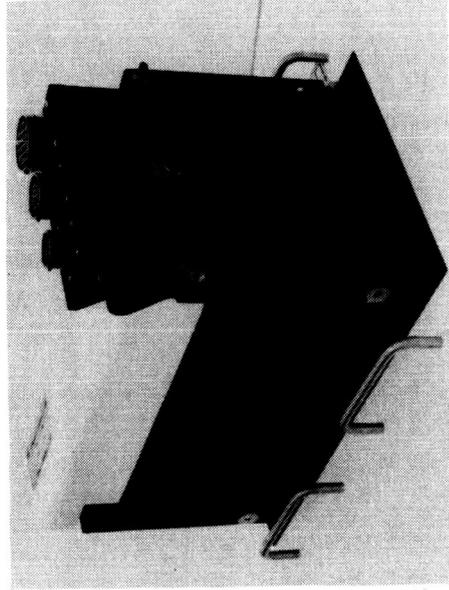
Figure 319

Figure 321

BATTERY PHYSICAL PARAMETERS

	MAX	MIN
LENGTH*	13.307 IN	12.854 IN
WIDTH	7.81 IN	7.79 IN
HEIGHT	9.82 IN	9.79 IN
WEIGHT*	52.50 LB	45.30 LB

*DEPENDS ON CELLS SELECTED

Figure 318

STRUCTURAL TESTS

VIBRATION

o SINE   1/2G AT 0 TO 28 HZ
            20G AT 28 TO 100 HZ
            15G AT 100 TO 2000 HZ

o RANDOM   27-1/2G, RMS UP TO 2000 HZ
            START 0.5 PSD, SWEEP AT -3DB/OCT

SHOCK

PLUS AND NEGATIVE ACCELERATION
57G TO 200 HZ TO 300G AT 4000 HZ

Figure 320

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POWER BALANCE EQUATION

$$\text{HEATER POWER RATE} + \left[\text{BATTERY HEAT DISSIPATION RATE} + \text{BATTERY AND BATTERY MOUNT HEAT STORAGE RATE} \right] = \text{COOLANT HEAT REMOVAL RATE}$$

Figure 323

THERMAL TESTING

PURPOSE: CONFIRM ADEQUACY OF THERMAL FIN DESIGN.

TEST APPROACH: MINIMIZE OR ELIMINATE HEAT STORAGE AND BOUNDARY EFFECTS.

Figure 322

THERMAL RESULTS

o ORBITAL AVERAGE WASTE HEAT: 35 WATTS
   (90 MIN ORBIT - 30% DOD - 25.2 WATTS)

o HORIZONTAL DIFFERENTIAL: 0.75°C (3°C ALLOWABLE)

o THERMAL RESISTANCE AT BASE INTERFACE: 0.2°C

o BATTERY WASTE HEAT: 18% - 21% OF DELIVERED ENERGY

Figure 324

ELECTRICAL CYCLING RESULTS

TEMP (°C)	DOD (%)	MAX ΔV (MV)	CHG LIMIT (V)	C/D RATIO DESIGN	ACTUAL
0	29.5	4.0	32.9 (LVL7)	1.03-1.06	1.04
20	12.0	2.4	30.1 (LVL3)	1.08-1.11	1.13
20	29.5	4.2	31.1 (LVL5)	1.08-1.11	1.03
	29.5	4.6	32.0 (LVL7)	1.08-1.11	1.18

Figure 325

THE 100 KW SPACE STATION

G. McKhann
McDonnell-Douglas Astronautics Co.

This is my subject for this morning. It is the space construction base which formerly was called for about the last ten years "space station." This is a new name for the space station. I will talk about solar array power systems.

I guess I should mention that at this point we are departing from the world, at least temporarily, of nuts and bolts and separators, to the never-never land of conceptual advanced design, since the space station work was all Phase A level, very gross system tradeoff types of study.

This work was done on a combination of funding from ERDA and OAST, under the guidance of Lee Holcomb. The specific detailed technical direction was the Johnson Space Center in Houston. I should mention that this study was a very broad study. We looked at reactor power systems, reactor Brayton cycle systems, reactor thermionic systems, reactor thermo-electric systems, solar concentrator systems, the Brayton cycle, and thermionic convertors.

There were a couple of major solar array options. I will only show you one this morning. We looked at some energy storage options that I will talk about mostly here since I am sure that is the subject of interest here.

(Figure 326)

Things will rapidly degrade after we get past this color rendering in terms of what you see. This is the space construction base as we finally evolved it. The function of the space construction base is primarily construction of large structures. Shown out here is a 30 meter radiometer being built in this construction location with the assistance of a two arm space crane and a space construction module at this point.

This module here is what was called a "construction shack" which is basically a crew quarters and habitability area of the space section. Of more interest is the solar array system depicted here which is at this point and extends on out for a ways. I will show you momentarily what that looks like in full perspective.

There is an interesting thing down here at this end, a U-shaped channel which serves as a construction fixture for constructing this particular version

of the solar array and also the batteries and power conditioning equipment is mounted on the bottom side. The surfaces of this serve as radiator for the power system cooling.

(Figure 327)

This shows the solar array at full perspective. It is a one axis gimbal system about an axis along here. Some of the characteristics of the system are 100 kilowatts of average power output, and this is for a low earth orbit, 456 kilometers, normally 28 and a half degree inclination. That is 100 kilowatts average to the load buses, and the array output, when illuminated, is about 215 kilowatts.

The technology date that we would have to select the technology, select the type of energy storage system, is around 1980, inasmuch as we would have an orbital IOC in 1985 per our study ground rules. The mission life is ten years. The solar array active area is about 2400 square meters. Radiator area is 210 ·square meters. The launch weight for the entire electrical power system, the batteries, array, radiators, and so forth, is about 35,000 kilograms, which exceeds the shuttle capacity. So part of the batteries are launched on second shuttle launch, about half the batteries would be launched on a subsequent shuttle launch.

(Figure 328)

We evaluated a number of energy storage systems. We have looked at nickel-cadmium batteries as current technology. We looked at advanced technology nickel cadmium batteries that might be available in a few years. We looked at nickel-hydrogen batteries. We looked at regenerative fuel cells. And we also looked at flight wheels as energy storage options. We have prepared system block diagrams for all of those systems. And I just have a representative example here.

The energy storage part of the system is within the dotted lines and the rest of the system is common for all of these energy storage subsystems. The load requirements are 100 kilowatts average at the bus. This is provided by eight modules; in this case, each module provides 12-1/2 kilowatts to the bus, so there would be eight of these modules in a total power system.

The guideline was that we would have 400 cycle AC output. So we have an inverter here and a solar array. The batteries or fuel cells, or whatever, operate through the DC regulator, through the inverter, to the loads at night, and then the solar array recharges the energy storage system during the day time.

I selected the regenerative fuel cell area storage, and now I am going to go inside that dotted box that is the energy storage part of the system, and I selected as a regenerative fuel cell system since some of you are perhaps not familiar with that and I think you are mostly familiar with the batteries. Regenerative fuel cell systems are an interesting candidate for this application.

The way this system operates, we have stored gaseous hydrogen and oxygen operating at fuel cell through the regulator on up to the inverter and the loads going this way at night. We are generating, of course, water with the fuel cell operation which is stored in the water tank.

Then in the sunlight part of the orbit, we pump water out of the water tank through a water electrolysis unit and that electrolyzes the water back to gaseous hydrogen and oxygen. The gaseous hydrogen and oxygen are stored at pressures ranging from 100 to 400 psi, cycling up and down depending on the quantity of gas in the tanks.

The fuel cells are about 65 percent efficient. You could use either the shuttle type technology, which appears to be very adequate, or the General Electric solid polymer electrolyte fuel cell technology, which also looks very good. We would use one fuel cell in each energy storage unit. Remember, there are eight units in the total 100 kilowatt system so there would be eight fuel cells in the total system, but each of these energy storage units would have one fuel cell.

The fuel cells operate at around 60 to 80 degrees centigrade. Fuel consumption is about 8/10ths of a pound per kilowatt hour, perhaps there is a more familiar number than that. This is one fairly large unit. That unit would be about four times the size of the present shuttle unit so you would use shuttle technology but you would build it in a larger size.

Over on the electrolysis side, General Electric is the only company that seems to be actively pursuing the water electrolysis business at this point, so we would use the General Electric units. They are about 89 percent efficient, operate at about 1.6 volts per cell, and temperatures are about 100 to 120°C.

One point I might mention about the regenerative fuel cell system is the hydroelectric depth of discharge with this system. We normally, during an eclipse period, require about three kilograms of water to handle the energy requirements for the eclipse period of this energy storage module. We have provided about 11 pounds of water or gas, depending on what the case may be, so

effectively we have 33 percent depth of discharge. We wanted to operate not more than that because manned systems have long term load averaging requirements. When the guys are awake, they are doing more, the loads are higher; or when they are asleep, the loads are lower. So you want to have the capability for long term load averaging.

So we selected a fairly low depth of discharge. This system could go much higher than that, I would say, it is just a matter of changing the size of these three tanks. So this particular system has a lot of flexibility for long term load averaging if you want to clear a little extra water and some extra tankage.

(Figure 330)

Battery life and energy density is obviously a very important factor. It affects how frequently we have to replace the batteries during a ten year mission, and the weight that you have to take to orbit, which costs a lot of money because the shuttle transportation costs then. We will compare these systems on a cost basis toward the end.

Life and energy density is very important. We looked a couple of years ago at some of the Crane data. If you use the Crane failure criteria of 60 percent of the cells fail when a peak fails, the zero degree C data, you get a curve that looks like this one in terms of life versus usable density and watt hours per kilogram.

We assigned a 36 watt hour per kilogram as the current technology. I should mention that the dark solid lines are the current technology, the dotted lines are projected or advanced technology. We used 36 watt hours per kilogram for the current technology. That is based on some 100 ampere hour cells that were developed by NASA JSC a few years ago for the space station.

I should mention that JPL did some studies of this and was reported in this reference. They also put together a white paper for the purposes of the space station study that had these same curves. Their projection for current technology is 33 watt hours per kilogram. It is a curve very close to the one we were using.

We didn't think that the 60 percent cell failures was suitable for system design purposes. We looked at the distribution of cell failures as a function of pack life. We found if you go to the point of 10 percent cell failures, you have to back down. The life is about 60 percent of the life to go to 100 percent pack failure. In other words, 10 percent cell failures represent a life that is 60 percent of the cells failed or pack failure. So you back down by that 60 percent

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factor, you end up with a curve like this, which is where 10 percent of the cells have failed. We think that is more realistic for our spacecraft design purpose to use a life and energy density curve like this rather than one over here which is like average cell failure essentially.

For advanced technology cells, we raised the energy density, and this is along the lines that Lee Holcomb talked about in their light weight long life battery program, from 36 watt hours per kilogram to 65 watt hours per kilogram. So you get a curve like this for advanced technology which might be available in the mid-'80s or perhaps the technology freeze design selection in 1980.

We then picked a design point for the life of the nickel-cad batteries in this region of five years life and about five watt hours per kilogram. Those are the numbers that are used in the cost analysis and so forth that will subsequently be discussed.

I should also mention, I have shown on here, with a great deal of trepidation a nickel-hydrogen curve. I talked with Don Warnock at the Air Force a few days ago, and he mentioned that they have 6,000 or 7,000 cycles of low earth orbit cycling on nickel hydrogen at 80 percent depth of discharge, which is way over here off this curve, going this way. He also mentioned that he felt that it was reasonable to get 50 percent depth of discharge and five years' life, which would be a point here. I am not sure I should do this but I did it anyway. I drew a curve parallel to the slope of these curves. It turned out that the two points Don mentioned are beyond that curve. So this might be representative of what you might do with nickel hydrogen.

We selected a design for nickel hydrogen of about 18 percent depth of discharge, compared to 14 or 15 percent for the nickel-cads. Just because of lack of data, we wanted to be conservative and use something nearer the nickel-cad, but I think there is excellent chance that this will come on over and maybe the 33 percent depth of discharge that we are using on the fuel cells might be a good point as a potential growth capability of nickel hydrogen battery.

(Figure 331)

This is a summary of the characteristics of the candidate systems. I should mention that we also looked at fly wheels and went through the energy balance diagrams and so forth, but they didn't look that attractive and we did not carry them through the final evaluation of costs and so forth.

The output of the arrays are listed here. Some typical values, which is at a beta of 23 degrees, and if you have beta of 0 where the array is normal

to the sun, you have these solar array values which are a little higher. The differences in output and array area are the result of differences in energy storage efficiencies. Of the fuel cell system, the 54 percent overall energy storage from energy out to energy into that block diagram which includes charges and regulators and so forth fuel cells is 54 percent.

Just for reference I have listed the depth of discharge we assumed in our analysis. The life situation, of course, is very, very difficult to predict. There has been a lot of life demonstrated on nickel-cads. Five, maybe ten years of life, depending on how you look at the data and so forth. There has been none on the advanced nickel-cads that are being studied and developed right now. One or perhaps more with nickel-hydrogen, depending on how you want to interpret the limited data there.

The regenerative fuel cell life looks like it can be extrapolated from shuttle technology up to in excess of five or ten years by derating temperatures, you are only operating part of the orbit, running at lower loads, lower energy densities. The electrolysis cell is not quite as good, but it also looks pretty promising in terms of test data.

So we selected five years across the board for comparison purposes. You may not agree with that, I have some parametric data that lets you adjust the cost if you don't like our selection.

The launch weights are 34,000 kilograms for the nickel-cad, 26,000 for the advanced nickel cad, 21,000 for the nickel hydrogen, and 16,000 for the regenerative fuel cells. Launch weight per se is not terribly important. It is a cost penalty to the program unless you exceed the shuttle capability and even there it is not really a problem, it is just a cost penalty. You do have to watch some of the batteries separately in this case.

The resupply weight over a ten year mission at the indicated life assumptions are shown here.

(Figure 332)

This is a summary of the total program costs for the various candidate systems. I would like to point to the difference in the fuel cell. First off, we have over here DT&E costs; production costs, which is buying a ship's set of flight hardware; operations costs, which include the cost of launching the initial complement of equipment at the shuttle rates, replacement of hardwares and spares, buying that hardware, replacement logistics, getting that to orbit, and a drag propellant penalty associated with the solar arrays and the varying solar array areas.

First I would like to note that the regenerative fuel electrolysis cell has a fairly large non-recurring cost, but it makes that back up down here in buying the flight hardware and the replacement hardware and the replacement logistics.

There is a $45 million dollar beam fabrication module thrown in here. This is for constructing the solar array. It is not clear whether that should or should not be charged to the power system because it is a general purpose piece of equipment, but we did throw it in for this purpose.

The bottom line says that all of these systems at the assumed five year life for each of them are pretty close in total program costs.

(Figure 333)

Now I have got this chart that summarizes the bottom line. This was the bottom line you saw previously at five years, and if you don't like my assumptions on life, you can adjust your own program costs for a different program life. These, as I say, are all pretty close in total cost. It is a little hard to say which system is really the best system.

(Figure 334)

I would like to conclude by saying that the nickel-cadmium batteries, nickel-hydrogen batteries, and regenerative fuel cells all appear to be equally attractive to the level that we have been able to study them to date. Further evaluation is required for the energy storage subsystem life considerations, particularly for low earth orbit conditions, especially important would be some development of life testing of nickel-hydrogen batteries at low earth orbit conditions and the water electrolysis part of the regenerative fuel cell system.

The shuttle fuel cell technology and the General Electric solid polymer electrolyte fuel cell technology appears to be adequate for this application. We would recommend using larger units, approximately four times the shuttle size, to keep the number of units down. We have eight fuel cells in the total system, if you use shuttle size, you would have something like 32 which is a large cost penalty to build that large number of small units.

We selected a conservative nickel-hydrogen battery depth of discharge because of lack of data. There is an excellent chance that, that can do better, on up to the 33 percent depth of discharge we would probably recommend as a maximum because of this multi orbit load averaging and reserve capacity requirements consideration.

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DISCUSSION

ROGERS: Hughes Aircraft. To make a comment on the nickel-hydrogen system as well as the fuel cell, it is an assumption that reducing the depth of discharge in nickel-hydrogen will give extended life like you have indicated. Probably it will, but we haven't shown it.

MC KAHNN: Right.

ROGERS: The other comment is that it is not really a regenerative fuel cell. It is a primary fuel cell and electrolysis cell. The system may be regenerative. It is what people have spoken of in the past as a regenerative fuel cell.

MC KHANN: That is right. I have always wondered what we really ought to call that thing. It has been called the regenerative fuel cell system, but it is not really. You are absolutely right.
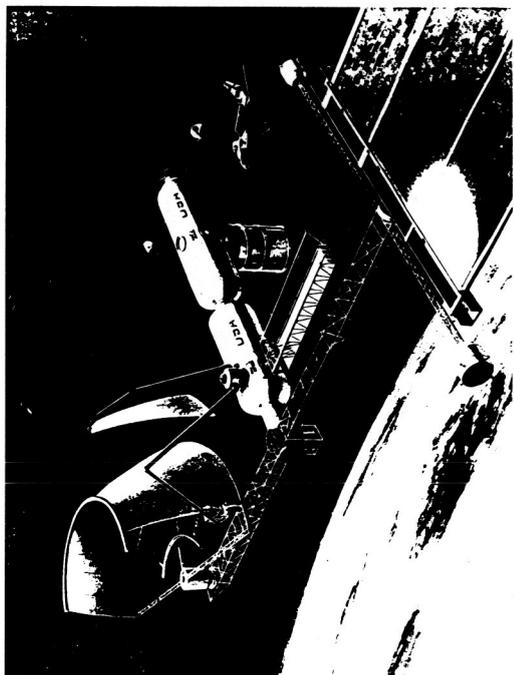
SCB CONFIGURATION
(FAB AND ASSEMBLY SOLAR ARRAY)

EPS REQUIREMENTS/CHARACTERISTICS	
TECHNOLOGY READY	1980
IOC	1985
ORBIT	456 Km/28.5°
MISSION DURATION	10 YEARS
ARRAY AREA	2,407 M² ACTIVE
ARRAY/SYSTEM OUTPUT (BOL, β = 29°, KWe)	214.7/100
RADIATOR AREA	210 M²
LAUNCH WEIGHT	34,760 Kg

30 M RADIOMETER
Z AXIS
X AXIS
SPACE CONSTRUCTION MODULE
CONSTRUCTION SHACK
ORBITER
STRONGBACK
Y AXIS
ENERGY STORAGE AND POWER CONDITIONING
RC PODS (4)
POWER PLATFORM SYSTEM (100 KWe, TYPICAL, AVERAGE)
±180°

Figure 327

Figure 326

SOLAR ARRAY/NiCd BATTERY SYSTEM
(1 OF 8, 12.5 KWe EACH, FAB AND ASSY)

34642

26.84 KWe (BOL)
300.9 M²

SOLAR ARRAY

26.84 KWe
25.95 KWH*
112V

13.40 KWe
12.95 KWH*

BATTERY CHARGERS

NiCd BATTERIES

13.44 KWe

Q = 1.475 KWH*

INVERTER η = 0.93

AVERAGE LOAD – 12.5 KWe

13.44 KWe
8.06 KWH*
0.800 HR*

DC/DC REGULATOR

ENERGY STORAGE SUBSYSTEM

Q = 4.89 KWH$_T$*

*PER ORBIT
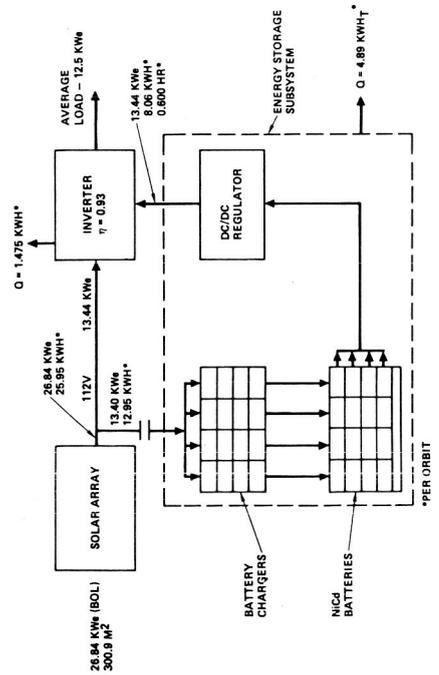
Figure 328

REGENERATIVE FUEL CELL ENERGY STORAGE
(1 OF 8)

34627

13.44 KWe
8.06 KWH*

REGULATOR
η = 0.94

Q = 0.51 KWH*

14.30 KWe
8.58 KWH*

FUEL CELL (1)
η = 0.646

1 UNIT AT 14.32 KWe
118-136V
T_{IN} = ~ 60°C
T_{OUT} = ~ 82°C
Q = 4.71 KWH*
0.35 KG/KWH

(1)

(2) H₂O

690-2758 KPa
(100-400 PSI)

0.56 KG/HR

GH₂
759-2827 KPa
(110-410 PSI)

(3)

GO₂

4.50 KG/HR

P

(4)

0.35 KG/HR

2.79 KG/HR

15.40 KWe
14.90 KWH (0.987 HR)*

ELECTROLYSIS CELL (1)
(GE; η = 0.891)

$\eta = \frac{8.06}{14.90} = 0.541$
DOD = 33%

OUTPUT - 3.14 KG/HR
4.92 KWH/KG
1.59V/CELL AT 650 ASF
T_{IN} = ~ 99°C
T_{OUT} = ~ 121°C
Q = 1.62 KWH*

(1) 5.06 KG/HR;
X 0.6 = 3.03 KG H₂O
(2) 9.11 KG**
(3) H₂—1.01 KG**
O₂—8.10 KG**
(4) 3.14 KG/HR

*PER ORBIT
**USEABLE CAPACITY

Figure 329

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BATTERY PERFORMANCE

*BOGNER AND UCHIYAMA, AIAA PAPER 77-516, MARCH 1-3, 1977; CELLS: 0-10°C

Figure 330

ENERGY STORAGE CHARACTERISTICS SUMMARY*

	NiCd	ADVANCED NiCd	NiH₂	REGENERATIVE FUEL CELLS
ARRAY OUTPUT, BOL, KWe				
• TYPICAL	214.7	209.0	217.1	230.7
• SOLAR ORIENTED	233.4	227.2	236.0	250.8
ARRAY AREA, M²	2,407	2,343	2,434	2,587
STORAGE EFFICIENCY, %	62	65.7	60.8	54.1
DEPTH OF DISCHARGE, %	14.5	14.5	18.6	33
ENERGY DENSITY(2) W-H/KG	3.93/27.08	6.39/44.1	9.49/51	25.0/75.1
EXPECTED LIFE, YEAR				
• DEMONSTRATED	~5	NONE	1+	5+/3+(1)
• DESIGN	5	5	5	5
• POTENTIAL	10	10	10	10
LOAD AVERAGING POTENTIAL	FAIR	FAIR	FAIR	GOOD
LAUNCH WEIGHT, KG	34,763	25,868	21,450	16,083
RESUPPLY WEIGHT (10 YR), KG	23,328	14,328	9,658	2,994

*100 KWe AVERAGE AT INVERTER OUTPUT; FAB AND ASSEMBLY POWER PLATFORM
(1) FUEL CELL/ELECTROLYSIS CELL
(2) BATTERY: USABLE/ABSOLUTE

Figure 331

SYSTEM COST/ENERGY STORAGE LIFE

	ENERGY STORAGE SUBSYSTEM COST ($M)			
ENERGY STORAGE LIFE (YEARS)	NiCd BATTERY	ADVANCED NiCd BATTERY	NiH₂ BATTERY	REGENERATIVE FUEL CELLS
3.33	349	338	335	329
5.0	324 ✓	315 ✓	315 ✓	317 ✓
10.0	300	294	294	303

Figure 332

POWER PLATFORM ENERGY STORAGE OPTION COST*

ITEM	COST (MILLION $)			
	NiCd	ADVANCED NiCd	NiH₂	REGENERATIVE FUEL CELLS
DDT&E				
SOLAR ARRAY	36	36	36	36
ENERGY STORAGE/POWER COND	18	19	20	40
STRUCTURE/MECH/MISC	19	19	19	19
PRODUCTION				
SOLAR ARRAY	70	68	71	74
ENERGY STORAGE/POWER COND	32	34	31	20
STRUCTURE/MECH/MISC	2	2	2	2
OPERATIONS				
INITIAL LAUNCH	25.9 ①	20	20	20
REPLACEMENT HARDWARE/SPARES	20	23	24	16
REPLACEMENT HARDWARE LOGISTICS	15.8	9.7	6.6	2
DRAG PROPELLANT	40.0	39.0	40.4	42.7
SUBTOTAL	278.7	269.7	270.0	271.7
BEAM FABRICATION MODULE	45	45	45	45
TOTAL	323.7	314.7	315.0	316.7

*FAB AND ASSEMBLY ARRAY; POWER MODULE SUPPORTED; 5 YEAR ENERGY STORAGE LIFE
① ONE-HALF OF BATTERIES ON SUBSEQUENT LAUNCH

Figure 333

SUMMARY AND CONCLUSIONS

- NiCd AND NiH2 BATTERIES ARE EQUALLY ATTRACTIVE RELATIVE TO REGENERATIVE FUEL CELL SYSTEMS AT 5 YEARS LIFE

- FURTHER EVALUATION OF ENERGY STORAGE SYSTEM LIFE (LOW ORBIT CONDITIONS) IS REQUIRED –

    DEVELOPMENT/LIFE TESTING – ESPECIALLY NiH2 BATTERIES AND H2O ELECTROLYSIS MODULES

- SHUTTLE AND SPE FUEL CELL TECHNOLOGY APPEARS ADEQUATE; LARGE UNITS (~4 X SHUTTLE) ARE MOST APPROPRIATE AND SHOULD BE STUDIED FOR A 100 KWe SCB SYSTEM

- A CONSERVATIVE NiH2 BATTERY DOD (18.6%) WAS SELECTED DUE TO LACK OF TEST DATA -- OFFERS CONSIDERABLE IMPROVEMENT POTENTIAL

- MULTI-ORBIT LOAD AVERAGING AND RESERVE CAPACITY REQUIREMENTS LIMIT NOMINAL DOD TO 30-50% MAXIMUM, INDEPENDENT OF LIFE CONSIDERATIONS

Figure 334

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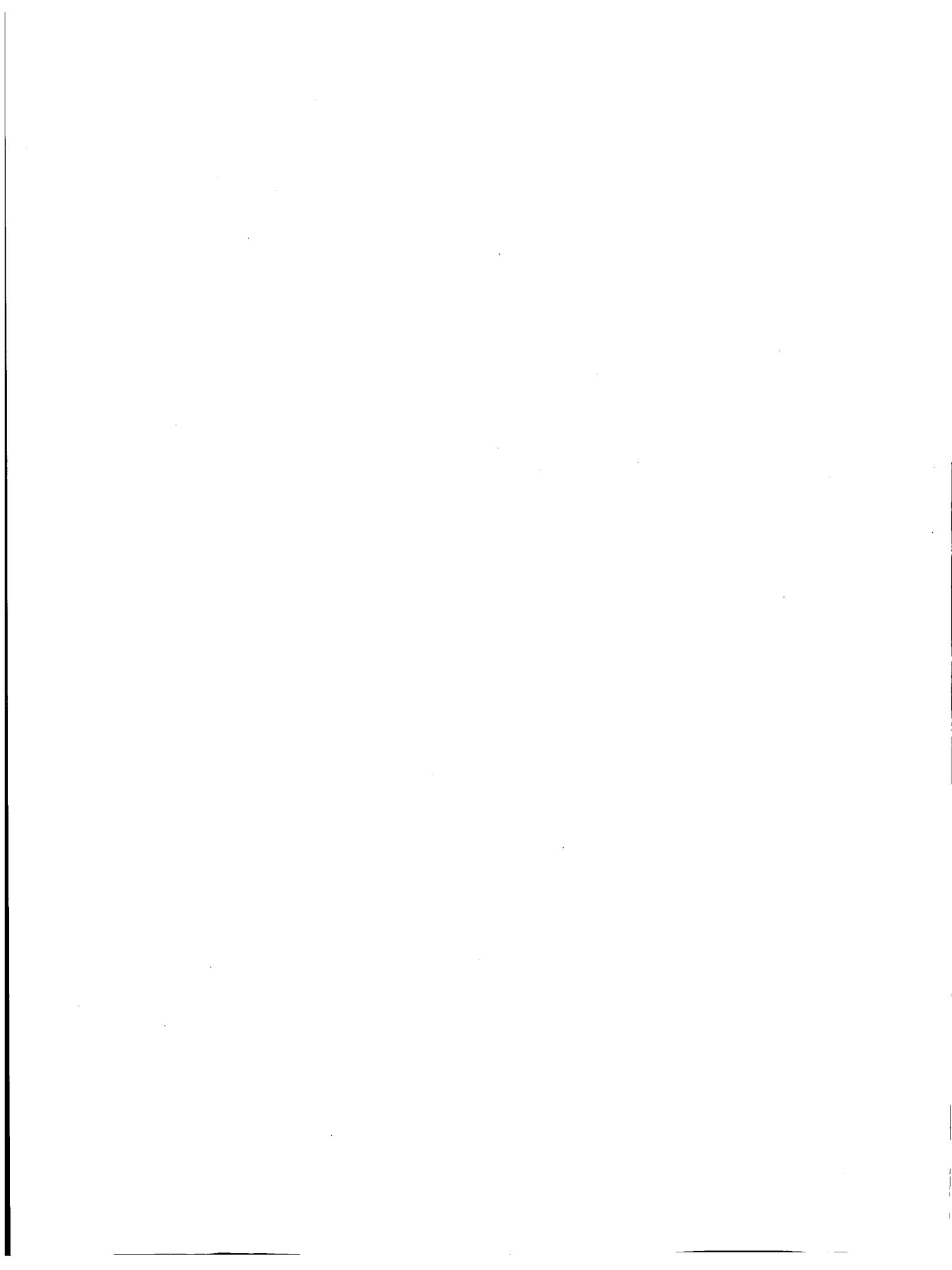
THE 25 KW SPACE STATION

B. Clark
Grumman Aerospace Corporation

This was a parallel study to the one you just heard about. A lot of the figures are going to be similar to the last presentation.

(Figures 335 and 336)

We were funded from Marshall to look at the space construction base, which is as mentioned with the space station but several years later. Really, the prime emphasis of the study was to look at power sources. Specifically, we were looking at three types of power sources, photovoltaic, nuclear reactor, and solar thermal systems, to see if the changes in technology from roughly 1970 when this study was done once until today had influenced anything or if the changes in mission requirements had changed any of the decisions made.

(Figure 337)

Those are the three systems that we looked at. Solar array system is on the top, the middle one shows the solar Brayton, the bottom is the reactor system.

(Figure 338)

I will show you some nice pictures. The photovoltaic system, that is in the process of buildup to the final solar array.

That is the solar Brayton system, two collectors, two equal halves to the system. And this is the reactor system. This large piece of structure here is the shuttle external tank.

A little more detail on the candidate power systems and photovoltaic, we looked at silicon and galeon varsinate. In the solar thermal systems we looked at solar collection with either Brayton conversion or thermionic conversion. In the nuclear systems, we looked at Brayton conversion, thermionic conversion, and thermo-electric conversion.

The load for sizing the system was 100 kilowatts with peaks up to 130 kilowatts. For worse case assumptions we allowed that 130 kilowatt peak to occur during every eclipse for a ten-year lifetime.

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This is actually a profile buildup to the 100 kilowatt load. It takes something like three years before there is enough fabrication stuff up there to actually run at 100 kilowatts.

(Figure 339)

One portion of the study, and I do want to emphasize it was a portion of the study, was to look at energy storage. I guess the attractive elements there wound up being nickel-cadmium and nickel-hydrogen and the regenerative fuel cell system, whatever we are going to call that system.

Thermal storage was of interest for the solar thermal systems. We looked at some of the silver electrode batteries but really they are not very attractive, as you know, for lone-life missions. They very quickly got taken out of the study.

(Figure 340)

This is the data that we put together as a baseline for the battery traits. The left curve is an estimate of what today's cells could be expected to do based on compilation of popular data that is used for sizing batteries. The right side represents a projection of what batteries might be capable of doing in 1983. We wound up using a projected capability based on either doubling the life of a nickel-cadmium battery or raising its 100 percent energy density capability up to 55 watt hours per kilogram, but not both.

(Figure 341)

The question is, what would nickel-hydrogen be able to do? We used 100 percent energy density capability at 70 watt hours per kilogram and heard numbers ranging anywhere from no different life between nickel-hydrogen and nickel-cadmium, up to two years, five years, two times, five times the life capability. Frankly, it is a swag, I guess, at this point what nickel-hydrogen would do, but that is the curve that was defined and it was defined in terms of double the life capability as being conservatively optimistic.

That is cell performance. Battery performance, the same curves are taken. Over on the right hand side, it derated by 35 percent. Batteries were constructed using series redundancy for cells, by-pass circuitry to store and get around failed cells, and heat pipe technology in the batteries.

(Figure 342)

This is a comparison of nickel-cadmium and nickel-hydrogen. We were looking at this condition, 130 kilowatts of eclipse power. This carpet is the nickel-hydrogen carpet. The dotted carpet is the nickel-cadmium. This line across here is constant 130 kilowatt eclipse power requirement. The curve is showing the mass of the batteries as a function of years of life. This point is the design point for the nickel-hydrogen battery. The ten-year life of nickel-cadmium for 130 kilowatt capability as you can see, is really too far off the curve.

(Figure 343)

That is not necessarily true that you would try to launch ten years' worth of batteries when the space construction base is first put up. In fact, for nickel-cadmium it is more effective to launch two battery systems, each with a five-year life capability. For nickel-hydrogen on the other hand, it appears that it is most attractive to launch the full complement of batteries right away. Launch up ten years' capability of batteries.

The dotted curve on this figure shows something we tried to evaluate. Because the mission doesn't really immediately spring into being with 100 kilowatts on the system, it is somewhat of a penalty to say we are going to size based on an average of 100 kilowatts or 130 kilowatts eclipse load right from day one. We tried to look at how could you reduce the battery complement weight by taking advantage of the fact that early in the mission the loads are somewhat lower.

Although we did put the data together and did present it, we really didn't want to base any decisions or recommendations on it because it says, you can look at an average depth of discharge over a battery lifetime, and just race into those DOD versus life curves, and say, that is my average and that is the way I am going to operate the battery. There is really no validation that we can take a battery and change its depth of discharge over its lifetime and still say that its life is going to correlate to the average depth of discharge.

(Figure 344)

You saw a similar figure before, regenerative fuel cell systems. We did look at sharing the system with some other elements on the system.

(Figure 345)

These are the technology projections we used for fuel cells. Advanced shuttle is taking shuttle fuel cell and doing what can be done to it to extend its

life. It looks like it is probably something like a 10,000 hour limitation in its capability. On the other hand, if you want to put about $10 million or so into a development program, a space station fuel cell, for lack of anything else to call it, could probably be developed with something like a 40,000 hour life capability, which approaches five years.

The tankage, specifically we used 5,000 psi composite tanks.

(Figure 346)

Photovoltaic system: again, we have 130 kilowatts load power during the eclipse for the entire 36 minute eclipse. Nickel-hydrogen batteries, I have highlighted them here on this chart because that was our final selection. Regenerative fuel cells are somewhat lighter, but weight was not the sole criterion here.

Just for comparison, we did look at how much lower would the nickel-cadmium batteries be if we did not have to supply 130 kilowatts. In other words, the 30 kilowatt peak load delta during the eclipse, if the peak loads only occurred during the sunlight, that is this single point down here.

