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THE 1975 GSFC BATTERY WORKSHOP

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GODDARD SPACE FLIGHT CENTER
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INTRODUCTION & KEYNOTE ADDRESS

FORD: I would like to take this opportunity to extend a hearty welcome to all of you to Goddard Space Flight Center. A lot of you are familiar, have familiar faces. Some of you may be here for the first time and for whatever your reasons for attending the workshop, we are glad you are here and we encourage your participation.

The workshop is labeled as a Goddard workshop, but in reality it is your workshop because without you we would not be here today. We have a very busy session today. We have the rechargeable cocktail hour tonight and then tomorrow we finish up the ni-cads in the morning session and tomorrow after lunch we have an afternoon planned for nickel hydrogen.

As in the past, we have kicked off the workshop with a keynote speaker and in view of the current NASA impetus on standard spacecraft, standard systems, and standard components, it seemed most appropriate that this be the subject for this morning's guest speaker. We are honored to have with us this morning a speaker that has spent most of his professional life devoted to the space program. He was involved in the early sixties in a number of Goddard programs including the very successful OGO, Orbiting Geophysical Observatory. In the latter part of the sixties he served as project manager of the highly successful OAO program. Subsequently, he directed a number of study programs at Goddard which has formed the basis of the standard spacecraft concept, so it is with pleasure and honor that I introduce to you this morning Joseph Purcell, Director of the Engineering Directorate at Goddard Space Flight Center and the leader and principal motivator of the standard spacecraft concept. Let us welcome Joe Purcell.

PURCELL: Thank you, Floyd. I feel a little bit taken aback. I suddenly saw the program and saw this was to be a keynote address and Floyd had asked me to stop over and say a few words, so I hope I will have a few things of interest for you and then let you get on quickly with the rest of the day.

I have a personal interest in ni-cad batteries that extends back to the early sixties where in the Orbiting Geophysical Observatory we also were attempting to use silver cadmium batteries and after that exposure, have certainly come to appreciate the nickel cadmium battery. A little bit later on I got involved with the OAO program, the first OAO suffered from a power system failure. So as I became project manager for the succeeding OGO's, you can imagine quite a bit of attention was paid to the design of the power subsystem, batteries, the battery charger, solar arrays and the entire subsystem and in spite of all of that attention several months, maybe four or five months before launch of the next OAO, during the system level thermal vacuum test, we discovered we had a battery problem. The third electrode failed to give a proper signal and on further investigation we found that hydrogen gas was being generated and we really had a catastrophic failure mode on our hands, so with the help of both a lot of contractor and government people there was a real crash program put together to build a new battery with integration at the Cape which we did and flew and that spacecraft lasted 50 months until we finally turned it off because the telescope systems had failed, but the power system was still working well.

And the last OAO is still up there working well after more than three years with, again, a good battery system in it, so that really the battery systems that we are using are the cornerstone of some of their longer-lived missions.

As most of you know, we have started a standard cell program and later speakers will discuss that so I am not going to go into detail, but I would like to tell you how it relates to higher levels of assembly, subsystems, standard spacecraft, into the future.

First, we are serious about standardization. Over the past 15 years Goddard has launched some 100 spacecraft having 25 different types of spacecraft and they were probably 25 different types of battery packs in those spacecraft and we cannot afford to continue that. We don't have the money to put into the non-recurring development of spacecraft which are needlessly alike. We have pushed the standardization, not only at the component levels, but at subsystem and system levels and I see in the future that we will accomplish our missions with perhaps a half a dozen different types of spacecraft and there may be even fewer unique components inside of that spacecraft, like transponders and computers or even batteries.

Now, the spacecraft that is sort of the cornerstone of this new venture is the so-called "multi-mission spacecraft". It is a few weeks away from final approval. It will handle almost all of the so-called "large spacecraft mission model" that NASA has involving over 40 flights. It is modularized at the subsystem level, controls module, communications and data handling module, power system module, and finally a propulsion module and this allows a lot of things. Two of the most unique features, of course, are the ability to service in orbit by removing degraded modules and substituting new modules and finally, it allows subsystem level type of contracts, because it is a power subsystem, an entire entity, with the batteries, the battery chargers. The only thing external to it are the solar arrays.

We will be coming out with an RFP in January for those subsystem modules. The power subsystem is capable of around 1 kilowatt orbital average power up to 3 kilowatts peak. It can have from one -- it has options from one to three 20 ampere-hour batteries or from one to three 50 ampere-hour batteries.

Now, we will, in those specifications, call for a battery pack design that can accommodate either the standard cell now under development and here I am speaking of 20 ampere-hour, or conventional cells. We will require proposals with pricing for both the standard cells and the conventional cells. At the time of contract negotiation, the standard cell option will be selected if it is available. We are not presuming that it will be. We want to keep the option open to go to conventional cells, but we are pushing the standard cell program hard and that will be our main line of course if it is available.

The battery pack itself will be, of course, part of that power subsystem and we will set up the contracts so that battery packs can be ordered separate from the power subsystem, should people have use for them on something other than the multi-mission spacecraft, so we expect a vigorous competition on that power subsystem RFP.

So in conclusion, again, I appreciate you all coming to Goddard every year. I will try to answer a few questions at this point related to the future if you have any, or if not, perhaps we can set up some time for me to come back later.

Yes?

SPEAKER: Will the power system include the solar arrays?

PURCELL: The solar arrays will not be part of the power subsystem. They are considered mission unique. Some missions have two arrays. Some have one array. Some are fixed. Some are driven. We don't consider those as a standard item, although we are looking at the development of standard panels which could then be configured into whatever size array a mission would need.

FORD: Please identify yourselves by name and company affiliation.

SULLIVAN: Ralph Sullivan, APL. Has there been any study to determine a standard voltage or a number of a series of battery cells that you are now thinking on?

PURCELL: The study has been conducted. We have basically settled on the unregulated buss of 28 plus or minus 7 volts for the large spacecraft mission model.

Okay, again, Floyd, I would be glad to come back or Frank Cepollina come back if there are questions that develop later relating to the procurement of the power subsystem and how the standard cell program fits into it.

FORD: Okay. Thank you, Joe.

I believe this marks the seventh year we have had a workshop and in looking back over the past years, it has come to my attention that there are a couple of people here at Goddard that have put a lot of effort into it every year and I would like to acknowledge those people. You are going to be seeing them and talking to them and you all know them, but I would just like to acknowledge one, Gerry Halpert, the prime motivator of the workshop and the principal contributor to putting this thing together every year and also Tom Hennigan as far as their contribution to the workshop.

HALPERT: At this point, I would like to give you just a brief update on the standard cell program.

As you know, there are two phases. The first phase involves the documentation phase which requires the production of an MCD, Manufacturing Control Document, from each cell manufacturer. The Manufacturing Control Document will be a complete document detailing all processes, stepwide procedures the manufacturer utilizes from the plate manufacturing through the end of cell delivery. It will, as we view it, include all QA and QC documentation, all drawings/document numbers, revision numbers, and all of those documents dealing with the manufacture of a cell.

We have assured the cell vendor that this will not give license to anyone other than the authorized government official to go in and look at their plate making operation. They are entitled to a proprietary operation and obviously, plate making is one of those operations. We are going to assure through this contract that the documentation does exist, that measurements are being made, and that the cell manufacturer is living up to his requirements under the contract for standard cells. The documentation will be maintained for a minimum period of five years so that he can then reproduce the cell to the same documentation over that period.

(Slide 1)

As you see, we have awarded at this time four contracts with the vendors shown. They are in the process of producing the MCD's. We have received at this moment four advanced copies. Actually, I have received three, one, I understand is here at Goddard somewhere, draft copies of the non-proprietary documents. These are documents which they agreed to ship to us for our review. The proprietary documents would be reviewed at the premises of each manufacturer. Two of the draft copies of the master MCD which will include all documentation, have been reviewed at the facilities and they are being upgraded and updated to encompass all of the requirements.

(Slide 2)

The second phase, will be awarded based on the performance under phase A. The basic for award is the inclusion of all required documents and the meeting of the standard cell work statement. Upon meeting those requirements, we will then award contracts for building standard cells in the following manner; we are going to build 40 sealed flight quality standards from which we will select 22 for our first standard battery. The remainder of the cells as shown under A, B, C, and D in the second section there will be used for testing at either NAD Crane or other facility to determine what the characteristics of these standard cells are.

HALPERT: The only specifics at this moment are that the capacity range has to be within 22 to 26 ampere hours with a tolerance from the average of plus or minus five percent, that the cell be within an envelope which was shown last year at the last workshop and it weigh less than 1 kilogram. We haven't put a requirement on the actual weight. We assume that the manufacturers will, in their MCD, have a weight with a tolerance requirement in there.

We are scheduling the award, or start work, on January 1st. We assume that we will have the cells in house at nine months after the award. Now, the key thing about this operation is that we hope to be able to select those 22 cells from the cell manufacturer's data, not wait and do a cell selection at the standard battery vendor's facility as we have done in the past with primes who selected batteries based on their own testing. This is an anticipation of trying to reduce costs by eliminating the major cost item, namely, all the additional testing and, or course, to reduce the wear out on the cells.

Following this will be, as Joe Purcell mentioned, the Standard Battery Program. These available standard cells fitting into that envelope will be fitted into a Standard Battery design which will be the output of a contractor selected for developing the ZOAH Standard Battery package. That will come later on next year, as indicated.

That is all I have with regard to the standard cells. Does anybody have any question with regard to the present situation, the standard cells, or where we are going?

Please identify yourselves by name and company.

GROSS: Sid Gross, Boeing. Gerry, is the geometry of the standard 20 the same as the geometry of the existing 20?

HALPERT: Yes. The geometry was selected so that a cell can fit within an envelope which is the accepted envelope for all manufacturers. In other words, none of the manufacturers will be precluded or have to redesign their case. Another one? Yes?

KRAUSE: Stan Krause, Hughes. Gerry, you said one thing that worried me a little bit and I wonder if you could refresh my memory also about the level of general industry participation in the evaluations and the direction that the standard cell is going, because as I see it, some day you are going to come to a Hughes or a Boeing or TRW and say, "You have got to use our standard cell." We are responsible for it in building your standard batteries. You guys have designed it the way you want to design it, and now on top of that you are talking about reducing costs by eliminating a lot of testing which we have done in the past which we may feel is relatively important. Is that the way you intend to go? Is there going to be any additional industry participation in the design of the standard cell and what are your general plans in that regard?

HALPERT: We are essentially not designing the standard cell. We feel as though the vendors, the cell vendors, have much more experience and knowledge in building cells than we do as contract monitors and as technical people from this end, so the cell vendors are being asked to themselves come up with an MCD which details their process. All we really are asking for is for them to document their own process and for us to be assured that certain measurements are made as they say they are going to make them. If plaque thickness is an important property, we would ask that they make that measurement, that they tell us they are going to make it and what the requirement is, who is going to make it, how often it is being made. That is all we are asking for. We just want them to document their process. We are not telling them how to do it.

With regard to the relationship between a vendor and a prime, it would be up to the vendor and the prime to work out an arrangement. If the vendor wants to show the prime certain aspects of his process, that is certainly up to him. We are not requiring him to open up his facility to anyone, that it would be on a relationship with you and him.

Now, we are also not saying that we eliminate all testing. Obviously, some testing has to be done, but all we are going to do is eliminate the redundant testing of having manufacturers, the cell manufacturer, go through a whole series of tests, come out with data and which essentially matches cells under the same conditions and then have a prime go and do the same thing. All those tests that would be additional would be as we see them, tests that would be required for his particular mission rather than another set of cell matching. Now, we would like to minimize that because we already have the data. We have to do the cell selection from the manufacturer's data. Does that answer your question?

KRAUSE: It answers the question. It doesn't allay my fears.

HALPERT: We aren't in a position to be able to say obviously, we can do it or we can't do it. This is the direction we are going and we would certainly hope that that would be the way. It also depends on the manufacturer's testing ability whether he can test in a uniform way so that we are sure that we have a match. Our concern is about lot-to-lot variations and I will say something about that tomorrow. We have fears and we have concerns ourselves, and this is the goal we would like to look for. This is where the cost saving really is going to come. The cost saving is not going to come on a cell basis as we see it, in talking about standardizing the cells and low cost office supporting us on this. We don't think we can lower the cost on them, per cell, because we are asking for more testing, but we think we can lower the cost by reducing the amount of electrical testing that we do. That is where we think we can save.

Any other questions or comments?

HELLFRITZSCH: I haven't been to the last few of these. Hellfritzsch. I represent myself. I take it from the papers or the Vugraphs I saw there, that each vendor will prepare a master set of drawings including his non-proprietary and his proprietary data and then these 54 cells will be made each by his own. The real test of whether or not you have an adequate MCD is whether someone else can take the set of drawings that you think describes everything and duplicate what the vendor whose drawings we are talking about makes. Has any thought been given to that?

HALPERT: That is okay for wire wound resistors, but in the battery business and the nickel cadmium business in particular, there are different processes and to set up one process that would encompass one manufacturer's operation and have everybody do that same process would be extremely difficult if not even impossible.

HELLFRITZSCH: Well, the only reason I bring this up is that the experience we have had in trying to get the same sort of thing is that even the most conscientious man often does not write down things that are pertinent. They may do them the same way all the time and then once in a while because of a change in personnel, the guy that does a certain thing which is not written down, the other guy does it a little differently and all of a sudden the quality isn't the same and yet all of the items which have been written down were done in identical fashion.

HALPERT: Well, we are quite concerned about that aspect of it and that is why we have required that as part of the quality documents that the stepwide testing, all tests done, the frequency of tests, the responsibility of the individual, all will be required for each step of the process, not only at the very end. We don't want to just take a cell and see that it is 1.2 volts and say, "Okay, you made it just like the last one." We are going to start and by accepting at the various levels. If they haven't met the plaque requirement, we are going to be concerned about that and if they haven't met the impregnation level, we are going to be concerned about that, and these are going to be documented. These tolerances will be documented.

HELLFRITZSCH: Okay.

HALPERT: Any other questions concerning standards? Okay, if I can now deviate for a moment -- oh, another question? Why don't you gentlemen come have a seat? There are plenty of seats up here.

SPEAKER: Gerry, what test or verification do you people at Goddard plan once you get these cells in?

HALPERT: Well, there are a whole series of tests and they are fortunately not under the standard cell program. They are part of the follow-on program with the standard battery. There will be a series of test that Crane has done before which we will include. Characterization tests, accelerated tests, chemical analysis and life tests.

HALPERT: At this point we will begin the first of the regularly scheduled sessions. This session is on separators.

Our first speaker for this morning, as indicated on the first slide here, Hong Lim is going to speak on separators.

LIM: I am Hong Lim from Hughes Research Laboratories. I am going to talk about stability of nylon separators this morning. We have been studying the stability of nylon separator material for ni-cad batteries in accelerated conditions.

LIM: This is a continuation of the study on which Dr. David Margerum gave an introductory talk last year. The studies are still going on and this is another progress report. Hermetically sealed ni-cad batteries are extensively used in space applications, but the failure mechanisms which control their lifetime are not well understood. Several of the important problem areas of the ni-cad batteries may be related to the stability of the separator which is widely used in the batteries, loss of overcharge protection, cadmium migration, internal short formation, separator dry out, gas pressure build up, and dating of cell voltages are the examples of the problem areas which might be related to the separator stability.

(Slide 3)

LIM: First I would like to talk about possible pathways of nylon degradation in ni-cad batteries. There are three possible ways. One is hydrolysis followed by further oxidation, electrochemically or chemically by molecular oxygen or chemically, the direct oxidation of mylon and followed by further oxidation of the primary product, and direct electrochemical oxidation.

This morning I would like to talk mainly on the first pathway and a little bit about the second pathway. The sample that we use is Pellon 2505 nylon woven felt material which is widely used in space ni-cad batteries. The material was identified as Nylon 6.

LIM: The hydrolysis reaction was studied in flooded conditions in 34 percent KOH in sealed teflon tubes. The temperature ranged from 110 down to 70 degrees. The 70 degree one is still going on and we are planning to study it at lower temperatures in future studies. The reaction was followed by three methods, decrease of the sample weight, change of the average molecular weight, and by chemical analysis.

(Slide 4)

LIM: This Vugraph shows the weight decrease as function of reaction time. This is heterogeneous reaction. The theoretical rate equation is not available at this moment. However, it is important to know the rate constant at different temperatures in order to extrapolate the rate data to the battery operating temperatures which is olose to room temperature.

(Slide 5)

LIM: We plotted 2/3 power of the weight decrease against the reaction time and this plot empirically gave us straight lines and we took the slope of the straight line as the relative weight constant at different temperatures in order to get the activation energy.

(Slide 6)

LIM: We did the same thing on the change of the average molecular weight of the sample by the weight of the viscoscity average of molecular weight. We took a log of the average molecular weight and plotted it against the reaction time. Again, empirically it gave a straight line and we took the slope as relative weight constants at different temperatures.

(Slide 7)

LIM: This activation energy plot by two different methods gave 19.7 kilocalories per mole of activation energy by the weight decrease and 19.3 kilocalories per mole by molecular weight change. These two data agree very well, indicating that an empirical method of obtaining the relative weight constant is working well, but the actual value of the activation energy is discussed later.

LIM: A chemical analysis shows the main hydrolysis products are the six aminocaproate acids. However, the quantity of the six aminocaproate acids analyzed did not account for 100 percent of the weight decrease, meaning that there was a small amount of unknown compound which we are planning to analyze.

(Slide 8)

LIM: The mechanism of the hydrolysis is shown here. This mechanism was suggested by others as a result of the study of the base hydrolysis of caprolactam which is a cyclic monomer of Nylon 6. The reaction is by molecular reaction first order and the concentration of the substrate first order and the concentration of the hydroxial ion and given the overall nylon reaction of this, the nylon reaction is nylon reacts with hydroxial ion to give 6 aminocaproate.

(Slide 9)

LIM: The next thing I would like to discuss is the effect of oxygen on the reaction rates of nylon. We studied the reaction of the nylon in 34 percent KOH solution at 100 degrees under one atmospheric pressure of oxygen and the weight decrease data is compared with the hydrolysis reaction which is in nitrogen. This is shown in this slide, on the Vugraph.

LIM: The reaction in the oxygen is a little bit faster than the hydrolysis reaction, indicating that it is a contribution of direct oxidation by molecular oxygen. We are planning to study this reaction in further detail, but I would like to point out that this oxidation reaction, even though it is just a little bit faster than hydrolysis at 100 degrees, it might be relatively more important at lower temperatures because of the higher oxygen solubility at lower temperatures.

(Slide 10)

LIM: The chemical analysis of the reaction product showed ammonia and adipate ion in addition to six aminocaproate which is the hydrolysis product, indicating the mechanism, the probably mechanism of the oxidative hydrolysis, the first mechanism is suggested again by others as a result of a study of oxidation of caprolactam and caprolactam melt. Oxygen attacks the carbon atom next to a nitrogen atom to give a super oxide and giving dicarbonate compound and a compound with carboxylic group and amide group and this amide group would be hydrolyzed in the presence of aqueous KOH so that the net nylon reaction expected is this, giving adipate and ammonia which is confirmed by chemical analysis.

(Slide 11)

LIM: The next topic I would like to discuss is electrochemical oxidation of the primary hydrolysis product which is six aminocaproate. We studied six aminocaproate and caprolactam which is a cyclic monomer of nylon, by cyclic photometry. In 30 percent KOH the nickel oxide electrode and carbon electrode at room temperatures.

LIM: The black curve shown is the blanker cyclic photomogram of the nickel oxide electrode. This couple is nickel 23, a redoxicouple and six aminocaproate is added. An irreversible oxidation peak was observed at potentials slightly annotic to the potential of the electrode couple, while the caprolactam didn't show such oxidation, indicating that six aminocaproate is oxidized in this condition in an appreciable rate, while when the reaction was, the study was repeated, the glacycarbon electrode, no such oxidation was observed, indicating that this oxidation of six aminocaproate might be catalyzed by nickel oxide.

(Slide 12)

LIM: In order to find out what the reaction product of this oxidation is, we electrolyzed six aminocaproate using battery electrodes in 34 percent KOH, again, at room temperature, and analyzed the reaction product by gas chromatograph. The black curve is the gas chromatograph of the aminocaproate solution before electrolysis and after 30 minute electrolysis at about 1.7 C rate the six aminocaproate was oxidized to adipate and further electrolysis shows -- indicates that all aminocaproate oxidized to adipate and adipate is partially oxidized to glutarate and succinate.

(Slide 13)

LIM: As indicated by the reaction, the reaction rate is quite fast. In about -- well, the last oxidation condition was a seven minute at 1.7 C rate and 18-1/2 hours at 1/10 C rate. All the aminocaproate was oxidized to adipate, indicating that the oxidation rate is quite fast and the oxidation of the adipate ion to glutarate and succinate was further confirmed by repeating the experiment using a sample of adipate ion.

(Slide 14)

LIM: The probably sequence of the electrochemical reaction of aminocaproate ion is this; aminocaproate is oxidized to give adipate, liberating ammonia. The adipate which is a six carbon diacid is further oxidized to give a five carbon diacid which is glutarate, glutaric acid, and four carbon diacid and probably three carbon, two carbon, and finally two carbonate.

LIM: We identified ammonia, adipate, and glutarate and succinate by chemical analysis and we are planning to study this reaction in further detail in future studies. The confirmation of this sequence of reactions is important for understanding the overall degradation mechanism, overall degradation reaction of nylon and especially concerning the geometric nature of the reaction.

LIM: We also observed the oxidation, the chemical oxidation of aminocaproate at 100 degrees, giving adipate and ammonia too.

(Slide 15)

LIM: This is the summary of the probably overall reaction of the nylon separator. Nylon separator can be degradated by hydrolysis and reaction to give aminocaproate ion and the aminocaproate ion is further oxidized electrochemically to give adipate or by oxygen to give ammonia or by oxygen, direct oxidation by oxygen or by direct oxidation electrochemically. Every step should give a lower molecular fraction of the nylon which is fed back to the original reaction and the adipate ion is further oxidized by successive oxidation probably to carbonate and ammonia might involve a so-called "nitrogen shuttle reaction" to promote the self discharge of the battery and finally ending up with molecular nitrogen.

The rate lines and the compounds, the pathway drawn by red lines indicate that we were so far working on and a little bit on the second.

We are planning to continue this work to have a complete picture of the overall mechanism of nylon degradation.

(Slide 16)

LIM: Assuming this adipate ion is oxidized all the way to carbonate and ammonia with molecular nitrogen, the overall reaction of the nylon would be this: one monomer unit of nylon would react to 16-1/2 cadmium hydroxide and 12 KOH giving cadmium and potassium carbonate, nitrogen, and water.

(Slide 17)

LIM: We calculated the consequence of 10 percent nylon oxidation in typical 24 ampere-hour ni-cad batteries, assuming that it initially contains 13 grams of nylon and separator and 80 grams of 31 percent KOH solution and 10 to 13 hours ampere-hours of overcharge protection. After 10 percent nylon degradation, the overcharge protection would be virtually gone and 9-1/2 grams of potassium carbonate would be produced and the concentration of KOH would be reduced to 19-1/2 percent from 31 percent and approximately 16 grams of water would be generated and 141 cc of nitrogen would be generated at the standard condition. This indicates, especially the reduction of the overcharge protection that 10 percent nylon degradation by this mechanism is fatal to the battery life.

(Slide 18)

LIM: I would like to come back to the meaning of the values of the activation energy we observed. Assuming that is a hydrolysis pathway, a slow hydrolysis, fast oxidation, neglecting the glass transition effect which is reported to be observed between 40 and 52 degrees centigrade depending on the others reporting the value. In the flooded condition we observed 19.3 kilocalories per mole of activation energy by the average molecular weight change and 19.7 kilocalories per mole by weight decrease method. This corresponds to 6.3 here and 7.1 here for the time and for 10 percent degradation of nylon. This result indicates that the separator of ni-cad batteries would be degradating at a significant rate even on the shelf without being used. Thank you.

HALPERT: Do you have any questions?

HENDEE: Hendee, Telesat/Canada. This isn't my field, but the question I have is how much oxygen is used up in your intermediary processes and your end carbonate result? In other words, the carbonate is the end product. There has got to be a timeframe in there. I just don't understand. Assuming we remove so much oxygen from a cell, some of it is being tied up in the intermediary before it gets to the end, say, carbonate, that we can observe in that cell. Do you have any feel whatsoever for what the percentages are?

LIM: Well, the percentage is indicated by this reduction of cadmium hydroxide. The oxygen would be the continuously generated positive electrode and reacts with cadmium on the negative electrode to give cadmium hydroxide. The reduction of the cadmium hydroxide is the equivalent of using up the oxygen. Is that answering your question?

HENDEE: No, not really. Okay, out of a cell I can observe now much oxygen I have lost, probably due to separator degradation. I can also see build up of certain end products such as carbonate, what have you, but somehow that oxygen is tied up in intermediate processes and I am wondering if I take a look and I know how much oxygen I started out with, I see I have reduced this much, I have got so much carbon, I can't account for the entire -- I can't account for it in a normal electrochemical analysis of a cell. What I am wondering is percentage-wise how much oxygen is normally in that cell, say, running at 25 degrees C? How much is tied up on these intermediate steps as opposed to where I am able to see as an end result, i.e., carbon?

LIM: I guess I don't still completely understand your question, but in the intermediate step we don't -- in my study I cannot predict how much oxygen is involved in the intermediate step but my guess is the percentage of oxygen involved in the intermediate step will not be very important.

HENDEE: Thank you.

MCDERMOTT: Pat McDermott, Coppin State College. I was just wondering if in cells cycled at high temperature you certainly find more carbonate. Do you detect nitrogen and what form would you expect to show up? I mean, you have seen the cycled cells. Have you detected the nitrogen as one of the end products, given a lot of degradation in the separator?

LIM: Well, we didn't study the actual cell, but I heard that some people had detected the nitrogen in the cycled cell. I forget who.

HALPERT: Dunlop, Comsat?

DUNLOP: Dunlop, Comsat. We have two programs that substantiate the work you have very nicely in terms of longterm testing where one program is Telesat's program in which you do an analysis. Those cells have been testing over a period of I think four years now and our cells are over a period of six years now in Comsat IV and we have been making the carbonate level build ups. We would like to know the increase and the shift in precharge. The numbers seem to correlate very well with your numbers except that we were using an activation energy that we got from Dr. Mauer's paper about four or five years ago on the hydrolysis. I think that the interesting thing is that we predicted --

LIM: I guess the worse, then, may not be the hydrolysis because it was obtained by the degradation of the cell by the continuous overcharge, if I understand right.

DUNLOP: That is what I meant.

LIM: So I guess with that activation energy it might be from the combination of the hydrolysis and direct oxidation.

DUNLOP: That is absolutely true. I think the interesting thing was if you take -- the numbers are that if you take a standard cell design the way they are today you generally can predict on a real time basis about seven years lifetime before you will complete the overcharge protection and get some results and we are beginning to approach that point now in the results we have had on a real time basis. We do see the nitrogen build up. We do see the increase on pre-charge about what we would predict. We see the carbonate build up of I think it has been about six or seven grams in the cells and it is approaching a limitation in the overcharge protection very much due to this.

LIM: Thank you.

HALPERT: Before we go on from here, I think we have several more papers on separators and maybe we can defer it a little bit and then come back.

Tom Hennigan is our next speaker on separator materials.

HENNIGAN: For the past couple years we have been reporting on various tests on separators made from different materials and last year we had a grocery list of materials up there from Grace, one material from the Canadian -- some radiated WEX 1242 which is a GAF type material, and the usual nylon. The way we cycle these cells is as before, 25 percent depth of discharge, 25 degrees centigrade. The overcharge has to be kink of tailored for each type of material, but it is of the order of 110 percent and at every 2,000 cycles we remove a cell and it is opened up and analysis is made of the separator and then the whole pack is extracted to determine the amount of carbonate and so forth in it.

(Slide 19)

HENNIGAN: That is the Pellon nylon 2505. We tested it a couple of years ago, but in that cell we had 26 cc's of electrolyte which is quite a bit for a six amphere-hour cell. On the Y axis I have the retention of electrolyte in grams per cc. The electrolyte is hydroxide, carbonate, and water, and anything else that might come up. The X axis shows the number of cycles.

HENNIGAN: We tried a Grace nylon this time and in this one we put I think it is 22 cc's of electrolyte. This seemed to stay fairly stable and putting in 21 cc's in the Pellon cells this time it stayed stable there. One of the problems we had with test 1 was a very high pressure cell, but we could nurse it along and make it run and finally it would settle down and cycle. It is always difficult to determine how much electrolyte to put in these cells with new separators.

(Slide 20)

HENNIGAN: Well, we had some materials from Grace. These appear pretty good. They weren't drying out too fast, but there is one little problem with the set. We analyzed this after we made our capacity check and I think we are reconditioning these cells by driving the electrolyte back into the separator. A couple of years ago I showed tests where we cycled about 10,000 cycles and we took a cell out before we reconditioned and after and you could definitely see an increase by about a factor of two in the amount of electrolyte in the separator.

HENNIGAN: One of the ones here that came out pretty good was this 32W which stayed pretty stable during the whole test and I have some data to shown that.

(Slide 21)

HENNIGAN: We did have two more materials which was a Canadian material which was used on the ISIS satellite and it is a polypropylene. I don't know why it took this dip, but that is the data we got. The other GAF material which is a WEX 1242 was grafted with acrylic acid by RAI and its performance was fair during the test.

(Slide 22)

HENNIGAN: Here is some typical information on these materials. Pellon is on the top and the initial capacity was 7.6. Now, the capacity, the top number is obtained by running the cell down in cycle and see how much capacity you have to .75 volts. In that case the voltage at the midpoint was about 1.07 which you expect. Then when you recondition or do another capacity check, the capacity is about the same but you have improved the voltage, and you might say it is similar for Grace nylon. You will see most of the polypropylene has really lost capacity but if you've conditioned them they will come back up. It looks like you would have to recondition polypropylene cells of this type to improve capacity and also to improve voltage where nylon build up will hold its capacity fairly well. Also, for information, the voltage at end of discharge at 5,000 cycles is shown. It looks like Grace nylon is doing fairly good and the polypropylenes are coming down in voltage.

HENNIGAN: We will continue these cells until about 6,000 cycles where we take them out and then discontinue the test, but I really feel that those polypropylene cells were really drying out on us and that capacity check we give them puts them back in the ballgame. So I would like to thank the people at Crane for running these tests, Jim Harkness and the fellow who did the analysis itself, Don Lewis. Thank you very much.

HALPERT: Any questions for Tom?

SULLIVAN: Ralph Sullivan, APL. Tom, are these standard cells made by GE or --

HENNIGAN: I am sorry. Eagle Picher six ampere-hour cells. That is what they normally furnish.

SULLIVAN: Okay, thank you.

HALPERT: Yes, Helmut?

THIERFELDER: Thierfelder, GE. What is the definition of a cycle?

HENNIGAN: 25 percent depth in 30 minutes and recharge in one hour.

THIERFELDER: One hour?

HENNIGAN: Try to keep the overcharge down around 110 percent but some you have got to do a little more and some a little less, but on an average.

SCHULMAN: Joe Schulman from PSI. What type of conditioning cycle did you go through?

HENNIGAN: It was timed for 16 hours at 600 ma. and then discharging at a 3 ampere rate to .75 volts.

HALPERT: Sid?

GROSS: Sid Gross, Boeing. Tom, do you attribute the loss of electrolyte retention as a change in wetting and surface tension characteristics?

HENNIGAN: Well, I really don't know. It seems to be a competition going in the cell for the plates and separator, but why it happens I really don't know. Nylon does hold up fairly well as you notice and with an agent, I don't think there is any magic.

SPEAKER: What was the difference in the overcharge voltage between the separator?

HENNIGAN: I couldn't hear you.

SPEAKER: The difference in end of charge voltage.

HENNIGAN: Well, I gave you the midpoint voltage, okay? We take them down to .75, each cell.

HALPERT: End of charge.

HENNIGAN: Oh, I am sorry. As I remember, they stayed fairly constant, 1.45 and 1.42.

HALPERT: Thank you, Tom.

HENNIGAN: Okay.

HALPERT: Our next speaker, Pat McDermott, Coppin State College, is going to speak on some work that he did on cadmium migration this last year.

MCDERMOTT: This is some work that I did during the summer as a summer fellow with the minority colleges program here at Goddard.

MCDERMOTT: I was looking at some of the test results that have come from Crane and some other data to try to see if we could build some sort of a model for cadmium migration and what I have done here is just to outline several, oh, seven or so occasions where we tend to find more cadmium migration and less cadmium migration. Cadmium migration, of course, is difficult to define precisely, but it would be just the movement of active material out of the negative, either redepositing on the surface of the plate or even in the separator area and some tests at Crane have shown that in general the near-earth orbit seemed to have more difficulty with cadmium migration than the synchronous orbits.

When you have hot temperature versus low temperature you have, particularly around 40 degrees and so forth, you have a degradation of the separator and a heavy migration there. High carbonate versus low carbonate seems to increase the cadmium migration quite a bit. There is -- this was shown rather conclusively in a study reported by Barney and colleagues at the Seventh International Power Sources Symposium in 1970. The conclusion that they reached was that high carbonate contents resulted in reduced cycle life due to cadmium migration through the separator.

(Slide 23)

MCDERMOTT: Now, I indicate here a random storage mode test versus shorted or trickle charge test. This was done also out at Crane and the results shown that the random storage which included various charge and discharge regimes coupled with a long open circuit discharge, the cadmium migration was much larger here than with either the shorted or the trickle charged cells.

In other tests the polypropylene separator versus the nylon separator, the polypropylene picked up a lot of cadmium and in the same test regime with the nylon the cadmium seemed to penetrate totally through the polypropylene whereas on the nylon it remained much closer to the surface of the negative electrode.

(Slide 24)

MCDERMOTT: The next, dry separator versus wet. This is very qualitative, of course, but -- and this is possibly related to the type of separator material. When you break down a cell and you find heavy cadmium migration the separator tends to look dryer. This is not quantative at this point and I am not sure what the cause and effect here is. In other words, this heavy cadmium migration dry out the separator or does the dry separator cause more migration?

The last one there, heavily loaded negative versus lightly loaded. Here again it is a qualitative observation and possibly one that we would be looking more to in the future if negative plates are continuing to be loaded as they are. All right, this is more suspicion than a direct data.

Now, just looking at a model of how cadmium migration might take place, we see that several steps must occur for this to happen.

(Slide 25)

MCDERMOTT: One is the generation of a soluble cadmium species in the negative and its transport toward the separator area, toward the positive, and its recrystallization in the separator on the surface of the negative plate, and we did some x-ray defraction on what that material was and several other people have done this and it looks pretty much totally as beta cadmium hydroxide, hexagonal form. We did tests on these polypropylene separators and found almost 99 percent in one and 95 percent in the other.

Now, looking at what might be the mechanism for generating the negative ion, we find here on this charge using a dissolution precipitation model, that the cadmium would pick up three hydroxides and form a cadmiate ion. This would be during discharge. Also, some residual cadmium hydroxide in the cell could pick up hydroxide and also become a cadmiate ion. Then there is some evidence of the generation of a tetrahydroxi cadmiate ion here. Lake and Goodings and others have shown this will occur in solutions of high alkaline concentration. Other possible ions are carbonate cadmium complexes.

Then, two mechanisms for transporting these ions into the separator area would just be a simple convection type migration of electrolyte in and out of the negative plates during charge and discharge and probably the most prominent would be the electroferesis effect where negative ions would be transported by the electric field toward the positive plate and when they reach the separator area we would have reverse reactions here where the cadmiate ion would be reprecipitated and would be reprecipitated as cadmium hydroxide.

(Slide 26)

MCDERMOTT: Now, looking at the solubility of cadmium in alkaline solutions we find here that the cadmium solubility as a cadmiate ion would depend very heavily upon the KOH concentration and the temperature, so it is very temperature dependent and very dependent on the alkalinity just in the range that the cell would operate on, here, probably around 7 normal we find that from zero to 25 there is an increase and a very high increase up to 50 degrees C. Also, with carbonate in solution let us take around two to three normal that we would also have an increase here.

Now, again, the cadmiate species would be this cadmiate ion in the tetrahydroxicadmiate ion and these would predominate with the higher OH concentrations.

MCDERMOTT: Now, here is a table which shows -- this is reproduced from an excellent X report which Gerry Halpert just put out which shows the change in the solubility of the cadmium hydroxide with the changes in the KOH concentration. Now, you stick 31 percent KOH in the cell and you add percharge and you start cycling it. The KOH percent will decrease just by the generation of water during charging and these changes, I think, might be very significant in terms of the reprecipitation of the cadmium hydroxide in the separator. A six amp. cell, for example, between total charge and discharge would range somewhere from 23 percent KOH up to over 28, so you see here that this could range from .8 to, say, 1.25, almost 50 percent change in solubility there.

(Slide 27)

MCDERMOTT: Now, looking now at the transport mechanism, how the cadmiate ion gets into the separator space, I have mentioned two here. There might be more. General convection, we are looking here at the change in the void volume inside the negative plate as you go from discharge to charged negative using just some data from Miller and Thomas. It shows that a porosity change from, say, 50 percent to 67 percent would, in a sense, squeeze the electrolyte back out into the separator area during the charge-discharge cycle. Just a little calculation on a six ampere-hour cell, if you totally discharged it, you would change the void space in there by a couple of cc's. Now, of course, this is not in an operating cell. This wouldn't be hard and fast because you would have blockage of pores and so forth, but there is a notable migration of electrolyte in and out of that negative.

Electroferesis probably accounts for most of it. Here I show some results reported by Meyer at the fall meeting of the Electrochemical Society where he took cadmium hydroxide, put it into a 34 percent KOH solution and increased the carbonate concentration. It ranged from .8 to 9 percent. The data shows very dramatically that the increase in the carbonate ion increases the weight of the cadmium hydroxide which is migrating and this, we assume, is again in the cadmiate ionic form and the mobilities down here would show a significant strength of the field for moving these negative ions.

(Slide 28)

MCDERMOTT: Now, if we get the negative ions into the separator area we have got to talk about the recrystallization process and here I am relying a lot on the precipitation, dissolution-precipitation reaction of charging and discharging and the crystal growth.

Now, if we look at what effects crystal growth, we see that small crystals will generally be formed in highly saturated solutions whereas in more dilute or less saturated solutions we will grow large crystals and let us look at here the factors which would indicate more or less saturation.

MCDERMOTT: The first two are higher temperature and higher alkaline concentration. In the previous slide we saw that the cadmiate ion was more soluble and therefore less -- you would have a less saturated solution at the higher temperature and higher hydroxide. The same, of course, over here, that lower temperature, lower hydroxide, the solution would be more saturated.

MCDERMOTT: Looking at lower discharge rates and higher charge rates, in the case of the lower discharge rates, the dissolution reaction would occur more slowly and so would as a result, the precipitation reaction, so you would have less cadmiate ion around and therefore a less saturated solution, therefore, this would encourage larger crystal growth. Also, with the higher charge rate the cadmiate ion here would be -- would form the cadmium more quickly and therefore this would be removed at a faster rate and therefore you would have a less saturated solution. The same logic would hold over here that for higher discharge rate and lower charge rate you would have a more saturated, highly saturated solution so the crystals would tend to form more quickly in the negative plate itself.

Now, I am assuming here that the factors which encourage large crystal growth will also encourage more cadmium migration, for two reasons. One is, in a less saturated solution the cadmiate ion would have more time to be moved out into the separator area either through electroferesis or convection and after it gets out there if you have conditions which will precipitate larger crystals, then you will build up a residue in the separator area which is difficult to dissolve and we found, for example, in the polypropylene separators that had heavy cadmium migration that we had a difficult time dissolving the crystals even in the solution that we use normally for the analysis of cadmium hydroxide to dissolve the cadmium hydroxide. I am not sure at this point why this occurred but this very heavily concentrated ammonia extraction solution did not dissolve these crystalline growths very rapidly.

MCDERMOTT: Comparing the near-earth orbit with the synchronous orbit, now relative to each other, near-earth versus synchronous, the near-earth is going to have a lower discharge rate and a higher charge rate. Now these are relative terms again. If you are discharging to 25 percent in 90 minutes, that is going to be a lower discharge rate than, say, the 72 minute discharge to 80 percent for the synchronous orbit. Higher charge rate, you have to put back 25 percent in 90 minutes whereas here you have to put back 80 percent in maybe 16 or 20 hours. So you have different relative rates here and we did notice this higher content of cadmium migration.

MCDERMOTT: Looking, too, back to the higher temperature more cadmium migration and higher temperature, we can see that the solubility here would be different and also in the case of the carbonate, now, you intend to have a less saturated solution with the carbonate and therefore encourage more deposit of cadmium. Looking at the storage tests -- I don't have the slide with me which shows the large amount of build up in the random storage mode as opposed to the shorted or trickle charge, but we might look at some of this in terms of the mechanisms that we have discussed.

In the random mode we have long periods of open circuit discharge. Now according to the work of Okinaka and Whitehurst and others they show that long periods of open circuit discharge will build up very large crystals on the negative surface. The reason for this, again, is that dissolution-precipitation reaction. You have less saturated solutions and encourage this large crystal growth, so long low rate discharge maximizes the conditions for crystal growth.

The charge-discharge regime would promote convection and, of course, you always have the electrical field present for electroferesis. In the case of the shorted cells you have the maximum amount of cadmium hydroxide present but you don't have a build up of the cadmiate ion via the discharge reaction and you have no or little convection there and no electric field so the shorted would tend, according to this model, not to give you the intense cadmium migration.

MCDERMOTT: Also, on the trickle charge, we would have a minimum of cadmium hydroxide present because it is fully charged. I mean there will be a lot of it there but it is minimum at that point. You have some cadmiate ions via self discharge but again you are working against the continual charging process. There is no or little convection in terms of the charge-discharge reaction, although you have a continuous agitation of the separator area by the oxygen generated at the positive plate, so this would tend to retard crystal growth. Electric field is present so you would have the electroferesis.

MCDERMOTT: These are just some -- working on some basic hypotheses about the growth and retardation of crystal growth. I think we can begin to explain some of the migration of cadmium. Thank you. Any questions?

HALPERT: Any questions for Pat?

SCHULMAN: Bill Schulman. What was your trickle charge -- what C rates do you mean by this trickle charge?

MCDERMOTT: I am not sure about the exact figures, but C over 30.

HALPERT: Yes?

WROTNOWSKI: Wrotnowski, GAF. Did you have a theory why polyprop. tended to migrate more than nylon?

MCDERMOTT: This is a hard one at this point. I think with the -- I didn't mention some factor which I think is also important, the growth of the plates and the squeezing out of the electrolyte of the separator. Now whatever mode we are thinking of, of why polyprop. has less electrolyte in it than nylon, if the polyprop. has less wettability than nylon, then the plates are competing for that electrolyte with it, so let us say the plates are loading up with more of the electrolyte. Then you would have more of this convection present, all right? So that might be one possible explanation.

Also, if you have a dried out separator with the charge and the discharge you will have a continual movement of electrolyte into that area and back out again and here we have the possibility of increasing the size of the crystal growth. If it is wet, okay, you would have the migration of the cadmiate ion. As it is drying out, the cadmiate ion has less tendency to dissolve, so it will tend to occupy that space until the next charge-discharge, which would tend to build it up some more, but that is rather speculative at this point, yes.

SEIGER: Seiger, Yardney. When you add electrolyte to the polypropylene versus nylon cells, are you making any compensation for characteristics of the material? Are you using the same amount of electrolyte in both cells?

MCDERMOTT: I think, Tom, when that test was set up, were the electrolytes gauged for pressure and so forth or were they pretty much the same?

HENNIGAN: I think in the first test they were flooded and then it was spun and dried out the electrolyte and then it was given a cycle and it wouldn't come up to capacity and you may add two or three cc's, but they had to balance out of the pressure because it was pretty hard to do but I say, the cells that had polypropylene had 23 or 24 and the nylon had 26.

SEIGER: You did have it, then.

MCDERMOTT: Yes.

SEIGER: I would like to make another comment, something in retrospect that we observed. Cadmium hydroxide is a semi-permeable membrane.

MCDERMOTT: Yes, okay, so that the cadmium hydroxide stays on the surface of the plate, of the negative plate.

SEIGER: You have cadmium hydroxide in the solution.

MCDERMOTT: Yes.

SEIGER: And you have a possibility of an electrolyte air exchange.

MCDERMOTT: Yes.

SEIGER: Due to the trapped air. You would be getting a less concentrated solution going inside the electrode due to the increasing amount of cadmium hydroxide on the surface.

MCDERMOTT: Yes.

KRAUSE: Stan Krause, Hughes. I want to compliment you on a very clear organization to the presentation. However, our experience, I think, seems to be the opposite of what you have been observing. We have found that in our low-earth orbit or accelerated life test that the growth of large crystals was almost never observed at the high charge and discharge rates. As we think would be expected, it does not promote large growth, but rather, small crystal growth and our experience is that the large crystal growth occurs on synchronous orbit tests and in almost every instance it seems to be related to the degree of electrolyte retention in the separator.

Without doubt, every cell we pull apart that has high cadmium migration has a dry separator.

MCDERMOTT: Has a what?

KRAUSE: Has a very dry separator.

MCDERMOTT: Yes.

KRAUSE: Cells with wet separators do not have cadmium in them, in the separator, but I just want to point out that our experience is somewhat the reverse of perhaps what you have observed.

DUNLOP: Dunlop, Comsat. I don't know if you can answer this question, but one thing that has been taking place in the battery industry is there are a number of different cadmium electrodes, primarily process variables such as concatenation, et cetera and those seem to have, just in our experience, more effect on cadmium migration than all of the other things you talked about.

MCDERMOTT: Yes.

DUNLOP: I just wondered if this, since there is such a controversy these days over, at least in my opinion, over what the best choice of negative is, the question is, has this been part of your study?

MCDERMOTT: I didn't go into the teflonation. I am not sure all the results are in terms of life testing and longterm effects, but the early results would show that it would cut down the migration which I think would be obvious through convection. I am not sure electroferesis, how permeable the teflon is to this migration of the cadmiate ion, but certainly in terms of convection it would cut it down. Yes, Tom?

HENNIGAN: I think you showed the result of teflonation some years ago. I don't remember the numbers on it, but it considerably reduced the cadmium migration.

MCDERMOTT: What might also be occurring there is that whether the cadmium migrates off the plate, the separator can get imbedded into the surface of the soft plate just by means of the pressure in the cell so that the teflon could be acting just as a barrier there so that the fibers don't get intertwined with the deposit that is on the plate surface itself.

DUNLOP: Is it consensus, then, that the teflonation reduces cadmium migration? Is that what Goddard says?

FORD: Yes, I would like to comment on Stan and yours and then leave a lot of this to this afternoon when we talk about open discussion because this is the very type of thing, I think we will have to really get down and address in rather detail. To answer your question, from our experience in testing teflonated cells in low-earth orbit, that the tests we ran we did find considerably less cadmium migration in the cells without teflonation and bear in mind teflonation may mean many things to different people because you have got different ways of doing it, all right? Also, there are different levels that are referred to.

The second thing I would like to -- the point I would like to make in regard to Stan's interpretation that they are getting entirely different results. What we are comparing is predominantly near-earth orbit cycling or a synchronous orbit. Bear in mind the synchronous orbit cells at Crane with the exception of those cells that are labeled for specific projects like ATS, were made prior to 1970 and therein I think may lie a major difference in what we are comparing. You are not buying the same cell today, not by a long shot, that you bought in 1970. Chances are you will never buy it again, but the point is, we are comparing apples and oranges every time we stand up here and compare results and until we establish a common denominator which I hope we can get into in this discussion this afternoon, until we establish some common denominator, we are going to continue to piecemeal these problems to death.

Now, it is our experience from the tests we have conducted at Crane, that cadmium migration is not a problem inherent in synchronous orbits. However, I will go on record as saying for a near-earth orbit ultimately it is the failure mode we have to contend with and we have seen the symptoms and missions for years and beyond, end of life.

(Brief recess.)

HALPERT: Our next speaker is Lee Miller from Eagle Picher who will speak on some new developments.

MILLER: The application of a thin teflon barrier to the negative or cadmium electrode in the nickel-cadmium system has been of some interest to both the battery manufacturer and the battery user. The presence of a thin layer of teflon on the surface of the negative electrode was believed to offer the advantage of reducing or eliminating cadmium migration which is known to occur in present systems over time. The obvious disadvantage is the existence of the teflon material may increase the internal resistance of the cell and reduce its useful power.

Approximately three years ago Eagle Picher initiated a study to evaluate different teflonated negative electrode designs. We considered the successful achievement of a suitable design would result in the elimination of a potential failure mode and significantly enhance the reliability of the nickel-cadmium system. This paper is concerned with the results of this study.

May I have my first Vugraph, please?

(Slide 29)

MILLER: Basically, we looked at three different teflonated negative electrode designs. The first one I will refer to as the slurry process in which the negative electrode was just simply dipped into a slurry of teflon in a suitable solvent and we tried rolling it on and we even tried bringing a little paint brush and painting the material onto the electrode.

The problems that we experienced with this design was that the cell performance was always subject to a high charge voltage and a high discharge voltage. The layer appeared to be just too thick for the cell to function properly and we couldn't really apply it by that method then enough to achieve the desired results.

MILLER: Next we looked at the spray process. This was considerably better and we did get some results, good results. However, it was difficult for us to reproduce. It seems like in some occasions you get the spray on just right and the next time it will be too thick and in addition we had indications that the teflon applied in this manner wasn't entirely permanent. It seemed to be some change in it when you examined the cell after a number of cycles.

MILLER: The last process, we had an idea that possibly we could just find a film, a negative, a teflon, that could just be applied around the electrode just like a separator material. This resulted in an investigation of a large number of candidate materials which was really one of the problems with that process. However, with each investigation, we seemed to get data which indicated the direction to be taken and finally, working with a vendor of this teflon material, I think we came up with a particular material which we buy to our specifications and the spec. calls these parameters thickness, density, porosity, and gas permeability. We had experienced some rather satisfactory results with this. Could I have the next Vugraph, please?

(Slide 30)

MILLER: I think we have got those in the wrong order, Dale. Let us try the -- all right, that is fine. This is just typical acceptance tests I think that most people in the room are familiar with, that nickel-cadmium cells are subjected to. You can probably compare the results here to other cells that you are familiar with. We had two cell designs, two three ampere-hours and two 50 ampere-hours sealed nickel-cadmium cells. This was pretty much our standard design and used Pellon 2505 non-woven nylon separator material. They were tested at the normal temperatures, 75 degrees fahrenheit, 32 and 100 degrees fahrenheit.

As you can see, the voltages were really out of line. At the 75 degrees, the voltages I think are maybe just slightly higher than a nickel-cadmium cell without the film in it. We were somewhat surprised that the film seemed to greatly help the recombination of the oxygen generated. These cells, as you cab see by the test parameters, have all gone way into overcharge, but are operating at a very low pressure.

At 32 degrees about the same results were achieved. The voltage is probably slightly higher, but it is still, I think, an acceptable voltage for that temperature and that charge rate. Again the cells were well into overcharge and still operating deep in a vacuum. At the high temperature we really thought the pressure would climb at this temperature, but again the cells operated at very satisfactory voltage and again for the most part stayed in a vacuum.

Let me have the next Vugraph, please.

(Slide 31)

MILLER: We then took the two 50 ampere-hour cells and put them on a simulated near-earth orbit cycle and accumulated a total of approximately 3,000 cycles. The testing went on beyond the cycle that is reported there to about 3,000 cycles. The voltage, I think, was still satisfactory and the cells stayed in a very deep vacuum. I think the performance was very satisfactory.

Next Vugraph, please.

(Slide 32)

MILLER: These same two cells after completing the 3,000 near-earth cycles were then subjected to a simulated synchronous orbit cycle regime. The temperature on the first series was 80 degrees. However, the temperature was not adequately maintained and they climbed to a higher temperature. Actually, probably in those latter cycles from about approximately 44 on up to 300 cycles, I am sorry, up to about 110 cycles, the temperature was around 100 degrees fahrenheit.

This test, the cells finally did climb to a positive pressure but they reached equilibrium at 10 PSI. The cells were then placed into a temperature chamber and the temperature closely controlled and put on an accelerated synchronous orbit cycle which is simply a charged 12 hours and the same 1.2 hour discharge. These simulated synchronous orbit cycles went on for a total of 300 cycles. However, we moved our operation from one building to another and lost some of this latter data, but still the cells went back into vacuum and operated continuously in a vacuum, deep vacuum.

Let me have the next slide, please.

(Slide 33)

MILLER: This is just simply a data graph of one of the cycles. It happens to be one of the higher temperature cycles. The cycle number is listed up in the legend and I think it is pretty much self explanatory. It shows the pressure coming up and reaching equilibrium at that 100 degree fahrenheit temperature at around 10 psi.

I believe I would like to have the slide now.

(Slide 34)

MILLER: This is actually one of the electrodes taken from one of these cells after completing the 3,000 near-earth orbit cycles and approximately 300 synchronous orbit cycles. The electrode is probably about 1/3 of the way into the stack. It is about in the center. It is on the outside edge. If you can see here, this is the negative electrode and you can see the teflon film. As I stated, it just simply wrapped around the electrode just like a piece of separator material. The teflon has the physical characteristics that it bonds itself together and you can form the sealed edge all of the way around the electrode where it is broken over. There is nothing protruding except the electrode, electrical tab.

The separator material, in our design, is wrapped around the positive electrodes and these two surfaces here that you see exposed were adjacent to negative electrodes in the cell. The slide doesn't really show this, but the separator is remarkably free of any indication of cadmium migration. We were fortunate in that in the construction of one of these two cells the teflon film when they inserted the electrode in the cell actually pulled the film down leaving a moon shaped slice in this fashion here that was not protected by the teflon film. On that piece of separator material there was the distinct moon shaped grey shadow of cadmium migration.

I believe I will have the next Vugraph, please.

(Slide 35)

MILLER: In summary, I think that the teflon film that we have developed really offers these advantages: it has a simple application during cell fabrication. It is a commercially procured material which may be obtained in large quantities exhibiting uniform characteristics. The material is pure teflon. There are no additives or process treatments used to convert to a secondary form for application. We have developed simple but discriminating quality control measures to assure that we get the product which we have developed. I think this is important here, that the critical interface between the teflon film and the negative electrode surface is a physical-type contact but no physical bond exists. Reactions, changes, occuring at the negative electrode and other mechanical blistering, flaking, or gassing, would not effect this interface.

The teflon film really has a strength in its own right and serves as an additional separator material. The material exhibits like I already pointed out, strong tendency to adhere to a cell which allows forming sort of a bag around the electrode in the fabrication process.

The immediate future that we see for this process is we are fabricating additional cells which are to be put on a longterm cycle test to further evaluate it, but the material at this point looks very good to us. Thank you.

HALPERT: Are there any questions of Lee? Yes?

THIERFELDER: Thierfelder, GE. What is the thickness of the teflon film?

MILLER: It is approximately 2 mils.

PARK: Park, consultant. What about the increase in the internal resistance of the cell?

MILLER: Like I pointed out, the only indication that we could see between this and just the standard cell without the teflon was just that very slight increase in the voltage on charge.

SEIGER: How much electrolyte did you put in and what accommodations did you make inside the cell for the extra 2 mils per separator?

MILLER: The cell, of course, has to be designed for the increase in this thickness. You just have to take the thickness out of the electrode or the cell has to be made that much wider. The electrolyte is just, I guess you would say, just our standard quantity that we activate the cell and there is no provision made to change any of our standard processing to add this film.

ROGERS: Howard Rogers, Hughes Aircraft. Is there any process used to make the film wettable or is it already fairly wettable?

MILLER: No, there is no process used to make it wettable.

ROGERS: Is it already wettable?

MILLER: No.

HILL: Freeman Hill, Westinghouse. Who makes it?

MILLER: I don't think I would like to disclose my source on that if you don't mind.

HILL: You said it is commercially available.

MILLER: Right.

HELLFRITZSCH: In addition to thickness you mentioned about three other items that you buy in procuring it. Can you tell us the porosity and the numbers on that?

MILLER: The thickness and the density, the porosity, and the gas permeability.

HELLFRITZSCH: Yes, but what are the numbers?

MILLER: Again, I would not like to disclose those numbers.

FORD: Ford, NASA Goddard. Is there any indication that with the use of this teflon layer that you can, in fact, put more electrolyte in the cell and get the same acceptable, quote, "acceptable", unquote for those parameters?

MILLER: Yes, there is indication that the cell will operate with a greater amount of electrolyte without the teflon film in it.

FORD: Do you have any idea how much?

MILLER: No, we don't have any quantitative information on that.

GROSS: Sid Gross, Boeing. When teflon is used in fuel cell electrodes to maintain a three-phase interface, one of the problems is over a long period of time, wettability changes. I would think that would be a real critical factor in this application to determine that it is -- whether the longterm effects would change the wettability and whether increases in wettability would make a significant change in performance. Do you have any information on that subject?

MILLER: Again, nothing quantitative. Like I said, the film, there is no provision made to make the film wettable. As a matter of fact, we tried teflon films that were intentionally made to be wettable and they did not perform satisfactorily, so --

GROSS: That suggests that if this film for any reason were to become wettable due to changes, due to the longterm operation, that there could be a problem.

MILLER: That is possible, yes.

FORD: Ford, Goddard. Did you say you used nylon in these cells?

MILLER: Yes, this was the nylon Pellon 2505.

HALPERT: Okay. Thank you, Lee. I want to make sure that you please identify yourself and your company affiliation clearly because the only way you can hear is through those microphones up there. We don't have anybody listening for your names, so please speak clearly so we can identify you for the records.

Our next speaker this morning as we get away from the subject of separator materials, but along on the subject of electrolytes is Dr. Lee May of Catholic University who is going to speak on electrolyte distribution and potentials.

MAY: To make, perhaps, for a better understanding of how the cell operates, we started to make calculations on the open circuits, voltages that occur in the nickel-cadmium battery in potassium hydroxide solution, also in the presence of carbonate.

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MAY: These calculations were made while I was holder of a summer faculty fellowship this past summer here at Goddard. The calculations are based upon the usual set up of the induction. The potentials, for example, for the overall cell, nickel-cadmium cell, they were writing the reaction as usually it is written, 2NiOOH + $2H_2O$ plus cadmium going to 2NiOH taken twice, plus CdOH taken twice and the potential, the open circuit potential, equilibrium potential, would be equal to 1.299 plus 8.619 times 10^{-5} time the temperature, times the natural log of the activity of the water. The constant I am using here involves the numerical value for all of the constants involved in the equation.

Since the activity of the water is related to the vapor pressure above the solution divided by the vapor pressure of pure water, we need values for vapor pressure for various potassium hydroxide solutions. This has been evaluated by Burrow and Kahn in the form of the pressure is equal to a constant times E to the minus a constant over the temperature. If you take the logarithm of this last expression and put it into the Nurss (?) equation for the open circuit potential, we then have an equation which involves directly in terms of the constants for the potassium hydroxide solutions and as a function of temperature.

These, then, lead to calculations which give us the open cell potential at various temperatures. There was very little change in the potential at various KOH concentrations with the temperature, but you will note the change in the open cell potential as a function as we increase the KOH concentration.

MAY: The change perhaps can be exemplified as going from, let us say, in the range of 20 to 40 would give us a change of roughly 10 millivolts and the variation with temperature was extremely small.

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MAY: The next type of calculation was involved with the individual positive and negative cell potentials. In calculating for the positive potential one has to involve also the activity of the hydroxide ion. This can be evaluated when one knows the activity coefficients of the KOH solutions which one can obtain from measurements actually made by Akiloff (?) and Bender from EMF measures, and then one could evaluate the activity of the hydroxide ion and from that calculate the potential for the negative half cell and the positive half cell. I would like to point out that these are written as reduction potentials and there is some confusion in the literature. Some people write the half cells as oxidation potentials. Some times they write it as reduction potentials. Some times they are kind of mixed up. I think it would be easier if everyone wrote the potentials in this form.

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MAY: This plot shows the potential of the negative and the positive as a function of the KOH concentration. Again, the change with temperature is rather minimal and you can note the change that we have at each of the half cells. There have been similar calculations by Falk which confirm, as well as experimental measurements which confirm these calculations here. Halpert has made some calculations of the change in the KOH solution as a function of the percent of depth of discharge. You will note that as we go from full charge to 100 percent depth of discharge there is a change in the KOH concentration from 22.9 to 29.8. This is for a six amp. AH cell. The change in the open cell potential goes from 1.291 to 1.285, a change of roughly six millivolts.

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MAY: The next part of the calculation involves the use of carbonate solution. The effect of the carbonate in the cadmium and nickel-cadmium cell would be solely to change in this, using this kind of calculation, solely to change the activity of the water so that we use the same equations as before but it was necessary to determine the activity of the water. If we know the vapor pressure above solutions of potassium hydroxide in the presence of carbonate, we can then determine the activity of the water. Walker has made a series of measurements of the vapor pressure at various concentrations of carbonate and also at various concentrations of hydroxide and at various temperatures so from this data we can calculate the activity of the water or directly in terms of this equation.

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MAY: The results of these calculations for the open cell potential for the whole cell is given here. You will note that as the potassium carbonate increases there is a diminution in the open cell potential. The change from low KOH concentration to high KOH concentration increasing carbonate becomes much larger at the higher potassium carbonate concentrations.

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MAY: Again, the change over various temperature ranges is very slight. In the case of the calculation of the open circuit potential for the positive and for the negative, again, these involve also the activities of the OH ion in which we have to know in order to calculate the activities of the hydroxide ions, we must know the mean activity coefficient. The mean activity coefficient of the hydroxide ion is influenced by the presence of the carbonate. Kamio Mashia (?) published a paper in which they measured the vapor pressures over mixtures of carbonate and hydroxide and they also measured the mean activity coefficient of a variety of mixtures and over a variety of temperatures. Unfortunately, not quite in a range that we needed it, so we had to find the means in which to find the mean activity coefficient in the particular solutions we were dealing with and this can be found by the Harnitz (?) rule which related the log of the mean activity coefficient equals the log of the mean activity coefficient in the hydroxide solution when there is no carbonate present, minus a constant alpha times the molality of the potassium carbonate.

This constant alpha is a function of the temperature as well as the molality and this has to be obtained by graphical integration and from this we could calculate, then, the potentials of each of the half cells which are given here. On the top we have the potentials. As we change the carbonate of the negative electrode, this is with low potassium carbonate present and going up in the top we have an increase in the potassium carbonate. You will note that as we go up the potential becomes less negative, so the addition of the carbonate decreases the negative potential of the negative electrode. Note that from zero to roughly four percent we have a very large decrease in the potential at the higher KOH concentrations. Not as large at the lower KOH concentrations.

It is interesting to note at the lower KOH concentrations, as we increase the carbonate concentration there is a large increase increment in the potential, whereas at the higher KOH concentration the addition of a small amount of the carbonate has less of an effect on the potential.

On the positive side you will note that the effect of the carbonate, of a small amount of carbonate, is to lower the potential and as you increase the carbonate the potential increases even going higher than the potential where there is no carbonate present.