(Figure 347)

Solar thermionic system: I guess an interesting item on this chart is the thermal storage element here. That is lithium fluoride contained in the heat receiver. The walls are lined with lithium fluoride that changes state. Here, another interesting phenomenon. The fuel cells are heavier than the nickel-hydrogen batteries. The basic reason being that the fuel cell system is considerably less efficient than the battery system and you are paying a larger source penalty to make up for that inefficiency for the solar thermionic source than you do for the dossimer solar arrays.

(Figure 348)

The other system that showed something interesting is the solar Brayton. The Brayton system really wants to run at a constant speed. It doesn't want to be cycled up and down as load requirements change, so the ideal way to operate the Brayton system is to size it for the highest load you will ever see and let it run, parasitically sap off excess power when you are not running a full load. That is why the thermal storage line winds up being flat. Once you have sized the system for any given power, it doesn't matter how long you have to hold that power up. There is a cross-over point depending on how long you have to supply peak loads and it crosses over at something like 20 minutes or so.

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Since we were sizing for a 36-minute peak load, relating to the eclipse time, the thermal storage is really the way to go for the solar thermal systems.

(Figure 349)

Mass comparison of fuel cells and batteries. The fuel cell system, based on the advanced fuel cell, does come out to be lightest, but very close to it is nickel-hydrogen. The advanced shuttle fuel cell and nickel-cadmium battery systems are considerably heavier, basically because they don't have the life capability and would have to be replenished throughout the mission life, raising the total weight for the systems.

(Figure 350)

Costs look like this. The advanced shuttle fuel cell is really paying through the nose here for having to fly up a lot of one-year life capability energy storage elements. Nickel-hydrogen comes out to be cheapest. That is basically the reason that we wound up recommending this for energy storage, although it was, if you will remember from the previous charts, slightly heavier than the regenerative fuel cell system.

(Figure 351)

These were all conclusions. We did recommend nickel-hydrogen batteries. As stated in the previous presentation, regenerative fuel cell system is still very competitive and very attractive, and certainly feel that development on that should be continued. Solar thermal systems really aren't of too much interest to us here. Silver batteries are not competitive for long-life applications. I guess along with our recommendation of nickel-hydrogen batteries, the largest technology issue that we feel staring us in the face, and we recommend the study heavily, is the verification of long cycle life estimation for nickel-hydrogen systems.

DISCUSSION

FORD: Goddard. What size capacity? Are you talking about 100 ampere hour, 200 ampere hour?

CLARK: No. We wound out recommending a nominal 270 volt DC electrical distribution system, and directly interfacing the batteries with the bus on that system. That is a high voltage battery. That certainly is a technology issue to be examined for the future. But based on a high voltage battery, we are talking about capacities in the order of 25 to 30 ampere hours.

ROGERS: Hughes Aircraft. On that verification, do I understand you correctly that it would be roughly 60,000 cycles, ten years?

CLARK: Right. Ten years of life at 5,000 cycles or so a year.

ROGERS: I guess what I don't understand is how we would verify; we would have to project something, and I think it has been previously covered that it is a little difficult to try to figure out what is going to happen to the batteries unless you really understand them.

CLARK: Sure. I guess that is kind of where we were on ni-cads ten years ago asking the question, do we have any long life data? No, we don't. Will we ever have it? I guess all that it comes down to is somebody going to spend the money and the time to start it and run real time tests.

ROGERS: We are starting testing in low earth orbit of the nickel-hydrogen cells, but this will be at 80 percent depth of discharge.

CLARK: That is a healthy whack.

ROGERS: I think you will be faced with the problem, let's say after we get a reasonable number of cycles, say a year, of projecting what the effect of reducing the depth of discharge.

CLARK: Right. I guess the range we wound up operating at was about 20 percent depth. It is all paper, when I say, "We wound up operating at, " on a paper and pencil study.

LACKNER: Canadian Defense Research Establishment. When you run through the projections of 55 watt hours per kilogram that you would like to see in the nickel-hydrogen, nickel-cad system, what sort of technical base is this set on? Is it technically accomplishable or is it something that you would like to see accomplished?

CLARK: It is a stated goal of JPL, developing ni-cad batteries to include the energy density in the order of 33 watt hours per kilogram today to 55 watt hours per kilogram in the future.

LACKNER: I appreciate that it is a stated goal. I am just wondering how technically achievable it is and what sort of background has gone into it.

CLARK: I would have to refer the question to JPL. In my personal opinion, I think we will probably get there. I have some doubts about whether

we are going to get to considerable extension of the lifetime of nickel-cadmium, but I think that in terms of reducing the weight of the system, it will happen. That is a personal opinion.

LACKNER: It just seems that we are having trouble extending the life and the reliability at the energy densities that we now have. We are asking for a doubling of energy density and a doubling of life.

CLARK: That was one of the key points I had to wrestle with. The goals of JPL were stated as 55 watt hours per kilogram and/or doubling the life. I wasn't sure how to interpret that goal. I kind of put my own interpretation on it that I believe the "or" more than I believe the "and" by 1983.

space station systems analysis study
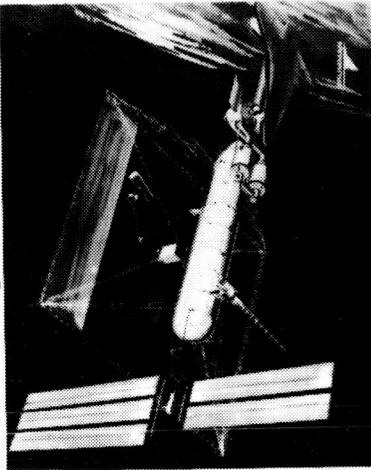
FINAL REPORT (PART 3) ADDENDUM – VOLUME 5: POWER SYSTEM TECHNICAL REPORT
31 August 1977
Contract No. NAS8-31993

Report No. MSS-82-HP025

Figure 335

SSSA PART 3 – POWER SYSTEM TASK OBJECTIVES

- EMPHASIZE PERMANENT MANNED SPACE CONSTRUCTION BASE
- CONSIDER 10-YEAR OPERATION
- FORMULATE & COMPARE PRIME POWER SYSTEM OPTIONS
  - SOLAR PHOTOVOLTAIC
  - SOLAR THERMAL
  - NUCLEAR REACTOR
- CONSIDER ISOTOPE POWER SYSTEMS FOR AUXILIARY POWER APPLICATIONS
- IDENTIFY REQUIRED/DESIRED TECHNOLOGY DEVELOPMENT

Figure 336

SCB POWER SYSTEM BUILDUP

ADVANCED PHOTOVOLTAIC BUILDUP

SOLAR ARRAY/GSS BUILDUP

NUCLEAR/BRAYTON BUILDUP

Figure 337

CANDIDATE POWER SYSTEMS

ALL SYSTEMS SIZED FOR 100/130 KW BASE/PEAK LOADS EOL 10 YR

235 KW Si ARRAY

235 KW GaAlAs ARRAY

152 KW SOLAR-BRAYTON

157 KW SOLAR-THERMIONIC

152 KW NUCLEAR-BRAYTON

157 KW NUCLEAR-THERMIONIC

157 KW NUCLEAR-THERMOELECTRIC

Figure 338

470
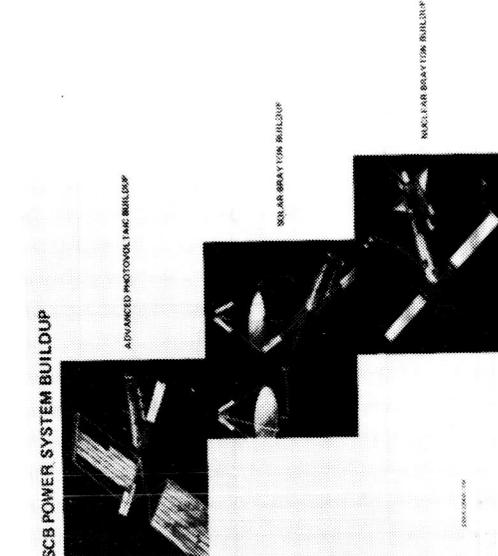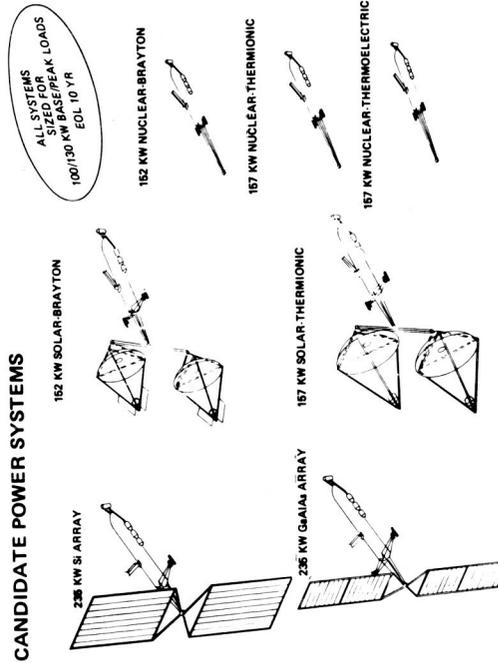
ENERGY STORAGE

● BATTERIES

   – NiCd/NiH$_2$

   – AgH$_2$/AgZn/AgCd

● REGENERATIVE FUEL CELLS

● THERMAL

Figure 339

BATTERY PERFORMANCE IN LEO
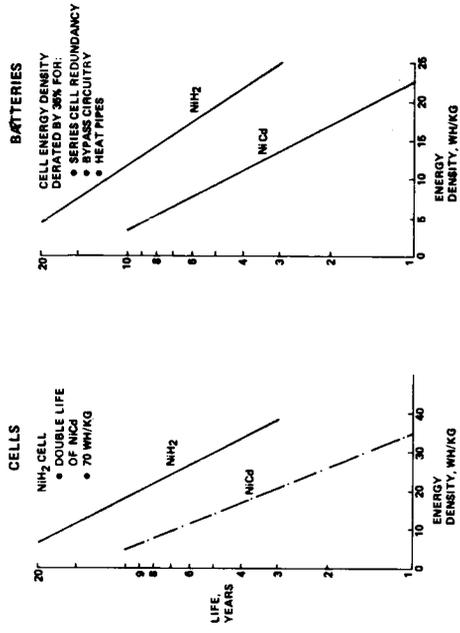
Figure 340

NiCd CELL PERFORMANCE IN LEO
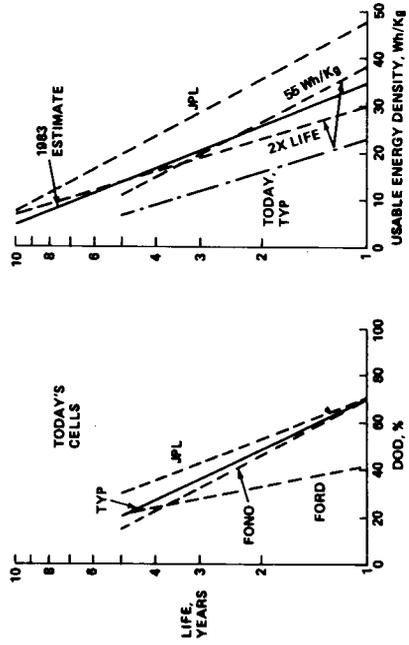
Figure 341

NiCd/NiH$_2$ BATTERY TRADES (200 N MI, 28-1/2° INCL)

Figure 342

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REGENERATIVE FUEL CELL SYSTEM

Figure 344

TOTAL MASS OF SHUTTLE-LAUNCHED BATTERIES OVER 10-YEAR PERIOD

BATTERY SIZED FOR:
— MAX (130 KW) REQMT
--- AVE DISCHG DEPTH FOR EACH SERVICE INTERVAL
● 70 KW/1 YR
98 KW/3% YR
130 KW/5% YR
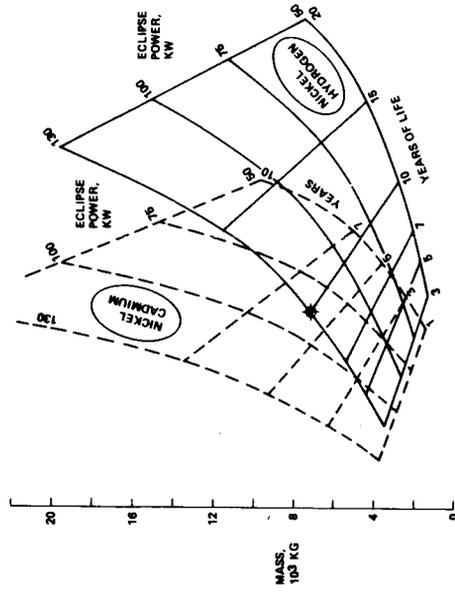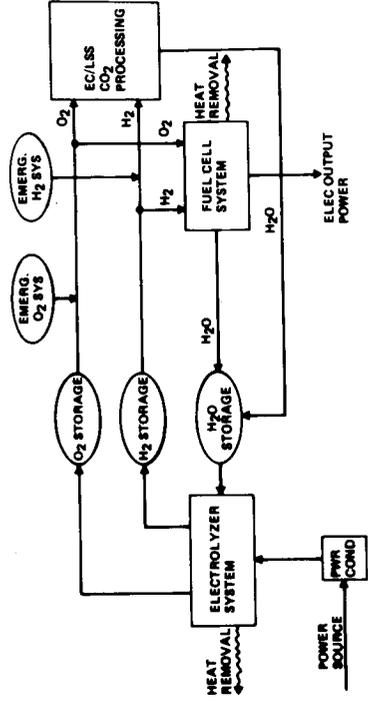
Figure 343

PHOTOVOLTAIC SYSTEM ENERGY STORAGE FOR 130 KW_e ECLIPSE LOAD
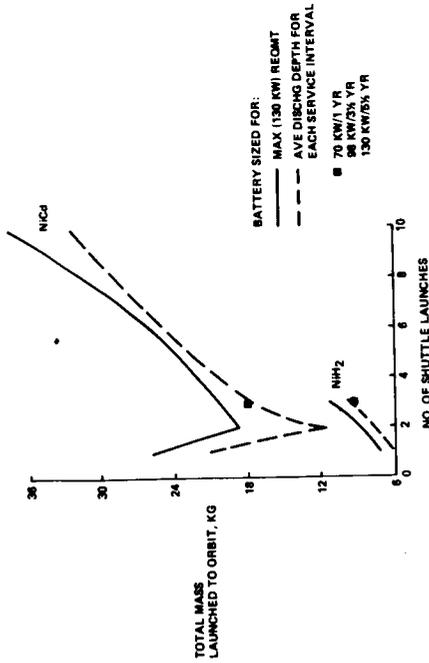
Figure 346

ENERGY STORAGE TECHNOLOGY PROJECTIONS

FUEL CELLS

CHARACTERISTIC	ADV SHUTTLE	SPACE STATION (1983 TECH READY)
● REACTANT CONSUMPTION (WH/KG)	2,915	2,970
● EFFICIENCY	79%	90%
● MASS, KG/KW	6.5-9.0	4.5
● VOLUME, M^3/KW	.015	.014
● OPER LIFE, HR	10,000	40,000
● OPER TEMP, °K	400	400
● COST		
– UNIT	$30K/KW	$20K/KW
– DEVELOPMENT	$200K	$10M

ELECTROLYZERS
● ENERGY CONSUMPTION: 5.49 KWH/KG OF O_2
● ALL OTHER CHARACTERISTICS SAME AS FOR FUEL CELLS

H_2 & O_2 STORAGE TANKS

	400-PSI STEEL	5,000-PSI COMPOSITE
● TANK WT/O_2 WT	1.25	1.04
● TANK WT/H_2 WT	20	11.1

Figure 345

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SOLAR-THERMIONIC ENERGY STORAGE FOR 130 KW ECLIPSE LOAD

Figure 347

SOLAR-BRAYTON ENERGY STORAGE FOR 30 KW PEAK LOAD
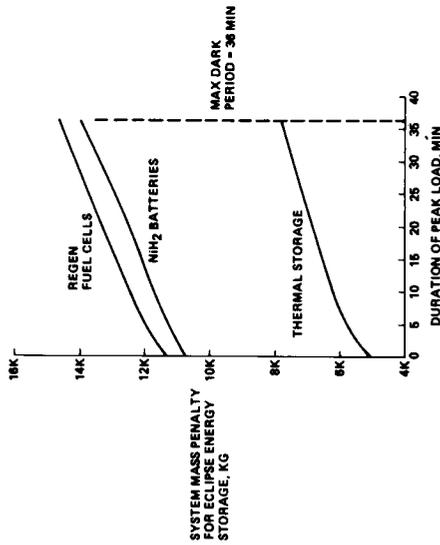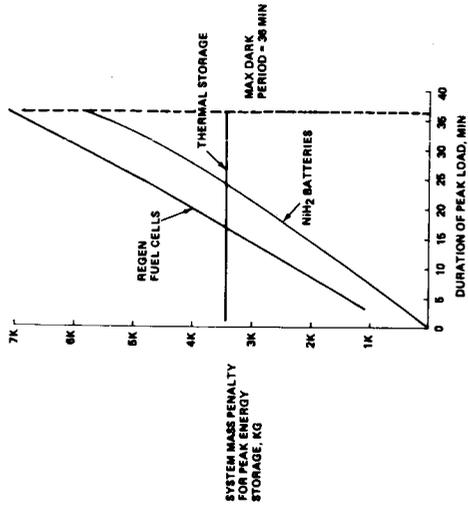
Figure 348

BATTERY/REGENERATIVE-FUEL-CELL COMPARISON FOR PHOTOVOLTAIC SYSTEM – MASS SUMMARY

- DISCHARGE REQMT = 84 KWH
- ELECTROLYZER O_2 GENERATION REQMT = 26.5 KG/HR

Figure 349

BATTERY/REGENERATIVE FUEL CELL COMPARISON FOR PHOTOVOLTAIC SYSTEMS – SYSTEM IMPACT/COSTS

Figure 350

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CONCLUSIONS — ENERGY STORAGE

- PHOTOVOLTAIC SYSTEMS

  - USE NiH_2 BATTERIES, CONTINUE DEVEL FOR 10-YR LIFE
    - NO RESUPPLY
    - LOW COMPLEXITY, HIGH RELIABILITY
    - ADV REGEN FUEL CELL SYSTEMS COMPETITIVE,
      CONTINUE DEVELOPMENT

- SOLAR THERMAL SYSTEMS

  - USE THERMAL STORAGE FOR ALL CONVERSION SYSTEMS
    - LOWEST MASS
    - LEAST COMPLEX

- REACTOR SYSTEMS
  - DO NOT USE ENERGY STORAGE

- $AgZn$, $AgCd$, AgH_2 BATTERIES NOT COMPETITIVE FOR LONG
  CYCLE LIFE APPLICATION

- TECHNOLOGY ISSUES
  - LOW COST NiH_2 BATTERY PRODUCTION
  - DECREASE NiH_2 PACKAGE VOLUME
  - NiH_2 LONG-CYCLE-LIFE VERIFICATION
  - LOW-COST CELL BYPASS CIRCUITRY
  - HIGH VOLT CHG CONTROL
  - FUEL CELL/ELECTROLYZER LIFE, EFF
  - HIGH TEMP THERMAL STORAGE MATL/INTEG

Figure 351

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ENERGY STORAGE CYCLING TESTS

B. J. Bragg
Johnson Space Center

I will give you a little bit of history on our nickel-cadmiums. We did a program with Grumman about '71-'72. Floyd Ford gave us a lot of help. Jim Cioni in our organization, the Propulsion Power Division at JSC, ran the test, and ran the program. Floyd Ford contributed a great deal. Steve Gaston, at the time from Grumman, I think did a lot of work on the thermal part of the program. The cells are Eagle-Picher cells. I think Bill Harsch from Eagle-Picher worked on the program.

We developed a four cell module. We did quite a bit of thermal testing and design. They did some life testing, very limited life testing. It is not really life testing but characterization testing and I would say some parametric testing, particularly aimed at the thermal part of the program.

(Figure 352)

We ran out of money at that point and were not able to continue on as we had planned, that is to do some considerable life testing at Grumman. Therefore, we salvaged what cells we could out of the program and tried to distribute some of them around the country. I think TRW got a few, Floyd Ford got several, Lockheed, and MDAC, I believe, got some. At any rate, we did this on a very low cost basis. It was no cost, is what it was. We gave them the cells and we hope to get back some data.

Those various efforts are in various levels of completeness. Our own effort was, as you see here, seven 3-cell packs running, or did have. The results that you see there at the two temperatures, two depths of discharges. The program involved several different kinds of separators, such as nylon and polypropylene. It also had, which you can not see in here, a couple of different plate pieces.

Of the seven packs we had running, we had three failures. Four are still running. All the polypropylene cells had failed. I did not do a failure analysis. I just took this program over recently from Jim Cioni, and so I haven't really done a whole lot in the way of trying to analyze what happened. Later on I hope to be giving you more detailed data.

We had eight test stands, seven operational and one backup. We have

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four now in use and three empty. I hope to do something with those.

(Figure 353)

Right now our battery testing is down. We have a facility problem. The air conditioner went out. I don't know whether that says batteries last longer than air conditioners. We are going to replace the failed ni-cad stands with 20 ampere hour nickel-hydrogen batteries.

Where we are in that effort, the entrie test is down right now, but we are going to get it up very shortly again. We have test fixtures for the 20 ampere hour nickel-hydrogen just about finished and ready to plug into the test stands. We are going to be looking at conditioning. I guess we will get on that bandwagon too. I am not sure, after hearing what I have heard here at the workshop, what kind of conditioning we ought to be looking at.

I should note that on our nickel-cadmium every 500 cycles we have run a capacity check. That is a sort of conditioning. We ran that down, I think, to three volts on a battery pack, three cells. So this is a volt per cell average. The capacities on all those four that are still running have degraded. We have felt that we would try reconditioning. At any rate, we may or may not continue that. I will have to take a look at it when we get our tests running again.

I plan to do the same thing basically on the nickel-hydrogen cells, running capacity check every 500 cycles. I will also look at the reconditioning on those packs.

Now the configuration of those packs, what I had planned to do was as the nickel-cadmiums fall out, replace them with three cell nickel-hydrogen packs. Since I have three right now, I was going to put all of them on a 75 percent depth of discharge at 50°, that is one of our current temperatures that we are running. I was also going to, on one pack, keep the pressure vessels as independent pressure vessels. On another pack I was going to manifold those cells.

(Figure 354)

Some in-house testing that we are doing are on a corner on a workbench. On the nickel-hydrogen, I have more of the same nickel-hydrogen cells, they are cells from Eagle-Picher and from Energy Research. As you see, they are 1975 manufacture and this is still in the projected test title that I had earlier. I have some real good shelf life on those batteries. We hope to get some data out on them pretty quickly now with this section we have going now.

What we plan to do is wind up with four test stations effectively in our Tech Services Battery Shop. We are going to arrange the cells as you see there. We are going to take, number one, the two 10-cell manifold packs, that is 10-cells packs that are electrically in series, but one 10-cell pack will be an Eagle-Picher pack, the other will be an ERC pack, and continue that kind of arrangement on through this configuration.

Looking at two different depth of discharges there. Again, conditioning, if we see some good data coming out of a particular kind of conditioning we try, we may wait and choose the particular conditioning procedure. That is basically all I have.

DISCUSSION

GASTON: RCA. Do you have any idea why the polypropylene cells failed prematurely?

BRAGG: No, I don't. We haven't done any kind of a failure analysis on them. I would plan to do something on that to try to understand it better. As I say, I just recently had this program transferred over to me. When we find out, I will tell you.

GASTON: You gave me credit as being the cell manager. Just for the record, I was the project engineer in charge of the program at that time.

WADHAM: Telesat. What was the failure line in the propropylene cells?

BRAGG: My failure criteria was during cycling if the pack went down to three volts.

ROGERS: Hughes Aircraft. How do you intend to manifold them? Just roughly, what would you do?

BRAGG: Plumb them together, isolated electrically.

PROJECTED TESTING

o CONTINUATION OF FOUR 100 A-H Ni-Cd BATTS

o THREE 20 A-H Ni-H2 BATTS UTILIZING EMPTY TEST STANDS
  o TEST DOCUMENTATION PREPARED
  o TEST FIXTURES 75% COMPLETE

o INCORPORATION OF CONDITIONING PROCEDURE (EVERY 500 CYCLES)
  o PERFORM CAPACITY CHECK AT RATED LOADS TO 1 V/CELL
  o CONTINUE DISCHARGE TO BATT VOLTAGE OF ZERO AT LOW LOAD
  o RECHARGE AT LOW RATE

o TEST CONFIGURATION/MODE
  o CELLS TESTED IN 3-CELL PACKS
  o INDEPENDENT AND MANIFOLDED PRESSURE VESSELS
  o LEO AT 75% DOD AT 50°F

Lyndon B. Johnson Space Center

NASA

Figure 353

TEST STATUS

o SEVEN 3-CELL 100 A-H Ni-Cd BATTERIES ON 1.5 HR CYCLES
  o GAC CHARACTERIZATION TESTING - TENS OF CYCLES
  o GAC PARAMETRIC TESTING - HUNDREDS OF CYCLES

o TEST RESULTS TO DATE
  o NYLON SEPARATORS
    o 50°F, 30% DOD - 2 BATTS AT 7500 CYCLES AND CONTINUING
    o 50°F, 15% DOD - 1 BATT AT 7500 CYCLES AND CONTINUING
    o 64°F, 30% DOD - 1 BATT FAILED AT 4354 CYCLES
    o 65°F, 15% DOD - 1 BATT AT 7500 CYCLES AND CONTINUING
  o POLYPROPYLENE SEPARATORS
    o 64°F, 30% DOD - 1 BATT FAILED AT 1381 CYCLES
    o ... ... - 1 BATT FAILED AT 4915 CYCLES

o TIA TEST STAND STATUS
  o 8 TEST STANDS BUILT: 7 OPERATIONAL, 1 BACKUP
  o 4 TEST STANDS IN USE, 3 PRESENTLY EMPTY

Lyndon B. Johnson Space Center

NASA

Figure 352

IN-HOUSE INSTITUTIONAL PROGRAM SUPPORT

NICKEL-HYDROGEN BATTERY TASK

o EAGLE PICHER AND ENERGY RESEARCH CORP, CELLS OF 1975 MANUFACTURE

o FOUR TEST BATTERIES (20 A-H) ON LEO AT 40°F

  (1) TWO 10-CELL, MANIFOLDED PACKS IN SERIES AT 50% DOD

  (2) TWO 10-CELL, MANIFOLDED PACKS IN SERIES AT 75% DOD

  (3) TWO 5-CELL PACKS (INDEPENDENT PRESSURE VESSELS) IN SERIES AT 50% DOD

  (4) TWO 5-CELL PACKS (INDEPENDENT PRESSURE VESSELS) IN SERIES AT 75% DOD

o CONDITIONING PROCEDURE AT REGULAR INTERVALS

Figure 354

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SESSION VI

NICKEL-HYDROGEN
AND
LITHIUM

F. Betz, Chairman
Naval Research Laboratory
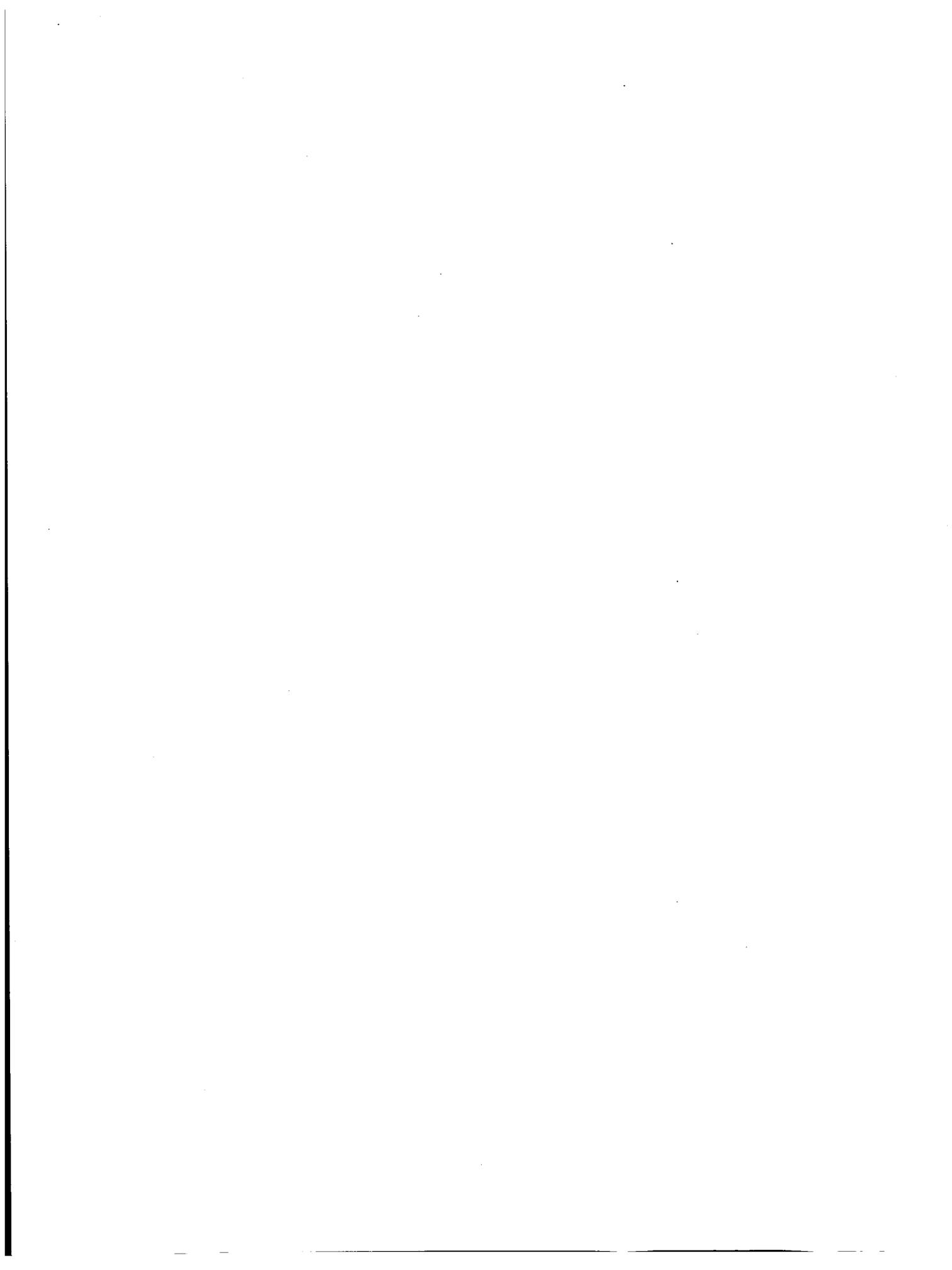
LOW ORBIT NICKEL-HYDROGEN
BATTERY DEVELOPMENT

H. Rogers
Hughes Aircraft Company

I am going to be talking about some test data that we have developed primarily on low earth, but also a little bit of accelerated synchronous orbit data, on first 40 hour ampere hour boiler plate cells which were built on our nickel-hydrogen program with Air Force support, and a couple of cells which were made by Hughes Aircraft on our IR&D program which we have been using in synchronous orbit.

(Figure 355)

The first boiler plate cell is very conventional construction, back to back, hydrogen electrode and, in this case, a gas permeable separator, niconium oxide cross, is used as a separator rather than asbestos which has been previously used.

The hydrogen electrodes were supplied to us by ERC Corporation. The nickel electrodes are Air Force impregnated Eagle-Picher electrodes, so they are electrochemical. This particular cell has 34 positive electrodes and both the cells I will be describing run roughly 40 ampere hours.

(Figure 356)

This design is what we call the recirculating design which has been previously described both by Gerhard Holleck and Don Warnock in previous talks. I just want to make a couple of comments on it. The electrodes in this are the same as I previously mentioned. The two major factors in this are one, we do have electrolyte which recirculates, and also oxygen which circulates through the stack. The other item I want to cover is in previous designs we have always used intra-stack reservoirs, not just one, but many. In other words, each nic-electrode had an adjacent reservoir. In this current design, we do not do that. We depend on the depth permeable separator also to act as a reservoir. Again, the niconium oxide.

(Figure 357)

This is a charge/discharge voltage characteristic after 250 80 percent depths of discharge cycles, at the charge/discharge ratio of 1.05 to 1; 80

percent, of course, being based on the roughly measured capacity. The two cells were operating fairly similar with actually the cell with the greater number of plates, the back to back, having a little bit higher voltages.

(Figure 358)

The cells both had reference electrodes. The reference electrodes are somewhat unusual in design. They are built by immersing a piece of hydrogen electrode beneath the surface of a small pool of electrolytes so that you avoid the problem during operation of the cell where you get some oxygen accumulated in the cell, and having that oxygen react with the electrode, changing its potential.

In essence, what you have is a hydrogen electrode which operates at potentially the same state throughout the entire cycle. So the data has a lot more meaning. We found that the two cells did have different potentials at the hydrogen electrode, although I am not quite sure of the reason or that it is that significant. You are only talking about 15 millivolts or so, and it was consistent throughout the cycle.

(Figure 359)

In these cells, both cells had thermocouples, those in the core, now when I say in the core, what I really mean is, this is a pineapple plate design where the leads come up the center of the electrodes. The thermocouple that we are talking about when we say core is immediately adjacent to the plate. So what we are really doing is measuring the temperature at the inside of the plate, which we feel to be the hottest point in the cell. The end plate is in the center of the end plate, and I will speak about the wall temperature when I show the next figure. You will notice that the coolest time is at the end of charge, which one might expect, because our 1.05 to 1 charge/discharge ratio isn't enough to get into overcharge.

(Figure 360)

You notice in this figure we do have a wall temperature. Our cooling system, which really consisted of a coil or copper tubing around the cell, wasn't quite sufficient to keep the cell wall temperature constant. You will notice we had roughly about five degree temperature rise within the stack. That is very much dependent upon two things, the charge/discharge ratio, if we went, for example, to 1.10, you would have seen a significant rise in temperature at the end of discharge, in that we would not be running quite as low an end of discharge voltage.

482

(Figure 361)

We quite intentionally put the cell (and this again I will remind you is a 40 ampere hour cell) into overcharge. You will notice we see the typical rise in voltage and then drop off due to heating. This is the back to back cell I am referring to. At the same time we measured the percent oxygen and had to re-check the electrode to make sure it was working properly because we noted no change in oxygen concentration. The initial high oxygen is due to the fact that the electrode takes a little time before it comes down. The oxygen electrode operates at low levels, it takes a while before it gives good answers at the low percentages.

So in essence we have no accumulated oxygen, and the next figure will show you another way of looking at that.

(Figure 362)

You will notice that the cell pressure, which was also monitored, virtually levels at the point where we discontinued the test. Again showing that our oxygen is all recombining within the stack. The reason we discontinued the test at that point is seen in the next figure.

(Figure 363)

The core temperature was rising at a very high rate. You will notice that we reached 50° Centigrade, at which point I decided not to abuse the cell. It is an indication of where limitation exists in nickel-hydrogen in these large cells in low earth orbit. You really cannot tolerate a large amount of overcharge or you are going to boil the cell. That temperature would not have taken long to reach 100° C.

(Figure 364)

The cell I am going to be talking about now, actually two cells, are 18 ampere hour cells using the same type of electrodes that I have previously described, the same separator system, niconium oxide, they are back to back, and they are in a lightweight case three and a half inch diameter, and are an example essentially of our synchronous design which is close to the low earth orbit design with a few minor changes like in leads.