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MAY: We did a calculation which involved what might happen to the open cell of one circuit potential as a function of time. Last year at this conference Van Omeron (?) presented the figures that there is an increase of 1.16 grams of carbonate per year. Using this calculation and taking the percent of the KOH in a cell at 29.07, let us say, let us start as our baseline, zero time, no potassium carbonate, the potential is 1.280. If we assume that we have roughly eight percent of carbonate in the average cell, then the potential drops to 1.278. With the increase of 1.16 grams per year there will be an increase in the carbonate and assuming that the carbonate only comes from the plates we would have a change in the percent KOH and we will have this increase in the percent of carbonate and a change in the open circuit cell potential where there is a decrease of roughly .002 volts per year.

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MAY: The presence of carbonate in the cell gives rise to, or sets up a number of other half cells. For example, we would have the nickel carbonate half cell and the cadmium carbonate half cell, the nickel carbonate half cell of course is the positive and its potential would be a function of the activity of the carbonate.

Likewise, the cadmium carbonate, cadmium coupled at the negative electrode would be a function of activity of the carbonate. Unfortunately, there is no data available to allow us to evaluate the activities of the carbonate half cells. In addition to those cells being set up, we would have a nickel hydroxide, a cadmium carbonate cell set up in which the potential would be a function of the activity of the hydroxide, activity of the water, and the activity of the carbonate, so there is no way to calculate at this present time how this potential would vary with the carbonate concentration.

The final electrode system that would be set up is a nickel carbonate cadmium hydroxide -- I am sorry. It is not the final, but this would be again a function of the activity of the carbonate and the activity of the hydroxide. The final one would be a nickel carbonate cadmium carbonate where the potential is not a function of the concentration. It would be a constant of 0.29. Now, we can consider a nickel-cadmium cell with the carbonate present as a series of cells in parallel.

MAY: The top one, of course, would be the nickel-cadmium hydroxide. The second one would be nickel hydroxide cadmium carbonate. The third would be nickel carbonate cadmium hydroxide and the final would be nickel carbonate cadmium carbonate. I have listed them in order of their equilibrium cell potentials and you might consider that since they have the electrolyte in common that the electrolytic resistance will be in common.

One analysis of this might include that first the nickel hydroxide cadmium hydroxide cell would discharge. The second cell would take over and so on down the line. A highly speculative passage of the voltage with time would then be given by this lower curve where the plateau is of each of these potentials. Recognizing, of course, that these are the potentials where the activities of all of the components are equal to one. There is some evidence where a study has been made of a cell which was allowed to sit on the shelf. It started at 1.44 and after a period of time it went down, the voltage went down to 1.23 volts.

Another analysis might involve the concept of mixed potentials where we would consider first the nickel hydroxide cadmium hydroxide and then the development of a mixed potential with the nickel hydroxide cadmium carbonate. These are rather difficult to try to calculate because you have to know the over voltages that are involved and other factors such as the current which might be involved in the formation of these electrodes. Thank you.

HALPERT: Are there any questions for Lee?

LIM: Is there any effect on the theoretical analysis of the solubility of cadmium hydroxide? For example, I understand that the activity of the cadmium hydroxide is taken as a unity and is that going to be effected by the solubility, at different temperatures and different concentrations of carbonate?

MAY: Well, this is a problem because we are not -- the particular species of the cadmiate depends on the KOH concentration. In other words, you could have KOH four times, KOH three times and some of the literatures indicates that we have present these species, so this is a very difficult kind of calculation to make because we would have to know the equilibrium constants between the various cadmiates to know which one was present at a particular hydroxide concentration. We can define the cadmium hydroxide solid as activity if we would want, but we would still have to make mention of this in solutions of this nature, so this is even further away than the carbonate and then, of course, in the carbonate you have the cadmium carbonate which would also be a soluble species with its own activity.

HALPERT: Any other questions or comments? Okay, our next speaker is Stan Krause of Hughes who is going to speak on new reference electrode technology and technique.

KRAUSE: I am going to open my presentation by making some excuses. I wasn't supposed to be giving this presentation. Dr. Schoenfeld (?) of our organization, unfortunately, couldn't make it. He handed me his Vugraphs at the airport before the plane left and asked me if I would give it. I debated. I decided I wasn't going to and then Bill Edgar (?) talked me into it.

Just last year, of course, Dr. Schoenfeld made a presentation related to the work we do on cell analysis. We have some fairly extensive procedures which are developed. Very recently we have developed an apparatus for reference electrode that can be inserted into cells without disturbing them before we tear them down to try to find out how the individual electrodes are behaving and our primary objective is to try to relate to techniques to measure precharge because there has apparently been controversy in many instances over what the specific precharge measurements of a cell mean. Some people use the overall cell voltage when it goes through zero voltage and reversal. They then measure the negative capacity until it reaches, say, negative one volt, or negative 1-1/2 volts. They say that is the precharge. Other people are using gas measurements. When they observe the presence of oxygen they know the positive is essentially depleted of capacity and then they look for hydrogen when the negative runs out of capacity.

In this instance we think that the use of the reference electrode allows the measurements to be made in an undisturbed cell without tearing it down.

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KRAUSE: We have added a pressure gauge and we also use a gas chromatograph on the apparatus to measure the gases as they come off. We can also play some games with it and modify the amount of precharge or the overcharge protection and study the effects on the performance of the electrodes.

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KRAUSE: This is kind of a schematic of what the set up looks like. We are using an apparatus in which we can mill off the weld of a fill tube on a cell which has been pinched off, open the fill tube where it has been swaged, and insert this apparatus. We can do that under nitrogen and keep -- and then reseal the cell with the reference electrode assembly. It is a mercury mercuric oxide reference. We have separator material at the tip that is inserted until it is in contact with the separator right above the plates. We use a platinum wire buried in an essentially 50-50 mixture of mercury mercuric oxide and as you can see, it is connected to a gas chromatograph port. It also goes to a vacuum pump which is actually attached to water displacement apparatus for measuring the volume

(Slide 46).

KRAUSE: I will show you some of the results that we have gotten recently. As I say, we have really just gotten started with it. I am not going to show you anything spectacular. I don't pretend to understand some of the results we are seeing so far.

We took a cell that had run through about 4,000 cycles and the four hour type of orbit. This particular one actually had a polypropylene separator. It doesn't make any difference apparently, and we discharged it down. The interesting thing about it is we got relatively clean results on both the positive and negative voltages from the reference. The other interesting thing is that at this point where it was obvious that we were in a negative limiting condition, we were getting quite a bit of hydrogen out of the cell, apparently off the positive electrode which I really wouldn't expect at that point, so we don't know what it means but we see in the reference it does work and we are going to continue trying to relate some of the strange bursts of gas that we are getting at different point in the discharge to these voltages and maybe next year we will have something more interesting to show you.

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KRAUSE: I have another piece of data that we have collected on another cell in which we overcharged the cell, imbedded it to bring the negative up to full capacity, and as you can see, the cell was, of course, positive limiting, but the dotted line on the negative was kind of interesting. The voltage on the negative, the polarization changed kind of drastically right at the point just after the positive went into reversal and we are not really sure why, but the little dotted lines that you see are where we are doing current interruption and we are looking at the components by using current interrupter circuits. We are trying to measure the components of IR loss, activation, polarization, and concentration polarization and as you can see, with the interrupted current on the negative at that point, even though the polarization shifted drastically, with the current interruption the polarization on open circuit would look relatively normal.

That is really all I have to report. As I say, we have just gotten started but we think that reference electrodes might play a little more useful part in -- when people are doing cell analysis and trying to measure precharge and understand what it means as well as to determine the specific performance of some of the components in the cell as a result of aging and cycling.

That is about it.

HALPERT: Any questions for Stan?

SULLIVAN: Sullivan, APL. I am not sure I understood one thing you said. Were you saying that you saw an evolution of hydrogen at about 1/10 of a volt negative, that sort of a thing? Is that what you experienced?

KRAUSE: Yes. We were seeing hydrogen.

SULLIVAN: On conventional cells?

KRAUSE: Yes, one that had been cycled, however, for some period of time.

HALPERT: Dr. Scott?

SCOTT: Scott, TRW. How long after interrupting the current were those interrupted current voltages measured?

KRAUSE: The voltages are measured immediately. We have measured response time in microseconds. The current interruption periods were about 15 seconds duration, the total interruption was a 15 second duration, but we measured those voltages at the end of 15 seconds. However, we are measuring the components down at microsecond response time to look at the IR loss which of course was fast.

SCOTT: Doesn't the voltage immediately after opening the circuit change rather rapidly for the first fraction of a second or several seconds?

KRAUSE: It changes rapidly in microseconds, primarily the IR loss, simply IR loss response immediately and then you see a change in the slope due to primarily concentration.

SCOTT: What I am getting at is what portion of the difference of the two voltages is IR and what part is not?

KRAUSE: I can't tell you. I don't have the details. I am sorry.

HALPERT: Bill?

WEBSTER: Bill Webster, Goddard. Stan, if we wanted to contact your laboratories, is it possible to get some more detailed information on the actual technique or is there internal documentation of this that you would disseminate to other laboratories if you wanted to follow this experimental approach?

KRAUSE: We put the thing together on company money. There may be some problem in divulging the specifics of the apparatus but it is really very simple. It is pretty much standard reference electrode technique. There is nothing very exotic in it.

WEBSTER: I was referring to the mechanical technique, Bill, the electrochemical.

KRAUSE: Well, let us talk about it.

HALPERT: There is a question over there on the far side.

SPEAKER: Is it possible your dips in you reference readings are caused by gas reactions on your platinum wire? You might be better off using a silver wire.

KRAUSE: Yes, we thought about that. We thought about other little dips caused by changes in the KOH content of the separator during the course of this. We have some more work to do. However, we ran a bunch of control tests on the electrode to find out which of those kinds of things were artifacts. When we first started we did get quite a few artifacts that were artifically induced due to changes in the KOH concentration right where the reference is in contact with the separator.

However, we think this is real and you may be right. We will continue to look at it and try to reduce all those strange things so that at least whatever is strange, we will know that it is real.

SPEAKER: If it helps, is the ideal any better than seeing these cells too (?) and now the people who use salt electrolytes are seeing that.

KRAUSE: Very good.

HALPERT: Floyd?

FORD: Ford, Goddard. You showed the little dip in the negative and I think you implied you weren't sure what that was attributed to?

KRAUSE: Well, I can guess. One of the things is, of course, that the positive runs out of capacity and goes into reversal. The current density on that negative might shift pretty drastically and that is a possibility.

FORD: Has there been, by any chance, a correlation with that dip with when you vented the cell to relieve the pressure?

KRAUSE: No, no. We did that before this discharge started.

FORD: So it was vented during the whole discharge profile?

KRAUSE: No, no. We resealed it at the start of the discharge. The cell was sealed, and we were measuring gas volume.

FORD: Okay.

KRAUSE: So we are not sure really what it is.

FORD: Yes, but when you reversed this you started getting gas but you had to relieve that pressure, right, to keep it from building up?

KRAUSE: No, we let the pressure go up to a limit, obviously. At that time we were using a pressure limit of like 80 psi and at that time we will begin venting to measure the gas volume. But we didn't vent at that point.

HALPERT: Okay, thank you. On the subject of analysis, there were a couple of questions from Dr. Cheh of Columbia for Pat McDermott.

CHEH: I have two questions about your presentation. On one of the Vugraphs you showed that you processed the nickel electrode potential and the cadmium electrode potential as a function of KOH concentration and also potassium carbonate concentration. If you take at a given level of KOH concentration then you see a maximum of electrode potential from zero to four percent on K_2CO_3. Then it comes back down, essentially, towards 40 percent and then the other interesting feature is that -- or the same thing apparently is observed for the cadmium electrode and I am just wondering what causes this? Instead of the mathematical formulation what is the physical basis? Why should this thing go through a maximum and come back down? Is there any reasonable explanation?

It has something to do with the activity of that.

KRAUSE: The activity, right.

CHEH: Right. But why should it go from zero percent to a high value and then as the potassium carbonate concentration decreases it started coming back down?

KRAUSE: At the moment I can't answer your question.

CHEH: Okay. I think that the second question I have is that I feel that when you have coupled potentials and things like that that you correctly pointed out the mixed potential is in this and I didn't quite understand that when you put four cells in series and electrolyte resistance what actually happens and what makes that -0 it is sort of an equivalent circuit. I don't quite understand that figure.

MCDERMOTT: In my circuit I had them in parallel.

CHEH: Right.

MAY: This I did after consulting with electrical engineers.

CHEH: I am not an electrical engineer.

MAY: Well, I consulted first with electrical engineers and read my old electrical engineering text of 50 years ago, and in fact they do consider systems like this as batteries in parallel.

CHEH: I see. It has to be a mixed potential?

MAY: Oh, yes, there is no question about that, that that would be perhaps a better approach to most of them.

CHEH: Okay, thank you.

HABPERT: Are there any other questions in regard to separators or some of the analysis work that was done here this morning? All right, then I think we will just move on into our second subject. Floyd Ford is chairing the second program.

FORD: Cell manufacturing.

FORD: We are getting a jump on the afternoon session and I am kind of thankful for that because I think it is going to give us more time to get into some of these very deep discussions, questions, debates, and deliberations this afternoon. I guess the session, when I thought of this session on cell manufacturing one of my favorite commercials on tv came to mind, and that is this girl that advertises cigarettes saying, "You have come a long way, baby," and I think that is where we are today with cell manufacturing. We have come a long way. We have just begun to scratch the surface, and I think, and I am very optimistic that the next five years are going to be double rewarding what the past five years have been, particularly, and further increase in uniformity of products, reproducability.

There is no greater frustration than to have a flight program get into a bind simply because the last lot of cells had different characteristics than the lot we initially flew on the first spacecraft, but as I said, the commercial explains my feelings altogether. We have come a long way but we are still on the uphill pull, so we are going to talk about cell manufacturing. I think we have about five different discussions along those lines.

The first one is appropriately led off this session by Dr. Harvey Seiger with Yardney Electric and his topic -- oh, you withdrew?

SEIGER: Yes.

FORD: Oh, beg your pardon. Well, now we only have four left. Okay. Moving on, then, we have a topic called "Teflonated Negatives" and that is Stan Krause of Hughes Aircraft.

For the benefit of those I am going to be calling on and I don't want to surprise anyone else, the one to follow will be "ni-cad results, the Results of Battery Tests on Ni-cads" by Dr. Scott of TRW. Following that will be "Nickel-cadmium Manufacturing Problems in QC" by Sid Gross of Boeing and then the last one will be a paper on "Effects of Pulse Charging". Stan?

KRAUSE: I want to talk about some of the results we have been getting with teflonated negatives on an internally funded IRD program whose objective really started out to test cells at very high depth of discharge for synchronous application and along the way we started to look at teflon as well. We have not flown any cells at Hughes with teflonated negatives but we are obviously interested.

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We have got a test which is on-going at the moment which we run 46 day eclipse seasons on a real time basis similar to synchronous orbit load profile. At about 20 degrees centigrade the maximum depth of discharge which occurs in the middle of the eclipse season is about 100 percent based on a rated capacity of the cell. We are running six amp.-hour cells in this test.

We run a one week reconditioning between the eclipse seasons so it is sort of a quasi-synchronous test. There are no storage periods and that is obviously going to effect the results of the test to some extent.

Theoretically, we have heard this morning, that teflonation can produce a better balanced electrolyte distribution which in turn either is the cause of or in some way effects retardation of cadmium migration and potentially we think that with better separator wetting there might be some reduction of voltage fading over the long term although this necessarily has not been demonstrated.

KRAUSE: The results that I will show you just very briefly summarize it. I didn't want to take too much time. They are on the comparison of teflonated cells versus non-teflonated cells with Pellon 2505 separator after four eclipse seasons. We are up to 10 eclipse seasons now and we are getting ready to do some more cell analysis.

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KRAUSE: Very briefly, we think the results were significant, even in the four eclipse seasons. The cells with teflonated electrodes had 50 percent less electrolyte within the negatives than the same cells without teflonation. It is obvious that the negative was running much drier and that teflon was acting as a membrane or water barrier, which one would expect.

Additionally, we analyzed the separators for electrolyte content separately and found that there was between two to three times more electrolyte in the nylon separator running in cells with teflonated electrodes than those without, and as I am sure we will get into in the discussions later this afternoon, I think this is significant to the longevity of the cell in terms of keeping that separator wet.

KRAUSE: The third item that we think resulted form the test was that we found that the cadmium migration was virtually negligible, at least at this stage. It will be interesting to see how it is done after 10 of these simulated eclipse seasons.

The other thing that was kind of interesting that I am not sure I really believe was that the discharge voltage at the end of discharge in the maximum eclipse was slightly higher on cells with teflonated electrodes, than those without. I would have expected that the teflonation might result in a slightly lower voltage, but in this case it was slightly higher although not substantially, as you can see, about 10 to 15 millivolts. That is all I have.

FORD: Yes?

SCOTT: Scott, TRW. Your first slide or one of the first, said that there was some kind of reconditioning or conditioning between eclipse seasons. What did that consist of?

KRAUSE: Yes, right. That consists of a C/2 discharge down to about 1.15 volts. We purposely reconditioned these similar to the way it is typically done in orbit as opposed to the way some people do lab tests. They stick individual resistors on cells. Sometimes it effects the results. We recondition them in series like a battery. There are 76 cells running. We recondition them 24 at a time. We run it down to an average voltage of about 1.15 volts per cell at C/2 and then we recharge it for 24 hours at C/10. We run two of those cycles and that is it.

FORD: Harvey?

SEIGER: Seiger, Yardney. Did you have the same amount of electrolyte in these cells that had teflon that is usually put in?

KRAUSE: To my knowledge, yes.

SEIGER: Thank you. I have one other question. Since you put the same amount of electrolyte in, you are finding less in the negatives, more in the separator, or perhaps unchanged in the separator. Do you also find more in the positive? Or the same?

KRAUSE: Yes, we did analyze the electrolyte in the positives and I am trying to remember specifically the numbers. I believe there was a little more hydrate in the positives since the separator was wetter than one might expect.

SEIGER: Thickening of the positive measured?

KRAUSE: Not enough to make a difference between the two. Not enough to be really discernable.

FORD: Gerry?

HALPERT: Halpert, Goddard. What about the beginning? Did you analyze those sample cells' negative plates and separator and was there a difference right in the beginning before you even started cycling?

KRAUSE: No, we did look at them in the beginning and there was really no difference.

HALPERT: No difference in the amount of electrolyte in them?

KRAUSE: No, not at that point. Of course, that would all depend on how you cycled them or whether they were sitting on the shelf two months before we looked at them and allowed the electrolyte to come to equilibrium. It is possible that that -- because the cells had been sitting around for a while before we did the analysis.

FORD: Dave Baer?

BAER: Baer, Goddard. How was your cold temperature capacity performance?

KRAUSE: I believe it looked essentially the same. These were six amp.-hour rated cells. They all put out about 7-1/2 amp.-hours. We ran standard acceptance tests as we would with flight cells, both the 25 C. and zero C. and they looked like they were both over 7-1/2 hours, both at zero and at 25.

MILLER: Miller, Eagle Picher. What sort of electrode design was this, Stan?

KRAUSE: The electrode design was proprietary and General Electric.

MCDERMOTT: McDermott, Coppin State College. Did you do any porosity measurements before or after or do you think this is important? How would you try to explain why this electrolyte goes down after cycling?

KRAUSE: What do you mean how it goes down?

MCDERMOTT: Well, you say you end up with less electrolyte in the teflonated electrodes. What would suspect is the reason for this and do you have any measurements which would -- like porosity, which would tell you about the void space and so forth?

KRAUSE: No, we didn't do that. However, the beginning of life analysis shows a relatively low contents of electrolyte in both types of electrodes and we run other cells thousands of cycles and we have periodically gone in and torn a cell down and looked at the negatives and there is an increasing electrolyte content in the negative plate with time and with cycling and it goes up from a low level to a higher level as you are cycling. In this instance it just seems, then, that the teflon retarding that process of the continual pick up of water in the plate.

SEIGER: If I understand that correctly you are saying that you have a cell similar to this without the teflon and you have a certain amount of water in that negative electrode and if you now cycle that the amount of electrolyte in that cell increases, but if you start with teflon you have about the same amount of electrolyte in the negative electrode but as you cycle the amount remains unchanged?

KRAUSE: That is what it appears like.

SEIGER: Thank you.

FORD: Any more questions? Thank you, Stan. Next we have a talk by Dr. Willard Scott from TRW systems on the subject of better test results and discussing the performance of plates in different spirals. Dr. Scott?

SCOTT: Would someone like to -- the numbers are not correct. The order is. Before you put the first one on, a few introductory remarks. What I am going to talk about is a particular case that we are following where we are trying to correlate the electrical performance of cells during life testing, in this case, synchronous orbit testing, with the physical and chemical characteristics of the materials that went into the cells in the first place by consideration of manufacturing data and data that we are obtaining from sample materials gathered during the manufacturing phase of the cells.

This work is still in progress and it will be much more complete maybe next year than it is at this time, but I would like to show you the interim results that we have today.

SCOTT: The results were obtained from an Air Force sponsored advanced development program aimed at developing a 1 kw. battery for use primarily in synchronous orbit and the program involves manufacturing and testing 1 kw. batteries with -- some with nylon separators and some with polypropylene separators. The results I want to show you now relate to a battery made with good old Pellon 2505 nylon separator material.

SCOTT: I will have some other data to show you tomorrow comparing the results of batteries made with nylon and polypropylene under essentially identical test conditions. Right now I want to show you a -- some curves obtained during the longest discharges of -- during synchronous orbit testing of this one battery with nylon separators. By the way, these cells are 50 ampere-hour cells made by General Electric.

If I could have the first one on there, please?

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SCOTT: This Vugraph shows complete discharge curves for two cells in the battery during the first eclipse season of a life test. The uppermost curve of the two curves at the top is for the highest voltage cell, highest voltage at the end of discharge. The curve just below it is for the lowest voltage cell in that battery during the first eclipse season of the life test. Now, is there a pointer around?

FORD: You can point on the Vugraph.

SCOTT: These cells all have built in reference electrodes so we are obtaining continuous and exhaustive data on individual electrode potentials while we are conducting these life tests and as Stan pointed out, this is getting us some very interesting data, but the reference electrode potentials with respect to -- this is the negative electrode compared to the reference electrode with the sign changed so that the potential here is positive so we can plot it on the same graph compared directly with the cell voltage curves up here. You can see the reference electrode potentials of those two same cells are relatively flat and don't show too much going on. The two lower curves, this is the current. These batteries are discharging under a constant power load so that as the battery voltage declines, the current tends to increase during the discharge. The lower two curves are the cell pressures recorded here for reference for these same two cells.

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SCOTT: The next Vugraph shows these same situations for the highest and lowest cells on the fourth eclipse season. By the way, this test is being run in a compressed time accelerated program where each cycle is 12 hours long instead of 24 and there are only six days allowed during each eclipse season during which the battery is on continuous trickle charge.

These tests also are conducted at a fairly low temperature averaging around 35 degrees fahrenheit.

First of all, you may note that the two highest and lowest cells are not the same ones that we started with. The highest voltage cell, plotted here, the lowest voltage cell, as you can see, is rolling off and ends up here in a relatively lower voltage. The lower curves, the next lower curves again, are the negative to reference potentials from these same two cells and note here that the cell voltage reflects pretty faithfully the potential of the negative electrode in these cells, and I would characterize this situation by negative limiting.

Again, the current, you see how the current tends to increase more rapidly as the battery voltage decreases more rapidly because of these low voltage cells. I should say, when I say "low voltage cells" I am letting the cat out of the bag a little bit here. This one cell shown here was only the lowest voltage cell and in reviewing the data from this battery it turned out that there were a total of seven cells that were much lower at the end of discharge after several eclipse seasons than the average of all of the rest of the cells of the batteries, and in further reviewing the data it turned out that those seven cells were all from the same cell lot and that the voltage of all of the rest of the cells which were from three other cell lots they used to make that battery were all considerably higher, so we did an analysis by lots.

At this point I should say that in this program we did something a little different in terms of lot control of plates and cells. We isolated the plate material made from each spiral during the manufacturing process and assigned a separate lot number to the material from that spiral and kept those lots isolated all of the way through and so the cell lots in this program each one reflects only a single spiral. There was no mixing of plates between spirals, but there was intermixing of plates within a single lot when the cells were made, so that the properties that we are going to see here relative to lots can be traced back to an individual spiral in the manufacturing process.

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SCOTT: The next Vugraph shows the results of analysis of the electrical performance by lots for this same battery. You see here four lots, 7B, 8B, 10 and 11. For eclipse season one, eclipse season five, and eclipse season No. 8, which is about the last one for which the data was available when this data was compiled. I guess in order to look at this rapidly right now, look at the mean end of discharge voltages on the first eclipse season for which that qual. was shown and the spread is not really too bad and as a matter of fact -- first, I will tell you that lot 11 is the lot from which those low voltage cells were obtained and you can see that it is a little bit below lot 8B but not so much to bring any attention to that at that time.

Coming over here to eclipse season five, you note here that now the average for lot 11 is 100 millivolts less than the average for lot 7B, for example, and almost -- these three lots here are reasonably close together and lot 11 is way down.

Now, after eclipse season five the battery was reconditioned by allowing the voltage, allowing the battery to discharge on a resistor all of the way down to a very low voltage. I will talk about the results of that more tomorrow, but then after that the test was continued and you can see over here now that after that particular treatment the performance of lot 11 is quite comparable at least to that of lot 10 and not too far different from the other lots in the battery.

So the big difference before reconditioning was of some concern and so that we went and proceeded then to analyze the data obtained during manufacturing to a certain extent by these same lot numbers and the next Vugraph will show the results of that.

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SCOTT: The first column here shows the results calculated by the manufacturer for what should be obtained for the flooded capacity during formation for each of these lots and you can see that at least the positive capacities were very close together and actually the net calculated negative flooded capacities for each of these spirals involved in these four lots were very close together. This column shows the net electrolyte weight, an average of the net electrolyte weight for each of these lots and the variation around that average was not particularly large. It is interesting to see this one is -- this average is way above that of the other ones, but again, lot 11 is not the lowest in terms of electrolyte.

Steady state pressure after adjustment during manufacturing, here again we begin to see something showing up, namely a relatively much higher steady state pressure of lot 11 compared with the other three. Number of electrolyte adjustments required before we got a steady state pressure, one for lot 7B and 8B, two for lot 10 and two for some cells in 11, but three adjustments required for other cells in lot 11.

Capacity as measured at the supplier, once again, not particularly alarming spread between the maximum and minimum. These again are averages for each lot. Then similar capacity except to a slightly higher end voltage at TRW. It is interesting that even though our end voltage is higher, we got higher capacities, I believe this is because we maintained a somewhat more rigid temperature control of the cells than was done at the supplier and at a somewhat lower temperature which gave a more efficient charging.

Then after a 30 cycle burn in test which is part of the acceptance test procedure used for these cells at TRW, again, to 1.1 volts, and here again, well here lot 11 did show up the lowest, but the differentials before and after 30 cycle tests were not anything alarming. That is, this differential on lot 11 was actually less than the differential on lot 8B.

Now, from our previous experience we had no particular reason to suspect or reject lot 11 cells based on the data shown here, although by hindsight you can do a lot. In advance of that this data we did not consider to be out of line considering our previous experience with this type of cell. So the higher pressure and the fact that more electrolyte adjustment had to be made in these cells to obtain a satisfactory pressure performance, is suggestive of something interesting going on. We are not sure exactly what. We have obtained during the manufacturing of these cells a large amount of sample material, including samples of the center during the manufacturing process at 50 foot intervals, a sample of all of the powders and solutions and various other intermediates used during plate manufacturing. We have all this stored at TRW and we are going to be able to take a brief look at some of the other parameters that we haven't looked at such as the porosity of the center and other similar properties. However, right now, our capability of doing this is quite limited, but we will have -- we will be taking a deeper look into the details of the manufacturing materials over this next year's time and hopefully we hope to find a more fundamental correlation back in the properties of these materials with the electrical performance that we saw here.

I should say that this material, these four lots, as well as all of the lots of plate material that are being tested on this 1 kw. battery development program were all made within a period of two weeks at General Electric and so we consider that if any plate material is going to be uniform from lot to lot that the material we are working with here is as uniform as the state of the art of present procurement permits. I shouldn't say "present". This material, I should say, was made in 1971 and it was stored under sealed conditions until it was put into cells approximately a year later, so that it is getting along in age, but still we feel it is high quality plate material as far as that period of time was concerned, so we would like to do a lot more wtth this sample material than we have in the past and I hope we will be able to have the opportunity to do that before next year.

That is all I have to say.

FORD: Way in the back?

HELLER: Heller, Hughes Aircraft. You had your capacity after burn in. Did you by any chance have discharge voltage performance for that cycle?

SCOTT: For which cycles?

HELLER: The 30th cycle.

SCOTT: 30th cycle of the 30 cycle test itself?

HELLER: Yes.

SCOTT: Yes, we do have all of that data. I have not looked at that.

HELLER: I suggest if you do you would never have used those lot 11 cells.

SCOTT: That may be right, but again, that was not our criteria at the time. I guess our thinking was that we will give the cells the benefit of conditioning following that cycling and that probably was the basis of accepting those cells.

HELLER: My point is I think that is a very significant parameter for cell selection in battery manufacture.

SCOTT: Good point.

DEBAYLO: Paul DeBaylo, Global Comm. Dr. Scott, can you define the temperature and charge rate that was utilized during your steady state overcharge?

SCOTT: Those were done at the supplier. They are done at room ambient using a C/10 charge rate, usually for periods of 48 to 72 hours.

Jim?

DUNLOP: Just from your -- I think you inferred from your data that the problem you had was a negative one itself, is that correct?

SCOTT: It turns out that all of the cells in the batteries are negative limited. I will talk about that more tomorrow, but this is just one of them.

DUNLOP: All these cells in all these lots are negative limited?

SCOTT: The life tests to date involving cells from all of the lots that we ended up putting into batteries are all negative limited at this point in time, including said batteries made with nylon and those with polypropylene.

DUNLOP: Have you ever stopped that test and taken any of those electrodes out and see if you can discharge them in the flooded condition?

SCOTT: We are right now in the process of a tear down analysis. We have not actually done flooded discharge measurements but I suspect that if we do the capacity will be right back up.

DUNLOP: Well, I am not talking about that. I am talking about whether or not you can continue with this, whether it is really negative limited or limited by your electrolyte.

SCOTT: Well, okay. When I say negative limited I mean just empirically by looking at the voltage. I am not ready to say what the ultimate cause was, okay?

FORD: Okay. Thank you, Willard. Oh, Gerry, do you have a question?

HALPERT: Yes. I was going to ask, since you have spiral data, Will, do you happen to have along with that, loading data for the different spirals?

SCOTT: Yes. The first column in one of those tables is calculated from the loading by using a factor which in experience of the manufacturer relates the loading to the expected flooded capacity of the cell so those numbers indicate the loading. However, those, the measurements made on each spiral to determine loading are only as a result of a grab sample at one end of the spiral and I have no idea exactly how good a measurement that is. Guy?

RAMPEL: Guy Rampel, General Electric. It seems to me, Will, that possibly the explanation lies in the depth of discharge based on the initial capacity. The DOD is higher on that spiral than it is on the others.

SCOTT: Based on the positive capacity data?

RAMPEL: Yes, yes.

SCOTT: Only a few percent maybe, though. The calculated flooded capacity number is -- oh, you mean based on the measured capacity of the cell after completion, not on the capacity of the spirals as determined from loading?

RAMPEL: Right.

SCOTT: Well, okay, but of course, when we build a battery we can't usually compensate for the variations between cells and even between lots I guess. The only choice we would have would be to reject maybe the whole lot or reject all of the cells but the point I would like to make is that we have another battery made in a very similar manner with the same kind of cells or we have the same capacity spread at the beginning of life where no such split based on cell lots occurred in the performance so I don't know what criteria to use.

RAMPEL: The other possibility is since the cells are more negatively limited in that lot, the possibility is that the negatives from one spiral to another spiral started off with less residual charged cadmium possibly. I don't know. You could look at that.

SCOTT: You mean less precharge?

RAMPEL: Yes, on the negative plates prior to added precharge. I am talking about the initial residual charge on the negative spirals as they came out of manufacturers before we added precharge in aerospace.

SCOTT: Well, that is a possibility. If that is so and that can have this much of an effect, then that is something that we should be looking at and I don't know very many people who are looking at that particular parameter.

FORD: Ford from Goddard. One of your Vugraphs you showed electrolyte adjustment. Two questions: Is that adjustment by the manufacturer in the process of meeting acceptance test criteria?

SCOTT: Yes.

FORD: The second one: Would you care to comment on the relative amount of electrolytes between the two lots as a final cell assembly?

SCOTT: Well, I am not quite sure what you are really asking but the data presented there shows that the net final electrolyte quantity in this one lot 11 was comparable to that in two of the three other lots that were in that battery and then there was a fourth lot which was significantly higher in electrolyte.

FORD: Okay.

SCOTT: Harvey?

SEIGER: Seiger, Yardney. In that group, the last group that was giving the problem, there were two to three electrolyte adjustments made. I also noticed that the pressure was higher in that group. Was the adjustment an attempt to take out electrolyte?

SCOTT: The adjustment was made at that time in both directions to try to narrow the range of pressure. The cells showing up with very low pressures had the electrolyte added. This was, I don't remember whether that was standard procedure or something that was arranged for this particular contract, and then, of course, if the pressures are too high, then some electrolyte is removed to try to get the pressure down. In that particular lot 11, if you look at the data carefully it shows that quite a few of the cells on the first run, there is a first 48 hour charge, exceeded 80 pounds, but interestingly enough, more cells in one of the other lots of those four lots also exceeded 80 pounds than for lot 11, yet when they were adjusted they seemed to be performing better, but when this lot was adjusted, the pressures did not come down very far. They just came down far enough to pass the acceptance criteria.

SEIGER: And you have not torn them down yet? You haven't looked at the cells themselves?

SCOTT: We have some of them taken apart. We are starting to look at them now.

SEIGER: Any different visual appearance in the negatives?

SCOTT: None.

DUNLOP: Jim Dunlop. I just want to make one comment somewhat in regard to the general data. We did have to reject a particular lot of cells on the Comsat IV program. Interestingly enough, it was a lot 11. I don't know what is the problem with lot 11. Seriously, the way we discovered our problem which turns out to be a real problem in performance was not through electrical measurement. We discovered the problem when we did the electrochemical and chemical analysis and when we did the electrochemical and chemical analysis we discovered that the manufacturer really had inadvertently put in an excess amount of precharge in the cells to the extent that there was no overcharge protection or practically no overcharge protection of these cells at the beginning of life, but interestingly enough, with no overcharge protection or practically none at all at the beginning of life you can still pass almost every acceptance test most battery manufacturers put on it, so our contention from this has been since that time that straightforward electrical measurements are not the full answer to the acceptance of batteries and since that time we now do an analysis on every, at least two cells from every lot that we fly in any of our space programs and this has been in our opinion a much better way to differentiate between what seems to be questionable lots of cells and acceptable lots of cells.

Since that time, by the way, we only really have run into one lot which it was mutually agreed on to not fly because of some question when we made an analysis.

SCOTT: But the sooner that we can get correlation between that more in-depth type of testing and electrical performance out into the open the sooner I will be able to convince some hard-headed program manager that he can't use those cells no matter how much chemical this and chemical that they have in them and we need more of that kind of data I think.

BETZ: Fred Betz, Naval Research Lab. I agree with Jim. You can build cells and they will pass all young tests with high precharge. I also know that in addition to too much electrolyte giving you a high pressure, it could also be a very low precharge in those particular cells can give you high pressure in the beginning of life and since those cells were negative limited first, it may well be that that is the relationship on those cells.

WADHAM: Wadham, Telesat/Canada. I would like to support Jim as well on this business of the electrochemical analysis. The first lot of cells we had on our Telesat program had a very high precharge and overcharge protection and luck was on our side because these also turned out to be some mechanical leakers and we had -- and the precharge was adjusted right there and on the new lot we have had fairly good results so far but the original lot we have tested in the lab and they, in fact, are now showing extremely high voltages after whatever it is, four years? After four years they are showing extremely high voltages, so I would agree.

SCOTT: I might have one response to that and that is relative to the particular problem during the testing, during the electrical testing that we are seeing, it would appear that if anything, the cells may not have enough precharge at this point in time because they are being limited on discharge. We are not seeing any particular problem on charge but that is because in these batteries we have individual cell bypassing on all cells which control the cell voltage and keep it from going too high.

HALPERT: Halpert from Goddard. I would like to ask Jim Dunlop a question and that is, do you use as one of your criteria exceptions the results of those cell tests, those two cell tests that you do?

DUNLOP: Well, the answer to the question is no, we do not. It is acceptance by -- as from the battery manufacturer. The question is not so much acceptance from the battery manufacturer. The question is whether we are going to accept them for flying in a spacecraft. What we do use them for is acceptance for flying in the spacecraft. There are lots of things you can do with cells when you buy a whole lot of cells for a program and you get a particular lot of cells and you decide you don't want to use them in your spacecraft. Then you put them on some other kind of -- one of your -- you use them as back up, a spare, or some other kind of test, whatever. You just don't put them in your spacecraft and that is what we do with them.

RAMPEL: One more. Guy Rampel, General Electric. One more comment to this. We had four separate lots. Now, that means that we had four different processes, four different times and I want to emphasize a point that I made before. What is different in that fourth lot, at least much different than the other three is the overall precharge level in that lot and we avoid that since 1971, whatever year you stated, by procuring a dry cell.

SCOTT: Are you saying it wasn't used?

RAMPEL: No, it was not but it is now.

FORD: Thank you, Will. I would like to comment, while I have seen the detailed papers to be presented tomorrow, I happen to know that some of the papers are going to discuss or touch on this subject of electrolyte management, precharge, and the effects of it with life tests and setting up the agenda for this type of program is very difficult to get all of the typed papers in one session and not get them inter-mixed, but I think it also has a positive aspect in that it encourages a lot of discussion as we go along.

I would like to move on now. I have one more presentation before we break for lunch and that is by Sid Gross of Boeing and his subject is nickel-cad. manufacturing problems in QC. Sid?

GROSS: The subject of this presentation is electrolyte leakage detection and the work was carried on at Boeing by Larry Eckhardt (?) and myself. The customary method for detecting leakage is with phenolphthalein and it is a very good system. It has some drawbacks, however. Its sensitivity is not as high as we would like. It is qualitative rather than quantitative, and since the detection depends on the OH ion concentration, this changes in atmosphere due to the reaction with carbonate, with carbon dioxide from the air.

We had a number of occasions when we thought we had some leaky cells, but these cells all passed the phenolphthalein leak test so we tried to develop a more sensitive method to do this.

The approach that we settled on was to rather than detect the OH ion we would detect the potassium ion which is also available on leakage and we used an atomic absorption spectrograph as a means for making this detection. We found that it worked extremely well. What we wanted to do is develop a technique that would be used either on a cell alone or on a cell that is already built into a battery. This is the laboratory set up that we used for this.

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GROSS: We took the cell and put it in this fixture with a plastic vial which went over the terminals and it was placed over the terminals beforehand and filled about 2/3 full with double distilled water, which poked through the plastic and then we filled the vial completely with water all of the way to the top, and let it rest for 24 hours to get the complete dissolution of the soluble potassium hydroxide or potassium carbonate into the water and we then measured the water for carbonate content on the atomic absorption spectrograph.

We also ran tests with phenolphthalein for a comparison. The results of a variety of tests are shown on this chart.

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GROSS: We pulled out a number of cells from inventory, some of which we thought were leaking and some which we weren't sure of and the phenolphthalein test showed a mix, some which were found to be leakers by that test and others were not. The comparison which we used for the atomic absorption test was the double distilled water which had a very -- 160 parts per billion was the sensitivity on that particular sample.

In essence, we found that we were able to detect leakage on some cells by this method, even though the phenolphthalein test showed that they were not leaking and this cell here showed a considerable amount of leakage, over 300 ppm. This was shown to be leaking. Phenolphthalein did not, and this one was showed to be a no leaker and probably was not also.

In addition to giving us a more sensitive threshold of leakage, we have quantitative values and using this it is possible to determine leak rate. That is all of my presentation.

SCHULMAN: Joe Schulman, PSI. Did you try taking a plain piece of cover, for example, dirtying it with KOH and try to clean it off and then seeing what you would get just to see if the very tiny residuals that you couldn't clean off was what you were detecting?

GROSS: A cell cover?

SCHULMAN: Yes.

GROSS: We did not do that.

SCHULMAN: Did you try creosol red?

GROSS: No, we did not try creosol red.

SULLIVAN: Sullivan, APL. Were those leaks intentionally induced for the purpose of this test or --

GROSS: No. These were cells which were old and some of them which we knew leaked because we could see it had some carbonate on the cells and some which we thought possibly might be leaks.

SULKES: Sulkes, USAECOM. I think there has been some interest in this type of testing for mercury watch batteries for heart pacers, that type of thing, as well as watches as a quality control method, and I don't know if the results were as clean and as well showed what your test did show. They had a lot more scatter and that type of thing which of course, were not truly hermetically sealed.

END OF SESSION

AFTERNOON SESSION

FORD: Okay, we are going to stray away from manufacturing process and variables briefly to hear a presentation by Professor Cheh with Columbia University. The title is "Effects of Pulse Charging."

CHEH: Thank you. I would like to describe a research project which is currently being carried out in our laboratory at Columbia. The title of the project is "A Study of Pulse Charging Electrochemical Cells" and it is being supported by the Jet Propulsion Laboratory.

Since pulse charging of secondary cells is a relatively new subject and we have only gotten into this area, really, on a part-time basis about a year ago, my presentation will, therefore, begin with a short description of the general background of pulse charging. This will then be followed by a discussion of some of our preliminary results, a few conclusions and speculations based on these results and our plans for future work.

Pulse charging of batteries has only become an area of investigation during the last 10 years or so. However, in a related area, namely electrodeposition or electroplating, the application of pulse or periodic reversed currents have been studied and have obtained practical results since the 1940's.

Now pulse charging involves the application of a series of pulsed currents. Now let me move over here and bring the Vugraphs over.

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CHEH: The two most commonly used methods of pulse charging involve the following wave forms; a straightforward pulse charging consisted of a series of pulsed currents. They are square in shape. It consisted of an on-off cycle and the battery has never discharged. On the lower part of this Vugraph it shows what I called a periodic reverse charging following the terminology from electrodeposition. The currents are still square in shape but the off period of the pulse now is replaced by a discharge current.

Since any charging method other than the straightforward easy method involves somewhat complicated instrumentation, the next Vugraph, on this Vugraph I have listed some of the advantages which have been claimed in the literature concerning pulsed and periodic reverse charging.

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CHEH: The results listed here on the zinc silver oxide cell were mostly obtained from literature from the mid to late 1960's. It was reported that by pulse charging the charge acceptance can be increased. Also, better adherence of zinc electrode was observed. By periodic reverse charging reduction of dendritic formation of zinc was also observed. The nickel-cadmium cell results were only reported in the last five years or so. There are three major advantages. It was reported that gas evolution during overcharge can either be reduced or in some cases completely eliminated. Also, faded cells can be reactivated using pulse charging methods, and finally, there are some indications that the charge acceptance can also be increased by pulse charging methods.

CHEH: Since all of these results were obtained from various laboratories using specific systems, it is generally very difficult to extrapolate the research results without a basic understanding of the process. In our work we proposed a three-step research project to explain the effect of pulsing.

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CHEH: First, we carry out a systemmatic investigation on the effect of pulsing by using half cells involving relatively ideal film electrodes. Concurrent with these experiments, a study is being carried out to understand the three basic aspects of charging, namely, a mass transfer of energy and structure of the electrodes. Finally, actual testing will be initiated with nickel-cadmium batteries to establish a model for pulse charging which may include establishment of a set of optimum charging conditions.

Now, unfortunately, at universities, we normally do not have facilities to carry out systemmatic evaluations of battery performance and we certainly hope some of you may be interested enough to look into that.

I must mention here that we are aware of the valuation work which is currently underway at the U. S. Army Electronics Technology and Device Laboratory at Ft. Monmouth, New Jersey.

Now, let us now consider the three basic aspects and what is known about them and also what is being done about that.

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CHEH: First, take mass transfer. Electrolysis by pulse or periodic reverse currents change the concentration distribution of the reacting species. In contrast to DC conditions, the transport of the reacting species is reinforced during the off cycle of the pulse. This results in a net increase of the reacting ion concentration at the electrode solution interface, thereby leading to a reduction of concentration over potential. That is item one.

CHEH: This consideration is important in delaying side reactions such as gas evolution, leading to a higher charge efficiency with faster rates. Also, the reduction of concentration over potential can lead to power savings. Quantitative calculations on the increase of the reacting ion concentration, the reduction of concentration over potential and power saving has all been made.

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CHEH: The next Vugraph shows you a typical example of the reduction of concentration over potential based on a theoretical model which we have set up. Shown here on the abcissa is a ratio of the concentration over potential and the pulsed condition versus that under DC conditions, so it is a ratio of the two and plotted on the abcissa of this figure is a ratio of the instantaneous pulse current to the DC limiting current.

Theta one over theta known as the duty cycle is the fraction of the time for which the current is on. There are two features worth noting from this figure. As the duty cycle decreased the reduction -- there is an increase of reduction of the pulse over potential, but this is reasonable because as the duty cycle decreases you allow more time for the reacting ion to diffuse back to the interface.

Also, as the pulse current increases, there is a general trend of decreasing concentration over potential, but this is also reasonable because as we approach the DC limiting currents, the DC over potential gets larger and larger. Theoretically, at the limiting currents, you would -- the DC over potential would approach infinity. In fact, that is the reason why all these currents drop to zero as this ratio approaches one.

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CHEH: The next Vugraph shows a calculation based on the last figure on the total power savings, simply resulting from the reduction of concentration over potential. We see here as we increase the duty -- as we decrease the duty cycle in the selection, the reduction is increased and also, of course, if we increase the pulse current the reduction is also increased. For instance, at a value of IP over I sub DCL of .6, the total power saving at a duty cycle of .2 is 29 percent. At the same time at a duty cycle of .8 it is roughly 11 percent. Okay? The saving is about 11 percent.

SPEAKER: Power or energy?

CHEH: Power. Okay.

CHEH: Electrokinetics can also be effected by pulsing in two ways. First, during each part of the on-off cycle, part of the current is used for a non-faradic process, namely, charging and discharging of the electrical double layer. For battery electrodes which are typically porous and have large surface areas, the capacity effect can be rather significant. That is item one here. Unfortunately, there is little quantitative information of this particular aspect.

Also, electrochemical kinetics can be effected, especially in systems involving more than one electron transfer process and we have at this stage made a general formulation of the effect of this particular effect which includes the transport and kinetic considerations. It is very likely that this can also have an effect in the overall charging process effecting the efficiency of charging.

There is a third and very important aspect which is structural considerations. Electrode structures can be effected by pulsing also in two ways. First, the composition of active materials can be effected by pulsing and also crystalline size and structure themselves can also be effected. Now this, unfortunately, is an area that is somewhat beyond our field of competence. Meanwhile, it is our feeling that this aspect may turn out to be one of the most important considerations of pulse charging.

For instance, there are numerous reports in the literature which have indicated the tendency of reduction of dendritic formation of zinc by pulse charging. At the same time the crystalline size has been reported [illegible] drastically -- of the active material has been reported to be drastically [illegible] in nickel-cadmium batteries by pulse charging and there are a number of other comparable kinds which were made in the literature. Consequently, a basic understanding of the effect of pulse charging of secondary cells must include in our view, structural considerations.

CHEH: Now I would like to briefly describe experimental results which were obtained in our laboratory and our future plans for the project which is supported by JPL. We have carried out a systemmatic half cell study of nickel and cadmium filament electrodes using a 60 hertz pulse with duty cycles and the charging currents as the major independent variables. Both the pulse and period reverse charging were studied. Our results have shown so far that under the conditions we have studied, a straightforward pulse charging has relatively little effect on the charge acceptance. On the other hand, the charge acceptance can be increased rather drastically by period reverse methods.

Currently, we are studying the electrokinetics of the half cell behavior under pulse conditions. We are also initiating some structural studies, both on the composition and the crystalline modifications by pulsing. However, there is, in my view anyway, there is considerable conceptual and practical difficulties in doing structure analysis for battery electrodes. The difficulty arises from preserving the integrity of the electrode in a battery environment and transferring it to an analytical experiment. I have no idea what happens to an electrode when you take it out from an active cell and you dry or whatever you do. Apparently, the active materials may not be, for instance, stable, and things can change by the time you look at the crystalline structure and composition. You are really looking at a different piece of material and here is a problem that we are thinking of. Well, we have some ideas how to overcome some of the difficulties, but any suggestions from this audience would be most welcome.

This concludes my very brief and short summary of a project which, as I have stated earlier, which has started recently in our laboratory. I thank you.

I must acknowledge one more point, that although I am directing the project,most of the work is carried out by Ms. Redozian (?) who is the only woman in the audience today. She is a graduate assistant and does most of the work.

BRIGGS: Briggs. In your denominational parameter of theta one over theta, do you have a pulse charge? I would like a definition of pulse charge and when does it go from a pulse to DC? Is it a matter of minutes or is it minutes or do I have to say in the 60 cycle --

CHEH: No, you don't have to stay in the 60 cycles. I mean, theta one over theta is only a ratio. The practical pulse rate varies all over from miniseconds, the total cycle time, up to seconds. Years ago in electrode deposition people were using seconds, but as electronics get better and better they go to shorter and shorter times and apparently shorter cycle time gives more beneficial results, but as you go to very fast pulses, you will run into this nonfaradic interruption, charging and discharging of the electrical double layers. In that area it is fine. People talk about on one pulse -- now we have repetitious pulses and we have no idea at this stage without a further study to appreciate what effect it would have.

To answer your questions, we are looking at 60 cycles just for sort of convenien , but if you go into the literature you find that there is a range that people look at pulses.

BRIGGS: Mr. Dunlop was looking at that, I believe about eight or nine years ago and most of us were working in this area then.

CHEH: Right. What sort of cycle time did you use at that time?

BRIGGS: Jim, you were looking at about 60 cycles, weren't you?

DUNLOP: I did a lot of different things going from minutes to seconds.

CHEH: Yes.

BRIGGS: That was primarily in minutes, you know five minutes on and off and stuff.

CHEH: Right. I mean, in order to see the effect of pulse, if it is a very slow pulse in minutes, if it is an open circuit kind of pulse, it is like a DC, right? You turn the current on and you shut it off or two hours you turn it on again you are not going to see much effect. Okay? But it has to be in a range that the effect of pulse can be important. That would go to the range more like in the 10 milliseconds or 15 millisecond range.

KUYKENDALL: Kuykendall, NOAA. Can we say then that we have a satellite spinning at 100 rpm. If we are charging every time we look at the sun, what 1-1/2 or 2 hertz, --

CHEH: Right.

KUYKENDALL: -- that is also considered a pulse?

CHEH: Yes. Now, one other parameter in my figures I did not mention and nobody -- I was hoping that we would not get into that, if we look at -- let me show you what I mean here. There is a figure in here, or there is a parameter, which says A theta equals .5. What is this A, this mysterious A? Okay, it is a reciprocal time, and it has something to do with the mass transfer characteristics of the pulse with the sturring of a solution, you know, what we call a diffusion layer or something like that. A is an inverse of a dimension of a diffusion layer, so now that means in order -- if A theta gets to be -- if theta gets to be very, very large, eventually you no longer have a pulse. You have a DC condition. If A theta gets very short you have pulse conditions, so it would depend on the individual system. You have to evaluate what is the corrected mode? What is the diffusion phenomenon in your cell and you are spinning at 100 rpm itself will introduce a motion and that actually can be calculated into, absorbed into parameter A and look at the overall effect, so that is is the combination of the two, okay, that when you have a range of .2, .3, that would become important. Above 1.5 it is like a DC. It is equivalent to a DC with interrupted currents.

SULKES: Sulkes, USAECOM. One thing that you mentioned about your power curve, you talked -- I think there may have been a confusion on that.

CHEH: Okay.

SULKES: You said savings of, say, 26 percent or something like that. I assume that is an over potential type of saving.

CHEH: Exactly.

SULKES: Okay. But that is not total power. In other words, a ni-cad is 130 and you are charging at 140. You are saving 26 percent of that from 130 to 140.

CHEH: You would then multiply that by the charging current. The saving of the over potential you multiply that by the current and you get a net saving of power.

SULKES: No, no. It is not a saving of power. In other words, you have got to put the open circuit as well -- or you have got to put 1.4 volts in. You are saving .02, for example.

CHEH: Right.

SULKES: Which would work out to be 1-1/2 percent or that type of power saving.

CHEH: Right.

HELLFRITZSCH: Hellfritzsch. You asked for suggestions on how to examine a freshly deposited layer. If you don't know about it, the Naval Research Laboratory published in the Journal of the Electrochemical Society, oh, maybe 15 years ago, I guess Steve Burbank would be one name and Wales and Simon.

CHEH: Yes.

HELLFRITZSCH: And what they did, they had a rotating electrode.

CHEH: Yes.

HELLFRITZSCH: That was almost totally immersed.

CHEH: Immersed, right.

HELLFRITZSCH: And as it came up through the surface they then looked at it with their light beam for spectrographic examination.

CHEH: Yes. There are some -- we have some of that. For instance, people have kinds that you can do in situe measurements, X-ray defraction studies.

HELLFRITZSCH: Right.

CHEH: But electron microscopy is out of luck. There are certain things you can do and that you cannot do. Of course, one can hope that by the time we take it out from the cell and you analyze it, nothing happens, but that is -- I cannot verify that. There are some suggestions that we have got from the people at JPL, from electron microscopists saying that you can seal it in the same mylar tape and by reasonable care of the tape you may be able to preserve a sample.

One of the things that we are rather new in the field and that bothers us most was reading from different sources you have got different results and you look back, in the methods you are not really sure whether these, based on different systems or different techniques, and the reproducability is frequently not mentioned and those sort of things, and we, at this stage, are finding a lot of difficulty in trying to do -- I mean, we can generate lots of pictures of crystalline sizes with electron microscopes. You can just stick in a sample, but is that what you really have in the battery is what we are concerned with. We think that is the important thing, but yes, we have seen some of that work.

GROSS: Gross, Boeing. It would appear to me that an important aspect that would be worth examining is the effect of an AC ripple on a DC current because that can easily be implemented and practically every application.

CHEH: Yes. There are other methods people have done charging based on something called asymmetric AC which can either be what you said where you superimpose the AC on the DC. That is what you meant, a ripple, and there are, in fact, people who use two truncated sine waves, one for the charge and one for the discharge. It is not an addition of the two, of DC and AC. Both have been looked at, mostly not in batteries but in electrode deposition.

I sort of got onto this because of my work in electrode deposition under various types of current waveforms, but certainly those are important aspects, but I think the most drastic aspects would be the pulse.

GROSS: I might expand my comment to mention that in most applications that use boost dischargers, you get that sort of discharge because you discharge in pulses and so you effectively get an AC superimpose over DC for the discharge, so it would seem to me to be essential for the industry to examine that particular problem, or that particular aspect of it.

FORD: Other questions on pulse charges? Okay.

Okay, at this time I would like to give a short presentation I had planned for tomorrow and two reasons. One is the schedule tomorrow is kind of full and second is, I think this presentation will fit very nicely with some of the subjects that were discussed this morning and probably lead us into some good controversial topics for discussion.

I am going to show you the effects of reworking cells, namely "reworking" being defined as removing electrolyte below the normal specified level that had been used in this cell design. I am going to talk about it in a Gulton 6 ampere-hour using SAFT commercial plates manufactured in 1971. The cells were processed in late '73. We used Pellon 2505 separator material bought to the quote, "Goddard specs.", unquote.

FORD: We did the things, all the good things, plus a couple of bad things. A little background is that these plates were screened. In fact, they had been screened a whole lot and the plates used in these cells were rescreened on the high side of the previous weight screen that is specified, so in essence, a new baseline was established on a lot of plates for screening and as a result we ended up with some cells that were fairly high capacity. The initial capacity during flooded tests was in excess of eight ampere-hours on the positive. We fabricated the cell, put the specified amount in, and then proceeded to test the cell and during tests they found out that the cells would not meet the pressure characteristics as specified. As a result, electrolyte was removed. A couple of cycles rework were involved and they were resubmitted to test and most cells met the requirement of the spec.

As a result of losing electrolyte, we saw an initial decrease in the deliverable capacity from about 7-1/2 to 8 to down to approximately drop in a half an ampere-hour to around 7, and as results of these problems with these cells Goddard accepted them on a conditional basis. That is, we life test the cells for one year, sample cells prior to taking delivery on the complete production lot. This was one of the few cases in my experience where I am working and trying to buy flight cells when I had the luxury to test the cells before I had to commit them to flight.

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FORD: The cells were placed on life test at NAD Crane. They were run at 20 degrees C., 25 percent depth of discharge, using a voltage limit of approximately 1.416 to 1.417, with a C to D ratio of 110 to 115 percent.

FORD: Shown on the bottom of this Vugraph is the aeration and electrolyte levels as a function of end of charge voltage at two different points in the early cycle life. Not shown is the end of charge voltage for approximately 2,000 cycles. End of charge voltage is not shown, but it suffices to say that there is not a significant difference between what was shown here for 377 cycles and just over 2,000 cycles. But bear in mind we have two distinctive groups of cells, those with 13 to about 14-1/2 cc's of electrolyte and those in the range of 17-1/2 to 18.

(Slide 63)

FORD: The next Vugraph shows the end of discharge voltage as a function of early cycle life, approximately 1/2 a year and then at the end of the one year test and also summarized in the bottom lefthand corner is the test condition and the pact identification.

Showing the typical drop in end of discharge voltage compared as a function of electrolyte levels. That in itself is not too surprising and on an individual basis or looking at a single group of cells you probably wouldn't get too excited about the performance of either one. I am presenting this in a relative basis to try to give you some insight into what effects truly are realized and I reiterate the point that the initial performance of these cells all fell within a very nice limit as far as pressure, as far as voltage, and capacity.

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FORD: The one you just saw was end of discharge voltage at the end of 25 percent. After 5,000 cycles, 5,052 to be exact, we did a capacity check to see how much capacity we had in the 10 cells. The little triangles indicate the capacity discharge immediately following cycle 5,051 showing the spread in capacity versus by the function of the amount of electrolyte. Also shown is the capacity following the discharge cycle of one volt, one ohm, C/10 and then another discharge at the cycling rate which in this case was 3 amps for a 6 ampere-hour cell.

You notice the significant increase in capacity of the low electrolyte cells versus the some increase in capacity of the high ones, but basically the grouping stays about the same as that obtained after one year of cycling.

(Slide 65)

FORD: There were a total of 10 cells involved in the test and this depicts the best and the worst voltage and capacity on that final discharge that we made to determine capacity. Now what I have tried to indicate here are a couple of things. One is a comparison of the voltage degradation as I showed previously in the discharge and a comparison of the capacity degradation. They are not one and the same. The numbers indicated are indicative of the cc's of electrolyte contained in each cell shown at the upper and lower curve formed an envelope of the performance of 10 cells, showing basically that these are the capacities of all other cells and their discharge curve fell within the limit as identified here.

(Slide 66)

FORD: Following the one ohm, as I indicated previously, we recharged and discharged again and this is the subsequent voltage and discharge curves that we got showing one for one volt. We are now above rated capacity on the worst cell and we are getting a little bit better performance out of the cell with the high electrolyte, as indicated, as previously I showed the capacity spread of the other eight cells and their voltages would dip within the envelope of that shown here.

Now, looking at this, one might immediately say, well, why do you have initial discharge voltage that is different? Well, the simple fact, these cells now have high pressure characteristics again. You cannot overcharge these cells after 5,000 cycles, so in essence the cure or whatever you want to call it, was only temporary.

I presented this data to illustrate a very valid point. There is nothing that the manufacturer does in the process of building this cell prior to welding that tube that doesn't effect the performance of the cells in my application. Now tomorrow I think you are going to see a lot more of this, but a couple of the points I would like to follow up are we have building ni-cad cells since 1960, make it 1959, and in late 1960 we got in a big hullaballoo about positive and negative ratios, precharge. Fixes were made and I can mention today that is exactly what was done. Fixes were made with apparent delinquent cell characteristics. I point out to you that the negative-positive ratio increase that we are getting today was not done at the sacrifice of positive plate capacity. It was done at a sacrifice of increased loading on the negative.

In the aerospace process that is followed, the aerospace users have built themselves into a box. I am not so sure we are not buying less quality cells than we did five years ago when we were getting negative-positive ratios of 1.3. I contend that the negative-positive ratio isn't the critical thing in the cell. It is how you build those numbers, both positive and negative capacity and the efficiency of those, not only in the first 30 to 60 days that the manufacturer tests his cells, but throughout the five years that I need to meet my mission requirement.

Another point I think is very interesting, a rule of thumb if you look at present generation cells, you see that irrespective of which manufacturer you look at, you will find about three cc's of electrolyte per ampere-hour, rated. You see right here on this when we are talking about 18 cc's and on six and it went below that.

Also, you have seen, if you have followed aerospace cells very closely, an increasing difference between rated and actual capacity. With this evolution you would also, if you have looked at it very closely, you have seen a declining trend in the number of cc's of electrolyte per rated ampere-hour. Today what started to be electrolyte-starved cells are now cells so critically starved of electrolyte that we are seeing wide variations in performance, especially in the life of the cells. I think it is time that as aerospace users, we re-evaluate our criteria for success and what we need to do a mission.

Do you need 40 ampere-hours of negative capacity in a 20 ampere-hour cell? Do you need 35 or 30 ampere-hours of positive capacity in a 20 ampere-hour cell? I say you don't, not if it is at the sacrifice of the amount of electrolyte you put in the cell. Thank you.

Any questions? Ralph?

SULLIVAN: Sullivan, APL. I am wondering, Floyd, on this question of negative to positive ratio, wasn't it Goddard that made that such an important factor back three or four years ago?

FORD: Yes.

SULLIVAN: Okay, just wondering.

FORD: Okay, you are very right and I am a user and I am no more blameless than other users. You are going to hear me criticize users today and tomorrow. I am going to also criticize manufacturers. It is time we start reckoning with what we are doint to aerospace cells, both on the manufacturing and from the user's viewpoint. The user has pressed the manufacturer to deliver more capacity, but in pressing for that capacity he has further restrained the weight you will allow him to deliver with and the volume to put it in, all this in absence of any real significant advances in the technology of making plates.

SEIGER: I will let the last sentence that you just made go, but you have had a beautiful opportunity with cells with various amounts of electrolyte to take a look inside, look at electrolyte distribution and the various species and how they are distributed. Do you do this before your - you know, we have had several thousands cycles done before you recondition and then after recondition? That would be interesting.

FORD. In this case, no. We have other tests going where electrolyte is a variable, and interestingly enough, the conclusion that I can draw so far by increasing the electrolyte and I am using as a kind of a definition, a baseline definition, three cc's per ampere-hour, okay? You have to use something as a basis so I am using that for discussion. In increasing the electrolyte we don't see the collapsing of the capacity curve, but we still see the double plateau effect.

SEIGER: About two years ago at this audience, I was talking about electrolyte and ways of putting it in, where it is distributed at the beginning and I came to a rather different kind of method of putting electrolyte into the cell and I wanted about 95 percent of the residual void volume figured on the basis of the discharged cell. That was the amount of electrolyte that I wanted.