You will notice between cycle 5 and cycle 230 there was really no observable change in the cells. The small amount of change there at the end I don't think is significant as you will see in the next figure.

483

(Figure 365)

We find that virtually for 250 accelerated cycles, these are six hour cycles at 120 percent return, 80 percent depth of discharge, essentially we are seeing no degradation in either cell.

CELL 1 – BACK-TO-BACK DESIGN
34 POSITIVE ELECTRODES

GAS SPACE
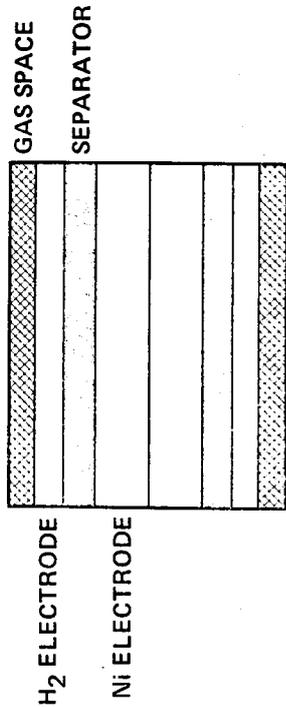
SEPARATOR

H₂ ELECTRODE
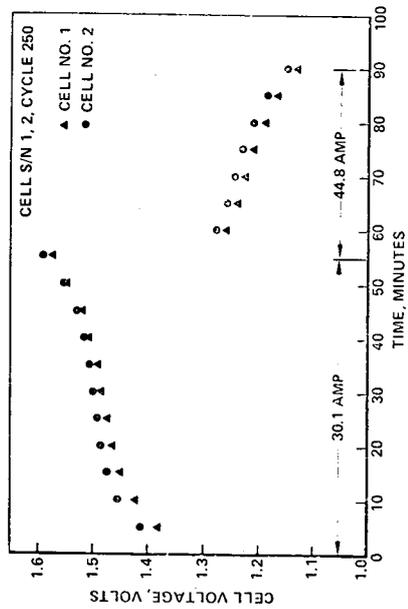
Ni ELECTRODE

Figure 355

CELL 2 – RECIRCULATING DESIGN
GAS PERMEABLE SEPARATOR
30 POSITIVE ELECTRODES

GAS SPACE
H₂ ELECTRODE
SEPARATOR
Ni ELECTRODE
RESERVOIR
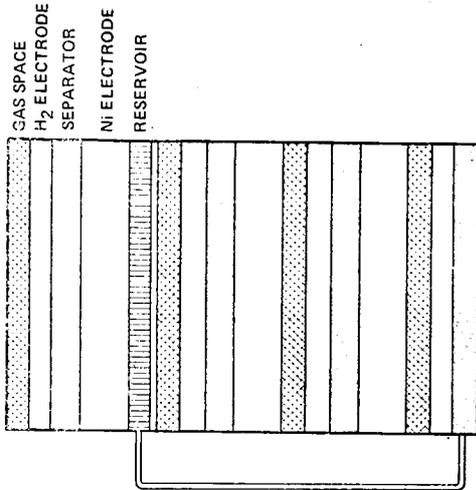
Figure 356

CHARGE/DISCHARGE
VOLTAGE CHARACTERISTIC

CELL S/N 1, 2, CYCLE 250

▲ CELL NO. 1
● CELL NO. 2

TIME, MINUTES

CELL VOLTAGE, VOLTS

30.1 AMP   44.8 AMP

Figure 357

CHARGE/DISCHARGE
REFERENCE VOLTAGE CHARACTERISTIC
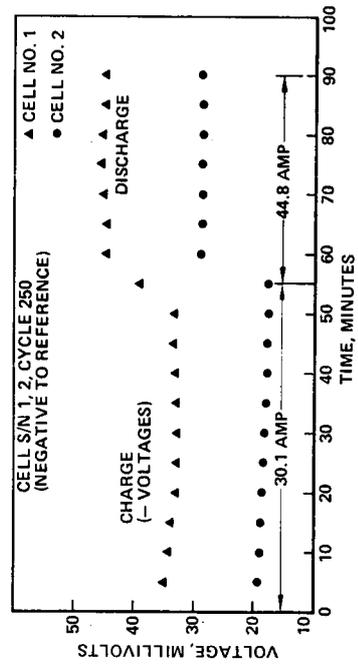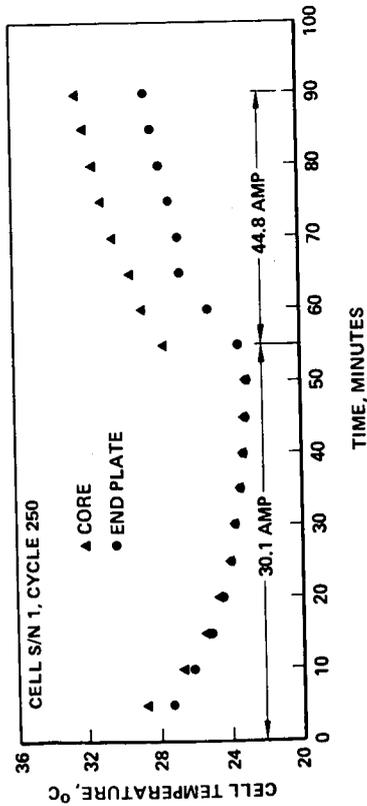
CELL S/N 1, 2, CYCLE 250
(NEGATIVE TO REFERENCE)

▲ CELL NO. 1
● CELL NO. 2

DISCHARGE

CHARGE
(– VOLTAGES)

VOLTAGE, MILLIVOLTS

TIME, MINUTES

30.1 AMP   44.8 AMP

Figure 358

485

CHARGE/DISCHARGE
TEMPERATURE CHARACTERISTIC

CELL S/N 1, CYCLE 250

▲ CORE
● END PLATE

CELL TEMPERATURE, °C

TIME, MINUTES

Figure 359

CHARGE/DISCHARGE
TEMPERATURE CHARACTERISTIC

CELL S/N 2, CYCLE 250

■ CORE
● WALL
▲ END PLATE

CELL TEMPERATURE, °C

TIME, MINUTES

Figure 360

VOLTAGE CHARACTERISTIC

CELL S/N 1, FAILURE MECHANISMS BOILER PLATE OVERCHARGE TEST

CELL VOLTAGE, VOLTS

% O₂ 1.0 0.5 0.0

30.1 AMP

TIME, MINUTES

Figure 361

PRESSURE CHARACTERISTIC

CELL S/N 1, FAILURE MECHANISMS BOILER PLATE OVERCHARGE TEST

CELL PRESSURE, PSIG

30.1 AMP

TIME, MINUTES

Figure 362

486

TEMPERATURE CHARACTERISTIC

CELL S/N 1,
FAILURE MECHANISMS BOILER PLATE OVERCHARGE TEST

▲ CORE
● END PLATE

30.1 AMP

TIME, MINUTES
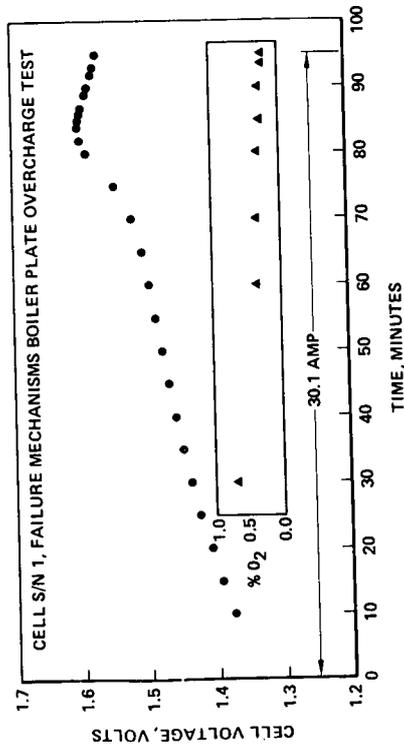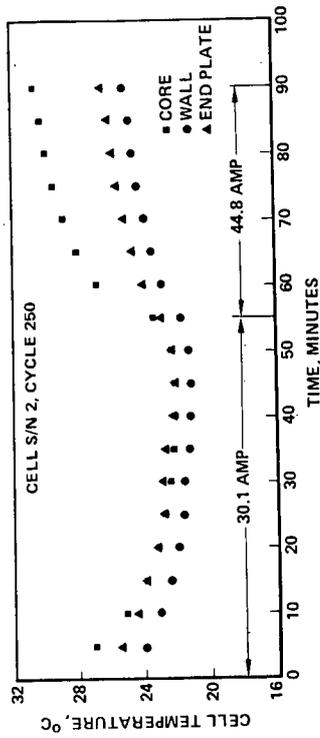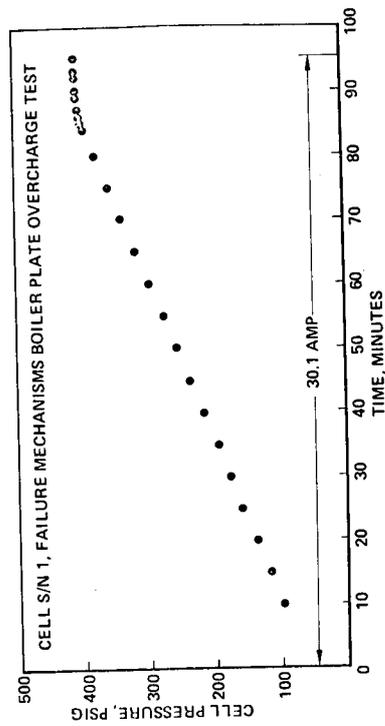
CELL TEMPERATURE, °C
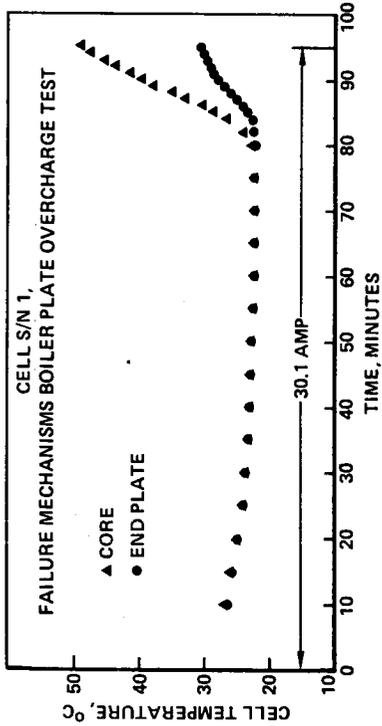
Figure 363

DISCHARGE VOLTAGE CHARACTERISTIC

CELL S/N 6

END-OF-CHARGE	VOLTAGE
CYCLE 5	1.489
CYCLE 230	1.493

▲ CYCLE 5
■ CYCLE 230

12.0 AMP

TIME, MINUTES

CELL VOLTAGE, VOLTS
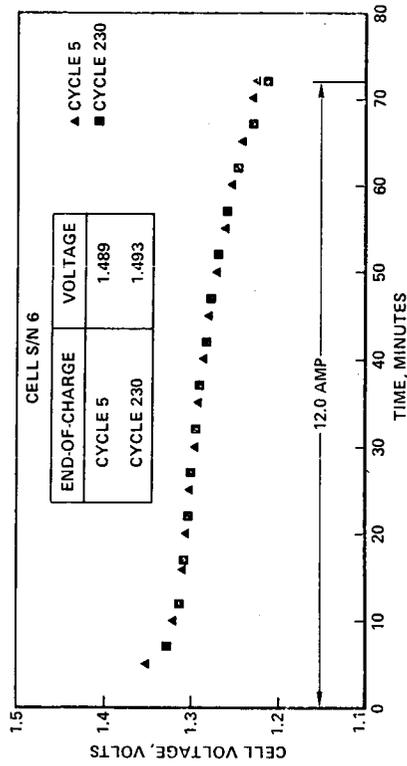
Figure 364

DISCHARGE VOLTAGE CHARACTERISTIC

CELL S/N 6 AND CELL S/N 8

END-OF-CHARGE	VOLTAGE RANGE
S/N 6	1.486 TO 1.497
S/N 8	1.483 TO 1.491

▲ S/N 8
■ S/N 6

CYCLE NUMBER

CELL VOLTAGE, VOLTS

Figure 365

487
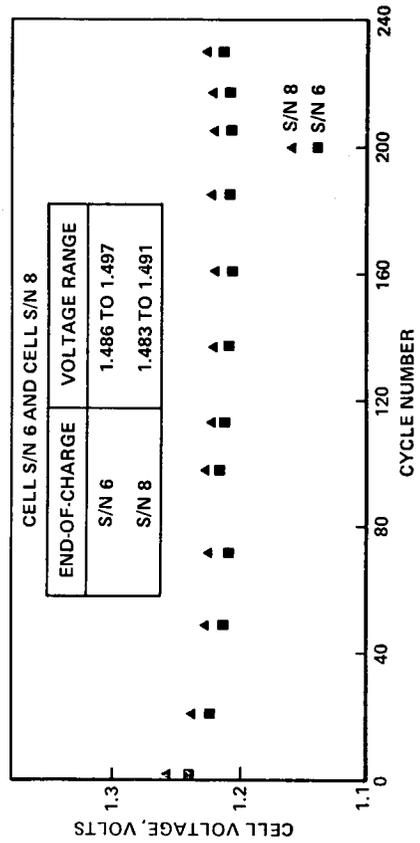
THE NTS-2 NICKEL-HYDROGEN BATTERY

F. Betz
Naval Research Laboratory

The NTS-2 satellite built by the Naval Research Laboratory in Washington is the first satellite launched in orbit with an operational nickel-hydrogen battery. We actually lucked out. We beat the Air Force by about three days, but we slipped two, then they slipped, and it was almost a tie. We understand that one was launched first by JPL on a sounding rocket, but this one is up and working.

(Figure 366)

I would like to go back a ways to the beginning. This program actually started just a little more than three years ago, in the summer of '74. We had conceived that it might be a good application for a nickel-hydrogen battery. We came to technical agreement with INTELSAT in the Fall of that year, and Comsat Laboratories would provide nickel-hydrogen battery cells to the Navy, the Navy would fly them on the NTS-2 satellite.

The dash line indicates the area of technical agreement. The star incates how long it took for the lawyers to come to legal agreement. The contract is in effect, and it will carry on for years, and will be providing data as long as the satellite is up and in operation.

You can see that shortly after legal agreement was reached we received prototype battery cells in November of 1975. That is just about two years ago. In fact, we built our first prototype assembly, we brought it over here, set it on the table, and laid out our program, in effect, how we intend to operate this satellite.

That battery came back and went through a thermal vacuum cycle. We learned a little bit about it based on the thermal vacuum cycles. We plan to modify the battery sleeve design a little bit. We went through vibration. The first vibration lasted a few seconds and we lost the terminal on one of the nickel-hydrogen cells.

TRW studies had shown that that was the weak point and it was confirmed. I am going to tell you everything about the program. Like any program, it is not all sweet. There were rocky spots, but we have got over the hurdles and we got it up there. I think the whole story should be told.

Shortly after that we identified that the cell cases were extraordinarily hot electrically. When the spacecraft manager leaned over the satellite and shorted one of the cases to ground, the hydrogen vented out freely through the burned hole. There was no fire. It scared him a little bit. He was on a ladder.

Incidentally, we did vibrate again and we passed the vibration at 18.1 GRMS in all three axis. We did have to upgrade the battery and we rebuilt a prototype battery using new longer sleeve design, replacing some cells we found were defective, and one that we made defective, that was the broken seal in the hole, and then we proceeded into some oh, also that upgrading incorporated for the first time strain gauges on the cells. The electrical testing that followed was identified how we could relate the strain gauge capacity and pressure.

Following those electrical tests, the prototype battery went into spacecraft integration and spacecraft testing and was in the satellite for the best part of that year. It went through quite a bit of those nine months that Floyd Ford was talking about.

That was followed in the summer of '76, just a little less than a year before launch, with the delivery of the flight cells and flight battery assembly. That really went smoothly. We didn't have too many problems with flight battery thermal vacuum vibration. I think some of our thermistors came off. Since we were using those for charge control, we decided we really wanted to make sure they stayed glued on there so we did vibrate again later on.

The thermal vacuum tests in this one were the full-up spacecraft tests, and again verified our concept of charge control which we will get into a little later.

In the Spring of this year, that battery went into the flight spacecraft for final full-up thermal vacuum test on the flight spacecraft, spacecraft vibration, acoustics, RFI, a number of other spacecraft tests before we went to the Western Test Range for launch.

You see up there it says "AC", that is acceleration. The prototype battery we ran in constant acceleration for a period of nine hours at about 8 g's. This was one of the modes of operation that we found out we were going to have to face during the spin stabilized mode of the satellite before the solar arrays were deployed.

We did get to the field, and we launched on June 23, 1977 the nickel-hydrogen battery. I should say, operating on the nickel-hydrogen battery. The system has the nickel-hydrogen battery as the prime power supply and is backed

up by the nickel-cad and is an automatic trip over from one to the other or auto-
matic operational change from one to the other, so we saw no reason not to launch
with the nickel-hydrogen batteries supporting the loads and that is the way we
went off.

When we first came into view, the nickel-hydrogen batteries were re-
charged. Temperature was up around 22°C. We launched in the middle of the
night. In fact, it was so foggy you couldn't even see it from about three miles
away. The satellite in its eliptical orbit went through three half-hour eclipses
and finally came into view of the earth station, charged up, and switched into
trickle charge all by itself.

During that period of time, however, everything looked like it was going
so well that the main charger for the nickel-hydrogen battery was commanded
to trickle charge and then the loads were increased, and the nickel-hydrogen
battery was reversed. Or should I say, reconditioned. We did have a full re-
versal on the nickel-hydrogen battery. ' Our monitors only go to zero, so we
were below zero volts. Nickel-cadmium was supporting the system when it
came back into view, and the main charger was then turned on.

A little later on, once the gravity gradient blooms on the satellite were
deployed and the solar array was deployed, we were attempting for a few days
to have the satellite stabilized. The gravity gradient system is not as strong as
it might be way up there and it took a few days. During that period of time, we
reversed the battery, reconditioned the battery a second time. The satellite
attitude system was unable to control or keep the arrays pointed to the sun for
a period of time there.

(Figure 367)

Anyway, that is the good news. I would like to point out some of the
features of the battery itself for those of you who are not exactly sure what it
is. The nickel-hydrogen cell that we are using is a Comsat laboratories design,
Eagle-Picher manufacture. As far as I know, it might well be the first to fly
electrochemically impregnated positive electrodes. These were done by Eagle-
Picher to the bell process.

As far as I know, it is also the first to use Ziegler-type plastic com-
pression seals. The test is a good one. The cell operates in the range of 600
psi maximum and it holds that pressure between eclipses so it looks like the
seals are doing their job. We have an asbestos separator. There are four strain
gauges mounted on the cell containers. It is kind of hard to track them all at
the same time. We don't have enough memory channels to get all the data we

would like to get, but we are using two of those now to monitor the capacity of the batteries.

The mass of the cell is 1.026 kilogram, and that funny little mark there that says 0.034 kilograms is the strain gauge. There is a difference. The 34 grams is a small penalty to pay for that.

The battery structure itself consisted of two 7-cell assemblies. I will show you those in a moment. It is a direct radiator design. The comment here is that the primary criterion of the design of the battery was a good thermal test bed for the battery cells. We didn't try to optimize weight and you will see that in a second.

We do monitor individual cell voltages. We have, I believe, five temperature monitors on the two assemblies, that is five total. We monitored the four strain gauges. We found out that we do have a little problem with both cell voltages and strain gauges. During the eclipse period, our booster, which is a resonant switching frequency booster, high efficiency, does put a little too much noise on the bus for these low signals. The values we see during the eclipse itself are not very reliable, but we do have the values immediately before going into eclipse and immediately after eclipse, and we do have the entire battery voltage to monitor. So you can get a pretty good idea of what is going on.

There is the battery mass with 14 cells, it is 20.72 kilograms. Our ratio not quite optimized, 1.43 pounds total for each pound of cell. The energy density at rated capacity is 28.4 watt hours per kilogram, it is 12.9 watt hours per pound. A more typical number based on a 39 actual typical ampere hours we get out of the battery is something like 31.6 watt hours per kilogram, and that is 14.3 watt hours per pound not kilogram again.

I put the volume down because you would have to compare that with some of your own batteries, but our gross volume is somewhere around two cubic feet, one cubic foot per assembly. That is a pretty big structure.

(Figure 368)

That is what it looked like before it was launched. Those are the flight batteries, the flight assemblies. If you compare this perhaps to the photographs in your other workshop, the sleeves come up higher on the cells and they are actually a slight bit thinner also. That was the major structural change. You can see the mounting of the thermistors. There is a thermistor here, another one in there, two more on the other battery pack, there is a thermistor mounted down here on the heat sync and one in the center of the heat sync. There are also

some thermostats on there and there are heaters on the base plate should we go into a low shed condition and the battery gets too cold.

(Figure 369)

The first eclipse season, which actually started just a few days after our launch, we launched June 23, and our first eclipse started on July 10, in fact I didn't think we were fully stabilized at that time, we did start eclipsing then. These are essentially the times. This is taken from data we provided Comsat Laboratories and Comsat Laboratories put it into a very readable form for us, Thanks to Joe Stockel. Any misspelling you see in here is Joe Stockel's computer's fault incidentally.

The discharge times and the profile look like a synchronous type of orbit. There are 60 eclipses during the season. The maximum eclipse period is only 0.94 hours, someone less than a true synchronous application. There are two seasons a year just like the real thing.

(Figure 370)

Here is the battery voltage characteristics during the middle of the eclipse season. We have a constant power. We take this 14 cell battery and boost the voltage up to the bus voltage of 27 volts constant power system. You can see the current in the middle of the eclipse season starts somewhere 21, I think it starts lower but it goes up rather rapidly to 21 amperes and ends close to 24 amperes. The beginning of discharge voltage is up in the 18 volt range. The minimum voltage we saw throughout the entire center of the eclipse period on the battery was 16.44 volts. The voltage recharge characteristic we charge at three and a half amps constant current based on temperature, which I will show in a second. We switched to a 600 milliamp trickle rate.

(Figure 371)

That is that same discharge period a little bit accentuated. The line in the real world is a little bit smoother than that, but the data points are taken at every 102 seconds, I believe. We don't use them all anyway. We did look at and wondered why our voltage was down around this 118 area at eth end. We looked into some of our data and we found that there is quite a bit of impedance in the wiring and in the system. The two battery assemblies are 30 or 40 inches apart, and even with a fairly substantial harness, these is some voltage drop in the battery. If you try to look at it from cell voltage point of view, you have got to divide by 14 and then add a little bit back in.

493

(Figure 372)

This is the temperature profile in the middle of the eclipse season with essentially the same voltage characteristic you saw before. It almost looks like the curve we showed here three years ago which said, "This is what we expect to happen." The battery temperature increased from 15°C to 25°C max. We have not seen any temperatures above 25°C. It cools down to 12°C, due to the endothermic reaction during charge. As it goes into the overcharge period, the battery heats up, it automatically switches to the trickle charge as it passes 15°C. There is some thermal overshoot during the charging period, but there doesn't seem to be any thermal overshoot at the end of discharge. We come back again to 15°C at the end of the orbit.

Now that we are in a full Sun period, the temperture is approximately 10°C to 12°C plus or minus 2. There a is little more gradience between the battery packs than we had predicted. That doesn't seem to be a problem, they are working fine.

(Figure 373)

This is what the strain gauge produces. The beginning of discharge and end of discharge are two points taken just before the beginning of discharge and just after the end. The recharge during the constant current period indicates a nice linear increase in capacity and pressure, as you would expect. Then when we switch to trickle, there is a little fall off there. You will see the 35 ampere hour nominal capacity. It looks like that one maybe about 38 ampere hours at the end of the charge and trickle charge period.

(Figure 374)

This is the daily battery voltages during the entire 60 day season. I might comment that in the first 17 days of the season, we were not on full load. We were running about half of the bus power that would be required when we went to full load at the 17th eclipse. That is how fast things were happening. We have just had to get the thing up to full power and get it stablized and working. So that explains, perhaps, the nice linear point decrease during that period and then stabilizing. You can see that the charge voltages are fairly regular during the entire season however.

(Figure 375)

Daily temperature data. Again, you can see the effect of the first 17 days at half power. We had trouble keeping the satellite warm and occasionally

you can use nickel-hydrogen battery to heat up the satellite a little bit just by overcharging it a little bit. That dissipates quite a bit of energy.

After that we get to our middle of the eclipse period. You can see the end of discharge temperatures throughout the main period of the eclipse season were fairly constant. End of charge is nice and constant. We have a little gimmick in there that says if the battery temperature is below 15 °C at the beginning of the charge period, end of charge will be terminated at 17°C, or plus one degree. It comes out to close to 17°C. If the battery temperature is above 15°C at end of discharge, then you only recharge for 15°C. That took some uncertainty out of it if you come in right at 15°C. That is why in the beginning you see the higher end of charge temperature and then going back to 15°C.

(Figure 376)

Daily battery capacity, based on the strain gauges end of charge is the top line, end of discharge, of course, is the bottom, and the end of trickly charge. We started off a little higher. See, the reason this fell down is due to the increased temperature, average operating temperature of the battery. We found that there is quite a bit of temperature correlation. Capacity and temperature due to correlate rather well. As you get warmer with this battery, you lose a little capacity.

We are still in pretty good shape. You can see we are up around 40 ampere hours so it is nothing really to complain about too much.

(Figure 377)

Finally, Joe Dunlop's picture of daily and recharge ratio, current integration. This is just to the trickly point; the 600 milliamps, I believe, is not included here. We are running during the main part of the eclipse season slightly over 1.2 or 120 percent recharge ratio. That is based on current integration. The early period in the short eclipses where the thing was running cold, you have to use a little more energy just to heat it up to the 15°C trip point.

The bird is still up there. It is working fine. We went through an eclipse last Friday from the moon just to remind us that everything was alright. The battery discharged a little bit and went back into recharge and switched into trickle, so we know it is still good and get ready for our next eclipse season in January.

HH2 BATTERY FEATURES

o NICKEL HYDROGEN CELL

   COMSAT LABORATORIES DESIGN, EAGLE-PICHER MANUFACTURED

   ELECTROCHEMICALLY IMPREGNATED POSITIVE ELECTRODES

   "ZIEGLER" TYPE SEALS

   ASBESTOS SEPARATOR

   STRAIN GUAGE ON CONTAINER

   35 Ah NOMINAL CAPACITY, 39 Ah TYPICAL

   MASS: 1.026 Kg. (PLUS .034 Kg. STRAIN GUAGE)

o BATTERY

   TWO 7 CELL ASSEMBLIES, DIRECT RADIATOR DESIGN

   CELL VOLTAGES, TEMPERATURES, AND STRAIN GUAGES MONITERED

   CHARGE CONTROL BASED ON CELL TEMPERATURE

   MASS: 20.72 Kg., BATTERY TO CELLS MASS RATIO - 1.43:1.0

   ENERGY DENSITY AT RATED CAPACITY: 28.4 wh/Kg.,(12.9 wh/lb.), TYPICAL: 31.6 wh/Kg.,(14.3 wh/Kg.)

   GROSS VOLUME: .0577m³, (2.037 ft³)

Figure 367

Figure 369

Figure 366

Figure 368

NTS-2 BATTERY - BATTERY VOLTAGE

VOLTAGE x

CORR.VOLTAGE ●

TIME(HR)

Figure 371

NTS-2 BATTERY - CAPACITY DATA

TIME(HR)

Figure 373

NTS-2 BATTERY - CURRENT & VOLTAGE DATA

CURRENT x

VOLTAGE ●

TIME(HR)

Figure 370

NTS-2 BATTERY - TEMP. DATA

TIME(HR)

Figure 372

497

Figure 375

Figure 377

Figure 374

Figure 376

498

AIR FORCE NICKEL-HYDROGEN EXPERIMENT

W. Harsch

Eagle-Picher Industries

As Fred alluded to earlier, there is another flight program going for nickel-hydrogen. This, of course, is not an operational battery, but an experiment. The objective of the experiment was to obtain some flight experience with a nickel-hydrogen battery in low earth orbit where the Navy is working in a more or less synchronous regime.

The battery was designed and developed by Eagle-Picher under contract to the Aeropropulsion Labs at Wright Patterson, with Don Warnock as the technical monitor. The battery is on an Air Force satellite.

The program began in June of '75 and the experiment was shipped to the Air Force in August of '76. During the year, we did the design and development of the battery itself. We used state-of-the-art technology, 1975 state-of-the-art-technology, which was the existing 50 ampere hour cell. We built the battery to be as compatible with the satellite bus as possible because we are using the satellite bus for our recharge power. The battery is mounted on an experimental pallet on the satellite. It has its own charge control system which, unfortunately, there was not time to develop probably optimum charge control system for this battery, so it is a modification of an existing system that is used for nickel-cadmium, which primarily uses temperature compensated voltage as its criteria.

Also on the pallet is a load bank, a resistive load bank, which allows us to switch to various load regimes. There is some other equipment on the satellite for which they are using the nickel-hydrogen battery to power it. Let me give you some of the details on the battery.

(Figure 378)

As I said, the cells were the 1975 vintage 50 ampere hour cell, which delivered about 55 ampere hours. The electrochemically impregnated positive nickel electrodes, the teflonated platinum catalytic electrode. The separator in these cells is an EP reconstituted asbestos, gas spacers are woven teflon. Cell cases is hydroformed Inconel 625, which again is 1975 cell case. The terminal is a dual plastic or Zeigler-type compression seal.

499

(Figure 379)

The battery is a 21 cell battery. It is housed in an investment casting, an aluminum investment casting. We have quite a bit of instrumentation on this battery compared to most batteries that you fly. We have individual cell monitors, 21 voltage monitors, and one battery voltage monitor. We have a current monitoring device which is a bipolar electromagnetic sensor that will sense up to 20 amps charge. It says 50 amps discharge but the scale has been expanded to 75 amps.

The temperature monitors are thermistors mounted on all of the 21 cells plus two battery thermistors which we are using now. The data I will show you later is from these two battery thermistors. We are monitoring pressure using strain gauges on each ecll. The battery is equipped with redundant heaters, photoetched heaters. The heater controllers are solid state devices.

The battery weight is 110 pounds. I might also add here that the battery was not optimized for weight, and unlike Fred Betz's battery, there was a specific reason. We are on a pallet, as I said, and we are thermally and electrically isolated from the vehicle, from the host vehicle. So we have to provide all of our own thermal control, so consequently it was decided to use a rather large mass because it was much easier to control.

(Figure 380)

I might say there were three batteries built in this program. There was a mechanical model that was used for all the dynamic testing. A thermal model battery built that we used to do all the thermal acc testing and one flight unit. We tried to handle the program as we would a normal flight battery program as far as documentation goes.

The cells were run through an acceptance test program which looks very much like ni-cad test program. We did gas leakage tests, capacity test at C over 2 rates, at various charge rates and temperatures. There was an additional test here because the system is capable of reversal and we wanted to make sure that we would get a stable condition in reversal so we added a test where we would discharge from one volt down to zero volts at C over 2. The criteria, of course, was pressure.

We ran a charge retention test, electrolyte leakage, a cycle test which consisted of six cycles, continuous cycles, and that indicates the incapacity there. And then followed by another leakage test at the conclusion.

500

(Figure 381)

The battery went through an acceptance test program. All the batteries did. A visual inspection, weight check, dielectric, thermistor, testing at the temperature ranges we expected to be working in, insulation resistance tests, stray voltage, check the current sensor, the temperature sensors, the battery capacity, the heater tests both the primary and back-up heaters for on and off operation, and then the dimensional pressure sensor calibration, C.G., and then we did an instrumentation and heater bus consumption test mainly for the systems people.

(Figure 382)

The battery was qualified as a normal flight battery would be. After completing the battery acceptance test, we ran acceleration tests at 15 g's; thermal shock tests from minus 20 to plus 115°F; random vibration at 12 g's RMS, we only did it one time. We did sinusoidal at 7.5 g's; mechanical shock at 30 g's, 1/2 sine wave; pyrotechnic shock at 2600 g peaks. We ran a thermal vat test. All of the tests down to the pyrotechnic tests were done on a mechanical model battery. All of the thermal vac tests were done on a different battery. This was mainly because we were running them parallel during this year of programming.

In the thermal-vac testing at vacuum and the various temperatures, 32, 59, and 86°F, we ran cycles at the 5, 25, and 50 amp charge rate, and the 50, 25, and 5 amp discharge rate, varying the different cycle regimes. We ran an additional cycle test in vacuum which was a simulated orbit test at 50 percent DOD. We ran 32 cycles like that. Then we ran a special thermal-vac test that was asked for by the thermal people to get enough data to predict what the battery would do in order. The testing we stated there that we did was mainly getting things like the specific heat, the charge efficiencies at the various states of charge and rates, and also came back and ran more simulated orbit cycling with a thermal shroud on the battery so that we could zero out the peak.

Before I go into the actual flight data that we have available today, I think we will take a look a little bit at what the hardware looks like.

(Figure 383)

This is the cell, as I mentioned, is a garden variety 50 ampere hour cell which I am sure you have all seen before.

(Figure 384)

The cell pack is again a standard back to back positive configuration.

(Figure 385)

This just shows the components as they go together.

(Figure 386)

This is the internal components laid out as we had them in some parbombs, doing some testing. As I said, they are standard type electrodes of which is referred to as the "pineapple slice" design.

(Figure 387)

This is just a typical curve that we put together. This is some testing that we did on some 50 ampere hour cells in-house under simulated snychronous regime. These cells were run at 100 percent depth of discharge. This shows the charge and discharge voltage curves out to 600 cycles. I think we ran out of money at that time.

(Figure 388)

We are using strain gauges to monitor pressure. This is the assembly on each cell. The signal conditioning circuitry is housed right at the site of the strain gauge rather than somewhere else in a black box.

(Figure 389)

This shows a little bit about how we are doing it. The active strain gauge is mounted on the surface of the cell. In the picture here on the left you see the temperature compensating strain gauge is mounted on a flat washer and put in a bridge network with the active strain gauge.

(Figure 390)

This represents our signal conditioning circuit that goes on top of the strain gauge.

(Figure 391)

This, of course, is just the other side of that little circuit board.

(Figure 392)

This is the battery housing which, as I said earlier, is aluminum investment casting. It has individual pockets for the cells which is a good satellite conservative thermal design.

(Figure 393)

This is a picture of the mechanical model battery in early stages. The cells are potted into the various cavities and all of the instrumentation wiring brought forward.

(Figure 394)

This is the front of the battery where the signal conditioning circuitry is. As you can see there, the two solid state computer cont rollers, there are two DC converters we use for the strain gauges, and there is some conditioning circuitry there for the various thermistors.

(Figure 395)

At the base of the battery the heater is located. Two 20 watt redundant heaters.

(Figure 396)

Showing the way the battery is wired.

(Figure 397)

And a protective cover that was put on. Incidentally, this battery on the pallet is mounted in the inverted position, covered by a thermal blanket. There is about a 4x4 inch hole right at the very center of the battery for thermal control.

(Figure 398)

This just shows the vibrations.

(Figure 399)

This is just the thermal-vac arrangement with the shroud around it.

Again, I don't have a lot of data to show, mainly because of the nature of the satellite we have not got all of the data available to us yet. We are in the

process of getting it all released and then we are going to prepare a paper and try to get in it ICC. So if anybody is interested, we will have more data on it.

(Figure 400)

This represents the beginning of the flight. Nothing really happened. The battery was on opened circuit. This just shows the temperature of the battery at launch and the cooling down. We turned the instrumentation power on at about the 10th rev to check everything out. Everything worked fine. The heater came on finally here and the temperature stabilized.

(Figure 401)

Later on at about the 52nd rev the auxillary load on the vehicle was turned on to the nickel-hydrogen bus. The nickel-hydrogen was powering the auxillary load plus boot strapping its own heater. This shows the battery voltage coming down and the cell pressure tracking quite nicely.

At that point the data coming back showed there was a cell that had gone astray, one of the 21 cells. It was thought at that time that we had a cell short. So everything was terminated at this point. The loads were thrown back on to the host vehicle bus, all the relays were open. We went back to open circuit and had a big meeting at that time. So the battery sat on open circuit for a period of time. We decided that with the data we had, we really couldn't tell what was going on and we decided to totally discharge the battery to get it back to a known reference point, recharge it, and then do some playing to see if we could see what was wrong.

(Figure 402)

That is what we did. We turned on the 5-amp load, which there was not a lot of capacity left in the battery. So in about three revs under 5-amps you can see the voltage dropping out. We allowed the load to stay on the battery for an additional two revs. What happened is we took the battery voltage down to about two volts. The pressure decayed as it discharged. If you notice right here, we hit about 50 psi indicated on the strain gauges and then we began to get a pressure rise indicating that several of the cells in the battery were in reversal and generating hydrogen. We went back up to about a 10 psi rise at that point.

We shut the battery off. We were going to start playing and then we found out that the signal we were getting was not a correct signal. There was a problem in the software in the computer and the battery was fine.

504

(Figure 403)

Rather than do anything from that point, we went back on powering the auxillary loads again and the battery just sat and cycled for a long period of time until just recently where we were able to run a controlled discharge at 10 amps which shows very good voltage regulation, pressure is very good, and temperature is also good. I think we come up to about 60 degrees from 42 degree grees. We got 47.8 ampere hours. The capacity is down simply because we never do get back to 100 percent steady charge. We specifically set the voltage limit so we only go back to about 90 percent steady charge.

(Figure 404)

We did another controlled discharge at 20 amps. The dotted line here shows the load is resistive load and drops off here at the end, and also pressure and temperature.

(Figure 405)

We have just now completed a 40 amp discharge. Again, in all cases, the voltage looks very good and so does pressure signals. Pressures are linear all the way and very predictable. They are always starting out at around 430 to 450.

Right now we have completed these controlled discharges. We are back in a standard regime and we have talked to the program people and they have now put us on to a 50 percent DOD orbit cycle which takes several revs to accomplish because we don't have that recharge power available to us all the time. But we are going to do continuous cycling at 50 percent DOD, I think, for the life of the satellite, however long that is.

DISCUSSION

NAPOLI: RCA. What is the cell weight on that? You have the mass weight but what is the cell weight?

HARSCH: I don't remember exactly. It is about three and a half pounds. But like I said, it has a 625 cell case which, if we went to the now available 718, would take about a half a pound out of the cell.

ROGERS: Hughes Aircraft. You had a spec that I can't figure out, a 21 psi discharging from one volt to zero?

505

HARSCH: That wasn't a spec, that was an actual data point.

ROGERS: On what kind of chart? The amount you get between one volt and zero would be greatly influenced by how high up you charged it, if you put in any overcharge or you didn't. I don't know what meaning it has.

HARSCH: That was done at the C/2 discharge rate from discharge to one volt, and then from one volt to zero volts on a group.

ROGERS: But what was the charge take? Was it near full charge?

HARSCH: Initially, yes, we were at full charge. It was done as one of the capacity cycles.

LACKNER: Defense Research. You said you deliberately set the voltage limit so you wouldn't get 100 percent charges. What sort of compromises were you making there? You didn't want to overheat it, you wanted to extend the life?

HARSCH: No, the compromise was they wouldn't let us do it any other way because of the satellite's main mission, they said in no way will we jeopardize the satellite. So we do everything very conservatively. They didn't want to push the battery any harder than they had to. That was the only criteria.

PASCHAL: Marshall Space Flight Center. Do you have any internal temperature measurements on your thermal vacuum test where you can measure the cold temperature?

HARSCH: No, we didn't.

RNH-50-9

CYLINDRICAL CELL DESIGN FEATURES

CAPACITY — 55 AH

CATHODE — ELECTROCHEMICALLY IMPREGNATED NICKEL ELECTRODE

ANODE — TEFLONATED PLATINUM CATALYTIC ELECTRODE

SEPARATOR — EPI RECONSTITUTED ASBESTOS

GAS SPACER — WOVEN TEFLON

CELL CASE — HYDROFORMED INCONEL 625

TERMINAL SEAL — DUAL-PLASTIC COMPRESSION

Figure 378

SAR-10005

BATTERY DESIGN FEATURES

NO. OF CELLS — 21

BATTERY STRUCTURE — INVESTMENT CASTING ALUMINUM A-356-T61 ALLOY

VOLTAGE MONITORS — 21 INDIVIDUAL CELLS 1 BATTERY

CURRENT MONITOR — B1 POLAR ELECTROMAGNETIC SENSOR (20 AMPS CHARGE - 50 AMPS DISCHARGE)

TEMPERATURE MONITORS — THERMISTORS (21 CELLS - 2 BATTERY)

PRESSURE MONITORS — STRAIN GAGE - 21 CELLS

HEATERS — REDUNDANT PHOTOETCHED

HEATER CONTROLLERS — REDUNDANT SOLID STATE

BATTERY WEIGHT — 110 LB

Figure 379

CELL ACCEPTANCE TESTS

GAS LEAKAGE TEST 10^{-8} CC/SEC @ 250 PSIG

CAPACITY TEST @ C/2

CHARGE RATE	TEMP	CAPACITY
12.5 AMP	68°F	48.8 AH
3.0 AMP	68°F	51.2 AH
12.5 AMP	45°F	51.2 AH
3.0 AMP	45°F	52.5 AH

DISCHARGE FROM 1.0 TO 0.0 VOLTS   21.2 PSIG

CHARGE RETENTION TEST   39.2 AH AFTER 48 HOURS

ELECTROLYTE LEAKAGE TEST   NONE

CYCLE TEST   52.9 AH @ 6TH CYCLE

ELECTROLYTE LEAKAGE TEST   NONE

Figure 380

BATTERY ACCEPTANCE TESTS

VISUAL INSPECTION

WEIGHT CHECK   110.0 LBS

DIELECTRIC TEST   10-20 MEGOHMS @ 250 VDC

THERMISTOR TEST @ 77°F AND 40°F

INSULATION RESISTANCE TEST   50 MEGOHMS @ 50 VDC

STRAY VOLTAGE CHECK   LESS THAN .05 VOLTS

CURRENT SENSOR TEST @
12.5 AMPS CHARGE, ZERO
AND 25.0 AMPS DISCHARGE

TEMPERATURE SENSOR TEST @
40 AND 77°F; EXCITATION VOLTAGE
24, 28.5 AND 33 VDC

CAPACITY TEST @ C/2   68°F - 50.0 AH
                                    40°F - 51.7 AH

HEATER TEST   PRIMARY HEATER ON - 41°F
                                    BACK-UP HEATER ON - 36°F
                                    BACK-UP HEATER OFF - 38.6°F
                                    PRIMARY HEATER OFF - 44.3°F

DIMENSIONAL CHECK

PRESSURE SENSOR CALIBRATION CHECK

C.G. DETERMINATION

INSTRUMENTATION & HEATER BUS POWER CONSUMPTION CHECK

Figure 381

BATTERY QUALIFICATION TESTS

ACCEPTANCE TESTS

ACCELERATION TEST	15 G FOR 5 MINUTES (3 AXES)
THERMAL SHOCK	-20°F TO +115°F
RANDOM VIBRATION	12 G RMS FOR 5 MINUTES (3 AXES) 0.1 G^2/Hz
SINUSOIDAL VIBRATION	7.5 G FOR 25 MINUTES (3 AXES)
MECHANICAL SHOCK	30 G; 1/2 SINE WAVE; 11 MS
PYROTECHNIC SHOCK	2600 G PEAK ACCELERATION; 200 – 10^{-4} Hz

THERMAL-VAC PERFORMANCE TEST   10^{-4} TORR @ 32°, 59° AND 86°F

CHARGE	DISCHARGE
5.0 AMPS	50.0 AMPS
25.0 AMPS	25.0 AMPS
50.0 AMPS	5.0 AMPS

THERMAL-VAC CYCLE TEST   10^{-4} TORR @ 40°F
30.0 AMP CHARGE FOR 55 MINUTES
42.8 AMP DISCHARGE FOR 35 MINUTES
32 SIMULATED ORBITS, 50% DOD

SPECIAL THERMAL-VAC TESTS   INSTRUMENTATION POWER DISSIPATION
HEATER CALIBRATION
SPECIFIC HEAT MEASUREMENT
CHARGE EFFICIENCY VS.
   TEMPERATURE
   STATE-OF-CHARGE
   CHARGE CURRENT
SIMULATED 90 MINUTE ORBIT CYCLES

Figure 382
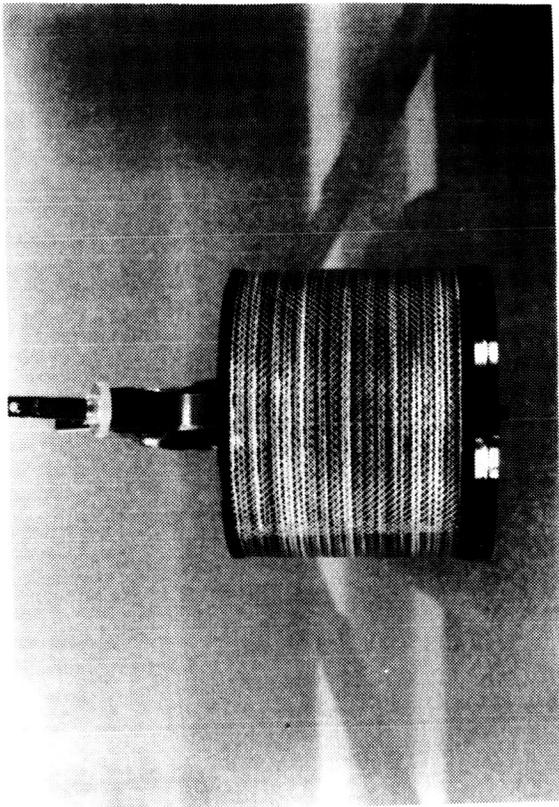
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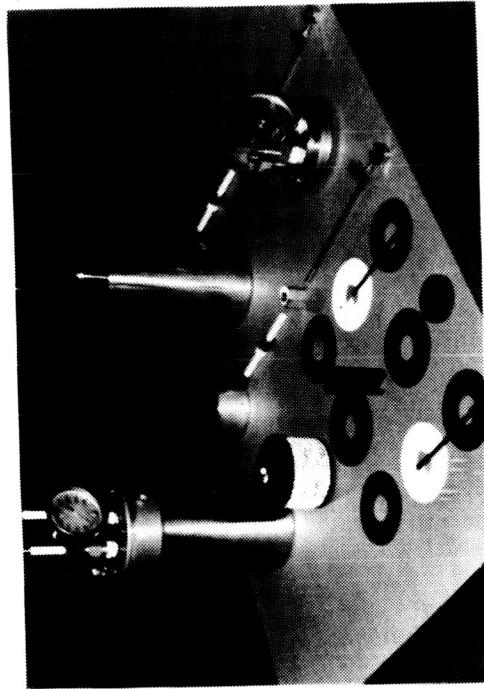
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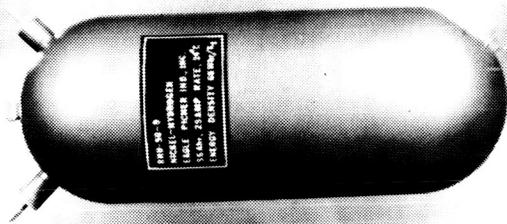
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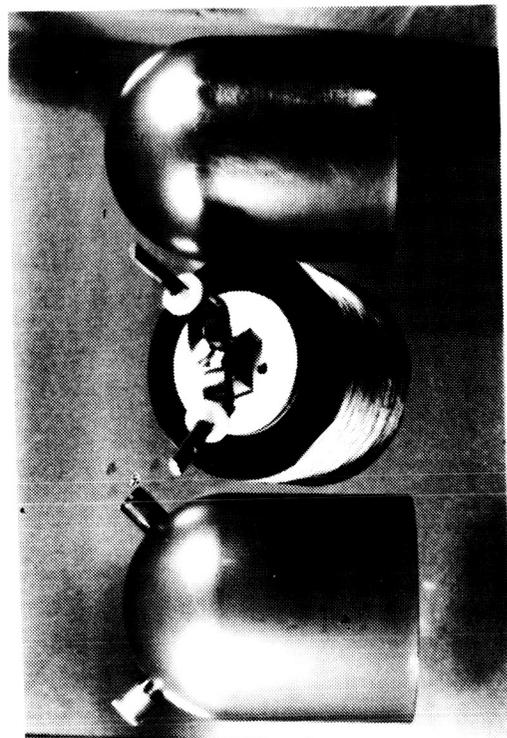
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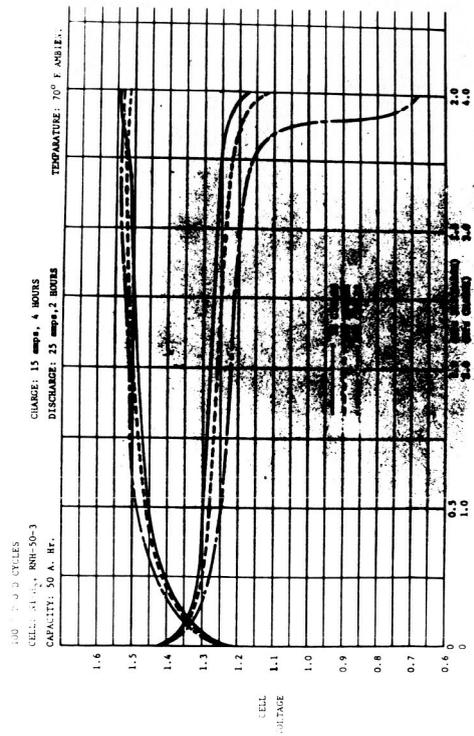
Figure 388

Figure 387
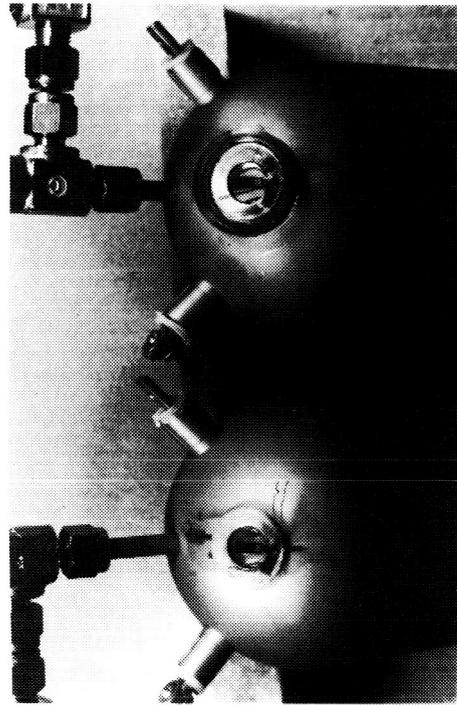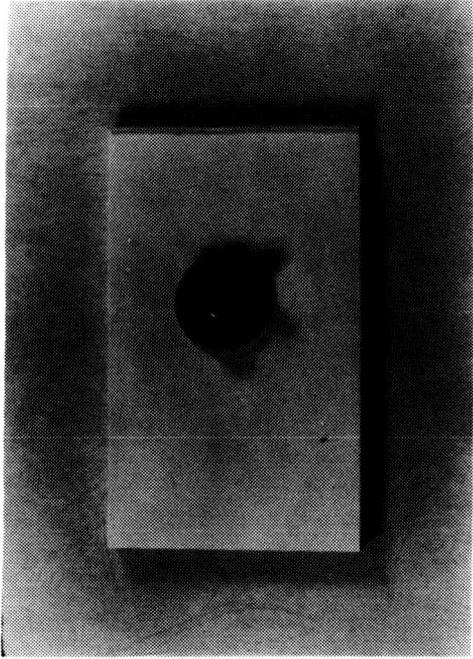
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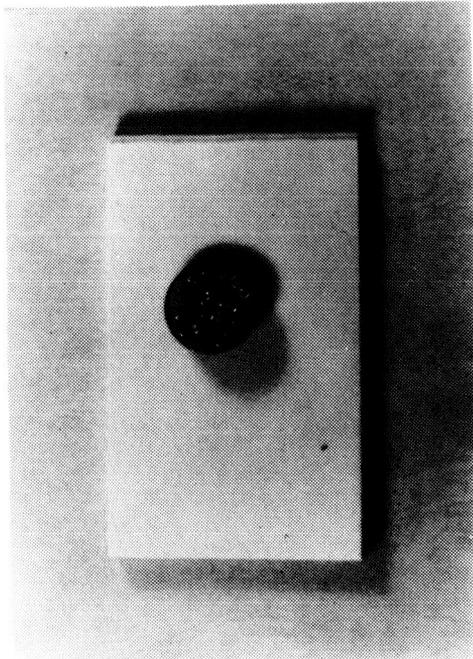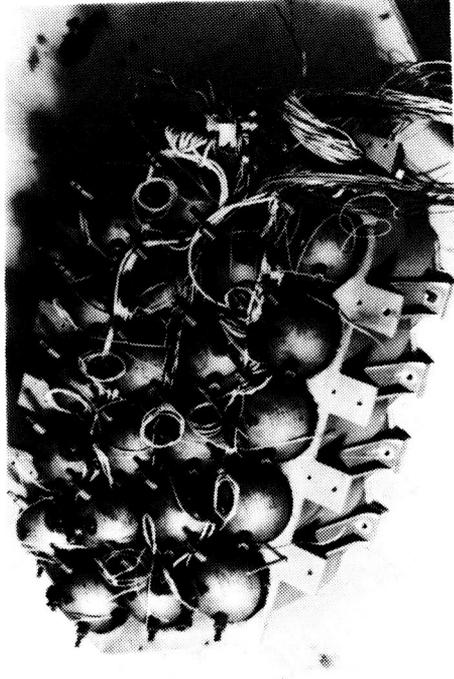
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Figure 390

Figure 392

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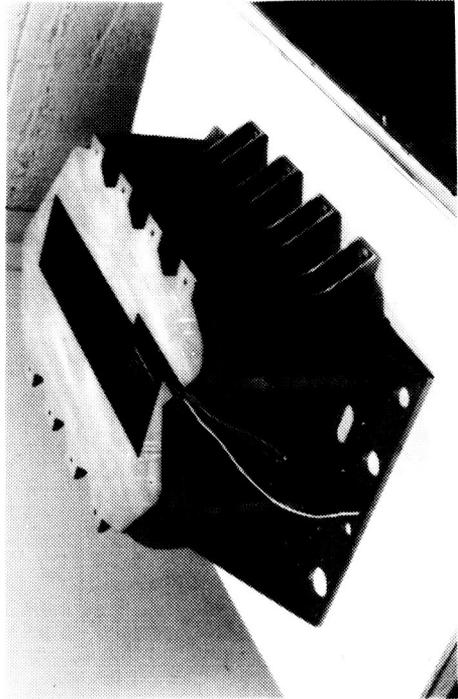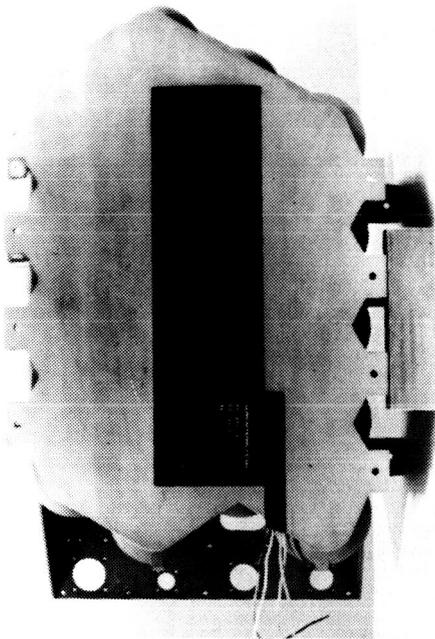
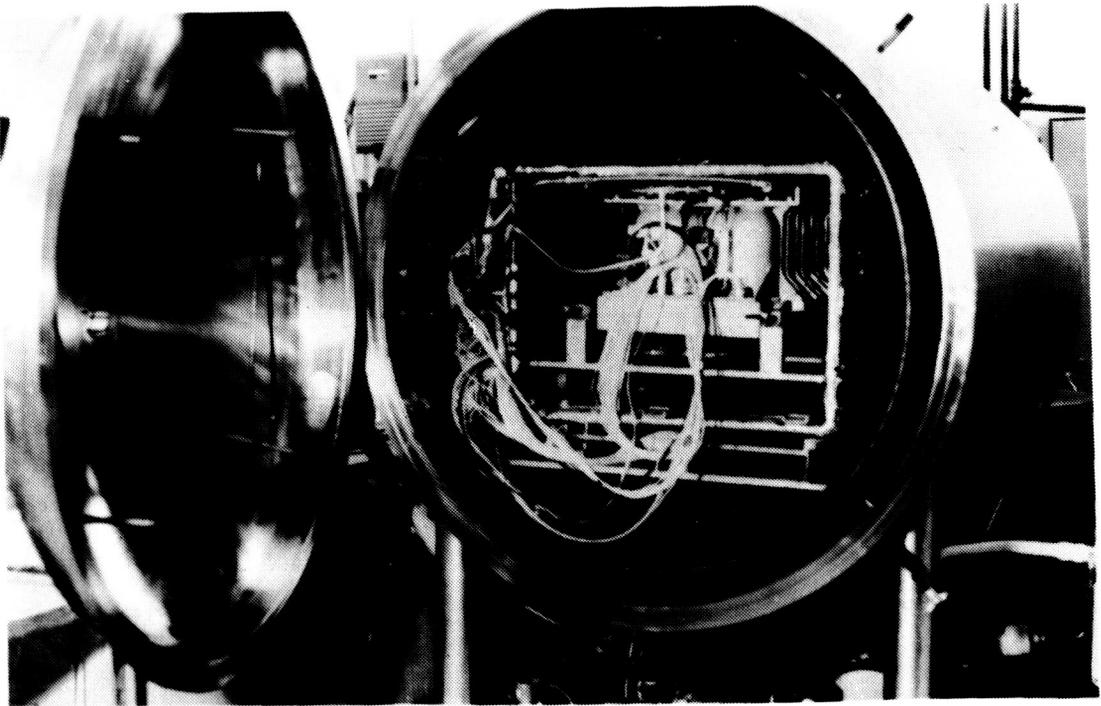Figure 395

Figure 397
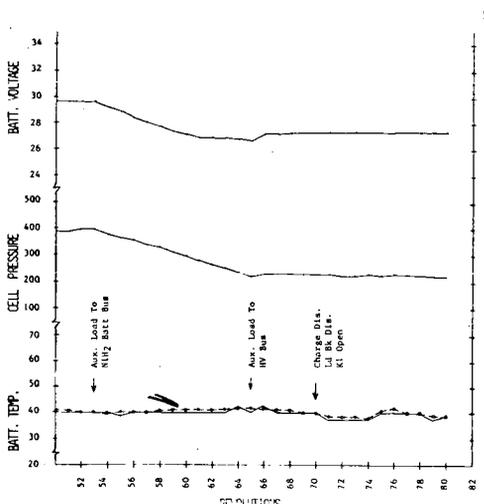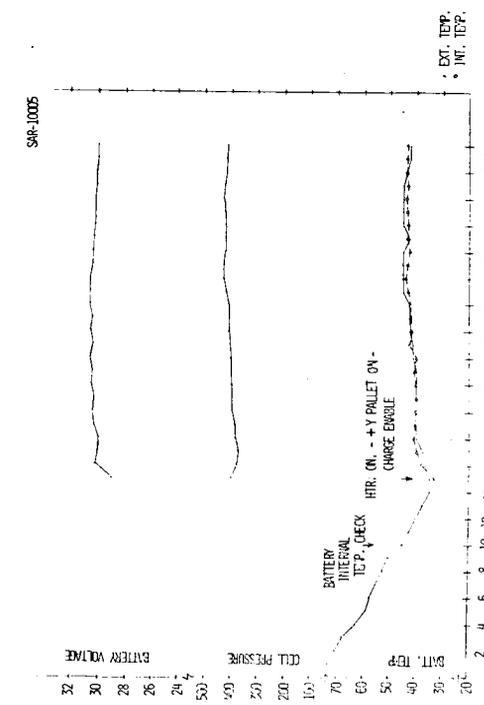

Figure 394

Figure 396

513
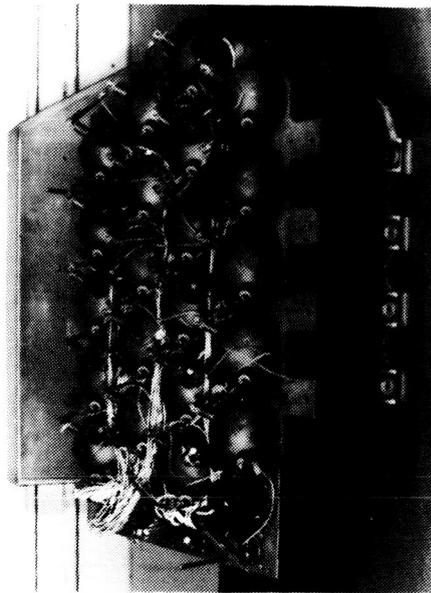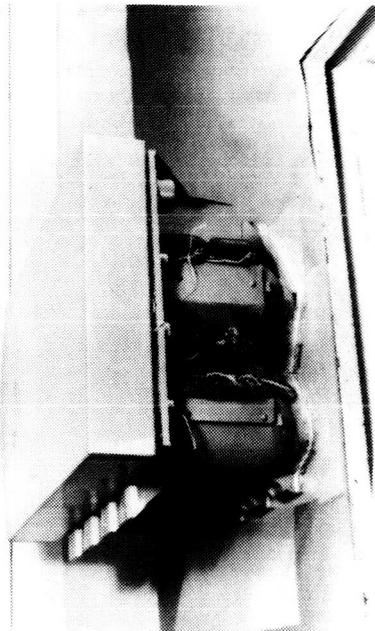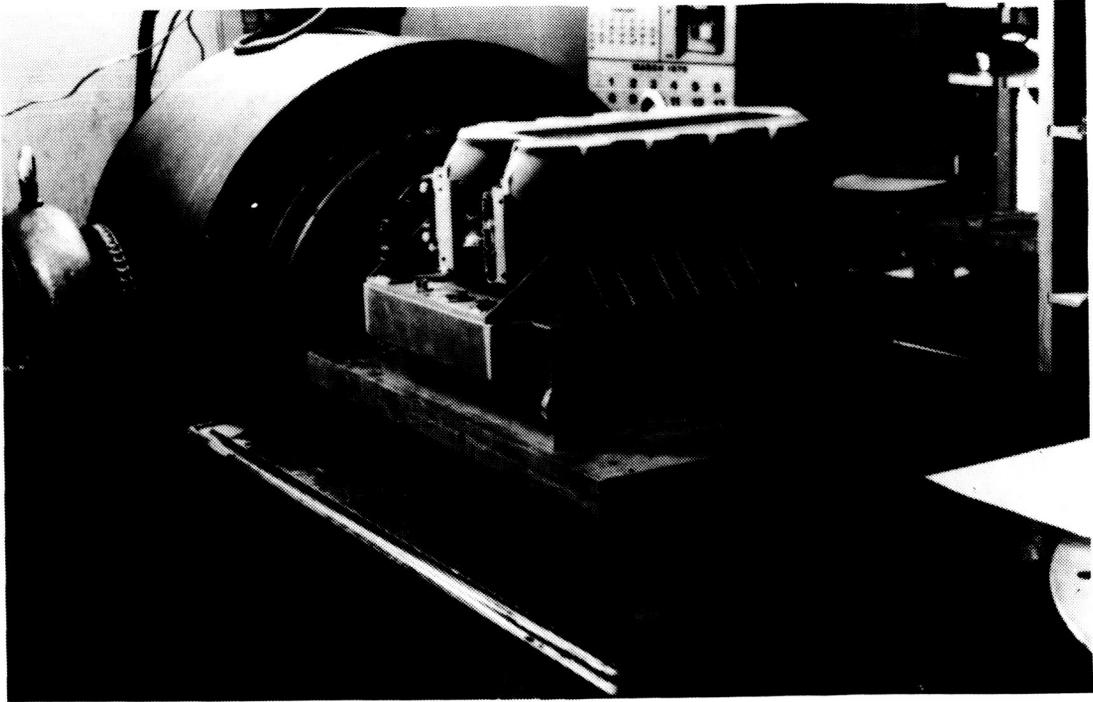
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Figure 399
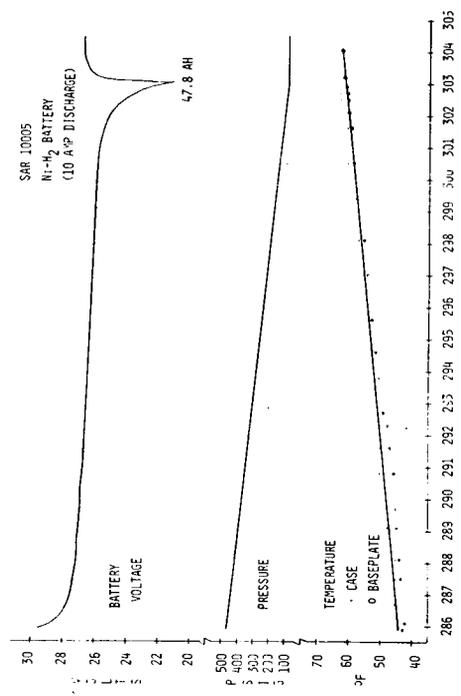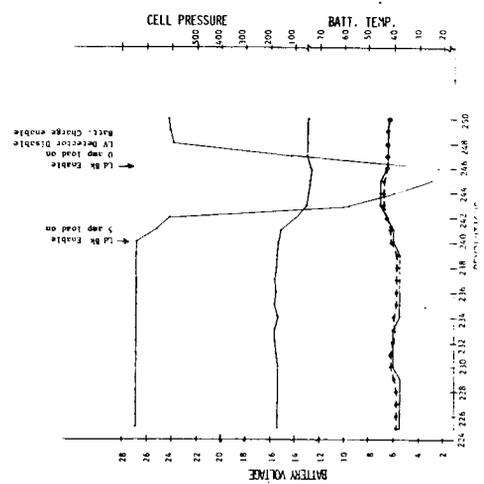
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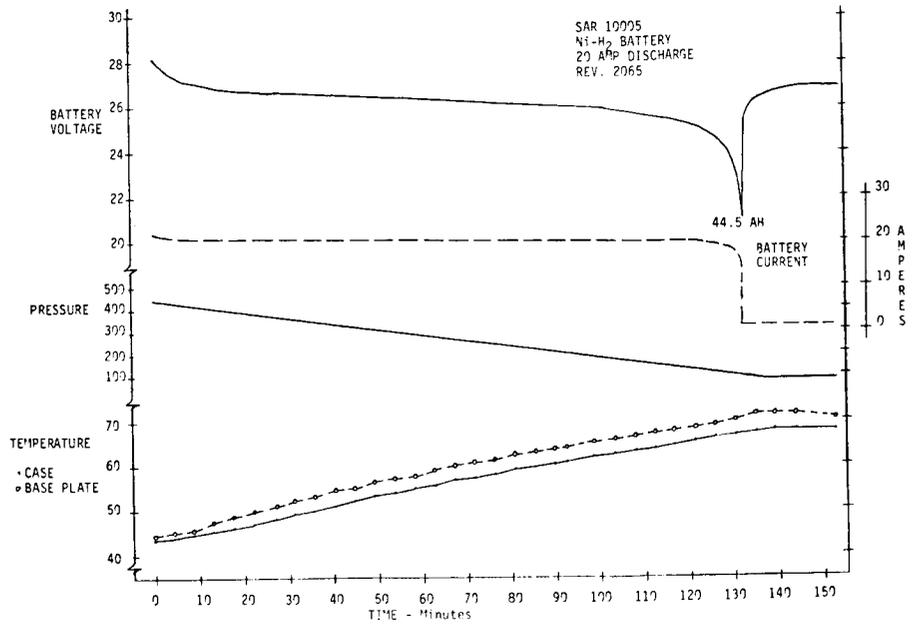Figure 401

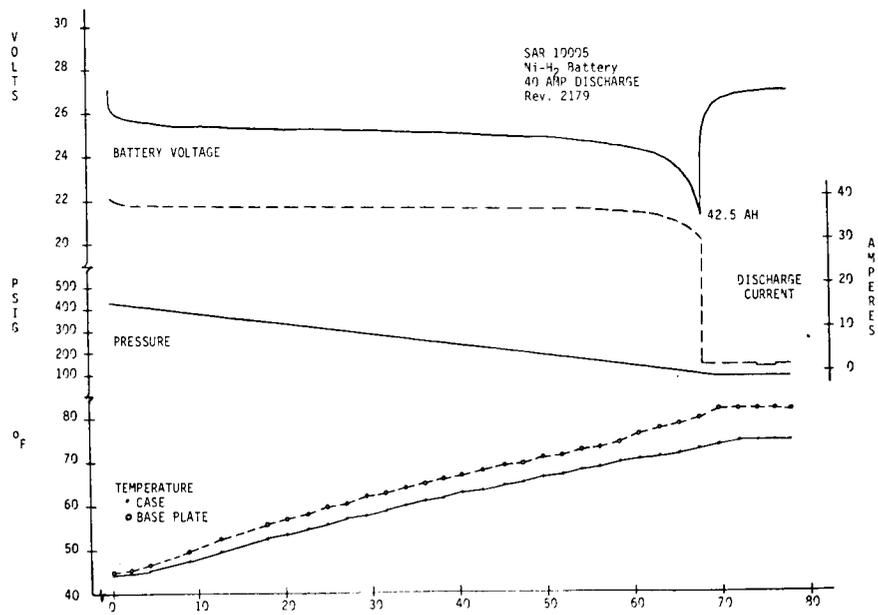Figure 403

Figure 400

Figure 402

Figure 404

Figure 405

516

AIR FORCE NICKEL-HYDROGEN TEST PROGRAM

M. Gandel
Lockheed Missiles and Space Company

The mechanical model which Bill Harsch described in his presentation is now at Lockheed. The Air Force loaned it to us for test purposes. The plan is this. First we are flying 60 ampere hour ni-cad batteries in some of our low earth orbit missions. My intent is to subject the battery, after using all of the instrumentation that is available on it, to the same low earth orbit cycles that we subject the 50 or 60 ampere hour ni-cads to. Hopefully there demonstrate real differences on a system level between the two batteries.

We would vary the thermal environment to simulate what we might see on flight and also vary the criteria for charge control. The charge control scheme is a little bit open because you can't exactly simulate charge control that you are using with the ni-cad battery, but as close as we can we will do that simulation comparison.

The next thing I want to do is to increase the depth of discharge. That is, if possible subject the one nickel-hydrogen battery to the same kind of regime we might subject to the ni-cads, or whatever the proportion happens to be. And then continue testing until we noticed some failures or until some degradation or spread between cell performance is demonstrated.