Now, generally, I come up with numbers that could be like 2-1/2 milliliters per ampere-hour up to numbers that were almost 5 milliliteres per ampere-hour, but they were all the same kind of thing. It depended upon the loading. It depended upon the inter-electrode spacing, separator chosen, and it did have a wide variation. I think I would prefer that kind of rule for a baseline rather than three milliliters per ampere-hour.

FORD: Okay. I didn't mean to establish that as a rule. I am saying that is a relative comparison point. I am using that for saying plus or minus, minus being what I presented here, plus versus what we did on some other programs.

SEIGER: Could you please, then, carry along with your work as you proceed, your number not only as milliliters per ampere-hour, but also percent of filling of the residual voids so when you come to a conclusion we may be able to extrapolate more if one ismore correct than the other.

FORD: You are talking about residual plate voltage?

SEIGER: Yes, plus separator.

FORD: Jim?

DUNLOP: Jim Dunlop from Comsat. I really have about three comments. The first one is one of the things that I think we have talked about in the last two or three years is that if you are designing a cell for a synchronous satellite, I think you have got one set of criteria. If you design the cell for a low-earth orbit satellite I think you have got another set of criteria, and one of the problems is that you continually mix the requirements up in terms of everybody buys basically the same cell and you are trying to use the same cell for the high rate, large number of cycle tests that they do for the long life synchronous satellite tests and I think that is one of the things that from my point of view has always been very confusing.

I contend and I have for the last four years here, that the nickel-cadmium battery that we use today in synchronous satellites was designed for low-earth orbit spacecraft. It never has been properly designed for a synchronous satellite application to date. That is No. 1 point. No. 2, the other one, when this comes up I really get confused by what the position of Goddard is because I hear all of your complaints and at the same time I hear you guys talking about a standardization program and I simply do not understand whether you are trying to standardize a bettery or whether you are trying to improve a battery.

FORD: We are trying to do both, Jim. I would resist all pressure to standardize on the current cell that we are buying.

DUNLOP: But that is what you are doing.

FORD: No.

DUNLOP: You are going to standardize.

FORD: One of the very key factors that we are doing and I think the point was overlooked this morning, in the past we have never specified a maximum capacity that a rated cell could deliver and therein is where we have gotten into, I think, some different problems. Today in the standard cell we are saying a standard 20 which is specified with an envelope that encompasses the tolerance designed for the basic manufacturers cells. We are specifying, also, that that cell cannot deliver over 26 ampere-hours and therein is where we have gotten outselves seriously into problems. Where in the world we get the idea as engineers and battery users that the higher the capacity the better the cells, it alludes me as how to we arrived at that conclusion. I would rather work with a cell that is 21 ampere-hours and pay for a 20 than where I am paying for a 20 and getting 28 without the technology to support that 28.

MCHENRY: McHenry, Bell Lab. You were talking about the excess negative in there. Now if you are going to keep the same electrode and just stuff more cadmium in, you had better not. That isn't going to get you anywhere. What you need is excess negative that has some volume, excess volume included. You want to lower the negative lighter per cubic inch and a battery heavier per ampere-hour of negative. In other words, you have got to make it a lot bigger. You have larger volume of negative and the density of the negative is lighter. You don't stuff it so full that what happens, I think what happens is the pores get so small they slide and then they don't recombine at all.

But if the excess negative is two to one, it is a grand idea but you have to have the increased volume in order to hold it and still have the void there for the electrolyte. You have got to have some empty space in there somewhere. I think the smaller the pore the deeper it was.

SPEAKER: Floyd, if I understood you correctly a little while ago you said that previous to now NASA had not specified the maximum capacity. The way I understand the 761 spec., the positive capacities are in a range of 120 and 150 percent of rated and the negative shall be 150 percent of the maximum positive. That kind of sets it. What you probably want to do now is reduce that 120 to 150, but you did specify a lower and an upper limit than the 761 spec.

FORD: Okay. Let me qualify the statement. We have not stated a maximum capacity on the finished cell. You are referring to flight pay capacity and the P6 to P761-6 does in fact limit the capacity in the flooded plate to the numbers you stated.

SPEAKER: That yields the net finished cell?

FORD: Yes.

SPEAKER: Another point is this: in reducing the loading of an electrode, you will increase the void volume. You will then require more electrolyte. Fine, but the thing then that is important now is what is the effective electrolyte, namely, in the separator during the dynamic charge and discharge? That is what counts. Just putting more electrolyte into the cell and laying in the electrode is not the whole solution. It is the effective amount in the separator during the cell charge and discharge.

FORD: Well I had to point out the similarities between the data I showed here and some of the test results that have been shown with polypropylene separators, whereas the capacity degradation is very severe in a relatively short time of cycling. Now it does recover with so-called "reconditioning" as shown here. We have got a substantial recovery of it, so therein it seems that it is basically electrolyte management problem. Now, if you start off with a cell that is suitably charged with all of the information we have today we have pretty well established certain characteristics such as positive plate expansion, plate growth, whatever you want to call it, and with these things working for you, I think we have the information so really the engineer has a good cell design, and acknowledging Jim's comment, there is no question in my mind that for certain applications there are factors that are more critical than others, and I agree wholeheartedly that the optimum cell for a near-earth orbit would not necessarily be compatible with the maximum life and optimum cell for a synchronous orbit, but I quite frankly don't see where electrolyte starving a cell does us any good in either orbit.

SPEAKER: Floyd, there is one thing that has always troubled me a little bit about these meetings. Most of the discussion about how a cell should be designed comes from the battery user and very little of that discussion comes from the battery cell manufacturer. I would think it would be the other way around. Wouldn't it be better to take the government money and put it into the few battery cell, flight batteries, that is spacecraft battery cell manufacturers that we have, give that money to them and let them do the electrochemistry and analysis and whatever rather than the battery users, or is this heresay?

I happen to be a battery user, by the way, but from my viewpoint I would rather not have to go into all of the electrochemistry. I really don't care about it. I would rather just order a cell.

PARK: Park. I think the sticking point there is that if you take the government money, the government owns it, isn't that right?

SPEAKER: What is wrong with that?

FORD: We haven't built a battery plant yet.

SPEAKER: The government owns it anyway. I mean, what is wrong with that?

PARK: Ask the battery makers and see what they say.

MCHENRY: I believe that most of the batteries are sold for toys and hearing aids, stuff that breaks before the battery does, so if the battery will last six months, the tooth brush will be dropped before that and then you don't have to worry about it, and that is where the guy makes all his money, and then you come in and you want a different battery. Well, if you give him money he is going to spend it on the one that makes him money, not on the one that you want him to spend it on.

SPEAKER: That is correct.

MCHENRY: And he is in business to make money, not as a philanthropist so – he just says to you, "Well, I make all of my money on toothbrushes and that is what I am making for a battery."

PARK: I still think, to be very frank, because I have been working with the government during the war six years, starting very early before Pearl Harbor and was involved in a lot of contracts and everything, and the minute you take the government's money the manufacturer has something proprietary, it isn't proprietary any longer.

Now, not too many people that are making things and have some proprietary knowledge they want to give it out. You might just as well recognize that right in the beginning because you will never make any headway.

MCHENRY: He isn't going to do you any good in other words. He is going to do his good for him and he won't tell you what he has. What good is he?

FORD: Okay, Rampel?

RAMPEL: Yes, General Electric. Floyd, I absolutely agree that the more electrolyte the better, no question about it. But in looking at your data and 18-1/2 cc's is about the right amount in a 6 ampere-hour cell. Certainly five percent below that, from your data, is within the population for 18 or 18-1/2 and there is not a problem. Going to the extreme that you showed, there is no question tht you have got to stop somewhere and I would say that five percent is reasonable and the other end to this, really, to eliminate some of those adjustments is to have initially a much higher pressure allowance in the specification.

SEIGER: When are we going to start the general discussion because I think we could put some of thd pieces together.

FORD: We are going to have a break in a few minutes, but go ahead.

SEIGER: Shall I hold it until after the break?

FORD: All right, let us take a 15-minute break. But first I have an announcement. On this table over here you will find the document on the Goddard Standard specifications. That was referred to this morning. There is a correction to be made on page nine of the slope of the V versus T curve. I might comment on the standard Goddard spec., to use as a baseline in establishing a standard battery. Now I am not talking about the standard cell any more. I am talking about the standard battery package that was referred to this morning, and in this spec. we have the requirement we feel that should be reflected and I emphasize that word "reflected" in a standard battery design.

It also gives you some insight into the charging technique that is going to be implemented or that is going to be requiredto be implemented in the standard spacecraft; namely a multiple V versus T. We took this approach because in the standard spacecraft it has to accommodate brand X, Y, and Z. Now once you cross that obstacle others become kind of small as far as variation, particularly in voltage performance of cells. I think you might find that very informative and useful. We obviously welcome your comments, both negative and positive on it and perhaps some of you will get a chance to really go over it in the distant future.

Also, there is a copy of a tech. brief on silver cad. battery heater, more or less indicating how the life of silver cad. batteries through the use of some very unique thermal principles has been significantly enhanced in orbit. I think, Bill, correct me, we have got one silver cad. now that has exceeded three years –

NAGLE: That is right.

FORD: – in orbit and this talks about how we were able to do that showing again the effects of temperature and how it reduces or increases the life of the battery and I want to announce at this point and I will make the point again, we will start in the morning at 8:30.

RAMPEL: Guy Rampel, General Electric. One more question before we break, on that subject. You said the cells went back to high pressure. Is that oxygen orhydrogen?

FORD: The recombination of the gas in a relatively short period there indicated it was still oxygen. We saw no problem with hydrogen generation on these cells that we identified as such.

FORD: Okay, the rest of the afternoon we are going to proceed with what we call open discussion. We are going to keep the groundrules very simple. Everybody not only is invited, but you are encouraged to participate. We, in planning the workshop for this year, and looking back to our past experience and what hashappened at the various workshops, we wanted to add to the informal atmosphere that we try to generate here each year, but we also want to ask you as a user and we in no way imply that this is limited to aerospace users. We are interested in all user problems, and you, the manufacturers. We are also interested in your problems, so I hope for the remainder of the day we can be honest and sincere and have a frank exchange. I have asked the gentleman that you see before me and I think they have all been introduced sometime. I guess Fred, Fred Betz, the NRL gentleman, hasn't been up here formally. I have asked these gentlemen to sit up here to support me.

After the last session I think I need it. I think it is time we take stock of where we are, basically what we known, where we are, and probably more important, where do we go from here today? What direction do the ni-cad cells take? What importance is it going to play in future aerospace needs and then along with that, what importance is the ni-cad system going to play in other needs of this country?

In looking at this we feel like we have a world of experts here before us and with us, each in his own right has made a contribution to where we are today. For the sake of Goddard's planning and looking at the future we want your comments. We want to know what the problems are today. Obviously you have already heard a lot of mine, but we want to know what yours are and putting it in proper perspective, given the money to solve the problem, which one would you put the money behind and with that I would like to kick off this open discussion.

I am going to ask that we, the panel members here, that they will support me and I think you should attack and I will run to their defense at any time. I hope we get the participation primarily from out there and me and the panel members are a catalyst to get the discussion going. With that I will ask one of you and I haven't asked specifically an individual but one of you if you would like to kick off with some comments on what you consider your problem is and what you think should be done about it.

KRAUSE: All right, I will start if you like. I think over the past several years at Hughes we have been doing a lot of cell analysis which has been correlated with the results of a number of life tests, especially aimed at synchronous orbit problems because that has been our primary business and it seems evident that if I were to be given free run to start a program on improvements of specific ni-cad problems our major problem, clearly, is electrolyte redistribution. The results of most of our life tests and our analysis shows that electrolyte redistribution is the eventual and ultimate cause of the cell to either completely fail or degrade so that it is no longer usable for the satellite power subsystem. I don't think, for example, that cadmium migration in and of itself is a problem any longer because I think we are understanding now better ways to handle it and, for example, trickle charging clearly for synchronous application, our data shows that it reduces cadmium migration to a very reasonable level for periods of five years and more. Secondly, I think we know that if we can run our satellite batteries cooler, the batteries are going to last considerably longer. We are using information such as we have seen this morning on rate reactions for nylon to twist the arms of our satellite program managers and tell them that if you want a 10 year satellite, buddy, then you had better get that thing cooled down, and we are now coming up with that kind of information and they are becoming convinced that they are going to give us cooler environments for the batteries. I think, third, teflonation will probably contribute to a reduced cadmium migration in the future and I think overall that cadmium migration is not a problem per se, but the significant problem which can cause cadmium migration and can cause voltage fading, which can cause loss of capacity is probably electrolyte redistribution. It also apparently causes swelling of positive plates which can lead to shorting, compression of the separator, and we have seen evidence that that kind of a problem will lead to reduced oxygen recombination. If you close down the pores of the separator the gas can't get through.

Electrode deposited or electrochemically impregnated positive plates may help to solve that problem, since it is not expected that they will swell very much or that they will hydrate badly, but in general, I think electrolyte redistribution is the major problem and if I were given a program to embark on, what I would like to see is to develop a semi-flooded or even a flooded ni-cad cell with appropriate charge control systems to limit pressure. I think running the cell flooded will lead to a very long life. I think lower active material loadings will help the electrolute redistribution problem and I think it might be interesting to even consider reservoirs similar to what is being considered for nickel hydrogen because a reservoir, and I don't know if anybody has considered it in the past, a reservoir might help over a 10 year period with a synchronous design, but it –

FORD: Thank you.

SEIGER: Seiger, Yardney. It was two years ago that I presented a paper at this forum talking about electrolyte redistribution and those data, and I did present some hard data – are sitting in the transcripts of the 1973 meeting. At that time I pointed out that there were three items to be considered with electrolyte redistribution. Item one, considering the cell as having two fixed walls, that if the positive electrode swells, then it will be compressing something. Something must be compressable. The something that was compressable is the separator. Now it is very simple to show that if you thicken six mils. on the positive electrode, you thin the separator by six mils. and there is a one to one and this automatically will take some volume, an equivalent volume out of the positive – out of the separator, and redistribute it into the positive electrode. Now, that means that when you analyze that particular cell, you take it apart, you find less electrolyte in the separator, so that is one of the things. Now we nkow that it does swell.

Jim Dunlop and Jose Guena (?) had a paper on nickel hydrogen cells in the Journal of the Electrochemical Society at the beginning of this year that showed some numbers of thickening that were almost double, 50 percent to double on vacuum impregnated materials.

All right, so now we have one of the three mechanisms operating to cause electrolyte redistribution. How do we solve that one? You have mentioned it. The electrochemical impregnation of the positive electrodes and we gave a paper on that also at the IECEC last year, 1974, that treats of how the plates are to be impregnated, that there are certain upper limits and if these are followed, then the amount of expansion that one sees on charging and discharging of those electrodes, is rather small. I think Scott in his degradation work for JPL reports that type D and F, which were the TYCO and the Heliotech impregnated plates, both had a very small amount of thickneing, something on the order of two percent compared to double digit numbers, for vacuum. The reason, corrosion. It is another subject to talk about.

Now, also in that paper in 1973, that was presented here, I spoke about degradation of the separators, and that wasn't anything original. It was taken from the Bell Telephone Laboratory work and also from Comsat where they have shown that there was degradation and we have seen an excellent treatment of it this morning showing quantitatively that you do get the ammonia and sometimes when you open a failed cell you can smell an ammonia or an ammide type material, so Dr. Lim showed us the effect on precharge and the change of carbonate with the degradation of the separator. Now polypropylene apparently doesn't degrade. We don't know about asbestos. It may not. Potassium titanate may hold up, so we have at our fingertips things we can work with, including polypropylene, and as an aside, this morning I asked Tom Hennigan a question about polypropylene in his data and how much electrolyte he actually had in that cell. I believe the cells with polypropylene, if my numbers, if I recall correctly, require a little bit more electrolyte than cells with the 2505, something with the GAF WEX separator requires a little bit more electrolyte. On the other hand, we found that there was something like 24 milliliters, whereas the cells with the nylon had 26, so the data is biased at the time of manufacture against a separator and we are testing the nylon and the polypropylene in two fashions. Fine, so we can take care of the second cause.

Now, the third item that I mentioned in the 1973 paper was the entrapment of air and I traced it right down to the negative electrode, and this morning I heard some additional evidence on entrapment of air. I think it was Stan Krause who I am responding to. I had understood him to say something and I repeated it in which if you have a cell without the teflon, you found a certain amount of electrolyte new in that negative electrode than if you cycled it and took them out.

You found an increase in the amount of electrolyte. This says that more electrolyte is going into that. What is it replacing? Is it replacing active material or is it replacing possibly air that had been there and then taken out? There is only one way to really shut the door on air entrapment and that is for somebody to find argon in the cell because argon would come from the air that would be entrapped.

Now, I am trying to find that. I had no means of checking it myself. I can't get any positive evidence of that, but you also pointed out that when you have the teflon around it, that the amount of electrolyte in the negative electrodes stayed constant. Now we have something with a different kind of characteristic and I haven't had time to clear it all through, but it appears that you are stabilizing something with the teflon. I would also like to point out some other information that was given to me by Tom Hennigan, that some cells with extra electrolyte in them were cycled at a 40 percent depth of discharge, 20 ampere-hour cells for close to 3,000 cycles and there was no cadmium migration, and this was indeed done with a cell in which the total voids in the pack, that in the positive, that in the negative, that in the separator. Those total void volumes contain an electrolyte about 95 percent of that void volume.

I think I have covered most of these things and I would like to see some of it worked on. You have asked for a research program, Stan, that I think we have done a lot about, that we have actually researched, and it is not in your cell. Let us give that some consideration.

WROTNOWSKI: Wrotnowski, GAF. On the redistribution between the plaque and the separator, I have been very impressed with the capillary, let us call it strength of the plaque because of its fine cells, and to get them to be balanced the separator would have to match that capillarity or it would be starved forever and that is not impossible, but that is my reaction to your distribution problem.

KRAUSE: I think if you prevent the wetting of the plate, the excessive wetting, such as teflon does for the negative and you go with an electrode deposited positive plate, and let us say you had a reservoir in addition, you can keep that separator fairly well saturated.

WROTNOWSKI: But on the automatic, simpler system, if they were both – had the same, say, working height, they would then have the same capillarity and it would be an easier thing to stop the polypropylene from starving.

KRAUSE: Yes, it would be, but I am expressing my personal approach to the problem would be that I have been working with nylon, with the Pellon 2505, for 10 years. I know what it will do and I know what it will do over a long period of time. I don't want to introduce another variable in trying to achieve this flooded condition or to achieve the proper electrolyte balance by going to a completely new separator.

SCOTT: Besides, you can't completely flood the separator or you won't have any oxygen transport to keep the pressure down.

DUNLOP: I would like to make another comment along that line about some data that was obtained for us on the positive electrodes, conventional positive electrodes loaded with a normal saft or G loading, when they expand, we reported – everybody has observed this expansion. The one thing that hasn't been reported yet to date that I know is in addition to expanding there is a significant change in their micropore structure and what you find out is that on the expansion of the electrode, you do have a micropore measurement, you do find a significant increase in the micropore structure of that electrode in addition to the expansion. It is rather interesting because what happens is in addition to that electrode expanding as you were talking about, it also has a lot higher micropore structure which sucks up a lot of electrolyte and I don't think very many people know that to date. It is a rather interesting fact that has come out of some of our studies on the conventional Saft electrode or conventional GE electrode. I will tell you, when you go the other thing about it, just talking about your electrochemically impregnated electrodes, they don't expand as much. That is for sure, and the other thing, you do get better utilization so you actually can take an electrode, electrochemically impregnated. That is 30 percent less active material per cc of void volume, and you obtain the same ampere-hour capacities that you do on conventional electrodes with 30 percent more loading. That is our experience with the nickel electrodes and nickel hydrogen cells.

The other factor is you take a conventional Saft electrode and underload it which means you only impregnate it with two or three cycles rather than a conventional seven cycles, you get about 60, 70, 80 percent, depending on how many impregnation cycles you use. If you do that, you find that it can run that electrode with 3,000 to 4,000 cycles with no expansion, so one of my conclusions is that nobody who builds a nickel cadmium battery today, whether I am talking to GE or Saft, or any of these guys who represent TRW or Hughes Aircraft, have been making nickel-cadmium cells properly for synchronous application. Now I am not going to talk about low-earth orbit. I think the same thing applies to both because they are overloading the electrodes and this goes back to some concept about commercial electrodes which doesn't have a damn thing to do with aerospace electrodes and they have just been overloading electrodes for years.

The people who have recognized that fact for years have been Bell Laboratories, a long time ago.

BOGNER: I would like to add something to that, Bogner, JPL. I just happen to have a little curve here similar to what you were talking about.

DUNLOP: We had that.

BOGNER: Somebody was asking why didn't the government fund some research? Well they have, through the years, and this is a little piece of information thta came out. Unfortunately, it was never followed through to maybe a good conclusion, but this shows how you can load the plate. The squares show how much material will get into the plate, the capacity on the right side of the graph, and it shows that as you go up you get more capacity in the plate as you load it.

(Slide 67)

BOGNER: Someplace up there after you get out past 10 impregnations, it is going to go down on the other side, but then looking at the curve with the circles, that shows a material utilization. This is for one type plate, one thickness of plate, and I think we need that kind of data for different thicknesses of plate. This is a new plate data. You need that data for cycled plates and you can find out what kind of efficiencies you are getting and now it is dropping off and you know something about the loading and you know something about the pore size. This is for the negative electrode. I don't happen to have one for a positive electrode. I assume maybe Jim does.

DUNLOP: No, but I think the point is the same on that one. If you run an electrolyte redistribution, you start attacking problems where you can avoid the things that cause electrolyte – which was what Seiger was talking about and one of them very obviously is to stop trying to stuff 10 pounds of sausage in a five pound bag which is what the battery manufacturers have been doing and it is not the battery manufacturers that do it. It is the aircraft manufacturers that asked for that kind of battery design.

BOGNER: We are using aircraft plates.

DUNLOP: Right.

BOGNER: We are not designed for high rate cells. We are usually in the synchronous orbit using it for low rates, so we could possibly go to the thicker electrodes.

HALPERT: I would like to make a comment with regard to supporting Sam's work. I have a free piece of data. I don't have it on a slide right now but I have it in a briefcase that shows the surface area impregnation, 1, 5, and 9 and it shows that impregnation 1 is something like 19 square meters per gram.

Impregnation 5 is 25 square meters per gram and impregnation 9 is down to 23 square meters per gram which means that we are getting to the point where when we continue to load, we are clogging up the pores. It is obvious that we just can't get to the active material in there. It is only three points, I recognize, and it is on the positive plate, but it certainly supports the same kinds of things we have been talking about.

Now, I will just mention one other thing in support of this also. I am concerned when I talk to the manufacturer who tells me that the only way to measure the thickness of a can with a cell, after the cell has been cycled, is to leave the restraining plates on because if you remove the restraining plates the cell bulges and that means to me that there is something going on that he is trying to do that can't be done. He is obviously putting too much in and he is getting too much expansion and thta concerns me, so it is along the same lines that we are speaking of.

LIM: I would like to ask a question concerning the electrolyte distribution and oxygen transportation through the cell. I heard a lot of discussion and in terms of the part of this discussion about the separator materials in the cell, as a newcomer, relative newcomer in this area, I didn't hear anything about the physical texture of the separator. Does anybody have any information on that or comment on that?

FORD: Yes, I see a hand way in the back.

LYONS: Gary Lyons, Howard Textile Mills. In answer to that question and the previous questions, that can be accomplished. If it is desirable to improve the flow of the electrolyte. There are many mechanical means on battery separator materials that can accomplish this. The material can be made so that it can channel the flow of electrolyte in the direction that is desired and that may also help keep this bulging effect that we are speaking about down because there could be room for the electrolyte to travel within the channels of the fabric and this can and has been accomplished in the past.

SEIGER: I would like to ask Dr. Lim's question. There is a paper from the meeting of the section of the Electrochemical Society written by Dr. Tom King of Canada in which he treats the air permeability and some of the characteristics of their separators. Interestingly enough, he did that work with polypropylene and the Canadians have been flying polypropylene and I believe that there are some others that have been flying polypropylene too.

LIM: What year was tha. .o you remember?

SEIGER: 1970? I believe it is 1970.

WROTNOWSKI: Wrotnowski, GAF. As a direct answer to your question on pore size, GAF makes filter media and we have developed a mathematical pore size to predict pore size using denures (?) and the assumption is that all fibers are straight and parallel and then you can calculate the pore size and we do use this quite successfully, and can predict, in actual fact, straining of particles using fiber diameters, and produce related to structure – paper as well.

SEIGER: I would like to get back to the discussion that Sam Bogner and Jim Dunlop were on with the impregnation of the positive electrodes in which they were getting utilization in talking about overloading. I had a very interesting little experiment run in which I measured the electrical conductivity across the face of a plaque just as Dr. Scott has done, and did that during an impregnation and we did it cycle by cycle and let us say that when I get a change in the electrical conductivity measurement, that I could say I am not starting to get corrosion. I went from four impregnation cycles with a vacuum process with essentially no corrosion. When I went to No. 5 and No. 6 I was getting an awful lot of corrosion. I just didn't know what I was weighing. I don't know how much of the scinted (?) I oxidized. I don't know how much it was weakened, but those plates indeed did shed and blister.

BAER: Baer, Goddard. Stan, you are saying about putting more electrolyte in the cell may back off on the loading. Last year Floyd gave a presentation where he in a 12 ampere-hour cell and –

KRAUSE: That was the IUE cells, right?

BAER: Yes, and he put 51 cc's in it. Okay, we have gone back a[illegible] that on two of the plate lots. We backed off on the loading 10 percent a [illegible] 46 cc's in them and we probably could have gotten more in them except [illegible] had third electrodes, well some of the cells had third electrodes and they were starting to swamp. Now these cells, even with the reduced loading, they still delivered – 12 ampere-hour cells, still delivered 15-1/2 ampere-hours and [illegible] was at room temperature measurements and also at 35 degrees C. The only place there was something a little funny was the cold temperature capacities and initially we didn't do too well there but then after cycling it picked up and we got up in the neighborhood of 15 at 10 degrees C. after 10 cycles, so you can put extra electrolyte in and unfortunately we don't have any life data on that yet.

GANDEL: Gandel, Lockheed. Floyd, when you adjust the electrolyte in the cell what care do you take to exclude air from the atmosphere? Just what is your technique?

FORD: I don't adjust the electrolyte in the cell. I buy cells where it has been adjusted and that is one of our fundamental concerns about the care that could be exercised or the degree of care that could be exercised to preclude contamination and also how repetitive it can be. One basic contention I have about building flight cells, you fill the second ones like you build the first ones. If you go through three electrolyte adjustments on the first group of cells, you had better damn well be prepared to do it three times on the second group because if there is one thing that makes a difference it is the lack of reproduceability and the way you put cells together.

But there are steps that have been proposed and implemented where electrolyte adjustments do take place. I quite frankly don't like it, but I am not suggesting the technology is not within our grasp to do this if it is proven absolutely necessary. Quite frankly, it is an extra step. It costs manpower. It costs time to do that. If you could get that without doing it it would make the process a lot simpler and therein I think lies some of the fallacy. The simpler the process can be I think the better the cell is going to be. Perhaps a manufacturer would comment on that. I can't, not directly, to answer your question.

PARK: In speaking of the flooded cell, what – how many cc's per ampere-hour were you thinking of?

KRAUSE: I didn't have a number in mind. I guess I am thinking along the lines that Dr. Seiger has suggested, essentially having the plate pack almost saturated or nearly so, removing entrapped air if it does exist. Not necessarily, but if it does, I don't have a number in mind.

PARK: May I ask, on the trapped air, does a vacuum filling fail to remove the air?

KRAUSE: Do you want to answer that one, Harvey?

SEIGER: I am sorry. I didn't hear.

PARK: Does a vacuum filling fail to remove the air?

SEIGER: It sure can fail. It would have to be particular with the way you go about it and you can even eliminate the air without a vacuum. There is more than one route.

KRAUSE: Yes, some of you may be familiar with the silver zinc cells that have been built at one time or another. You take silver zinc cells at ESP for example, and you fill that thing with electrolyte. In fact, you have a chim on the top and you would run that thing flooded, run through some formation cycles, take the excess electrolyte, dump the cell over until it stops dripping and off you go and they were highly saturated in that manner. Maybe a ni-cad ought to be built that way. I don't know.

HENNIGAN: Since you mentioned the silver cell, let me say a few words on that. I think the biggest mistake we ever made in the space program was how to charge the cells when we flooded them and we came up with a charge control method that would work. We did the same with silver zinc, but when we got up to – let me say a few words. Harvey, quoting some numbers, I don't think I said them, but there was one cell up there with 26 cc's. That was the top, nylon. That was – we ran that one four years ago. We had a lot of trouble running that cell. How many cycles did we have to go, 100 or so before we got the pressure to come down?

Then on the second go around we put in 22 cc's but a lot of the polypropylene cells have 24, so they were not less than the nylon. The other thing was those cells we did run that time were in the 20's. What was that separator, 2140?

KRAUSE: Yes.

HENNIGAN: Remember that separator? You said how great these cells ran after 3,000 cycles and 40 percent depth. Again, they were very tired and they expanded like balloons and those cells were taken apart and the separator was extremely dry. It was the dryest part of the cell.

SEIGER: And thickened positives?

HENNIGAN: I don't remember the number there.

SEIGER: That was the reason.

HENNIGAN: They had expanded so much that –

SEIGER: Pardon me?

HENNIGAN: I don't think that the positives would have squeezed out the electrolyte.

SEIGER: That was also RAI material.

HENNIGAN: The cells were getting larger and larger.

FORD: Okay, now, I think one more and then we will come back to the panel and then we will keep going, okay? I would like to keep the panel going.

ROGERS: Howard Rogers, Hughes. I would like to ask Harvey Seiger a question on the vacuum filling, that if you pump the cell out you get the pressure way down, I don't see where the air could stay if you have a decent vacuum pump.

SEIGER: I agree. Now what?

ROGERS: Why does it trap air? I guess that is really my question.

SEIGER: All right. I was asked that question at the Electrochemical Society meeting last year and I will repeat the answer to that. You now have pumped it out and removed the air from the cell. You now inject electrolyet into the cell and it will fill all of the pores very quickly. However, if at the instant you put that in you break the vacuum to permit air to get into the cell, you now have two things, highly viscous electrolyte looking for those pores and air which is not viscous and so you have this competition and it is in this way that even though you use a vacuum you do not necessarily have to get all of the air out.

Let me also talk about another experiment that I reported on here two years ago in which I had taken electrodes, negative electrodes, dumped them into electrolyte, pulled the vacuum after they were wet, and we had a quantitative measurement of how much air was entrapped. We compared that, incidentally. We pulled the vacuum. Now we compared that to another group in which we pulled the vacuum first and while that vacuum was broken we added the electrolyte and did not permit the air in and I hate you because I have just revealed one of my two methods.

FORD: Okay, but I would like to bounce back. My panel is losing interest here. Let me get back to the panel and then we will go back and forth a while. Gerry, do you want to take the next one?

HALPERT: I would like to say that we have made significant strides over the years and just listening to the discussion now brings to mind the fact that we no longer are just looking at voltage and pressure to say whether a cell is good or bad. We are talking about impregnation and we are talking about loading and we are talking about plaques and pores and so on, which certainly is of help, but I think in my dealings, certainly, in looking for, in looking at cells for a space use and putting them into battery packs for flight missions, I find the difficulty continues to come up that we haven't made the lots – one lot of cells the same way or multiple lots the same way for the same requirement. We have a document that says we have – we have an MCD, so to speak, that has been made to the so-called, quote, "Goddard spec." that we said before, and we have a lot of controls that we try to exercise, but when we take and we put in a purchase for a lot of cells or we put in a purchase for cells, we may get one, two, three shipments of lot one, or one shipment of lot one, one shipment of lot two, one shipment of lot three, and no matter how you cut it, none of those are the same and so you end up putting three different, essentially three different batteries on the same spacecraft and having to tune the power supply to it, which is not always the best way to go.

So what concerns me then is the lot to lot variation and then I go back and I listen to our discussions here in the meeting and we are talking about vacuum and impregnation and we are talking about electrochemical impregnation but we still haven't really characterized or at least said, "This is the plaque we are using to start with. This is the pore volume of that plaque," or "This is the porosity," or "This is the average pore volume." We haven't talked about the impregnation or the loading per cc of surface area. We have mentioned all of these terms but until you start characterizing a particular cell on the basic materials, unless you start using that as the criteria, we are still talking about lot one and lot two and lot three and they have no relationship to one another. I am not sure how we go about this because all of the basic processes are proprietary and I can understand the companies wanting to maintain their proprietary nature. On the other hand, I think we have a great need for producing a plaque in a uniform way and saying, "This is the plaque we are starting with on point one. This is what we are going to load to in grams per cc of void volume, No. 2, and this is the result of that. Now we are going to assemble our cell. We know how much the expansion is going to be and we know what the electrolyte distribution is," but until you go back to the beginning and make uniform the original product, the plaque material, we are going to have problems so I think one of the things that we should be looking at for the future, certainly, in a program, is to make a uniform plaque in a reliable way, a reliable and reproduceable way, and that is going to take some doing.

GANDEL: Gandel, Lockheed. Gerry, my only suggestion is I think you ought to have a uniform cell program instead of the standard.

HALPERT: Right.

FORD: Another question?

ROGERS: I would like to ask Gerry a question. Rogers, Hughes. I guess wouldn't it depend what you want, wouldn't it depend on the plaque being of uniform quality, breaking strength, et cetera, porosity, it would have to be identical each time we made the plaque and is that expected to come out of each manufacturer the same way? I would be very surprised if it did.

HALPERT: I would certainly not expect company A to make the same plaque as company B or company B make the same plaque as company C. Obviously they use different methods. All I am saying is that it ought to be in some kind of control so that when they do it again the second time or when the impregnate the second time they ought to have some control, and I am concerned about this. Now maybe what I was trying to do was throw you something loaded. I was trying to have you tell me that you don't need this. I was hoping that somebody would get up and say, "You don't need a uniform plaque. You can take a plaque of any porosity as long as you know the pore volume and you can load it to the right amount and get the right efficiency and get the right loading. You may not get as much loading in a plaque that is not as porous. Maybe you get something less than you want but it still can be done and it still can be done in a uniform way." Is anybody going to tell me that? I would like to hear it. Maybe some people have some ideas on that.

Because it is obvious – I will just make one more comment – it is obvious that Bell Labs has made something different than everybody else has made. They have made a positive plate that is maybe thinner and more heavily loaded and a negative that is thicker and more lightly loaded and they get the kind of performance that they need for their particular long term standing on a pole operation. We have a different kind of requirement and if we know what we were going to start it with then maybe we can also develop it toward that end.

DUNLOP: Well, I would like to make a comment. First of all, in these cells that we made, these nickel hydrogen cells that we made for Fred Betz, we had them made by Eagle Picher using the Bell Lab process and fortunately, we were able to use their procedure which involves using their controls which involves having a control on the plaque based on a sample that is taken periodically and a measurement that is done to determine all of the things you are talking about and I don't know of any aerospace battery that we have gotten from an aerospace company that is done this same way but there is a major reason and the question is, the real question that you are asking seems to me not the one that you asked, but the way Bell Laboratory does that, or that Eagle Picher does it for Bell Lab is on a small private production run where they have got a lot of people plus a lot of money and it supposedly can go into a production basis someday but right now it has got to be a relatively expensive process and all of the major aerospace battery manufacturers are the major nickel-cad. suppliers which use major large production facilities which have plaque producing processes which don't lend themselves to the type of control you are talking about.

HALPERT: You are saying plaque-making is expensive, the plaque-making step itself is expensive?

DUNLOP: The question is whether you want to build, have somebody build – whether you want batteries made by a standard company because you can't – you are not going to convert GE, I don't think, to a different type of production process, not unless you want to pay for it.

KRAUSE: They might not want to do it even if you want to pay for it.

DUNLOP: Right.

KRAUSE: They might not be interested.

DUNLOP: Absolutely.

KRAUSE: I happen to agree with you that –

DUNLOP: I am just trying to bring out what the question is. I am not trying to debate the fact of whether GE wants to do it or not. I am just pointing out that their facility that they use to make batteries, the commercial production of plaque which is used to make aerospace cells is not set up to meet what you are asking for. It is not really a matter of whether you can do what you are asking for. It is a matter of practicality of making cells that way and that is the real question you have to address yourself to.

KRAUSE: But, for example, there was a company recently who set themselves up in business to produce limited quantities of very high quality plate and nobody beat their door down, unfortunately.

DUNLOP: That is right.

Why don't you comment on that since you are one of the major users of those batteries?

KRAUSE: We in the past have talked to battery manufacturers and strangely enough, we have gone in and said, "Your stuff doesn't cost enough money." If you look at the overall cost of battery cells that you have to buy for a satellite, the cost of the cells is really insignificant.

DUNLOP: Right.

KRAUSE: It is really cheap. And we have had spacecraft managers say, "Gee, if those things are really cheap, why don't you get them built better?" and you go to the manufacturer and say, "We will give you double the price for that cell. Instead of $200 a cell, we will give you $400 a cell, but we want you to build it the way we have been building it. We have got equipment tied up and processes and money and we don't want to make any big changes." They are commercially oriented and so I agree with your comments. I would like to see more high quality limited scale kinds of production but it does cost more money. The manufacturers perhaps feel that they might not be priced competitive if they get over into that kind of mode.

PICKETT: Okay, since the Air Force sponsored recently a program with a small company to manufacture exclusively aerospace cells, I feel we are probably one of the most competent to comment on this, so I will put my two cents worth in. It is true that you are not going to attract very much business with an exclusively space line. The Air Force has realized this and because of this we are planning to go out with an RFQ which was mentioned in the Commerce Business Daily, the July 15th issue and we have had some responses to that, but I will just say this, that we feel that anything like that to be attractive is going to have something other than just exclusively space, and I think we are going to aircraft production as well because we also need aircraft cells which have high quality and we also need electrodes for nickel hydrogen cells which have high quality and because of this the Air Force is taking a step forward in this matter and I hope this offers some help to the problem.

FORD: Lee Miller?

MILLER: Miller, Eagle Picher. As back up on Stan there, there is one battery manufacturer that will gladly change its process if you want to double the price of the cells.

HALPERT: Dave, can I ask you a question? Are you saying that we are going to have a sole source for aerospace cells, that we will go that direction?

KUYKENDALL: I am not saying that at all. I am saying that what we are doing is we are going to sponsor a manufacturing technology program for the manufacture of electrochemically impregnated plates for both aircraft and spacecraft cells, and it will be a competitive procurement. It may or may not be sole source. The technology is owned by the government and anybody can use it that wants to as far as that goes. We are just taking the initiative in sponsoring the program.

HELLFRITZSCH: I am afraid I can't sit here and not make a speech. Hellfritzsch, formerly of the Naval Ordnance Laboratory some 28 years, now retired. I do a little consulting in batteries from time to time. What I am about to say is what I said a generation ago. When I come back to meetings like this, my comment is that they haven't progressed. Now there are several things that are just ridiculous that are being stated around here. I am just going to make a number of assertations. I am not going to mention any company's name. In the course of working as a government employee I learned a lot about a lot of companies, and have not always preserved their proprietary secrets. On the other hand, I have often been amazed how three or four different companies making the same battery consider the same process proprietary with them, and that is the truth.

I also got to know companies well enough to know that they really don't know exactly how they are making the batteries at any given time, and the best proof of that, you see, when a company, a big company that is making a commercial product at a profit wants to set up a new client. If they go into another country it is even worse, but they write down. They put on drawings, they write and they design buildings and production lines and all of the instructions that they know how to do, and what happens when the plant is built? They try to make batteries and they are no damn good and what finally has to happen, they have got to take two or three of their best engineers and send them over there to that plant and keep them there for at least six months before they can make good batteries. In other words, they do not know how to write down what can be followed by any intelligent engineer in engineering terms, purity of chemicals, processes, and the quality control methods, and then when you get into powder technology, of course, you are pushing the technology of quality control to powders, for example, and compressing powders. Progress is being made. I looked into that about 10 years ago and I am sure they are further ahead now, but there are things it is hard to inspect for and know that you have got it the same way.

On the other hand, this is the only way that you are ever going to achieve what Halpert wants and that is what we wanted. We had Navy mines. Now when you talk, when I hear him talk about, "Oh, we are happy to have three different companies or any companies just as long as they keep repeating what they make." You don't have the kind of production. You don't need this thing. The Signal Corps had to do this kind of thing because there aren't enough dry battery companies to make all of them. They need all of the capacity in order to make the flashlight cells and all of their ramifications and hence they have to accept different qualities and they put down minimum performance levels and whatnot and let each one make it the way he can, hopefully getting the performance that they want, but you want something more than that, just as we do in mines and the other things that again, similarities are great. I mean in ordnance, Navy Ordnance, we buy batteries to store them and the Defense Department, by and large, except for maneuvers and whatnot, they don't buy batteries to use them. They buy them to store them and have a stockpile. With the snap of a finger if there is a war you are ready to use them. We would like to store them for 20 years if they are stable enough to store.

Now, the thing that will make the difference between the battery that will store 10 years and 20 years will be some minute differences that the commercial field isn't at all interested in because the commercial user buys batteries to use them and he uses them up in six months, and now when you talk about some of your 10 year programs and five years flying and whatnot, you are getting into the same sort of thing that we had. While you are using them, you are using them under conditions where you are interested in, it is very important that they last for five and 10 years, and nobody in industry has ever been geared to that. It is a waste of their stockholders' money for them to study these things, and I think you have got to face all of those things clearly and the remark somebody made back there, you don't want a standard battery, you want a uniform battery and maybe not just one. If there are several kinds of operations one may be a high drain battery and one is a low drain. They are probably going to have to be made differently if you are going to optimize the construction, but what you need to do is spend whatever money and effort and if industry won't do it, I mean, the DOD has done this before. I mean, industry didn't make cannons and guns. The gun factory made the cannons and the metallurgy that went into it, it is not my field, but I am sure they had to do some of their own metallurgy to get it by some hook or crook, that industry wasn't particularly concerned about, learn how to do it, write it down, and teach anybody if you can't do them yourself, teach somebody else to do them, and I mentioned this morning, just in passing, on this manufacturing drawings and all, the complete disclosure and whatnot, you are content to have the companies say, "We have got it all written down and we are going to keep doing this over and over."

They don't know how to do that. We know that when they tried to set up another plant, so forget about that. If you want a disclosure and you want to know if it is any good, you have got to validate that disclosure and the only way you can validate a disclosure is to give it to a bunch of competent engineers that don't know a damn thing of what went into the drafting or that and pay them to do it, and if they succeed you say, "Well, I guess we got a pretty good one."

Now we did that with thermal batteries. Ulrica (?) Williams did a complete job for us on disclosure. Pat and I went out there and spent two days there and listed about 50 things that they didn't have in there, so then the boys went out there and got all of that in and then NAD Crane went in and said, "Well, we could build them cheaper," and they never built a thermal battery in their lives. Well, this was excellent. We gave it to them. They built 1,000 cells and they were good. They followed the disclosure and unless you do that with a disclosure, you don't know whether you have got it or not. You can do it yourself if you want in government and if it gets acute enough anyplace in government where you really have to have these things, then if billions of dollars worth of satellites are in the throw, or the defense of the nation depends on it critically, why then you are just going to have to do it, but a lot of these things, I mean this kidding around here where people don't want to say something like this polypropylene is, "Well, we found out it is two mils. thick," but they won't tell us what the density is or the porosity is.

Now this is a bunch of proprietary hogwash because I got hold of a piece and I could measure these things, you see. Now the thing that is proprietary about it is the technique of making it that way, not what the final product is, so I think industry ought to be a little objective and not just use a lot of descriptive adjustives and not give the quantitative numbers. You don't give anything away, and far too many things are considered to be proprietary. I mean, there is a big difference between here and Europe. You go over to England to the battery conferences you realizes, "Hey, they tell a lot more than anybody here tells at a battery meeting," and if you go into a plant and have the confidence of the chief engineer there he will say, "We have only got about two things here we are not going to tell you. Anything else we will tell you all about," and there will be only two or three things that they know are really proprietary. This business of batting this "proprietary" thing around, it is either to cover up ignorance, meaning what we don't know, and if you don't know the best thing for the whole industry, government as well as themselves, is to come out and say we don't know and then let us find out how it should be done because without that you are not going to make any real progress in a scientific way.

Going back to NASA when Walter Scott was here and we got all of these nickel-cadmium batteries in and you know, we ran a testing program at the Naval Ordinance Lab. He wanted me to test their batteries because he knew we had a pretty good crew to do it. I said, "Well, how are they going to be made?" "Oh, well, they will be made according to a performance spec." "Are they going to be made all different ways?" "Yes." "Well, I don't know what you learn by testing if you don't know what it is you are testing." That has been my philosophy. Then, I knew NAD Crane had a group that could do it. They build these other batteries for us. They could follow instructions there. They can test batteries, and that is how the program got started out there. See, you have got tons of data but you still are not any smarter, you see.

Now, as you accumulate these decades of data, we begin to realize, "Hey, they are no longer making them the way they did." We don't know how they made them then and we don't know how they make them now. This is not science. This is -- you talk about the blind leading the blind. My good friend Parks there, when he said, no, that is the way it has got to be, I mean, you are going to have to pay industry and they will do the best they can but they are not going to tell you, we cannot tolerate that attitude in the kind of business you are in or the kind of business that the Navy is in in critical ordinance batteries. Thank you.

MILLER: I don't feel as much at home as when I first arrived here. As far as this proprietary business goes, I don't see how it can be avoided in a competitive set up. Now, if you want to set up a government battery manufacturer, then I think you can have all of the details.

MAURER: Maurer, Bell Lab. I might make a couple of somewhat unrelated comments. First of all, on this question of writing a disclosure and having a second firm discover when he sets it up that the battery doesn't work, we have referred to that as a leather apron effect, so the second firm proceeds to find some of the problems with the first disclosure and gets a battery that works so he writes a new disclosure which presumably eliminates some of that. Now you give it to a third manufacturer and he goes through the process all over again so gradually you weed out the leather aprons, so I might suggest that NASA plan to finance something like 10 or 15 battery companies in series to find out how to make them completely and weed out all of the leather aprons.

HELLFRITZSCH: There is nothing elite, really, about this. I mean round robin testing when you have samples of steel or salt water or whatnot, where it is difficult. You are pressing the technology on how do we analyze it in order to standardize the methods of measuring things. Laboratories have cooperated before and sent the samples around and you find out some people just can't do it. As a matter of fact, the Germans and the United States were off I don't know how many microvolts in the standard volt one time and Dr. Vanell (?) had to spend a whole year over there to find out what the difference was. I mean scientists can cooperate when they are seeking the truth. Now, if we are not going to be scientists about this, then forget about it. Anything I said, I was thinking if we have a scientific technology here and there are many things we don't know and we are all striving to learn about them and unless we do that -- other nations may do that better than we and in the long run they are going to be ahead. I mean, if we just keep what little we know from each other because of some economic lever and others don't do that, in the long run they will be ahead of us technologically. I mean it is as simple as that.

PARK: I am still in favor of free enterprise. I want to speak my peace and I did.

MAURER: My second comment was on Harvey's question of air in the negative electrode and why doesn't it come out when you pull a vacuum on the cell. I refer you to vacuum technology and the fact that this electrode has very fine pores. The pumping speed of those pores is very slow and it turns out that if it would take you the time constant of these pores is roughly 10 to 15 minutes, you would have to pull your vaccum, a high vacuum for that length of time in order to get all of the air out of the plates. My third comment is related to Jim

Dunlop's comment about our facility being a pilot scale operation and I would just like to note that we still pay less for our cells than you people do and the third one is on Gerry's question of screening electrodes by weight. I think you do have to go back to the plate because there is a variability in plates and the way we do this is to take samples periodically along the plaque and require that the weight gain on each section of plaque falls within the same values. But the total plaque weight, of course, is different. The total electrode weight is different. It is going up and down with the plaque going up and down, but the total weight gain remains the same.

The problem you might get into with that kind of a routine if you are using heavily loaded plates is that the porosity has dropped. In order to get the loading you want you are now using up too much of the void volume and the plate will then swell unless you use electrochemical impregnation.

PARK: At any rate, I have been involved in the government quite a bit during the war. I got started in the Naval Ordinance Laboratory before Pearl Harbor involved in the mines that Hellfritzsch was talking about and we did pretty good service not only during the war but also in Haiphong Harbor and there are two ways of doing it. One is to have the government do it and the other is to have industry do it and they are quite different ways. Now, if you have industry do it you at least have different groups competing and one of the great things about industry is the people can go broke if they aren't any good, and you eventually get some pretty good people left in it.

Now, in the government they don't do that too much. You are stuck with what you have got and I know at the Naval Aircraft Factory in Philadelphia they were making very great big beautiful planes and one of the exceptions, there are places, probably, where you should have the government do it. I don't think you have got as much different approaches of things. The Russians aren't doing so well because they don't have free enterprise, I think. They don't get the variety of approaches. Now, I know Hellfritzsch has always been in favor of government doing it, but I am not too sure that that is the best way, but they are two entirely different ways I think.

KIPP: Ed Kipp, SAFT America. I feel someone has got to say something in defense of the battery manufacturers. Nobody else seems to want to volunteer so I will stick my head way out. I have been associated with the aerospace industry for a lot of years as most of you know, on both sides of the fence, and most of the time has been spent as a battery user rather than as a battery manufacturer and from that standpoint I have got to say that the battery manufacturers have done one hell of a job to satisfy the needs of the aerospace industry over a long number of years. If you look at the record of batteries that have performed in space going way back to early ballistic missile programs, and the efforts of all of the companies including Eagle Picher and Yardney in the early silver zinc days, you have just got to look at that record of performance and say it has really been tremendous and especially when you look at the percentage of the dollar volume of the business that has been involved.

I think NASA might be taking a step in the right direction now. Before, up until now, they have looked at controlling cell manufacturing processes as far as cell assembly processes are concerned and the new spec., 74-15,000 they are now looking at trying to control plaque and plate making processes. Maybe this is going to be the way to go. I am not so sure the standard cell program is going to be all that successful, but time is going to tell whether or not their approach now to plaque and plate control may pay off.

DUNLOP: I would like to make a plug for the free enterprise system, since I have been on the other side of the track most of the time. We have actually had very good results with the cells that GE has made us. In the last -- we do analyze. By the way, you are right. One of the things that has been surprising to me in the nickel-cad. business is the fact that everybody puts a voltmeter on the cell and never cuts it open to see what is inside, but the last few years there really has been a good deal represented by the people in this conference. We are really taking a look at what the degradation mechanism and things of this kind are and it has been very evident, I think, by a number of the papers that were presented earlier today, and these types of analysis can tell you a great deal about the cell and I think that kind of theme has been evident from time to time throughout this conference today and the cells that GE has been making for the Inosat (?) and the domestic satellite systems for Comsat we do analyze because we want those satellites to work for seven years. Now, we are a commercial enterprise, but we damn well want them to work for seven years and Hughes Aircraft wants them to work for seven years and we do analyze them and GE has been making in the last three or four years a very reproduceable product for us. I don't know what they make for Goddard, but for what they have been -- this is a good example of the guys making a pretty reproduceable thing, but if you also note, something else that is being said here is that these cells are going to work for six or seven years and that is about what all our test data says and that is what our analysis is.

The problem you run into here is you are trying to -- this the other half of the coin. You are trying to look at something that is going to work for more than six or seven years. You are trying to look for something that is going to work for 10 years. That is what I am interested in, and when I looked at that I knew that there were certain inherent problems like that nylon separator that the guy says it is going to last for seven years and on our analysis it shows that it is only going to last for seven years and in our test data it shows it is only going to last for seven years, so we are looking for something a little bit better and unfortunately, we are not getting it right now from any of the R & D programs that are going on. Unfortunately that is the case, and we do see things like the work that the Air Force is doing and the work that Bell Labs is doing that looks very good in terms of new types of electrodes. That is one of the most interesting things, that promise you more lifetime and the question is, how the hell do you implement that into this free enterprise system that is already made up of people with set production processes? It is not so much that you are knocking those guys. It is a question that you don't know how to implement new technology that is coming along and one of the ways is to go with the new small companies and that is what seems to be going on here and that is where the battle seems to be taking place.

FORD: I would like to come back to the panel now and let us pick up perhaps another subject. I haven't been told what these batteries are all about, so who would like -- Sid, would you like to go next?

GROSS: Let me mention first a few relatively minor problems and then a few more important ones. One of the minor problems is reconditioning. There is a penalty associated with putting reconditioning equipment in spacecraft, especially small spacecraft and although there is a lot of bits and pieces of information on this subject there still is no composite gathering, collection of all this information with any kind of attempt to fill in the holes, so this is a small subject that I think needs to be taken care of.

Second small subject is life prediction. Every time we have -- many times we have occasion to have to predict the lifetime and reliability of batteries that we use and we are faced with the task that the data available is inadequate to do the job. A lot of the data is old and many of us feel that today's batteries are probably better than the older batteries that this statistical data represents, yet we don't know how much better. We have no factor that we can confidently apply, so in the final analysis we end up doing a punk job on predicting life of batteries.

Still, it is a minor problem. I would rather have good batteries that I don't have any data on but I am confident of a real good than old batteries -- lousy batteries that I have got good data on.

The third minor item is accelerated life testing. We have had to do a variety of accelerated life test programs and each time we embarked on these we found that the information available to give guidance to these tests was inadequate and we ended up concocting our own programs on the -- essentially using our own judgment. Hopefully, the work that Hennigan is doing may give us some guidance, but our hope is that that or other work is carried to some conclusion so that we can get this problem solved and make use of it in the future.

Then as far as the more important problems, certainly the most important is the one that has been talked about. better plates. We really have to get down to basics and this is the real problem, that for years we really have been ignoring. We have been doing everything with batteries, everything except to really make better plates. All kinds of quality control, all kinds of data, working on seals and -- but we really have ignored, I think, except in occasional spots here and there, we have ignored facing up to the real critical subject of better plates, starting, of course, with really good plaques and the right kind of plaques and porosity and the right kind of loading.

Related to that is the polypropylene separator. We don't really know why the polypropylene separator is not appropriate, why it doesn't work, and it may be because the plates we have aren't right. We do have to eventually get away from nylon. We have to start making polypropylene or something else work.

The second important subject is shorts. Shorts in cells, there has not really been an epidemic of shorts in cells, but we have had then occasionally and most everybody else I know of has on occasion had shorts and one short will wreck one cell, can wreck one battery, which can wreck one spacecraft. That is too much. I think that problem is really related to the problem of a better plate. I think the plaques are not strong enough. The third important subject is vibration. We have had -- we have run tests to find out just how good cells are under vibration and in brief it looks like that if you are happy with a two or three sigma success probability, or if you don't -- if you are not the kind of a person that likes a good safety factor, don't worry, but if you like good safety factors, you ought to worry about vibration, so we have had to make some changes to come up with cells and batteries that give us the confidence we want.

But the real solution on the vibration problem is essentially to get greater confidence, to get greater capability, involves really going into the cell and making some major changes.

FORD: Okay, thank you.

IMAMURA: Imamura with Martin-Marietta. There are about three or four related items that Sid brought up and I wasn't going to bring up the topic, but in terms of cycle life prediction, Floyd, and I think the rest of us, we always hunt around for data and of course you have to go to the old NAD Crane data, Naval Weapons Center, I guess, and my thoughts were should Goddard continue the testing at the five cell level, the 10 cell level? What kind of parameters, on top of that should you be testing?

I had a suggestion on how to possibly make best use of the Crane data, such as possibly going to a single cell, cell level, parametric type testing in order for the data to be useful. One could go to, say, a 21 or 22 cell test and you have a horrendous number of battery packs to test under various conditions of temperature, but I feel that maybe we ought to seriously look at single cell testing under controlled conditions, now, temperature, C to D ratio, of course charge and discharge rate comes into play there but I feel that temperature, depth of discharge, C to D ratio could be looked at seriously at the single cell level from the standpoint of using -- try to make use of their data in the future. I really think that we ought to have in a document when each cell failed rather than 40 percent of the cells that failed, and I think something like that is always useful in trying to – you know, we are in a game of trying to come out with a failure rate and reliability types, like some of us, for instance, would have to take that data, translate it to the cell level, put it in some form of model and try to predict it. There are an awful lot of ways to go, and I thought I should get some discussion on that.

HELLFRITZSCH: Hellfritzsch. I think you have got to make one remark in answer to that, though. It sounds like, well, everybody knows that you don't test reliability of anything. You have got to design reliability into the thing, and all you can do with testing is find out whether you succeeded or not, so I didn't want anybody to get misled by reliability suggestions, I am sure, but that is the thing you want to be careful of, whether you test one or you test 1,000. If you are just testing you are not going to increase the reliability one bit. You have got to design it and that is where you need the information which I am talking about which we lack and what we really should do instead of what do we know about batteries is let us make a long list of what we don't know about them that we think we need to know in order to come up with a sound design and then set up a program to get the answers to those questions.

MCHENRY: McHenry, Bell Lab. Has anyone tried making separator material – not actually separator material, must take nylon 12 and see if it wets and then if it does you chop it up in little shavings and see does it oxidize? Now nylon wets and apparently polypropylene doesn't, and nylon 12 has got a little nammide group every 12 carbons instead of every six and it absorbs something like one percent of its weight in water where nylon six will absorb 10 percent and I presume the ability to absorb water has a little bit to do with your dissolving and, well, nylon 12 is getting closer to polypropylene that nylon six is and I don't know if you can make a nylon 24 or something, but is there another material that does not hydrolize so easily as nylon six does, that still will wet? The Japanese make fishing nets out of polyvinyl alcohol and I presume it doesn't dissolve in water. They have for years.

SPEAKER: It doesn't dissolve in sea water.

MCHENRY: I don't know if it falls apart in KOH, but is there something that will wet that will also stand up to the environment inside of that battery? Has anyone tried to look around and see what kind of materials there are.

COHN: Cohn, NASA Headquarters. Let me repeat a speech I made a few years ago. I don't think we ought to be looking for a material for a separator. I think we ought to be looking for materials for a separator. There is polyphenolene oxide, polyphenolene sulphide, potassium titanate, which are three materials I know that are KOH resistant. One of them has been used as an absorbant just like a separator in fuel cells. The other two have been used for sterilizable cases. I don't know whether they wet or not, but presumably a phone call to GE will find out or maybe somebody here already knows, in addition to which, there may be three dozen other polymers, organic and inorganic polymers that I have never heard of, but I would like to say that if you are going to look for a better separator, for God's sake, don't stop at the next one that looks interesting, but stop after you have gone through them all to date and if you are going to spend some money on having to test five dozen of them, it will be money well invested rather than spending five years on polypropylene or something and then you will find out why it won't work.

MCHENRY: Yes, well actually what you are looking for is something that stands up to KOH and will wet and the point is nobody has done much looking.

WROTNOWSKI: Wrotnowski, GAF. There are three materials that wet out and are more stable than nylon six. We did this type work in our lab looking for a red mud filter media and nylon – and what we do is use an autoclave and did a 100 hour exposure and in that order of – I believe it is nylon 11 which is just one digit off, but above nylon six is nylon 66 and more stable than nylon 66 is cotton. This is confirmed by Dupont's own chemical stability data and then nylon 11 is more stable than cotton and above that is teflon and polyprop. in an autoclave extended life. This is work that we have done and it is just a matter of autoclaving. We did our work in 10 percent caustic, but it separated these materials out damned fast, and that is why we like polypropylene and we have been hanging in there trying to make it work because it is obviously – it is as inert as teflon in these autoclave conditions.

ROGERS: Rogers, Hughes Aircraft. To answer the question about polyphenolene oxide, this does wet very easily. But my question is more who makes a fiber out of some of these materials like polysulphones or polyphenolene oxide or polyphenolene sulphide? I know who makes the material but I don't know anybody that makes a fiber. You can't use them as a block of solid plastic.

RAMPEL: Guy Rampel, General Electric. In relation to your comment on polypropylene, Sid, I would say that there are many users here who have received many thousands of cells as we have made with polypropylene and I don't see any problem with polypropylene other than specifications which say that I am to use nylon.

GROSS: We have tested polypropylene cells and they work fine. The only reason to not use them is the data that has cropped up here and there suggesting at this time it doesn't appear to be wise to use them.

FORD: Yes, if I could comment on that, it is unfortunate that two gentlemen who had planned to be here could probably give you firsthand information on the Viking cells that were done on tests at Martin. Are you aware of what I am talking about?

SPEAKER: Sure.

FORD: They have experienced some – this was life testing, only, obviously, but they have experienced some symptoms of high degree of dryness with life testing of polypropylene. I don't think it is unlike what we have talked about here today.

I have a couple of suggestions. I think one is we have been testing polypropylene, be it whatever number you call it, but by and large we have been testing, based on our previous knowledge and previous technology. If you can build a cell with more electrolyte to start with and I think it was two years ago I showed a curve where the amount of electrolyte you found in nylon after a cell had been through acceptance tests, was linearly related to the amount of electrolyte put into the cells in the manufacture, so there we have the baseline for cycle life. If you could start with more in the cell you could tolerate the same rate of degradation if you start with less, but the endpoint is much further out in the life of the cell.

What I suggest we do is take the technology we have learned by backing off on the loading and I don't know how far we can go on that today. I do know that we demonstrated to our satisfaction. We can go down 10 percent with no compromise in cell design. In fact, everything looks like it would be quite to the contrary.

Back off the loading, give up a little bit on capacity if that is what is required. Put the polypropylene in the cell and put more electrolyte in to start with. It may well be we have got a cell, a 10 year polypropylene cell. I think that deserves looking at. I am not so sure we need to continue to beat the bushes for new separator material. I know we have got a couple of dozen that we have looked at already and we have some pretty good characterization from the NBS work and from some work done internally. I think we ought to reassess what we know in light of polypropylene and apply that and take a look at it.

The second point I would like to follow up on is this question about reconditioning. I am convinced the need for reconditioning is built into the cell. I think the data this morning on the effect of electrolyte shows that conclusively. It is either built into the cell initially by some design constraints that the manufacturer is living with, either outer or inner imposed, or it is by an arbitrary definition of voltage on the cell that the user applies and we at Goddard think there are other approaches which are simpler and cheaper than reconditioning in state, and that is to start with, to build a better cell. We have the technology. All we need is the willpower and the tenacity to get in there and do it.

Let us move on. Fred, would you? We will get back.

SCOTT: Well, one disadvantage of being fourth or third or something is that you can't quite be as original, but I must say that independently, I have written down here prior to any of this discussion many of the points that have been made. I have a slightly different slant on a couple of them that I would like to put forth. First of all, I agree with Stan 100 percent, at least as far as geosynchronous orbit applications are concerned and my views are a little bit slanted in that direction since I have had most experience with that kind of usage. The main problem is electrolyte redistribution, and I believe that if we can solve or limit that problem alone that most of the other problems that we see in the cell may go away, at least for synchronous orbit type applications. There certainly are a different set of failure modes applicable to low-earth, high cycle life type usage than applied to synchronous orbits and yes, we should keep that in mind too. There are a few failure modes that are common, but there are also a number of them that are not common and this you have to keep looking at, but time after time we have taken apart cells which – whose voltage on discharge and this is at relatively high depths of discharge which are necessary in a synchronous orbit in order to make the system practical.

Where the voltage of a cell at the end of discharge is way down below one volt, but which discharged essentially normally, when we take them apart we see nothing that is visible to the unaided eye. The separators are apparently in visibly almost perfect condition. There is no cadmium visible in the separator. There is nothing obviously going on but the separators are relatively dry and the plates are relatively wet.

Now, undoubtedly, this distribution effects the condition of the plates. There are other side effects that follow from electrolyte redistribution which can be permanent and can be cumulative, so I believe that to a large extent if one could prevent the redistribution of electrolyte in the first place, many of these other follow-on failure modes may become under control.

In order to do that, I think, and I think I have some data which I will show you tomorrow unless you insist upon seeing it today, that show that the order of events with normal plates, vacuum impregnated positives in particular, is that the positives swell first and then the electrolyte migrates, not the reverse. The data is not conclusive, but that is – it looks to me like the positives swell regardless of the condition of the electrolyte and the result is following that, is a redistribution of electrolyte that probably goes along with the squeezing of the separator, the expansion of the positive to increase its porosity and the ability to absorb electrolyte and so on. So that brings me to my second point which has been brought up here previously and that is that I think one of the first steps that we could take to make cells perform more reproducably to implement life testing, comparative testing, and so forth, is to get a positive plate that does not swell appreciably under a wide variety of conditions. Put it in the cell and I believe that alone would tend – that alone would give you more stable positive electrode characteristics and it would result in much less electrolyte redistribution which then would result in less of all of the follow-on degradation modes. This is what I think we need to do first and I think we have the technology to do it today and it is just a matter of practical implementation in terms of utilization of the electrochemically deposited positive plate in place of the vacuum deposited plate.

The other thing that I see more and more often these days is signs that good old Pellon 2505 is not always what it is supposed to be. And then I say, "Well, what is it supposed to be?" And I find that there is no real specifications that I can get my hands on as to what the molecular weight is, what is the average molecular weight? What is the chemical, real chemical composition? I can find data which some people find it has a molecular weight of such and such when it is new and then over here somebody analyzes it and finds out that it has a molecular weight of 1/4 of the other reference, presumably for the same product. I submit that possibly some of the differences that have been observed in the degree of chemical stability versus hydrolysis, oxidation, and what all, are due to a variation in the basic product and that we should find out what it is we have got. We should if possible get a more uniform separator product if we are going to be working with nylon of this particular type and then we can know what we are doing, but I think we ought to be more concerned with the exact nature of the nylon material that we are using and control its properties better.

The final thing I think that we are still floundering around on after all of these years is what is the optimum excess negative for a given application? I suggest that we could try, if possible, to limit the question to just two basically different types of operation, multiple 1-1/2 hour cycles at relatively low depth of discharge and the type of operation, let us say, from 50 percent depth of discharge on up that you get in a synchronous orbit, and really try to tie that question down. As far as I am aware, I don't know what the answer is as far as – I mean as far as the optimization. We have done a lot of work in trying to maximize the excess negative. I agree with Floyd's earlier comment that we have probably gone overboard. We could probably back off but how far can we back off? I think we need some pretty controlled sets of tests to really tell us what that optimum ratio should be.

WRONTNOWSKI: Wrotnowski, GAF. I would just like to mention that we are a felt company. One of our products is the felt marking pen and the felt magic marker type thing is made up of two things, a reservoir felt which is a low density felt, and the nib which is a high density felt. The high density or the nib has greater capillary or pumping power and will draw the ink right out of the reservoir. I just take that as an analogy on the plaque taking the caustic right out of a low density separator and I say it is an analogy. I think it just locks right in as a physical, a simple, common thing.

FORD: Gerry?

HALPERT: Yes, I would like to make a comment with regard to some of these points that have been made which I think are very reasonable points, the separator, the excess negative, and another thing that we do quite a bit of and that is adjust precharge and electrolyte during cell manufacture. One of the things that has most bothered me is the, and I will use this quote from some memo that I once saw, of "engineering on-line". I think what we are trying to do is engineer as we go along and we are trying to – we are putting in materials like separators and we are testing the cells as they exist to see how they will work and we are going adjustments to see how they will work. We are trying different amounts of loading and excess negative to see how they will work. I think this is really the wrong way – well, I think for a long time it may have been the right way to go because we had to see what could happen, at least on the basis – some of the baseline tests to see where we would be going if we would make some of these changes. It seems to me now we know quite a bit. We have been working for a fair amount of time in these areas and it seems to me now that we can make some awfully good scientific judgments about the kind of separator we want from a physical standpoints, not just putting one in and seeing if nylon 66 will work, or whether it is chemically stable. Chemically stable, I think, is a very important specification or requirement. I think that is, but there are obviously physical parameters that are so important to the electrolyte optimization, as is the plaque, and excess negative is the same kind of thing. What is it, what kind of balance do we want? It is not how much active material can we put in the plate, but how much do we really want in terms of what kind of porosity is available? The same thing holds true with when we go to build the cells. If we build the cells and the pressure doesn't come out right, let us not just put a couple cc's extra to make the pressure come out right or take out a couple of cc's. Let us make a good scientific judgment and have a requirement for taking out the electrolyte and then maybe we can understand and be willing to accept more about why these changes are made. The continuous change that we go through in the process of cell manufacture, and well, let me finish my statement. The continuous changes that we go through in the process of cell manufacturing and the process of understanding what goes into the cell is at this point no longer acceptable. We just cannot accept the changes. We have got to have a good reason for making the changes, a good scientific reason, and then I think it is much easier to buy. Now, I don't want to take away from the battery companies. It was said nobody stands up for them. I think they have done a very good job over the years and improved along the lines that we have required them to do. We have squeezed them and squeezed them and squeezed them and they have followed along and I think now is the time that we have some communication between the battery companies and the users. I think we have some good communications and I think it really has to open up now in a way such that we know what we are going to do before we make the changes at the cell manufacturing level so that we know the implications of what is going to happen later on and not just make them arbitrarily.

LIM: Hong Lim from Hughes. I just would like to make a brief comment on the question of the –

FORD: Louder, please.

LIM: – question of the nylon separator, especially about the molecular weight. Depending on the method of measuring molecular weight and the absolute value of the molecular weight, it is different because they use different standards, but I think that has a minor importance for the chemical stability, whether you have molecular weight beginning from the 30,000 or 60,000. That is relatively less important than the other characteristics. I think a more important thing is probably the physical shape of it. I may have some answer to the previous question about the physical shape, but I didn't get a complete answer.

I think there might be some way of putting more electrolyte without blocking the oxygen transport by just changing porosity or the size of the fibers, for example. I would really like to see with the same material and not trying to confine nylon polypropylene, but with the same material and change of the physical parameters and see how the battery characteristics are effected.

FORD: Okay.

MCHENRY: McHenry, Bell Lab. Well, I think one of our major problems is that we can't make anything the same twice. We can't even make the damned can weigh the same twice. As far as the electrodes, how much excess negative do you need? Well, if you don't know how much negative you have in the first place, in the plate, you have got to be able to make two plates the same or more than two the same and our problem is we have the plus or minus 15 percent in the loading of the plate in the first place and then when you have that you have a certain loading, you don't know what percentage of that loading is usable, so that given the worst case of every thing that you didn't load very much and then what you did load didn't work very well and all of that sort of stuff, you will have a 70 or 80 percent difference between one plate and the next, and you will never get the answer to how much excess negative you are supposed to have, certainly not by experiment with things that are off by 50 percent in the first place and what you have to do is make your electrodes so that you can make two of them the same weight, you know, the same weight change, and you get the same amount of capacity out of both plates and that ought to be about 289 milliampere-hours per gram is about the theoretical plus two to plus three, and if you can't do that you lose. I mean, that is the first step and if you can't take the first step you just can't get anywhere.

With the electrochemically impregnated electrode this is something you can do. We can get quite reproduceable and you will blow a lot now and then but you can get a pretty narrow range and they all pretty well give what they – according to their weight, they give you about 100 percent of their theoretical, pretty close to that. You can have some confidence as to what it is going to give 10 or 20 cycles from now, but the vacuum impregnated plate, you start cycling it and it gets more and more and more and more and more capacity while your negative gets less and less and less and less and less, and you put two to one in and you find out after 50 cycles you have got a bigger positive than you have negative, you see, more measured capacity. We have just got to make the plates the same in the first place and that is what you have to work on. If you can't get past that step you forget everything else unless you want to put in a six to one negative.

PARK: One point on that, I wondered if you could say what you do get for variation in the vacuum process. I mean, it has been spoken of as being less satisfactory. I am sure it is the uniformity of the negative or positive plates both as compared electrochemically. It would be interesting to know whether you have statistics on that as to how it might be better and another point, on the Pellon 2505, why couldn't it be evaluated in some of Mr. Lim's tests at high temperature or the kind of thing he was describing this morning, you would have an evaluation of it. I would ask that question.

Then another thing I would like to ask Mr. Wrotnowski or somebody else, what about nylon 11? Has it been tried, if it is more durable? I guess those are the three points.

FORD: Okay, we have three questions on the floor. Would anybody care to field the first one? The first one was along the line, well, in saying that the electrochemical impregnation process is more reproduceable and more uniform, what is the number? What are the statistics to support this? Jim?

DUNLOP: I would like to make one comment. There is a difference. We have weighed all the plates, for example, of all of the cells that we have analyzed in a large number of cells and we determine what kind of capacity we get out of it for chemically impregnated electrodes made for production cells. The plates weigh fairly uniform and as a matter of fact, the manufacturer can easily weigh plates and separate them out on that basis and generally will. There is a difference, though. In the chemically impregnated process there doesn't seem to be an easy way to go from a weight gain in the impregnation process to the capacity because there is a substantial corrosion of the plaque in the impregnation process which seems to be the major uncontrollable variable in chemical impregnation. When you enter the electrochemical impregnation process there is a direct correlation between the weight gain, as shown by Bell Laboratories and it seemed to work out very nicely in the electrodes that were made for us. There is a direct correlation between the weight gain and the capacity you measure, and that seems to be a true statement and it turns out that you can, indeed, weigh the plaque and weigh the plate and determine what capacity you are going to get and that is the capacity you get.

PARK: One further question. How about the fading characteristics? Do they vary?

DUNLOP: Let me make a point. We do not see this fading in an underloaded electrode or in an electrochemically impregnated electrode. Somebody made an interesting statement, that was Floyd Ford a little while ago. Cut into the cell. You can't get away from this fading business. We are going to make a paper one of these days. The reason we know this is in a nickel hydrogen cell test you don't have to worry about the cadmium electrode, so when we get voltage performance it is characteristic of whatever the effects of the nickel electrode are and so we have established more of a baseline on nickel electrode performance in that kind of cell, which seems to be a little easier to do.

FORD: It seems there is a second part of that question, has anyone tried nylon 11? It was that question, and has anyone tried nylon 11 in the nickel-cad. system?

WROTNOWSKI: Well, it is a French fiber and it really isn't in this country. Someone would have to go import it. Probably that is why it hasn't been done. It is available in France but someone would have to go bring it into the country.

FORD: That rings a familiar bell.

HALPERT: Floyd, let me comment about that, about the separator. Separator in general, we are in a real bind with regard to nylon 2505. We have one separator supplier in the world and he is making it for coats or jackets or what have you and making it for ourselves. If we lose him we don't have anything other than this polypropylene. It seems to me that we ought to be on the road to understanding a little bit more about the separator so we can select alternate sources. I don't say one, but maybe more than one, not eight or 20. We don't need that many but certainly an alternate candidate for a separator, or we are going to be in serious hot water if we have to make that decision.

PARK: There is one further question I have and you were going to answer it.

HALPERT: Oh, was I?

PARK: What about using Mr. Lim's evaluation of the rate of attack of a caustic at high temperature to evaluate the 2505 lapse?

HALPERT: I think that is what he did, isn't it?

PARK: No, I mean, why don't you do it?

MCHENRY: Quality control.

PARK: Quality control.

HALPERT: Well, all right, we have -- I am not sure I am going to answer your question, but I guess we have --

PARK: I am saying use that process to evaluate every lot that you get.

HALPERT: All right, the answer to your question is we have received, have requested from the manufacturers and have received all of the test data from their 2505 test that we have required them to run for the last five or so years.

PARK: But do you test at high temperature?

HALPERT: We don't test at high temperature. They were not tested at high temperature for our particular application, but --

PARK: But Mr. Lim's data would then give you an index of the quality that you couldn't get any other way quickly.

HALPERT: You mean the physical properties? Is that what you mean?

FORD: Let me field that one, please.

HALPERT: All right.

FORD: Yes, I think it is a good suggestion. I was impressed with what was shown this morning and the linearity and some of the data. It seems to be a tool that may be available to use to look into. I think it is well worth considering. To my knowledge, I am not aware that it is being used today. I think it is a fairly new approach of looking at separators in general, but you have to bear in mind we could stand up here and criticize 2505 until we are blue in the face but it is still the only thing that is really doing the job over the long haul.

HALPERT: Dean?

MAURER: Maurer, Bell Labs. One of the things that I have been hearing is the generalization here, I believe, that polypropylene tends to dry out over a period of time and nylon tends not to dry out over a period of time. I would like to call your attention to Mr. Lim's equations from this morning which show that a substantial amount of water is produced in the degradation of nylon as well as the carbon and nitrogen, and maybe the reason nylon doesn't dry out is because it represents a source of water so that the liquid content of the cell is increasing.

I would like to ask Will Scott if on any of his tear downs of these cells have you looked at where the electrolyte is on cells that have just been removed from cycling without reconditioning versus with reconditioning? Is there any electrolyte huddled in the bottom or anything like this?

SCOTT: I don't recall ever seeing any free bulk electrolyte except just a film on the inside of the cans. Regarding the other question, we have some data which will come up tomorrow in connection with looking at the effects of longterm storage which shows the proportion of total electrolyte and hydroxide in carbonate in the separators before and after storage and before and after some limited kinds of tests, but not a very complete approach to the differences that you might see during a real life test. We will be doing that kind of work in connection with our test program on the 50 ampere-hour cells.

IMAMURA: With regard to polypropylene, I don't know what problems you were talking about. A couple comments. We have been cycling two battery packs, 24 cells each, made of polypropylene separator cells, and it is about 7,000 cycles now, low-earth orbit. Nothing to do with the Viking lander type operation.

Secondly, in the last two days in fact we have been trying to tear a couple of cells made of polypropylene, Viking lander cells. Because of sort of a light dryness, and cells were originally made to be much more dry or less electrolyte than the average cell and Guy Rampel back there could say something if he wished, but it had to do with sterilization, okay? A problem that we have encountered in the last three weeks is one of the test batteries out of the mock up which had been randomly cycled, at a fairly low depth of discharge. We took it off to recondition it and out of the two packs we got two or three ampere-hours, and strapped it down overnight, in fact over the week-end, started the charge. They were extremely high impedance cells, varying from something like 2 ohms up to 16 and 25 ohms.

In line with that I wanted to say that it is really not peculiar to the polypropylene based cells, and it is true that dryness contributed but we really don't know what are the basic modes at this point.

FORD: Okay, my point was not that I was trying to pinpoint polypropylene as the culprit, but we have seen similar types of -- or we have observed similar types of things on nylon, for cells containing nylon, but it is definitely an indication of a high degree of dryness within the cell, whatever the separator system you have, okay? I think it relates back to the capacity of the positive electrode and is part of this expansion, the ability to tie up more electrolyte and to further compete with the separator system, be it nylon or polypropylene, but quite frankly, if you don't start with enough from day one you never expect to have enough.

BOGNER: I would like to ask a question of people who have been testing polypropylene and nylon on their failure analysis if they have noticed the same quantities of carbonate in the cells or if there is a significant difference in the amount of carbonate.

FORD: Does anyone care to field that question?

HENNIGAN: This was all done. I don't have the numbers in my head but I could probably get them to you. Every separator that we have checked has had that analysis. I would like to mention one other thing. I wanted to tell you this morning about the Grace nylon which I would say is comparable to the 2505, cycles about the same way, and one of the things you may find with separators, you remember about two years ago we had the polypropylene called Hercules. It was a microfiber type thing and that worked very well in the Eagle Picher cell and we did have a little trouble with it in the GE cell, but still that separator material was very good, but Hercules did not want to fool with it at all. In fact they surveyed the market and they said the whole battery business wasn't big enough for them to go into operation. I talked about a pilot plan type thing and they just didn't want to do that either. So some of these materials maybe you could never get.

FORD: Okay, if I may, I have one other member on the panel that hasn't had a chance to say, in all due respect -- but did semi-volunteer to support me. I would like to give him a chance to have a say.

BETZ: Floyd, everything has been said. I just have a couple of things. One, relating to Matt's problem, we had some polypropylene cells, one with I believe, 15 percent short in electrolyte, if you will. It was specified that way to sustain a C/10 charge rate at zero and another was approximately, from a different manufacturer, with approximately 20 percent extra electrolyte compared to the normal value, so taking a normal on a six ampere-hour cell with 18, that is somewhere around 16-1/2 and somewhere around 22, and both cells in random operation, the wet cell and the dryer cell, occasionally exhibit the same problem Mattie has, 30 ohm cells, 30 ohm impedance cells.

Strangely, we have been tracking the balance of our cells which do have the nominal electrolyte quantity and none of those after more than a year are showing any of the characteristics, so it may not even be electrolyte all by itself. Maybe there is something else.

Like I say, everything has been said regarding battery cells or quite a bit and I guess my concern now and I think one of the major problems is how do you implement these concepts? It seems to be that the implementation has been almost random in nature. Bell telephone discovers an impregnation technique that looks superior. There are teflonated negatives popping up that appeared superior, but you can't -- impregnation of electrolyte techniques, maybe even separators improving, but you can't get it. You can't get it all together. Maybe it just takes time.

We seem to have started the nickel-cadmium investigations, I think, backwards. Nickel-cad. got used in spacecraft because it was the only thing available in 1960 and it worked well through the late sixties and somewhere around the time that the workshops started and cells started failing -- but that is when we really started looking at nickel-cadmium. It is only five or six years, really. Great seals are available. That was one of the major problems in the early days, and there are electrodes available now and there are separators, but you can't buy it and it doesn't look like in the near future we will be able to buy it and if we could buy it from a new company because maybe the major companies might not want to get involved for commercial reasons, could such a company stay in business until we finish testing it?

It is the truth. Could we then convince our program managers on programs that we have a better battery and we are we are ready to fly it when the general technique is we want to standardize -- maybe that is a bad word today. We want a battery with a reputation of success and we do have, as Kipp and Jim have mentioned, the batteries that are being built have a reputation of success, but yet we need the improvements, but how do we implement? That is the problem.

It is all yours.

PARK: Another point that maybe is pertinent, I notice the man that talked the first thing this morning expressed standardization and standardization certainly has a place, but also if you are just going to standardize, you wouldn't be able to get this 10 year business. Now it seems to me that to standardize then you also have to try to find somebody to fund further development and it seems to me that you ought to have two different things and I don't see a whole lot of impression this morning that there were funds for anything but standardization. I don't think that is right.

BETZ: That is right.

PARK: It isn't right.

FORD: No. Let us put it this way, though. While I am not qualified to comment on the dollar values of the OAST budget over the period, I do know that the impetus on the OAT research and development has been gradually declining. Today we have one basic task, to produce workable hardware and to quit designing a new wheel every time we want to launch a vehicle. That is the full reality that we have to accept as a part of the aerospace and the scientific community. Now with that in mind what we have to do is take what funds for research and development that are available and try to squeeze the maximum. Herein is one of the primary driving forces behind us wanting to have this open session. We are looking to set priorities. We within NASA and I certainly hope that the cooperation that we have had between NASA and the Air Force continues, that we have the same priorities, but this is basically what we have to do, scrutinize those programs, those potential improvements that are available, and fund the ones that we feel like offer the most potential and basically what we are trying to establish is what other ones offer the most potential.

PARK: I have a further point. This is to Dunlop. He seems to be aware of the value of the 10-year life. If you have a battery that costs four times as much but you get 10-year life instead of six, is that a justification for some research?

DUNLOP: Yes, but it is a very hard thing to convince management to put up a couple of million dollars for it. See, that is a tough argument. You can say that -- you can argue, say, for communication satellites, the pay off is immense every year a satellite stays up and is in operation and a lot of people in this room are in the communication satellite business who are well aware of that fact. At this same time they are also well aware of the fact that to tell their management that they should put up $2 million or whatever or $7 million if that is the figure, to build it, the question is, you are going to go out and build a battery, if you don't like what the battery manufacturers are doing what do you do about it? That is I think the point that is really being addressed here today. If you really don't like, if you really don't think that the battery manufacturers are making you a seven year cell, then what do you do about it?

In addressing the question of making a 10-year cell, first of all, since you asked me, I will make this statement; frankly, I don't see the reason for the standardization program, period, because GE is making a good cell today and I don't think they can make a better cell than they are making right now on a production basis. I just think that the limitation is not going to be done by making a lot of measurements. I am just going to go right back to what Halpert was talking about, that the technique is limited by the technique of what they are doing. They have got a centering process that is the best that they can do in their production room. They have got a lot of rollers and wheels and so forth and that is the way they make it and they aren't going to make it any better simply because they chop a piece out every 50 meters. They make a pretty good product right now.

The problem is that the electrode they make may not be the best electrode available. The best electrode available may be an electrochemically impregnated electrode and the best centering process may be one of these 12-zone furnaces.

PARK: What I was trying to say --

DUNLOP: I am sorry, but I am not just -- I think the point -- maybe I am missing your point, but I don't understand how standardization is going to improve a product here.

PARK: Well what I was going to say, couldn't you just to standardize in something fairly elementary and say this is it and then have funds available -- you can't do things overnight --

DUNLOP: But what are you going to say is this it? I mean GE makes a cell and SAFT America makes a cell and --

PARK: I won't argue that.

DUNLOP: -- Eagle Picher makes a cell.

PARK: What I am trying to say is can't you just say, you will do something around there to get a reasonable compromise standard cell and then -- I don't understand why management isn't prepared to sponsor something. Why won't they do it?

DUNLOP: Well, I think they would. The question is how. See, the problem is, unfortunately, people looked to NASA for a lot of years to lead the R & D programs and still do, and NASA has taken the position, as Floyd just said, NASA has taken a position of standardizing batteries and they put all their money into that kind of a program. Now who the hell is leading the area of advanced development?

PARK: I know something very similar to industry, is GE and Westinghouse used to do a lot of research of all sorts of things in the power industry and the industry got to depend on them. Then they decided that they didn't get too much thanks for it. At any rate, they decided to cut back. Then the industry wasn't prepared too much -- they have been getting around it, to put some of their money in to do the things that GE and Westinghouse weren't doing.

DUNLOP: Right.

PARK: Now, I think, if you say, well, they always look to NASA to do this work and NASA hasn't got the budget, you are going to have to do something.

DUNLOP: Right. Well maybe the Air Force and maybe Bell Laboratories.

PARK: Right.

GOLDSMITH: I take a look at Goddard's or NASA's missions and I think most of NASA's missions are not the kind of missions that require long life. I take a look at NASA's missions models and I think most of their missions now and tied in with the shuttle are like six months or one year missions in orbit and I think for those missions standardization may in fact be cost effective because without being able to quantify it, I think that in the long run they could standardize it, but the question, the real question is for the government, since NASA isn't putting money into the synchronous orbit long life that is required not only for Comsat but for a lot of the military communications satellites, NASA isn't doing that. I don't see the Air Force putting any money into nickel-cadmium development. I think somebody in the government who may think that NASA is looking after all of the battery requirements, I think these guys are being misled as to what the requirements are. Do you want to comment on that, Floyd?

FORD: Well, approximately two years ago, maybe it was longer, NASA made a major policy decision to get out of the communications satellite business. By and large that is synchronous orbit satellites.

GOLDSMITH: Right.

FORD: ATS was one of the last synchronous orbits that we have had that has really had a communication role. Now, we are still working in synchronous orbit satellites, but the emphasis, obviously, isn't the same as is on near-earth orbit, and I think your awareness of this NASA mission model, the projection of future NASA missions, something like 70 or 80 percent of them are near-earth orbit, you know, the lower altitude orbit and the standardization program is geared toward the shuttle. If it wasn't, the shuttle was not coming down the pike, you would not see a standardization program I don't believe, so it performs in a sense cost effective, this is exactly what they said and that with the resupply capability we no longer have to push systems that -- we no longer have to design systems or have to require systems to last five to 10 years because basically they are going to replace them every two years. It is the modular concept that was mentioned this morning.

Now with that as your guideline --

DUNLOP: One question. Why is it that you and the Air Force act together? Like you mentioned a minute ago that you act together and you have the same goals.

FORD: Why is it that we do?

DUNLOP: Why do you and the Air Force, then, have the same goals because the Air Force had a lot of synchronous satellite missions.

FORD: I didn't say we had the same goal. We have common goals and common goals, the Air Force, as we do, put up a lot of the near-earth orbit satellites. We are still putting up, the U. S. government, is still putting up synchronous satellites, primarily for weather.

DUNLOP: Since this is an open discussion, isn't it true that the Air Force is doing a lot of work -- I don't know that I totally follow your comment, Paul, because isn't the Air Force really coming up with a program for the one that Pickett mentioned earlier today on nickel-cadmium cells which is directed at advancing this new technology with somebody?

GOLDSMITH: Yes, that is right, but I think we all should realize that most of the work that the Air Force, I think, is going to be doing in the future, is funding nickel hydrogen and other advanced systems and Goddard isn't funding nickel-cadmium, so I just think that kind of a problem should be brought up at like the inter-agency advanced power group or what have you, which is designed to get all government agencies together and look at the big picture.

DUNLOP: Probably one of the things that should be mentioned here that does confuse the issue is that, and probably Comsat as much as anybody has been lately pushing nickel hydrogen as the replacement for nickel-cadmium for battery systems starting in the 1980's. We think the nickel hydrogen system will meet the 10-year mission requirement and that is going to be a subject that will come up tomorrow, so we really expect to replace -- we really expect to be able to replace nickel-cadmium systems with a 10-year battery and that is something that confuses the issue a little bit. That is an awful nut that confuses the issue a little bit. That is an awful nut today.

FORD: Ernst, did you want to comment? I saw your hand go up and then you pulled it down. I wasn't sure.

COHN: I just thought I might mention that this may be Goddard's workshop but Goddard doesn't have the whole NASA program and there is a NASA program that has as its goal a new lightweight ni-cad cell, 35 watt-hours per pound, 100 percent depth of discharge, lightweight ni-cad cell, and a new ni-cad battery with an individual cell control ala Air Force and that we are starting to implement this program, namely, through JPL. If we can get Goddard to help us, fine. If we can't we will do it all at JPL, or if we can get Lewis to help us, fine, but if not we will do it all at JPL, and we intend fully to do something about ni-cad before we give up on it. We also have some ni-cad missions for more than five years because every time we go into deep space if you use a battery, the deeper you go into space the longer it has to last. We are talking about planetary orbiters. We are talking about landers that have to operate for weeks or months, so that it isn't exactly that 10-year life has gone out the window. This may be the view locally but it is not the view of NASA as a whole and when you get these impressions you want to make sure that you know something about the total program.

Also, of course, the new lead at IAPG. The IAPG has not been abolished yet. We have at least one meeting a year, a planning meeting, where we discuss the various programs that are going on and we do take advantage of each others' advances in nickel electrodes, for example. We have asked the Air Force and the Air Force has agreed to cooperate with us in letting us have some of the electrodes, and we have also, incidentally, fairly well completed, we are not fully completed yet, a non-gassing or virtually non-gassing ni-cad cell at JPL which looks like we can run it wet, which will avoid many of the problems that people are complaining about here, so if you would pay attention and listen and look to JPL for the non-gassing ni-cad maybe we will find something that you could use that would look interesting to you.

GANDEL: Gandel, Lockheed. I am surprised you are having us sit here until 5:22 for this. I wish you had started earlier in the day on the technology.

KUYKENDALL: Kuychendall with NOAH/NESS. We are working on the synchronous orbital SMS/GOES. Our problems isn't so much where we are going but just knowing where we are at today because of missions priority changes, failures in spacecraft and so forth. We would like to use the spacecraft batteries in ways other than they were tested. We would like to use them 60 percent depth of discharge every eclipse. We would like to use them 10 or 15 percent every day under certain seasons of the year. We find that when we ask for this data it is no one's fault here necessarily, but the information isn't available and we need to know how much the battery life is going to be shortened by using them and what are the trade-offs, whether we should maybe use them to maximize the data that we are going to get in tape shortage and battery life. How much is it going to cost us and these are the things that we find don't seem to be available.

COHN: Again, if I may answer that one, Cohn, NASA Headquarters, we don't have the answer because we started with a bum test program, okay?

What Hellfritzsch said before I can second and state it was fully though through. We were stuck with it. By the time I got aboard it was too late to change it, so we are just piling data on data which has relatively limited meaning. They are better than nothing, believe me, but they have limited meaning. I have tried for years and finally succeeded to some extent in getting a statistically designed test going at Crane. To the extent that I will continue to get that input and co-operation from Goddard and Crane in getting a meaningful statistical design and getting data out of this program, the questions you ask should be answerable because it should be designed in the program, so give us a little time.

FORD: I can honestly say I have never seen two even similar missions profiles on a battery.

THIERFELDER: Thierfelder, GE. When the RFQ comes out for the standard battery will there be a life requirement and if so what will it be?

FORD: It will be what is specified in that standard specification that you are welcome to a copy of. There is a life requirement. I do not know off the top of my head what it has in there.

We will take one more.

LIM: I would like just to make a short comment about the comment you made about the relative wettability between polypropylene and nylon. I am not sure about the change of the wettability in polypropylene, but in the nylon, after nylon degradates, the wettability would be increased, not by production of water but by the generation of more end groups which are ionic in character, so I would expect that the wettability would be increased as the nylon degradated.

FORD: One last round of the panel.

GROSS: Just one comment before you get that fellow in the back of the room. It certainly appears that we have got -- that the aerospace nickel-cadmium battery users can look forward to getting a very good nickel electrode but through the back door by means of the nickel hydrogen system. It didn't come about deliberately as a deliberate attempt on the nickel-cadmium battery user to get it. What does it take to get a good cadmium electrode? Do we have to wait for a similar circumstance?

FORD: Guy?

RAMPEL: Rampel, General Electric. On this standard cell, 20 ampere-hour cell, there are at least four very important components and one of them is the separator. You have a lot of specifications for tests and so on and so forth, but I kind of feel that since we are locked in for the next five years and not being able to make a change, I kind of feel at the mercy of the one vendor on 2505 and I kind of feel that while Gerry is going to get control of the pack and all of the measurements he is requesting, I don't see that same kind of control at the separator end, and I think we had better do something about it.

HELLFRITZSCH: I would like to make just a warning. You mentioned cadmium, and I have heard about small vendors being the one you ought to specialize in. The Navy needed a mercuric oxide cadmium cell for a standardization program, incidentally. It was a field group that wanted it, so they let a development contract with a small vendor and I haven't seen all of the data. I wasn't involved but I knew of it. He made some that performed like we wanted. When we wanted to buy some, the Navy contracting people went out there on a survey and found out, "Well, Heck, we can't give you a contract that big. You have never made anything like that." So another battery company said, "Well, I guess we will have to bid on it." He was supposed to have given a complete disclosure on how you make them. This was a big battery company and a good one but they never made that kind of a battery. After a couple of years of trying they gave up and a third battery company has finally made some and of the lots they have developed the first ones after a delay of a year or so were pretty good but then the next lot or two that they were going to make just like the first lot were just no good at all, and cadmium is one of the difficult technical problems in that particular battery, so this is merely a true story. It is still going on right now. There are a couple of government agencies vitally concerned with the fact that the batteries are not performing. Their standardization program, of course, has been waiting at least five years in the case of the Navy.

PARK: But you said they didn't give it to the company that knew how to make it?

HELLFRITZSCH: Because the company was not competent, really. But he was supposed to -- part of the contract was that he write down how to make it, but -- he didn't want to and in all honesty, if any one of you try it sometime, write down how your wife could bake the cake all of the way and every detail and then you do it and it is not a good cake usually the first time.

HARKNESS: Harkness, Crane. As you know, we are involved in the battery testing for NASA and we currently have 12 ampere-hour battery packs, nickel-cadmium, that have exceeded 10-year life. This is in a near-earth orbit flight test regime. I have heard the comments before and I think the standardization program is a good step toward this step. Wouldn't it be nice if we could duplicate that battery now? I think a lot of problems and questions that have been brought up today would be answered now.

HELLFRITZSCH: But it can be duplicated.

MAUER: Mauer, Bell Labs. I think Dave Pickett would go along with you about small vendors. They have a tendency to go out of business.

END OF AFTERNOON SESSION

SECOND DAY PROCEEDINGS

WEBSTER: Good morning. I have two ways I could do this job. I could simply say that we have approximately 16 speakers and go ahead and begin the program or I could be young and maybe a little naive and go ahead and make a few comments about some of the things I heard yesterday, so I think I will be young and naive.

First, I would like to welcome you to the world of flight experience and testing. This is a world where experts who tell us that bees cannot fly and that cells cannot cycle for 10 years are proven wrong. This is a world unlike the sixties where test results are now more than just electrical test data. It is now related to such things as negative to positive ratio, amount of precharge, excess negative, teflonation levels, amount of electrolyte, carbonate, and process specifications.

In yesterday's session we heard that the electrical performance cannot be related to just these terms and we must be more sophisticated in identifying control, the more basic cell components, such as plaque manufacture and plate loading. While I agree with this wholeheartedly, I feel obligated to point out to my colleagues that before we can walk -- I am sorry – before we can walk we must crawl, and before we can run we must walk, and I submit that without attempting to develop the process specifications of the early seventies and couple this with electrical performance testing we could not all be the battery experts that we claim to be and since the evolution of the perfect reproduceable battery has not yet been reached there is still need for electrical performance data to enable a project to know how to manage its satellite in orbit.

The area of improved technology which was not mentioned yesterday was the increased knowledge we have gained in system handling of batteries. That is, we are now generally accepting that in near-earth orbit cells can be recharged with merely 105 percent C to D ratio or 1.05 C to D ratio. Also, in synchronous orbit, a low rate continuous trickle charge seems to be adequate to maintain the state of charge and give us exceptionally long life performance. How did we know this? How did we arrive at this? We arrived at this by electrical performance testing coupled with chemical analysis. Do not mistake my comments for the fact that I am – do not interpret my comments that I am in favor of Edisonian research, that is, trial and error research, but there is a need in today's world because of where we are, for a little of each.

Also, there is another need in today's world, one which I am sure everyone that has ever been associated with a real satellite has encountered, and that is while you might work five years on a program developing cell specifications all the way to the battery supporting it at the Cape, once that satellite is launched it is turned over to completely different people, maybe of a different firm, a different corporation. These people are referred to as operations control people. We have some of them in our audience today as a guest.

Now, these people basically in some areas are electrical engineers. They do not have a strong background in batteries like we have, and when they are in the control center and they have been operating a satellite as it was turned over to them, for a period of three to four months and they start to see the voltage going down, the first thing they do is they say, "We had better increase the C to D ratio. We had better start throwing the charge to the battery." It makes it very difficult for the battery expert to educate these people on the spot unless we can take test data and show them such things as we are quite familiar with, the two-step plateau, for instance, where we still have the capacity but we don't have the voltage, so I believe there is a real need for the work that is going on today and I strongly support that we become more scientific in our approach.

Thank you.

I would like to introduce our first speaker of the day which is Mr. Stan Krause of Hughes Corporation and he will be talking on the subject of near-earth orbit testing.

KRAUSE: I was debating whether to get up here after listening to yesterday afternoon's session. I guess one of the conclusions out of that session was that gone are the days of putting voltmeters across batteries and just seeing how they perform. We are much more sophisticated and we start changing ions around in fours, and this morning I am just going to give you the results of some life testing where we put the voltmeters across the batteries. It is not very scientific, but as Bill says, it is the real world. That is ultimately what we are all in business for, the ultimate test of all of our science and sophistication and knowledge is when that battery gets up there and operates in a power subsystem for the duration of a satellite mission.

Very briefly, this morning, I wanted to give you a very short summary of the results of the low-earth orbit battery life tests that we have been running at Hughes. The test was started in support of the OSO program and this particular life test has been running since 1972, almost three years, although the total cycle life so far is in excess of 11,800. I think as of today we are well over 12,000 cycles running at 15 per day. As you can see, it is a low-earth orbit, 96 minute duration. We have a 36-minute discharge at 3.2 amps. on a 12 ampere-hour cell. The charge time available is 60 minutes. However, we use a voltage regulated current tape ring with temperature compensation and I think the reason I wanted to present this was two-fold, No. 1, to show what 1972 vintage cells can do in low-earth orbit. I think we can get three years of low-earth orbit operation which is interesting and significant, and secondly, that the type of battery charger that NASA is proposing for its standard battery system appears to work very well for this kind of application and I think the data here tends to show that.

(Slide 68)

KRAUSE: On the upper curve you can see is a plot of the end of charge pressure for the first 2,500 cycles. As you can see, at about cycle 1,000 there were some adjustments in the C to D ratio in the specific charger level that was selected and then finally we reached a fairly stable equilibrium pressure in the first 2,500 cycles or so. It has remained in equilibrium now for the 12,000 cycles, although later on the pressure level did step down when the C to D ratio was stepped down right about cycle 2,500.

The end of discharge voltage, as you can see, is relatively flat and has looked very good in the 12,000 cycles and looks very flat for the 4,000 cycles and the interesting part of the test is that we finally continued to step the charger level down to ultimately determine what the optimum C to D ratio was for low-earth mission like OSO and as you can see, we are running at a voltage level which gave a very constant C to D ratio of about 1.05 and that thing has been continued from cycle 2,500 out to cycle 12,000 with a 1.05 D to D ratio and has performed very well.

As I say, most significantly, I think the results of the test show that even a 1972 version cell is adequate for nearly three years in low orbit and secondly that the temperature compensated multi-level charger that NASA is looking at as its standard is very flexible and very, very neatly controls these cells keeping the pressure down, keeping the voltage up, and limiting the C to D ratio very well. That is all I have.

WEBSTER: Thank you. Fred Betz?

BETZ: Fred Betz, NRL. Stan, what are your level four and level two voltages at 25 C.?

KRAUSE: I wish I had brought the curves with me. My recollection is that the level two voltage at 25 C. is somewhere around, I think somewhre around 1.41 volts and the level four might be somewhere around 1.425, something on that order.

BETZ: Are these nylon separator cells?

KRAUSE: These are nylon separators, yes, good old nylon. My prejudice is showing.

HARKNESS: Stan, were you running at 25 degrees C. to start with? Did you run a 1.25 C to D ratio?

KRAUSE: Yes. I should mention that we were actually running at the beginning at 12-1/2 degrees C. for about the first 2,000 cycles and then the test went to 25 degrees C. for the remainder and as I say, we were running level four at the beginning of the test and stepped it down later because it was obvious that we could get by with a much lower C to D ratio.

SULLIVAN: Sullivan, APL. I probably missed it. It was probably on there. What was the depth of discharge?

KRAUSE: I didn't put it on there, but the depth of discharge is around 16 percent.

SULLIVAN: 16 percent?

HELLFRITZSCH: I heard in both of these speeches some remarks which indicated they didn't quite agree with something that was said yesterday. I didn't think anybody would think that a science can be put together without numbers. You do have to measure it. The key point that I tried to make yesterday is that if you don't know what it is that you are measuring you don't learn very much because no matter how many numbers you have until 10 years ago, unless you know that the cells you are buying today are identical with them you cannot count on them behaving the same way and even lot after lot of current production unless you know in every detail that the lots are uniformly alike you have to be careful about using the data based on lot No. 1 and apply it to lot No. 3, 4, 5, and so on. That is the only point. You definitely have to have numbers and you have to analyze them.

There is one number I would like to see people use in batteries. They use it in other places, as an index of overall quality, and that is the coefficient of variation on any attribute of any commodity that you measure. It is a ratio of the standard deviation to the average and it has no dimensions. Therefore when you say, "Our product has a standard deviation of five percent, well actually for any chemical product that is a pretty good average. If you get into the mechanical things like watch making then of course you are going to get down to fractions of one percent in that battery, but there are many, many batteries in the primary battery business where coefficients of variation of 10 percent and 15 percent of the same lot exist and it is a very useful number. The battery people haven't used it. It is used in other engineering fields and you see, since it is dimensionless, you don't need to know anything about batteries to get an idea of what the quality is and I think it would be very useful whatever testing quotas – it is a very simple thing to do. They usually calculate the standard deviation and the averages, but nobody ever bothered to divide them one by the other and it is a real good index. It is dimensionless so you don't need to know what it is, voltage or cycles or whatever.

SULLIVAN: Sullivan, APL, Stan, have you discharged any of these cells to see where the second plateau is at this point in time or if not do you plan to do so?

KRAUSE: No, we haven't done it. We plan to do it some time in the future, but we are planning on doing it when we see any signs of difficulty in continuing to run the tests this way. Then I suppose we will probably do some capacity measurements and try to find out if we have double plateau or fading or what have you, but right now it is running so well we don't want to disturb it.

Floyd?

FORD: Stan, correct me if I am wrong, but I would like to clarify a point. These are, to my knowledge, some of the first cells Goddard has flown that had this now patented treatment by GE on the negative. I am pretty certain there is a patent out on that. It is a proprietary treatment but these did have that treatment, is that correct?

KRAUSE: I believe you are correct. These do have the treated negative.

FORD: Right. Just for the record.

PALANDATI: Stan, I was wondering, have you tried to analyze the gas content as to what actually the pressure build up is as to whether it is all hydrogen or what?

KRAUSE: We haven't analyzed it. We don't have any means to attach it to these cells other than that apparatus I showed yesterday which we would have to pull the cell out of this pack and we could put it in that apparatus. However, in looking at the pressure gauges, we see a fairly sharp decline in the pressure at the start of discharge and so it is obvious that it is still primarily oxygen. I don't believe we have seen any hydrogen. The residual pressure is very low at the end of discharge. Fred?

BETZ: Betz, NRL. Stan, do you recall what current you tapered down to at the end of your charge period, approximately?

KRAUSE: I believe it is something close to about 500 milliamps.

If there are no questions, I would like to make a quick statement since we are making statements. To clarify my remarks, I had nothing against science. Obviously we are involved in my organization in trying to understand what is happening inside of batteries. However, I have a general feeling that on occasion we sometimes lose sight of the eventual application of these little electrodes and separators that we are working with and we have to keep in mind that the eventual application of the battery is to power a satellite, to become an integral part of a power subsystem, and in that respect I think perhaps one thing that didn't come out in the discussions yesterday afternoon was that I think the basic cell designs that we are flying today are perhaps relics or vestigial organs of batteries which were designed to meet requirements in the early sixties. This is my own personal opinion. However, I don't think that we have taken enough time to tailor battery designs to the capability of our electronics that are available to us today for charge control. I think everybody is worried that you can't get cells wet enough because they are going to build up pressure if you overcharge them extensively. Well, nowadays we are smart enough to build microelectronic circuits that can very neatly control battery charging. There is no need to have to run batteries at C/10 at 0 degrees C. unless you have some very special and unusual mission requirements. Most of our synchronous satellites today have temperature control systems that will limit batteries in overcharge to temperatures probably at 15 degrees, perhaps 20 degrees C. and in addition to that, the control circuits can easily limit the overcharge only to that necessary perhaps to get a decent C to D ratio and at the same time keep the negative plate fairly active. I think we can go to much wetter cells and I think we can modify cell designs by integrating them into power subsystems that are designed to provide the care and feeding for the batteries. I don't think we should continue to build these things to take extensive overcharge for long periods at ridiculous temperatures. We are just not designing in many instances to meet the environments that are available to us or to take advantage of the subsystem hardware that is available to us, and I think we should in the battery area take a more active role in general and play the tail wagging the dog and get our licks in first with the subsystem designers in having them meet our requirements. That is about all I have to say.

MCDERMOTT: Pat McDermott, Coppin. Would you extend your remarks about, say, individual cell control? How would you feel about that with the state of the art being at this point?

KRAUSE: I think I am not going to do any advertising, but we have been developing at Hughes some large area hybrid microelectronic circuits that are capable of individually monitoring voltage and pressure and temperature of battery cells and capable of individually controlling battery cells. I think NASA Lewis is working on that very thing for their silver zinc batteries with the inorganic separator to extend the life. I think it is worthwhile if we are considering, perhaps, 10 year synchronous satellites with much higher depths of discharge, than we are operating at today, individual cell control may prove to be advantageous, although I don't know if extensive trade-off studies have been done with regard to that kind of mission model.

WEBSTER: Thank you, Stan. I will be the next speaker on our agenda and the reason is that some of the work that I have been following at Crane overlaps some of Stan's discussion here. The topic that I will be discussing will be a brief snapshot into the life cycle test data that we have on the cells which are flown on the ATS-6 satellite and the OSO-8 satellite. The cells which Stan was referring to were originally part of the OSO-8 procurement and Hughes under their own money has continued to cycle these cells and this is what Stan was reporting on and I think I have some of the answeres to some of the questions people are raising as a result of our Crane data.

The reason why I am presenting this ATS data is one of the overriding things we have heard is that we are not able to correlate performance with the actual cell. This program was initially with Fairchild and Fred Betz, formerly of Fairchild, was the battery engineer on the program. He worked very closely with us in 1971 and was running a parallel effort to try at the same time we were generating our first specification, Fred was trying to incorporate some of these ideas in the ATS specifications, so we have a first attempt and now we have some data from that attempt.

While we are smarter today as we were then, there are certain things that were documented. This was a 15 ampere-hour Gulton cell and they were the first cells, to my knowledge, to be dry stored.

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WEBSTER: They were manufactured up to the point of filling with electrolyte and then they were dry stored in argon. The flight cells were removed from storage and activated in 1973. In May of '74 the satellite was launched. Some of the highlights of the specification were that the negative to positive ratio must be at least a minimum of 1.4. The excess of negative would be six ampere-hours minimum and the grid charge, you will note is rather low, but it was one ampere-hour. The electrolyte in this cell was 43 cc's.

Now, we have made it a policy at Goddard and I think this is a general policy for anyone buying space cells, to out of each procurement lot save so many historical samples and we have in our laboratory historical samples of the plates and of the separators so that if these cells should prove to give us 10 year life, hopefully as our knowledge improves, we have samples that we can go back and analyze and we can say, all right, the porosity is this, the plate loading is this, and so forth.

We have done a minimum amount of chemical analysis. We have not done much physical chemical analysis and our laboratories are now changing to incorporate more physical chemistry into their test programs.

(Slide 70)

WEBSTER: The engineering cells would be those cells that were manufactured in 1971 and were not stored in argon, but immediately went on tests at Crane. The test consisted of a normal synchronous eclipse mode where the cells were charged at the C/10 rate to a voltage clamp, I believe, of 1.41 volts at 20 degrees C. Then the current was allowed to taper. In most cases the current would taper down to approximately C/30. This gives you a synopsis of what has taken place at Crane. You see, well, this column is not filled in because the test was run yesterday. You can see that the discharge voltages are holding up very well through six eclipse seasons, that the end of charge current is ranging anywhere from .4 to .7, that the ampere-hours returned ranged between 7 and 20 and that the capacity of the cells are holding up very well. The initial capacity was somewhere in the vicinity of 20 ampere-hours and now after seven eclipse seasons we are still obtaining 18.8 ampere-hours.

The first two eclipse seasons were run here at Goddard and due to lightning storms, et cetera, the data was destroyed that was on the magnetic tape.

We have another pack on test at Crane and this pack represents the flight cells. Now these cells were stored in argon until 1973 and were activated with the flight cells. They have experienced three eclipse seasons, the last just yesterday. You will notice also that we are talking about something in the initial capacity of 19 to 20 ampere-hours and we are still getting 17.2 ampere-hours per cell.

The original intent of this satellite was to operate for a period of two years, one year over the United States and one year over India where it was to be a synchronous orbit satellite with load sharing taking place for approximately a 90-day interval over India to support educational television programs. As with most programs once the bird is launched things change.

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WEBSTER: What we are doing is we are taking our engineering pack and we are keeping it as a standard comparable to the other synchronous orbit testing and our flight cell pack, however, the test program has been modified to reflect what is currently going on in the satellite and what is going on now is that in addition to the normal eclipse season discharge that takes place, they are discharging the battery one ampere-hour – I am sorry, one amp. per two hours, recharging for six hours, discharging for one amp. for three hours, then recharging for six hours and then going back into the normal eclipse mode.

Some operations personnel are considering doing as much as two 30 percent depths of discharge a day, well, maybe more conservative, one 30 percent depth of discharge and then one 50 percent depth of discharge and the questions we are getting hit with is how long will the cells last? What will they do? This is some of the concern that was expressed yesterday, so I think it will be of interest to the community if we continue to follow this test and hopefully I will take about five minutes a year to update you on this.

HELLFRITZSCH: Those last two columns I don't understand.

WEBSTER: Okay, how was it obtained?

HELLFRITZSCH: Well, no. It says ampere-hours returned. That sounds like capacity of some kind. I wonder what is that.

WEBSTER: Okay, let me explain that. During the eclipse mode what you have is a bell-shaped curve where at the peak of the curve you are in shadow for 72 minutes and the maximum depth of discharge at that point is 50 percent. What this represents is the number of ampere-hours. When you remove the 50 percent depth of discharge at the peak point that would be the high number and you are recharging under the conditions I gave you, C/10 is the voltage clamp for 20-some plus hours. You recharge two of those cells at approximately 19 ampere-hours. Where you have extremely shallow depth of discharge at the start of the eclipse season, where the shadow is very brief, you are maybe only discharging seven percent depth of discharge. The cells are essentially fully charged, but under this charge design, in this regime, in the 24 hours period we are returning 11.6 ampere-hours.

The last column is a capacity test and that is performed by when the cells reach the midpoint of the eclipse season, that is at the 50 percent depth of discharge, they are allowed to continue all of the way down at the spacecraft rate to one volt. The capacity data is taken, the cells are allowed to recharge and then continue on with the test and some people will say, "My Gosh, you are reconditioning the cell." That is true in a way. We are causing some effect, but we are trying to get capacity data to judge the degradation of the cell with life, so that is the explanation of what the capacity is and how it was obtained, what the ampere-hours are.

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WEBSTER: This is a curve of those very capacity checks and for the fourth, fifth, and sixth eclipse seasons you can see that we have our classic two-step voltage shaped curve and that in each case we are obtaining in the vicinity of 18 to 19 ampere-hours. That is on the engineering cells.

(Slide 73)

WEBSTER: Similar data is available for the flight cells. You can see that they are delivering about 19 ampere-hours and this represents the test data for the first and second eclipse seasons.

(Slide 74)

WEBSTER: This last slide on ATS data shows a comparison between the two packs and what is required by the spacecraft to support, initially anyway, to support the spacecraft requirement it has to deliver at the 6.25 ampere-hour rate for 72 minutes as indicated by the dotted line. At the present time, as a result of our capacity data, we see that they are delivering in the vicinity of 175 minutes at the 6.25 rate.

(Slide 75)

WEBSTER: Now the next program I would like to talk about is OSO. OSO came along a little later, 1972. The Goddard specification was out at that time. Hughes worked very closely with us, came out with their own specification, but it reflected an awful lot, the philosophy of the Goddard Specification. To my knowledge these are the first cells that have been dry stored in nitrogen. The flight cells were activated in March of '74. The launch took place in June of '75. The negative and positive ratio was specified at a minimum of 1.5. The excess negative at 11 to 9.3 and ampere-hours for the precharge on these cells was 3.3 ampere-hours. The amount of electrolyte in each cell was 35 cc's.

(Slide 76)

WEBSTER: This is a curve of typical performance data taken from the Crane test. If you care to follow this test it is pack 7B. The mission requirement is for a 36 minute discharge and a 60 minute charge at the 3.2 amp. rate in both cases. As Stan pointed out, the mission uses a voltage clamp temperature compensated circuit and the voltage limit presently being used is 1.43 volts and this is for 10 degrees C. You see that the clamp is reached in approximately 26 minutes and that the current does taper to 500 milliamps as Stan indicated. This represents data taken from cycle 6,389 at Crane. The test is continuing. We are trying to match the – we are not accelerating this. We are trying to parallel the operation of a spacecraft. At the present time the end of discharge voltage is running approximately 1.2 volts per cell.

(Slide 77)

WEBSTER: Someone asked do we know what the capacity curves look like for these particular cells and did we have the classic two step? The answer is yes. The way this test is being run is we have a five cell pack and every six months one cell – let me start off this way – on a six month interval we discharge one cell. At a year interval, two cells. At 18 months, three cells, and so forth, so that we can get a measure of how the capacity is doing and still leave some cells on the test as a control for how the system would perform without a capacity discharge.

One thing I would like to call your attention to is that on the OSO spacecraft, indicated by the dotted line, the undervoltage is sensed at the spacecraft buss. With sensing at this particular position plus setting the value high it means that the undervoltage for the spacecraft occurs at 1.17 volts per cell. This is something that we do not advocate for the obvious reason which you can see there.

On the ATS program the undervoltage is at one volt per cell. This undervoltage on the ATS program is detected by sampling across nine and 10 cell groups. However, the requirement for the program is that the battery be capable of supporting a 15 to 16 percent depth of discharge under a moderate temperature of about 10 to 15 degrees C. and we envision absolutely no problem with the cells' performance as required by the program.

Thank you.

Fred Betz?

BETZ: I think if they continue with ATS we will have to void the warranty for that battery pack.

WEBSTER: I think they have exceeded their warranty, Fred.

BETZ: On your first slide dealing with the ATS battery cells that are specified, if my recollection is correct, the excess – what you have there is the excess negative requirement, was the excess uncharged negative requirement representing the overcharge protection which does make it quite similar to the larger positive to negative ratio cells.

WEBSTER: Thank you. That is correct.

KUYKENDALL: Kuykendall, NOAA. The data you showed on ATS, the test data, did any of that reflect the modified test procedures for the additional cycles of discharge and if so, do you have enough data to give some indication of the effects?

WEBSTER: Okay. I have to put that in the proper perspective. I got input from the project management at the end of August. We implemented this new additional test regime in September, but we performed the capacity tests in October. I just got the end point. I have not received the data from Crane and I think what I am saying that not yet. We haven't analyzed the data. We don't know the impact, but we surely will within six months, because we will be doing more of this testing. We have a control pack which is the engineering cells and now we will have this accelerated pack if you will.

Fred?

BETZ: Betz, NRL. One other thing. There were some extra cells built and stored, dry stored, were originally designated manufactured from the same lot and designated for a second spacecraft which did get cancelled. Have those cells been activated and what is the intent for those, do you know?

WEBSTER: Yes, okay. As some of you may or may not know there is a decision made by NASA management that we would not be in the communications business any longer. However, I hear that decision is being reversed. I don't know whether that is true or not, but anyway, sitting out at Fairchild Industries is a whole spacecraft, ATSF-5, almost totally complete. In conjunction with that spacecraft, the initial battery procurement, I believe, is for somewhere in the vicinity of 300 cells or somewhere near that quantity. The cells which were at Gulton have been activated. The contract has been closed out. Two frost-free refrigerators were procured and a lock and the cells are at Fairchild. They are just being moth-balled. They are short circuited – shorted, rather. Short circuited sounds rough. They are discharge shorted and being stored in a cold environment. We would love to get our hands on the cells but no one will make a decision.

WADHAM: Wadham, Telesat. I would like to comment on this business of measuring capacity in the minimal eclipse seasons. As many of you may know, we have a very similar test program running on flight cells and after about six eclipse seasons or on the 6th eclipse season we got a little impatient and wanted to know what the cells were really doing, what the capacity really was if they were discharged, so we discharged them all down to a level of one volt, one cell at a time and we took the discharge curve.

The next eclipse season we saw remarkable improvement in the performance of that batch. We can't do this in orbit. The result is that we now have about a half a volt per battery improvement in the voltage. so when you are getting discharge from the cells to one volt in the seventh eclipse season all except one cell, that one cell still held that voltage up throughout that eclipse season.

This season we decided we would only discharge one cell to one volt to measure its capacity. All the other cells are still holding up including the seventh cell which has now gone two eclipse seasons since that reconditioning and is still holding up, so the point I am trying to make is that if anybody wants to measure the capacity of cells in the battery pack, that they should limit it to one or two samples rather than the whole pack because it completely screws up all your data if you can't compare it now with what is going on in flight, because you have now reconditioned those cells and they just do not get back down to the voltage that we are seeing on the flight cells and we cannot do that on the flight cells.

WEBSTER: Thank you. This is essentially the philosophy we are following in the OSO tests, taking one cell at a time and leaving the rest as control. Any additional comments? Okay, fine.

I would like to introduce our next speaker as Mr. John Armantrout of Aeronutronic Ford Corporation and he will be discussing the SMS battery performance.

ARMANTROUT: This morning I would like to discuss some flight experience that we have had with the synchronous meteorological satellite that was developed by what was Philco-Ford, now Aeronutronic Ford for NASA. This is a spin stabilized satellite. We could show the first slide if we could, Gerry.

(Slide 78)

ARMANTROUT: The general design features are summarized in this slide and later on in the minutes you will be able to review the details but the satellite power is provided by a cylindrical solar array in two parallel connected three ampere-hour 20 cell nickel cadmium batteries. Could we have the next slide?

(Slide 79)

ARMANTROUT: This will give you an idea of what the satellite actually looks like. Could we have the next slide?

(Slide 80)

ARMANTROUT: This satellite has been designed geostationary operational environmental satellite or GOES and some of the capabilities that it has are summarized there, continuous storm tracking, cloud analysis, surface temperature mapping, space environment, sun-earth interaction. Could we have the next slide?

(Slide 81)

ARMANTROUT: This is a typical picture as you have seen on the evening weather report. Could we have the next slide?

(Slide 82)

ARMANTROUT: The battery performance requirements that were originally stated or as are summarized here, we have a main buss battery load of 35 watts per battery. Our discharge voltage range is 28 to 23 volts. Our maximum depth of discharge is 60 percent of the rated capacity. Our peak discharge rate is 25 amps. The maximum discharge time, 1.2 hours or 72 minutes. We have a planned five year mission that would be 440 cycles and our operating temperature range is from five to 28 degrees C. with approximately 138 days between seasons. The actual weight of the battery, we indicate 7.9 pounds maximum but it weighs approximately 7.5 pounds. Could we have the next slide?

(Slide 83)

ARMANTROUT: This is a picture of the battery assembly itself. You can go ahead to the next one, please.

(Slide 84)

ARMANTROUT: This table you can review in more detail in the minutes, but it summarizes some of the design stresses and factors of safety in the battery assembly. Could we go to the next slide?

(Slide 85)

ARMANTROUT: Our typical temperature profile, with time, is shown in the upper curve. You can see that as we enter eclipse we go from a range of 25 to 30 degrees C. down to as low as five degrees C. and then as we exit eclipse and get back into charge, the temperature comes back up. The power dissipation is plotted on the lower curve and again you can review these in more detail in the minutes. Could we have the next slide please?

(Slide 86)

ARMANTROUT: Here I have summarized for the flight batteries that were, if I can get over here – this is capacity data where we have 100 percent of the rated capacity which would be three amp-hours. We are plotting from 30 to 90 degrees F. and our screening data for the batteries, for the cells, I have plotted the mean capacity value with temperature and you can see as you approach 90 degrees F. we are getting down to approximately the rated capacity of the battery. At the operating temperature range we are probably about 130 percent and this represents a pretty good summary of our capacity of this cell. Could we have the next slide?

(Slide 87)

ARMANTROUT: This slide summarizes for the first two spacecraft, SMS I, we have here our battery voltage and I have indicated the average cell voltage, as we go through eclipse, and although there are ups and downs on SMS I, that satellite has been operated in a different mode other than what was originally designed, but the typical profile here. We also have some Crane data which represents a similar cell lot as was used in the SMS I satellite. Why don't we go to the next slide.

(Slide 88)

ARMANTROUT: Here you can begin to see in the second season the SMS I which is operated at a deeper depth of discharge throughout the eclipse and we are still maintaining approximately 1.17 per cell on that satellite and then on the second, SMS II, we are up around 1.2 volts. This shows some of the degradation that takes place when you do cycle at deeper depth of discharge as you approach 60 percent DOD. Could we have the next slide, please?

(Slide 89)

ARMANTROUT: This is the most recent season. One comment that I might make about eclipse seasons, I find that in reviewing life test data and orbital data that by the third or fourth season you have pretty well bottomed out as far as the trend down. Your voltage degradation is going to occur, will occur in the first, I would say, three or four seasons and then it should be pretty stable thereafter. Could we have the next slide?

(Slide 90)

ARMANTROUT· This is a typical discharge plateau near the max. eclipse. I have the SMS I curve in the center here. This is our life test of a cell representative of the cells used in that satellite and then after five years of cycling you can see the lower curve represents unreconditioned degradation that you might expect. That basically is my presentation. Are there any questions? I would be glad to answer.

FORD: Leave the slide on. It is hard to see from the back of the room. Can you make it any larger? Is that better from the back of the room? Okay. All right, do you want to turn the lights on?

WADHAM: What type of cells are these and secondly, why did you have so much variation in the end of discharge voltage on these curves on SMS I?

ARMANTROUT: It is an Eagle Picher cell and perhaps Laverne Kuykendall might comment on that from NOAH. The operation of that satellite has been different. Vern, do you want to comment on that?

KUYKENDALL: Yes. Kuykendall, NOAH. The reason for the difference in the voltages, the actual depth of discharge we obtain on any given day is somewhat random. We are operating the satellite in a mode where we have to keep our S-band transponder on in high power due to possible failures at cold temperatures. The satellite was not designed to operate in this mode and we have to play several games in order to try and keep it as warm as we can while also trying to maintain battery constraints. The techniques that we use are not very accurate and you get a certain amount of randomness in the depth of discharge.

In addition, we are also trying to maximize the amount of data that we can obtain during the eclipse so we are pushing it. We plan to go to somewhere around 55 percent every day of the eclipse and the randomness comes in. We have reached a maximum of 63 percent I believe it is and some days it is as low as, say 45 percent, so that is it.

One other thing I might mention, we have also used these batteries as was mentioned earlier on the ATS. We have also used these batteries outside of the eclipse periods to support operations and have gotten into them 15, 20, 30 percent depending upon the satellite and –

FORD: I would like to follow up on his comment, a more general comment from our viewpoint here at Goddard. Typically, we find a case where the battery demands usually go up for operational reasons. Now we can sit here and be curious as far as battery engineers but we also have to face reality once that satellite is up there. The satellite program office usually is faced with some very crucial choices, particularly if they have a component that is subjected to failure. They are trying to maximize the useful life of that satellite and it might not be conducive to the useful life of a battery, so therein is where the trade-off begins so in keeping with what was said yesterday, it seems like there are inconsistencies sometimes when we look back on these meetings, and yet I think there is a lot of consistency in what is said. Basically, that we are trying to produce the best cell we know how. We are trying to get the best cell we know how from the manufacturer in order to be able to have some degree of margin in these unknown situations and believe me, unknown is a lot more frequent than the known.

KRAUSE: Krause, Hughes. On that last slide of yours you showed a five year curve. Is that a test curve or an extrapolation?