We would also be looking at different charge control modes and the plans have not been totally firmed up yet, but the general idea is to be able to demonstrate a reasonable life. Again, these cells are not the most advanced technology, but mainly to be able to show some real comparisons on energy density so that we have the wherewithal to sell a new program manager on the virtues of nickel-hydrogen over nickel-cadmium. All indications, everybody is becoming very positive, the MDAC and Grumman trade studies are encouraging for nickel-hydrogen. It seems that the ni-cad guys aren't getting any more optimistic with time. In fact, I sensed a note of pessimism. I can only say their pessimism is our nickel-hydrogen encouragement.
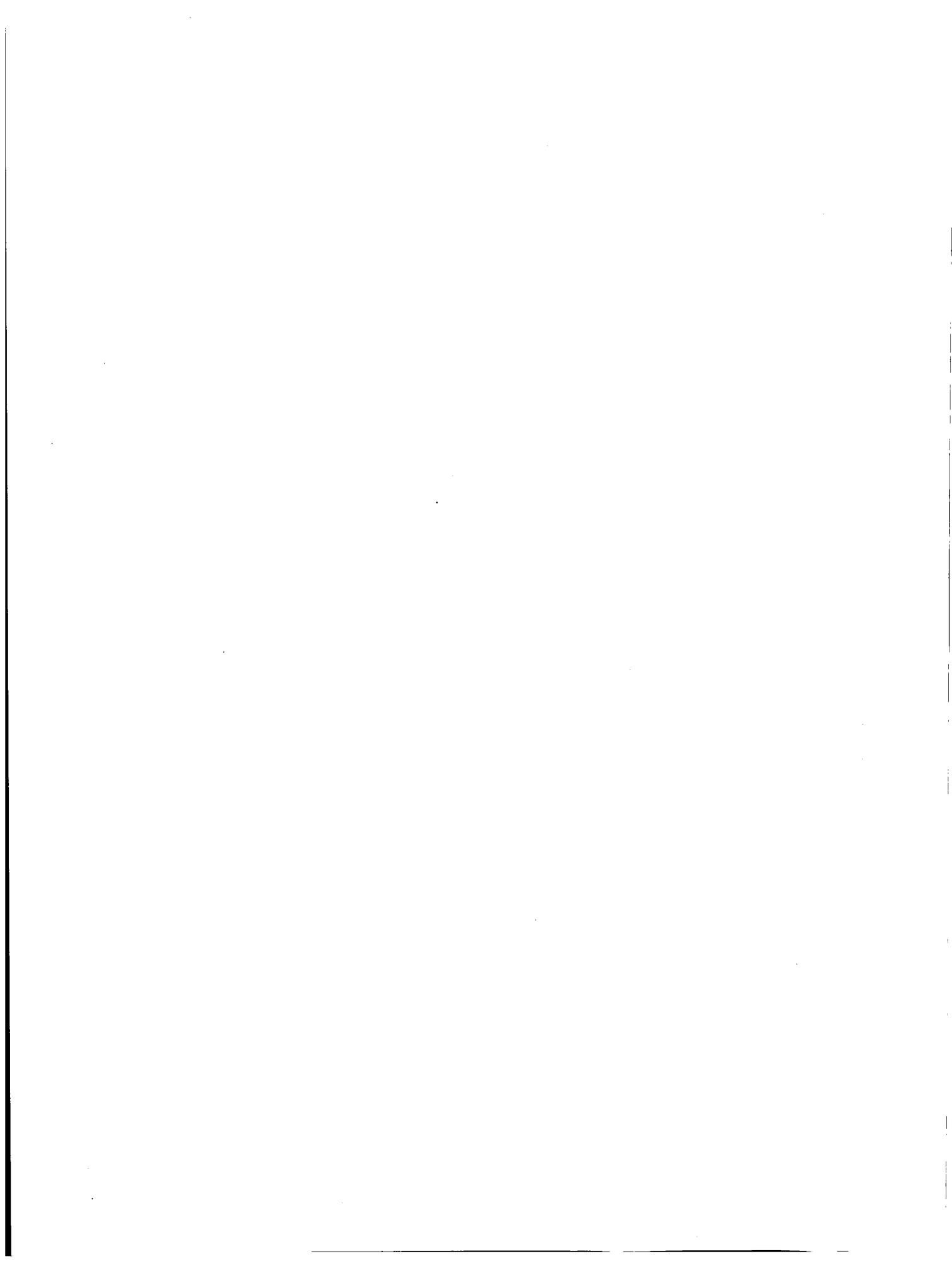
MULTISTACK NICKEL-HYDROGEN UNITS

J. Smith
Eagle-Picher Industries

This morning I would like to briefly introduce you to what we are doing at Eagle-Picher with our multistack design.

(Figure 406)

When I say multistack, I am referring to, as Bill Harsch showed in some of his pictures, those patched for putting more than one pack inside one container. These two cells up here we built under contract to Rockwell, and with the aid of Lloyd Barnett we are going to test these in the upcoming future. Hopefully, real soon. I had hoped to have some data by this time, but presently we are still waiting to get testing equipment.

The cell on the right is a two stack design. It is in our typical 625 Inconel pressure vessel. It looks like a monster. It has got a lot of monitoring on it. It has got four thermal couples in it and it has got voltage taps, not only for the cell, but also for each stack internally.

The one on the left is a four stack design. This is building our pressure vessel.

(Figure 407)

We like to use a pressure vessel. It is easy and it is accommodating to our purposes. As you can see, this is slightly larger than our whole cell. This piece right here, this small, is a volume compensator. With a power bomb where we avail ourselves or give ourselves the ability to take this apart and examine it, tear it up, replace things, and actually change the volume from time to time if we deem it necessary.

There are four stacks in this. They are separated mechanically with about half inch Plexiglas. They are all connected through the center. These are pineapple designed electrodes connected at the top. Those little curlicues you see at the top are voltage taps we run out to monitor during testing as well.

(Figure 408)

This is a figure of our two stack design. It is a little different. They are separated by our weld ring. They are joined together, they form one solid group. It is a somewhat complicated procedure to put this all together. I am sure in the future we can come up with a lot better design, but right now we are chasing the feasibility of actually working or not. We don't have a lot of data; what little data we do have is from activation. In activation, we see a problem may exist, I don't think in the testing of it. We see the capacities there with each stack. With activation we see possibly electrolyte shorting.

(Figure 409)

This rough figure is showing the first four charges, that is what the numbers indicate, the first four charges after activation. We activate these cells. One of the advantages of nickel-hydrogen you know is in activating it, you can flood the cell and thereby remove some of the carbonates. Well, with multistack configurations, you aren't able to charge the cell and force the electrolyte out. You must do it by a vaccum. As a consequence, you leave a lot of electrolyte in there, and you have small shortings from the start. You see with each successive cycle, or nearly so, we increase the capacity.

We saw that this being a four cell stack design, the internal stacks were real short, the first stack, the bottom stack and the top stack, kept the voltages well. The two internal stacks showed signs of shorting. As a matter of fact, on charge retention tests they dropped real low on their voltage after inducing a small bit of charge. With increased charging we saw this burn out and they gradually picked up, we think we can develop some sort of charge schematic, we can burn these electrolyte shorts off or possibly develop a better type of activation system.

I guess for now I would like to express that we are doing a lot of work with this and we hope to do a lot more work in the future. We think this is something that could be optimized. It offers the advantages of reducing the weight and it also may lower the cost. Obviously, when we use one cell instead of three or four it is going to reduce some costs. We have the ideas in mind now. We need more than ideas in somebody's pocket.

DISCUSSION

BETZ: You say you have electrolyte shorts, do you mean you can't run current through these center cells or you do run current through but it doesn't do anything?

SMITH: We do but they are stray shorts. I assume they are loose electrolyte, floating electrolyte, and mechanical bridging, electrolyte bridging, in different stacks.

BETZ: Between stacks?

SMITH: Correct.

ROGERS: Hughes Aircraft. When you designed these cells, did you do anything to avoid electrolyte bridging between cells in the stack?

SMITH: We did some. We didn't enhance it greatly. That is part of my comment in that it can be designed better. The separation is mostly mechanical in nature in distance. Like I say, it is a half inch between stacks. That is quite a little distance to be having shorts.

ROGERS: How far from the walls?

SMITH: The Plexiglas goes almost 40 mils, I think, from the can wall.

ROGERS: No. How far is the edge of the positive or negative plate to the can wall?

SMITH: It is roughly, I think, 90 mils, something like that, between 90 and 150 mils. The positive is a little bigger than the negative. The other part is a lot closer to the wall, or separation. We keep our physical separation very close.

BETZ: Do the separators themselves actually touch the wall, do you know?

SMITH: No, they don't. Not the plate separators, but the separation from stack to stack, the mechanical separation between stacks. It is very close. It doesn't touch the wall, but it is much closer.

BETZ: I mentioned before that in our cells you could draw quite a bit of current off the case. I think the reason for it was that our separator might have been physically in contact with the wall and you had an electrolyte path there. That has been substantially reduced. I might comment that both of the problems in our cells that I mentioned, the terminal and the high current, were problems solved before flight.

FORD: Goddard. What type of pressure? What are you talking about; 500, 1000?

SMITH: On the two stack design? We designed that for 500 psi, although we would see 600, and we typically pressure tested up to 1,000.

FORD: Would you like to comment on what the limitation is on multi-stack design? I mean, if you go three, isn't the pressure going to go up according to the number of stacks? Might you see a 2,000 pound pressure container, if this comes up to be proven?

SMITH: Your pressure is going to be directly related to your volume. It is going to be the same amount of space for the same amount of hydrogen evolved. I mean, if I have a 25 ampere hour cell with two stacks in it, it is going to create just as much hydrogen as a 50 ampere hour stack by itself, singular. So we aren't talking about great volume reduction at all. It doesn't change that property in any way.

HELLFRITZSCH: What are you trying to achieve then? I am confused. Apparently they are parallel cells.

SMITH: The stacks are connected in series.

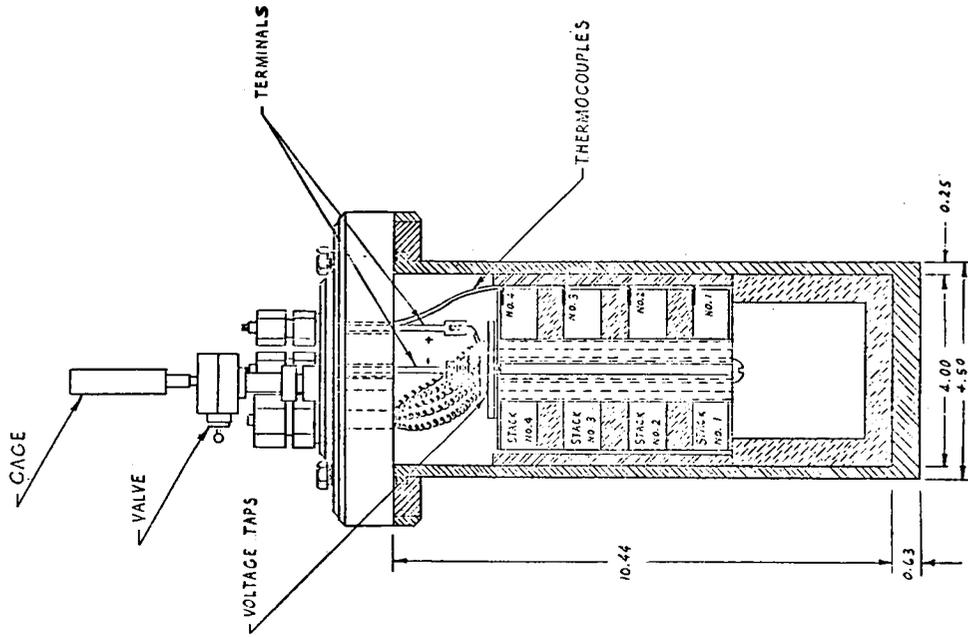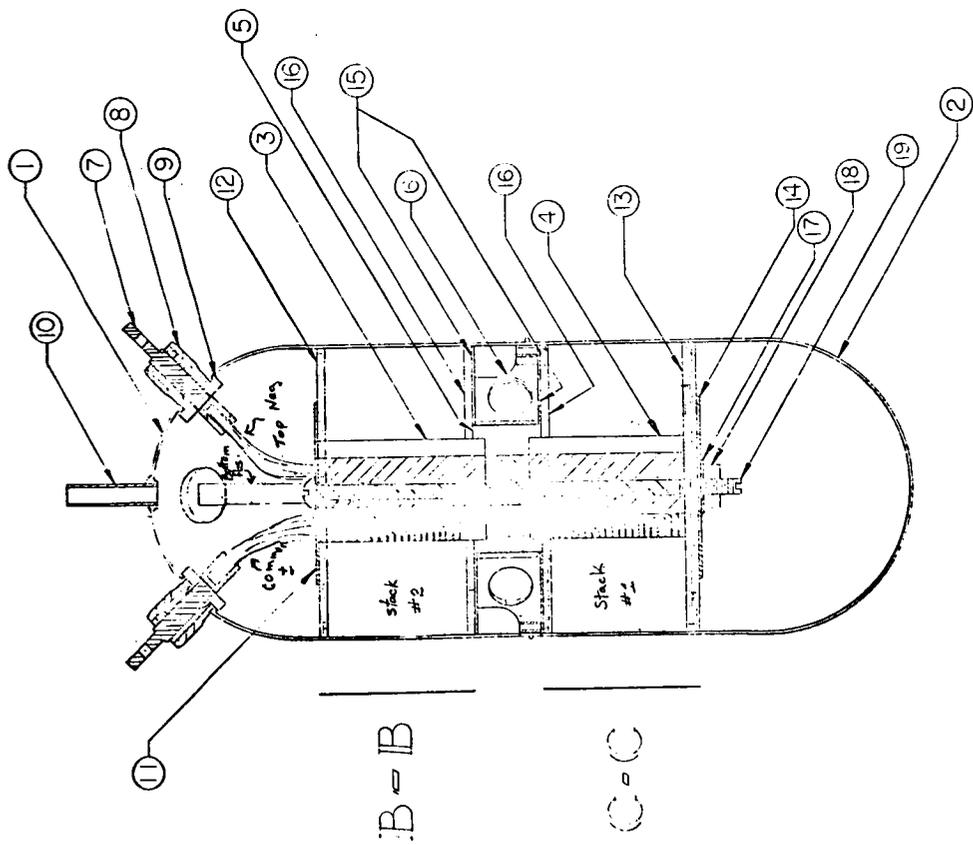Figure 407

NOT AVAILABLE AT TIME OF PRINTING

Figure 406
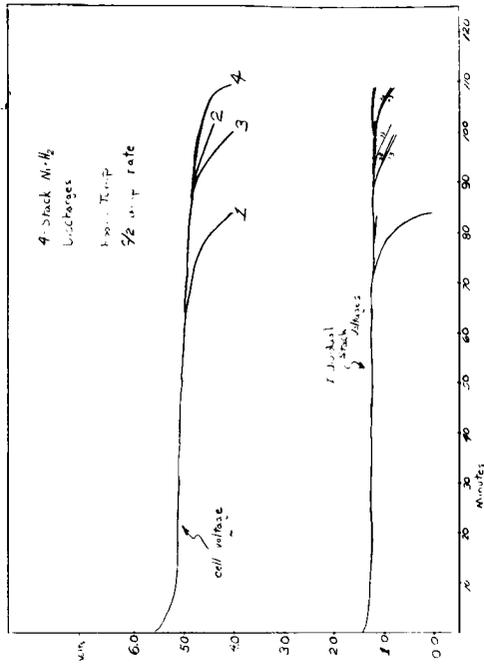
523

Figure 409

SECTION 'A-'A
SC-LE-FULL

Figure 408

524

SELF DISCHARGE OF NICKEL-HYDROGEN CELLS

G. Holleck
EIC Corporation

I want just to shortly tell you something about the self-discharge behavior of nickel-hydrogen cells. From this we obtain not only values for the capacity loss with time, naturally on open circuit stand, but also information regarding the minimum amount of circuit charge that you have to introduce to keep the cell charged. Furthermore, the rate of reaction between hydrogen and a charged nickel electrode is also open for nickel-cadmium batteries.

In a nickel-hydrogen cell, the hydrogen is stored as pressurized gas and the cell stack with the charge that is oxidized nickel-hydroxide electrode is in direct contact with the hydrogen. Therefore, the rate of reaction can be measured easily and precisely by monitoring the charge, the change in hydrogen pressure with time. We have carried out such measurements on twelve 15 ampere hour nickel-hydrogen cells of different stack configurations which we have built for COMSAT on an INTELSAT contract.

(Figure 410)

HOLLECK: Let me show you typical pressure time curve for a nickel-hydrogen cell with a 500 psi upper pressure limit.

(Figure 411)

I will show you the same type of behavior basically for a cell which has an upper pressure limit of 1,000 psi. We have actually carried it beyond the 400 hours, but it just continues.

When we analyzed this data, what we found is that it is first order in hydrogen pressure reaction rate and it is independent of the state of charge which is remarkable.

(Figure 412)

So it follows a rate relationship, rate equation, that I have denoted here of the change of the mode of hydrogen with time proportional to a rate constant and the hydrogen pressure. It seems to be independent of everything else. With the idea that you can conform it to this equation and by integration you obtain the lowest equation which tells you if you have a behavior that follows this

rate equation. What you should find it a plot of logarithm of P, hydrogen pressure, versus time should give you a straight line with a slope of K RT over V.

(Figure 413)

Now here I have plotted the hydrogen pressure of the two cells that I have shown you, and the others follow the same way, on a log pressure versus time curve. You see they very nicely follow a straight line. I may mention here that the higher pressure cell is actually the same capacity as the lower pressure cell and it has a higher precharge, 450 psi precharge, to life it up. That means at the end of the 400 hours this cell is practically completely discharged.

(Figure 414)

Now the result of this is a rate constant of 1.3 times 10^{-6} modes per hour atmosphere and ampere hour. If you now think of what type of reaction might be rate limiting in this process, the first thing you want to consider naturally is diffusion. You have diffusion, for example, of hydrogen to the nickel electrode. If you do that, you have to realize that even if you completely protect the backside of the nickel electrode, the furthest away you can get from hydrogen is the thickness of your separator. So I calculated the rate of hydrogen diffusion from literature values of diffusion coefficient and solubility for diffusions through a 10 mil KOH layer. What you find is that the rate should be two orders of magnitude higher than what we find here.

What this means is diffusion in the electrolyte cannot be the limiting factor. This again is in agreement that we found the same rate of cell discharge whether the cells had a reservoir or did not have a reservoir, just doesn't make any difference. Diffusion in the solid material is also difficult to find a model which is independent of the state of charge of material. The most probable mechanism is some kind of an interface reaction that is the limiting case.

I might mention here that it is proportional in hydrogen, which is somewhat different from, for example, the dissolution of hydrogen as a hydroxide into cadmium, for example, where it is proportional to the square root where the atomic H is the governing factor.

(Figure 415)

What does that mean in practical cases, for example? This means for an average battery, let's say, with 500 psi, 34 atmosphere upper pressure, approximately 10 percent loss in one and a half days, or 50 percent capacity

loss in 10 days, or 90 percent loss in 27 days, just to give you some feeling for this self-discharge rate.

I should mention also, I noted it on previous figures, that this is calculated with the 1.3 times 10^{-6} rate constant which is measured for fresh cells. We have also measured the rate of self-discharge on cells that have been cycled, and it decreases with cycling.

The minimum rate of trickle charge to maintain the capacity can calculate from this value and it would be for a 500 psi cell about $C/430$. With respect to nickel-cadmium cells, you have heard about the hydrogen recombination over discharge. There you have a different mechanism. There you have the reaction of hydrogen with cadmium electrode, which is cadmium hydroxide. But if you have a cell which runs out of this cadmium reserve and becomes cadmium electrode limited and on overcharge involves hydrogen at the cadmium electrode, then the only mechanism to get rid of this hydrogen is by reacting it with the nickel-hydroxide in the other side. This reaction, at a pressure of two atmospheres, about 30 psi, would be about $C/7,000$. So this is a very slow reaction and you do invariably, if you get into that mode, accumulate hydrogen pressure in the cadmium exercise.

BETZ: I think we have all seen higher self-discharge rates in nickel-hydrogen. I know we did. Ours weren't necessarily all that uniform. It had us going a little bit for a while, but we did see it.

DISCUSSION

KIPP: SAFT America. I had one back on yours. One of the questions I had was just for curiosity. On your NTS-2 spacecraft, you are using your nickel-hydrogen as a primary battery. How are you treating your nickel-cadmium backup battery during this period of time?

BETZ: We are treating it as the prime power source. It is a secondary battery.

KIPP: How are you using it then?·

BETZ: The nickel-cad battery is on trickle charge when the nickel-hydrogen battery has received its full charge. It is during the eclipse operation. When we come back into sunlight, all the available charge current is first directed to the nickel-hydrogen battery to recharge it. If there is excess current available, it will recharge the nickel-cadmium battery. Other than that, we

maintain the nickel-cadmium battery in tripe charge mode in back of it. We tried to heat up the satellite with nickel-cadmium once and succeeded. We had nickel-cad up to 63°C, but it still looks good, it has cooled back down.

KIPP: Can we assume that your nickel-cadmium battery plays no role during eclipse seasons then, or does it play some role?

BETZ: The nickel-cadmium battery plays no role during the eclipse season. It will only come into play if we have a problem with nickel-hydrogen. It is on the line, electrically on the line. If the nickel-hydrogen battery voltage drops below 14 volts, the nickel-cadmium battery will support the load.

SEIGER: Yardney. I wonder if Dr. Holleck would like some immediate reconfirmation of this data?

HOLLECK: Go ahead.

SEIGER: There was some data that Geena and Dunlop published in 1975. They had a self-discharge of the nickel-hydrogen system there. I went through the same kind of analysis as you did. I came to the same first order of conclusion. I think even the recombination constants are about the same order of magnitude. I can go back and check that. I have been looking at it a little further. I have been looking at it even in nickel-zinc cells in which you can add hydrogen to the nickel-zinc cell and actually see the recombination. I flooded them out. I still see the hydrogen recombination. I have the effect of the flooding.

ROGERS: Hughes Aircraft. You mentioned that you saw a change in the recombination rate as a function of cycling? I wonder what that is specifically and how many cycles.

HOLLECK: After 500 cycles of 80 percent depth of discharge we measured at rate of cell discharge which is almost high initially. It is a sizable change. It may actually give us, when we understand it better and what its mechanism is, some insight also on what is happening with the positive electrode because it obviously is a reflection of changes at the positive electrode. After recycling, you don't see any change in voltage behavior or capacity. So the normal cell performance does not change, but obviously something does change.

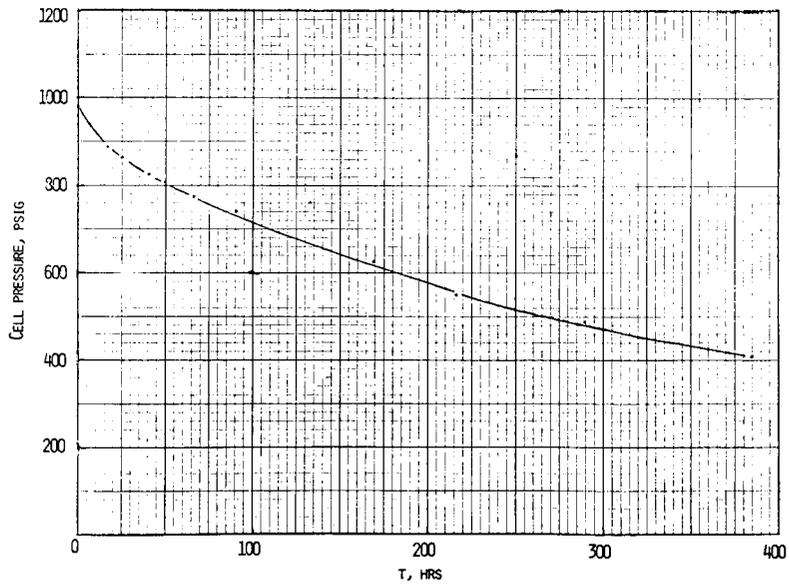ROGERS: What kind of cycles were those?

HOLLECK: Those were three hour cycles to 80 percent depth of discharge.

BETZ: This data may be useful for users of nickel-hydrogen to establish a beginning of life test. For instance, a self-discharge rates, since they are fairly predictable.
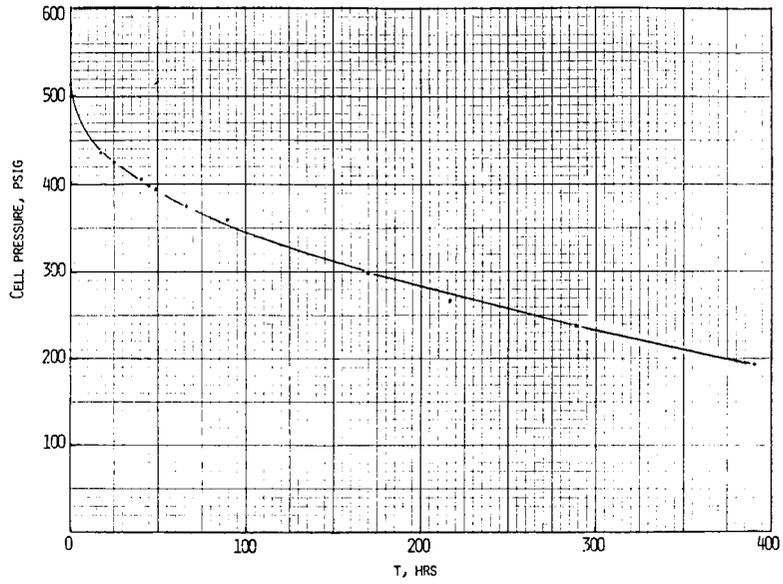
Self discharge of Ni-H$_2$ cell No. 1 @ 21°C.

Figure 410

Self discharge of Ni-H$_2$ cell No. 12 @ 21°C.

Figure 411

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Logarithmic plot of cell pressure vs. time during self discharge, 21°C. Upper, Cell No. 12; lower, Cell No. 1.

Figure 413

PRACTICAL IMPLICATIONS

CAPACITY LOSS P_{MAX} = 34 ATM (500 PSI)

10%	~ 1.5 DAYS
50%	~ 10 DAYS
90%	~ 27 DAYS

MINIMUM RATE OF TRICKLE CHARGE TO MAINTAIN CAPACITY

$$C \Big/ \frac{10^5}{7 \cdot P_{MAX}(ATM)}$$

P_{MAX} = 34 ATM (500 PSI) $\approx$ C/430

H_2 CONSUMPTION IN Ni/Cd CELLS
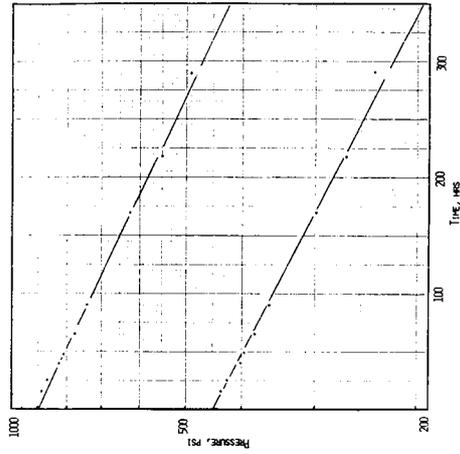
P_{H_2} = 2 ATM < C/7000

Figure 415

$$\frac{dn_{H_2}}{dt} = -k \, P_{H_2}$$

$$n_{H_2} = \frac{V}{RT} \cdot p$$

$$\frac{d \ln p}{dt} = -k \frac{RT}{V}$$

$$\log p = \log p_o - k \frac{RT}{2.3V} t$$

Figure 412

RESULT

SELF-DISCHARGE RATE CONSTANT (FRESH CELLS)

$$K = 1.3 \pm 0.3 \cdot 10^{-6} \text{ MOL HR}^{-1} \text{ ATM}^{-1} \text{ AH}^{-1}$$

SUGGESTED MECHANISM:

INTERFACE REACTION OF H_2
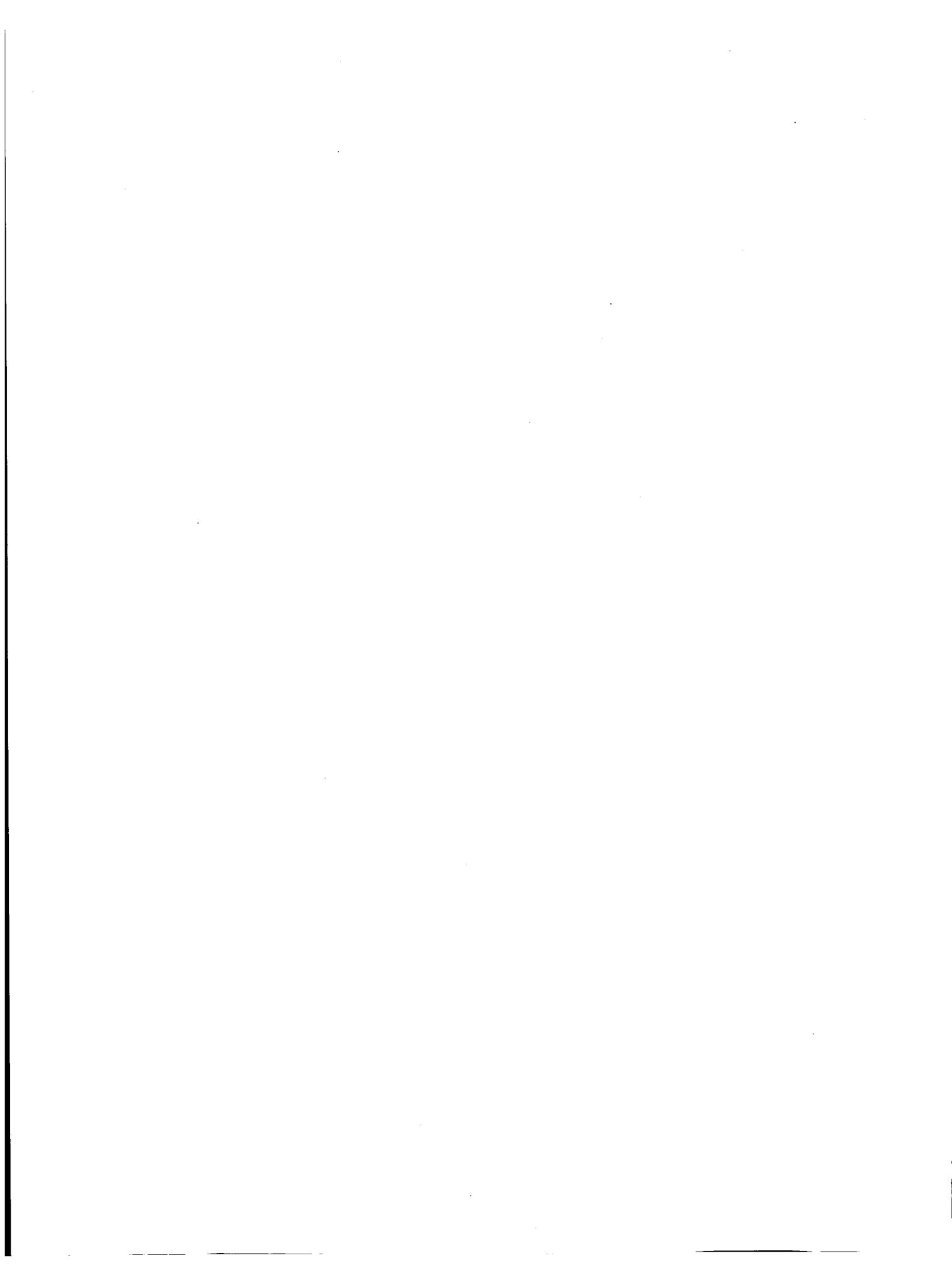
Figure 414

NICKEL-HYDROGEN

E.J. McHenry
Bell Telephone Laboratories

Some of the figures include material that you all know about.

(Figure 416)

This we assume everybody knows.

(Figure 417)

This figure just shows the pressure goes up if you charge it up and goes down if you discharge it.

(Figure 418)

There is great advantages to the nickel-hydrogen system and we all know what they are.

(Figure 419)

There are a few disadvantages. Essentially, what it comes to is you can have lots of volume and little pressure or lots of pressure and little volume.

(Figure 420)

This is reprinted from the Phillips material. Everybody has probably seen this one, too. Obviously, there are a number of these hydrogen absorbing materials. This is $LaNi_5$. They will absorb a considerable amount of hydrogen at an essentially constant pressure. As the temperature rises, that pressure plateau rises, but even at 81°C, that is probably about 220 pounds or something of that kind, which is not really outrageous.

(Figure 421)

This is a new design of cell. The problem with the $LaNi_5$ and all those materials, they tend to disintegrate as the lattice expands on absorbing hydrogen, the metal cracks into a very fine powder and it is difficult to fabricate electrodes and all that sort of stuff. So we have designed a cell here which is very similar

to nickel-cadmium. We have a positive electrode which is wrapped in a micro-porous separator, and then the leads are insulated also so that there is no way for anything to get at the positive electrode or any of the leads.

Then you put in a negative conducting grid and this is welded to your terminals. You then weld the top of the can into an open ended container and we turn it upside down and fill it full of lanthanum nickel powder. The negative material is just the lanthanum nickel powder. It has no structure. It simply occupies all the space that is not occupied by the rest of the components. Then we weld on the bottom of the can. We have a fill tube either on the bottom or the top of the can.

When it is welded shut, we put the cell into a pressure bomb and activate the lanthanum nickel at about 1,000 pounds of hydrogen. Now this is necessary, otherwise the material doesn't absorb and desorb. It tends to expand a little on this so this further fills the can and leaves no empty spaces.

Then we have to add electrolytes to the cell, pump it down and add electrolytes, then we add whatever amount of hydrogen precharge you want, seal it off, and we are ready to go.

(Figure 422)

These are advantages. We don't have to fabricate a negative electrode. It is just the cost of the actual hydrogen absorbing material. You can pour this material down a hypodermic needle, it flows very well. So there is not much problem in putting the cell together. You save all the trouble of fabricating a negative. There is no binders or anything of that kind which sometimes tend to interfere with the electrochemical function of the cell. You don't have to change the design of this cell if you want to change your absorbant. You can put anything in there. As a matter of fact, you can even throw in cadmium of zinc or something like that, and see how it works in that case. It does work as a nickel-cadmium, I never tried the nickel-zinc.

(Figure 423)

This shows the discharge of this type of cell as compared with a nickel-cadmium cell. They are essentially the same and it is reasonable because you are actually looking at the discharge of the positive electrode, which in both cases is nickel. The negative is in excess on both charges.

(Figure 424)

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The next figure shows you the charge/discharge curve and the pressure that follows this curve. On overcharge, you will get about 58 pounds or so of pressure, this is at the five hour rate. It functions quite well and very similar to nickel-cadmium. Fifty-eight pounds is not really much pressure. Most of the commerical nickel-cadmiums run around that pressure anyway.

(Figure 425)

The next figure shows how the cell would cycle. This one here at two and a half ampere hours of positive and about eight ampere hours of negative. As the cycles progress, the capacity begins to drop off. I added hydrogen, where the little stars are, and then the capacity comes back and then it begins to degrade again. You add a little more hydrogen and it comes back again.

(Figure 426)

You see a similar sort of thing on long term overcharge. It was charged at the five hour rate to start with for ten hours, discharge at the five hour rate to get a capacity. That is the solid line. It was then put on a C over 20 overcharge for eight days and then discharge again at the five hour rate. That is the dashed line and the capacity is still there. But after 23 days of C over 20 overcharge, and once again, all the discharges are C over 5, and all the overcharge is at C over 20, we see the capacity beginning to fall off and then at 57 days it is pretty bad. If you add hydrogen at this point, the dot-dash type line or double dash, you see that a lot of your capacity comes back again. So I was thinking possibly that we had leaks in the system and this is what was happening, we were losing our precharge.

(Figure 427)

When we go on to the next figure and we have a negative limited cell. It took a couple of cycles to get it adjusted to be negative limited and electrolyte and all. But we see that as you cycle the cell, your capacity just decreases. This had a pressure transducer on it which cut off charge once you hit 150 pounds. So this meant all your lanthanum nickel was saturated and it just doesn't absorb, progressively less on each cycle. So it wasn't a question of leakage, we were actually losing our capacity.

What I was seeing in this other cell was excess negative, so I would be discharging merrily along and finally you hit the point where you degraded to here, and then you start seeing yourself lose capacity. If you add more hydrogen, you get more capacity. What we are using up here is our negative precharge. So once you get rid of your precharge, then it starts going down. If you add more precharge, it will go back up again. Eventually you will end up where you have

added so much hydrogen you have gotten rid of all that excess 6-ampere hours of capacity, then you will just get high pressure.

I didn't know exactly what was causing all this problem, whether it was the cell itself, possibly. I used a separator which I didn't describe. It was a micro-porous polyvinyl chloride. It was material that was used for a biological filter in a Di system. I thought it was possible that that was beginning to degrade and leach out and cause troubles too, so I decided what I would do is cycle the lanthanum nickel in just a hydrogen-oxygen mixture. I quite wisely chose a mixture which had only half a percent oxygen so that it wouldn't blow up.

(Figure 428)

Here we show a comparison of pressure cycling. This has nothing in it except for the lanthanum nickel and the gas. If you pressure cycle in pure hydrogen, it just cycles on and on. The ordinate there is the fraction of the initial capacity. In other words, you cycle the first time to see how much hydrogen is absorbed, and then on progressive cycles, what percentage of that will it do on the second and third cycle. So it remains stable in hydrogen, but I have shown the electrochemical degradation on this figure also. Then the hydrogen-oxygen mixture, this is half a percent oxygen in the hydrogen. The ability to absorb or desorb hydrogen continues to decline on cycles. The log of the initial capacity is linear with the cycle. So I don't really know what the problem is here.

(Figure 429)

It can be either that you can get the hydrogen to absorb but then it won't desorb, it just won't absorb it; or there is some sort of surface barrier which prevents the hydrogen from getting back and forth at an appreciable rate. I am not exactly sure which one of these problems it is, but it does seem that the problem with the cell is not with the design of the container and all that sort of stuff, or the separator, it is the oxygen somehow is interfering with the lanthanum nickel and preventing it from functioning so that the cell then does fail.

(Figure 430)

With this type of design, we have very good short term performance. It is just about the same as a nickel-cadmium battery. You can get about 30 percent higher energy density out of this, volumetric energy density, out of this type of cell. But the cycle life is very poor. The failure is probably due to the metal hydride. Somehow the oxygen destroys it. Future work should be directed toward perhaps some sort of protective coating on the metal alloy or looking for other metal alloys which stand up better in this type of environment.

DISCUSSION

NAPOLI: RCA. I am a little confused about the achievable energy densities in the nickel-hydrogen battery. I have seen one that was presented by yourself which achieved about 28 watt hours per kilogram. I have seen one presented by Eagle-Picher which was 66 watt hours per kilogram. And I have seen Mc Henry's 47 watt hours per kilogram. What is the number?

MC HENRY: The 47 watt hours per kilogram was on the nickel-hydrogen cell and I got that simply by calling people who make it, measuring the size, weight, capacity. This is a real cell.

NAPOLI: I have seen the real cell which Eagle-Picher is flying and I have seen the one that NTS is flying.

MC HENRY: It could be one with cells and one with batteries.

BETZ: Jim Dunlop, do you have the answer on the cell?

DUNLOP: Yes, by the way, the Eagle-Picher and COMSAT are NTS-2 spacecraft. The Eagle-Picher cell was kind of heavier, as you pointed out. The battery was kind of heavy. The cell was probably very good. But the energy density for cells is typically running somewhere around 40, 50, 60 watt hours per kilogram, somewhere in that range, depending on how hard you increase the pressure. That is simply a safety factor. One used a four to one safety factor, five to one safety factor, and then you drop off in your energy density. If you want to push the energy density, you drop off these safety factors. The actual energy density that we are shooting for for batteries is probably around 44, 40 to 44 watt hours per kilogram, and the usable energy density is something on the order of 60 or 70 percent of that, which is quite a bit higher than anything we are using in space right now. Usable energy densities come out to be about 12 watt hours per kilogram.

NAPOLI: Then I take it that the NTS-2 approach is quite conservative in terms of pressure, and they only have 27 to 28?

DUNLOP: The ATS-2 is almost twice as good as we got on the INTELSAT-4 in terms of usable energy.

NAPOLI: Are you saying at 44 is the number we are trying to achieve with the nickel-hydrogen, is that correct?

DUNLOP: Forty-four, that is a battery.

NAPOLI: Battery. And 28 watt hours per kilogram that you showed in your figure on the NTS-2 is what? Is that cell or is that battery?

BETZ: That was based on the rated capacity of the entire battery. The cell weighed 1.026 kilogram and delivered about 47 watt hours of capacity actually. So it is well up into the mid-40's on energy density on the cell basis. We did not try to minimize the weight on our nickel-hydrogen battery design on this first go-around. TRW in some past papers has cut our structure weight by more than half in their own design for a battery structure and it has reported to the IUCC, I believe.

SULKES: U. S. Army. That reaction of the lanthanum nickel, is that both wet and dry, the reaction of oxygen block?

MC HENRY: That was dry. I didn't try it wet. You will get a little bit of water because hydrogen-oxygen catalysts make water. I did dry the material in one of the cycles at about 30 cycles. Took it out, put it in a vacuum oven, dried it, put it back in, and you see no break in the curve at all. Also, the amount of water with that much hydrogen and that much oxygen would be less, it is about 30 percent of what it would take to saturate the hydrogen when you vent it. I vented it through a gas purette to atmospheric pressure. So it probably would have been carried out with the hydrogen.

HOLCOMB: NASA Headquarters. The question relating to the energy density we were just talking about in nickel-hydrogen batteries and gas storage, how does utilization of this mechanism compare in theoretical energy density to just pure pressure vessel?

MC HENRY: What are you going to do is you are going to lose energy density. But actually what you are trying to do is replace the nickel-cadmium cell. Nickel-cadmium and lanthanum nickel have essentially the same watt hours per gram, one is 372 and one is 367 or something of that kind. But when you make this type of cell, you don't put any nickel sinter in with the cadmium. Almost half of the weight of that cadmium electrode is sinter or supporting grid and things of that kind. So you should gain, essentially, the weight of the supporting grid.

BETZ: Right now it doesn't have migrating cadmium either.

DUNLOP: Comsat. Since myself and several members of my group have a patent on this technology back in 1972, of course we have been working on it for a long time as you know, we did report a long time ago about a separate reservoir where you use lanthanum nickel and cycle it that way. That works

pretty good if you don't allow oxygen contamination. But what we did do, in a fairly detailed study of that concept, we found there really wasn't a weight advantage. There was almost a toss up in terms of weight, being that you can save a little bit of weight when you chase, but you sacrifice in wear of the hydride. So it actually comes out to be almost a toss up. But of concern I think for aerospace application is that if a hydride ever gets contaminated, you have got an absolute bomb, which is a little bit of a concern.

The other thing is that there is a lot of work that is being carried on now by Harwell in England under our support and there will be a paper given, I hope, in the conference. They are using the electrode electrochemically. I have achieved some fairly interesting results with that. They have failed a number of patents describing their work, about a year or so ago, that will be interesting too.

$Ni-H_2$ CELL REACTIONS

$$NiOOH + H_2O + e \rightleftharpoons Ni(OH)_2 + OH^-$$

$$2OH^- + H_2 \rightleftharpoons 2H_2O + 2e$$

Figure 416

HIGH PRESSURE NiH₂ CELL CHARACTERISTICS

Figure 417

ADVANTAGES OF Ni-H₂ SYSTEM

1. HIGH MASS ENERGY DENSITY - 47 WH/KG

2. LONG CYCLE LIFE - >3,000 CYCLES

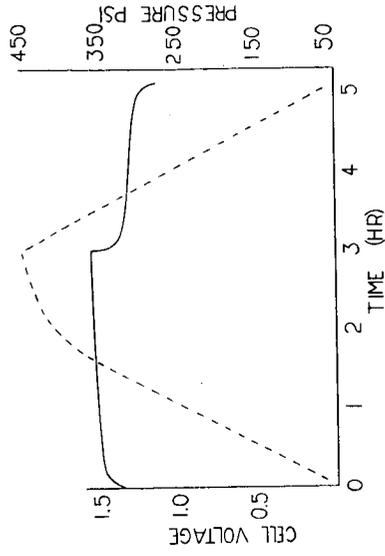3. UNAFFECTED BY REVERSAL

4. HIGH RATE PERFORMANCE

Figure 418

DISADVANTAGES OF NiH₂ SYSTEM

1. LOW VOLUMETRIC ENERGY DENSITY - .92 WH/IN³

2. HIGH OPERATING PRESSURE - 500 PSI

3. PLATINUM CATALYST

4. CONTAINER FATIGUE PROBLEM
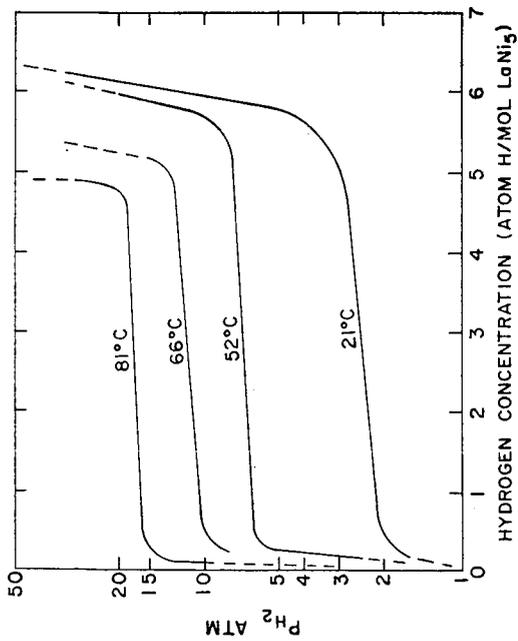
Figure 419

Figure 421

Figure 420

ADVANTAGES OF NEW DESIGN

1. NO FABRICATION OF NEGATIVE ELECTRODE

2. NO BINDERS OR SUPPORTING STRUCTURE

3. ACCOMMODATES WIDE VARIETY OF H$_2$ ABSORBING
   ALLOYS

Figure 422

Figure 424

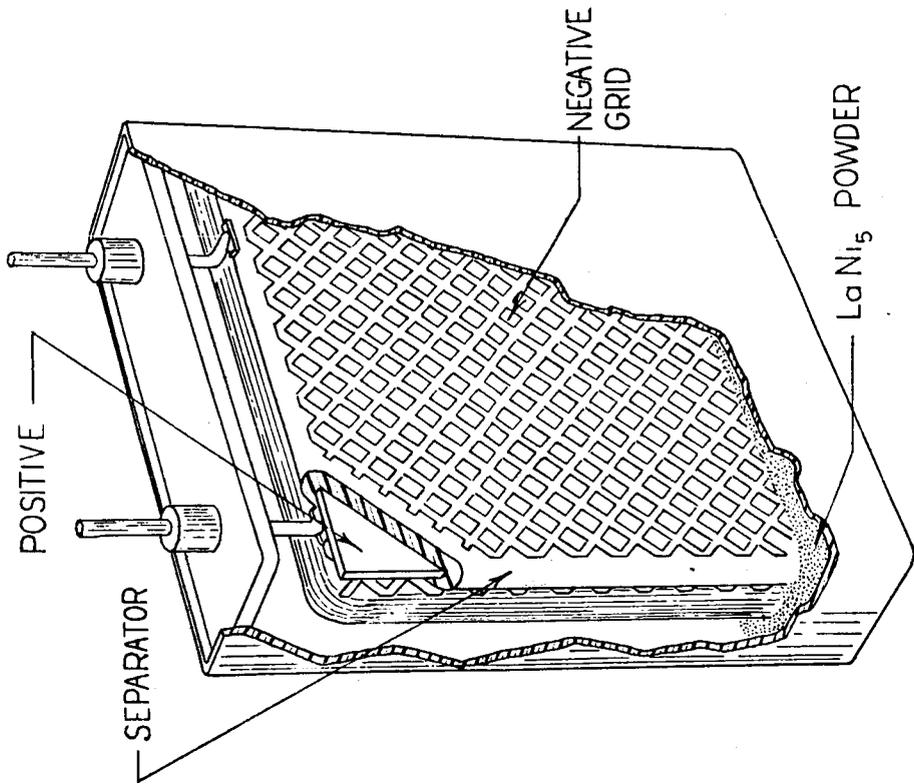

Figure 426
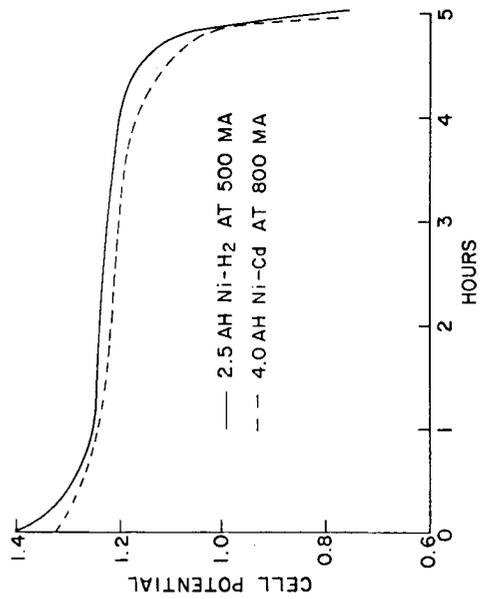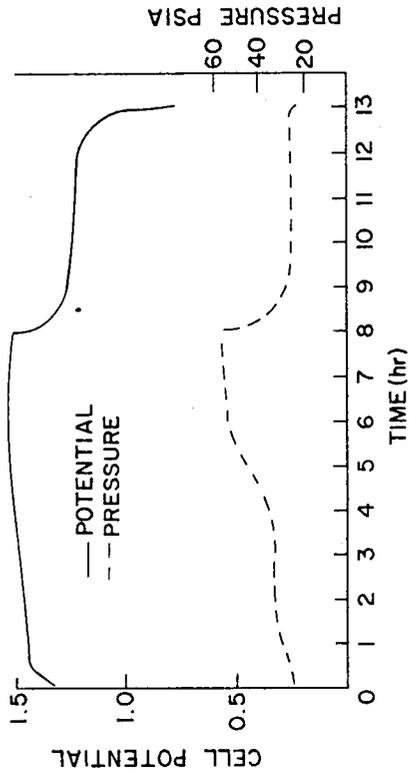

Figure 423

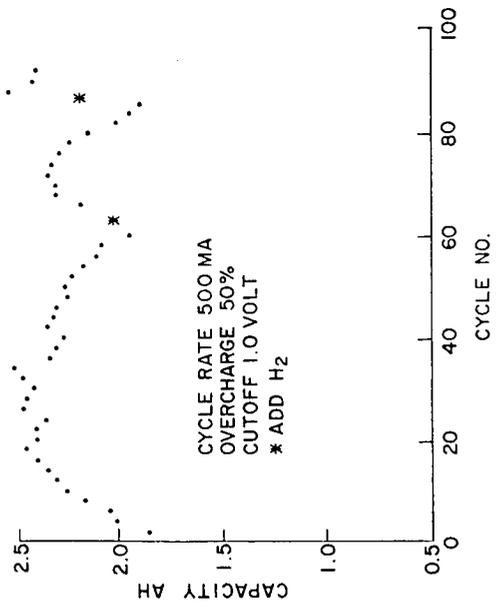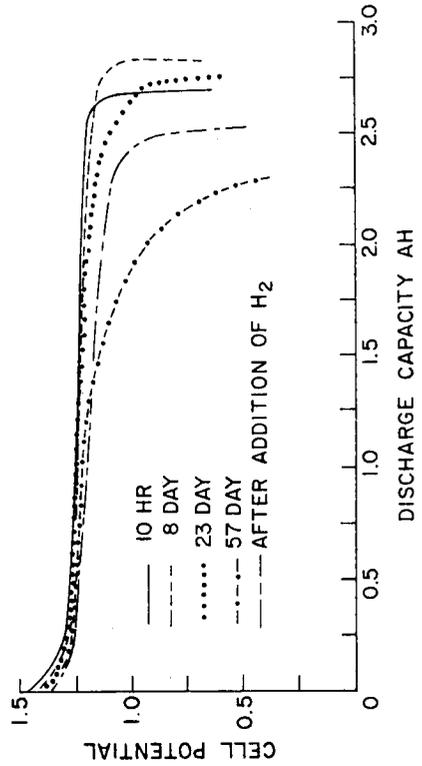Figure 425
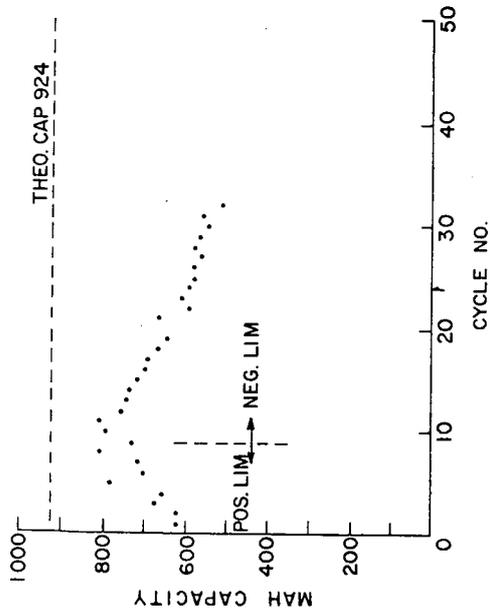
Figure 427

Figure 428

POSSIBLE CAUSES OF CAPACITY LOSS

1. STABLE HYDRIDE

2. CORROSION OF BULK MATERIAL
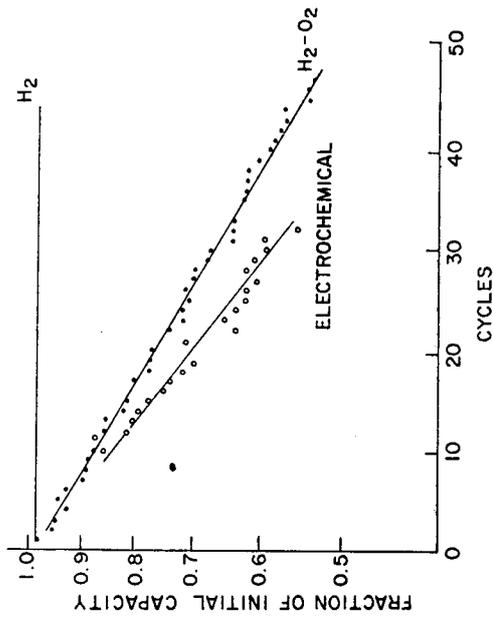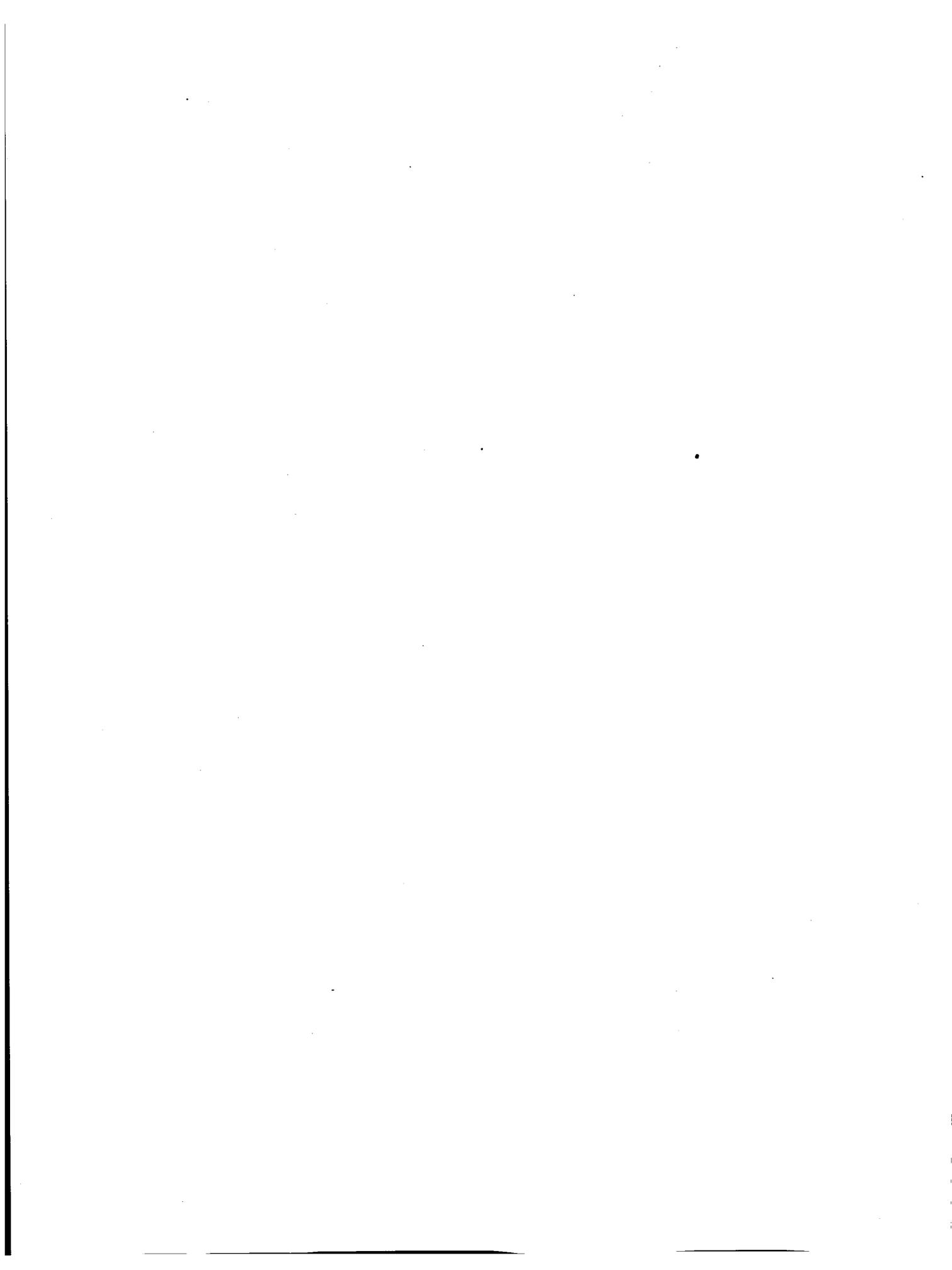
3. SURFACE BARRIER

Figure 429

CONCLUSIONS

1. SHORT-TERM PERFORMANCE EXCELLENT

2. CYCLE LIFE POOR

3. FAILURE DUE TO METAL HYDRIDE

4. FURTHER WORK SHOULD BE DIRECTED TO PROTECTIVE COATINGS OR CORROSION RESISTANT ALLOYS

Figure 430

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SHUTTLE SAFETY

R. Bragg
Johnson Space Center

I am supposed to be saying something about safety. I might first explain where my organization stands relative to this safety responsibility. I am in the Propulsion Power Division at the Johnson Space Center (JSC).

The JSC apparently has the safety approval for safety on payload. That is their responsibility, and when they get into areas that they need some support in, they will contact other organizations, that is how I get the Power Generation Branch into the picture. When they run across a battery on a payload, they will pull me into the picture.

I may or may not get involved at all levels of review that they have access to. So, depending on how much they want to pull us in, that is how much we get in. Hopefully, we have gotten into a situation with safety that we don't have to have two, and three, and four failures postulated in a battery design.

An informal philosophy might be that we would assume that we can sustain one functional failure in a battery and it still doesn't present a hazard. That is very informal and that is not a published thing by any means, but for lack of a published criteria, that is what we have sort of agreed on. Bobby Miller in our safety organization and I have tried to work out an agreement where we are not butting heads all the time, which was the situation when I was the user and trying to get my batteries on the spacecraft and he was bringing up questions on safety, what if this fails and that fails? So we fix it and it is going to fail anyway and then what do you do? This, I hope, will give you some feeling for the kinds of things that we feel are reasonable and give you an idea of some kind of a safety criteria. This may be a little pretentious because this is the position of my individual organization. This presentation has not been passed on or put out by the safety organization who has the basic responsibility, but from a battery standpoint, this is what we look for.

(Figure 431)

We are interested in everything from the handling through the mission to taking the batteries back off the spacecraft. We would get into, depending on the extent to which we are drawn into as an organization at JSC, the review of these batteries. We would get into activation procedures, installation procedures, how they are installed, and the environments they have to look at on the pad.

During the mission, we are looking at the pressurized spaces in the vehicle, that is the vacuum conditions. And, of course, the thermal conditions during orbit. When we come back, we are concerned about how they are removed, what they have to go through on the way back, whether or not you dispose of the battery or you plan to reuse it.

(Figure 432)

Safety precautions. We are concerned about safety of ground and flight personnel, first about physical harm to personnel and damage to equipment; and secondly, we are concerned about the vehicle, i.e., damage to the vehicle. Only thirdly do we get to mission success.

(Figure 433)

That is a proposed standards criteria. We have a standards criteria document, that, by the way, is not in it. As I say, we have in the past treated battery safety on an individual battery basis and we don't have that proposal in the document. It is somewhere in the mill. Whether or not it finally gets published, is questionable. It is something that probably needs to be put in and a great more detail than what you have there. That is a very generalized kind of approach. By the way, the last item there is aimed primarily at primary batteries rather than secondary batteries, particularly with all this good reconditioning.

(Figure 434)

There are broad safety concerns: any substance that is emitted, liquid, solid, gas, whatever, must not be toxic or toxous to the personnel, it must not be corrosive, nor flammable or explosive in a confined environment. Whatever is there is there, so what we are saying is you have got to handle it in a safe manner, and be aware of what it is.

We are concerned about failures, functional failures that affect crew safety. That is, if the equipment doesn't work, does the vehicle work well enough to get the men back or does it harm the crew? Any kind of heating we would be concerned about is whether it is due to internal shorts, or cell shorts, or electrolyte leakage shorts. External shorts are more easily protected by electronics. That concern still exists.

This last statement is a rather strong one, I guess. It is one that my organization feels it has to stand on to a large extent when we are designing a battery. This is what we would try to do in terms (particularly this last item)

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as we do the off-limits and over-stress tests to show that what the outer limits condition or postulate failure modes are and test those batteries through those failure modes, to be sure that we have a safe design ("even remotely" it is qualitative).

If you can show from historical data that the item in question is not a problem, that is a way to get around the statement or to satisfy it. One way in terms of eliminating the hazard is you design around it. Some of the methods I have heard proposed are the diodes giving the by-pass protection for the cells.

Most importantly, though, we would like to see the overstress test data for those situations which prove to be hazardous.

(Figure 435)

Some of the specific examples which in past experience with silver-zinc batteries primarily, that is in my major background, on Apollo Skylab ASTP, some of the things that we were to some extent forced into and to some extent determined that this was a good deal and we ought to do this on all the batteries, in terms of gas handling, remember, these specific examples again are directed to a large extent to silver-zinc and as they apply, generally apply them unless you have a battery can with cells sealed inside, talk about minimizing the head space volume, possibly covering or backfilling it with an inert gas blanket. What we have done also is minimize the head-space volume by simply potting all the free volume that we can. The reason for this is that as you minimize the amount of volume of a combustible gas, you minimize the energy content in the event that you get a combustible gas in the head-space.

We have in the past (in our limb batteries, our primary silver-zincs) had to go to a manifold venting system where we connected up a manifold to each individual cell. The individual cells had relief valves and through the relief valves they would vent into a manifold. The manifold went to the battery case interface which had a relief valve. The problem you get into there is you have all those separate volumes that you need to check out for leaks, and that the valves operate correctly. That sort of a procedural problem gets to be quite large when you wind up with a manifold.

The pressure relief valves should be checked. We incorporated pressure relief valves in most of the systems that we have looked at where we have battery cans with cells inside, both at the cell level and at the battery case level. The idea of a cell can being a pressure vessel and forgetting about it being a battery or cell and treating it strictly as a pressure vessel was kind of

new to us when Apollo 13 occurred. After Apollo 13 a Safety Board was convened, a Pressure Panel came down on us, and suddenly all these plastic cell cases had to be made pressure vessels. So we went through all of the precautions we could, in terms of taking new looks at the settings on our relief valves, for example; making sure that the variations in these relief valve settings were such that they didn't create an over-pressure condition on the cell case and possibly crack.

Liquid vapor separation. I don't know if any of them really work, but we try. If you have a system with relief valves, that is, cells in sealed cases with relief valves on them, you have to have some kind of a test for it to be able to test the system during activation.

Back in Apollo on the limb batteries, we had to go through an electrolyte quantity optimization. The object there being to make sure that we didn't have excess electrolyte in the cell that could possibly get out and give us problems in terms of electrolyte shorting.

Some of the electrical features we are looking at is encapsulation of the current carrying parts. All the current carrying parts we can we pot over. Painting the inside of the case to preclude the exposure of a case that can prevent, in some systems, the negative terminal or ground of your system from going to a cell through an electrolyte ground, that gives you an extra precaution against that happening to you.

The two-wire system (I say two-wire system, a floating system or whatever you want to call it): In Apollo, we used structure ground so the battery case became, just outside the battery effectively, the negative terminal of the battery. Therefore, all we had to do was go from one cell to case, and depending on which cell, you could have almost the full battery voltage across that electrolyte ground. So with the two-wire system, if the case is isolated, it becomes necessary to get two paths if you are talking about electrolytes. That seems to be a step in the right direction to help preclude this kind of thing happening to you.

Sizing of intercell connectors, wiring is obvious. External battery short circuit protection is something that is also usually included in designs.

Structural features, where we ran into problems here came into being while trying to thin down plastic cell cases. They started cracking on us. So for various reasons, some of them being material, in some cases we didn't have a thick enough battery case to contain the cells when they tried to expand so that we got into overstress conditions on the cell cases and broke them.

Handling features comes into play for any kind of battery preparation. Any of the pressurized volumes that we are talking about that are protected by relief valves need to be tested to make sure that they do function. The pressure relief valves need to be tested as closely as possible to putting on board to make sure that they will meet their required function. The IR test and the hi-pot testing gave us indications. Sometimes those tests we wished we didn't have because they gave us indications that we had problems where we had more of a spec problem then we had anything else, but they are good indicators.

We had to be concerned about materials' compatibility, particularly when you are talking about activating silver zincs, particularly down at KSC where we ran into numerous problems. Something that was done normally at the vendor and had been done normally at KSC suddenly jumped up and bit us because we were placing cells into possibly a little bit higher stress situation. What I am talking about in particular is incompatibility of normal cleaning agents that you would use like isoprophyl alcohol to ABS for example, it lowers the stress capability of ABS.

Also in that category is acetic acid which is generated from certain RTVs. Boric acid is also a problem that is commonly found in a battery lab or an activation area to neutralize KOH.

These are typically some of the things that, when I would be called upon to look at the safety of design or review safety of procedures, I would be looking at them in support of the Safety people at JSC.

DISCUSSION

NAPOLI: RCA. The safety feature criteria that you have established here are for the actual battery that is going to be used to support the shuttle itself. What about the safety criteria for the batteries that will be in the payload? Is there any criteria that is going to be generated for that?

BRAGG: Again, this effort is not meant to establish or be the criteria for safety. It was only meant to give you an idea what we look for. There needs to be established a specific safety criteria for batteries, to give people, (users) a much more specific idea of what they need to do to get the safety approval of the safety people. I have just tried to give you an idea. If somebody comes and asks me what I am going to be looking for on a particular battery, we will do it on an individual battery basis based on my background and experience of various problems I have had in batteries.

NAPOLI: I am not sure if you have answered my question. The payloads that are going to be flying in the shuttle bay itself will have their own batteries which will be used to support the payloads.

BRAGG: Right.

NAPOLI: If there going to be a separate set of criteria for that?

BRAGG: No, this is not published nor does it exist anywhere except as a piece of these things that you have seen right here in terms of a criteria. The things that went into preparing the figures are the background that I would use in evaluating the safety of an individual battery if I get involved in it. There is no criteria as such for spacecraft batteries or for payload batteries, as far as that goes. I am saying that probably there very definitely needs to be.

NAPOLI: I think one of the problems that I am facing right now is that we are looking towards, say, a 1981 launch of future satellites and we would have to look for some either interface of safety document right now which defines the kind of safety criteria we have to have for our flight batteries which are going to be launched in the shuttle. We are talking about today's timeframe to get the stuff ready for 1981. It is not that far off. If we were to go a spare trade that we have now for our F-3 mission, we would satisfy but 50 percent of the criteria that you have established. We would never meet that.

BRAGG: Again, the criteria are indicators. I don't know what to tell you. There isn't any criteria.

NAPOLI: The impact on the design to meet that is tremendous. You are talking about taking an existing design where many of the parts are already built and are in storage to come up to meet that.

BETZ: It sounds like the people who do intend to use the shuttle had better start thinking about the problems.

I think what Bob Bragg just put up here would give you something to think about now until some formal criteria does come out, until you find out what it is, maybe you want to get ahold of Bob and the safety department that he is referring to, to find out what ultimately their goals are.

BRAGG: The man at JSC in the safety organization is Bobby Miller.

HUDGINS: Goddard. Bob, you said you had gotten together with Bobby Miller. Is this presentation a result of your meeting of minds?

BRAGG: No, he didn't have any input in this presentation.

HUDGINS: He hasn't seen the presentation?

BRAGG: No.

HUDGINS: Is this your result of the conversation with him?

BRAGG: Yes.

HUDGINS: In other words, he is satisfied with these criteria.

BRAGG: I can't say satisfied because he hasn't seen this particular document.

HUDGINS: I guess maybe I am trying to put words in your mouth and maybe I am wrong, but this is your assessment of what he would be satisfied with.

BRAGG: He has been trying to get my name along with his on a safety approval document. He is not a battery engineer. I am. That doesn't mean that the safety people are always going to be working with us. He is going to be trying to make sure that I stay involved to help protect himself if nothing else in terms of being able to sign that safety document.

HUDGINS: Your last statement was that there is no criteria as such for the orbiter or for the payload batteries and there is a need. Is there a move at JSC to create the criteria for this?

BRAGG: No, not really. Barry Trout of my organization has prepared this general criteria that you see there, but that isn't a complete kind of criteria that people can put their finger on and really answer the questions that I am sure they are going to have.

HUDGINS: So JSC's handling would be on a payload-by-payload basis?

BRAGG: That is what it had been.

HUDGINS: I think it would be good to provide some guidelines for people and JSC has responsibility in this area.

BRAGG: I agree, the need is there, it ought to be done.

BETZ: Bob, I really think you probably ought to bring that back to Barry, that the users of batteries are going to need criteria years in advance for the safety considerations of the batteries.

HELLFRITZSCH: You work with batteries, not in the shuttle but at the Johnson Space Flight Center, there are more than you, there are a dozen people or more.