ARMANTROUT: That is a test curve. We have simulated on an accelerated basis the eclipse profile and that was the discharge characteristic at the maximum eclipse.

KRAUSE: What kind of acceleration do you do?

ARMANTROUT: What we do is we do a regular 24 hour cycle but we do not simulate the solstice period. Paul?

GOLDSMITH: That five year test, there was no reconditioning.

ARMANTROUT: Right.

GOLDSMITH: That was about 60 percent depth of discharge?

ARMANTROUT: At maximum eclipse.

GOLDSMITH: Well, I think Scott maybe later on may be showing some data on higher depths of discharge and Floyd Ford was mentioning the fact that the battery may experience more loading than originally designed for and we have some data which shows – and I don't know whether there is anything magic about 60 percent or 70 percent, but at least we have a lot of data which shows that when you go from 60 percent to 70 percent there is a different ballgame with respect to the cell characteristics, that a lot of the data that we have had at cell discharges that are somewhere around 70 to 80 percent depth of discharge

ARMANTROUT: I would reinforce that. In fact, to answer Paul, I believe that as you get above 60 percent DOD, depending on the depth of discharge on the negative, we normally talk about depth of discharge in terms of the positive electrode, but I think the real answer here is the depth of discharge on the negative as far as the voltage degradation is concerned and Don Briggs will be commenting on that a little later.

ROGERS: Rogers, Hughes Aircraft. Just a brief comment on what you just said; in tests we are doing on nickel hydrogen where we don't have the same negative electrode, and this was 72 percent depth of discharge with a four hour cycle, we saw some voltage fading after a while which was helped by a couple of capacity tests, so in that case, of course, it couldn't have been the negative.

WEBSTER: Thank you. Our next speaker will be Mr. Donald Briggs from Aeronutronics Ford Corporation. He will be delivering the talk for Mr. Ronald Haas of the same firm and the topic will be the NATO III battery performance. Don?

BRIGGS: First of all, I think Ron would like to be here to give this presentation himself and I am a mediocre substitute for Ron, but I do want to make a few comments on my own, particularly relative to the ultimate statement made by Mr. Krause.

The marriage of science and practicality has got to be engineering, and don't lose sight of the fact that our ultimate objective is to build hardware and to build it at the lowest cost that we can to meet the requirements of the mission. I want to make a statement relative to cost because cost is what we are dealing with. Cost to a particular mission may be weight. It may be reliability degradation. It may be complexity. It may be dollars. I have yet to work on a spacecraft where it was dollars. It is always weight.

The main thrust of our synchronous satellite development programs at Aeronutronic Ford has been to maximize the weight gain potential to the payload by a reduction in the power subsystem weight and still maintain a high reliability, high performance system.

With that, I would like to present part of the development of the NATO III battery which is an extension of the battery technology demonstrated by Mr. Armantrout. John and Ron Haas have worked long and hard to develop this lightweight technology with the great cooperation of Lee Miller from Eagle Picher who I feel now is making a very reproduceable, high performance, lightweight battery cell that we hope to even improve on still. If I may have the first slide, please, I will show you a picture of the NATO III battery which the similarity to the SMS battery will be obvious.

indicate that the end of discharge voltage curves are quite different and that you begin to really need reconditioning and that at the higher depths of discharge you need reconditioning down to zero volts as opposed to one volt per cell.

So I guess Floyd's comment just turned me on about the fact that we are talking about 60 percent but I think we should all realize or be attuned to the fact that we talk about higher depths of discharge, assuming that all cells work approximately alike and where we have tested a lot of different cells from different manufacturers we see this repetitive pattern. As you go into your 75 percent depth of discharge you need reconditioning and at the higher cell DOD you need reconditioning at zero volts in order to get performance and maybe Scott will be showing that later on.

ARMANTROUT: Yes, I will comment on that. Okay, Fred?

BETZ: Betz, NRL. I guess my concern with depth of discharge up in the order of 80 or 90 percent would be what Floyd would say. If you plan on those numbers to begin with what happens when the spacecraft operational people get a hold of it and want to go a little – you don't have any margin left. You are already reconditioning. You are right at the hair's edge.

FORD: Let me make one comment along that line, Paul. We talk about reconditioning. We talk about the improvement of voltage limits. Coming back with some information that was presented yesterday, it is my firm belief that reconditioning, the need for it, is being built right into the cell. Now when you look at what happens when you try in the near-earth orbit test yesterday, when you try to get the capacity out, it is not there and it was related to the electrolyte starvation, so as a conjecture on my part, I have seen indications that the capacity to one volt, if the fall-off of that is electrolyte management problems, and that if we can get more electrolyte in the cells we are going to see that these cells will last longer or the capacity degradation of one volt is going to be less than what we are seeing now.

Now the second part, the voltage degradation, I have not seen any indication that that softening and degrading of the discharge voltage is going to be enhanced by more electrolyte, so I am suggesting that we look at two fundamental mechanisms which may be interrelated but indeed are different, that the capacity loss that we are experiencing, whether it be near-earth orbit or synchronous orbit, is very dependent on electrolyte. Where there is a voltage loss, it is going to be reflected in a capacity loss too, but in cell tests where we increase the electrolyte level, we have seen the lower plateau come in but we haven't seen the capacity loss, so I am suggesting that the voltage plateau, the voltage degradation, is perhaps a function of the negative electrode. The capacity degradation is a function of electrolyte starvation.

(Slide 91)

BRIGGS: The next one.

(Slide 92)

BRIGGS: This battery is a 20 ampere-hour rated battery delivering around 25 ampere-hours with an energy density of 22.4 watt-hours per pound based upon actual capacity. If I may have the next slide, please.

BRIGGS: This slide presents some of the data, and as I present this data I recognize the difficulty of following it. It will be presented in the proceedings and we will be glad to discuss it on an individual basis if you have questions. The main features of the battery cell are that it uses standard state of the art electrochemical technology. We use a thin stairless steel case with a dual ceramic seal. The battery assembly is 20 cells in parallel and I am going to skip through this.

SPEAKER: Series.

BRIGGS: What did I say?

SPEAKER: Parallel.

BRIGGS: I am sorry. I am trying to read and talk too and I shouldn't do that.

The current status of the battery is that the flight qualification tests have been completed. We have five years of life test performance which is identical to the synchronous orbit cycle testing that John described for the SMS cells in batteries and I have got a little bit of data to present. Flight hardware production includes 14 assemblies that have been built today which is presented to establish the fact that this is a production item.

(Slide 93)

BRIGGS: The next slide presents the development of the lightweight technology. The first battery was our Skydent (?) I battery with the conventional packaging design. We then went into the SMS/GOES type battery which used the structural design that we are currently pursuing, producing a 5.8 watt-hour per pound at 60 percent depth of discharge and this is a usable energy density.

The following battery was one built for NASA Lewis which showed the adaptability unversality of this design and that it was a 16 cell battery for a specific mission, one of the advantages of the design.

(Slide 94)

BRIGGS: The next slide shows an NRL battery built for Fred Betz using six ampere-hour cells with 22 cells in series and the total weight of this battery is 13.75 pounds producing a battery with about an eight percent packaging factor. Again, the main emphasis has been on maintaining the standard electrochemical technology or the state of the art using the best available while minimizing and doing our engineering design. Mechanical engineering of the data, I feel, is all important.

The final, the middle picture there, is the one that I showed you originally, the NATO III battery which we have had a fantastic success with to date using the lightweight cell container. This was our main breakthrough here. We went to a thinner can, got rid of what we considered to be dead weight for a synchronous orbit application and tried to design a battery with the synchronous orbit requirements as guidelines for mechanical engineering. The same technology is being used producing 11.2 watt-hour per pound, 60 percent depth of discharge, which has been verified by our flight test data for a commercial program.

(Slide 95)

BRIGGS: On the next slide we project our hopeful developments. The new design that we currently have has reduced the depth of discharge to 55 percent using an advanced lightweight container design, so it is a much larger battery. We are hoping to still further enhance the cell container design itself.

Now we hit the advanced designs and this alludes to the question that John answered relative to 35 percent depth of discharge on the negative electrodes. If you will notice in what we project, the AFC-7 design, we are looking in our R & D studies at Ford at something like a 2-1/2, 2.5 negative to positive capacity ratio and I will give you some more information on that just a little bit later.

If I can revert now to the NATO III cell the next slide will present the data on the cell that Eagle Picher has built for use and which we are producing in very reproduceable manner today in relatively large quantities.

(Slide 96)

BRIGGS: The most impressive thing is the weight, 583 grams. The lower portion of the test data verifies that the tests that we have done in-house matched those provided by the manufacturer, Eagle Picher.

(Slide 97)

BRIGGS: The next slide I don't even expect to go through except to show you that every component in the battery pack has been analyzed structurally, thermally, and our engineering design has been relatively complete. It is of interest to note that the factor of safety is very low and if we try to optimize the design we must live with low design margins. We are trying to squeeze everything we can out of the battery package and this is where I feel engineering takes over and utilizes the data generated from science.

(Slide 98)

BRIGGS: The next picture shows the temperature profile predicted for a maximum eclipse on the NATO III program with the equilibrium temperature during overcharge in the neighborhood of 21 degrees C. or 70 degrees Fahrenheit. The lower temperature of 40 degrees F. is controlled by heater assembly which is an integral part of the battery and utilizes the electronics in the power control unit for control. The main emphasis is to try and limit the temperature range which brings another point that I would like to make. As we design the batteries and put on the constraints that the battery people and the battery cell technology provides, you can't lose sight of the fact that it is a functional part of a big system and you have to evaluate the penalties you pay and in a synchronous orbit spacecraft these penalties are weight, power, power consumption, and one of the main things we must try to do is to find out what the minimum charge current is to adequately return the charge during the synchronous orbit, thereby minimizing the impact on the spacecraft, plus the thermal power required.

(Slide 99)

BRIGGS: The next two slides, and if we will go through them slowly, show a hell of a lot of data that only is worthwhile if you sit and read it and what I would like to do is go over to the next slide –

(Slide 100)

BRIGGS: – and state that after all the tests that are up there which were done on our development program, the capacity of the battery is 24.7 ampere-hours, very close to the original capacity that we had before we started the development tests. Included in this data is things like insulation, resistance, impedance measurements, all of the typical standard battery type performance measurements and I think that you will probably find them useful when you get the proceedings of the conference.

(Slide 101)

BRIGGS: The next slide shows the results of our synchronous orbit life cycle data after nine eclipse seasons. Our capacity is holding very constant. I would like to point out relative to an earlier comment, that the battery consists of 20 cells. At every other eclipse season cells 11 through 20 are – the capacity on cells 11 through 20 is measured but not on one through 10, thereby we have a comparison of this effect of measuring the capacity and the numbers in the upper line across the top represent the cell voltage differences observed between cells 11 through 20 and one through 10, and there is a noticeable difference in cell voltage at the end of discharge at our maximum eclipse period.

Without further ado, I think I will go on to the advanced designs.

(Slide 102)

BRIGGS: The next slide shows some results of an R & D study that we currently have going on at Aeronutronic Ford. The curve on the left represents a conventional design with a negative to positive ratio of 1.5 and a review of the results indicates that we can expect a usable end of life watt-hour per pound based upon a 20 cell 20 ampere-hour battery for a typical long life synchronous orbit mission of about six watt-hours per pound or a maximum design potential of around 50 percent DOD. Using the advanced design we can increase the energy density as high as 12 watt-hours per pound and still maintain the same depth of discharge on the positive electrode with the negative electrode experiencing 34 percent DOD.

With some of the advanced designs the six and seven, the intermediate curves, by maintaining the same depth of discharge on the negative and these are paper studies, gentlemen, I am not – theoretically with a negative to positive ratio of 2.5 we can expect somewhere on the order of 15 to 16, 16-1/2 watt-hours per pound usable density with a positive electrode depth of discharge in the range of 85 percent which we feel is really the design goal.

(Slide 103)

BRIGGS: The next slide presents the objectives of our R & D program which I have sort of alluded to all of the way through this presentation, is to optimize the energy storage for synchronous orbit missions with a seven to 10 year life time, improve the component reliability, and try to increase the energy density as much as possible to maintain good engineering.

The design approach is to select positive electrode depth of discharge in the 70 to 80 percent range and we use as a basis for this work the NASA-Crane data. Limited negative depth of discharge to 35 percent which we feel has been demonstrated, increased the negative to positive ratio and maintained standard plate loadings, which I feel is very important, and to evaluate the electrochemical electrode process which we have discussed in rather detail yesterday.

If we do those and we hit the design numbers that we are anticipating, we will produce a battery that will have an equivalent energy density and this is the energy out compared to a standard battery design or a typical conventional battery design of about 35 to 36 watt-hours per pound which is our goal.

(Slide 104)

BRIGGS: The next and final slide shows the results of our analysis on the weight savings to the spacecraft as we go from one design to the next, starting with the conventional design for a one kilowatt battery in the neighborhood of 200 pounds with the lightweight ni-cad battery that we feel is at about 100 pounds operating at a depth of discharge of 50 percent could be achieved. Using our advanced lightweight nickel-cad technology we can gain another 20 pounds, so that the battery will be 80 or we will have 120 pounds of spacecraft payload capability, an increase of about 120 pounds on a kilowatt system. The upper two are comparisons of the nickel hydrogen and silver hydrogen which serve as a reference and I think will be discussed more fully this afternoon.

That concludes what I have to say.

Stan?

KRAUSE: Krause, Hughes. I would like to offer what I think perhaps might be some perspective on these developments. I think Don and Ron Haas are to be commended for developing some new technology and getting out in the forefront in thinning down cell cases and doing battery engineering at the battery level. Two things, as I say, just as a perspective, this information, No. 1, with regard to the accelerated life test extrapolations, we have run both five year real time tests and five year accelerated tests and I find it difficult to see a reasonable correlation from the five years of accelerated tests to five years of real time. I am sure you know that things happen during long solstice periods and on a real time basis that do effect the outcomes of those extrapolations from the accelerated test.

Secondly, I guess the NATO III batteries are operated at a 30 percent DOD in the system and with a 22 watt-hour per pound battery weight, that is about six watt-hours per pound effective energy density. The state of the art for commercial communications satellites for five to seven year operation is 60 percent DOD. On most of them, and we run fairly conventional locomotive type batteries at about 14 or 15 watt-hours per pound for an effective energy density of about nine watt-hours per pound using the state of the art today. I just say this for perspective.

BRIGGS: I would agree with everything that Stan says and as I pointed out in the development in our commercial programs the NATO III battery is operated at 60 percent DOD with an effective energy density of about 11.2 watt-hours per pound at 60 percent and this is usable energy density.

GOLDSMITH: Okay. Goldsmith, TRW. There are so many numbers that have been tossed around in the past few minutes that I am confused. Are you saying that you have a design for NATO III that appears to be able to survive five years at 60 percent depth of discharge or 45 or 30?

BRIGGS: That is correct. I am saying that I have a design of the NATO III battery based upon the life test data that we have to date which is not as conclusive as I would like, that I have committed to a flight program at 60 percent DOD.

GOLDSMITH: But Stan was saying something about NATO III flying at 30 percent.

BRIGGS: The NATO III spacecraft is designed for a 45 percent depth of discharge with one battery failed. It is a three battery system which results in a 30 percent depth of discharge design requirement imposed by the customer. The test results, the SMS battery which uses the same electrochemistry, has a little heavier case, is actually flying at numbers that Vern Kuykendall reported at 65 percent depth of discharge for a slated five year mission with some perturbations. I think that Stan's comment relative to the stand time is very important. It is something that we don't know too much about and we as engineers should know more about. Vern asked some questions yesterday that I think are somewhat embarassing to us. "Hey, I want to use the battery for a 10 percent depth of discharge once every 10 days. Give me some data that says either it is good or bad." I can give you data that says it is good. I can give you data that says it is bad. You take your choice.

GOLDSMITH: Okay. Your numbers are very interesting for two reasons. First of all, if that technology proves successful, both for real time testing and so on, the weight numbers are very compatible to what people are projecting for nickel hydrogen and there are a lot of dollars going into nickel hydrogen and –

BRIGGS: Thank you, Paul.

GOLDSMITH: The numbers you are projecting for advanced development cells are even lighter, larger energy density than what people are projecting for nickel hydrogen, so that is very interesting.

The other interesting thing is, of course, that NASA is standardizing on a cell which is like 1/2 or 1/3 as efficient as the technology you are working on right now.

BRIGGS: I don't want to comment on NASA's standard. I have, as you do and Stan does, have a variety of customers. There are some – I think that the customer philosophy is critically important to what we propose in our proposals and what we build. The degree of conservatism, the objectives that they operate to, the criteria that they are after, are important considerations when we design a power subsystem. You know as well as I do that the Air Force philosophy of design which is in the documents, is substantially different than the requirements for a NASA mission and we have to know those as complaint suppliers to our customers, so –

BARNETT: What vibration level did you qualify that NATO battery for?

BRIGGS: Do you have a number, John?

BARNETT: In random vibration.

BRIGGS: 18 GRMS.

BARNETT: GRMS. Is there any spectral density, G_2 per G?

BRIGGS: I haven't looked at that data in over a year so I really can't comment on that. I would be glad to supply the answers. Can we have your name?

BARNETT: Mine? Barnett, Rockwell.

BRIGGS: I am sorry I can't answer the question. John is the battery engineer and he has got numbers but –

BARNETT: How about the lightweight?

BRIGGS: The advanced lightweight or the NATO III design?

BARNETT: Advanced.

BRIGGS: The advanced lightweight is currently under development and has not been tested. Floyd?

FORD: Don, would you care to comment on the technology that is being utilized to get the advanced lightweight? I mean what basically is being improved or being done to it, in general terms? I don't mean specific details. I am confusing the lightweight with the NATO. You are talking about advanced now and you have gone through and you have really shaved weights and you have really optimized a lot of mechanical parameters that probably should have been done years ago, but now beyond that point what is advanced? Are we talking about new technology or are we talking about just applying present technology?

BRIGGS: Floyd, I think the answer is both. I think we are taking, and this is Ron's work predominantly, and it is work that is going on right now. He is looking very carefully at the relative merits of the positive-negative ratios, the depth of discharge on the negative plate and trying to maintain that constant looking at some of the data. As I pointed out, this is paper study. It is R & D work that we are doing to try and figure out where we can go from where we are now. We feel we have gone a long ways.

FORD: But is there new electrode technology involved? Is it something being done that we are not doing today?

BRIGGS: No.

FORD: Okay.

KLEIN: Klein, Energy Research. What is the basis for trying to freeze 35 percent depth of discharge on the cadmium electrode as being the limiting design criteria?

BRIGGS: Marty, we are not trying to freeze it. That happened to be a number that as we reviewed the data from Crane and reviewed data from test programs that had shown successful results, that number kept coming out from the positive to negative ratios of actual measurements. Again, maybe John would like to amplify on that. I am not that conversant on the answer. John?

ARMANTROUT: Armantrout, Ford. It is the result of a study that we did where we knew certain types of cells had certain negative to positive ratios.

Those cells were life tested and it is not all of our data either, and some of the data that I am aware of through various means, but we did find a common factor in successful tests was this number, 34, 35 percent DOD. We are not saying that you can't go more than that. We are just saying that that is data that we believe at this point in time. It has proved successful. I believe we could probably, with the proper test program, perhaps go more.

BRIGGS: It is just a result of reviewing the data and it kept coming out. It is the result of Ron's personal evaluation of the data and John trying to bring some light to bear on what the parameters are that we could improve with the ultimate objective of improving the energy, usable energy density.

DILLON: Dillon from JPL. I have got a question about your NATO III design. I really can't see it too close because we are so far back here, but a question I have got is regarding the thermal control of the design that classically with batteries, aerospace, spacecraft batteries, you are conducting heat or radiant heat exchanges. Do you do the same, is the same concept there? It really isn't clear by looking at it because of the end caps that you have that are tied with bars.

BRIGGS: The intercostal members between the cells, the battery is composed of groups of four cells built around a T-fram member, which is a thermal design conductor to the baseplate for radiation and heat transfer purposes. The thermal control on the low end is controlled by heaters applied to that end plate which is controlled by temperature sensors to try and maintain the low end and we thermally designed by radiation coupling to the spacecraft the high end.

DILLON: How do you control your conduction between cells? Is there any –

BRIGGS: That is part of the design and the conduction between cells, to have these intercostals or T-frame members with the four cells mounted on each side of the spin to conduct the heat to the base. It provides a very uniform cross-sectional temperature variation across the battery. Stan?

KRAUSE: Krause, Hughes. Once more I would like to interject my own point of view. We spent yesterday afternoon trying to decide how best to proceed on problems with state of the art cells because we are all concerned that they don't live long enough to satisfy some of our requirements, and one of the things we are concerned about over a long haul like five or seven years is plate swelling. It appears to be a function of depth of discharge and inter-electrode space is critical as a result of the plate swelling, as a result of the need to retail electrolyte in the separator and as a result of the need to pass gas through it and I would express some concern that if a cell case is thinned down too much that the mechanical compression on the cell over a five or seven year period with the plates inside swelling and squeezing the separator, one must be very careful in watching out and looking at the interelectrode space. Eagle Picher plates – Lee Miller is here. I am not trying to say anything nasty, Lee. Everybody's plates swell. Eagle Picher plates do swell like everybody else's and I would be concerned about trying to squeeze down too hard on the cells.

WEBSTER: Fred?

BETZ: Betz, NRL. I want to make a statement that kind of ties in with something Stan said earlier and the gentleman from JPL said and you have, that the design you had for NRL essentially could not be used in the NRL spacecraft because the design concept the battery has was not brought into the spacecraft at the very beginning and the thermal control system couldn't tolerate it. We were mounting it on a honeycomb and we couldn't get the laterial heat transfer. We have got boxes mounted around it with various dissipations and where that battery was located in the spacecraft it literally had to have its own physical thermal mass to transfer heat back and forth between the cells to get a uniform temperature. You have got to take a design like this and get it into the spacecraft right in the beginning and let the tail wag a little bit to do it, to take advantage of the light weight. Otherwise you are putting the weight right back in for thermal control.

BRIGGS: That is true. Anyone who loses sight of the fact that a subsystem is a subsystem or a battery is a battery unto itself, what we are building is satellites and satellite systems and the system approach to the whole satellite is extremely important.

WEBSTER: Can we limit it to two more questions? We have 16 speakers today.

BRIGGS: Yes. I am aware of that. Dr. Maurer?

MAURER: Maurer, Bell Labs. Would you define just what you mean by 35 percent depth of discharge on the negative? Are you referring to measured capacity, theoretical capacity, and 35 percent of what?

BRIGGS: John?

ARMANTROUT: Measured capacity and the 35 percent would be based on that, the flooded capacity test.

MAURER: Is it 35 percent in the cell in the discharge state?

ARMANTROUT: If you vent a cell and flood it and overcharge it and then go into reversal until you see minus 1-1/2 volts and measure that capacity, that is the excess negative that we are talking about taking 35 percent of it.

PALANDATI: Charlie Palandati, Goddard. There is one area here that you mentioned a few minutes ago that it is weight, not dollars. I think you will find it is dollars and that goes back into the launch vehicle required to put that satellite in orbit, such as GOES was mentioned. GOES flew on a Delta vehicle. That Delta vehicle required two 21 ampere-hour silver zinc, two 15 ampere-hour silver zinc, three ampere-hour silver zinc, and a half ampere-hour silver zinc battery to put that vehicle in orbit. You find that the Delta vehicle has been used for 105 missions and it is not just simply that we design a satellite now that is 20 pounds overweight. We won't use the Delta. We will now go to a Titan missile or something like this because the cost of that Delta is essentially looked at as a standard launch vehicle. If one looks at the net generation of rocket to put the satellite in orbit and looks at the actual cost it increases by factors of three, four, and five, and this is why the weight is so critical in every satellite because of what the capability of the launch vehicle is.

BRIGGS: Yes, my point was that it was not the cost of the battery. It all reflects back into dollars. Mr Dunlop's statement yesterday looked at the operational dollars for lifetime, the dollars for launch. It all relates to dollars. It all is a cost, whether you pay for it in reliability, whether you pay for it in weight, whether you pay for it in performance. It is dollars and that is the business, gentlemen.

Thank you very much.

WEBSTER: Thank you, Don.

Our next speaker will be Dr. Will Scott substituting for Dick Sparks from TRW and according to my information there will be three separate systems discussed. One will be fleet SATCOM. One will be the M35 battery and the last will be the one kilowatt battery design. Dr. Scott?

SCOTT: As advertised, I am going to present test data and some orbital data for actually four different kinds of batteries, one in addition to the one that Bill mentioned, a second - the M35 is an Air Force spacecraft system and one other Air Force system will be included in the presentation.

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SCOTT: First I will start with ground test results. The first system that I would like to talk about is the fleet SATCOM satellite system which is still in the manufacturing stage and has not as yet flown. The testing that I would like to describe is that of a life test of two half battery packs. The battery consists of 24 cells in total so each of these packs was a 12 cell pack and this graph which I won't need to belabor here. You can look at it in the proceedings. It describes some of the details of the life test. It is a condensed time accelerated test, seven to 15 degrees base plate, two different depths of discharge have been used, one during the early part of the test to indicate the design nominal and a higher level 75 percent to simulate a one battery failed situation, increasing the depth of discharge arbitrarily during the test.

Most of the sunlight, continuous sunlight periods, this is a synchronous orbit application, most of the sunlight period was omitted and capacity measurements were made only during reconditioning discharges on the one pack that was reconditioned and I will talk about that more in a minute. Charge control is constant current, essentially constant current charging to a temperature compensated limit which is adjustable over a wide range by command in the actual satellite.

In order to simulate the expected temperature profile on the battery, the baseplate temperature had to be driven with a controller to simulate actual spacecraft platform conditions.

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SCOTT: This is a plot of some data from during the first eclipse season of the life test on one of the packs and I just wanted to point out that the heavy dashed line shows how the baseplate temperature was programmed to simulate the platform temperature projection and the dotted line is, then, an actual cell top temperature profile as measured and the upper curve is the pack voltage obtained at that particular time.

Now, what I am going to discuss primarily are two types of data. One is the minimum end of discharge voltage observed during the longest discharge of each eclipse season during these life tests.

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SCOTT: This is plotted here on a semi-log plot for each of the two packs. The semi-log plot is shown here because during the early part of the test it appeared that the voltage plot was nicely linear on a semi-log plot. As you can see at this point where the depth of discharge was increased to simulate a failed battery, the plots no longer were linear on a semi-log scale, but still we retained this particular plot to show that difference.

As you can see, this lower solid line represents the data from the pack that was not reconditioned at any time during the test and just continued on until it finally reached a one volt per cell point which was the lowest acceptable voltage for that program application and at that point the battery, that particular pack was discontinued.

The upper dotted curve shows the results of the pack that was reconditioned between each eclipse season. Now, two different types of reconditioning were used during this test on pack B, as it is called up here. Up until after the 12th eclipse season the battery was discharged down to approximately one volt per cell using the constant power load that used during thenormal test and that was the extent of the reconditioning. Subsequent to this point the battery was, that pack was reconditioned by putting a resistor on the pack and allowing the pack to discharge down to below one volt at the pack level and two different things may be pointed out here. One is the difference between the two packs with the type of reconditioning used initially on pack B and one gauge of that difference is that if you look at the difference in the effective cycle life or actual equivalent years in orbit there is a difference down here at around 1.1 volts per cell of almost a factor of two in the life expectancy based on the number of eclipse seasons completed.

These points up here now show what the end of – minimum end of discharge voltage was following the type of reconditioning involving discharging at a relatively low rate down to a very low voltage at the pack level and obviously a very marked increase in the voltage performance was obtained out here and you will note that at this point that completed 20 eclipse seasons which is equivalent to, without talking about real time yet, 10 years in a synchronous equatorial orbit.

However, it is obvious that without the change in the approach to reconditioning that was implemented at this time, that the performance of this other pack here was even with the type of reconditioning used initially, was heading for the bottom and would probably not have lasted very long, although I would not expect necessarily that this curve would just continue straight down. I believe it would probably have gone down and leveled out somewhere down here but we don't know where.

A couple points here might be made. One is that it appears that if reconditioning is of any basic value that first of all, a different approach to reconditioning is needed for deep discharge applications and I am talking about anything over 50 percent of that order of magnitude, then is required for, say, depths of discharge below 25 percent and below, which are more typical of a low-earth type application. It looks like the effects, the need for reconditioning, the mechanism for reconditioning, and its benefits are different at the high depth of discharge than they are at low depth of discharge, so you can't compare too precisely the results obtained by reconditioning in a low-earth orbit and reconditioning under test conditions such as this without being very careful of what you are talking about.

Then in addition, it appears that reconditioning of a battery with relatively few cycles is a different ballgame than reconditioning a battery that has been heavily cycled. Different methods, different voltages, different approaches are required. To be more specific, usually reconditioning by discharging down to the order of one volt per cell or .9 volts per cell is quite adequate to give very nearly – a very good recovery when the cell is fairly new, has very few cycles. However, after cycling of the type especially involved in this type of a test, reconditioning to that voltage has relatively small effect and you must take the battery down to a lower and lower voltage as the condition of the battery becomes more and more heavily cycled.

I believe that some preliminary results of discharging the battery to a very low voltage were presented last year at this meeting. I just want to say once again, for those of you who might be wondering what is happening to the cells that are presumably being reversed while these series strings are discharged to a low voltage, the point is that we have determined that if the rate can be kept low enough that the cells will not increase in pressure significantly during this kind of a discharge. By "significantly" I mean to above, say, the order of 40 or 50 pounds pressure, and the rates that appear to be suitable for most cells that we have tested so far are in the range of C/100 on down so ordinarily in a synchronous equatorial orbit one has plenty of time during eclipse seasons to utilize a very low rate of discharge. We are not saying that you would, in an ordinary operational spacecraft, you usually have to have more than one battery in order to be able to implement this because you usually need at least one battery fully charged all the time during eclipse seasons, I mean during solstice seasons in order to implement emergency procedures or do fault clearing and so forth, so the general approach that this information suggests is that, say, if you have two or three batteries on the line, that you can take your time, discharge each one sequentially down, bring it back up, and go on to the next one and you do this generally whenever it is convenient between eclipse seasons.

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SCOTT: Now there is always a question what is the capacity beyond the normal usage conditions? As I said before, we did not measure capacity under full load conditions in this test, but for general information, this is a plot of the capacity to an average of one volt per cell during the reconditioning discharges that were used between eclipse seasons on pack B and you can see that during the use of the first type of reconditioning the capacity declined down to a low point of 22 plus, 22.6 ampere-hours and then on the first time after the battery had been reconditioned to a very low voltage, the capacity measured began to come back up and then on the second time it was all of the way up to 28 ampere-hours and then it began a decline as shown here.

Now, an interesting point, again, here, is that these three points down here it was found out later, were obtained when the temperature of the baseplate during the cycling was about two degrees above what it was originally set for and had operated on during the rest of the test. Our only explanation for this displacement is that this is the effect of two degrees difference in temperature on the baseplate. Now that is sort of hard to swallow but that is the best explanation I can offer you right now. There may have been something else going on but when we returned the baseplate temperature back to the original value this was the final point that we obtained during the various capacity measurements.

I am told that I have to condense some of this material so you will see some of it in the proceedings but I will leave out a few here and go on to – I have the other data for the fleet SATCOM which consists of discharge data during reconditioning discharges, some of it including separate measurements of the positive and negative electrodes with respect to the case to the cell which shows roughly which of the two electrodes was responsible for cell voltage behavior. It indicates generally that initially when the discharges down to close to zero volts were started, the cells were all negative limited and then after one or two reconditionings the cells again became positive limited.

The other ground test that I would like to cover is that of the one kw. battery made with 50 ampere-hour cells that I mentioned yesterday. Beg your pardon?

GROSS: We can't see it.

SCOTT: Well, "it" is coming up here. I don't have a photograph of "it," the hardware, but I want to say that we are testing two one kw. batteries, one made with polypropylene separators and an essentially identical one, identical as far as we know, made with nylon separators, and they are being tested under essentially identical conditions and this data, I think, will begin to show up some of the possible limitations of some of the statements about the comparison of nylon and polypropylene that were made yesterday.

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SCOTT: Here is a cross plot of the minimum voltage on discharge during eclipse seasons during an accelerated test of the two batteries. 1-2, which is the one that has proceeded the furthest, is the one made with polypropylene. 1-3 is made with nylon. These tests are being conducted at an average temperature of around 35 degrees F., fairly cold. The temperature is being maintained by use of heat pipes in this particular system and we are using a 12 hour cycle during eclipse seasons and six days between eclipse seasons, a normal 45 day eclipse season duration.

First of all, you might note that contrary to popular belief at least in this case, the performance of the nylon battery was not as good as the polypropylene battery, and as a matter of fact, well, this lower line, this battery is the one that I mentioned yesterday, had the one lot of less than optimum performing cells and that accounted largely for the difference between these two but still if you discount that one lot the performance, then, of the polypropylene battery and the nylon battery were essentially identical, at least so far as this test has gone.

Now, not all of the captions got on this diagram and you will see, I think, a more complete version in the proceedings, but this upper battery was reconditioned by discharging to 22 volts between this eclipse season and this eclipse season and that is the reason for the increase in the voltage at that point. This battery was also reconditioned again down here but it was not reconditioned at any other time during the test, just twice, there and there. That battery is now in its 14th eclipse season. The minimum acceptable voltage for the program is 24 volts, so it looks like we are going to complete the test well above 24 volts.

By the way, I should point out that this test is being conducted – the test started out at 82 percent depth of discharge and as the voltage degrades the depth of discharge has been increasing slightly because this test is being run with a constant power load so the current increases as the battery voltage decreases so the ampere-hours out when a given 1.2 hour maximum time period increases as the test proceeds, so down here we are up to over 85 percent depth of discharge. This is a development program. It is not related to any specific spacecraft program at this time and we were trying to explore the limits of high depth of discharge in order to maximize the energy density of this system.

A note here, we – well first of all, it doesn't say here but there was a reconditioning of this battery 1-3 to 22 volts after this eclipse season and in the case the reconditioning appeared to have made the battery worse instead of better although I don't really believe that it was due to the effect of the reconditioning per se, so because the voltage was getting dangerously near the lower limit, we then, after the next eclipse season reconditioned that battery down to zero volts or close to zero volts on a resistor, and the results are pretty startling. This shows the following eclipse season and the next one after that with no reconditioning between these two.

So, again, we feel that if you are obliged to operate at very high depths of discharge in order to meet a certain energy density requirement or a certain minimum weight requirement that it looks like the use of the right kind of reconditioning may be the only way to assure that you are going to have a mission success.

I might say in response to a comment made a little bit earlier that we would not recommend that a spacecraft be designed initially to operate from day one at 80 percent or 85 percent depth of discharge. However, in a sense this test is primarily indicating what you could expect if, from some sudden change in the system or some failure, that you were forced to operate at this high a depth of discharge. In addition to that, there is a general guideline that we would necessarily impose that if you get up too high a depth of discharge, that the spacecraft operations would presumably have to back off on some of their loads in order to prevent – to keep the battery from being forced to too high a depth of discharge, and this is a generally accepted operational procedure, at least with some of our spacecraft programs.

Just a couple of other quickies here, if I might. We also have eight packs of 50 ampere-hour cells separately being life tested in a similar type of life test of the batteries, in terms of programming. We have four packs running at approximately the same temperature as the battery, around 35 degrees. We have another four packs running at – with a 70 degree baseplate. We are using a different simulated sunlight season period between each of the four packs at each of the two temperatures. The point of this is that we are trying to get data which will answer one of the questions raised a little bit earlier as to what is the relationship between these kinds of accelerated tests and the real time test and we hope by the time we get through with this program that we will be able to take the results obtained in these variable periods and extrapolate to real time in order to determine what the results of that test would have been had it been done in real time.

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SCOTT: In this test plot, this shows the plot of only two of these packs, the ones that have completed the most eclipse seasons with the shortest intervening time periods and you will note the packs at 35 degrees are doing rather well. Incidentally, three of the cells in each pack are polypropylene and three with nylon. The nylon ones are doing somewhat better than the polypropylene ones at the low temperature.

Look at what is happening at 85 percent depth of discharge at 70 degrees. We are getting a very rapid degradation in the voltage. At this point in the test the cells essentially had failed as far as supporting the mission requirement are concerned, so we did a reconditioning to zero volts again. The voltage recovered to here. Now we have gone these two additional eclipse seasons with no further reconditioning and it looks like the same thing is happening all over again.

We have done one more of these reconditionings that doesn't show on here and the voltage is again back up here. Now we are going to continue to recondition in this way every eclipse season for a while to see whether we can maintain even these packs even at this high temperature and the high depth of discharge.

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SCOTT: I will show you one more if I may. This is a combination of one ground test which is the labeled life test, 40 percent depth of discharge with no reconditioning. The dashed line is orbital data for that same battery in flight where, for the first two eclipse seasons there was no reconditioning. Then they did one reconditioning after this point and we are here on the next eclipse season and then they did two reconditionings in a row between here and here and now this is the last data point available. In this case the reconditioning is only a discharge at a moderate rate down to about one volt per cell at the battery level.

The upper curve is all flight data. It is a pretty smooth curve. It is drawn through points obtained by telemetry from another flight program, 42 percent depth of discharge, where there were two reconditionings in a row to about one volt per cell have been done during every eclipse season and the end of discharge voltage has remained very constant throughout that test.

So we believe that reconditioning has a real value under real operating conditions. It allows one to utilize a higher depth of discharge and therefore a higher design energy density on the battery and that it can certainly be used very effectively to return the battery from some low voltage degradation if that should occur.

WEBSTER: Thank you very much, Dr. Scott.

Our next speaker will be Mr. Ralph Sullivan of Applied Physics Laboratory and he will be discussing the Transit and SAS battery performance. Ralph?

SULLIVAN: Bill Webster has politely informed me that I am standing on a trap door which he is going to actuate in 15 minutes so if I disappear in the middle middle of a sentence you will know what happened. I would like to compare the battery performance of two types of satellites which are built, at least in part, by the Applied Physics Laboratory. The first type is a Navy navigation type satellite and the second is a Goddard managed SAS, Small Astronomical Satellite and I would like to just draw a simple-minded picture on the board here for a minute for talking purposes. This is the earth and navigation satellites are near-earth orbits and I will represent the plane of their orbit by a line north-south through the earth and the SAS spacecraft are also near-earth orbits and I will represent the plane of their orbit by a line east-west through the earth, whole orbit, equatorial orbit.

The navigation satellites are a constellation, actually, of about six satellites but we will just talk about one of them for the moment. If we consider the situation where the sun is normal to the board, both of these satellites are experiencing maximum eclipse, 35 minutes in the case of the Transit, 36 minutes in the case of the SAS. If we consider three months later when the earth has moved and the sun is in the plane of the blackboard, the SAS spacecraft is still experiencing the 36 minutes eclipse time. The Transit spacecraft, however, are in 100 percent sun.

The basic difference, then, between the satellites is that the Transit satellite has a variable depth of discharge, zero to 11 percent. The SAS spacecraft have a very constant repetitive depth of discharge going to, in the case of SAS B, 21 percent depth of discharge. In the case of SAS C, 24 percent depth of discharge.

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SULLIVAN: I will skim through the first slide. We are comparing, clearly, not just apples and oranges, but apples and bananas here. This is the Transit spacecraft. I am comparing three of them or averaging three of them, I should say, from say back in 1967, average cells built in the mid-sixt The SAS B spacecraft was launched three years ago. The SAS C spacecra is just launched last spring.

Let us skip over the rest of the nonsense and get down to the bottom line through the usual simple-minded calculation. It is anticipated that this should have a 50-month projected lifetime based upon that curve that shows cycle life versus depth of discharge and that is as it should be. The Transit satellites are an application type satellite.

The SAS B had a design criteria of one year minimum and the projected lifetime was 22 months and 17 months on the SAS B and C respectively.

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SULLIVAN: Now, at the risk of Bill actuating that trap door just a little sooner than he expected to, I would like to tell a story and that is about a man standing on the corner in Belfast, Ireland one dark night and another man walks up behind him and sticks a gun in his back and says, "Are you Protestant or Catholic?" He thinks, "Oh my God, oh my God, I had better take a neutral position." He says, "I am neither. I am Jewish." So the man behind him says, "Glory be, I must be the luckiest Arab in all of Ireland."

Now, as a power system type I feel very much like the victim in that little story because I am trying to always take a middle position, box in the battery with a charge control system so that the battery doesn't get out of bonds, so that it lasts a long time and I feel as though the system is getting shot to hell every time I try to do that.

We started way back with a very old simple system. The Transit system looks very much like you see here. A simple solar cell array charging a battery. You worry about over-voltaging the battery so you put four zeners across it and those are four actual zeners. There is a lot of line resistance worry, about what voltage we are actually reaching on a battery is really not determined because there is a lot of line resistance on the battery leg. There is a lot of line resistance in the zener legs.

It is a witch to analyze, but it is a very simple system to put together and has worked very effectively.

The next generation, when we went to SAS B, we said, "We know better than to do that again. We are going to do something we can analyze," so we put the battery cells all on one pack. These are not all in one pack. There are eight cells in this battery pack spread throughout the spacecraft, because we couldn't fit them all in one place. These are all in one battery pack. We monitored the temperature and we set a temperature compensated voltage limiter on there which I am sure everybody is familiar with, these days, and it drives this shunt. That system alone would have worked but we wanted to add a redundant system and we also wanted to try a coulometer so in parallel with that system we put an electronic coulometer on there which would count the number of ampere-minutes taken out of the battery and then allow 105 percent of the same number to be put back into the battery.

That is a little bit misleading because at the end of that time we cut down to a trickle charge level which would vary between three and 600 milliamps depending upon battery temperature, so by the time we finished that trickle charge period we would have probably have put back in not 105 percent but something closer to 115 to 20 percent back into the battery.

The third generation when we went to SAS C, we said, well if the complexity is good, then more complexity is better and we went ahead and did very much the same thing with the voltage limiter except that we went to a two level type voltage control so that as the battery aged we would step up to a higher voltage, a quarter of a volt higher than the first voltage limiter was set.

We changed the coulometer concept a little bit and we decided we would like to have it under ground control variable from 101 to 125 percent return but now when we cut down to a trickle charge level, we cut down to 100 milliamps which is C/90 on a nine ampere-hour cell, in other words, zilch. We could control very definitely the percent return getting back into the battery by this ground control command.

Okay, so if we know what we are doing, then, if we knew what we were doing, going from the simplest system to the more complex system, we should have improved the battery performance.

(Slide 114)

SULLIVAN: I would just like to comment a little bit on the different types of cells. Again, we are comparing apples and bananas and the Transit satellites, way back in the sixties APL used Gulton almost exclusively, and now SAFT America. On SAS B, for the first time we used General Electric cells. We thought we had a problem with one of the cells in the battery pack. It turned out in retrospect that what we now think we were seeing was 1.05 volts, that second plateau on all eight cells in the battery pack, but at the time we thought we were experiencing a deficiency in capacity of one cell in the battery pack and we said, "Whoops, we don't want to use GE any more," and we went back to use Gulton. Okay? I owe GE an apology on that because we are experiencing almost the same thing, if anything, worse, with the Gulton cells and my point here today is that it has little to do with the battery cell manufacturer. I am not sure exactly what it is due to but I don't think it is due to that.

The thing that I think is important here is that the SAS B and the SAS C are not only different cell manufacturers, but there was a teflon coated plate used on the SAS B cell and there was none used on the SAS C cell. They are very different types of cells and yet for a first approximation they acted similarly. Again, I have to conclude that has something to do with the way we are using the cell.

Depths of discharge I mentioned, fairly high on the SAS B, and very low depths of discharge on the Transit.

(Slide 115)

SULLIVAN: There is some torquing but this isn't really very important. The charge-discharge profile; it is not only the discharge profile that is constant on the SAS's and variable on the Transits but because of our charge control system we have quite a constant recharge profile as well. The initial recharge rate comes on at C1.5 and stays there until you hit the voltage limit, tapers off until you return, say, 105 percent return, and it cuts down to a very small trickle charge rate.

The temperature ranges of operations are very much closer between SAS B and Transit than it appears from these numbers because SAS B went down to three degrees for only a very short period of time. Most of its lifetime was about 14 degrees C. This temperature range looks very close to the other two but at least in recent months SAS C has been hugging the upper end of its range so SAS C may have been running a little bit hotter than the other two on the average.

(Slide 116)

SULLIVAN: Now you can see from this slide quite clearly how we have improved these. This represents the end of discharge voltage during periods of maximum eclipse, so it represents a situation with the sun normal to the blackboard. It is data only for that situation, so that we are talking about 35, 36 minute eclipse periods in all cases. It represents, also, the typical end of discharge voltage at the typical discharge-end of discharge current, which are not identical but they are close enough for government work. It does not show the fact that when the spacecraft controller wishes to torque a SAS B or a SAS C and he runs over the knee and down to the second plateau, he sees a drastic drop in the voltage and drops below 1.1 volts per cell which is where we presently have our undervoltage detector set and it trips the switch and throws everything off the line and there is chaos, panic.

(Slide 117)

SULLIVAN: Okay, when we look at this the first thing that – the first explanation – if I look at the SAS's and say, okay, for a first approximation they are behaving as a group. The reason for that, I think, is not too surprising. Low depth of discharge, higher depth of discharge, as one reason. Variable charge-recharge – variable charge-discharge profile, and constant charge-discharge profile I think is another reason. That is a judgment. It is not something I have proven. It is something that I think is true.

(Slide 118)

SULLIVAN: What really puzzles me is why is there such a difference between the SAS B and the SAS C? SAS C clearly started to drop off at a much faster rate than SAS B did and we pulled various little tricks. As it went down we switched – we started off at 105 percent return. We switched to 110 percent return. We got down here and we decided to go to – even with 110 percent return we decided to go to the high voltage level. We went up for a very short period of time and again we headed for the basement and what is not shown here is we have had, after this point, we continued to go on down to about 1.12 volts per cell where we decided to do some reconditioning.

(Slide 119)

SULLIVAN: I am going to skip over the next three slides because they are simply blow-ups of that composite curve that you just saw and I would like to skip now to what the results of that reconditioning were.

Now, I should say that what we do and I think what most people do on these programs is we receive or purchase more cells than we need. Upon receipt of these cells we put so many into a flight battery, so many into a spare battery, and then we take so many and we put them aside for tests. APL doesn't perform their own testing. We sent them to Floyd Ford at Goddard. He discusses it with us and we come up with a test program. He sprinkles them with holy water, sends them on to Crane where Jim Harkness goes ahead and puts them on cycle.

Now what we are looking at up here is Crane cells versus flight cells. Same cells, same manufacturer, received at the same time. There was no selection – we didn't discriminate and pick out the best cells and send them the worst cells or pick out the – we didn't do anything like that. We simply picked out 10 cells and sent them to Crane without any testing. Clearly the Crane cells, although they are not behaving great they are getting down to 1.05 volts per cell, the so-called "second plateau" at around eight ampere-hours, after 2,404 cycles.

When we did our in-orbit conditioning just a few weeks ago on the SAD cells in orbit we get down to about 1.05 volts per cell in something like 3, 3-1/2 ampere-hours. This is after 2,680 orbits. It is 2,600, 2,400 orbits, very nearly the same kind of lifetime.

If I had to guess and it is a guess at this point, I would say that these are acting, behaving, very much like the SAS B cells behaved. I have had to do some soul searching and ask myself clearly here, clearly the difference between what is happening has to do with how these cells have been treated in orbit versus how these cells are being treated at Crane. We tried to make them identical but of course we couldn't and we didn't. The only differences that come to mind as being important are the Crane cells have been operating at a constant temperature of 20 degrees in C. In orbit the flight cells have been operating at a range of 14 degrees C. on up to 28 degrees C., but in recent months it has been closer to 25 to 28 degrees C. range, so am I willing to buy the fact that five or seven degrees difference in temperature will produce this kind of a difference? May be. I don't know. I am just raising that as a question. It is possible.

There is one other difference here and that is in orbit I mentioned we put the coulometer in parallel with the voltage limiter. It is a very expensive device. On the Crane cells we used simply the voltage limiter. We did not put a coulometer in parallel with it, so the Crane cells are experiencing, have been experiencing throughout their lifetime, a simple voltage limit type control. I believe it is like 117 percent return. That number might be a little bit in error, but it is on that order, whereas these have started out at 105 percent return for a long period of time, changed to 110 percent return, changed to other various percent returns back and forth to try to correct the situation and I have to ask myself, if perhaps with our fancy electronics we have gone one step too far in not allowing the battery to go into overcharge, we have perhaps forced it to experience low voltage faster than it would normally have done.

The only other conclusion I can come to is that if I ever have to do it again with a system, we will say, "Hooray for the second plateau," and design the system to work down to 1.05 volts per cell and let the scientists go ahead and try to decide why this sort of thing comes about. I feel it has to be because of the way we are operating it in orbit and I think, although all of the things that have been discussed so far here at the meeting about controlling what goes on in the cell, controlling the plate loading, controlling electrolyte, all of these things are important, there are an awful lot of things we can do in our charge control system to wiggle it just a little bit and change greatly the performance of the battery.

Open for questions. Yes, sir?

GOLDSMITH: Goldsmith, TRW. Doesn't Crane normally recondition the cells as a part of its testing program?

SULLIVAN: I am glad you asked that. Yes, they did have the foresight, Floyd and Jim did have the foresight on this program to not do that except that they do have a six month period. Anyway, the cells we are showing here were not reconditioned.

CLARK: Clark from Grumman. One thing you may not be considering is how would you handle flight battery before launch? Was that battery used in spacecraft integration and how well was the condition before launch?

SULLIVAN: Yes, sir. That battery more than any other battery, was held away from the integration people longer than – right up until the last minute. We kept it in the refrigerator. Okay. We stored it in the refrigerator and when I say the last minute, the last minute was about two months before launch at which point we had to install it for spacecraft vibration and it went through thermal vacuum but throughout it all the spacecraft was off the line, held open circuit, for I would say 98 percent of all of the subsequent testing. We are able to operate the satellite without the battery and that is the way all testing is done, without the battery, even though it is installed in the spacecraft. It is just sitting there dormant. Yes?

DUNLOP: Dunlop, Comsat. There must be tons of information in the literature on the effects, the difference in performance between 15 degrees C. and 28 degrees C.

SULLIVAN: There probably is, yes.

DUNLOP: It is bad to operate it at 28 degrees C.

SULLIVAN: Well, that was an upper range, but it is still operating – all right, 25 to 28, and that may well be part of the problem.

HARKNESS: Harkness, Crane. For clarification, the current recharge on a battery pack at Crane is around 112 percent, not 117.

SULLIVAN: I am sorry. Yes?

FORD: Two points. The high temperature operation is done because of the requirement of the experiment, again. I think we have been sitting like at least 30 days and maybe longer now, between 27 to 28. The battery temperature doesn't fluctuate very much but it is very sensitive or seems to be sensitive to orientation of the spacecraft. From my assessment, the real degradation has come about in this where the scientists are wanting to look at a condition that causes a high flux input to the spacecraft and the battery has been operating at 25 to 28 degrees C. and it is in the latter part of its life now or the latter part of the test program. Would you agree with that?

SULLIVAN: Yes. I really think, honestly, Floyd, I think that somebody of a thermal type or a power type should really look at the SAS B and the SAS C history and get a number that represents percent time at temperature because although we know the range we really don't know where it sat most of the time except in that field.

FORD: One other point I would like to make, as a general comment to what has already been said this morning, I noted with interest the two programs that have been discussed had less than three cc's per rated ampere-hour of electrolyte. I also noted that this one had exactly three cc's per ampere-hour or three cc's of electrolyte per rated ampere-hour of a cell and for the sake of further discussion this morning, if anybody talks about other batteries, I would just like to see you comment, particularly when you are talking about degradation characteristics. I think there is an inherent relationship between the electrolyte level and the degradation that we are seeing.

Now we have some experience up there with cells that have got a lot more electrolyte in them rated on a capcity basis. I would like to see it. We have got test experience. I think it is very important to try to get that one fact established.

SULLIVAN: Yes, sir?

IMAMURA: Imamura of Martin-Marietta. Two questions, Ralph. What is the coulometer accuracy over a stretch of cycles? Do you have any data on that, accuracy in terms of ampere-hours now.

SULLIVAN: Okay, its control accuracy is all right, but I am sorry, I really can't give you numbers. It is like 1/10 of a percent up – no, I am sorry. Stability is like 1/10 of a percent kind of thing over a year, okay, but the accuracy was better than a percent but it is really not relevant because of the fact that we are returning so much more than we are taking out.

IMAMURA: Second question, you have got two voltage limits. What was the resulting C to D ratio or recharge fraction? Do you have any number on that? What was the overcharge level for these successive cycles?

SULLIVAN: It was controlled by the coulometer, limited by the coulometer.

IMAMURA: Yes. What was the C to D ratio, 1.05, 1.1?

SULLIVAN: Okay, in the case of the SAS B spacecraft it is more like 115 to 120 percent. In the case of the SAS C spacecraft we started out at 105 percent. We went to 110 as we saw that voltage drop. We have since gone to just a voltage control at times without the coulometer where we have gotten up in excess of 115 percent so it is varied and none of these things seem to work, although going to 115 percent did seem to help for a while. It held us up for a while.

WEBSTER: Thank you, Ralph. I am sorry we have to conclude the questions here and proceed on. Thanks a lot.

Okay, this part of the meeting will be designated as testing but I am sure there is not really that much definition between one section and the other and my first speaker during this part will be Mr. Donald Mains of Crane and he will be discussing accelerated testing.

MAINS: Thank you, Bill. I thought I would briefly summarize the accelerated test program as it is being run at Crane. The program started with the analysis work that was done on the early testing. This was back in 1963-'64. We started a program at Crane with cells from several different manufacturers running under various test conditions with several different sizes and also with some design problems such as leaking cells, unknown plates and other quantities in that. As we began the analysis it tended to show a direction toward prediction but we were operating with so many variables and so many factors that we didn't have control over that at that point we began working with NASA and the Air Force to develop a new accelerated test program. The Air Force had already been doing some in-house prediction work and also working with Battelle Memorial Institute to come up with some designs. The people at our statistical group at Crane along with Dr. Anderson from Purdue University developed a test matrix with some specific designs in it. The one we are working on now has six ampere-hour sealed nickel-cadmium cells with various amounts of precharge, amounts of KOH and KOH concentration. These are set up in five level increments so that we can evaluate their effects.

These cells, then, are placed on test under various temperature conditions, depth of discharge, charge rate, discharge rate, and percent recharge. All of this was worked out in a factoral type design so that we can cross reference and cross evaluate the effects of the various variables that we have in there. The complete test design is elaborated on in the NASA X report which was put out a couple of years ago.

The testing consists of the manufacturer's data which has been compiled at Crane, a baseline test which gives us the preliminary information on which to begin to base some of our results, and the accelerated test itself where the cells are put on at a matrix rate and run. Once they have completed testing we run through a post cycling test. That is followed up by a chemical analysis and physical analysis. Since we don't really have the time to go through all of the various combinations of testing, I have picked out one area that I would like to look at today to give you an indication of some of the analysis that we have been able to start looking at.

(Slide 120)

MAINS: The area that I have picked out is the physical variables to see how they effect life. On the graph here we have plotted the average end of discharge voltage, showing, then, the high and low cells in the group, also the average pressure at the end of discharge, again showing the high and low values.

The number here indicates a cell failure has occurred. Some of these have not completed tests. Others have, so it will be a little bit hard to compare them on total life, but one thing that has been showing up is that the voltage in general is fairly consistent. Another thing that is fairly consistent too is as a cell begins to show rapid voltage decrease its pressure will begin to show a rapid increase.

HELLFRITZSCH: What temperature is that?

MAINS: These are all run at 40 degrees centigrade.

HELLFRITZSCH: Depth of discharge?

MAINS: Well, let me go through all of these. They are running at the same electrical conditions. They are 40 degrees centigrade, 60 percent depth of discharge, a 2 C discharge rate, a one C charge rate and 140 percent recharge.

DUNLOP: The pressure is taken at the end of charge?

MAINS: No, the pressure measurement is at the end of discharge.

DUNLOP: Is that the highest pressure or the lowest?

MAINS: Well, the solid line is the average.

DUNLOP: I know, but over the cycle, does that represent the high pressure or the low pressure?

MAINS: No, this was not really taken into account. We just go for the highest. It is intended to be the same all of the way through. Now as far as the end of charge, it will be the highest pressure, but again, the high cell was high from the beginning of discharge all the way through the end of charge.

GOLDSMITH: 90 minute orbit?

MAINS: No. I will have to look. This is on a variable time, each one of them depending on the charge rate and that would give a different number. After I get through this I can get that number. I have it over here.

(Slide 121)

MAINS: This is the next rate. This is at the – well the first one was at the lowest concentration of KOH. This is at the highest concentration of 38 percent and again the voltage is fairly constant. The pressure on this one shows an overall increase and the life appears to be slightly shorter for the 22 percent than it does for the 38 and again we have a test running.

(Slide 122)

MAINS: This curve is the median or the mole test at 30 percent. I had hoped to try to overlay these but sinc the graphs are the same color it gets kind of confusing and again this will be true of all of them. This is the middle condition of all of the tests that are running and the pressure on this on remains fairly low throughout life. Again, as we have failure occurring the pressure begins to rise.

(Slide 123)

MAINS: The next condition that I compared here is the percent of recharge. This is the one with the lowest percentage and this one is with the highest percentage.

(Slide 124)

MAINS: After evaluating this they really didn't show any distinct variations up or down so in this sense at the moment we are saying that from indications the percent of recharge doesn't appear to have much of an effect.

GOLDSMITH: Percent of recharge?

MAINS: I am sorry, the precharge.

(Slide 125 & 126)

MAINS: The next group that was compared was the amount of electrolyte. This is the battery with the smallest amount at 17 percent and on this one the lowest amount seemed to show the highest pressure rise and again, this is the one with the highest amount, the 21 percent, and again, the voltages generally tended to follow along the same pressure, rising just prior to failures.

(Slide 127)

MAINS: This is just a graph showing some of the typical cycles of cells that have not failed, or the batteries that have not failed to date and in order to give you a little more detailed information, I have a complete list of the cells that are on test and the number of cycles. Rather than covering all of the graphs I have got here, they will be in the proceedings, but let me go through and explain what we have here. We have the cell position, one through eight. The first three cells contain pressure transducers and these are the ones that were plotted in the graphs. The last three cells were the early removals that were put in to the program by the Air Force in order to help us gain information on degradation rates. The cycle numbers, which they were removed, are indicated on each battery and then the types of failures. On some of these the pressure climbed very rapidly, got very high. In order to keep from destroying the cell they were removed on the cycles listed. Others were removed because of low cell voltage. They were just slowly degrading down to the point where we were getting to zero volts at the end of discharge. We had others that were removed. Some of them were removed because the cells shorted internally and others were removed because the pack had no other control to monitor pressure, that all of the transducer cells had to be removed and because of the performance we were seing, indications were we probably would run into pressure problems on the remaining cells.

(Slides 128, 129, 130, 131)

MAINS: Thank you.

PALANDATI: Mr. Mains?

MAINS: Yes?

PALANDATI: Jack Palandati, Goddard. I am just curious, with all of your failures, did you dissect any of the cells and actually analyze the components to possibly find what is the mechanism that seems to be the point that is causing all of the problems?

MAINS: As I mentioned in the talk there, the chemical analysis is being performed. It was just one of these things. We couldn't bring everything together at one time. I think, as we get complete data, in fact, this only shows three of the five points that we actually have on each of these. Each variable that was pointed out has five levels, so we don't have all of the evidence in yet. We are analyzing the cells as they are taken off the test, as they are failed, and again we hope maybe next year to be able to go through and put the story together a little bit more to try and back up. My feeling is that we are probably seeing some drying out on these cells. It is not real consistent yet and the chemical analysis will point more toward this.

SEIGER: Do you have the analysis of the gas?

MAINS: On the cells, yes, we have analyzed the gas prior to opening them up.

SEIGER: What is the gas?

MAINS: In general we have been seeing hydrogen, but there is some hydrogen in there but most of it is oxygen that we are getting.

CHIN: Most of it is what?

MAINS: Most of it is oxygen.

WEBSTER: Okay, thank you very much.

Our next speaker in the testing section will be Dr. Pickett of Wright-Patterson Air Force Base and he will be discussing the subject of testing 50 ampere-hour Heliotech cells.

PICKETT: Actually, I don't have much test data or hardly any test data to discuss but we do have tests planned for these cells over at Crane so briefly what I will present to you today will be the tests that we have planned and maybe give you a little background on the cells that were built at Heliotech under contract with us. These cells have electrochemically impregnated plates where the processes were developed at our lab, the Air Propulsion Lab at Wright-Patterson and these are some of the few cells that you will see any test data on with electrochemically impregnated plates. I know there was quite a bit of discussion yesterday about the effect of electrochemically impregnated positive plates and the need for such. I hope we can have some data for you in a very short while.

But I will start off by showing a picture of the cell. It is a little shorter than the 50 ampere-hour cell that most of you are accustomed to seeing.

(Slide 132)

PICKETT: The capacity of this cell is actually 50 ampere-hours as measured by Heliotech prior to their shipment of the cells to the Aeropropulsion Laboratory. The internal dimensions are 1.28 inches in thickness, 4.925 inches in width, and 4.37 inches in height. Those were internal dimensions and we have two different designs. We have one design using polypropylene or actually we have three designs using polypropylene separator but the cell dimensions are all the same for the polypropylene type cells. The nylon cells are a little thinner case material. The polypropylene cells have 24 mils. thickness in the case material and the nylon cells have 20 mils. thickness in the case material. 304 stainless steel is the material used for the cell case.

(Slide 133)

PICKETT: The capacity distributing in the cells is shown on the next Vugraph and it should be about the same as seen in most cells that you buy from the various manufacturers today. There is not, I don't think, much difference in the capacity distribution or the relative capacity distribution. There is 11 ampere-hours of precharge and 55 ampere-hours of working capacity and 16.5 ampere-hours of cadmium hydroxide and the non-utilizable capacity is estimated to be about 21 ampere-hours for the negative plate, and then there is about 10 percent of the capacity and maybe more of the nickel hydroxide which we are not able to use.

(Slide 134)

PICKETT: These are the electrode designs for the three different designs of cells we had made under the program. We have 35 cells in all, 20 cells which have polypropylene separator. We have four cells with design No. 6, eight cells with design No. 11 and eight cells with design No. 15. In design No. 6, if you can't read that, that is 36 mils. thickness on each plate, 82 percent porosity in the positive plate, 90 percent porosity in the negative plate, 32 percent, well 84 percent porosity for design No. 11, 90 percent in the negative and 84 percent for the positive and in design No. 15, 90 percent porosity in the negative.

(Slide 135)

PICKETT: Okay. For the polypropylene cells which we call the phase one cells, these are some of the design parameters and I will just briefly show you these and with respect to Floyd's comment they do have more than three cc's electrolyte per ampere-hour. The capacity as measured is 50 ampere-hours approximately.

(Slide 136)

PICKETT: The other two designs I will just flash up briefly to try to conserve the time. You can get all of this information from the minutes if you desire. It is 50 ampere-hours capacity and enough electrolyte.

(Slide 137)

PICKETT: Okay, these are the nylon cells and they are a little bit lighter in weight. They have thinner cell case material.