BRAGG: No. Barry and I are about the only people at JSC.

HELLFRITZSCH: I know Barry, but somewhere you work with batteries, somebody tests some batteries on the ground before you put them up into a shuttle or fly them right?

BRAGG: That is right. We have qual tests like anybody else.

HELLFRITZSCH: They are not all battery experts when you hire them, you hire people out of college. How do you guide them to understand how many milliamperes through the heart, between two hands, between the hand and the foot, will kill a man? Or how many parts per million of anhydrous ammonia will kill him?

BETZ: I think the point is, I was about to say, if you think of a skateboard as a board with four wheels on it, when you think about it for manned spaceflight you have got to think about it with a cage on it because things are going to get very complex when you start dealing with manned space. The Apollo, as Bob Bragg mentioned, is part of it.

MIKKELSON: Convair. You stated that there isn't any written criteria that reflected what you put down, but I have already run into at least two or three instances where the very things that you have been listing up here are being listed in proposals; one being what we call the IUS vehicle that was to go on to the space shuttle, which listed quite a number of the items that you listed due to practical experience which can happen because I have had essentially the same practical experience. The danger that you get into is that the safety people lock on to these things and you end up in a non-negotiable position sometimes if you get the wrong kind of safety guy who seems to take these things at face falue.

For instance, I ran into a case where they said, "You shall not use any mercury in any component in this vehicle." It turned out I was using a silver-zinc battery, and if you are familiar with silver-zinc, you use mercury to inhibit hydrogen gas evolution.

Another requirement was that "you should minimize hydrogen gas flow." All of a sudden you were trapped. In looking into it further on, I found out that the safety guy had taken things and put them a little bit out of context. I later found out that you can use mercury in certain cases if you describe what the case is. After getting that across to the Navy, they accepted the use of mercury.

HALPERT: One can see that a whole room full of people are quite concerned about shuttle safety. The best thing to do is take this concern back to management and prepare an outline of what one has to do to get safety approval in a consistent manner so that we don't have to go through the whole operation of trying to get each particular application approved, unless there are special operations.

HOLCOMB: NASA Headquarters. I am involved right now in the interagency group working with isotope power systems in the shuttle. DOE and this committee is trying to establish safety criteria out of the safety office at Houston. They have established some basic safety guidelines that apply to the shuttle and criteria from an overall sense. They are working on trying to establish more detailed things. I think the recommendations that come out of this group need to be fed into this whole process. It is going to be looked at. I think when we get into the lithium battery part following this up, it is going to become even more interesting.

HOLLECK: EIC. One thing which is not clear to me and I think is generally not clear, you started out to isolate what the mission of JSC is. It it just to, let's say, review the safety aspects of some system that comes up to you? Or are you going to specifically set out criteria for various systems? These are three different levels of involvement with the safety aspects.

BRAGG: I think Lee answered that probably as well as I could. When I say JSC has the safety approval, the safety organization at JSC has to put their name on the dotted line. In the course of doing that and being able to do that, my specific organization is pulled into that effort for support, to give them some warm feelings that they are not getting into trouble by putting their name on the dotted line.

HOLLECK: But that means basically a rubber stamp after the fact.

BRAGG: That is exactly right.

HOLLECK: As opposed to giving guidelines for actually working actively toward a safe system.

BRAGG: That is right. It doesn't really help you.

HOLCOMB: The safety office at JSC is involved in supporting some of these safety considerations in terms of defining the environment in various types of explosions on the shuttle and all sorts of unusual environments that may come about, so they are actively spending money in developing specific environments to help in designing. That is a portion of their current on-going activity. As far as going out and trying to design safety in specific hardware, I don't think they are going to go that far.

PALANDATI: From the way you are talking, you are continuously referring to lithium and silver zinc, can I make the assumption that the batteries that we are looking for in regards to the pallets that will go into a shuttle will have to be exceedingly higher energy density batteries than what have been discussed here over the last several days?

BRAGG: I mentioned lithium and silver zinc only.

Figure 431

o EVENTS OF INTEREST IN SHUTTLE ORBITER MISSION TIMELINE

   o PRELAUNCH HANDLING

      o ACTIVATION

      o INSTALLATION

      o PAD ENVIRONMENT

   o MISSION EXPOSURE

      o PRESSURIZED SPACES IN VEHICLE

      o UNPRESSURIZED SPACES IN VEHICLE

      o ON-ORBIT THERMAL CONDITIONS

   o POSTLANDING HANDLING

      o REMOVAL

      o DISPOSAL, OR

      o RE-USE

Figure 431

Figure 432

SAFETY PRECAUTIONS ARE FOR PROTECTION OF;

o FIRST - GROUND AND FLIGHT PERSONNEL

   o IMPACT OF UNSAFE CONDITION ON PERSONNEL

      o PHYSICAL HARM

      o FUNCTIONAL DAMAGE TO FLIGHT EQUIPMENT

o SECOND - VEHICLE

o THIRD - MISSION SUCCESS

Figure 432

Figure 433

Cells and batteries shall be provided with systems or design features which will:

(a) Prevent electrolyte from escaping from cells to form electrically conductive random paths or to chemically attack the container or other nearby surfaces.

(b) Avoid generation of gases within the cells insofar as operations will permit. Where not limited by portability requirements, provide sealed passages to conduct excess gas pressures evolved by normal operation or fault to discharge locations which disallow gas reentry, gas ignition or material attack from discharging gas or entrained electrolyte.

(c) Contain all portions of any cell or cells in the event they burst, rupture or build.

(d) Prevent electrical short circuits through the use of optimized location of conducting elements of differing voltage, electrical isolation of the battery container, and application of compatible potting, encapsulation and/or protective coating, the latter also to protect surfaces from chemical attack or corrosion by spilled or escaped electrolyte.

(e) Constrain cell or battery temperatures to preserve load capacity and minimize hazard. Thermal requirements and heat dissipation loads must be established and verified by tests for conditions of storage, flight idle, heavy loads for short periods, and nominal loads for long periods (exceeding one day).

(f) Avoid discharge of cells and batteries to terminal voltage levels below 70% of the nominal load voltage of the initial fully charged condition.

Figure 433

Figure 434

o SAFETY CONCERNS (BROAD)

   o EMITTED SUBSTANCES (REGARDLESS OF STATE: L.S. G)

      o TOXIC/NOXIOUS TO PERSONNEL

      o CORROSIVE TO EQUIPMENT OR VEHICLE

      o FLAMMABLE OR EXPLOSIVE IN CONFINED ENVIRONMENT

   o FUNCTIONAL FAILURES IMPACTING CREW SAFETY

   o ABNORMAL HEATING

      o INTERNAL SHORTS: CELL SHORTS, ELECTROLYTE LEAKAGE GROUNDS

      o EXTERNAL SHORTS: TEMPERATURE EXTREMES IN BATTERY, VEHICLE EQUIPMENT, POSSIBLE FIRE SOURCE IN PRESSURIZED VOLUME

   o DESIGNER/ENGINEER MUST DEMONSTRATE THAT ALL FEASIBLE (EVEN REMOTELY) EVENTS DO NOT RESULT IN HAZARD

      o BASE ON HISTORICAL DATA

         o EXPLAIN KNOWN HAZARDOUS FAILURES

      o BASE ON PROVISIONS TO ELIMINATE OR CIRCUMVENT HAZARDOUS FAILURES OR CONDITIONS

      o BASE ON OVERSTRESS TEST DATA

Figure 434

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SAFETY IN DESIGN/HANDLING

o GAS HANDLING FEATURES

    o MINIMIZE HEAD-SPACE VOLUME WITH INERT GAS BLANKET

    o MANIFOLD VENTING SYSTEM

    o PRESSURE RELIEF VALVES

    o LIQUID-VAPOR SEPARATION

    o INCORPORATE TEST PORT

    o ELECTROLYTE QUANTITY OPTIMIZATION

o ELECTRICAL FEATURES

    o ENCAPSULATION OF CURRENT-CARRYING PARTS

    o PAINT INSIDE OF CASE

    o TWO-WIRE SYSTEM

    o INTERCELL/TERMINAL CONNECTION SIZING

    o EXTERNAL BATTERY SHORT CIRCUIT PROTECTION

o STRUCTURAL FEATURES

    o SUFFICIENT CELL RESTRAINT

    o NO INHERENT STRESS DUE TO CONFIGURATION/FABRICATION

o HANDLING FEATURES

    o LEAKAGE TESTS OF ALL PRESSURIZED VOLUMES

    o EXERCISE OF PRESSURE RELIEF VALVES

    o IR AND HI-POT TESTING

    o MATERIALS COMPATIBILITY

Figure 435

LITHIUM CELL TESTS RESULTS

R. Bragg
Johnson Space Center

I want to describe to you as quickly as I can the program we have just completed and some of our projected testing that we are talking about doing in lithium batteries.

(Figure 436)

About three years ago, we procured 700 cells, C-size, from seven different manufacturers. The incident that brought this around, and again brings to light the need for the safety criteria effort, the people were flying a camera battery on Apollo, or on Skylab rather. About the day before they flew they decided that they would call over to our office and ask us what we thought about it. They knew what the couple was, but they had no experience in the lithium battery area.

We have a crew systems organization which has been in the space power vehicle business. We supply electrical power to the spacecraft, whereas other organizations have in the past supplied their own batteries, small batteries I am talking about, camera batteries or radio batteries, that sort of thing. So we have not really been involved, nor been responsible for batteries in those areas. We would help people if they called on us for support.

That incident triggered this particular test. We couldn't answer any questions on the lithium battery because we didn't have any experience in it, so in order to try to establish some sort of an experience base and to be able to make evaluations of the new systems that were coming along, we got into this program.

As I say, we ordered 100 cells from each of seven manufacturers. We started out not to involve that many manufacturers and dug a few more up and battery on Skylab. About the day before they. flew they decided that they would of cells. All these cells were delivered around late 1974.

We had some three lithium SO_2 cells. We had two lithium CF cells and GTE came in with the vinyl chloride cell. I need to stress that these cells were all crimped seals. Most manufacturers have gone away from that, I think, except for the CF cell people where the pressure is not as high so the need is not as great. In many cases they were strictly experimental cells. They were

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the first cell; I don't want to say "off the assembly line" because all of them were basically hand made, but they were at a very early stage in manufacture.

(Figure 437)

We tested the cells over the kind of range on a normal discharge. The cells were discharged independently on resistors as much to ease up the test handling problem as much as anything else. They were discharged as individual cells; that is to say, they were not in series. Three temperatures were used. We used a couple of different storage temperatures. I might mention the 33° storage temperature didn't start until we were at least six months minimum in-to the shelf life of the battery.

Discharge rates generally on these nominal discharges were as shown there, 0.1 amp, 0.5, and 1 amp. We also did off-limits tests on a limited number of cells. The cells were discharged at a given discharge temperature and just before they went on that discharge they were placed on open circuit five days at 125°F. We took pulse load data. We made cell weight measurements before and after that five days at 125°F. We logged the cells in terms of that weight, in terms of the general appearance, primarily looking at leakage.

The weight measurement was made to say something about leakage and the physical description was done again to show the effects of leakage. The number of cells that we used per test mode is shown there. This matrix does not include the off-limits data.

Let's see, I need to mention that on a couple of manufacturers we did not get C cells. Honeywell gave us a CC cell. Most of them we used 100 mils as standard discharge. For the Honeywell since it was a CC we used 200 mils. The discharge for the GTE vinyl chloride cell was found to be too high, that is a basic discharge to determine cell capacity was found to be too high and the manufacturer suggested we got to 0.03 amps as the standard, 0.01 I believe, so they cut their weight way down.

Our results on these tests were what you might expect from cells in this stage of development. We first decided that crimped seals were not ade-quate, particularly for the SO_2 cells. Normal discharges presented no hazard. Again, understand they were single cells on a fixed load, on a fixed resistor. There was nothing driving them, in other words, except their own voltage. They all just discharged down to zero. All the cells involved in this test discharged to zero. They were all passive.

The off-limits testing, however, as we expected, did give us some fireworks. So one must then do something about that in terms of defining

exactly how that happens and what to do about it in terms of designing around it, or making the cell different so that it doesn't go down.

(Figure 438)

To give you a rough idea of what happened overall: The manufacturers are listed at the top of this figure. As their literature or discussions indicated, most of those rated capacities are at 100 mil down to 2 volts at room temperature. The number of cells involved in our nominal discharges are listed on the next row. Now these, I must point out, include cells over that entire range of the test matrix.

The cells that gave us that rate of capacity, over the entire matrix the two volt end voltage cells which we established the capacity for, are the 100 mil rates; the other capacities were measured at 1.5 volts, the half amp and one amp loads. So you see, we didn't do too well on rated capacities.

To give you another cut at how many cells gave any kind of capacity, we placed a 50 percent capacity row there and you can see the results of that.

(Figure 439)

Now to make that a little bit more meaningful in terms of rated conditions, I have here the numbers of cells that were involved in room temperature discharges at 100 mils, which was basically the established rate, to give you an idea of how closely those cells that were discharged (at close to the manufacturer's specifications) came out. Again, a hack at 75 percent of that rating and at 50 percent of that rating.

The GTE cells, again, we couldn't really draw more than 100 mils or so out of them and get any reasonable voltage at all so I included the 10-mil and the 30-mil cells in with the 100-mil cells; 100 mils is about the most we could get out of the cell with any kind of reasonable voltage. Again, the rates for the Honeywell cells were double, they were 200 mils.

(Figure 440)

This figure picks up again a few of the tailing off conclusions that I started on the first figure, indicating from the charts here that the performance was generally below manufacturer's specs. We have a report out on that test, the number is listed there if you are interested. Some of the future work we are talking about doing is dealing with some larger capacity cells from Mallory, both of them SO_2 cells.

We are interested in higher rates. We needed a cell to give us three hours at rates ranging three to six amps. The other capacity to be taken out of the cell would be taken out at much lower rates, more like 60 to 100 mil. So we have gotten these cells in-house now and we will be looking at various parametric testing on them to establish their capability to meet these kinds of rates, and will be looking at safety effects of the cells.

DISCUSSION

HOLLECK: EIC. I would appreciate it if you could say a little bit more about the cases where you did have safety problems; what type, where did you get explosions, for example, with what cell conditions? I think that is of great concern especially since you emphasized the safety aspects before.

BRAGG: On short circuit, most of the cells of the ones we tested, did vent but they vented quietly. The one that did not was an Eagle-Picher cell, CF cell, that did rupture and then burn.

HOLLECK: One CF cell ruptured and burned.

BRAGG: Both CF cells that were tested in that short circuit mode did rupture and burn.

HOLLECK: Which cells did explode?

BRAGG: Rupture, explode, whatever word you want to use, violent rupture. It exploded and burned.

HOLLECK: And which cells exploded on overdischarge?

BRAGG: On the overdischarge, the Eagle-Picher cell got very warm. The cells that did vent are the Honeywell cell, an SO_2 cell, and PCI cell. We tested several cells in each mode, several of the PCI cells, so I think those did burn also, then they exploded.

HOLLECK: They exploded? SO_2 cells on overdischarge exploded?

BRAGG: Both of them were SO_2 cells, right, on overdischarge.

HOLLECK: There is very little documented data on lithium cell explosions, especially hard data which gives the conditions. There is some general notion that they explode easily and under all conditions, but if you go and try

to do it, it is not that easy. I know you can make them explode but it is not that easy and there are very erratic and very strange conditions sometimes.

BRAGG: Maybe Jim Bene will change your mind.

HOLLECK: That is why I would like to get a little bit more concrete information.

PALANDATI: Goddard. I know a number of years ago when you were investigating the safety hazards of silver-zinc, if I recall right, most of the data that you people published said that if you stayed below about 300 ampere hours, the problems of violent fires, explosions on vented wilver-zinc and so forth were not there. It was only once you went up to a certain size battery or above. I notice here now you are talking about going to roughly a 4 ampere hour to about a 25 ampere hour lithium. Do you feel that possibly the results you will see now on the larger cells will possibly be different? In other words, will the size of the batteries as such or cells possibly present fewer problems?

BRAGG: I am not sure what you are talking about on the silver-zinc systems. Possibly you are talking about those on Apollo 14. I think we noted what we felt to be a cell that had developed an internal short. We observed that from looking at the open circuit voltage. We still had a lunar lander mission to do. We took a cell and discharged it and then put it back in series with the battery. We did that mission to try to understand what our capabilities would be if we totally depleted a cell on a short. Maybe you saw something that came out of that.

PALANDATI: No, this I believe the study that Chrysler Corporation did several years back to find out exactly what would happen with the silver-zinc cells. Evidently, you did have a problem of several cells violently rupturing in the battery can, fires developed, and so forth.

BRAGG: I don't want to put Paschal on the spot, but maybe he can help me out.

HARKNESS: Crane. Your explosion you are referring to, is this like a hand grenade explosion with the cell disintegrating or just like a shotgun blast with a rupture type?

BRAGG: The top blew off, as I understand it.

In the report there is some very graphic illustrations, I think, on the condition of the cell. They still had something to take a picture of after the cell exploded so it was like the top blew off.

BOWERS: Navy. On your GTE cells, were they the bobbin type or were they jellyroll construction?

BRAGG: I am not real sure. I think they were jellyroll. They were some of the first cells, in 1974, whatever they were building in that is what they delivered in.

METHLIE: Basically, these cells that you have here are old integration cells. Although the points you are basically making are not bad, the state-of-the-art if a long ways from there now from where it was at the time you got that.

BRAGG: I agree.

METHLIE: There is data available on most of those points from various places in the government which would confirm that there has been a big change there.

LITHIUM BATTERY PROGRAM STATUS

o LITHIUM BATTERY EVALUATION - THERMOCHEMICAL TEST BRANCH (COMPLETE)

  o 700 CELLS - 7 MANUFACTURERS

  o "C" CELLS, CRIMPED SEALS

  o 3 CELL TYPES OF LATE 1974 MANUFACTURE

    o Li - SO2

    o Li - CF

    o Li - SOCl2

  o DISCHARGE TEMP (-25°F, 15°F, 75°F), STORAGE TEMP (32°F, 75°F)

  o DISCHARGE RATES 0.1a, 0.5a, 1.0a

o OFF-LIMITS TESTS

  o SHORT CIRCUIT

  o OVER-DISCHARGE/REVERSAL

  o HIGH TEMPERATURE (165°F) DISCHARGE

o RESULTS

  o CRIMPED SEALS INADEQUATE; ESP. FOR SO2 CELLS

  o NORMAL DISCHARGES PRESENTED NO HAZARD

  o OFF-LIMIT DISCHARGES INDICATED VENTING, FIRE, EXPLOSION ON SHORT CIRCUIT AND REVERSE DISCHARGE, AS EXPECTED

Figure 436

LITHIUM BATTERY TEST MATRIX

SHELF LIFE (MONTHS) CUMULATIVE	6 (approx.)			9			12			15			18		
DISCHARGE TEMPERATURE (°F)	-25	15	75	-25	15	75	75			-25	75		75		

Table 1.- Main Discharge Phase Test Matrix

Figure 437

	MALLORY	PCI	EL-CH	E-P	ESB	GTE*	HW**
RATED CAP A-H	4	3	3.5	3.7	4.5	5.0	7
NO. OF CELLS ON 75°F 0.1a	28	28	28	28	28	36	28
NO. OF CELLS YIELDING 100% OF RATED CAP	0	20	2	1	0	5	0
75% OF RATED CAP	15	24	23	10	19	10	15
50% OF RATED CAP	22	25	26	21	23	16	16

* DISCHARGED AT {0.01 AMP (Y); 0.03 AMP (H); AND 0.1 AMP (C)}

** DISCHARGED AT 0.2 AMP; HW CELLS THE DOUBLE C

Figure 438

Figure 440

o RESULTS (CONTINUED)

   o PERFORMANCE GENERALLY BELOW MANUFACTURER'S SPECS

   o INTERNAL NOTE FOR LITHIUM BATTERY EVALUATION   JSC-12721

                           NASA JSC TECHNICAL LIBRARY

o LITHIUM BATTERY DEVELOPMENT - IN-HOUSE EFFORT

   o 100 - 25A-H MALLORY SO_2 CELLS

   o 30 - 30A-H PCI SO_2 CELLS

   o ELECTRICAL PERFORMANCE CHARACTERIZATION - MED-TO-HI RATES (3 TO 6A)

   o PACKAGING EFFORT

   o OFF-LIMIT TEST EFFECTS

   o SAFETY EFFECTS

   o SAFETY EVALUATION

Figure 440

—— THERMOCHEMICAL TEST AREA ——

	MALLORY	PCI	EL-CH	E-P	ESB	GTE	MM
Rated Capacity,* A-H	4	3**	3.5	3.7***	4.5	5.0	7
No. of Cells Used in Non-off-limit Testing	90	95	90	90	89	75	90
No. of Cells Yielding 100% of Rated Cap to 2.0 or 1.5 V	0	20	8	4	0	9	0
No. of Cells Yielding 50% of Rated Cap to 1.5 V or 2.0	59	73	74	69	59	23	49

* Temperatures and load conditions of many cells tested were outside of conditions associated with manufacturer rated capacities. For details see Test Program Discussion.
** Rated capacity of PCI "D" Cells is 8 A-H.
*** Rated capacity of EP "Hi-Rate" Cells is 3.5 A-H.

Table 2.- Cells Meeting Rated Capacity Requirements

JSC Form 388B (Rev Dec 78)

NASA-JSC

Figure 439

LITHIUM CELL TESTS AT
LANGLEY RESEARCH CENTER

J. Bene
Langley Research Center

Most people often ask why we are looking at lithium for spacecraft. I will just give you a little bit of background to get through this.

(Figure 441)

What we are working on is a payload called LDEF. It is supposed to fly on a mid-range orbital flight test. LDEF stands for Long Duration Exposure Facility. This particular one is a canister about 14 feet in diameter and 30 feet long, and has about 72 experiment stations on it. It was sold as a completely passive vehicle. When they got into it, they found it had to have battery power. All experimenters have to stand alone, no central power system allowed, so, therefore, primary battery power for the experimenters.

(Figure 442)

This is just another photo of LDEF. At the top is the grappling ball the shuttle will use to extract the payload from the bay, put it into orbit. One of the problems with this vehicle or probably any vehicle you have to retrieve, is that it can't rotate. It can only have so much roll in it, or they won't be able to grab the ball and put it back into the bay and bring it back. So that means the thing is going to be oriented in a given direction so if you happen to be on one side, generally in the sun you are going to run warm, if you are on the back side where you are in the shade, you are going to run cold. Hence we have a very wide temperature range requirement on the batteries.

(Figure 443)

As pointed out, the temperature requirements, we have something like -30°F to +150°F for the reason that was cited. The lifetime requirement looks like about 20 months to contend with from the time the batteries are built until the mission is completed. We would like to see it (lifetime) longer than that. What we would like to do is build the batteries and be able to store them. We are talking batteries in the order of something like 150 to 200 different batteries for this one particular flight. We are considering numerous flights. So costwise it would be beneficial to build a great number of them at one time.

We have about a 165°F to 170°F heat pulse going to be imposed on the battery on the way in. In this venting as far as venting is concerned, something always crops up at Langley. Langley in the past has generally insisted that a battery box not be sealed. This is no exception. So venting is a headache. We are trying to come up with a two amp discharge capability so we could satisfy more users.

(Figure 444)

Lithium/SO_2, if you can believe everything you hear, has good high temperature storage, good long active shelf life. When we started looking at lithium, we had one manufacturer who offered a hermatically sealed cell, and that was Mallory. I think PCI said they were going to have one and we placed an order with them, but they never delivered. Lithium/SO_2 systems are fairly cost effective if you consider them against silver-zinc or some other competing system.

(Figure 445)

To get into some of the things that we found very early in the game. The test results concern the Mallory LO-2054 cell only. Contrary to what a lot of people will tell you, these cells generate considerable heat during discharge. What we found is anywhere from about a half to 6/10ths of a watt at one amp discharge rate. When you get near the end of discharge where the voltage starts collapsing, you get a very high heat output rise. This is not due to polarization. That is chemical reaction heat you are starting to see.

If the cell is thermally insulated like some of the batteries that have been built in the past out of lithium cells, we found that the cells will vent and ignite and then burn if you try to discharge them all the way. These cells do not go into reversal.

When we were trying to run isothermal discharges to get a better handle on being able to predict what the performance of the battery would be over a given spectrum of temperatures of operation, what we found as we discharged at anywhere from +60°F to -20°F, anywhere from two amps to a half an amp, and removed it from that isothermal condition, and either put the cell in free air or put it in a thermal package where we were trying to get a better feel for the amount of thermal involved, the cells on many cases would explode in about 20 minutes and sometimes it would take as long as two or three hours before they would explode.

Other things we found, low temperature capability is not quite what we expected based on the published data, and the start up problems which I know most people have heard of are aggravated by cold temperatures, and much more severe than what we were led to believe.

(Figure 446)

This is the thermal package we started using early in the test game. What we are using it for is to try to get a handle on how much heat these cells generated. That was the first cell that burned. As a matter of fact, the first cell we discharged burned. So we got off to a good start and from there things just got worse.

(Figure 447)

If there is any question in anybody's mind about what happens to these cells, there are three that exploded. One has got the bottom blown out, the other has the top blow out, and the one on the right, the can has been completely reformed. There is a big question of what do you call an explosion. A technician said if you had been around, you would call it an explosion.

We have a film clip here. What we were trying to do is run a series of tests where we ran isothermal discharges into SO_2 exhaustion at two amps. at -20°F, they open circuited and then the cells were removed to a test fixture at ambient temperature. What we were trying to do was get the timing down so that we could get some high speed film of it to try to get a picture of the actual explosion. What we were trying to see is if the cell is ignited internally which all data we had indicated it did. If when it did vent or rupture, whatever you want to call it, if it came out running full fire and if it was emitting molten lithium or emitting sparks.

So let's run it and we will take a look at them. We have three of them. The first one, when the cell went off, the guy holding the handheld camera, just to get a feel for what is going on, jumped and missed everything.

(Film clip)

Anyway, none of these cells blew the bottoms out. I would call them a violent vent. I think there is no question in your mind that this is a pretty hazardous thing to have around. Bear in mind these cells are on open circuit.

HELLFRITZSCH: How did you know when something was going to happen?

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BENE: Monitoring the temperature.

HELLFRITZSCH: Oh, you are heating them?

BENE: No. You see that one when it came out, it was burning when it vented. That was a good one there. These cells are on open circuit. Like I say, we discharged them at -20°F, run in reversal up to the point were we had exhausted all the SO₂. So once the SO₂ is exhausted, what you run into is a chemical reaction.

HELLFRITZSCH: Roman candle.

BENE: Right. That is it. That is all three of them. We had a fourth of July celebration here in November. Like I said, those cells were discharged at two amps at -20°F to SO₂ exhaustion. What we were using as a gauge is hard to define here in words and I don't have a figure of it, but we call it an SO₂ notch. It is a notch that appears in the discharge curve. It is in the vicinity of the time when SO₂ should be exhausted. After that occurs, you start getting a lot of noise in the discharge curve. So we start using that as a guage. After that, the cells are put on open circuit and removed from the bath and just put on open circuit and let them sit there, and that is what happens.

As previously pointed out, if we ran discharges in the thermal package or insulated package, those cells vented and burned. In no case did we ever get an explosion under those conditions. We had cells which vented and then ignited. It was pretty obvious. You could see from the thermal data that that is what happened.

Another condition where we ran into problems which wasn't on that list, which we haven't seen too often, is at high temperature, 150°F bath, cells have vented violently while under load in reversal. They extinquished themselves in the bath, but there is no question but that they were burning internally. We will talk about some of the reasons for that in a minute.

(Figure 448)

After we ran into a little bit of difficulty with these things, it became pretty obvious that we were in a bit of trouble. So we went at this thing two separate ways. In one, we are going to continue to look at the problem to try to define it just in case the lithiums do work out and we can use them so that we can explain the problem and have a better chance of getting it approved. In the meantime, we determined that the root of the problem probably was the chemical reaction between the lithium and the acetonitrite (solvent), and based

on that, we went to Mallory and after about two visits we finally convinced them
they had a problem. We sat down and we redesigned the cell. We will talk
about that later on.

Also we started looking at some alternates, like the Eagle-Picher cell
and an alkaline.

(Figure 449)

This is just a capacity vs. temperature performance curve for isother-
mal discharges. It shows the extreme rolloff in available capacity as you go
down in temperature. What this says is if you drop below 60°, you are rolling
off pretty hard. After we ran some tests and I found that at -20°F performance
was pretty miserable, we also learned that the manufacturer has been discharg-
ing cells standing free in an air chamber. So their data might indicate that the
chamber was running at -20°F, but the cell sure wasn't.

(Figure 450)

Here again are some discharge curves. This is what happens at low
temperatures. The one with the lumps in it is the -20°F. Very little difference
between 75°F and 150°F. That SO_2 notch I was referring to is these dips you
see here. They occur about where SO_2 should be exhausted.

HELLFRITZSCH: Did that go negative?

BENE: Yes. When you get down in there you go negative.

(Figure 451)

BENE: What we have here is time to vent while on open circuit at
room ambient following an isothermal discharge at various rates and tempera-
tures. Rather than getting into arguing about what is an explosion and what
isn't an explosion, I just call them all vents. Whether they vent nice and gently
or they vent violently, they are still venting. As you see, as we come up in
temperature and as the rate goes down, it takes longer for the cell to vent which
is probably indicative of a number of things. One being that the time dependency
or the amount of time the cell is under load or the time the cell is under isother-
mal conditions well under load. In any event, does give you some indication of
the temperature dependence and rate dependence on how much time compression
you can obtain on the lithium-acetonitrile reaction.

(Figure 452)

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Here's another curve that most people have a hard time understanding. What we have here is a temperature differential (temperature rise above ambient) that we found that occurred when we took a cell and discharged it at 2 amps, at -20°F, and then interrupted that discharge some time prior to that SO_2 exhaustion point, which on the average occurred at about 9.75 ampere hours into the discharge. As you can see, as we come closer and closer to that point, the amount of heat generated in the cell on open circuit following the discharge increases. Once you get so close to SO_2 exhaustion you start getting ventings or violent ventings. If we interrupted discharge early enough, the cell would present no problem.

(Figure 453)

Gas analysis is still going on. We originally hired Old Dominion University to do it and they had some trouble with their mass spectrometer, it wasn't working too well. So now we have undertaken to do that ourselves. This isn't complete yet. I thought I had the data with me and I didn't, and I was trying to remember all the gases that we found and I couldn't. So I will label that "incomplete-preliminary."

As you can see, virtually all those gases are toxic, corrosive, or explosive. Cell A is a cell that went through this isothermal discharge bit and then was allowed to explode in a vacuum canister. Cell B is cell A but with the gas sample taken just prior to the time that the cell exploded. Cell C is a cell drain discharged to zero volts and that was not driven into reversal.

As you can see, what we are generating in these cells, once you use up SO_2, is predominantly methane, hydrogen cyanide, carbon dioxide and a few other gases. But after it explodes, apparently there is a lot of interaction going on in that cell.

(Figure 454)

Most people want to know what is happening, what happens in that cell, what causes explosions. What we thought it was in the beginning hasn't changed. We haven't seen anything yet in the data that would indicate that we were wrong in what we thought was going on. But anyway, what we think is going on in this kind of stepwise fashion, considering a -20°F discharge, at some point in the discharge we deplete all the SO_2. The lithium acetonitrite reaction is severely inhibited at cold temperatures. We have not run a test yet to determine the temperature dependence on that reaction except there is some test data that does kind of indicate that that is the case.

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Once the cell is removed from the bath, and either put in a thermal package or put in free air, I will point out that if I put it in free air, it vents sooner, the cell is now released from this thermal clamp such that the little bit of reaction that is going on can help boot strap itself up until you get the cell temperature up so the reaction goes faster and you get a kind of chain reaction going. At some point you get localized heating hot enough to melt the lithium and that in turn makes that reaction, the lithium acetonitrile reaction become very violent which generates a tremendous heat spill. At that time is where we get fuzzy because the data that we have so far, and whether we will ever get enough data to really explain completely what is going on I don't know, but anyway, it looks like we have two ways to go now. As this heat pulse comes up, it is hot enough to get the lithium dithionite to begin decomposing. If that happens, that should generate a tremendous amount of heat. Or for some reason unknown to us right now, something in that cell reacts with the dithionite, you get interaction between the dithionite and whatever is in the cell, like methane or hydrogen cyanide or whatever, that could also generate a tremendous heat and lead to an explosion.

(Figure 455)

I want to point out that this is where we are still working. We are trying to define the problem. As I pointed out earlier, we took a two-pronged approach to try to find the real cause of the problem, and what is our best guess what the problem is and let's see if we can fix it. We went to Mallory, discussed it, came up with four designs, evaluated them, and what we came out of there with was a design that right now looks pretty good.

I might point out that we have only looked at 17 cells. We have not run a complete safety test on them. Everything is still very preliminary. Until that is done, I don't know if we have a real cell that we can use or not.

But, here we compare the original cell, which is the 26 SH, that is Mallory's high rate cell, it is a fairly new one, and the new cell, what we call an SH Mod-1. With -20°F isothermal discharge, the plateau voltage on the old design was 2.5 and the new design was 2.4. The capacity in the new design indicated a little bit higher, but I think it is close enough so there is probably no change there.

Where we do see the difference is in the reversal voltage. In the old design, we only ran about -4/10ths to -5/10ths of a volt. In the new design we run at -2 to -4 volts, which is what we wanted. That is what we tried to achieve. Our approach to the thing was to stay out of reversal condition, or to get around it, then maybe we won't have problems.

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So there are two ways to go. I can either try to get a cell with open circuits when it goes into reversal or shorts. I didn't know how to make a short cell short, so we figured out a way how to make it go higher in impedance when in reversal so that we could use a bypass diode and in that way very little current passes through the cell. So that part has looked very good. At 150° you see that there is not a whole lot of difference in capacity between the old and new design. It seems to be a little bit less, which we expected. But again, the reversal voltage is still pretty healthy.

(Figure 456)

As far as safety is concerned, we already know what happened with the old design. The new design, if we run it at 2 amps without a bypass diode, the cell would sometimes vent but not burn. I would gather what is being vented under those conditions well, I forgot to point out something here. I am getting ahead of myself.

Under isothermal forced discharge of .5 amps to 2.0 amps to SO_2 exhaustion at low temperatures, such as -20°F, followed by an open circuit stand in an insulated package, the old LO-26 SH cells would usually vent violently. Under the same test conditions, the new cell design did not vent but did produce a slight temperature rise above ambient.

When the old type cell was discharged at 1.0 amp in an insulated package, it would vent and burn without having been into reversal. Under the same conditions, the newer cells with bypass diode exhibited only a mild rise in temperature. The temperatures indicated here are maximum, but represent only an increase of 40°F and 14°F above a base temperature of 140°F observed at the end of discharge.

(Figure 457)

And again, some more safety comparisons. Under high temperature forced discharge into reversal, the old design, generally events but occasionally we would get a cell that would vent that was a burning vent. The new design would sometimes vent only if the bypass diode was not in place. At one amp and half amps they are both about the same. That is it, gentlemen.

DISCUSSION

BOWERS: Navy. Would you like to tell us something about the new design?

BENE: What I can tell you about the new design is we have problems with what is proprietary and what isn't, whose is what. Anyway, what I can tell you about this design is that all the hardware is the same. That is one of the things we insisted upon. Whatever we did, we had to stick with available hardware. We didn't have time to develop hardware. So it is still in a D-sized can. That didn't change.