Okay. These have been sent over to Crane and undergone their acceptance testing. The results of acceptance testing were roughly that the cells were a little lower in capacity than measured at Heliotech. We are looking at possible burn in cycling of the cells maybe to recover some of the capacity. Then after that we plan to proceed to an accelerated synchronous orbit life test which was kindly provided to us by TRW, Dick Sparks in particular and I believe this test was planned for the fleet SATCOM battery and this will be the test that will be used over there. We plan to discharge the cells to about 60 percent depth of discharge initially and see how they perform and if the performance is good we may go to deeper depth and this is essentially the test that we have planned.

(Slide 138)

PICKETT: I will conclude with those remarks since time is growing short.

WEBSTER: Thank you. Any questions?

DUNLOP: Dave, what is the percent of active material in the positive plate, by the way, do you know, or the loading, some way to find out what the loading is?

PICKETT: Okay, the loading is somewhere around 1.9 to 2 grams per cc of void.

SCOTT: Scott, TRW. You showed a graph of the utilization of the positive and the negative. Was that in the starved condition or flooded or what that you got those figures, particularly for the positive where you showed certain percentage unutilizable?

PICKETT: Well, the total capacity is from the flooded condition. We think we can use about 90 to 85 percent of the flooded capacity.

SCOTT: The bar graph that you showed, then, was estimated for a flooded cell?

PICKETT: Right.

SCOTT: Excuse me, I mean for a starved cell under sealed conditions?

PICKETT: Well, I believe the capacity was measured and you can correct me if I am wrong on this, Harvey, the negative capacity was measured under flooded conditions and that is what this is based on.

GOLDSMITH: Goldsmith, TRW. What are the Air Force plans concerning this technology?

PICKETT: Okay, I mentioned something about that yesterday briefly and we do have a manufacturing technology program plan. Since this is a procurement I am not going to divulge very much of that except what was mentioned in the Commerce Business Daily and that is that we plan to make – use this electrode for nickel hydrogen and I think probably in some of the presentations tomorrow you will see its advantage in nickel hydrogen. I know you folks have been testing it in nickel hydrogen and we think it will probably be the best electrode and maybe the only electrodes in nickel hydrogen cells we use, is this type of electrode. I am not saying that exclusively our method of impregnation is the only one that can be used, but I think either one, the Bell method or something similar or something similar to what we have been using here will be used in nickel hydrogen.

Okay, with respect to the satellite cells, we also plan to make these under the manufacturing technology program. Probably one of the designs you have seen here will be made.

GOLDSMITH: Do you foresee, then, that there may be, as the result of some procurement exercise, that there may be some companies that will go into production?

PICKETT: Right.

GOLDSMITH: Is that the purpose of the –

PICKETT: Absolutely, and will also make some aircraft cells as well.

GOLDSMITH: Can you tell us anything about the schedules for this?

PICKETT: Well, I can't predict the procurement cycle, you know. Once it gets out of our shop and over to those fellows who knows when it will be, but the best estimate I can give you would probably be that it will be on the street sometime around March I would guess.

GOLDSMITH: Can you tell us anything about what your long range plan is with respect to being able to get these things into production?

PICKETT: Well, we hope that the successful bidder will go into production with the thing. We hope that the people that are bidding on the thing plan to use it in production and this really isn't being handled by the Aeropropulsion Lab as such. This is being handled by the Materials Lab and it is a manufacturing technology program so the gist of the thing is that we wouldn't even be considering it if it wasn't going to be something that would not be produced for the Air Force.

FORD: You implied yesterday, at least I understood you to imply that you also are considering them for aircraft batteries too.

PICKETT: Yes, I just told Paul that I was.

FORD: Okay.

WEBSTER: Okay, Dave, thank you very much.

Okay, our next speaker is Mr. Imamura of Martin-Marietta and he will be talking to us on the investigations of charge control parameters effecting cycle life of nickel-cadmium batteries.

IMAMURA: I would like to go ahead and start out with the first Vugraph.

(Slide 139)

IMAMURA: I will just show two and a third one is a proprietary one. Basically, I want to investigate single cell level, battery level charge control and the effects in extending battery life in the range of 13,000 to 20,000 cycles which really represents between three to six years depending on shallor orbit or a little bit longer and secondly, determine the extent of charge control flexibility required. The one that I took out is really our R & D work that we are doing with the microprocessor, so that is what we are trying to determine, the short limited funding program.

(Slide 140)

IMAMURA: Our approach is to basically – it is not really proprietary. I just cut out something that is not really pertinent. – perform simulated low earth orbit regimes using two packs consisting of 24 eight amp-hour cells each and make an assumption here that in the case of battery level control, no cell voltage monitoring or the cell bypass capability is assumed, although we had it, since we are running with the minicomputer, and secondly, on the cell level control pack, the cell voltage monitoring and cell bypass capability is assumed. By that what I mean is we had the hardware capability to do that in a real life vehicle.

Second, subject batteries to different overcharge levels at various temperatures to determine desirable charge control methods and I will go into that.

(Slide 141)

IMAMURA: The cells that we use are rated at eight amp-hour. G, supplier and the separator is polypropylene. Number of positive plates and negative plates, 11 and 12 respectively, and this is the cells that have been designed for the Viking lander and since the cells were available, we are using it in a low-earth orbit mode although the application here is really closer to the synchronous.

(Slide 142)

IMAMURA: Now, before I lead to the data, let me illustrate a couple of points in regard to the data that I am presenting here. One is the fact that capacity does seem to decay exponentially and it is a function of temperature. With increasing temperature, of course, you get a decreasing capacity measure and relative to changing conditions, after you start cycling, once you decrease the temperature the capacity will tend to go up and increasing temperature it seems to go back which seems to be almost like a reconditioning of the cell, of the battery and this one is, well briefly, 20 degrees, zero, and 10 degrees.

The only thing I wanted to mention about that is if you plot on semi-log paper, it is almost a straight line if you assume, if one is to assume exponential curves.

(Slide 143)

IMAMURA: These are the test conditions. I will briefly go through them. Orbit duration is 84 minutes cut down from a basically 90 to 95 minute type orbit, but it doesn't disturb the cycle regime at all, so it is essentially a real time test, 54 minute day, 30 minute dark, depth of discharge 25 percent, and the intent here was to more or less impose a bad condition on the cells so for the first 5,000 cycles we imposed a 40 degrees C. temperature on a battery and a 1.1 recharge fraction. Now as far as the control, you know, voltage limits as such, we opened the voltage limit so that we control by the recharge fraction so that we could try to bound the problem, isolate the effects of tapering and sulphur which really doesn't – it is a deeper subject but by controlling the recharge fraction we wanted to determine the effects of different levels of recharge and we have gone as high as 1.6, 160 percent of the C to D ratio or recharge fraction and then various recharge fractions are imposed and what I would like to show is just a couple of key points related to the 20 degree data at different recharge levels and we will repeat this data for testing at different temperatures to determine what the appropriate recharge fraction is.

(Slide 144)

IMAMURA: So I will be talking about just a couple of key parameters. We are monitoring watt-hour efficiency, amp-hour efficiency, along with the end of discharge voltage which the discharge shows.

Now, we show two curves. One is a cell level control and shows the cell voltage on this axis and for one, two, three, four, five decades, and this is the end of discharge voltage in each cycle and it shows that after 5,000 cycles we have reached almost a one volt level. I don't know whether you can see this. This is the one volt level, and here maintaining 40 degrees we changed the recharge fraction from 1.1 up to 1.3, I believe. Initially we started at 1.6, 160 percent, which is really sucked into the battery, and then reduce it to 1.3. It basically stayed there and the intent here was not to characterize the 40 degree temperature. We wanted to start earlier into different recharge levels but out of curiosity you might call it trial and error methods, some people may not like. We went ahead and changed the recharge fraction at that point and then went into different – went back down to zero degrees, 20 degrees, and repeated the test.

(Slide 145)

IMAMURA: Now this one shows the battery level control, in full and it basically shows the same relative effect as far as the gain in end of discharge voltage and when we changed the recharge fraction, obviously, or I guess it wasn't too obvious. It does go up.

(Slide 146)

IMAMURA: Now this charge is a late addition so I apologize if you can't see it too well, but I would like to just point out at 6,300 cycles in changing the recharge fraction we always wonder how long does it take to stabilize and when does it start going down, so this chart is trying to do that. This is 1.17, 1.18, 1.19 end of discharge voltage and on this axis we get one, two, three decades showing first cycle here, 1,000 and the intent here is to cycle it just a sufficient amount and I feel about 200 cycles is enough, but now we know that we should go up to about 500 cycles in order to characterize this linear decay pattern on a semi-log paper.

By that what I mean is when it stabilizes within about 50 to 60 cycles it starts to go down and sure enough, looking at end of discharge voltage it follows almost a straignt line if you take enough points there, and I just showed three poings there. It is basically a straight line. Nothing disturbs the conditions. That is important, which is temperatures, one of the key perturbators.

(Slide 147)

IMAMURA: This one – I am sorry. I forgot to mention one thing. The other one was 1.02 recharge fraction which tended to go down faster. This one is 1.1 of the same temperature and one could see that if you extrapolate the data from this point on that it does show that the life could be extended or the higher recharge fraction was better under this condition than 1.02.

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IMAMURA: This chart shows the recharge fraction of 1.06 at the same temperature and the slope was such that it was better in terms of the terminal point. If you extrapolate this all of the way down to one volt it would be much higher. I don't have the numbers to show you but that is just to illustrate that the slopes can be used as a quick criteria to use instead of running thousands of cycles and we feel that 500 cycles is enough.

Now, to verify this kind of thing, we are running over a long cycle under the same conditions, say about 1,500 cycles to see if it indeed follows a straight line.

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Now, in summary, I would like to point out that this assumes that you have the charge control flexibility, the level of control that is being used on OSO. Otherwise it really doesn't work and our feeling was that you do need charge control flexibility in the form of voltage limits in order to control the C to D ratio or a very active device like, say, a microprocessor that can be put in. We are working on that, or a combination such as the coulometer, anything that is for changing the condition of the charge, so we are looking from the standpoint of forcing the cells to operate in some fashion and I guess another point that I want to make on this is that "reconditioning effects," in quotes, could be achieved by adjusting the recharge fraction and I think this data tends to show that so you do need charge control flexibility to that extent, possibly in addition to the reconditioning. You do have other methods of trying to rejuvenate the cells. Thank you.

HARKNESS: Harkness, Crane. I noticed that at around 5,500 cycles at zero degrees C., I didn't notice any end of discharge graphs up there. Also, I noticed that most of your percent you started out with 117 percent recharge and then it went down. I also noticed that in the first test was 117 percent and you ran it an odd number of cycles. It only went like 80 cycles. All of the other ones ran 100, 150, 200, but was there any reason only [illegible] cycles for that?

IMAMURA: The reason is I wanted to run only 50 cycles to see the stable point just to try to show a straight line relationship. Okay? Now I don't think it was 80 cycles. It was about 150. In fact, in total in each case. I am not so sure whether I follow your question.

HARKNESS: How did the end of discharge voltages look compared to zero degrees?

IMAMURA: It was higher at the colder temperature. You know, polypropylene separators behave differently than the nylon separators and it doesn't seem to work too well at the colder temperature. Now it is a little bit higher than the Pellon 2505, but I didn't show the data. I do have the data.

GROSS: Gross, Boeing. Did you get a reconditioning effect by either increasing or reducing the recharge ratio or was it only when you increased the ratio?

IMAMURA: It seems to do both but the question is how long does it take to stabilize and what is the slope once it stabilizes? In trying to optimize what the recharge fraction is you have to pick a temperature and try to isolate these variables, of course. Otherwise you have random data, and if you take a look at the slope, 1.06 seems to have less slope in it. Therefore, it lasts longer. The cells last longer. Now the 1.02 was clearly a case of one recharging, at that temperature again. Now once you go into another temperature this relationship doesn't hold but the key here is it doesn't matter what type of cells you have. If you can run tests in that fashion you should be able to optimize what the control parameter is.

FORD: I didn't understand the significance of that nosecone shaped curve you have. You had end of discharge voltage versus cycles and you showed initially it increased and then it started tapering off. I don't understand that. What do you attribute that to? The increase, not the decrease?

IMAMURA: Why do you show that or why show it?

FORD: Yes, you know, typically you start cycling on a fixed set of conditions and the normal degradation curve is one that decreases with cycling. What is that first slope?

IMAMURA: This is a continuation of a series of tests and since we are using two battery packs now, starting at 60 – in fact the other one started at 6,300 but it is a 150 cycle increment. Once you change the condition from the last data point, end of discharge, what I am saying is that it has to increase and this is the stabilization time of cycles required.

Now, once it reaches a stable condition it tends to drop down exponentially which was reasonable under my assumption of the exponential decay now, so in each one of these changes, once you change the recharge fraction it does require some time for stabilization. I expanded the scale. Remember, this is the first cycle after changing that condition. This is 10. This is 100.

(Slide 150)

GOLDSMITH: What change did you make there on that curve?

IMAMURA: Just the recharge fraction, Paul, from 1.02 up to 1.1, so I was trying to isolate the one variable which is the recharge fraction now.

FORD: To get the recharge fraction you take, like, 300 cycles? Is that –

IMAMURA: Well, if you extrapolate this curve you take about 1,000 cycles.

FORD: I mean the positive slope, not the negative one.

IMAMURA: Oh, I am sorry.

FORD: You know, you are looking – you said you wanted to see the recharge of the stability so you suggested it takes 300 cycles before you settle out?

IMAMURA: Well, this is 1/1,000.

FORD: Okay, I am sorry.

IMAMURA: So this point is about 50 to 60 cycles and it seems to be repetitive.

FORD: That is almost a week.

IMAMURA: A week?

FORD: Yes, a week of testing.

IMAMURA: We get about 15 cycles a day now. I guess that is close enough for government purposes.

THIERFELDER: Thierfelder, GE. When you say you are only changing the C to D ratio you are actually changing the current too, aren't you? Aren't you keeping the same time?

IMAMURA: Well, I didn't mention about the current. It was a fixed constant, C/2 rate of charge.

THIERFELDER: But you are varying the time?

IMAMURA: Time, right. You could try to isolate all of this, once you change the current the other thing you can say, you have it part of this testing. Temperature-wise, I think it is very important since we are running it under a chamber. We had to make sure that the cells stabilized. You know, when we say 20, I wanted it to be 20 plus minus three degrees. Otherwise it really would be different characteristics, Okay?

WEBSTER: Thank you.

All right, our next speaker is Mr. David Jones of Radian Corporation and he will be addressing the subject of state of charge on vented nickel-cadmium batteries.

JONES: I am going to talk about the results of a feasibility study that we recently completed for the Aeropropulsion Lab at Wright Field. We were concerned with vented ni-cad batteries, these were 22 amp-hour cells. The Aeropropulsion Lab wants something practical that they could use as an on-board tester for state of charge for their aircraft and the test cell population they gave us kind of reflected that. The cells were from three manufacturers. Some of them were new. Some of them were used. A lot of them had actually been removed from various types of aircraft. They also gave us one lot of cells that was already kind of fading away into the sunset to see what we could do with them.

We developed the test based on single cell work and then we extended it to some four cell batteries just to see if it looked like it might be extrapolated upward to a multi-cell battery. The basic approach we used was to apply some very short duration high current pulses to the battery and look at its response. The short duration means one to 200 milliseconds. High current means one to 400 amps. We looked at both charging and discharge pulses. Under some cases we control voltage. Under some cases we control current, and I will show you a few of the results we have obtained.

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JONES: On the left we show the type of pulse that we ended up using. It is a constant voltage discharge pulse. The open circuit voltage was, of course, around 1.3. We discharged down to about 1.05 volts. What we monitored was the current response and that is shown on the right and it had a peak and then decayed to a fairly constant value with time.

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JONES: Our most successful test is listed here. We used a constant load discharge for three seconds across a .011 ohm resistor to kind of get the cell's attention, a quarter second delay open circuit and then a constant voltage discharge pulse to 1.05 volts. This lasted 120 milliseconds. This pulse, incidentally, the initial discharge conditioning pulse as we call it, because we don't collect any data during that constant load pulse, removes about 0.4 percent of the battery capacity or the cell capacity.

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JONES: Again, schematically, this shows the cell voltage as a function of time during our test, a three second constant load pulse, open circuit delay and then a constant voltage discharge pulse.

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JONES: Here is a schematic of the type of circuit we use. The current during the pulse flows through a loop formed of the test cell through ground. We have a power supply shown here for a discharge pulse, of course. We don't actually need that. We have an op. amp. that controls the current flow through a transistor such that the voltage of this cell is maintained at 1.05 during that constant voltage discharge pulse. We have a timing circuit up here that first closes a relay to discharge the battery through a constant load.

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JONES: And here are some results. These are single cells at 75 degrees F. You can see there is a good deal of scatter there, however. These represent a very broad history of cells. In addition, they are single cells. If you make up a battery out of a group of those cells there is some tendency to average out the cell to cell variations. You will notice we go up over 100 percent of full charge. The reason for that is that some of these cells would actually deliver a greater capacity than their stated 22 amp-hours. You can also see that the test response we get runs up close to 300 amps for some cells.

(Slide 156)

JONES: I have some results for a single cell here. There also is a little bit of scatter for a single cell. We repeated several points up in this area and I think this is in part due to our inability to make real accurate measurements of our test response at this time. With some circuit improvements I believe that can be improved.

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JONES: Here is an interesting set of results. The solid line here is the solid line you saw earlier. It represents average behavior of good cells. All of these other points represent some cells which were of questionable quality. What we did was discharge those cells and then we added an amount of charge that would have brought a good cell up to 100 percent, and then we tested these cells and this is the response we got. Even though these cells are in various grades of defective, they still fit our original curve pretty well.

(Slide 158)

HELLFRITZSCH: Is that the peak current?

JONES: I am sorry?

HELLFRITZSCH: Is that the peak current?

JONES: No, that is the current at 100 milliseconds.

HELLFRITZSCH: That is what I wondered.

JONES: We also did a little bit of test just to see what the effect of cycle life might be on this. We took some of the new cells we had and the two different points represent 100 percent of charge and 50 percent of charge we ran them through about 50 cycles and over that range there does not appear to be much difference in test response.

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JONES: We also did a little work to see what the effect of temperature was and it turns out there is a very significant effect. The three lines represent three different states of charge, 100 percent, 75 percent, and 50 percent, and then we have the test response versus temperature for each of those lines. You can see that at a given temperature there is a difference in test response depending on state of charge. For a given state of charge, however, there is an even bigger difference in test response for a large temperature change. What this means for a practical test is that we are going to have to know the temperature of the cell pretty accurately.

(Slide 160)

JONES: Next we extended this to some four cell batteries just to see what we got. What we really did was just change all our parameters so that each individual cell should see the same test environment as a single cell saw in our earlier test and this is what we came up with, three second discharge, but across .044 ohmes, a quarter of a second delay and then a constant voltage pulse discharge to 4.2 volts, again for 120 milliseconds.

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JONES: This is a plot of the test results we obtained. The scatter is decreased slightly by going to four cells and we believe this is because some of the cell to cell variations are being averaged out. This work all was done at 75 degrees fahrenheit. We did not extend this work to other temperatures.

The Aeropropulsion Lab also gave us a few sealed cells, 20 amp-hour cells and we tried this test on them and really had very little luck. The cell to cell scatter was so much that it really smeared out the variation with state of charge. We feel like this is because they are starved for electrolyte. The internal resistance of those cells varied over quite a large range. Thank you.

WEBSTER: Thank you. Any questions, comments?

GROSS: Gross, Boeing. What happens if you left off that initial discharge?

JONES: We got a larger scatter, not greatly larger but it improved it enough we felt like it was good to put it in.

KLEIN: Klein, Energy Research. On the defective cell test, I am not sure that your stated capacity –

JONES: Well, we discharged those cells and we put in enough charge that they would come up to 100 percent if they had been good.

KLEIN: Okay.

JONES: And then we tested them.

KLEIN: Right.

JONES: And using that test response we took the curve, you know, that we developed from good cells and predicted a state of charge for them.

KLEIN: Did you verify that by then discharging the cell and –

JONES: Yes.

KLEIN: – finding that you had 20 percent rather than 10?

JONES: Right. In all cases these points here represent actual measured state of charge.

NAGLE: Nagle, Lewis. Is this work published yet?

JONES: No, the final report was submitted about a month ago. Wright Field will be coming out with a published report soon. I don't know how long it will take them.

NAGLE: Thank you.

SEIGER: Is there any dependency on whether you approach given state of charge by discharging or charging and if so, does that initial pulse effect it?

JONES: We really didn't examine that much. We did a little at the 50 percent state of charge. We tried going up and we tried coming down and it didn't seem to affect it. This was a feasibility study and there are lots of things like that that we planned to look at but have just not done so yet.

SEIGER: Okay.

WEBSTER: Okay, thank you very much, Dave.

Our next speaker is Mr. Martin Sulkes of USAECOM and he will be discussing the subject of pulse charging.

SULKES: The work I will report on was actually done by Otto Wagner and Dottie Williams of our laboratory and unfortunately Mr. Wagner couldn't be here today. We will talk about the effect of pulse and direct current charging on the electrical performance of vented nickel-cadmium batteries. We have a little time for vented this afternoon, this morning.

We use a Gould rapid charge which was specially designed and constructed for us and this particular unit has a wide adjustability as far as frequency intervals, of on-off charge time and so forth. The particular batteries used was a vented nickel-cadmium battery which contained five BB 616 cells of 5-1/2 ampere-hour rating and these were made by Eagle Picher. Charging at the various test modes was carried out at rates between C/2 and 4C and the temperature range check was minus 40 fahrenheit to plus 125.

The particular input used was 100 percent of the theoretical capacity of the cadmium anodes which in this case was 12 ampere-hours. The theoretical capacity of the nickel cathodes on these cells was 7.3. All of our discharges were run at the C rate at room temperature ambient to one volt per cell. To determine the capacity of the cadmium anode a partially charged nickel hydroxide reference was used and discharge was carried in reverse until the half cell potential of the cadmium dropped to 0.2 volts.

The first graph, please?

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SULKES: Employing the Gould charger, it shows the four types of charging modes – no, it shows three. The fourth, of course, is DC. We used positive pulse which has no discharge. We call it a Romanov which does have a three amp. discharge for 11 milliseconds and what we call a McCulloch which had a 50 amp. for 0.2 milliseconds. In all cases the average charge rate was 10 amps.

In this case they were all 60 hertz pulsing.

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SULKES: In the next figure – that one came out lousy. Are there two of them there? It is marked on top. They are in order. Okay, this shows the capacity of the nickel and the cadmium as percent of theoretical capacity versus the charge temperature for the four different charge modes. We used an average 2C charge rate and the data does show that where you did imply some discharge pulse we did obtain approximately 10 to 15 percent higher capacity using the Romanov and the McCulloch type. This occurred in the range of minus 40 to about 100 degrees while above 100 to 125 it gets to be quite a bit less difference. Also, the positive pulsing does not show that great an increase over the straight DC.

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SULKES: The next figure shows the same data using a fixed temperature, in this case minus 20 fahrenheit and it compares the performance as a function of charge rate, and in this case we found we had our highest performance at about the 2C rate. At the very lowest rates, C/2, again, there was little difference appearing and the same general trend appeared with the Romanov and McCulloch showing approximately 15 percent battery performance.

The fact that the Romanov and McCulloch actually do have quite different wave shapes and yet we got basically the same type of improvement and the kind of conclusion that was drawn from this was that perhaps the energy which appears in the negative direction has an effect on this and it turned out that the amount of negative energy in both of these modes was about 2 to 2-1/2 milliwatt-seconds and if this energy is a critical factor then you could be able – it should be possible to change these amplitudes and times to kind of come up with a device which is simply built, does not have to have a very large current carrying capability.

Next slide, please.

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SULKES: In order to determine the importance of the energy of the negative pulse at various positive and negative pulse amplitudes and intervals we ran a test at minus 20 Fahrenheit extreme and a charging rate of 2C. Again the frequency was 60 hertz and this particular figure shows the relationship between the energy of the negative pulse and the capacity of the nickel and cadmium electrodes. The capacities at the zero energy level which is at the bottom represent the DC mode.

From the figure it appears that a maximum capacity for both electrodes is obtained at a minimum negative pulse energy of 2-1/2 milliwatt-seconds and when we put this into practical terms it results in about 10 to 15 percent of the energy being in the negative direction.

An important finding of this investigation was that nickel-cadmium cells which had lost capacity due to fade-out or crystal growth of the cadmium hydroxide could be restored to their original capacity by one positive pulse charge cycle. Next figure?

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SULKES: This particular figure shows the discharge curves of the cadmium nickel hydroxide of BB 616 cells that have been subjected to a fade-out regime and then reconditioned by a single positive pulse charge cycle and what we had done in this where we had an original capacity, the nickel, as you see, remained the same. We had 6.9 ampere-hours. The cadmium, on the other hand, was about 8.1 ampere-hours fresh and we subjected these cells to I guess you would have to call it an artificial fade out cycle which consisted of charging at 0.5 milliamps per square centimeter for 200 hours at 125 and then discharging at the same current density and temperature until we completely discharged the cadmium. When we subjected these cells to three normal DC cycles the nickel capacity remained at 6.9 while the cadmium anode had dropped from 8.1 to 6.5 ampere-hours. A total of 10 DC cycles was run and was unable to restore any of the cadmium capacity. A single positive pulse charge cycle run at the C/2 rate at 60 hertz, we have a pulse amplitude of 25 amps for an interval of 1.8 milliseconds and a total of 12 ampere-hour input and now in that subsequent discharge we had increased the cadmium capacity back up to 8 ampere-hours which was just about the same as the original.

Next figure, please?

(Slide 167)

SULKES: These are scanning electron micrographs of the – taken of the surface of the cadmium plates in the discharge state and we show the cadmium anodes before and after fade out and after the one positive pulse cycle. The magnification, I think we have a 10 micron marker in there somewhere. I don't see it. Okay. But in the upper lefthand corner we are probably around one to two microns. After the fade out we have gone up to about 50 to 100 microns. After the pulse we have brought the average particle size back down to around three to five microns, and there is no doubt that the performance change does correlate very well with the actual physical change observed in these plates. We ran normal DC after this pulse type of cycling and the batteries have remained normal after this.

After these rather good results we wanted to find out if prolonged pulse cycling would have any deleterious effect on a battery and in this particular case we used a five cell BB 406 battery and we ran it at a 60 percent depth of discharge with charge and discharge both at the C rates and we used what was basically the Romanov mode of charge and on every 50th cycle we gave deep discharge, three deep discharges to determine true capacity. Over 1,000 cycles we found no appreciable loss of capacity. However, in the next figure, we did find that there was a so-called "memory effect" as a result of the semi-shallow cycling and in order to recover the capacity a deep discharge was required to bring the cells down to zero volts.

SULKES: What this would tend to indicate is that pulse charging in itself will not eliminate memory. If the particular cause ascribed to it, in this case by Wagner, was the development of the alpha Nickelic state due to prolonged overcharge.

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SULKES: Well, we are basically finding some good results with the vented cells. We now decided to look at the sealed ones, then having the same equipment available and working basically with the same parameters we found we set up a five cell sealed D battery, that is the next figure.

(Slide 169)

SULKES: These are G four ampere-hour D cells. They are high rate design, Pellon separators. They were made as a very well matched group. In order to control charge conditions we have a pressure switch and also a thermal control, not knowing exactly what would happen, and we have looked at the range of charging rates between C/8 and 2C and over a temperature range of minus 20 fahrenheit to 125. All of the discharges were carried out at the C rate at two one volt per cell.

The next figure, please.

(Slide 170)

SULKES: This figure shows the input and output capacities for both constant current in DC at C/8 and the control on the charge in this case was by pressure and it was at 18 psi measured at the switch. In this case, basically, it turns out that there was no difference noted between either pulse or constant current.

The next figure?

(Slide 171)

SULKES: It shows the C/2 rate. Again, no difference between the pulse or constant current. Obviously, the capacity has improved quite a bit.

Next figure?

(Slide 172)

SULKES: This gives the performance at the 2C rate. In this case we find that we were unable to operate with the pressure control at the minus 20 because of hydrogen generation but in fact there is no difference for these particular cells between the pulse and the constant current. One point I would like to raise, that the voltage curves on charge were effectively the same so you didn't have a reliable method of controlling other than pressure.

We also looked at temperature control. I think the next figure will give you that one.

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SULKES: Okay. The particular control used in this case was a delta of 20 degrees fahrenheit measured from starting to final and in this particular case there was a center rise in temperature with the pulse. The straight lines represent, by the way, the output capacity there, and basically what we came up with from this is that for these particular cells at least, which happened to be very good ones, there was no improvement at all by using these particular pulse techniques which were found to confer some benefit in the vented cells and I think some of the patterns of greater capacity as a function of rate and so on are of course known, particularly at the higher temperatures. That will be all.

CORNELL: Cornell. Were both electrodes nickel?

SULKES: Yes.

CORNELL: Vented also?

SULKES: Yes.

FLEISCHMANN: Fleischmann, C & D. Do you think if you changed the frequency on the sealed cells you would see the effect of pulsing?

SULKES: I don't know if I made the point but we did look at the frequency on the vented and it runs from 30 to 2,000 hertz and over that range there was no difference. I think that same thing would tend to hold with the sealed – you know, you get into very high frequencies, there are certain strange mechanisms going on at very low – you are not doing the same thing any more, but over 30 to 2,000 there was no effect on the vented.

SCHULMAN: Joe Schulman, PSI. Did you try changing the ratio of your negative current, through negative or through positive pulse with an amplitude of those ratios to optimize it?

SULKES: Yes. If you notice, there was the Romanov and McCulloch they were rather striking differences. I think we had a three amp. discharge and I think it was a 50 – I have got it here – 50 amp. charge versus on an average of about a 12 amp. charge and a 50 amp. discharge and the particular point that was found was you might say the percentage of the total energy. In other words, that it was 10 to 15 percent rather than the particular amplitudes that were actually being used.

SCHULMAN: When you went up to higher frequency you just made the pulses proportionately narrower or you kept the same pulse widths?

SULKES: No, they would obviously have to slim down. Yes, Floyd?

FORD: Ford, Goddard. Do you have a control group that was constant current charged while you were pulse charging?

SULKES: You are talking about that cycle life thing?

FORD: Yes.

SULKES: No. In other words, we had basic data on what these batteries should do and the point that - we were looking at whether any data facts, you know, doing a lot of overcharge under these type of conditions and in fact we ran 1,000 cycles and we found no loss in capacity, which, you know, we typically rate our vented batteries under 60 percent depth of - at somewhere around 1,000 cycles, so we consider that had no bad effect. The point about memory is that it didn't do any different than DC as far as a loss of capacity after shallow cycling and the same way you brought it right back again, though. Yes, sir?

IMAMURA: Imamura, Martin-Marietta. When you went into a reverse or discharge, in the case of Romanov, what criteria do you use to test the bandwidth or how much discharge versus how much charge?

SULKES: It actually ended up being about 10 to 15 percent is what it worked out.

COHN: Cohn, NASA Headquarters. How do you explain the difference between the sealed and the unsealed cells, the difference in behavior?

SULKES: Well, you don't have to control a vented battery. You can gas. You can do anything you want. In a sealed one, of course, there are limits on what you can put in and perhaps having to work against those limits, in this case we use pressure, or temperature, we found we couldn't get any more out of it.

I think also a key consideration in all of this pulse work is the better the battery is or the closer to optimum performance, the less effect this type of treatment will have on it. It is most effective, for example, in silver zinc where you have a lot of layers of separator, a lot of diffusion barrier. That is where you see the greatest effect and the better the battery is the less you will have it.

Now also talking about diffusion, you remember in our vented batteries we do have at least one cellophane layer plus two woven nylons as separator whereas you only have the Pellon in the sealed, so there is a less of a diffusion barrier.

END OF MORNING SESSION

AFTERNOON SESSION

WEBSTER: Our first speaker is Jim Harkness of Crane and he will be talking about storage mode.

HARKNESS: What they first told me is that you are supposed to, when you give a talk, get nice eye contact and it looks like everybody is taking their afternoon nap right now, so it is just going to make the job a little bit more difficult. What we are going to talk about is I am going to try to update what was presented in the 1972 workshop by Floyd Ford of Goddard on the various storage mode testing being run for them by Crane. The type cell is an OAO 20 ampere-hour.

The various tests, when he presented it in '72 was that there was a trickle charge C/40. There was also a discharge and shorted condition and there was also what they called an integration test which is a random cycling type. Since this time the integration pack has been discontinued because it proved what we all know now, that the integration pack and the flight battery pack should not be one and the same, and the data that you have seen now will show this, what you already know.

Since that time we have also added one more test regime and that is a discharge OCV test. In other words, it is discharged under the OCV condition. Now, every six months, approximately two weeks is spent where the battery packs receive three capacity discharges, two zero degree overcharge tests and what we call an internal short test in which they are shorted for – shunted for 16 hours, shunts are removed and allowed to recover for 24 hours and you measure the voltage.

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HARKNESS: All of the capacity tests and discharges are done at the C/2 rate. Pack 215-B up at the top is the discharge OCV pack. It has only 12 months of testing on it since it was started later. Also remember that it is not of the same lot of cells that were initially used to set up the other tests. These are just the various capacities that were taken out following the six month's test. you can see the first discharge and then the second discharge. The second discharge actually follows the taper charge. Now this is down to 18 months and what was presented in '72 was the 18th month check.

(Slide 175)

HARKNESS: The other part of this, as you can see, the C/40 has fairly stabilized. The shorted condition pack has decreased somewhat. Now if you look, let us see if I can find it here, there. This is an increase. Now the reason being that after 42 months the third cell which was the limiting cell here, was removed for analysis. It probably shouldn't have been, but we picked the wrong one and I think it was a mistake at this time, but this is why you have got an increase here.

(Slide 176)

HARKNESS: This is the trickle charge pack. You can see the first capacity discharge after 18 months compared to the one after 48 months and then also the last one that it received on the two week testing regime. The curves here indicate that the third capacity check after 48 months was approximately one ampere-hour more than the first one but again if you look at the plateau on that the amount of watt-hours on the curve are approximately the same with the different plateaus here.

(Slides 177 & 178)

HARKNESS: Next is the open circuit voltage recovery. The 215-A is the random cycling. You can see it kind of went to pieces down in here. The C/40 trickle charge also has decreased. That was 24 months. This is the update to 48. As you can see, the random cycling or the integration pack is gone. The shorted pack seems to be maintaining much better than the C/40.

(Slide 179)

HARKNESS: Now the results of the zero degree overcharge test, this is the first 18 months. Your C/40 on the first 18 months looks the best as far as voltages. Your shorted pack has increased on the first one over to coming back to kind of normal on the second one.

(Slide 180)

HARKNESS: As you can see, the C/40 trickle charge now is going up to where it has to be discontinued after one hour and 28 minutes during this test. Now this test essentially is – we have put them in zero degrees for stabilization at C/40 for a minimum of four hours. We discharge at six amps. for five minutes and then it is a C/20 for five hours. As you can see the pressure limit got up too high on the C/40. The integration pack was way out all of the way. You can see why it was discontinued.

(Slide 181)

HARKNESS: Overcharge voltage results, the plateaus, as you can see, what we are showing is prior to when the test ever started and then after 18 months and then now after 48 months. As you can see, on the discharge and shorted, your peak has increased slightly and your plateau has increased, whereas at 18 months it was essentially very close to the plateau to the storage.

(Slide 182)

HARKNESS: This is your trickle charge. As you can see, the peak has climbed and now your plateau level has increased.

(Slide 183)

HARKNESS: Your integration pack, kind of looks bad.

(Slide 184)

HARKNESS: This is your discharge OCV test. The integration is labeled wrong and like I say, it has only had 12 months to date. Your pack 215-B is the discharge OCV pack. it is not the integration pack. It is labeled wrong. It was labeled right, I think, on the first one, but 215-A is the only integration pack. 215-B is the discharge OCV.

That is it. I think it was nice and quick.

WEBSTER: Thank you. Any questions? Dr. Scott?

SCOTT: Scott, TRW. You are tearing those cells down?

HARKNESS: Yes.

SCOTT: Quickly, what do you see?

HARKNESS: We see a tear down analysis. I don't have the results of that.

FORD: But it is available if you want to call on that?

HARKNESS: Yes, it is available.

WEBSTER: Any further questions?

SULLIVAN: I am not sure I followed everything you described, but do you have an opinion at this time for storage or would you like to see them store it open circuit or trickle charge or what?

HARKNESS: Initially starting out it looked like the trickle charge was the one to use after the first 18 months when Floyd presented it. Now, it does look like they are getting worse in the discharge shorted tests. Floyd, do you have a comment on that?

FORD: Two comments, two points I think should be realized, that after 48 months all of the packs, irrespective of their storage modes, had over four months of testing on them, so I think in the discharge shorted you begin to see the effects of the cumulative six months interval of testing, okay, so that added up to a total of four months, even with the discharge shorted.

On the trickle charge last year I presented a Vugraph comparing the amounts after 18 months, the amount of electrolyte in grams per cc that we found in the separator on the three types and the only thing we could see was at an 18 months interval it looked bad and this was internal, not external, a physical measurement, was that the amount of electrolyte found in the separator of the trickle charge was less than 50 percent of the electrolyte that was in the discharge shorted. The amount of electrolyte that was in the separator for the random or the integration mode was like about 80 to 90 percent of the discharge shorted, so I think what the suggestion is that the trickle charge mode while over the short haul doesn't seem to have too much effect, over the long haul it becomes of concern too and I think you are getting with trickle charging an expansion of the plates which we will have physical dimensions on, and I think you are seeing the effects of this now after four years, but you look at it in a real sense what it means to us and the initial purpose of the test was to try to find what the best mode was or what the optimum mode was for battery build up and getting them to the spacecraft and my conclusion is still discharge and shorted.

HARKNESS: Of course this brings out another interesting question that we do this every six months. Now if we would run the initial test and it didn't do anything for four years how would the batteries have looked? I cannot answer this. This was not the way our test was based.

SPEAKER: How about the storage temperatures?

HARKNESS: Storage temperatures are all room temperature, 23 to 25 degrees C. The overcharge test is the only one that goes down to zero degrees. Yes?

KUYKENDALL: Kuykendall. In addition to the previous problems I have talked about in using the batteries more than they were ever tested for, we are talking about storing spacecraft in orbit with the batteries. Does any of this data lead to recommendations about the best way to handle the batteries in orbit between eclipse periods where they are not going to be used at all for 4-1/2 months, that they could be trickle charged, charged off, discharged and charged off? What would be the best?

HARKNESS: Doesn't that go right in line with your question, Ralph, on which was the best mode? I thought we said that discharge was.

FORD: Okay, what we have ssen from this storage test, in orbit storage, because that is what you are talking about –

KUYKENDALL: Right.

FORD: The other one was ground storage, but in orbit storage, it looks like the best options we have available to us short of individual let down, strap out, you know, is a low rate trickle charge. Now a low rate trickle charge may mean C/60, C/70, in that range. Quite frankly, I don't know that we know what the lowest rate you go to as a function of temperature. The data today suggests that the low rate trickle charge, all that is needed is to maintain polarization on the cell voltages to offset self discharge, so I think if possible that you would go much lower than C/60 but that looks like to met to be one of the better modes for in-orbit storage.

WEBSTER: Last question.

SCOTT: Scott, TRW. I am sorry, I can't agree that that is the only option available to us in orbit. You have more than one battery, I think we have data which now shows that you can let the battery down if you just look for essentially zero volts, shorted out, and that alternated with possibly trickle charbe may be a better way to go for long missions.

HARKNESS: Floyd? Didn't you say outside let down, discharge, trickle charge?

FORD: Well, when I said let down discharge, I am assuming you have the ability to do it, to strap out each cell.

HARKNESS: Yes.

FORD: I think you are suggesting that you can do it at a battery level and not strap out each cell.

HARKNESS: That is right.

WEBSTER: Okay. I want to thank you very much.

Okay, our next speaker is Dr. Scott of TRW and he will be speaking on Cells Shorted for Years.

SCOTT: First of all, I am going to try to confine my formal presentation to storage on the ground. Maybe later on we can get back to talking about what that means in terms of storage in orbit.

Secondly, it begins to look now like if you know that you are going to have to store cells for a long time on the ground I think it is probably going to turn out that the best way to do it is to store them dry, not wet. We only have a very limited amount of data on that point for storage only up to about a period of about up to a year and testing only through acceptance testing, a very limited look, but we see no apparent difference between cells stored dry and cells stored shorted under controlled conditions, at this point in time.

Now, having said that, I am going to now talk about some results that we have obtained from looking at cells stored shorted wet up to about four years, which happens to be the same number as the maximum storage time of the cells you saw. The circumstances are that in this case the impetus behind this work was that a particular spacecraft program originally started out with launches very close together and so we built up a large number of batteries to support these launches and then the program became stretched out farther and farther and farther and now it appears that there may be no end to the launch schedule and we have all of these batteries sitting around and we are wondering what to do with them, whether to throw them away, or to use them or what, and the program –

SPEAKER: Buy new ones.

SCOTT: Could I quote you the estimated cost to the program of one of these batteries, namely, $35,000, so it was worth just a little bit of time to investigate whether we really needed to buy new batteries or not, so with that, –

We launched on a program which is still underway to investigate the condition of the cells in some of these batteries, mainly by looking at cells which have been stored shorted for comparable periods of time. We have done a little bit of electrical testing on some sample batteries that have been stored for a considerable period of time, and some of the testing on additional sample cells from these same lots stored shorted up to periods of the order of four years.

Now last year, some of you may recall, I presented a first peek at some data that we had obtained from opening up cells that had been stored for three and four years. The data I am going to present today includes those same cells and adds some additional cells to the data package, so we did some electrical testing of batteries and cells. That electrical testing was about the same as the original acceptance testing of those cells in the batteries. It was done when we first received the cells involved, so we retested under similar conditions and compared the results with how they behaved when they were new. This is a summary of the electrical testing that was done.

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SCOTT: You see here three flight batteries taken right off of a spacecraft in which the batteries were stored with the cells shorted on the spacecraft. Here are four cells that were isolated from each of those same three batteries and put through some additional cycles under controlled constant current conditions. This cycling was done under the system buss operating conditions which does not allow constant current charging, so we got a little additional data on cell performance here and then in addition we took six cells that had been stored as cells in a shorted condition and did conditioning cycle, three 24 hour cycles and then a low temperature overcharge test.

Without belaboring this, the results of all of this indicated that these stored cells did not behave significantly different than they did when the cells were purchased and most of the cells that were in this particular test group had been bought a total of four years since activation and they had been in storage for 2 to 2-1/2 years, so that was one aspect of the test program.

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SCOTT: The other was a cell tear down analysis and the scope of that work to date is summarized here. We are showing six different test groups, with total numbers of cells analyzed in each group and the number of different cell lots that were sampled under each line item. I am not going to read this but you can look at the – you can just get an idea of what the total scope of the thing was. The conditions, now, that we have covered, run all of the way from brand new plates before putting in the cells through the cells as received without any testing in house all of the way through to, as you see here, cells stored as long as five years after receipt and acceptance testing.

(Slides 187 & 188)

SCOTT: Now, I am going to show you only a part of the data because I didn't bring all of it with me and don't have time to present it anyhow, but I think one of the most interesting aspects relate to the question that came up yesterday and that is electrolyte distribution and positive plate thickness. This is a tabulation which compresses a lot of data in a small space. You don't have to really read this if you don't want to because I am going to show you sort of a graph of this data which I tried to indicate pictorially what is going on, but you can read it in the minutes here.

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SCOTT: Here is an attempt to pictorialize that data. It is also rather busy, but I want to make one point which seems to be coming out of this data which has not been clear at least to me before this time. That point is that of the total change in electrolyte quantities in the separator and in the plates, that we observe from the time that we receive the cell to the time when these various points in the history of the cell, of that total change, a very large percentage of that change has occurred right after acceptance testing before we do any storage whatsoever.

Apparently, what is happening is that the test conditions which include, by the way, in all cases here, a 30 cycle continuous charging test that goes along with, as part of our general test acceptance procedure, so you see, here is the changes in these various, the total weight loss extractable from the separator, positive plates, and negative plates, and the ALK, which stands for total alkalinity which is the sum of KOH and potassium carbonate concentration in weight percentage and, well. I guess in this case it is plotted in terms of mil. equivalents per square decimeter, and it shows that the separator starts to go down during acceptance testing and continues on down a little bit further during shortage, during shorted storage, but the larger changes that occur during this period of time occur in the plates and then they seem to – well, it is not obvious whether they really are changing further during storage or not, because the variability in these numbers is quite large and it could be that all we are seeing is the result of the variability from lot to lot because these are from cell to cell actually, because of course, we did not have precise controls over these data and these data here are obtained from entirely different lots in this case because we only started this whole testing program a year ago and of course we are talking about analyzing three and four year old cells now.

I think the point still is that it looks like the largest chunk of the total changes induced by the say we treat and store cells, we are introducing during acceptance testing and probably very little additional changes are going on during shorted storage.

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SCOTT: Those changes correlate rather well with changes in positive plate thickness. Here the change prior to the end of acceptance testing is even more dramatic relative to the change which appears to be occurring during various storage modes. So you can see this is the thickness, initial thickness in millimeters of the plates as they are put into the cell before they ever see any electrolyte. These are the cells as they come in the door and this is the range. This is the average of two different lots after we complete acceptance tests and then on downstream.

SCOTT: The other parameter that we tried to characterize and is much more difficult to do so in any quantitative fashion is the degree of cadmium migration in these cells, and I really haven't figured out a good way to describe the variety of cadmium migration phenomena that we see in these various cells. Even the cells as they come in the door are not entirely free from surface deposits of cadmium on these negative plates, but the occurrence and the intensity is relatively low in most cells.

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SCOTT: Then after acceptance testing I can only show you a few scanning electron microscope photographs of what is typical that we see typically after acceptance testing. This is the negative plate surface, a typical area on a negative plate after acceptance testing. This is magnification 100 times. This is – excuse me, 300 times, and this is 1,000.

Notice the widely scattered cadmium crystals, but you can also see down beneath there the original surface appearance of the cadmium plate before any of the larger crystals appear on the surface. You can see that even better here. This is the original grid structure down there. Starting with that, actually, when you get to – all I can say is that we have looked at a similar – take a similar look after up to four years of storage and generally speaking we don't see a great change of storage and generally speaking we don't see a great change in the degree and type of surface deposits after storage, so far we conclude that what happens during acceptance tests maybe must happen. I am not sure, and I am not sure how typical it is of great variety of cells yet. Then from there on the growth of cadmium deposits of this type in the cell is relatively small if there is any at all. As I say, our controls are not adequate to statistically separate the small changes.

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SCOTT: This is another form of cadmium migration which is the type that grabs the separator. Now, I have heard a number of statements about cadmium migration which I interpret as equating cadmium migration with sticking of the separator. In my view these can be completely independent. There can be a horrendous deposit of cadmium crystals on the surface of a plate and no sticking of the surface of the separator whatsoever.

On the other hand, there can be relatively little total cadmium on the surface and the separator can be stuck. In most cases there is both, but in my view I think we have to be a little more particular as to how we refer to and describe cadmium migration if we want to look at the question a little more carefully, but this is a form which you see if you have initially sticking of the separator and pull it loose and this is what is left behind. You see the imprint of the separator fibers? This is now a 100 X magnification and this is 300 and you see here the channels. You don't see any of the original surface visible at all. It is completely covered by a surface growth of cadmium deposits. The interesting thing about this is that in a few spots in some cells you can see this level of deposit and this type of sticking even after acceptance testing before the cell has been cycled to any greater degree or the cell has been used any further. The area of coverage is small but it does occur in some cells.

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SCOTT: Okay, I want to make one final point before I get cut off here. We did do electrochemical flooded capacity testing of the negative plates. Wait a minute. What is this? I grabbed the wrong one. I guess I don't have that one with me. This is another set of data showing separately the potassium hydroxide and the potassium carbonate concentrations.

Okay, I am not going to discuss this further. This goes along with the other set of electrolyte analysis data but I will just say that we did remove -- after we removed the negative plates from some of these cells and during tear down we did flooded capacity tests and we were particularly interested in seeing what kind of capacity we would get on certain plates from cells which had the heaviest deposit of cadmium on the surface and the greatest degree of sticking of the separator and in some of those cases we had to put the plate into the flooded condition with the original separator completely intact because we couldn't get it off and we charged and discharged the plate in that condition.

I can tell you that what we saw was about, on the average, about a 10 percent decrease in discharge capacity of those plates compared with those same plates when they were tested new prior to development of the surface condition or the storage, so there is about that degree of change in the flooded capacity, but apparently from the test data that I showed you originally, at least our acceptance test procedures do not show any impact of that condition of the negative plates on the electrical performance of these cells and so one wonders to what degree the negative electrode, the negative plates, have to become clobbered on the surface before they seriously impact the electrical performance of the cells. One can become very panicked by the obvious appearance of these cells, especially if you blow up the size of those crystals with a scanning electron microscope. You can scare any project manager if you want to, but the question is, what does that really mean and that I don't think I have a good answer for yet. I don't think we really know exactly what level of cadmium deposits on the surface are tolerable.

WEBSTER: Thank you.

FLEISCHMANN: Fleischmann, C & D. What was the separator material?

SCOTT: It was Pellon 2505 nylon in all cases here.

FLEISCHMANN: Do you expect that you are going to get degradation or do you think because it is shorted you are protected?

SCOTT: I am sorry.

FLEISCHMANN: At the shorted potential are you protected against the type of attack that –

SCOTT: If you are referring to the mechanism that was discussed yesterday –

FLEISCHMANN: Yes.

SCOTT: – you presumably have to have a charged nickel electrode in order to oxidize separator hydrolysis products and in the shorted condition you do not have charged nickel electrode, obviously, and so you presumably do not get that mechanism. You may still get hydrolysis because that is not effected by it, but to the – the question is, to what degree electrolysis can damage the separator during simply simple shorted storage. I don't have an answer to that right now.

WEBSTER: Last question.

PALANDATI: Palandati, Goddard. I am just curious, did you analyze any cadmium electrodes before the acceptance test to make the comparison?

SCOTT: Electrochemical?

PALANDATI: No, the x-ray? Microscope?

SCOTT: Oh yes. We have all kinds of photographs of new cadmium electrodes. I didn't bring any because I thought most of you had seen those but what they look like is what that one plate looked like I showed first. If you remove all of the cadmium crystals from the surface it is just sort of an amorphous sculptured surface which you can't see any well formed crystals whatsoever, but it doesn't stay that way very long. In fact, right after they go through flooded formation at the supplier if you take the washed and dried plates right at that point you could start seeing cadmium crystals beginning to form on the surface. That is pretty difficult.

WEBSTER: Okay, our last speaker of the testing section actually is a holdover from the flight experience section is Gerry Halpert and Gerry will be talking to us about ITOS and AE battery experiences. That sounds almost interesting.

HALPERT: Just speaking yesterday some of my words may have implied that I am quite idealistic about wanting a better control plaque and plate and that people have said to me, "Halpert, wait until you get up in the real world and find out what it is all about," so I would like to tell you a little bit about what the real world is, what happened in AE and ITOS and I might preface my comments by saying that in this last program, both on AE and ITOS there were four lots of cells for each. On AE there were four lots of cells and each one was treated in a different way and after the first lot of cells which went through perfectly all tests, went through cell manufacturer's tests and prime, RCA tests, and were launched without any difficulties. The second lot and the third lot and the fourth lot all came out different and required significant amounts of testing into which we ran into some problems and did re-testing and so on.

A similar thing occurred on ITOS except that ITOS was all one lot of cells. There were three different shipments or four different shipments I should say, and the first shipment again went through beautifully, no problems at all and went right through the test program to the end and RCA tested them and there appeared to be no problems. The second group of cells in this case, same plate lot and so on as the first, went through some difficulties and had to be re-tested again and re-worked at the RCA facility and so on and the same thing for the third shipment, and so some of the things that I have found in my evaluation of the program point out some of the areas we have had some difficulty in. And I am not saying that any one of these things could have caused us some difficulties but I just wanted to point out that these are the kind of things that can happen. We first discovered in one of the lots, in a couple of lots, an interruption in impregnation. There was a month delay between the fifth step and sixth step and seventh step if those are the right numbers. I can't remember exactly. That to me indicates that there is some problem. There is no reason for that stuff to be standing around. The manufacturer doesn't want it standing around and certainly that causes us some concern which causes me some concern and it did, and in the handling of plates I shoud say that is an inconsistency in handling of plates because it turns out that there were different storage times, different handling techniques. There were some that were stored in nitrogen immediately after and other plates were put through other kinds of steps but all lots of cells were treated in a different manner over a different time period but we don't know what the problem is exactly but we know that the handling in a different way caused us some – may cause us some difficulties.

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HALPERT: Also we found as we went from one lot of cells to another lot of cells that the electrolyte concentration was changed. We were not aware of this and it again gave us some difficulties.

Finally, the fourth, fifth, and sixth were tied together in the cell assembly area. The actual test sequence was changed. The electrolyte was adjusted more than one time, as many as three and four times or a combination of that and precharge was adjusted three and four times. It is one thing to be idealistic and want the ideal plaque and plate materials, but it is another to have to deal with the problem in which everything is being changed around you as you go along and so when I, in visiting with the manufacturers and asking them what sounds like absurd points, to write down that you are going to – write down a piece of data. I mean show me on your document that you are going to write down what this piece of data. It may be absolutely absurd but we have no choice but to say, "Here is the way we are going to have to do it because we haven't done it before," and this is an example.

Now, the point that I make under I, there, the lot difference as an effect of electrical parameters, we had different batteries for all of the ITOS and AE missions, that is they had different electrical characteristics on ITOS – sorry, on AE. There were six different batteries for the last three, last two missions, three batteries each. Each had a different electrical test pattern, so obviously this causes some concern when we are talking about VT curves and charging.

Now, I would just like to mention a couple of other points regarding the testing and implementation of cells and use of VT curves. We found that during this testing where we found some of the difficulties it also appeared that the cells were overcharging at a significant rate at the zero degree temperature test. That is, they were running on the order of one amp. at zero degrees and continuous overcharge. This is a 16 hours, I think, at zero degrees, and they were running at, in one case, 750 mils. – six ampere-hour cell, running at one amp. continuously which indicated to us that there was a rather high voltage on it.

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HALPERT: We took a look at the curve and I am sorry this is not in real good shape. It doesn't seem to be anyway. We found that on the upper curve that was the ITOS and, incidentally I want the same kind of thing for AE. The curve up in the upper part was the curve that was being used and that was in the specification. Considerably higher than we have, or we now believe that it should be but somewhere along the line, maybe a few years ago, that was the right curve for six amp-hour curves. At least we have to assume that because we were using them back in those days and somebody was flying them and they seemed to be working, but now we have changed our electrical parameters. Our cells have been changed and now we have new electrical parameters so we have got to change the VT curves.

Well, this level five and level six one, as I say, I am sorry for the quality of these figures, but you can see that GSFC level five and level six, surround the new ITOS and also a similar AE voltage/temperature curve which appeared to be giving us now the kind of C to D ratio that we espouse and I will show here on the next slide.

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HALPERT: That is the range, at least, we are looking for in C to D ratio for this particular program which encompasses a 120 minute test. This is 80 some odd minutes, 84 minutes charge and the rest discharge, and what is more, and maybe as important, it has only got a C/4 maximum current allotted, but we found that when we do charge and we do hit this C to D ratios that we have a reasonable end of charge current and it appears that this is the kind of level that we want. As a matter of fact, we are generally as far as our other battery programs are established in this kind of range.

One other thing I might point out is there was some concern with regard to whether we could get in this C to D ratio range for the particular mission, in this case ITOS and we ran some tests at 18.8 percent depth of discharge and both the little X in the middle has 18 percent for battery 301 and 302 and the little O there for battery 303 and 304 and after we had done these tests at RCA we decided that actually 18.8 percent wasn't good enough. We really wanted to go to 21.7. but the concern was that we were going to go to 21.7 and this is the important thing, at 21.7 a year and a half after launch, not until then and so the question was do you design for 21.7 now or do you design for it later on?

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HALPERT: I want to show you one other piece of information which will help make up our minds for us. This is some data that was run at Crane and RCA. The bottom curve represents the RCA test and it indicates that as long as you have got a fresh battery and you do the C to D ratio tests at various percent depth of discharge, you are going to get one kind of a curve, but if you take some cells, the same cells, or I shouldn't say identical, cells from the same lot and take cells from the same lot and test them for a while and then try the same C to D ratio tests you find you have something different. This is totally consistent with these curves. I won't say identically on Floyd's curves from OAO which we have which indicate that the continued testing will change your C to D ratio so if you are going to design for a 27.7 percent depth of discharge 15 months into the mission you don't design for it today. You have to throw in a factor which says, "Hey, in 15 months I am going to have a different C to D ratio in order to plan for that." In the meantime we are up in the area of 125 to 130 percent because the rest of the profile for the 15 months is on the order of 10 to 12 percent depth of discharge so you see what kind of C to D ratios wer are going to be getting way up in here over the period so why design it higher?

That is really all I have to say about ITOS and AE today.

WEBSTER: Thank you, Gerry.

IMAMURA: Gerry, what criteria do you use to establish one C to D ratio point?

HALPERT: I did it as a compilation of the testing that we have done, several of the tests that we have done at Goddard in which we feel as though this now is a reasonable range for the present day cells. I can't give you one particular program but I can show you the numbers. That is certainly one clear-cut reason why this should be here.

IMAMURA: Yes, well what I was after was whether you used life test results or is it kind of a forced function?

HALPERT: No, it was life test results based on OAO's five years of operation and based on some other – in addition to OAO some other tests we have done through Goddard, so it is not just a matter of arbitrarily doing it.

BETZ: Fred Betz, NRL. I just wanted to mention that old high voltage curve that you had there I don't think was originally established to use as charge control. It is kind of "Don't buy like this because you are going to have hydrogen evolution problems," and the use of FT curves for voltage control has been a lot refined from the days when you wanted to protect the battery from going over voltage for hydrogen, so that is one thing, but the second thing, I think as you reduce depth of discharge with any given orbit your C to D ratio has to increase. Its depth of discharge approaches zero and the C to D ratio approaches it too.

HALPERT: Obviously there are parameters that effect this. I was really pointing out for this particular type of an orbit and one more point I might make is that on the NOAH mission we only have one VT curve that we can do. We have got an operational satellite and nobody wants to change from one level to the other.

WEBSTER: Thank you, Gerry. Well, ladies and gentlemen – there are no ladies today. We had 14 speakers in about five hours and it is with great pleasure I turn it over to Tom Hennigan for the nickel hydrogen.

HENNIGAN: Thank you, Bill.

Gentlemen, remind everybody to check that list, that computer list we had going around for their correct address or to add their address to it. Does anybody know where that thing is? Okay.

Okay, we do have eight speakers on nickel hydrogen this afternoon, both for synchronous orbit designs and near-earth orbits, so to get along here, our first speaker is Joe Stockel of Comsat who will talk on the flight cell development for nickel hydrogen.

STOCKEL: Gentlemen, this afternoon I would, rather than give a slide presentation here it is going to be more of a show and tell of our new nickel hydrogen cell. I will talk mostly on the cell and Fred will follow and they will give more of a – talk more about the battery.

A complete set of working drawings were made by Comsat and where every specification of every component was identified.

STOCKEL: This is our baseline designed cell that we have been working on at Comsat labs for the last few years. The cells were jointly fabricated in a cooperative effort between Eagle Picher and ourselves. Here, this is our pressure vessel that we use in the cell and the pressure vessel material is 718 inconel and as you can see we do use the compression seal on both ends. It is hydroformed from a 20 mil. cold rolled stock and this particular vessel was burst tested. This one blew at about 2,300 psi. This other one I have here is the same vessel with a slightly different weld ring in it and I managed to get this one up to about 2,450 and it still wouldn't go and this was about the limit to where I could go, so it still held. The seal held and everything with no leaks whatsoever.

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STOCKEL: If you could put on the first slide but don't dim the lights too much I will go into the – if you could turn the lights on in the back that would be better. What I really want is the lights on so you can see. I can talk from this a little better. This is the 35 ampere-hour cell. Actually it gives a capacity of about 38 ampere-hours. It is, as you can see, gold plated, and the internal components of the cell are, of course, the electrode stack which consists of the electrochemically impregnated positives that were made at Eagle Picher by the Bell Telephone Laboratory's process. It is a reconstituted asbestos separator and the Eagle Picher negative electrode.

The buss bar design is kind of a cone-type arrangement where the tabs on the electrodes do come through and are resistance welded on the outside. It does have a center rod which – and the stack is held in compression by these two plastic end plates. If this can move this way to allow for any slight movement of the pressure vessel when it pressure cycles and therefore it will not stress the plastic seal.

It is held, the stack is held in place by mounting that right to the weld ring and the way it is assembled, the cell, is you first build the stack, put it on, put the buss bars on and weld the feed throughs on and then the cell is then actually slide into the can very carefully and these plastic seals really have been working fine for us. We have actually had absolutely no trouble whatsoever with these seals and after you do that, then the seals are crimped and you then do your weld on the outside.

The cell has been vibrated to about I think we used the qualification levels of about 18-1/2 G's rms.

STOCKEL: The cell, as you see here, does weigh slightly over a kilo. It gives, with these lightly loaded positives, it gives an energy of about 44 or 45 watt-hours. The operating pressure of the cell, the upper operating pressure, is about 600 psig and when you take out the entire 38 or so ampere-hours it runs itself down to about 100 psi, so this pressure vessel we have here right now does have a safety factor based on the burst of four to one and as you can see on the one pressure vessel that, when it did burst it did burst the actual material itself and actually the 2,450 psig that the vessel was subjected to was getting pretty close to the publsihed data on the ultimate strength of the 718 inconel and I am not really sure you can do much better than that, and the pressure vessel, like I say, it does work and it can be made. Thank you.

GANDEL: Gandel, Lockheed. What is the gauge of that can? 20 mils.?

STOCKEL: 20 mils, isn't it?

GANDEL: Yes, hydroformed starting at 20 mils.

FORD: Jim Dunlop?

DUNLOP: What you mentioned, there were actually a number of these cells made for the flight program. But the capacity that you measured was –

STOCKEL: Oh, the capacity – there were actually 30 cells that were made for the program and of course out of that 30 there was a show and tell and a few other ones that were used for various other reasons, but the capacity was about, of the whole 25 of them that we did measure, was about 37-1/2 ampere-hours or minus one, which is pretty good spread.

SULLIVAN: Sullivan, APL. What depth do you typically operate this to?

STOCKEL: Well, Fred will talk more about that, but it is about 60.

DILLON: Dillon, GE. Have you ever, looking at the design of the stack of the plate, would you care to comment on the effect of a lift off environment of, say, 11 G's of constant acceleration in the axial direction? Would you expect that would have any effect upon the capacity?

STOCKEL: No. With this buss bar design the plates are held fairly rigidly.

DILLON: Have you ever tested to any quasi –

STOCKEL: Sustained acceleration?

DILLON: Quasi-sustained acceleration?

STOCKEL: We just vibrated to random vibration.

DILLON: That is different.

HENNIGAN: We will go to our next speaker, Fred Betz?