One thing we did change, the old design had a lithium SO_2 ratio of about 1.6 to 1. Very high lithium content which is pretty standard in the industry. In the new design we turned that around. We have a 1.1 to 1 SO_2 to lithium now. So under any condition I can envision, we will not deplete SO_2. There ought to be excess SO_2 in the system.

The other changes I can't talk about right now. They are subtle.

NAPOLI: RCA. I have a general question regarding lithium batteries. About six months ago there was some literature that came across my desk with a trademark by the name of Eternalcel. I don't know if anybody else has seen them. It looks like they were making these things commercially available. Do those things have the same characteristics as these cells here?

BENE: We have not tested any PCI cells. We had ordered PCI cells some time ago and at that time they did not have a hermatically sealed cell, but were going to deliver one. After about eight months of nondelivery we finally cancelled the order.

BETZ: You don't force them into reverse. You put them on a load resistor. Jim Bene's are forced into reverse. They are apparently beyond that.

NAPOLI: Yes. But if you go out and they become commercially available, how do you control it when it is out in the field?

BENE: The reversal is a real thing if you are talking about dealing with 28 volt batteries. That can happen to you. That is real life.

SULKES: USAECOM. We have got several thousand of these things out in the field with the 28 volt battery. We have, of course, gone to the lithium limited design and various batteries are fuse protected and have a thermal upper limit. Of course, there is also a limit on the maximum rate of discharge. Our typical limits on the D size, and these are used by the troops and so forth with relatively no special precautions taken, the people have them on their back, they are going up to Alaska and everything else, the only limitation is there is

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a max discharge rate, there is a temperature limit, and of course, fuse. Once we made the change, which I guess took place a year and a half ago, through this lithium limited design, we have had no problem. Back in '73, '74, we had the same problems that were shown, but we don't have them anymore.

BENE: Let me make a comment about a lithium limited cell. I don't know that the Army is using. I think they are still using cells that have a little bit more lithium than SO_2. I don't know that they have gone the other way yet. Anyway, the most violent explosion we have had with an SO_2 system was a one to one cell.

SULKES: They still reversed there?

BENE: They went into reversal, absolutely.

NEWMAN: Federal Aviation Administration. I think there are approximately 50,000 general aviation aircraft with lithium powered emergency locator transmitters. We have had 27 cases in the past five years, prior to maybe three months ago, of violent ventings, or whatever you want or refer to them as. There have been some more recently. The Canadian Government has just issued an Airworthiness Directive requiring that all lithium batteries be removed from aircraft. FAA is in the process of doing probably the same thing. We have had problems. They have been going off with the ELT not operating. There has been no drain. They have just been sitting there and they go off. The last case, it deformed a metal ELT cabinet that was mounted near the skin of the aircraft and generated enough heat to pit the skin of the aircraft over the small area. So we feel right now with the ones that are in the field that we have a safety hazard.

We are not sure, there were some on one commercial airliner. I am not positive that they are off yet, but the airline agreed to take them off under their normal maintenance. Someone in the southern region, I don't know whether the sale ever went through but we didn't prohibit them at the time, but the light dust, some of them have little lights on them and they were trying to sell 5,000 of these lithium powered cells to sit underneath the seats in the cabin.

BENE: This is just some of the ways we can make the things explode, or vent and burn if you like. I am sure there are other ways. I can think of another one right now that would do the same thing.

BOWERS: Navy. I have a comment with respect to explosions. We had a series of experiments that we conducted under contract where cells were dropped from 16 feet on a concrete path. These cells were -65°F. We had three cells of the same design. All three cells exploded. Parts of one cell were found 150 feet away from the drop site. My authority for explosions are some of the explosive experts in the Navy. They classify these as low order explosions.

LACKNER: I would like to ask Mr. Newman is there any criteria on what you will be replacing the lithium cells with?

NEWMAN: We have a test procedure and certain requirements that will be included, I think, in the AD if it comes out that way as opposed to the legal process.   I don't think it guarantees 100 percent probability that there won't be another explosion, another violent venting, but we hope that it will minimize the problem.

LACKNER: You are not planning on going into another system?

NEWMAN: Well, something like a low rate cell or the cell that Mallory has designed would probably pass this criteria.   One manufacturer encountered a lithium vinyl chloride cell.   They said they have been running tests on it and have not been able to get it to explode.   The Canadian government, from what I understand, from their Ministry of Transport, they plan to go back to magnesium and alkaline cells in the interim.   Both governments are still concerned with low temperature operation.   Minus 20°C isn't really good enough for certain rescue crews.   It doesn't give them enough time in certain areas of the country to find downed aircraft.   So we like lithium the operates at -40° and hopefully these problems will eventually be resolved.

ROGERS: Did you say vinyl chloride?

NEWMAN: Vinyl chloride.   It is in a sealed cell.   They say it will explode if you put it in a fire.   There are other things on the aircraft that will burn, I think some of the seat plastics.   You have a problem, if you are in the aircraft and it is on fire and the batteries explode.
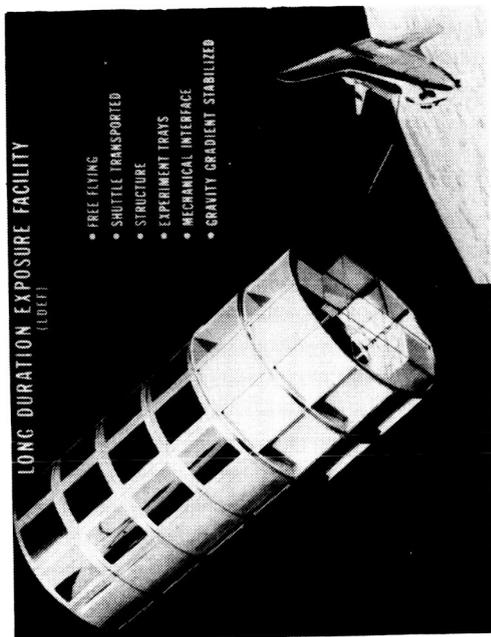
Figure 441

Figure 442

SOME LDEF PRIMARY BATTERY

CONSTRAINTS

1. OPERATING TEMPERATURE: -30°F TO +150°F

2. REQUIRED LIFE: APPROXIMATELY 20 MONTHS

3. +167°F HEAT PULSE - END OF MISSION

4. VENTING NOT PERMITTED

5. 2.0 AMP DISCHARGE CAPABILITY

Figure 443

WHY LITHIUM/SO_2

o SUPERIOR HIGH TEMPERATURE STORAGE CAPABILITY

o LONG ACTIVE SHELF LIFE

o HERMETICALLY SEALED

o WIDE TEMPERATURE PERFORMANCE RANGE

o COST EFFECTIVE

Figure 444

Figure 446

Figure 448

LITHIUM/SO$_2$ ADVERSE PERFORMANCE

RESULTS TO DATE

(CONSTANT CURRENT DISCHARGES)

1. HEAT GENERATION DURING NORMAL PORTION OF DISCHARGE IS HIGH -- .55 - .60 WATTS AT 1.0 AMPS

2. VERY HIGH HEAT GENERATED AT END OF DISCHARGE

3. THERMALLY INSULATED CELLS VENT AND THEN IGNITE AND BURN IF DISCHARGED TO EXHAUSTION

4. ISOTHERMAL DISCHARGES FROM +60°F TO -20°F CAN LEAD TO EXPLOSIONS OR VENTS WITH FIRES

5. LOW TEMPERATURE CAPABILITY (VOLTAGE AND CAPACITY) BELOW EXPECTATION

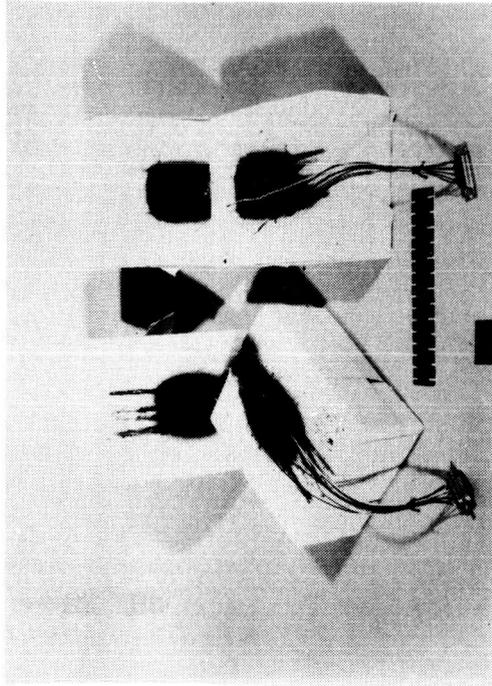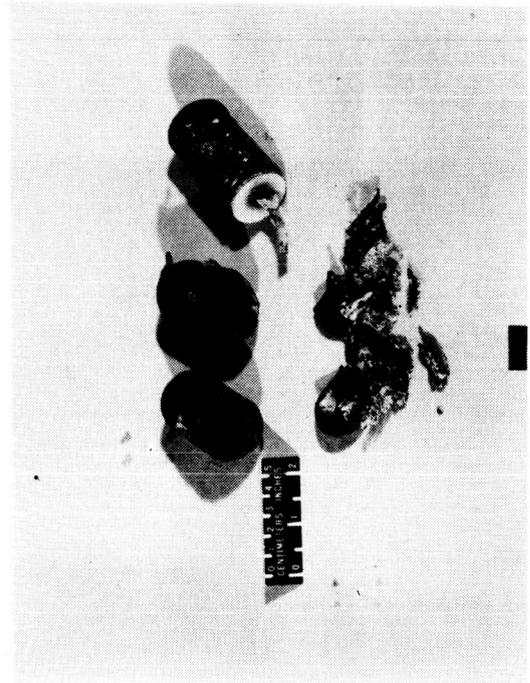6. START UP PROBLEMS AGGRAVATED BY COLD TEMPERATURES
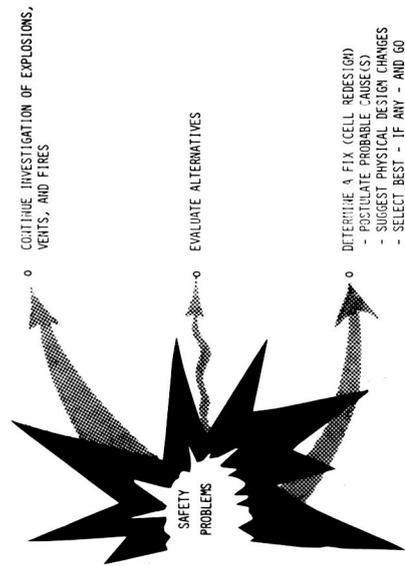
Figure 445

Figure 447

577

MALLORY LO-26HS

???? VOLTAGE
VS.
AMPERE HOURS OUTPUT

O - 20°F
□ + 75°F
△ + 150°F

AMPERE HOURS

VOLTAGE VOLTS

Figure 450

TEMPERATURE DIFFERENTIAL
VS.
AMP HOURS BEFORE SO₂ EXHAUSTION

TEST TEMPERATURE = -21.7°F
AT 2 AMPS

AMP HOURS BEFORE SO₂ EXHAUSTION

TEMPERATURE DIFFERENTIAL

Figure 452

MALLORY LO-26HS

AMPERE HOURS CAPACITY
VS
TEMPERATURE
@ VARIOUS DISCHARGE
RATES (ISOTHERMAL)

O 2.0 AMP
□ 1.0 AMP
△ .5 AMP

TEMPERATURE, °F

AMPERE HOURS

Figure 449

TIME TO VENT (MINUTES)
VS.
DISCHARGE TEMPERATURE
(ISOTHERMAL)
@ VARIOUS DISCHARGE RATES

.5 AMP
1 AMP
2 AMPS

TEMPERATURE, °F

MINUTES

Figure 451

Figure 453

GAS ANALYSIS
MALLORY LO-26HS

GAS	CELL "A" %	CELL "A" VOL.* cc	CELL "B" %	CELL "B" VOL.* cc	CELL "C" %	CELL "C" VOL.* cc
H_2	X					
CO_2	X		X			
N_2	X					
CO	X					
CH_4	X		X		X	
C_2H_4	X		X			
C_2H_6	X		X			
H_2S	X					
COS	X					
HCN	X		X		X	
CS_2	X					
CH_3CN	X		X		X	
SO_2	X		T		T	
"X"						

CELL A – EXPLODED IN VACUUM DURING O. C. FOLLOWING 2.0 AMP
ISOTHERMAL OVERDISCHARGE AT -20°F
CELL B – CELL A BEFORE EXPLOSION
CELL C – DRAIN DISCHARGED TO 0 VOLTS AT 80°F
T – TRACE

Figure 453

Figure 454

POSSIBLE VIOLENT VENTING
MECHANISM SEQUENCE

1. SO_2 IS DEPLETED

2. Li + CH_3CN INHIBITED BY COLD TEMPERATURES

3. RELEASE OF CELL FROM TEMPERATURE CLAMP ALLOWS Li + CH_3CN → CH_4 + HCN + HEAT TO PROCEED

4. LITHIUM MELTS LOCALLY

5. Li + CH_3CN BECOMES VIOLENT PRODUCING TREMENDOUS AMOUNT OF HEAT

TIME COMPRESSED TO PRODUCE HIGH THERMAL SPIKE

6. $Li_2S_2O_4$ BEGINS TO AUTOCATALYTICALLY DECOMPOSE

7. TREMENDOUS HEAT DEVELOPED WITH SUBSEQUENT CELL BURNING AND RUPTURE

6. $Li_2S_2O_4$ NOW ABLE TO REACT WITH ENVIRONMENT IN THE CELL

7. TREMENDOUS HEAT DEVELOPED WITH SUBSEQUENT CELL BURNING AND RUPTURE

Figure 454

Figure 455

MALLORY LO-26HS/LO-26HS MOD 1

PERFORMANCE COMPARISON

TEMP, °F	DISCHARGE CURRENT, A	PARAMETER	LO-26HS	LO-26HS MOD 1
-20°	2.0 OR EQ.	o HIGHEST PLATEAU VOLTAGE, VOLTS	2.50	+2.42
		o CAPACITY TO 2.0 VOLTS, AH	2.66	2.81
		o NOMINAL REVERSAL VOLTAGE, VOLTS	-.4 TO -.5	-2 TO -4
+150°F	2.0 OR EQ.	o HIGHEST PLATEAU VOLTAGE, VOLTS	+2.80	+2.78
		o CAPACITY TO 2.0 VOLTS, AH	7.49	6.78
		o NOMINAL REVERSAL VOLTAGE, VOLTS	-.4 TO -.5	-2 TO -4

Figure 455

SAFETY COMPARISON

TEST	RESULTS	
	LO-26HS	LO-26HS MOD 1
LOW TEMPERATURE (-20°F) ISOTHERMAL DISCHARGE TO SO_2 EXHAUSTION, FOLLOWED BY OPEN CIRCUIT IN INSULATION PACKAGE		
DISCHARGE RATE: 2.0 AMPS (CONSTANT CURRENT)	EXPLOSION OR VENT AND BURN	DID NOT VENT, +20° RISE AA
1.0 AMPS	SAME AS ABOVE	DID NOT VENT, +10° RISE AA
	SAME AS ABOVE	DID NOT VENT, +10° RISE AA
DISCHARGE WHILE INSULATED		
DISCHARGE RATE: 1.0 AMPS (CONSTANT CURRENT)	VENT AND BURN	MAXIMUM TEMPERATURE OF 180°F AND 154°F

AA = ABOVE AMBIENT

Figure 456

SAFETY COMPARISON (CONT'D)

TEST	RESULTS	
	LO-26HS	LO-26HS MOD 1
HIGH TEMPERATURE (+150°F) ISOTHERMAL DISCHARGE (FORCED REVERSAL)		
DISCHARGE RATE: 2.0 AMPS (CONSTANT CURRENT)	FEW VENTS IN REVERSAL	SOME VENTS ONLY IF NOT DIODE PROTECTED
1.0 AMPS	DID NOT VENT	DID NOT VENT
.5 AMPS	DID NOT VENT	DID NOT VENT

Figure 457

LITHIUM CELL TESTS AT
MARSHALL SPACE FLIGHT CENTER

E. Paschal
Marshall Space Flight Center

Well, I really don't have a whole lot of test data to come up and show you. We are still in a program of developing batteries for several applications. I want to show you the areas that we are working. The program, as I say, is still in progress and we have got a little ways to go yet.

(Figure 458)

Just as a matter of interest to show you the areas that we are proposing to use lithium batteries, what I have shown here is a picture of the Shuttle. They have got the two SRB's, the external tank, and on the other side is the orbiter. In each SRB we are proposing to use one battery for range safety and two batteries up in this area for frustum location aid. The other SRB will be similarly equipped. Up in this area on the AT we are planning to use two lithium batteries for range safety.

(Figure 459)

We started looking at lithium batteries about the fourth quarter of 1974. We ordered a number of cells from five vendors. I believe one of them did not deliver the cells. These were C and D size cells at that time. The order was relatively small, maybe six, eight, ten cells from each vendor.

These were put on storage tests and were evaluated under bench discharge as an initial approach. In the third quarter of 1975 we initiated a contract for a prototype frustum location aid battery. This particular design has undergone an evaluation test. Basically it included a mechanical vibration, acceleration, random and design vibration, plus discharge test. Also batteries of this type were used with the actual hardware with which they were going to operate to see how they would function from the standpoint of voltage characteristics and so forth.

I guess over the period of the last several years, we have tested half a dozen to ten batteries in this particular way. In 1976 we initiated a contract for a number of batteries. These were for two types, they were additional frustum location aid batteries and range safety batteries. The contract is designed to qualify both of these types of batteries for the respective application. Also in this contract are flight hardware to be delivered.

The qualification test is presently underway and will be completed sometime the latter part of this year and the early part of 1978. These tests consist of a wide range of mechanical type tests, where they first start out with a number of storage tests. The batteries are put on storage, some under very cold conditions, about 0°F, and others are put on hot storage tests, about 120° to 140°F. These remain on storage for 90 days without discharge amounting to other than temperature and voltage.

Following the storage tests, the qualification batteries are divided into groups and certain ones will undergo tests at high temperatures and others will undergo tests at a lower temperature. Here again, the discharge temperatures are 30°F for the colder temperature batteries and 120°F - 140°F for the hot temperature batteries.

Just prior to the bench discharges, they will undergo acceleration, design, and random vibration. The random vibration test will be of the type that they will experience when they lift off, during the boost, and during water impact. The frustum location aid battery will be used after water impact where they will provide power to a flashing light and to the radio transmitter for location purposes.

Sometime in 1978, we expect to start catheterization tests and safety tests. We have batteries on order and they are expected to be available and the test set up and ready to go at that time and a deeper evaluation of some of the safety problems will be conducted at that time. However, there is a report on several level tests that were conducted by the vendor on the particular batteries in the last couple of years.

To summarize these briefly, there were four cells that were provided with external shorts, initial current something on the order of 13 amps. None of these cells vented. The temperatures rose to something like 130°F - 135°F during these tests. The discharge was not complete and failure analysis indicated there was some corrosion on the positive plate to the positive tongue. These leads did break off when vent. This was attributed to the reaction products and the high temperature. When I say high temperature, understand there was probably higher temperature internal to the cell than what was observed out on the skin of the cells.

A fifth cell was made up with the much heavier positive tab and the vent was closed. This particular cell was also shorted. I don't have any temperature data on that one. After 20 minutes it was touched and it was not too hot. The cell did vent and smoke, but it did not catch fire or emit flame. These are very limited tests as far as number is concerned and we feel that additional tests are required.

(Figures 460 and 461 together)

I will put both of these figures up there. The first figure shows you the application and the figure on the right gives you the picture of the battery itself. The battery housing is of nylafil. It is nylon and fiberglass and, of course, of insulating type. It also has a relief valve and a means of pressurizing the housing. This particular one is a range safety battery and is mounted in four places on each side.

The housing is an injection molded housing so they can be manufactured fairly economically. We are talking something like figures as high as 450, 600 to 560 flights and if you need 5 of these per flight, it gets to be quite a large number. So use of the injection molded housing does save some money.

The cells are turned down, cylindrical, 18 ampere hour cells, and they are turned down and potted so that there is a space in front of the cell for venting into the area immediately in front if we have a problem.

(Figure 462)

This is a typical profile for the range safety battery. This portion back in here is several hours of ground testing at 18 watts. During the launch the nose profile is as shown here, starting around 18-1/2 watts dropping somewhat. There is a high spike here of about 98 watts or close to 4 amps. There are short periods of spike that are used to turn on an S&A device. Of course, your load drops somewhat and continues on at roughly 13-1/2, 14-1/2 amps, in the case of the SRB, a seven minute period, and in the case of the AT for a ten minute period, at that point it is stated no longer required.

I outlined earlier that that particular battery was tested for reentry and water impact and the reason for this is to make sure that the battery does not break apart and damage other equipment, shrapnel or what have you, since most of the hardware in the SRB is to be used 20 times.

(Figure 463)

This is the second type of battery that I mentioned, the frustum location aid battery. It is using the same cell design as the range safety; namely, 18 ampere hour cell, cylindrical cell. This particular battery does not have a top. Electronics will be able to fit over the top and form the closing on that.

(Figure 464)

I might show you one other picture here on the frustum location aid. This shows the two frustum location aids mounted within the frustum on this plane here. The main parachutes are packed inside the frustum. This, of course, sits up on top of the SRB. When the frustum falls into the water, a drove parachute extended down below the frustum and pulls the frustum into this position here such that the water is down in this area here and the batteries and the location aids are up above the water. This is your electronics in here and the battery is there, one there and one there.

(Figure 465)

There are two types of load profiles on the frustum location aid. One of these batteries feeds a transmitter which is approximately a quarter of an amp. The other one is for a light, location aid light, and it has a peak of seven watts and it is cycled for whether it is daylight or night. It is off during the day.

(Figure 461)

I took this particular figure of a little bit earlier to give you a little more detail on the design of the battery itself. I pointed out that the battery is in a nyafil housing in all of our applications with the exception of one, and that is the IECM. The IECM is an experiment battery that goes on the LDEF. It has a stainless steel housing. This is one of them that we have just started working on. The purpose of the stainless steel housing is to enable us to get the heat out of the battery. The battery will be discharged at a certain profile with some peak loads on it, but the main portion of the discharge will be in the order of 1.6 to 1.8 amps for something like five hours. Under those conditions, the battery gets quite hot.

The tests at the vendor's plant started with a temperature of about 80°F and, of course, the temperature rose to something like 160°F, which is the maximum that we want to operate the battery at, and well under the required five hours operating time. As a result, the battery was reworked and provisions were made to use a type of potting as a means of holding the temperature down.

In the second test, using the potting material, they again started at 80°F and attempted to run the five hour time at the, again, 1.8 amps. The temperature rose up to 160°F and held stationary at 160°F until the potting material had melted and then continued to rise. It made about four hours, four hours and a half under these conditions. It is still somewhat under the requirements. So further work is being done to hold that down. A different type of potting is going to be tried with a lower melting point in order achieve the required five hours.

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We will want to talk a little bit more in depth with Houston on the requirements for safety as well as satisfying our own requirements.

To continue in the battery description as we outlined, 13 cylindrical cells, D-size in diameter and lengthened as needed to get the necessary capacity. We have a pressure relief valve on each housing. The voltage requirements on open circuit as specified is 37.7 volts. On the load the requirement is 32 to 36 volts.

With the profiles that we have, it looks like we will get this. It is highly possible we may have to put a one or two ampere hour preload in order to not exceed the 32 volts initially, but we do have the capacity to do this and it will be no problem in setting up a procedure in this connection.

The temperature that we expect to operate is 30°F to 120°F. The IECM, as I pointed out, as a higher temperature requirement 160°F. The serial in a Naval picture, carbon monochloride cell. It is designed with the use of a polyprophylene separator. The electrolyte is dimethyl sulfide and lithium and arsenic and fluorine combination.

DISCUSSION

HUDGINS: Sounding Rockets. On your battery for LDEF, I believe you said it had a stainless case? Was that correct, it was something for LDEF applications?

PASCHAL: It goes as a passenger or as an experiment on the LDEF vehicle that we showed. The term IECM is Induced Environmental Contamination Monitor.

HUDGINS: You mentioned the case was vented. Do you happen to know what the vent pressure would be on that?

PASCHAL: The pressures? The vent pressures are on the order of 18 psi, I am not sure.

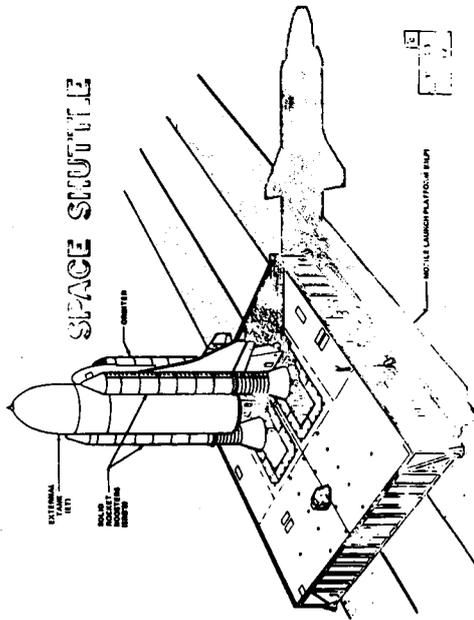HUDGINS: So this is a three pound over pressure?

PASCHAL: It is an over pressure. We don't expect, we hope we won't have any pressure on that, but if we should have a cell fade, the cell would vent into the area in front of the cell where it is potted in and any over pressure above the pressure relief valve will in turn vent. It is a safety sort of thing to keep from having a pressure vent.

HUDGINS: I had to leave the meeting for a few minutes so perhaps it was covered, but I don't know what materials are vented when this venting does occur. What are the gases?

PASCHAL: That is one of the areas we need to look at. I am not sure that all of these products are. The electrolyte, as I say, is dimethyl sulfide in a solution of lithium or arsenic and some fluorine, something of that sort. What all happens when that is combined, I don't know. We have had some of them to vent after they have been discharged. We have not had any of them that have caught fire or emitted flame. As I say, we still need to go a little further into the safety aspects of it.

HUDGINS: What prompted the question was wondering whether you had passes for JSC Safety and problems you have had with them, if you have.

PASCHAL: I don't think we got that far.

SPACE SHUTTLE

EXTERNAL TANK (ET)

SOLID ROCKET BOOSTERS (SRB)

ORBITER

MOBILE LAUNCH PLATFORM (MLP)

Figure 458

CHRONOLOGICAL HISTORY

o INITIATES EVALUATION PROGRAM .... 4TH QUARTER 1974

o PROTOTYPE FLA/BATTERY .... 3RD QUARTER 1975
  (A) DESIGN EVALUATION 18 AH BATTERY ..... 1ST QUARTER 1976
  (B) SYSTEM DESIGN EVALUATION 1976
      (1) ELECTRICAL TESTS
      (2) DROP TESTS

o INITIATED PROCUREMENT FLA/RSS BATTERY ... DECEMBER 1976
  (A) QUAL TESTS 1977/78
  (B) DEVELOPMENT FLIGHT BATTERIES 1978/1979
  (C) CHARACTERIZATION TESTS 1978

o IECM BATTERY PROCUREMENT .... 1ST QUARTER 1977

o EVALUATION FOR PLA APPLICATION .... 4TH QUARTER 1977

Figure 459

GENERAL DESCRIPTION

o APPLICATIONS

  o SRB LOCATION AIDS
    FRUSTRUM (FLA)
    PARACHUTE (PLA)

  o RANGE SAFETY
    ET
    SRB

  o IECM

o BATTERY DESCRIPTION

  o NYLAFIL HOUSING
    IECM – STAINLESS STEEL

  o 13 CYLINDRICAL CELLS

  o HOUSING RELIEF VALVE

  o VOLTAGE
    37.7 VOLTS OPEN CIRCUIT
    32 – 26 VOLTS UNDER LOAD

  o TEMPERATURE – $30^{0}F$ TO $120^{0}F$
    IECM $160^{0}F$ MAX.

o CELL DESCRIPTION

  o CAPACITY   18 AH
  o COUPLE   LI – CF
  o SEPARATOR   POLYPROPHYLENE
  o ELECTROLYTE   DIMETHYL SULFITE
                      IN Li As F_6

Figure 460

Figure 462

- WATTS -

* SRB ONLY - S&A SAFE

RANGE SAFETY BATTERY CONFIGURATION AND
AXIS ORIENTATION.

Figure 461

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FWD SEPARATION PLANE

EXTENDED POSITION

TORSION SPRING

FRUSTUM FLOAT SECTION, MTG SCREW

WATER LINE

FRUSTUM

Figure 464

20°
+Y
-Z
+X
-X
+Z
22°
-Y

RIGHT SRB

7.290

N85788-45N
ELECT CONN

FUSE

RELIEF VALVE

4.875

5.800

+Y
-Z
+X
-X
+Z
-Y
22°
20°

LEFT SRB
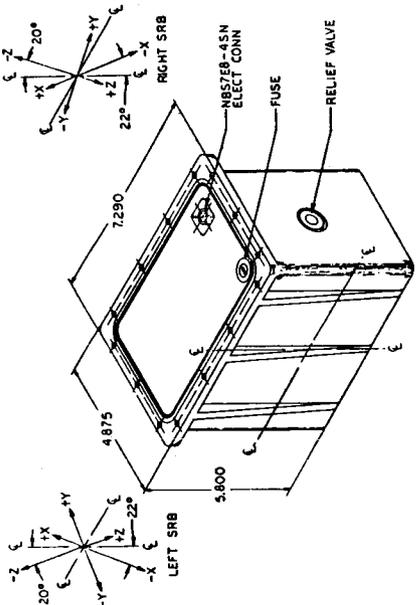
Frustum Location Aid Battery Configuration
and Axis Orientation

Figure 463

6.944

WATTS 7.0
6.0
5.0
4.0
3.0
2.0
1.0
0

.392

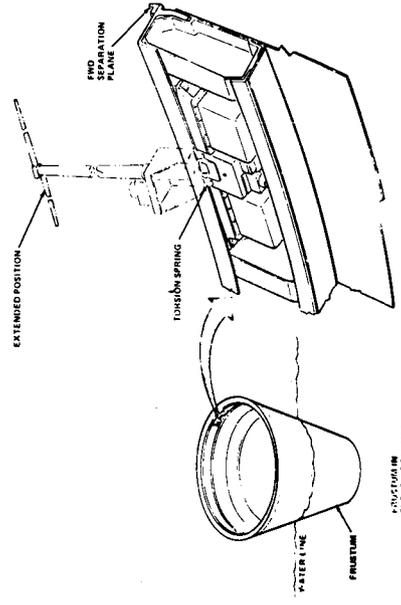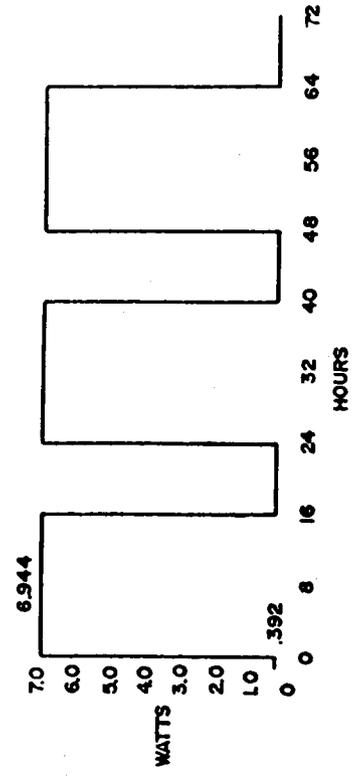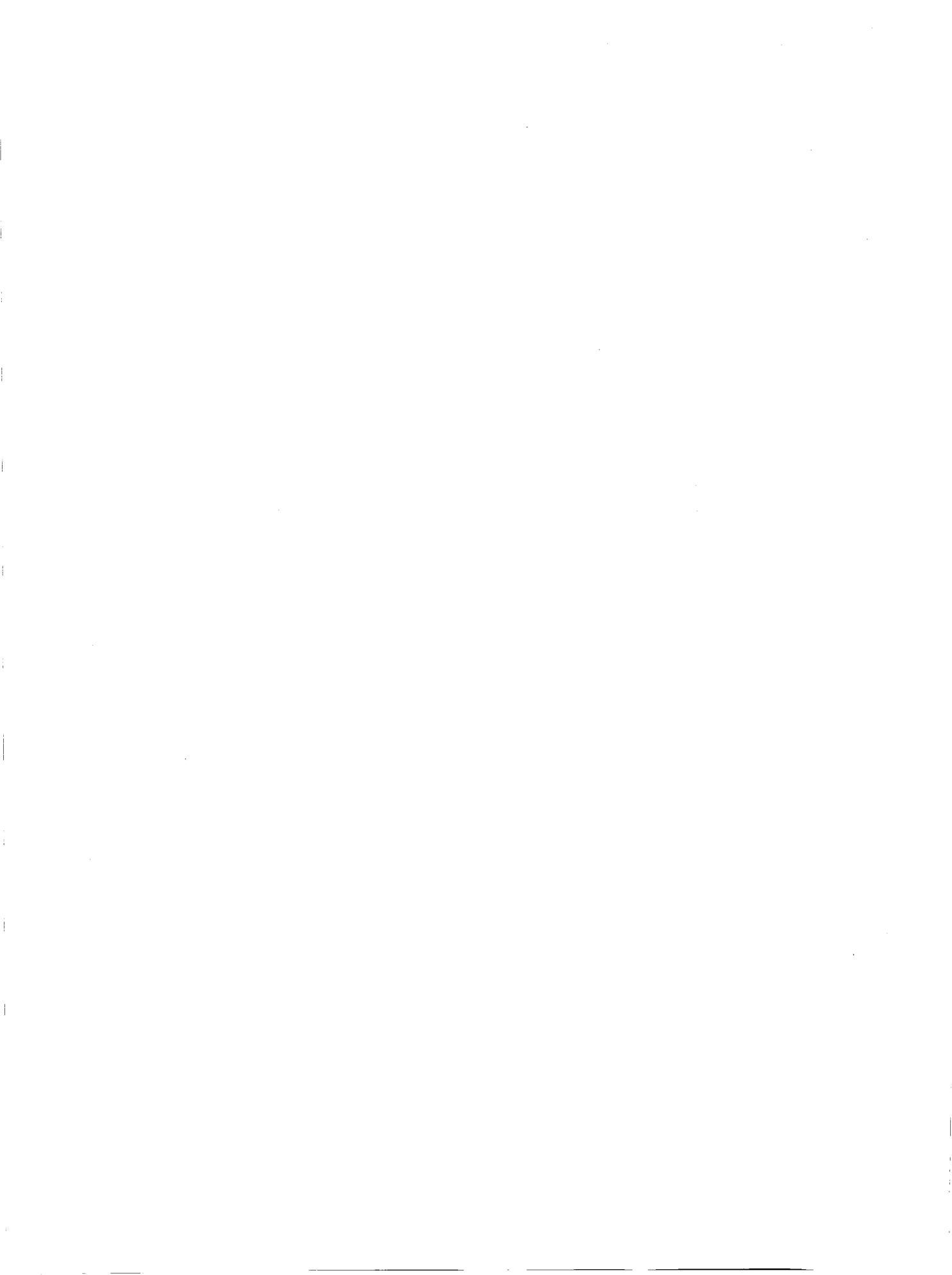0   8   16   24   32   40   48   56   64   72

HOURS

Frustum Location Aid Battery
Power Profile (Strobe Light Application)

Figure 465

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1977 GSFC BATTERY WORKSHOP
November 15 - 17, 1977

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