BETZ: I guess I will introduce this by saying that the Spacecraft Technology Center of the Naval Research Lab has entered into an agreement with

Comsat Corporation as a joint effort to get a flight demonstration on nickel hydrogen batteries. It is in the philosophy of exploiting commercial technology within the government. We have looked for it. Comsat is interested from their own point of view for their future satellites and the satellite that we had available is well suited to their needs.

(Slide 199)

BETZ: It is the Navigation Technology Satellite No. 2. It is part of the Global Positioning Satellite System. That is a joint services project. The first launch, NTS-2 is the Naval Research launch. Follow-on launches will be, I believe, from Rockwell at the present time. The spacecraft is gravity gradient stabilized. I will try to give you an overview of the whole program so you can get a feel for what we are doing. It is a gravity gradient stabilized system. We have reaction wheels to control it in pitch and yaw. The solar arrays are pointed towards the sun using the yaw axis of the spacecraft for the second control factor there.

Due to the operational considerations of the spacecraft as it goes around the earth, we have to do a 180 yaw and three faces of the octagonal surfaces never see the sun through the entire mission so we had a unique feature which we will get into a little later.

The orbital parameters, it is about 11.00 nautical miles altitude, 60 degree inclination and the orbital period is 12 hours. I believe it is 11.9 something. It is a very precise circular orbit.

(Slide 200)

BETZ: The eclipse season, in fact, we have got two of them there. The eclipse season you may not be able to see, but it does have two eclipse seasons per year varying 30 to 40 days in duration and since it is a 12 hour orbit you get two eclipses per day so we could accumulate something on the order of 60 to 80 nominal 35 eclipses per season, a maximum of .97 hours in mid eclipse and over the three year design life test about 420 total cycles, so within five years which we expect it to last, at least, that is about 700 cycles.

The depth of discharge for the nickel hydrogen battery within the system is 64 percent depth as a nominal test thing. That is at mid-eclipse.

(Slide 201)

BETZ: I want to show you the type of power system we are using because it does bear a little bit on the whole thing. It is a direct energy transfer system, a regulated buss of 27-1/2 volts, or 27 volts I guess it is nominal plus or minus about 3/4 of a volt. Our batteries have 14 nickel hydrogen cells and we do have a nickel-cad on board also with 18 cells. Both must be boosted to buss voltage level. If you look at the way the thing is set up here, normally in the sunlight we are out here in the shunt operating band. Both the nickel cadmium battery would be on a trickle charge and the nickel hydrogen would be trickle charging also.

For transition as you fall out of the sunlight you shut off the nickel-cad charger, shut off the nickel hydrogen charger, and transition to a boost on the nickel hydrogen for eclipse operation. Should there evolve any problems in the eclipse operation, well, you transition – we hit a low voltage on the battery and will transition directly into the nickel-cadmium battery.

The two batteries are nickel hydrogen. We have mentioned the prime battery, prime operational battery. That is Comsat designed. Eagle Picher manufactured it, 35 ampere-hour nominal. They were trimmed down for our particular application from the 50 ampere-hour basic concept. We are really not optimizing energy density. You carry along a little more structure as you get smaller and smaller. It is a 14 cell battery with two seven cell packs is the construction. We have got one pack up here. We didn't have time to get photographs processed but we had the hardware. I will apologize it is not finished. We are still in the middle of it but the battery department is here so the battery is here.

The nickel-cadmium stand-by battery consists of one pack. It is a General Electric fleet SATCOM 24 ampere-hour cell. They are nominal 24 ampere-hour 18 cell batteries, okay? Total stored energy, we actually don't have a 100 percent redundant system. It is about 90 odd percent. The nickel hydrogen stores are nominally 588 watt-hours by our calculations. We are a little more conservative perhaps than Jim and the 625 watt-hours actual based on 37 ampere-hours, we find that 38 will up that a little bit. The nickel-cad. has a 518 watt-hour nominal and we are estimating about 585 watt-hours actual.

(Slide 202)

BETZ: I mentioned before that the three bays of the satellite or three faces of the satellite never see the sun. This is a little busy. Most of these slides were produced for other purposes. We are not that strong on software. The three bays that don't face the sun, never see the sun, we got our batteries into those three bays for a constant temperature heat sink. This, again, along Stan's concept, this one we were able to get the batteries into the basic design of the satellite right at the beginning. We got them where we wanted them looking at constant temperature heat sinks. We have got thermal people involved right from the very beginning designing the thermal conductivity of the components in the battery, designing the surface finishes on the battery. We had them right in the beginning.

This shows the solar array's wrapped but actually in operation the two nickel hydrogen half batteries are these two sections out here and the nickel cadmium is in the center section. The discharge boost regulator for the nickel hydrogen is in the same bay. You can't see exactly where it is. It is somewhere in here. It is in the same bay as the nickel-cad. We are actually using that. It has been relocated a little bit. Not all the components are located exactly where they are shown except for the batteries. We are using that somewhat to heat the nickel-cad. during the eclipse period when it normally would be on open circuit.

The battery design concept, as I mentioned, was primarily a thermal control consideration. We did get them in right in the beginning. Our design limitations that we imposed were at zero to 25 degrees C. The battery pack with minimum gradients. I want to show you this one first here.

(Slide 203)

BETZ: The battery pack is – I guess you can see the battery pack. It is over here, but it is the concept of the direct radiant. The battery pack is mounted right to the spacecraft wall and the thermal control people have determined the proper conductivities down to maintain our battery pack within that temperature range. This concept was a Comsat concept for simplifying the battery for this particular mission. Again, it may be a little weightier than other concepts, but our attempt here was not initially to minimize the weight and try to get everything going. We want to have a good demonstration flight. We want a good thermal control.

(Slide 204)

BETZ: The battery baseplate is a quarter inch thick thoriated magnesium. It is selected for very high thermal conductivity, and reasonably light weight. The half shells wrapped around the battery cells, you can see a half shell here. You can actually see them a little better in the hardware. It is 1/20,000ths thick aluminum selected for machinability and availability and it is probably twice as heavy as what is needed, but the thermal guys really loved it and it does a pretty good job.

The interface between the cell and the sleeve is an RTV, a stabilized fiberglass cloth. The concept, I believe, was TRW's. Bob Patterson made a few words about that sometime, but it runs about a 20,000th thick and it seems to be an easy method of implementing a good interface between the cell itself and the halfshells.

I mentioned a couple of times that we are running kind of on the heavy side or at least heavier than previously advertised. I would like to give you some of the numbers. The total cell's weight for a 14 cell pack runs about 32-3/4 pounds. Incidentally, that is about 19 to 20 watt-hours per pound on the raw cell. The baseplate, 3.9 pounds of baseplate is there, 6.8 pounds of cell sleeves, about half a pound of top plate and somewhere around 2.4 pounds for accumulated nuts and bolts, connectors and wire, sleeves, things, RTV. It gives us a total estimated pack weight at this time of two 14 cell units or two seven cell units of about 46.3 pounds and a total energy density of about 13-1/2 watt-hours per pound and I am not going to apologize for coming in a little heavy.

The packaging weight is 40 percent of the cell rate. It does run a little heavy.

(Slide 205)

BETZ: Thermal, we looked at those three bays and the thermal guys came up and we – wait a minute I have the wrong slide. This is the nominal spacecraft temperature. This is the way the battery will operate or its temperature characteristics at the mid-eclipse and if the spacecraft thermal guys are exactly right. The other two curves indicate what happens if they are 10 degrees wrong on either side and they like to have that kind of margin capability to say, yes, we can be 10 degrees wrong.

We have made provisions to have heaters to keep us to zero C in sunlight and in the hot case, the worst case, where we penetrate the 25 degrees C. limit for a short period of time, if you extrapolate that over the entire mission I guess it is probably a couple of hours. It is a very small fraction in the worst case.

The stable or equilibrium temperatures in any one of the cases are – which is throughout the solstice period and the portion of the eclipse seasons are between zero and 25 C. and again this can be supplemented with heaters down here.

We looked at – we are considering a charge control for the battery pack and we are looking at the thermal curves thinking about pressure considerations which seemed to be an obvious way to go at first and it seems to be rather difficult to implement at this time. Looking at these we thought that perhaps we might be able to use a charge control technique based on temperature and it appears to be, and we do intend to test it and refine it, but selecting some temperature in the area of even 10 to 15 degrees C. here for the nominal case we could terminate charge. This does assume that charge is terminated by some technique. It does assume that you might be able to use temperature to terminate that charge, and some different things.

Nominal charge rate, C/10, 3-1/2 amperes. The assumed trickle charge rate is about C/58. That is 600 milliamperes, but the concept, to get back to the charge here, it looks like we could terminate charge based on temperature and since we would normally be stabilized out here and as you begin your eclipse season these fluctuations would build up, but terminating on temperature we might need a reset or an arming device on the blowing temperature. Then you just terminate charge on temperature. The interesting thing is, perhaps, if you have a cold spacecraft you wouldn't necessarily start down here but your first time you might drive it up to this temperature and then you tend to force the entire battery's operation up towards the nominal even though the spacecraft would like to be – this bay would like to be cooler simply operating it using a particular given temperature limit. You could force the eclipse season temperature of that pack up in this area and by the same token maybe at zero to 15 C. or the 10 to 15 C. area you might also be able to terminate charge a little earlier in a hot battery and restrict capacity maybe one hour, about 3-1/2 ampere-hours, and use the same technique to tend to force the battery a little bit cooler.

So that is the basic concept we are looking at right now, perhaps one or more temperature limits for charge control. It is nice when you have nice constant heat sink and you can think about these things.

The orbital data we will get from the battery while it is in orbit is not only battery voltages and charge and discharge currents. It will have two temperature sensors on each pack and every cell voltage will be telemetered back to earth so we should get some good data out of it for its lifetime.

We will be doing some testing at NRL on this battery pack and the primary area is to confirm the charge control or develop a charge control technique. We have a three bay model similar to the three bays that the batteries were sitting in that represent and will operate as the spacecraft for thermal testing so we will be testing on a three bay rather than a full bay aystem for storing.

The thermal guys really want to look at very carefully the steady state couplings and we certainly want to verify the transient characteristics here and get into the charge control in vacuum testing. We would also like to do some capacity, temperature characterization, get the voltage, capacity, and temperatures relationships. We will be doing battery vibration. We don't have much fear of it. It is a pretty substantial piece and it looks like we will be able to keep this battery active practically from the time we hook it up into the three bay model or the spacecraft until the time it goes out by utilizing the 18 cell nickel-cadmium whenever spacecraft power is not applied or ground power is not applied ADE. The small external circuit will be able to continuously trickle charge at the 600 milliampere rate, run the nickel hydrogen in the trickle charge mode for the entire period which gives us a real essentially uninterrupted long-term type of test during the integration period.

Any questions?

SULLIVAN: Sullivan, APL. Fred, did you mean by that last statement that either one of the batteries will work to complete the mission so that if either one of them fails you will still have a safe system or are you dependent on both of them?

BETZ: No, the spacecraft is designed to operate off either battery totally and solely. There is just slightly less capacity in the nickel-cad. than the nickel hydrogen. The main mission of the spacecraft can be supported but we will have to cut back I think if we go to nickel cad. one experiment during the eclipses to knock off a few – a small amount of the drain during the eclipse. But on the ground for ground testing, the 18 cell pack has a discharge voltage higher than the 14 cell charge voltage so with that we can actually keep the nickel hydrogen on active electrical operation whether or not we have ground power connected to the spacecraft.

WICK: Hugh Wick, Hughes Aircraft. Has much thought been put into the burst out average or that sort of thing? Once you get into the system, spacecraft integration and tests with pressure vessels on board the spacecraft and people working around it and integrating it?

BETZ: Well, I have been in nickel-cadmium for a long period of time and I have worked in the same room with 100 ampere-hour nickel-cadmium batteries and I have come in and seen them explode. I have found pressure gauges imbedded in the ceiling. I have – in fact I got called in the middle of the night on that one. I have seen batteries, 100 ampere-hour battery cells through a slight mistake blow their pressure jackets and drive bolts into the wall. They have come out like footballs, these big 100 ampere-hour cells. I really don't think the hazard involved here is any more substantial than the batteries you have been working with for a long time. The batteries are behind a relatively substantial piece of material. The burst levels, the safety levels involved with the structure itself seems to be quite adequate. I don't know what you are looking for but we are all exposed to hazards every day. What level of hazard do you want to protect against?

WICK: I don't want to pursue it here and occupy the meeting but let us say a mechanic is working there and you have got pressure within the nickel hydrogen cells and somebody drops a wrench or something and hits the side of the cell.

BETZ: Okay.

SPEAKER: Fred, you are not going to run with any pressure transducers on the battery?

BETZ: We have got enough spots in the connector to hook them up if we can figure out how to get good data off the cell. We do want to use transducers to take care of that, you know, the big hang on the end pressure transducer, but Joe has been looking at strain gauge stuff and if we can possibly get it we can make the provision for it. The connector room is there and we have budgeted the circuitry for it, then be able to telemeter that data back but it looked, the initial look see by Joe it was kind of difficult to implement at this time.

HENNIGAN: We have time for one more question. McHenry?

MCHENRY: Is it possible to develop any more than, what, I guess it is 600 pounds of hydrogen in that cell. You overcharged the positive and it will give off oxygen that I presume will be recombined in the negative, is that true?

BETZ: Yes.

MCHENRY: Now do you use platinum fuel cells? Doesn't that just eat up oxygen? Can you measure your particle factor of oxygen in that thing?

BETZ: I think Howard Rogers may have some comments on this. Dr. Rogers did some look sees to see what happens if, and basically on all operational cases we don't seem to get above that.

ROGERS: Fred, I will be commenting on that later.

BETZ: Okay, later on.

DUNLOP: You can't overcharge this at rates higher than nickel-cadmium without building up any appreciable amount of options. For example, at C rate overcharging, you can't overcharge this as a C rate at room temperature and I guarantee you if you try to do that with nickel-cadmium cell you would get in trouble, but you can do it and you have got a partial pressure that will be less than one percent of oxygen. Secondly you can overdischarge it continuously which has happened when we have had – you know, we have normally been cycling cells and we will have an interruption in our power supply so that the cells continuously run in reversal by mistake over the week-end on a cycle. We have run cells for as many as 30 cycles over a week-end. If that had been a nickel-cadmium cell it would have blown everything in the room up, for example, so there are certain inherent – partially in answer to your question, there are certain inherent things about a nickel hydrogen system that make it more stable than a nickel-cadmium. I am not necessarily saying it is more safe but certainly there are a number of arguments that you can use which inherently say they are safer and they do include things like the capability for a higher rate of overcharge, a capability for overdischarge, and I think in the next speech you are going to see that probably from a point of view of how a pressure vessel would fail, it would never explode anyway under any normal operating condition and the only other thing –

HENNIGAN: Yes, I would like to try to move on here.

DUNLOP: I want to say just one other thing. We talked about energy density a number of times on this cell and it has been pointed out is pretty low, but those electrodes are only loaded at around 60 percent of what current electrodes are loaded at. If we just loaded these electrodes like we apply today we would have a 30 watt-hour per pound cell, not a 20 watt-hour per pound cell. That is a true statement. All we would have to do is load these electrodes at the same level that you are currently loading electrodes in nickel-cadmium cells. I am talking about the positive electrode batteries. He would have between 28 and a 30 watt-hour per pound cell. One of the reasons that we have only a 20 watt-hour per pound cell is we were extremely conservative in everything we did. These electrodes are lighter loaded than the Bell Laboratory specs. call for, for example, but I guarantee you they will operate for about 6,000 cycles. I can almost guarantee that.

HENNIGAN: We have another presentation here and probably some of your questions will be answered because it is related to the first two presentations and this is Lee Miller from Eagle Picher, nickel hydrogen battery developments.

MILLER: Thank you. As most participants here today are aware, nickel hydrogen offers a potentially very attractive alternative to nickel-cadmium as a long life secondary battery system. Significant weight is saved in the replacement of the cadmium electrode with the lightweight gas electrode resulting in an energy density of approximately 30 watt-hours per pound, this versus 15 to 20 watt-hours per pound for nickel-cadmium.

The ability of the catalytic gas electrode to react equally well with both hydrogen and oxygen gas renders the nickel hydrogen system insensitive to both overcharge and over-discharge. In addition, a direct relationship between internal cell gas pressure and system state of charge offers a unique and reliable signal for charge control purposes. Significant progress has been made with respect to the design and the development of the nickel hydrogen system in the industry and the purpose of the paper today is to present a brief overview of the system as it has evolved at Eagle Picher. May I have the first slide, please?

(Slide 206)

MILLER: These are three different cell designs that we have been working with at Eagle Picher. Moving from left to right, the first design is the first design that we came up with, a 20 ampere-hour and we refer to it as the prismatic nickel-hydrogen cell design. This has really served as the workhorse for us in the design studies which are necessary whenever you get into a new system like this. Using this 20 amp-hour cell we are able to optimize the parameters such as electrode loading, electrode spacing, separator, evolve a suitable separator for nickel hydrogen, gas spacer requirements and the necessary hold down components for the electrode stack. That cell is a hydroformed part made of 304-L stainless steel and offers a safety factor pressure, burst pressure safety factor of two to one. It is approximately an 18 mil. base starting material.

As you can see, the ceramic to metal seals are internal to the cell. This is a high pressure seal design suggested by our supplier and it has worked very well for us.

One area that is very critical in the design of these nickel hydrogen cells was this weld joint. You can see it on the top portion of the cell. When we first started into this area by improper T-welding of that area there these cells were only good for about 100 cycles before you had a failure in that area. This resulted in an additional study that we didn't anticipate but we came up with what we could call, let us say, a weld joint back-up ring that it has been necessary for both of these prismatic designs as well as the cylindrical design, to facilitate that weld joint, but with this design incorporated, this cell that is shown here has passed over 40,000 pressure cycles without failure.

The next design in the middle is a 50 amp-hour prismatic cell. We have dropped the stainless steel and gone to inconel 625 in this case and this is a 12 mil. inconel 625. I am not sure just what you would call that cell. It has been referred to as a pancake, a hockey puck, and a few other terms, but we actually approached the designed goal, energy density goal of 31 hours per pound with this design here. It actually came in slightly over 29 watt-hours per pound with 55 amp-hours capacity. We did run into one problem that the seal is around the entire circumference of the cell and it appeared to be somewhat difficult in performing the Teague weld. I think possibly with an EB welding process that that joint could be accomplished.

Of course the last cell design is the cylindrical cell design and that is also an inconel 625 material. I think it is a 30 mil. wall on that. Also, we have dropped the ceramic seal and are now using in addition to the ceramic seals the compression seal that you saw in this previous cell. Let me have the next slide, please.

(Slide 207)

MILLER: This is the concept that was envisioned for packaging prismatic nickel hydrogen cells. It is very similar in its approach to nickel-cad. Of course what is interesting about this is that you can take a string of these nickel hydrogen cells arranged in that order and the strength requirements that you need in your tension rods and your end plates is just sufficient to restrain one cell. Each cell is accommodated with an aluminum thermal pin for its initial mounting on a thermal surface. This, of course, is just a laboratory-type nickel hydrogen battery intended just for evaluation purposes.

One of the problems that came up with this design is that it was asked, "What happens when one cell fails in there?" The two cells adjacent to it are operating at around 600 psig and obviously it would crush that one cell and probably would terminate the usefulness of the battery at that point so the thought was that possibly it would be better to connect these things in a common gas manifold arrangement. Next slide, please?

(Slide 208)

MILLER: This is done here, again, on a laboratory scale and with a demountable arrangement so you can replace cells, rearrange cells whatever you desire. All cells are connected to a common gas source. In other words, you have one of your electrochemical components common to all cells in the battery. The uniformity of the cells is rather remarkable from cell to cell. An interesting concept is you design this to be a gas limited battery. In discharge all cells will go out at the exact same time.

These two batteries were manufactured for one of the NASA facilities and are presently undergoing testing at that facility today. Next slide, please.

(Slide 209)

MILLER: It seemed, though, that most of the user interest in the industry was on the cylindrical design and most of our recent effort, I should say, has been in that direction. In this slide here you are seeing a 50 amp-hour cylindrical nickel hydrogen cell with a slightly different design approach than the one Comsat previously presented. Why don't we go to the next slide? I think it will show the internal configuration a little better.

(Slide 210)

MILLER: This is a boilerplate set up that was supplied on another job, but the electrode components and the cell stack design is very similar to what goes in the actual lightweight flight type cell. This is referred to as the donut electrode design and all of the electrical leads and the cell stack hold down components are accommodated to the center. This narrows the actual active material on the electrode surfaces to the outside peripheral area and it is thought to be a superior thermal design. We are really indebted to Hughes Aircraft Company for the suggestion of this particular design. Let me have the next slide, please.

(Slide 211)

MILLER: This is a performance graph on a couple of 50 amp-hour nickel hydrogen cells and what this is is a 100 percent DOD cycle and on two of these cells we accumulated a total of 600 100 percent DOD cycles and there was some slight fall-off in capacity as you get towards those 600 cycles but that design was really not the optimum design that has evolved today. This had an old-type separator material and the old-type chemically impregnated electrodes, but what interesting besides the fact that it did perform the 600 100 percent DOD cycles very well is that when we post mortemed these cells we were surprised at what you have already been introduced to, the swelling of these chemically impregnated positive electrodes. From what we could see in those cells it was determined that the just chemically impregnated electrodes are not suitable for nickel hydrogen systems when we subject them to these high rates or deep depths of discharge, so our efforts, then, was directed towards utilization of the electrochemical positives.

The next slide, please?

(Slide 212)

MILLER: I think you have already seen the cell on the left here, on the table. Eagle Picher was fortunate enough to be awarded not only the Navy nickel hydrogen flight experiment but also the Air Force nickel hydrogen flight experiment and on this slide you are seeing both cells. Of course, the one on the left is for the Navy and the one on the right is the Air Force cell. The one is 35 and the other is the 50 amp-hour design.

You see a small module. I believe I heard a question a while ago about the strain gauge or the pressure monitoring for charge control purposes. On the Air Force they will use the strain gauge concept to monitor cell pressure and the little module up towards the top of the cell near the pressure gauge is the strain gauge and it has all of its electronic components in there. It has its amplification and signal conditioning components in that little module there. Each cell in the Air Force flight experiment is equipped with one of these strain gauge modules.

It has its terminals coming out, obviously, on the same end in sort of a rabbit ear configuration. I guess we could say that probably these are the current generation of nickel hydrogen cells. We have now gone from inconel 625 to inconel 718. We are using the fuel cell grade regenerated asbestos separator material and basically the internal electrode components have been optimized for these designs.

As I stated, you were shown the Navy battery on the table here. I have a Vugraph with me that will let you have sort of an outline view of the Air Force nickel hydrogen battery.

(Slide 213)

MILLER: This is an aluminum investment casting that just has the cavities in which to accommodate the cells into the battery. There is nothing really – it is pretty much, other than its degree of instrumentation, it is pretty much straightforward, so if there are no questions, I think I would like to conclude the paper.

HENNIGAN: Any questions from the floor? Wick?

WICK: Wick, Hughes Aircraft.

HENNIGAN: Okay, very good.

WICK: How do you hold the cell in the casing, via RTB or epoxy or something like that? Is there thermal conductivity between the cells and the mounting?

MILLER: Actually, I am not really that familiar with the battery design. Possibly Don Warnock could –

WARNOCK: I think it is an epoxy, but I am not sure.

HENNIGAN: Another question?

HILL: Yes, Freeman Hill of Westinghouse. Don't you care about the energy density for volume in space applications or what kind of energy density do you try to get with this?

MILLER: I don't have the figure with me but yes, we are concerned with it, but it is sort of like Jim Dunlop pointed out. Both of these designs are very conservative at this point and so we are just looking for a successful mission first.

RAMPEL: Guy Rampel, General Electric. How many cc's of electrolyte per ampere-hour?

MILLER: Jim, are you going to answer that one?

DUNLOP: Yes, ours are from his cell. I don't know if you know it but it is four. We have four cc's of electrolyte per ampere-hour which is one of the advantages of nickel hydrogen.

MILLER: So the answer to Guy's question is it is approximately the same for both designs.

RAMPEL: Thank you.

DUNLOP: The answer to the other question here is the volume is really controlled by heat transfer characteristics, not by – the battery design and the volume is controlled right now still by heat transfer. It is bigger than the cell, the radiator area.

HENNIGAN: Ralph Sullivan, did you have a question?

SULLIVAN: Yes. Is it correct to say that the reason you went from the flatter version to the cylindrical version is because you can make the seal more reliably? Is that really – am I understanding that problem?

MILLER: You mean the T weld joint on the cylindrical or the –

SULLIVAN: Is that the driving reason to go from a flatter version of the cells to the cylindrical?

MILLER: Not really. It is just that you, the users, out there, just indicated the preference for the cylindrical configurations.

SULLIVAN: Thank you.

MCDERMOTT: Pat McDermott, Coppin State. Is there any problem with separator dry out with these safety cycles?

MILLER: Possibly Jim might want to address that question. He has probably more cycle life on these nickel hydrogen cells than anyone else.

DUNLOP: I would refer you to that article that we published in the Journal of Electrochemistry which covers about four or five different types of stuff in cycle flow.

MILLER: We really don't get enough cycle life to evaluate it. Some of these people who have had several years on it I think would be a better source of that information.

HENNIGAN: Okay. Thank you very much, Lee. Our next speaker is Don Warnock from the United States Air Force, Wright Patterson, and Air Force Approaches to Low-Orbit Nickel Hydrogen cells.

WARNOCK: If you come up late in the session you don't have much to say. Lee Miller has covered about the first half of my presentation. The Air Force has some very difficult requirements for energy storage and low-earth orbit, usually for short discharge times on the order of maybe 10 to 15 minutes to 30 to 35 minutes. For calendar life right now we are thinking of a year or less so the cycle life is not that bad. We do, however, have, in order to get the high energy density, we have to go to deep depths of discharge. We have thermal problems in doing that. We have to get the heat out. We have problems with oxygen generation getting it recombined. We had problems with the loss of electrolyte from the cell stack, so we are interested, of course, in nickel hydrogen and silver hydrogen. We have been working in nickel hydrogen. We have not been working yet in silver hydrogen but we may.

We addressed the thermal problem first and that is shown in the first slide.

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WARNOCK: The idea here is to increase the heat transfer area which is at the outer perimeter of the cell stack and to thin down the gas gap between the edge of the stack and the inside of the pressure vessel. To do that we have made pineapple slice shaped plates and when they are stacked up they leave a hollow cavity down the middle similar to the ones that were shown by Lee Miller just a few minutes ago.

In effect, this results in a redistribution of some of the stack material which would otherwise be in the hollow cavity and results in a slightly longer stack which increases the heat transfer area around the outside. It also enables us to bring the leads down the middle of the stack to get them away from the outside and it allows us to have a uniform gap all of the way around which in present designs is about 60 mils. This is a Hughes design, an implementation of an Air Force Propulsion Laboratory concept and it is the design that Lee Miller referred to on which his design is based also.

Information, some thermal information and other design information on this has been published as a tech. report and I don't want to go into very much detail on it right now. I would like to go on to the oxygen management and electrolyte management.

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WARNOCK: In a conventional nickel hydrogen cell stack such as shown here with back to back positive electrodes the oxygen management problem depends very strongly on what separator you are using. If you are using a relatively oxygen or gas permeable separator such as nylon or polypropylene the oxygen can go directly from the positive through that separator ard recombine at the negative rather readily. In some cells under certain conditions typically the more rigorous conditions there has been burning of separators due to heat release when that oxygen gets channeled through the separator, recombines locally with hydrogen at the negative, generates a lot of heat locally and melts the separator. In the extreme condition it can result in cell failure.

If you use oxygen impermeable separators such as nylon – I am sorry, such as asbestos or potassium titanate which most of us are doing right now, you get away from the separator burning problem but you now greatly increase the difficulty of recombining the oxygen because the oxygen now has to go, since it is sandwiched in those positive electrodes between two relatively impermeable separators, it now has to move radially out of the stack, exit the stack at the edge of the positives, quite possibly carrying some electrolyte with it, has to go around the outside perimeter of the separator and try to re-enter the gas flow space now from its perimeter. If the cell is still in charge it has to try to make that – it has to swim upstream in hydrogen in order to get back into the gas flow space and recombine.

As a result most of the recombination will take place at the perimeter of the negative giving you some somewhat greater heat production and water production there, both of which you don't like to have because if you get into a regime or you are transferring water vapor now from the stack to the pressure vessel and in essence depleting some of your electrolyte volume.

So if we are using oxygen impermeable separators, we need a better way of assuring a rapid, even recombination of the oxygen. One such suggestion is shown in the next slide.

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WARNOCK: On this case we have done away with the back to back positives. We placed the gas flow space behind each of the positives and any oxygen coming from the positive now has a very short easy path directly across the gas flow space, recombine on the surface of the negative. It gives you uniform recombination. You don't get the heating or the water production at the perimeter. It will occur even in the case of the significant outflow of hydrogen through the gas flow space because oxygen is moving into the same space. It is sort of being tumbled along in there until it recombines.

The problem is that the oxygen, say, we are looking at the top pair of plates. The oxygen from the positive on the top pair now is being recombined at the negative of the middle pair and in essence this results in the transfer of water because as it recombines with hydrogen then the water production goes into the second pair and the same thing on down the stack so you tend to get, because of recombination of oxygen, a net transfer of water from the top to the bottom of the stack.

Now, presumably, although we don't have numbers on this yet, we are in the midst of a program to get some of these numbers. Presumably there will be some entrainment of electrolyte from the back of the positive to the adjacent negative so it is quite possible that you will have a movement of both water and electrolyte, potassium hydroxide, down through the stack and what you need is some way of recycling the excess water and electrolyte that is moving down back up to the top and we are not quite sure how to do that right now. We are not pursuing this design in its pure form but we are looking at some ways of utilizing this concept and one of these is shown on the next slide.

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WARNOCK: If we look at half cell, it is essentially the same arrangement that we had in the previous slide where presumably some water and electrolyte will be moving from the top to the bottom of the stack. I have added – the only thing that has been added here is an extra negative sticking out right here which acts to recombine oxygen coming from this positive. I will return to that in just a minute.

Now if we look at the other half of the stack we have the same arrangement turned upside down, oxygen electrolyte tending to move in this direction and again we have a negative at the top to recombine the oxygen and also to collect any entrained electrolyte.

The effect is a scheme for recirculating both oxygen and electrolyte because the negative that collects them here is the same negative for the other half of the stack, the negative which collects them here is the same negative collected over here. We have placed a reservoir at each end to help effect the transfer so we have a closed circuit now for oxygen and electrolyte.

The advantages are that oxygen does not have to exit the stack at all in order to recombine. It can recombine uniformly and it works with a completely oxygen impermeable separator. You do not have uneven generation of heat or water. Hopefully you will have reduced the forces which tend to drive electrolyte out of the stack and if you want to assure that you can wrap the whole thing with a microporour membrane to keep liquid electrolyte from being forced out while allowing the hydrogen to breathe in and out of the stack.

We have built a cell based on this concept at the Propulsion Lab and the next slide shows some of the performance data for the first 500 cycles. I can't explain the deviation between the two at the beginning but it has disappeared and I would say that right now it is not of much consequence.

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WARNOCK: The performance has been very stable and although at 500 cycles the data isn't that significant. Let us show the second slide, the next one.

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WARNOCK: This shows the 900th and the 1,200th cycle and I think if we can put these two together –

You see that there has been practically no change in performance over about 1,200 cycles. This is a very small capacity laboratory-type cell but we have build several other cells of a conventional design of this same size and typically the cell gets in trouble at around 800 or 900 cycles, usually from dry out. You can take the cell apart and rewet it and the performance comes back. On the oxygen recirculation cell so far there has been no significant indication of loss of performance and compared to other cells that were similarly built and similarly cycled it is showing a much more – a much better ability to keep itself alive.

We have a contract with Hughes Aircraft right now and hopefully we will be able to give you some quantitative data in the future. That program is only a few months into itself right now. There will be, I think, some comments from both Dr. Holleck and Howard Rogers about aspects of that work. We hope to be able to give you a better report on it in maybe a year or so. Thank you.

HENNIGAN: What I would like to do, okay, are there any questions for Don? Jim Dunlop?

DUNLOP: What is the positive electrode you were cycling, Don, in the batteries you showed?

WARNOCK: Okay, the early cells not of this design were necessarily made of chemically impregnated positives. The current cell is an electrochemically impregnated positive.

MILLER: Do you know the loading level?

WARNOCK: I don't but Dave Pickett may know. I assume that it is about their standard of about 1.9 grams per cc of void. I think that is right. Is that?

PICKETT: It is a little less than that, I think. We have been loading the nickel hydrogen, nickel electrodes for the nickel hydrogen cells a little lighter than we normally do for the nickel-cad cells.

WARNOCK: It is at maybe 1.6, 1.7 grams?

PICKETT: About 1.7 to 1.8 grams per cc of void.

WARNOCK: Per cc of void.

DUNLOP: Who supplies these?

PICKETT: Eagle Picher.

WARNOCK: Eagle Picher.

HENNIGAN: Any more questions for Don? We have four more presentations on nickel hydrogen. I want to take a short five minute break and then we will finish up. Thank you very much Don.

Our next speaker on Nickel Hydrogen Battery System Development is Mr. Patterson from TRW Systems.

PATTERSON: At TRW we currently have two nickel hydrogen battery development programs. We have one battery development program with Comsat and then we have our own internal battery development work. In my talk today I would like to concentrate primarily on the battery development program that we have with Comsat and highlight some of the progress we have made the last year on that program and then I will conclude my talk with some of the results that we have gotten on our own internal research and development program at TRW.

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PATTERSON: The scope of the concept development program included both pressure vessel development and battery system development. In the way of pressure vessel development we looked at materials studies and weld studies. We did stress and thermal analysis of the pressure vessel and stack. We looked at manufacturing techniques for recommended pressure vessel designs. In the way of battery development we looked at mounting hardware design. We looked at charge control and bypass electronics. We performed stress and thermal analysis on the battery and finally we will fabricate a 10-cell battery and subject it to a number of tests.

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PATTERSON: The objective of the program was to develop a 50 watt-hour per kilogram energy density system. That is exclusive of charge control and bypass electronics and that is at 100 percent depth of discharge. This battery is to perform in synchronous orbit capable of approximately 1,000 cycles. That corresponds to about 10 years life in synchronous orbit.

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PATTERSON: The material study that we did was based on fracture mechanics analysis. Fracture mechanics analysis assumes that there are flaws in materials and these materials or these flaws tend to grow as the material is mechanically cycled, so what you try to do then is predict flaw growth, the rate of flaw growth, and then do an analysis to see if the thickness of your pressure vessel can stand the number of cycles that you plan to put on it.

What we did was we selected three candidate materials. We looked at 316 stainless steel, inconel 718 and titanium material. The reason we selected these three materials was because as Lee Miller pointed out a number of the original Eagle Picher cells had stainless steel pressure vessels. The 718 is a pressure vessel material that Comsat is now using in all of their pressure vessels and finally we wanted to look at a new material to see if possibly we could make an improvement over the materials that are currently being used. The motivation for the titanium alloy was that we wanted to come up with a material that had a lower density than the other materials that were used even if the ultimate strength of that material was less.

What we did want, though, was a material that had a higher strength to weight ratio. Now the rationale for this is that currently pressure vessels are approximately 20 mils. thick and you are really up against the limits, or you are really pushing the technology of hydroforming at that thickness, so if you could come up with a material of a lower density you could make it a little bit thicker and this presumably might improve the welding of the pressure vessels since you are welding across a larger cross section.

We performed static stress fracture toughness, sustained load and cyclic load tests. We then reduced this data and generated some flaw growth rate curves which I will show you a sample of that. Also, we looked at embrittlement characteristics in these three materials.

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PATTERSON: Okay, this represents kind of a final result of the fracture mechanics analysis for one of the materials. This material is the titanium alloy that I mentioned and here you see flaw depth plotted as a function of cycles to failure and this is for a 20 mil. thick material. We made the assumption that using non-destructive test techniques that you could probably detect anything greater than a five mil. flaw in a material so what we wanted to look at, then, was let us say that an undetected five mil. flaw existed in your material. How many cycles could you expect to get before that five mil. flaw would grow to 20 mils. and you would essentially have a leak in your pressure vessel, so you can see that right here that a five mil. flaw, the cycling of a pressure vessel to 650 psi, you could expect approximately 30,000 cycles before that five mil. flaw would grow to a 20 mil. flaw, so it was on the basis of this type of analysis that with respect to the flaw growth characteristics that we came to the conclusion that all three materials were satisfactory for use in nickel hydrogen pressure vessels.

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PATTERSON: In addition to the fracture mechanics analysis that I mentioned, we also did some hydrogen embrittlement studies and there again we found again all three materials were satisfactory for use in nickel hydrogen pressure vessels. Okay, we then went on to design a pressure vessel using the titanium alloy because of the reasons I mentioned earlier, the reasons I mentioned why we took a look at that titanium alloy. Now I will talk a little bit about the battery design work we did. A very important part of the battery design work is the mounting bracket design. We found that the mounting bracket design in the nickel hydrogen battery is primarily guided by thermal analysis. In other words, any bracket that would give you the thermal characteristics that you need in a nickel hydrogen battery system would be more than adequate to satisfy all of your structural requirements so the particular battery concept that we looked at was a bulkhead heat through design.

Someone asked earlier about if you are interested in volume energy density from a satellite and I suppose you are always interested in space on satellites, however, in a synchronous orbit satellite it turns out that the amount of radiator area that you need is actually larger than the cross section of the cell diameter. In other words you have to spread the heat out over and above the actual dimensions of the cell so you are really not paying at the mounting area, a penalty using this type of battery system.

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PATTERSON: Anyway, I just show some of the results of the thermal analysis here and you can see that most of the heat in the cell is conducted down through the mounting bracket and radiated from a radiator platform here. Very little of the heat is actually rejected from the top dome of the cell and this is for a reason. We don't want the dome of the cell to run significantly cooler than the cell stack because of possible problems with condensation of electrolyte on the inside surface of that dome.

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PATTERSON: Okay, as I mentioned, we will be building a 10-cell battery and prior to that, however, we are taking a look at – we are doing some tests I should say, on some two cell battery designs. Right here you see two 35 ampere-hour nickel hydrogen cells mounted to a honeycomb mounting surface. You can see the flange right here. That is how you actually hold the cell to the mounting surface. The cells are attached to the mounting bracket using an RTB bond and we use the fiberglass for insulation between the cell and the mounting bracket.

This particular two-cell battery is on test right now at TRW. We are pressure cycling these two cells between 50 and 650 psi. We plan to run this test to failure and see how good we were at predicting cycles to failure for this particular kind of material.

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PATTERSON: This is another view of the same two-cell battery you just saw. The point of this figure is to show the actual bulkhead feedthrough concept for the cell where it actually protrudes through the mounting platform.

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PATTERSON: This is a model of the 10-cell battery that we will be building. The reason we put this model together was to optimize the wiring diagram for this battery. It is pretty hard to do on paper.

The dimensions of this are 12 inches by 30 inches and the height of the cells is about 6-1/2 or 7 inches.

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PATTERSON: To show you some mass properties numbers for this particular battery design, now these are for 50 ampere-hour cells that we did the analysis on. The battery cell mass, 25 pounds, packaging and wiring mass, 2.2 pounds. Anyway, I guess the important number here is a battery system energy density of 15.4 watt-hours per pound. Now, I want to emphasize a few things here. This energy density is at 75 percent DOD and also this energy density includes both bypass electronics and charge control mass and you can see that the sum of these two is 5.5 pounds. It is 5.5 out of 32, so that is like another 15 or 20 percent so really we are looking at a battery energy density of over 20 watt-hours per pound and that would be at 100 percent depth of discharge.

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PATTERSON: In addition to the hardware development that we did for Comsat, we are also conducting a cell test program and here you see four 50 ampere-hour nickel hydrogen cells on test. These are aluminum heat sinks that are wrapped around the cells and they stand on top of an aluminum baseplate which is cooled with a circulating coolant. We use a mechanical heat exchanger for thermal control. As you see, all these cells are equipped with pressure transducers and currently are on an accelerated cycle life test. These cells have performed about five simulated synchronous orbit eclipse seasons.

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PATTERSON: That pretty much summarizes the work that we are doing for Comsat. The remaining things to be done on that program are building a two-cell battery which we will vibrate. It turned out originally we were just going to vibrate cells but we thought that we really wanted to do some vibration work on that mounting bracket design. We will be building a 10-cell battery and the tests that we plan to do are some characterization tests, thermal vac. test, and then some simulated eclipse season cycling.

In the way of the work that we are doing at TRW, part of our program was to verify some of the battery system energy density estimates that were made several years ago and to do that we conducted a test program and also had some analysis tests to come up with some paper designs of nickel hydrogen battery systems. Also as part of this program we did initiate some cycle life tests and I think one of the more interesting results that we have gotten is this right here. Here you are looking at minimum cell voltage on eclipse season operation as a function of eclipse season number and you can see that these cells were cycled at 80 percent depth of discharge. These are 20 ampere-hour cells and the actual initial capacity was a little bit less than 20 ampere-hours so they were actually cycled at a little bit higher than 80 percent of actual capacity. You can see that the minimum cell voltage was very stable out to about four or five seasons. Then it began to drop. We performed a reconditioning cycle after eclipse season No. 7 and you see the increase of performance. We performed another reconditioning cycle after eclipse season No. 8 and then we are now in the 12th eclipse season and we are essentially seeing no voltage degradation with respect to what we saw at the beginning of life so I think that this data looks better than any comparable data for nickel-cadmium cells that I have seen.

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PATTERSON: So now just briefly to go over some other results that we have gotten on our internal program, as I mentioned, we conducted some parametric studies to generate the kind of data that we needed to look at designing a nickel hydrogen battery system and what came out of that was that no significant difference was observed between nickel hydrogen and nickel cadmium. In other words, using the nickel hydrogen and nickel cadmium doesn't have any serious impact on power system design, if anything it simplifies it some because of the tolerance to overcharge and overdischarge.

Okay, I just showed you the data on the accelerated life tests. Those are now on the 12th season. We put over 1,000 low-earth orbit cycles and that was at 80 percent depth of discharge on a 90 minute orbit so that the discharge rate was about 2C and the charge rate was about a C rate, but what we found was a significant voltage degradation after about 500 cycles which couldn't be recovered by reconditioning. Finally, after about 1,100 cycles we took the cell apart and found that the positive electrodes had swelled in those cells by more than 50 percent. Those positive electrodes happened to be chemically impregnated.

Now these were also chemically impregnated electrodes here. In fact they were identical to the ones used on the low-earth orbit test so it just shows that using that same electrode in a low-earth orbit design at a pretty substantial depth of discharge, you just can't do it.

The cells appear to be safe against hydrogen as – or the leakage of hydrogen as a failure mode. What we did was we took two lightweight cell designs. One had ceramic seals. The other had the compression type seal that is used in all of the cells that you see up in front of you and that are being used on these various flight experiments. We crimped the fill tube and welded it shut and then put the cell in a vacuum chamber and using a mass spectrometer tuned to hydrogen we measured the hydrogen leak rates in these cells. We found that there were less than 10^{-7} cc per second and if you perform the arithmetic on that number and see what kind of hydrogen leakage you get in 10 years it is something like 10 or 15 cubic centimeters.

Now these, of course, were beginning of life, hydrogen leak rates, but we have these cells on cycle life test. We plan to periodically pull them off and remeasure this hydrogen leakage and see if there is any increase in the hydrogen leak rate.

The cells appear to be tolerant to overcharge and over-discharge. Now this does simplify the charge control and protection electronics requirement. I should emphasize, though, that this tolerance to overdischarge and overcharge is for typical synchronous orbit type operating conditions, say, C/10 charge rates and C/2 discharge rates. We did do some gas chromatograph, in situe gas chromatograph measurements on cells being overcharged and at these rates we couldn't measure any oxygen at all on overcharge.

In addition, we built some boiler plate cells and just let them overcharge at a C rate for – out of 37 days without seeing any abnormal performance or behavior, we also over-discharged, reversed cells for up to 30 days without seeing any abnormal behavior, but I emphasize that those were on boiler plate cells and the sample size is relatively small. In fact we only had one cell, but it does – I guess you can't get much smaller than that, or if you do you can get any results you want, but anyway, it does indicate that this cell has the potential to significantly improve performance with respect to overcharge and over-discharge.

We have come up with some lightweight bypass circuit designs to protect the cell in the event of an open circuit failure and finally we put together a nickel hydrogen, a total battery system design for both low-earth orbit and synchronous orbit and found the energy densities of 11 to 15 watt-hours per pound were feasible for synchronous orbit and six to nine watt-hours per pound were feasible for low-earth orbit.

HENNIGAN: Any questions? Sid Gross?

GROSS: On your energy density projections, why is the – where does the extra weight come from? It nearly doubles the weight in the close earth orbit.

PATTERSON: The thermal control hardware.

DUNLOP: That is usable energy density.

PATTERSON: Yes, that is usable energy density. That is not at 100 percent depth of discharge.

GROSS: What depth of discharge values did you assume for both cases?

PATTERSON: Well, we assumed 80 percent for the synchronous orbit and I believe something like 15 percent for the low-earth orbit, 50 or 60 percent.

GROSS: That is most of it.

PATTERSON: Yes. Also, thermal control hardware does add weight.

FORD: Ford, Goddard. You mentioned the expansion of the plates on the low-earth orbit, 80 percent depth, I think you said.

PATTERSON: Yes.

FORD: Do you see that plate expansion in your high rate time continuous overcharge?

PATTERSON: You say did we see the same –

FORD: Yes, do you see plate expansion, you know, when you said you had C rate overcharge which is about equivalent to the rate we are charging in near-earth orbit.

PATTERSON: Yes, we haven't taken those cells apart.

FORD: It would be of interest to know is it really the cycling, the discharging, or is it the overcharging or a combination of both that is causing that expansion and I had another question. Would you characterize the voltage fade in your nickel hydrogen cells similar to the nickel-cad?

PATTERSON: Well, when we took the cell apart we measured positive electrode capacity and found that it had reduced by about 20 percent and so I would say that the voltage fade at least on this test it looked like it was a natural loss of capacity at the positive electrode.

SULKES: Sulkes, USAECOM. Did you say what your reconditioning procedure was?

PATTERSON: Yes, it was a C/2 discharge rate so I believe one volt and then we put a one ohm or a two ohm resistor across the cell terminals.

HENNIGAN: Stan Krause?

KRAUSE: Bob, what separator were you using for that 1,000 cycle low-earth orbit test?

PATTERSON: That was a nylon separator.

KRAUSE: You used a nylon separator?

PATTERSON: Yes. It was kind of interesting. When we took the cell apart we couldn't find any burn holes or anything in there.

HENNIGAN: One more question back there?

KUYKENDALL: Yes, just a general question. Everything I have heard talked about here is in fairly high energy capacity cells. Is there anything being done in the lower energy?

PATTERSON: Like, say, lower than 20 ampere-hours?

KUYKENDALL: Yes, yes, or six, 10, 12.

PATTERSON: No. You don't get the same energy density advantage going to those lower cell sizes.

HENNIGAN: Okay, we will go on to another speaker. Thank you very much, by the way.

The next is Marty Gandel from Lockheed and he has some test results on low-earth orbit nickel hydrogen cells.

GANDEL: Thank you, Tom.

I would like to describe this afternoon some of the testing that we have done on some 20 ampere-hour Eagle Picher prismatic cells which you have seen a picture of earlier. The test program is being conducted under our Lockheed independent development program which was started in 1973. The testing program has both the synchronous orbit and low-earth orbit applications in mind and we have tried to obtain the parametric characteristics of the cells looking toward optimizing the charge control and the overall power and thermal management of the batteries themselves. The low-earth orbit work has taken on added interest. The Air Force sponsored flight experiment battery which is coming along and which is being built by Eagle Picher and provided by Don Warnock through SAMSO through Lockheed to fly.

Most of the data I will show today is based on the nylon separator cells and the chemically impregnated positive electrodes.

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GANDEL: I am showing this typical older data describing the synchronous-type 24 hour cyclic testing we ran and in this regime the max. pressures we obtained generally fell in this 500 to 600 psia range and then when we changed over to the low-earth orbit cycling on the same cells we experienced – am I right?

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GANDEL: We experienced excessive pressure rise. In the synchronous orbit testing we were charging at about a .75 amp rate and here in going to a 7 amp charge rate and went up to 700 pounds, stopped for a while to take a breather and started charging again and when we hit 750 pounds on this 1,100 psi burst pressure can we thought we had enough and we ought to stop.

Then we had some deliberations with Eagle Picher as to what do we do next, and we felt there was nothing to lose by discharging the cells down. As you can see the end pressure – we just displaced the pressure range and so the pressure on discharge under this rate was over 200 pounds and then subsequent discharging through a resistor brought us down in the range of 75 to 150 psia. At that point we bled off the extra hydrogen. I might digress a moment.

When we were seeing these very high pressures I had some gas chromatograph analyses conducted to see if by chance you could have oxygen in there which wasn't being recombined. There was no danger. There wasn't any oxygen that could be measured.

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GANDEL: Then subsequent to that, this goes back to the Middle Ages where I guess bleeding helped the body. So we went into low-earth orbit cycling. This shows the spread in pressure of the cells after that time. This is a six cell battery and the charge efficiencies varied somewhat. First we tried using pressure control off of the lowest pressure cell. Excuse me, off the highest pressure cell. In that case the lower pressure cells started dropping off in capacity, so we changed the procedure, went to the charge control off the pressure of the lowest cell and we went up just to where we were carrying the better efficiency cells just into overcharge and that was where we terminated the charge and we kept on repetitive cycling.

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GANDEL: This is the matrix of testing which we conducted on the six-cell batteries so far, with the charge rates ranging from a C rate to a C/10 rate and in these cycles we were charging for 31 minutes and then discharging for a max. of 29 minutes and when we were able to establish a repetitive cycle history or pressure history we adjusted the discharge time so we would have a balance, just enough charge to maintain that pressure profile.

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GANDEL: This is another, kind of a composite of the different charge-discharge regimes. The C, C/2, C/4 rates were very close to the same charge efficiency. You will note that at C/10 they were getting a lower charge efficiency which meant that we have a much longer charge-discharge time period and up about, you can see the linear pressure curves which indicate that we terminated the charge before we went into overcharge.

The voltage traces showed a peaking of some of the rates before we went into overcharge, which is indicative of if you are going to use voltage as a cut off you might be attenuating some of the total capacity available in the cell. If you are not operating to high depths of discharge maybe that won't make too much difference except that you won't have as much residual capacity to the battery.

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GANDEL: In this curve there are two things we see. One is the effect of temperature. The three upper curves are for the 20 ampere-hour Pellon cells. For comparison here I have also thrown in data on a 50 ampere-hour cell which is, I think, very close to the concept design and it is showing a higher impedance cell. That is all of the information we can get just from this curve.

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GANDEL: In looking at the value of a temperature compensated voltage-type charge controller, I have plotted here the peak voltage data obtained during cycling at these respective charge rates and plotted them as a function of temperature. At the lower charge rates the data naturally tightens up some so that if one is to use the temperature compensated voltage charge control then you would accomplish that by setting an operating line somewhere below the max. charge rate that you expected to obtain. We haven't formalized our thinking on the best charge control method. The pressure has been reproducible, very reproducible in the testing to date. We look at the temperature compensated voltage because that is what we have been employing on the ni-cads and it looks like at the lower charge-discharge rates, the lower depths of discharge, that the voltage system might very well work.

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GANDEL: I might just digress a moment and addressing Fred Betz' method of control using temperature by relying on going into overcharge and sensing that added heat, in most of the low-earth applications that I would think of, the thermal control is so sensitive that you want to assure that you stop somewhere before you where they go into very much overcharge.

In these repetitive cycles, there are, well, two ways of calculating charge efficiency. The easiest way is where you have the linear pressure time slopes, to figure charge efficiency as the ratio of the slopes of the charge versus discharge, pressure rise per ampere-hour. The other way is where we have this highly repetitive cycling over many cycles with its reproducible pressure curve of simply tallying ampere-hours in over ampere-hours out, excuse me, ampere-hours out over N.

When I plotted the data for the 20 ampere-hour prismatic cell design after 2,600 some cycles I found that the charge efficiency was lower than one might expect for this system or for ni-cad especially, where we were coming in at about a max. of about 75 percent. I then looked back at earlier data on the same cells and up to 300 and some cycles there was no attenuation of that charge efficiency but that from 300 to 3,000 that we were seeing some attenuation there.

As Lee Miller was presenting these designs I was thinking that ironically the prismatic cell design where you have the electrodes in parallel with the restraining faces, that you have a maximum allowance for the electrode growth. Excuse me, it can grow in two dimensions. That may be one of the reasons that we were seeing pretty stable operation through quite a few cycles. Although I haven't decided yet to go back to say, well, the prismatic cell is really the way everybody should go because the main detriment there is that if you are operating at high rates at all you are going to have a thermal gradient from the inside out so that each plate will be at a different temperature than its neighbor, and that way the cylindrical type design would be much better because the major thermal gradient is radially in the plane of the plate, so all of your plate should be operating at pretty much the same thermal environment.

If you look at some of the early data on this cell, then the charge efficiency curve moves over to the right as indicated by the triangles, and that is showing efficiency in the close to 90 percent range.

I also looked at charge efficiencies in the 50 ampere-hour cylindrical cell with the asbestos separator and I looked at data we have on an ERC 20 ampere-hour cell with the potassium titanate separator and in both those cases the efficiency curves fell in the 95 percent to 100 percent range.

In plotting these curves back to quote, "a zero charge efficiency," I made the simplifying assumption that the charge rate necessary would be equal to the self discharge rate. That may be a little bit off, but I think everyone is going to decide on what kind of a trickle charge rate he needs to offset his self discharge.

(Slide 241)

GANDEL: Departing from that cell and looking at thermal considerations in the 50 ampere-hour cylindrical cell, we bought cells from Eagle Picher with internal thermal couples. In this case we had four internal thermal couples in a cell and I wanted under high rates to see what kind of temperature gradient we might see and of course, we began from a cell which was equilibrated at room temperature and you see very little temperature rise during the charge. We are probably just beginning to get some bend over of the pressure curve and a little bit of overcharge, and then going into the discharge at a C rate, we were getting upwards of I would say 55 minus 33 over 20 degrees delta T from the thermocouple at the center of the stack out to the can wall.

What I should have shown at the time that I was talking about the parallel plates to the wall, this is an x-ray of that 20 ampere-hour cell.

(Slide 242)

GANDEL: I am just showing the plane of the restraining face. Okay, that was the last slide.

HENNIGAN: Do we have any questions for Marty? Don Warnock?

WARNOCK: Marty, on that last slide where you had the 20 degrees difference between the center of the stack and the can wall, what was the hydrogen gas gap on that cell? What was the hydrogen gas gap between the edge of the plates and the inside of that cell wall?

GANDEL: I would be guessing on that. Is Lee still here?

MILLER: Yes, Miller, Eagle Picher. I think in the early life that is probably about 100 mils.

HENNIGAN: Stan Krause?

KRAUSE: Marty, a general question that others can answer. In view of some of the nasty shots taken at Pellon 2505, here at this conference, you get a lot of tests data on cells with Pellon in it and there are some others. What do you think the future of that separator is for nickel hydrogen?

GANDEL: We have a separator study conducted at Eagle Picher where we looked at the regenerated asbestos, the natural asbestos, potassium titanate and the Pellon and we couldn't deduce any significant result from that test series to say which way to go and just operating as widely as everybody else I felt that in future cells I would want to go to the regenerated asbestos just to be one of the go-along guys. I can't refute the burn-through, the burn-hole experiences and I don't feel that I have got cells with burn-through experience here because I don't see anything in the voltage data to scare me.

On the higher charge, excuse me, the lower charge efficiency that I have seen, I am just guessing on that thing but I can imagine that if I have enlargened the plates where I am growing in the X and Y directions, that I have got fat edges that are exposing a lot of the nickel to the hydrogen and just things must be getting sloppy in there which is not a scientific explanation.

PATTERSON: Patterson. You made a statement that one way of determining the charge efficiency in a cell is when you have the pressure/time slope for constant current charge and discharge, you take the ratio of charge curve to discharge curve, but don't you also have oxygen evolution near the end of charge, so in other words, taking the slope of those two curves doesn't really give the efficiency over a cycle. It gives you something less than that.

GANDEL: Where you see the initiation of discharge, immediately following the charge, and the slopes are square –

PATTERSON: It seems you are getting no oxygen evolution at all.

GANDEL: Especially at the lower rates.

PATTERSON: Lower charge rates, yes.

GANDEL: Now, I am not relying entirely on that. I am saying that is where I have gone for maybe 50 or 100 cycles in a repetitive profile. I can check that by just adding ampere-hours in and ampere-hours out. I confirm it. I mean I don't have any data that tells me don't believe it except what I have noticed is where we are going, let us say we are operating on a C/2 charge and discharge profile. That, at the initiation of discharge that I will see a negative deflection to that pressure curve and one way of explaining it empirically is to say that if you superimposed self discharge on the power discharge then you would account for that kind of a pressure characteristic.

HENNIGAN: Jim, did you have a question?

GANDEL: I have checked temperatures and I can't account for that much difference just based on PV equals RT.

HOLLECK: May I make a short comment to that? You actually do get an overshoot of the pressure. The pressure continues linearly into the beginning of overcharge and the reason is twofold. First, it takes some time for the oxygen to get from the nickel electrode to the hydrogen electrode and secondly, the temperature increases which also increases your pressure so if you look at your pressure data it will continue linearly even though you start already going into overcharge, and your deviation over discharge is as you said. You can explain it as a super position of overdischarge if you want or self discharge and discharge, but it is not really self discharge. It is the using up of the oxygen which has been stored in the pores.

GANDEL: The only argument against that is the inability to analyze and find any oxygen at any time during that charging.

HOLLECK: During overcharge you do find oxygen in the cells. By the way, that was Holleck, EIC.

HENNIGAN: I think I will move on. You know, at 5:00 o'clock you can stay as long as you want. Our next speaker is Howard Rogers from Hughes Aircraft and his topic is on nickel hydrogen also and low-earth orbits of a nickel hydrogen cell.

ROGERS: May I have the first Vugraph, please?

(Slide 243)

ROGERS: The work on this that I am going to be discussing today was sponsored by the Air Force Aeropropulsion Laboratory and Herb Luke was the Air Force project engineer. We had three basic objectives in this work. One was to measure the degradation rate of what we consider the baseline nickel hydrogen cell which is really the stacked design in this case, only to do it under low-earth orbit conditions. Then what we are going to do is to build a stack of the design that Don Warnock spoke about where the oxygen recirculates and you compare those results with the ones we have gotten here. Another thing we did was to monitor the electrolyte loss during operation and finally we also measured the amount of oxygen generated under various conditions of charge. This was in a semi-continuous monitoring.

May I have the next slide, please, Tom?

(Slide 244)

ROGERS: The stack that we built was composed of, in the pineapple slice design which has been previously described. The positives were Tyco electrochemically impregnated plates of 3-1/2 inches, approximately, in diameter, and were set up back to back. Two negatives were used which were manufactured by ERC. The separator was Johns Mansville's fuel cell grade asbestos as received. Two polypropylene gas diffusion screens were used of Vexar polypropylene, 24 mils. thick. The electrolyte was the usual 31 percent KOH and I should comment about the leads. This is a boiler plate cell which I will be showing in a moment. The leads are fairly long and for mechanical reasons we couldn't use as heavy wire as we wanted to and we did have a significant voltage drop in the leads which does not really reflect anything particular about the cell but does make the data appear to be low. May I have the next slide, please?

(Slide 245)

ROGERS: The cell which you see pictured here in cross section is a rather solid boilerplate unit and would not be considered lightweight. I think it is somewhere around 30 pounds and for three ampere-hours. There are certain features of the construction I want to point out. One, if you notice a rather peculiar funnel shape of the plastic and the cell at the bottom. It is designed precisely like a funnel and there is an electrolyte drain valve at the bottom. That is how we measured our electrolyte loss. Any electrolyte you lose from the stack goes out and falls – goes down the funnel and out the bottom when we drain it which is periodic.

Another very important point is an oxygen tap or oxygen tube, actually a piece of teflon capillary tubing, which was placed adjacent to the stack over there on the right and in this way we are able to periodically sample the oxygen concentration near the stack so this wasn't an analysis after things happened. This was an analysis while it was charging at any point we wanted to.

Another feature of the cell was the extremely low gas volume that plastic, the plastic in there is solid. The idea is that we wanted to have a small cell but one unlike most small cells which cycled over the full pressure range, and this cell we were cycling over typical 100 to 500 or 600 psi pressure range.

May I have the next slide, please?

(Slide 246)

ROGERS: Now, these are curves of actual cycling data taken from the recorders and I first will give you the conditions and I will try to explain some of the rather peculiar looking data you see. It was 80 percent depth of discharge in a 90 minute cycle. The charge-discharge ratio is 1.15 to one and the cell was simply held at room temperature or I should say left at room temperature. There was no cooling used. It is rather large for its capacity.

The sawtooth effect you see is caused by periodic capacity tests which were done initially in the first couple of hundred cycles. We then let the cell cycle for a while to determine whether the end of discharge voltage would level out which it did. We did another capacity test and then finally for the remainder of the nearly 500 cycles we simply let the cell cycle without any interruption and the cell finally went below our arbitrary voltage of one volt at the electrodes which corresponds to the data here of .89 volts. In other words, that is that lead drop I previously mentioned. This was admittedly arbitrary but gave us some point at which we said, well, the cell is not deteriorated a certain amount.

One additional point, the original cell capacity was three ampere-hours measured at basically about a C/8 charge and a C/2 discharge and at the end of that cycling even though it was failing to operate at this 4.1 amp discharge rate, nevertheless, it was still giving 2.8 ampere-hours at a C/2 rate so there was very little deterioration in total cell capacity.

May I have the next slide, please?

(Slide 247)

ROGERS: The electrolyte loss which I previously mentioned was – first we did an initial five tests where we lost – these were parametric tests where we lost 2.7 percent of the electrolyte and then we went into the cycling and took periodic loss measurements of the electrolyte which indicated a gradual loss of electrolyte finally amounting to approximately 11 percent. An interesting bit of data is at cycle 432 which shows a very, very large loss, in fact nearly half and this was a special test we did where we charged at C/2 for four hours so it was a rather severe overcharge test and apparently blew out a substantial amount of electrolyte which had accumulated. My feeling is it accumulated within the stack and was blown out by the excessive oxygen produced.

(Slide 248)

ROGERS: In the next slide these are measurements we did of oxygen generation as I mentioned. We took the data at end of charge and at end of an open circuit period to see how much the oxygen would come down simply sitting without anything happening in the cell. The highest oxygen we got in this series of tests and remember that this is an impervious asbestos separator, was 10.8 percent which then, in nearly two hours went to five percent. At a much lower charge rate we had initially 4.7 percent. One of the most significant things to come out of this is that both at the C/2 charge rate if you compared runs two and nine and at the periodic capacity checks which are three, six, seven, eight, and 10, that the oxygen percentage during charge kept dropping and dropped substantially so that finally at the end we are only seeing 1.3 percent.

During the cycling, we also measured oxygen at the end of charge and that was well into cycling so it was sort of between tests nine and 10. We were seeing 1.8 percent at the C charge rate where there was, of course, very little overcharge.

We are continuing to study both electrolyte loss and oxygen generation and we will be looking at other stack arrangements. Thank you.

HENNIGAN: Any questions for Dr. Rogers?

DUNLOP: Let me ask a question for review. On these last two slides, on the electrolyte loss that was done with which kind of separator?

ROGERS: All these tests were done with an asbestos separator in one stack. The cell was not rebuilt or anything. We simply put the thing together and the results you are seeing here were done without having to disturb the cell in any way.

DUNLOP: Would you have any data with nylon for comparison, by chance?

ROGERS: Yes, but not at this time.

DUNLOP: Can you make any comment about whether it was better, worse, or the same?

ROGERS: We have not cycled nylon, but we did extensive parametric testing and the oxygen generation was considerably less. It also showed the effect of a series of tests increasing the ability of the cell to recombine oxygen, so that effect was also there. We were, for example, able to overcharge a cell at a C rate continuously, virtually, like we did it for nearly three hours. I might also add that we had no problem whatsoever with even minor pops in the cell under those circumstances.

FLEISCHMANN: Fleischmann, C & D. Do you relate this reduction in oxygen evolution with the loss of the electrolyte? Do you think it is because you are running a dry cell?

ROGERS: Yes. I discussed this point with Dr. Holleck and we came to the – well, I won't say conclusion, but the best guess we could make was that the negative electrode lost electrolyte and if you assume that the layer of electrolyte in the electrode is the limiting step for the reaction of oxygen. Then the thinning of that layer would cause an increase in the rate of recombination. That is guesswork at this point.

HENNIGAN: Are there any more questions? If not, we will go on to the next speaker, Dr. Holleck from EIC Corporation.

HOLLECK: In this last presentation of this workshop I will briefly summarize what I consider to be the main problem areas of the state of the art in nickel hydrogen cells. Then I will give you an idea of the approach that we are doing to develop solutions to these problems.

The main problem areas are electrolyte management and oxygen management. A further concern is, naturally, the positive electrode itself. As I mentioned, we have proposed solutions for these problems and we are presently working for the Air Force through Hughes on a program designed to investigate the various parameters of electrolyte and oxygen management. Our objective is to demonstrate practically viable solutions to those problem areas.

On overcharge oxygen is generated at the nickel electrode. It is needless to say that oxygen hydrogen mixtures are potentially dangerous. It is therefore essential to maintain low oxygen concentration well below the explosive limit. The recombination of oxygen and hydrogen on platinum, chemically or electrochemically is very fast and therefore the transport of oxygen to the hydrogen electrode is a critical factor.

The initial nickel hydrogen cells employed the same non-woven nylon that is used in nickel-cadmium cells. Since nickel hydrogen cells, at least after a few cycles, operate in a partially starved state, the separator shows a significant gas permeability and you have oxygen transport to the hydrogen electrode both around the cell stack and through the nylon separator. Typically in such cells oxygen concentrations are very low and are measured below one percent.

Such cells have shown, however, potential failure modes that can be traced to the heat sensitivity of the nylon. Localized heating, for example, by penetration of an oxygen gas bubble to the hydrogen electrode can result in melting of the separator and short-circuit of the cell. It is therefore desirable to replace the nylon with a heat insensitive separator, for example, asbestos or potassium titanate. Such separators typically are gas impermeable even when they are not completely saturated with electrolyte. We have to consider this and provide sufficient alternate diffusion passages. This can be achieve by suitable cell design.

If I may have the first Vugraph?

(Slide 249)

HOLLECK: This just shows a schematic of what you have actually seen before, a standard back to back design and forget about the other one at the moment. I will come back to that.

For example, a simplified diffusion calculation on the pathways of the oxygen in an asbestos cell, for example, where you do not have penetration through the separator, shows that the bottleneck for diffusion is the penetration into the gas space, at least in conventional cells as they have been built and a very coarse calculation shows that for example at the C rate overcharge which, granted, is quite severe, you can get oxygen concentrations of about, expect oxygen concentrations of about 13 percent.

Now, proposed solutions to these problem areas include the following; gas permeable inorganic separators, for example, which would be a heat insensitive simulation of the nylon, secondly, gas impermeable separators. Here a sufficiently wide spacing of the gas diffusion space is necessary to allow the necessary diffusion rates of oxygen to the hydrogen electrodes. The pineapple slice design derive by Don Warnock primarily, at least initially, on similar grounds, has a beneficial effect, also, of an increased edge area on the inside and the outside. Thirdly, a design with single positives and this is shown in the next Vugraph.

(Slide 250)

HOLLECK: In such a design the oxygen evolved at a nickel electrode would diffuse, cross the relatively narrow gas diffusion space and react at the opposite hydrogen electrode. You can see that in such a stack you have an asymmetry at the ends of the cell stack so what you ideally want is a circular cell stack. You have to provide, in order to close the loop, for either electrolyte or gas, a transport from the one end of the stack to the other side and one possible practical solution has been shown in the arrangement by Don Warnock.

The second major problem is that of electrolyte maldistribution, especially loss of electrolyte from the cell stack. During extended cycling changes in electrolyte porosity and wetting characteristics can also contribute to electrolyte management problems. The main mechanism of electrolyte loss is entrainment and expulsion by gases in motion. There are other mechanisms which may contribute which I will not discuss here because of the time limitations.

Proposed solutions to these problems include the incorporation of reservoir structures into the cell design, and the separation of entrained electrolyte from the evolved gas by hydroforbic membranes. These two features are also included into these designs which I have shown here. Several parameters enter into the consideration of selecting a suitable reservoir structure. Most important is the relative affinity of electrolyte to the various stack components. Pore size is the single most controlling factor. The reservoir structure has to be selected such that it will give up electrolyte preferentially to either the separator or the positive plate.

If one achieves this it should be possible to realize positive plate capacities approaching those measured in flooded condition. This effect may well compensate for the additional weight added by these components. Our present investigation is designed to obtain quantitative data necessary to define the relative importance of the various mechanisms in oxygen and electrolyte management to find practical solutions and to demonstrate the effectiveness of those solutions. Thank you.

HENNIGAN: Do you have any questions for Dr. Holleck? Dean Mauer?

MAUER: I have one for Jim Dunlop. Have you seen any evidence in your long term cycling of this electrolyte redistribution in this test here?

DUNLOP: Yes. We have seen drying out. Well, interestingly enough we tried polypropylene a long time ago. First we used polypropylene and that seems to fill it out to about 2,000 cycles, very repeatedly. We tried nylon which seemed to fill out to around 5,000 cycles or so. However, it all depends upon the depth of discharge and one of the problems seems to be related to the positive electrode that has been discussed before. We know that when the positive electrode expands you also have this increase of the microporosity along with the expansion and there seems to be a combination of two effects. You can actually get electrolyte pushed out of the stack. You can get electrolyte redistributed in the positive electrodes, about 50-50 and a corresponding loss of electrolyte in the separator.

MAUER: How about this concentration gradient where you get water at one end of the stack and KOH at the other?

DUNLOP: Well, one of the things I think is a difference and I think might make this difference, but one of the studies and a lot of the work that they are referring to is related to extremely high rates of charge-discharge cycles, and when we normally charge at a C/10 rate or even lower you don't run into a serious problem. As a matter of fact, if you looked at some of the data a lot of the charge-discharge cycles it is hard to tell if you are even getting into the overcharge mode a lot of times, particularly when you are using pressure as a cut off point and the charge – but I think that is a difference and there is more concern in the high rate C. They are talking about charging at the C rate in this 30-60 minute orbit and I think they have addressed the problem. It is a more severe problem for them.

HOLLECK: The effect is a principal one but you are absolutely right. It is much more elevated and more significant at the higher rates and it is also aggravated, certainly, by expanding of the positive but it is a separate effect.

HENNIGAN: Harvey Seiger?

SEIGER: I would also like to address this to Jim. You have taken some of those cells apart after the electrodes have thickened, the positives have thickened and you rebuilt those cells.

DUNLOP: Right.

SEIGER: Could you describe the electrolyte redistribution problem in those rebuilt cells? I think the thickening may have settled down.

DUNLOP: Yes, Joe, do you want to –

STOCKEL: Yes, we ran some small cells with nylon and they would fail at 2,000 cycles and just, of course, just refilling them they would run on until we stopped them, but it didn't happen with the electrochemically impregnated positive. I think I talked about that about three years ago, if I am not mistaken.

DUNLOP: Back to what was Gandel's point about when you charge a cell initially and depending on how much overcharge you put into it you do get many discharges done and you generally find a fair – you may not come down to the same point that you started with, particularly depending on the amount of overcharge that you are up to, and it is interesting with nickel electrodes, I think this has been one of the problems with nickel electrodes in nickel-cadmium cells in that it is difficult to give a state of charge comparison of one electrode to the other because when you are operating in the C/2 rate on a discharge, for example, you come down to something like in the nickel hydrogen, say, you may come down to 150 psi left in your cell at one volt or zero volts at the C/2 rate. Now if you start your discharging and put a resistor across there you may be able to discharge another four or five ampere-hours out of that cell, as a matter of fact. You will and the pressure will come on down to something like 50 psi or even lower and this is a very – this capacity if you can get, whether you call it reconditioning or whether you call it discharging at lower rates, is always very evident in nickel hydrogen systems because you can always equate it directly to the pressure that you look at and the same thing happens on overcharge. When you overcharge and the more you overcharge, generally, the higher pressure you go to and you get very concerned about whether that is oxygen or not and what you always find out is it is not oxygen. It is really excess capacity of the positive that you get by excessive overcharge.

IMAMURA: Either Bob Patterson or Marty talked about growth of the positive plate. I was wondering whether it is maybe Jim could answer it or somebody. Is the growth more effected by lower charge rate or a higher charge rate?

HOLLECK: Well, I don't have detailed data on this but I would think that it probably is more severe by the high, general high rate, but I do not have any data to back that up. Jim, do you?

DUNLOP: Well, we saw – I think everybody has seen more expansion with the discharged cycle. Somebody asked about the overcharge. We have done a lot of overcharge but where we really see expansion of the positive electrodes is with deep discharge cycles.

HENNIGAN: Marty?

GANDEL: Gandel, Lockheed. The only comment I would make there is that extra pressure rise is associated with the higher charge rate, so if that is related to expansion you can tie something together but I don't know that positively.

HENNIGAN: Dr. Rogers?

ROGERS: Yes, Rogers, Hughes. In answer to that question also, we had experience with some Eagle Picher -- in fact the cell that Lee Miller had shown on the board was one of ours that we had tested and these cells were the 50 ampere-hour and showed thickening up to 75 percent and pressure rises well above 700, 750 pounds, but that could be completely discharged if we were patient enough. You could actually get the pressure down to nearly to what it had been originally.

DUNLOP: That is right.

ROGERS: Much like Jim said, so --

HENNIGAN: Fred Betz?

BETZ: Just one comment on this increase in positive capacity. I remember seeing some data that the Royal Aircraft establishment in England generated a number of years ago trying to determine what overcharge rate. I think Floyd was talking about that before, what overcharge rate would suffice and we compared the capacities after 20 days of overcharge at rates, at 40 degrees C. The overcharge was performed for 20 days, 40 degrees C at various rates from C/120 up to C/5. In all cases they showed capacity increase, but at C/120 it was only about three or four percent but up at C/5 almost linearly increasing to about 15 to 20 percent if I remember the numbers correctly, and that is compared to a room temperature capacity, a 20 degrees C. capacity, so even at high temperatures you don't need much overcharge. You will tend to increase the positive capacity, I believe, and it is not there the next time.

HOLLECK: Well, the products that you make during charge is dependent on the column density on the potential which goes with column density, so if you -- that is especially obvious at the higher temperature, for example. If you, at 50 degrees C. or higher overcharge continuously at a C/10 or less you can overcharge as long as you want. You will never get the same capacity into your plate and out again during discharge than if you do it at a higher rate.

HOLLECK: Well, the products that you make during charge is dependent on the column density on the potential which goes with column density, so if you -- that is especially obvious at the higher temperature, for example. If you, at 50

degrees C. or higher overcharge continuously at a C/10 or less you can overcharge as long as you want. You will never get the same capacity into your plate and out again during discharge than if you do it at a higher rate.

BETZ: But these were continuous overcharge tests, multiply charged cells. They did show an increase in capacity from their standing capacities as a function of this overcharge period.

HOLLECK: Of the period?

BETZ: Right.

HOLLECK: Depending on the rate.

BETZ: Depending on the charge rates.

DUNLOP: Let me address that question. I think there is something that is extremely interesting which is related to the nickel electrochemically impregnated nickel electrode versus the chemically impregnated. If you take, for example, if you take the electrode that we have, when we measure the capacity, I forget what it is exactly but maybe Joe remembers, but Dirk was doing some very careful measurements on these measurements of the electrochemically impregnated nickel electrodes and comparing them to the flooded measurements that we have normally on chemically impregnated electrodes. I don't remember the exact number but we are getting 100 or some 105 percent, whatever, for the electrochemically impregnated electrodes of the theoretical, based strictly on the exact weight gain. It is a very difficult thing with the chemically impregnated electrode to know exactly how much active material to have so we did a chemical analysis and we tried as best we can to determine it but we know for sure that with a normal type charge cycle that we don't get the same kind of utilization with the chemically impregnated electrode that we are getting with the electrochemically impregnated. In other words, it was the same type of charging cycle. We are getting about as good as we can get with the electrochemically impregnated electrode, but there is obviously a lot of material in that chemically impregnated electrode that is not being utilized and I think that is the problem and when you go to the higher charge rates you are starting to utilize – you are overcharging more. You are probably utilizing more of the active material while you are seeing the difference in capacity.

HENNIGAN: I don't see any more questions here. Thank you, Dr. Holleck. I hope you all enjoyed your stay here at Goddard and the session on the ni-cad and nickel hydrogen batteries. I guess we will see you next year. You are welcome to stay in the room if you want to discuss anything or look at the nickel hydrogen battery. You want to look at it for a while, Jim?

DUNLOP: Don't touch it.

HENNIGAN: Okay, then have a good trip back home. Floyd has a few words to give you.

FORD: Yes, I just want to say that we have already been apprised that the Solar Voltaic Conference next year is scheduled for the week that we had the workshop this year, so if you want it for planning purposes, look for the week of November the 9th next year. That is probably when you will be setting up the workshop. Thank you for coming and thank you for participating.

PHASE A REQUIREMENT

TO PRODUCE A STANDARD MCD THAT EMCOMPASSES ALL ASPECTS OF CELL MANUFACTURE FROM ACCEPTANCE OF INCOMING MATERIALS STEPWISE THROUGH COMPONENT PRODUCTION, CELL ASSEMBLY AND TEST TO SHIPPING. ONE COMPLETE MASTER MCD INCLUDING ALL RELATED OR REFERENCED PROPRIETARY DOCUMENTS WILL BE MAINTAINED AT THE CONTRACTOR FACILITY.

CONTRACTS AWARDED FOR PHASE A TO.

EAGLE PICHER	NAS-5-22533
GENERAL ELECTRIC	NAS-5-22461
SAFT AMERICA	NAS-5-22416
YARDNEY ELECTRIC	NAS-5-22498

STATUS -

4 DRAFT COPIES OF NON-PROPRIETARY VERSIONS OF MCD'S HAVE BEEN RECEIVED AND REVIEWED 2 DRAFT COPIES OF MASTER MCD'S HAVE BEEN REVIEWED AT CONTRACTOR FACILITIES

Figure 1. Standard 20 AH nickel cadmium cells

PHASE B REQUIREMENT

MANUFACTURE 54 STANDARD 20 AH CELLS TO MASTER MCD
CAPACITY RANGE 22-26 AH
TOLERANCE ±5% OF AVERAGE

CELLS TO INCLUDE

A. 40 SEALED, FLIGHT QUALITY STANDARD
B. 4 SEALED, FLIGHT QUALITY STANDARD WITH AUX. ELECTRODE
C. 4 ITEM B WITH XDUCERS
D. 6 ITEM A WITH XDUCERS

STATUS

AWARD SCHEDULED BY JAN. 1, 1976
(MULTIAWARD PROBABLE)

CELL DELIVERY

9 MONTHS AFTER AWARD

Figure 2. Standard 20 AH nickel cadium cells

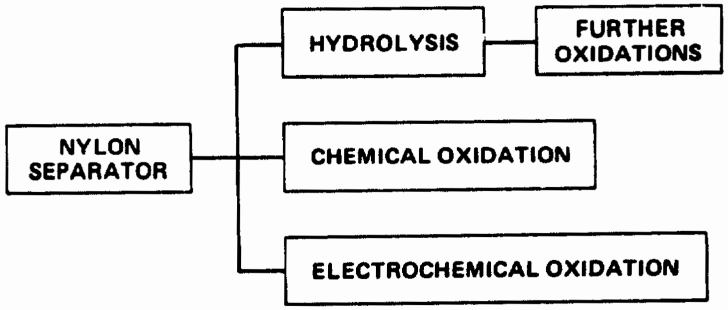


Figure 3. Possible pathways of nylon degradation in NiCd batteries

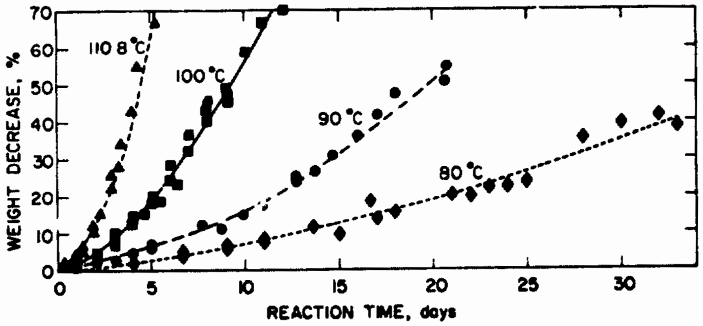


Figure 4. Rate of weight decrease of nylon in 34% KOH

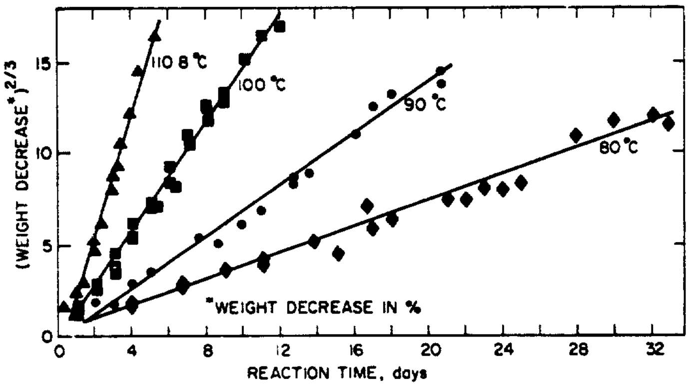


Figure 5. Relative reaction rates of nylon hydrolysis

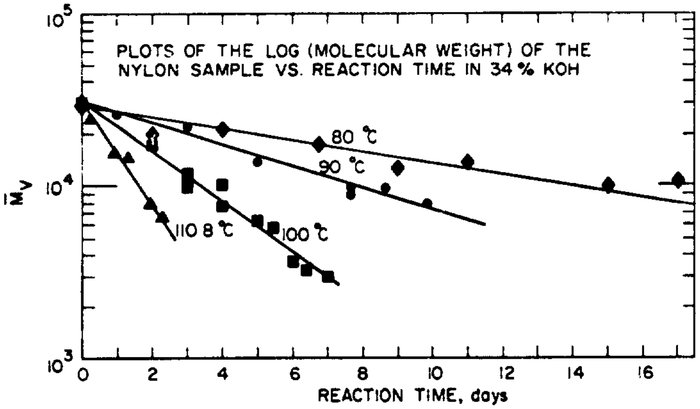


Figure 6. Average molecular weights

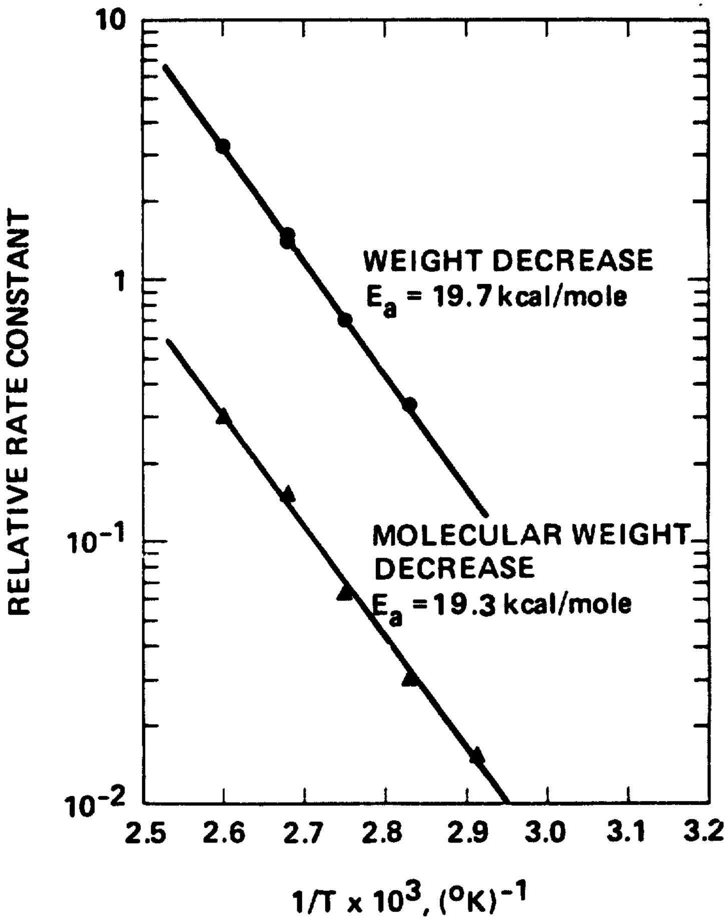


Figure 7. Activation energy plots

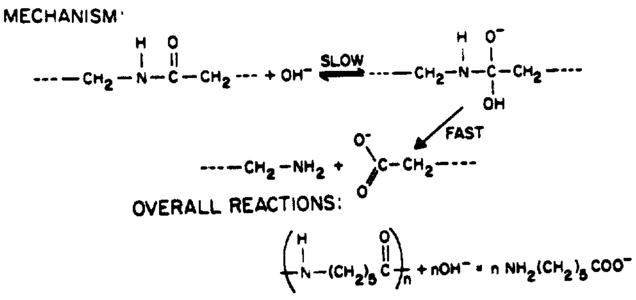


Figure 8. Probable Mechanism of nylon hydrolysis

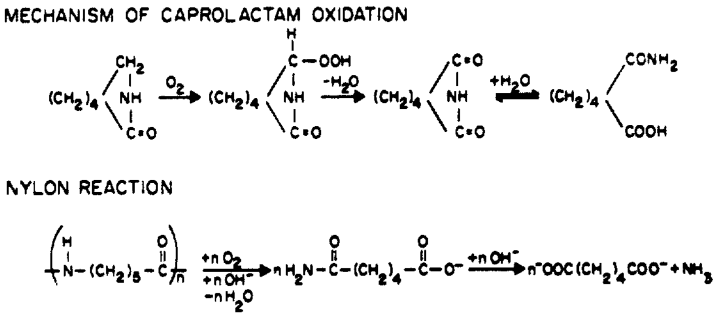


Figure 10. Probable mechanism of oxidative hydrolysis of nylon

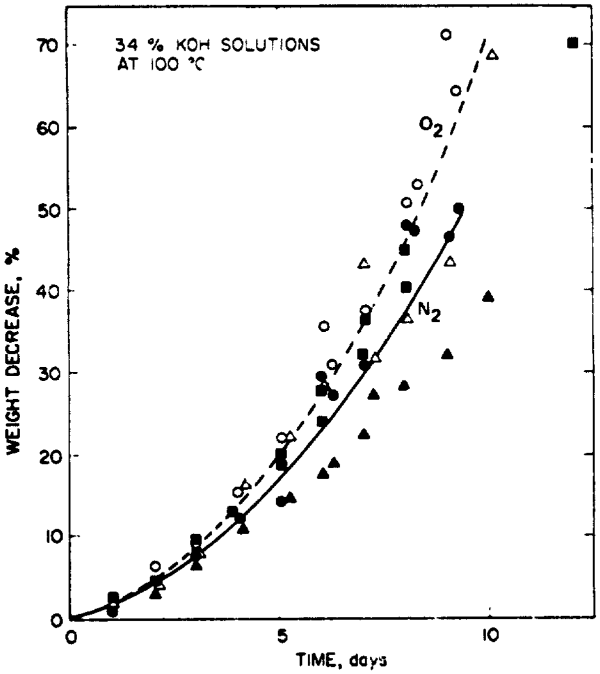


Figure 9. Effect of oxygen on the reaction rates of nylon

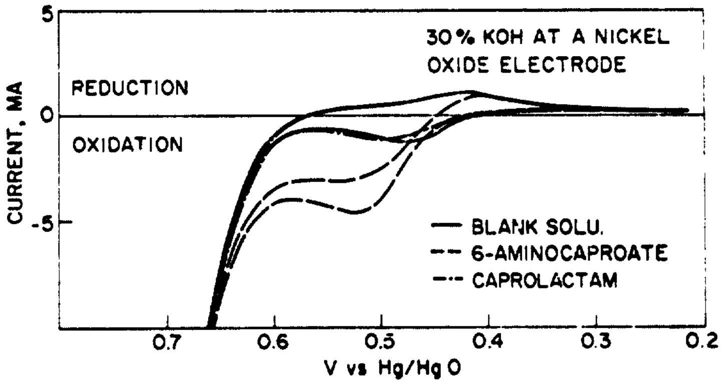


Figure 11. Cyclic voltammograms of 6 aminocaproate ion and caprolactam

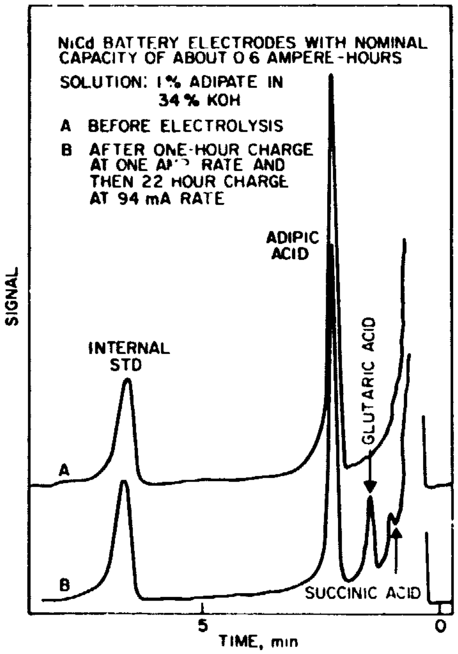
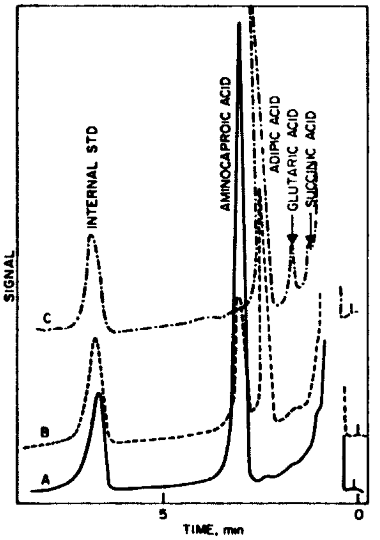


Figure 12. Gas chromatograms from the electrolysis products of adipate ions



ELECTRODES Ni-Cd BATTERY ELECTRODES WITH A NOMINAL CAPACITY OF ABOUT 0 6 AMPERE-HOURS SOLUTION 1% 6-AMINOCAPROATE IN 34% KOH

A BEFORE ELECTROLYSIS
B AFTER 30 minute CHARGE AT ONE AMP RATE
C AFTER 67 minute CHARGE AT ONE AMP RATE AND THEN 18 5 hour CHARGE AT 60 mA RATE

Figure 1. . Chromatograms from the electrolysis products of 6-aminocaproate ions

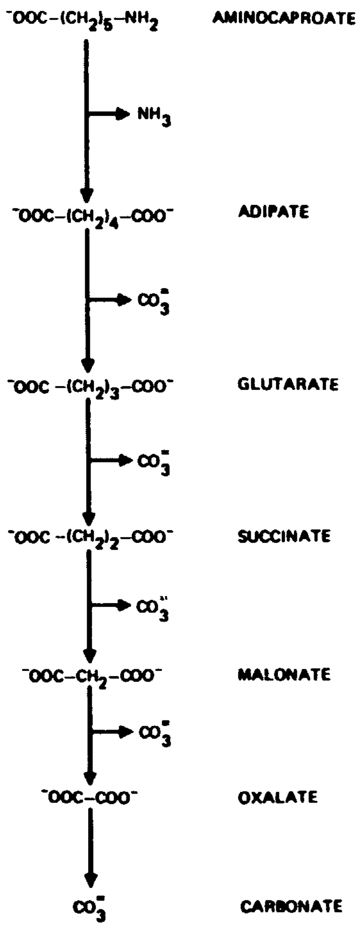


Figure 14. Probable sequence of electrochemical reactions of aminocaprote ion

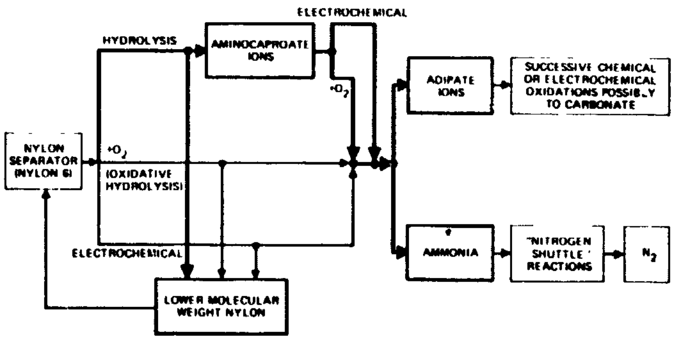


Figure 15. Possible nylon degradation mechanisms in NiCd batteries

$$[\text{-NH}(CH_2)_5CO\text{-}] + 45\,OH^- = 6\,CO_3^= + \tfrac{1}{2}N_2 + 28\,H_2O + 33\,e^-,$$

$$16\tfrac{1}{2}\,Cd(OH)_2 + 33\,e^- = 16\tfrac{1}{2}\,Cd + 33\,OH^-.$$

$$[\text{-NH}(CH_2)_5CO\text{-}] + 16\tfrac{1}{2}\,Cd(OH)_2 + 12\,KOH$$

$$= 16\tfrac{1}{2}\,Cd + 6\,K_2CO_3 + \tfrac{1}{2}N_2 + 28\,H_2O.$$

Figure 16. Probable overall degradation reactions of nylon

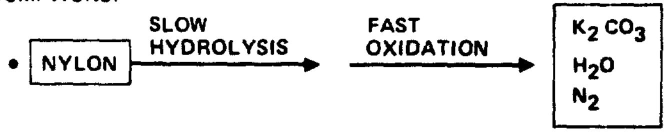
FACTOR	INITIAL*	AFTER 10 % NYLON OXIDATION
OVERCHARGE PROTECTION	10 TO 13 AH	0 TO 3 AH
K_2CO_3	0	9.5 g (10.9 %)
KOH	24.8 g (31 %)	17.1 g (19.5 %)
H_2O	55.2 g	61.0 g
N_2	0	141 cc (25 °C & 1 atm)

*ASSUMES THAT INITIALLY THE BATTERY CONTAINS 13 g OF NYLON-6 SEPARATOR, 80 g OF 31 % KOH SOLUTION, 10 TO 13 AH OF OVERCHARGE PROTECTION IN THE FORM OF EXCESS $Cd(OH)_2$, AND NO CARBONATE.

Figure 17. Consequences of 10% nylon oxidation in a typical 24 ampere-hr NiCd battery

Ea OF HYDROLYSIS (FLOODED CONDITION)	TIME FOR 10 % DEGRADATION OF NYLON
19.3 kcal/mole	6.3 yr
19.7 kcal/mole	7.1 yr

ASSUMPTIONS:



- GLASS TRANSITION NEGLECTED

Figure 18. Estimated stability of nylon at 25°C

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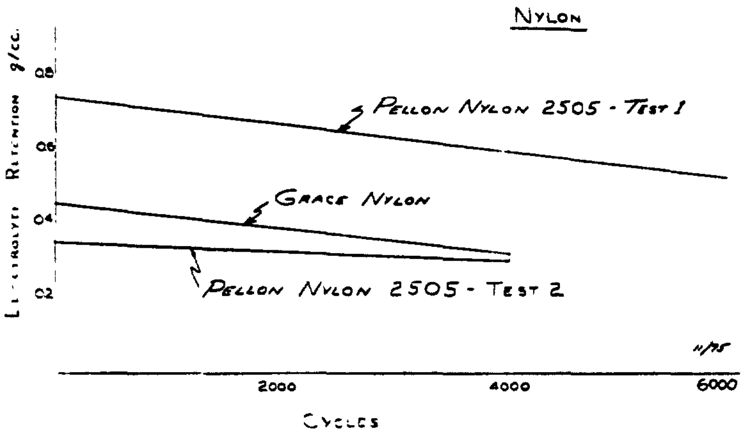


Figure 19.

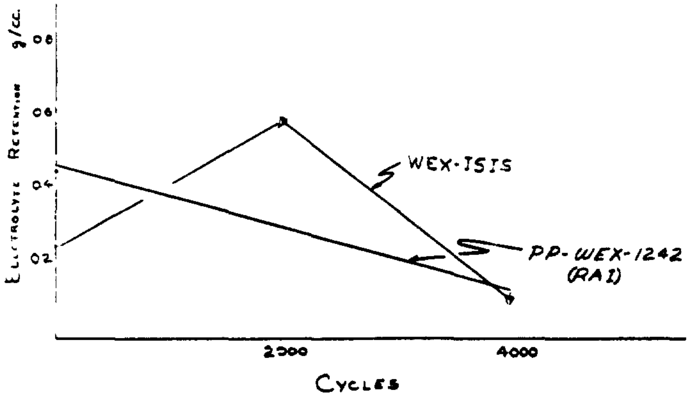


Figure 21.

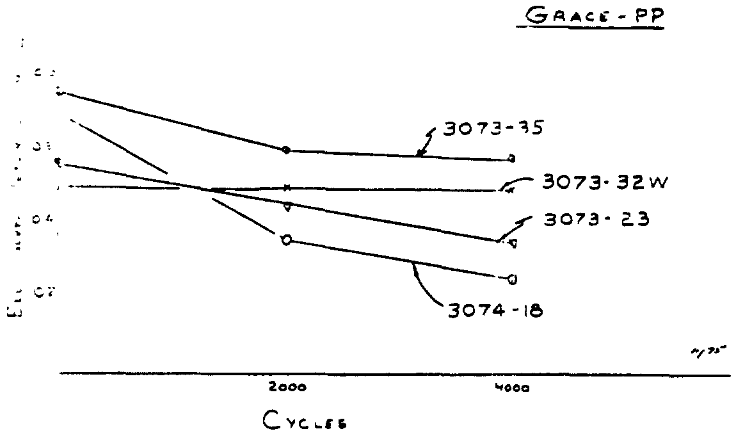


Figure 20.

PACK NO. SEPARATOR	INITIAL AVERAGE CAPACITY TO .75V	CAPACITIES AT 4000 CYCLES .75V	VOLTAGE AT 4000 CYCLES (MID-POINT)	VOLTAGES AT 5000 CYCLES EOD
9P PELLON 2505	7.6	6.7 6.9	1.07 1.23	1.19
9S Grace Nylon	6.9	5.7 6.9	1.06 1.23	1.21
9J Herc-PP	6.6	3.5 6.5	1.07 1.22	1.14
9K Grace-PP 3074-18	5.6	2.0 5.8	-- 1.23	1.14
9L Grace-PP 3073-23	6.2	2.6 6.7	1.13 1.23	1.07
9M Grace-PP 3073-35	5.6	1.7 5.6	1.24 1.24	1.07
9O Grace-PP 3072-31W	6.1	1.9 6.2	1.20 1.25	1.15
9P Grace-PP 3073-32W	7.1	5.4 6.4	1.05 1.24	1.15
9Q PP-WEX1242(RAI)	7.3	3.5 6.4	--- 1.23	1.10
9R WEX-1515	7.5	5.5 6.8	1.05 1.25	1.15

Figure 22. Summary of voltage and capacity 4000 and 5000 cycles

Near Earth Orbit	vs.	Synchronous Orbit
High temperature	vs.	Low temperature
High carbonate	vs.	Low carbonate
Random storage mode	vs.	Shorted or trickle charge
Polypropylene separator	vs.	Nylon separator
"Dry" separator	vs.	"Wet" separator
Heavily loaded negative	vs.	Lightly loaded negative

Figure 23

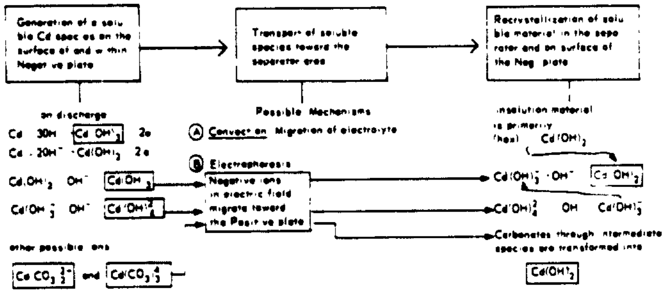
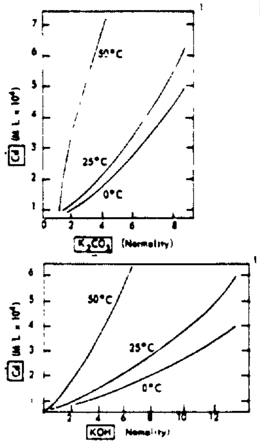


Figure 24

Solubility of Cd in Alkaline Solution



$Cd^{2+} + OH^- \rightleftharpoons CdOH^+$ – Predominate in

$CdOH^+ + OH^- \rightleftharpoons Cd(OH)_{2\,solu}$ – $OH^- < 0.5\,M$

$Cd(OH)_{2\,solu} + OH^- \rightleftharpoons Cd(OH)_3^-$ – Predominate in

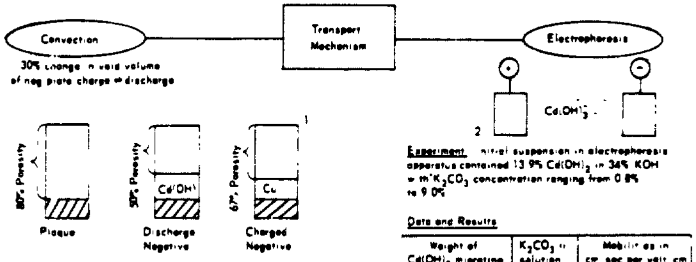
$Cd(OH)_3^- + OH^- \rightleftharpoons Cd(OH)_4^{2-}$ – $OH^- > 0.5\,M$ [2]

% KOH	Moles Liter	Solubility $Cd(OH)_2$ (M L × 10^4)
20	4.238	.75
22	4.740	.80
24	5.261	.90
26	5.792	1.05
28	6.342	1.25
30	6.908	1.38
31	7.182	1.43
32	7.488	1.50

[3]

1 P. E. Lake and J. M. Goodings, Canad. J. Chem. 36 1089 (1958) 3 G. Halpert NASA X 711 75-135
2 D. E. Ryan, J. R. Dean, and R. M. Cassidy Canad. J. Chem. 43 999 (1965)

Figure 25



In 6 Ah cell, the change in volume from charged to discharged cadmium is equivalent to a 2 cc less in void space. Approximately 10% of electrolyte present.

Experiment: Initial suspension in electrophoresis apparatus contained 13.9% $Cd(OH)_2$ in 34% KOH with K_2CO_3 concentration ranging from 0.8% to 9.0%

Data and Results

Weight of $Cd(OH)_2$ migrating	K_2CO_3 in solution	Mobilities in cm sec per volt cm
31.0 mg	0.8%	0.08
60.9 mg	3.1%	0.11
98.8 mg	6.2%	0.14
181.4 mg	9.0%	0.18

1 Data from P. C. Milner and U. B. Thomas. Advan. Electrochem. and Electrochem. Eng., 5 1 (1967)
2 Data from S. W. Mayer, Fall Meeting of Electrochem. Soc., 1974

Figure 26

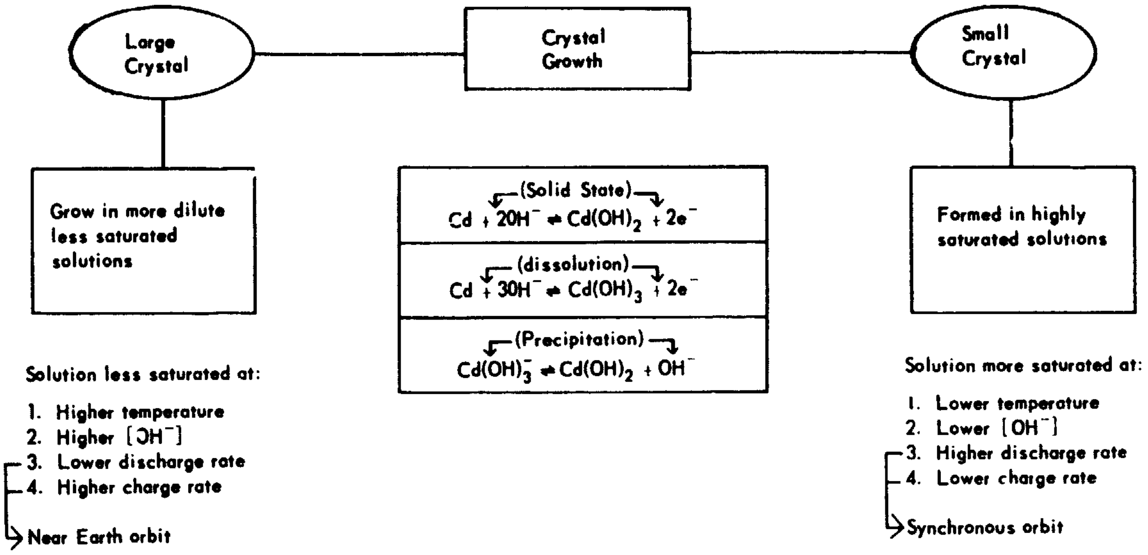


Figure 27

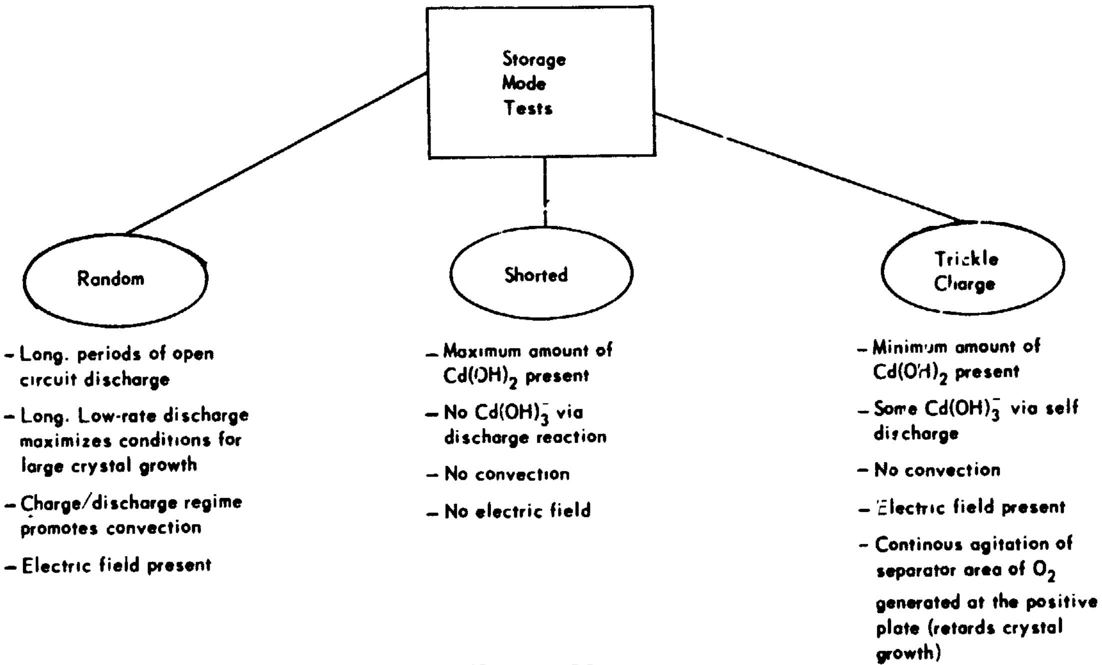


Figure 28

I. <u>SLURRY PROCESS</u>

APPLICATION DIP, ROLL, PAINT

PROBLEMS: RESULTED IN TOO THICK OF A LAYER A.D WAS NOT UNIFORM.

II. <u>SPRAY PROCESS</u>

APPLICATION. SPRAYED ON ELECTRODE SURFACE

PROBLEMS· POOR REPRODUCIBILITY AND INDICATION THAT THE APPLICATION WAS NOT PERMANENT

III. <u>FILM PROCESS</u>

APPLICATION. WRAPPED AROUND NEGATIVE ELECTRODE LIKE SEPARATOR MATERIAL.

PROBLEMS REQUIRED SCREENING OF LARGE NUMBER OF CANDIDATE MATERIALS.

Figure 29. Teflonated negative electrodes designs

CHARGE 24 HOURS C/10, DISCHARGE C/2 TO 1 00 VOLTS/CELL. TEMPERATURE 75 AND 100°F

CHARGE 48 HOURS C/20; DISCHARGE C/2 TO 1 00 VOLTS/CELL. TEMPERATURE 32°F.

	(3 AH)		(50 AH)	
CELL NO.	1	2	1	2
	<u>TEST TEMPERATURE 75°F</u>			
PV (CHG)	1.46	1.46	1.44	1.44
PP (CHG)	-23"	-23"	-24"	-28"
AH (CAP)	4.17	4.17	62.1	62.1
	<u>TEST TEMPERATURE 32°F</u>			
PV (CHG)	1.51	1 50	1.52	1.51
PP (CHG)	-16"	-21"	-28"	-18"
AH (CAP)	3 60	3.70	55 0	55.0
	<u>TEST TEMPERATURE 100°F</u>			
PV (CHG)	1.38	1 38	1.38	1.38
PP (CHG)	0	-10"	-19"	-13"
AH (CAP)	2.85	2 85	41 5	41.5

Figure 30. Acceptance type tests, 3 AH and 50 AH cells

CELL: RSN-50 (50 AMPERE-HOUR CAPACITY)

DESIGN: APPLICATION OF SEMI-PERMEABLE MEMBRANE (TEFLON) OF SPECIFIC POROSITY AND THICKNESS TO NEGATIVE (CADMIUM) ELECTRODE.

<u>NEAR-EARTH ORBIT CYCLE</u>

CYCLE· 45 MINUTES; 14 AMP CHARGE, 23 MIN./14 AMP DISCHARGE, 22 MINUTES.

TEMPERATURE. 40°F

<u>CYCLE</u>	<u>PV (CHG)</u>	<u>PP (CHG)</u>	<u>EOD</u>
1	1.458	-27"	1.232
640	1.463	-24"	1.242
1,270	1.460	-25"	1.238
1,910	1.459	-25"	1.236
2,650	1.462	-25"	1.235

Figure 31. Cycle test sequence of membrane design sealed nickel-cadmium

SYNCHRONOUS ORBIT CYCLE

CYCLE: 24 HOUR; 5 AMP CHARGE, 22.8 HR./25 AMP DISCHARGE, 1.2 HOURS.

TEMPERATURE: 80°F

CYCLE	PV (CHG)	PP (CHG)	EOD
3	1.405	-14"	1.217
14	1.412	-2"	1.194
27	1.413	2 PSI	1.199
44	1.383	10 PSI	1.197
110	1.396	10 PSI	1.190

ACCELERATED SYNCHRONOUS ORBIT CYCLE

CYCLE: 12 HOURS, 5 AMP CHARGE, 10.8 HOUR/25 AMP DISCHARGE, 1.2 HOURS.

TEMPERATURE. 40°F

CYCLE	PV (CHG)	PP (CHG)	EOD
156	1.474	-5"	1.206
162	1.480	-10"	1.200
185	1.480	-10"	1.202

Figure 32. Cycle test sequence of membrane design sealed nickel-cadmium

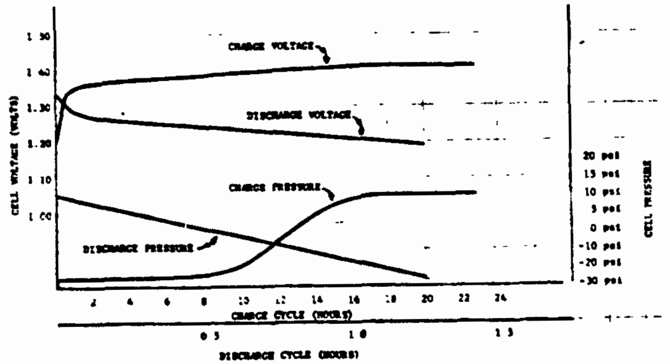


Figure 33. 50 AH sealed nickel-cadmium thin film membrane design

1. SIMPLE APPLICATION DURING CELL FABRICATION.
2. COMMERCIALLY PROCURRED MATERIAL WHICH MAY BE OBTAINED IN LARGE QUANTITIES EXHIBITING UNIFORM CHARACTERISTICS
3. THE MATERIAL IS PURE TEFLON. NO ADDITIVES OR PROCESS TREATMENTS USED TO CONVERT TO A SECONDARY FORM FOR APPLICATION
4. SIMPLE BUT DISCRIMINATING QUALITY CONTROL MEASURES HAVE BEEN DEVELOPED TO ASSURE THE VENDOR MEETS MATERIAL SPECIFICATION REQUIREMENTS PRIOR TO CELL MANUFACTURE.
5 THE CRITICAL INTERFACE BETWEEN THE TEFLON FILM AND NEGATIVE ELECTRODE SURFACE IS OF A PHYSICAL TYPE CONTACT BUT NO PHYSICAL BOND EXIST REACTIONS AND CHANGES OCCURRING AT THE NEGATIVE ELECTRODE SURFACE (MECHANICAL STRESSES, BLISTERING, OR FLAKING OF ACTIVE MATERIAL, CRYSTALLINE STRUCTURAL CHANGES, GAS EVOLUTION, ETC.) DO NOT EFFECT THIS CRITICAL INTERFACE (THE TEFLON FILM PROCESSES STRENGTH AND IS AN EFFECTIVE SEPARATOR MATERIAL IN ITS OWN RIGHT) AND THUS NO TIME (OPERATION) DEPENDENT DEGRADATION OR PERFORMANCE CHANGES ARE ASSOCIATED WITH THE SYSTEM
6. THE MATERIAL EXHIBITS A STRONG TENDENCY TO ADHERE TO ITSELF, THIS PERMITS FOLDING THE OVERLAP AT THE PLATE EDGES TOGETHER FORMING A SEALED BAG AROUND THE NEGATIVE ELECTRODE WITH ONLY THE ELECTRICAL TAB PROTRUDING THE SUBSEQUENT APPLICATION OF THE CELL SEPARATOR MATERIAL FURTHER SECURES THE INDIVIDUAL BAG SYSTEMS

Figure 34. Advantage of the film process

NO SLIDE REQUIRED

Figure 35.

$$2NiOOH + 2H_2O + Cd \lessgtr 2Hi(OH)_2 + Cd(OH)_2$$

$$E_{cell} = 1.299 + \frac{RT}{7} \ln a_\omega$$

$$= 1.299 + 8.619 \times 10^{-5}\, T \ln a_\omega$$

$$a_\omega = \frac{p}{p^0}$$

$$p = A \exp(-B/T)$$

or

$$\ln p = \ln A - (B\ T)$$

$$E_{cell} = 1.299 + 8.619 \times 10^{-5}\, T(\ln A - (B/T) - \ln p^0)$$

Figure 36

Pos: $2NiOOH + 2H_2O + 2e \lessgtr 2Ni(OH)_2 + 2OH^-$

$$Epos = 0.49 - 8.619 \times 10^{-5}\, T \ln \frac{a_{OH^-}}{a_\omega}$$

$$a_{OH^-} = \sqrt{\gamma_\pm m}$$

Neg: $Cd(OH)_2 + 2e \lessgtr Cd + 2OH^-$

$$E_{neg} = -0.809 - 8.619 \times 10^{-5}\, T \ln a_{OH^-}$$

Figure 37

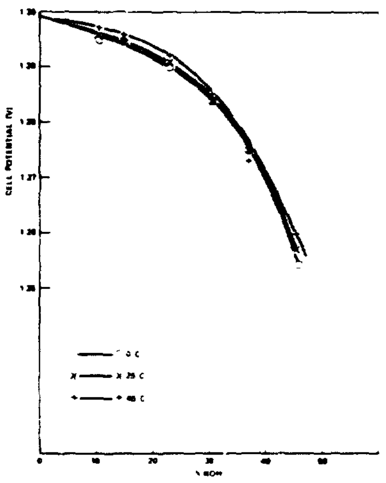


Figure 38. Variation of cell potential with KOH concentration at 0°, 25° and 40°C

Carbonate Solutions

$$\ln p = A + B\tilde{M} + C\tilde{M}^2 + D\tilde{M}^3$$

$\tilde{M}$ = total g - ions/1000 g soln

A - D = constants at each T

$$E_{cell} = 1.299 + 8.619 \times 10^{-5}\, T \ln a_\omega$$

$$= 1.29 + 8.619 \times 10^{-5}\, T \ln(p\ p^0)$$

$$= 1.29 + 8.619 \times 10^{-5}\, T[\ln(A + B\tilde{M} + C\tilde{M}^2 + D\tilde{M}^3) - \ln p^0]$$

p^0 = v. p. over pure water

Figure 39

$$2NiOOH(\sim 0.1\ KOH) + Cd + 2H_2O \lessgtr$$
$$2Ni(OH)_2 + Cd(OH)_2 + 0.1\ KOH$$

% DOD	% KOH	E_{cell}	
Full charge	22.9	1.291	
25	24.2	1.290	
50	25.5	1.289	6 A. H.
100	28.5	1.286	
120	29.8	1.285	

Halpert (X-711-75-135)
1975

Figure 40

$$E_{pos} = 0.49 - 8.619 \times 10^{-5}\ T \ln \frac{a_{OH^-}}{a_{\omega}}$$

$$E_{neg} = -0.809 - 8.619 \times 10^{-5}\ T \ln a_{OH^-}$$

$$a_{OH}^{\infty} = \sqrt{\gamma_{\pm} m_{OH^-}}$$

Harned's Rule

$$\log \gamma_{\pm} = \log \underset{C_{cos_3}=0}{\gamma_0} - \underset{f(m,\ T)}{\alpha m_{K_2CO_3}}$$

Figure 41

Carbonate

Time yr	% KOH	% K_2CO_3	E_{cell}
0	29.07	0	1.280 v.
0	29.07	8.00	1.278
1	27.65	12.71	1.276
2	26.34	16.69	1.273
3	25.15	20.46	1.272
4	24.06	23.91	1.270
5	23.06	37.07	1.269
10	19.09	39.60	1.262

Figure 42

pos $NiCO_3 + 2e \rightleftarrows Ni + CO_3$

$$E \quad -0.45 - \frac{1.985 \quad 10^{-4}\,T}{2} \log a_{CO_3}$$

neg $CdCO_3 + 2e \; Cd + CO_3$

$$E \quad -0.74 - \frac{1.985 \times 10^{-4}\,T}{2} \log a_{CO_3}$$

$Ni(OH)_2 \quad CdCO_3$

$2NiOOH + Cd \quad 2H_2O + CO_3^{=} \quad 2Ni(OH)_2$

$+ CdCO_3 \quad 2OH^-$

$$E \quad +1.23 - \frac{1.985 \times 10^{-4}\,T}{2} \log \frac{a^2_{OH^-}}{a^2 \, a_{CO_3^=}}$$

$NiCO_3 \quad Cd(OH)_2$

$NiCO_3 \quad Cd + 2OH^- \quad Ni + Cd(OH)_2$

$$E \quad +0.359 - \frac{1.985 \times 10^{-4}\,T}{2} \log \frac{a_{CO_3^=}}{a^2_{OH^-}}$$

$NiCO_3 \quad CdCO_3$

$NiCO_3 + Cd \; Ni + CdCO_3$

$E = +0.29V$

Figure 43

ALLOWS MEASUREMENTS TO BE MADE IN UNDISTURBED CELL.

REFERENCE ELECTRODE PERMITS SEPARATE MEASUREMENT OF POSITIVE AND OF NEGATIVE ELECTRODE VOLTAGES.

PRESSURE GAGE MEASURES GAS BUILD UP AND RECOMBINATION.

VENTING VALVES AND GC PORT PERMIT MEASURING GAS VOLUME AND COMPOSITION.

VENTING VALVE ALLOWS MEASUREMENT (OR ADJUSTMENT) OF OVERCHARGE PROTECTION OR PRE-CHARGE.

Figure 44. Reference electrode

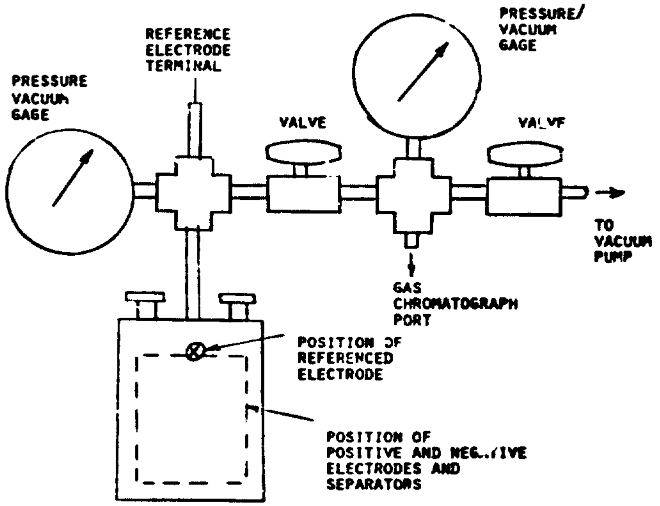


Figure 45. In situ nickel-cadmium test set-up

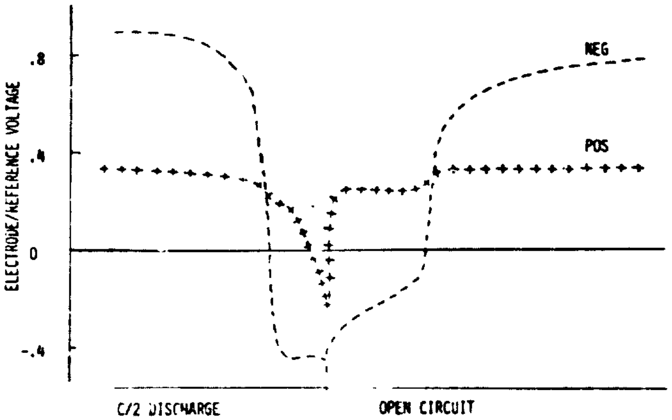


Figure 46. Discharge of aged cell at C/2, negative limited

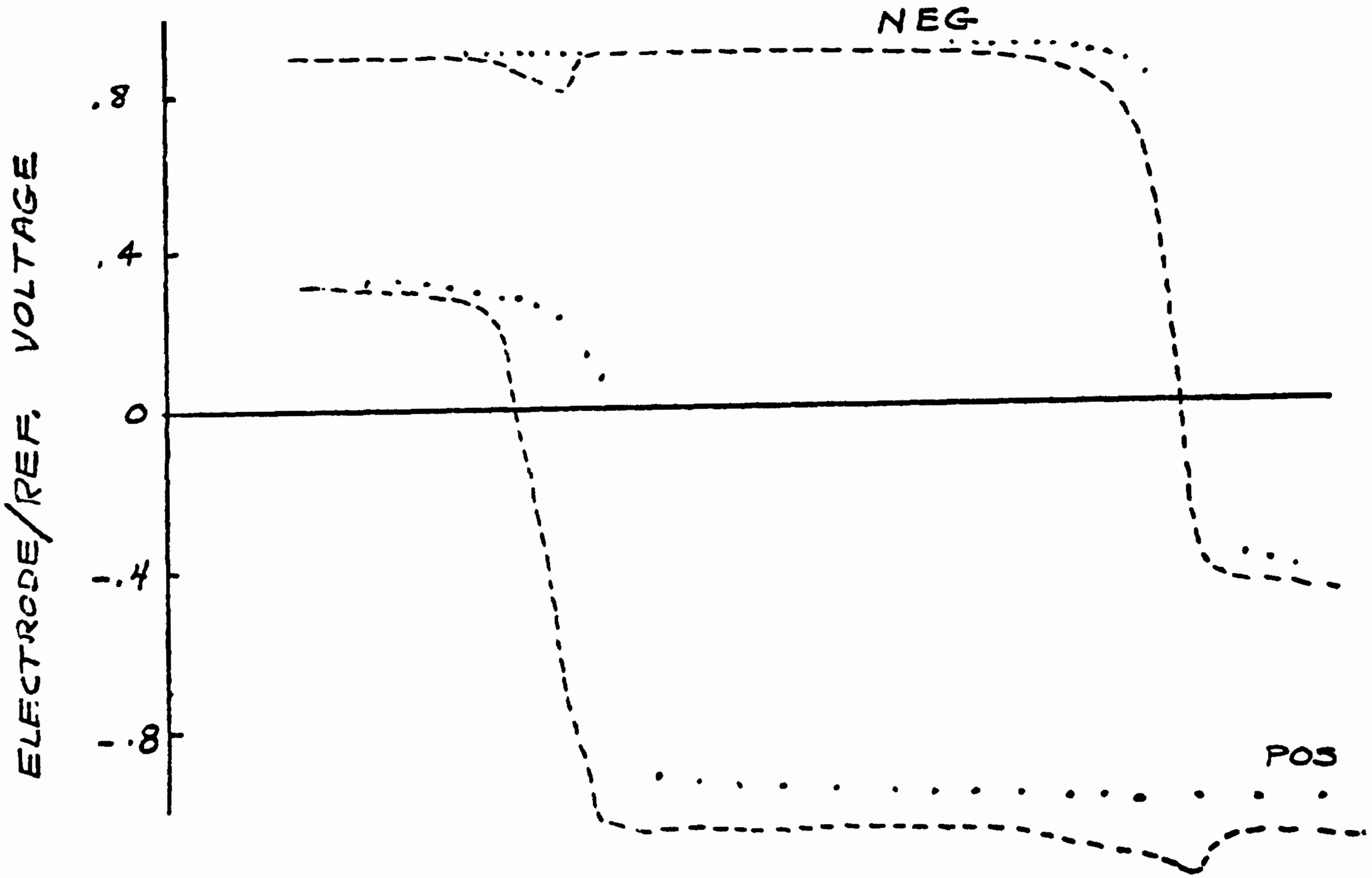


Figure 47

TYPE OF CYCLE: SYNCHRONOUS
BATTERY CELLS IN TEST: SIX AMPERE HOUR GENERAL ELECTRIC
TEST CONDITIONS. 46 DAY ECLIPSE SEASON
20° C COLD PLATE
100% DEPTH OF DISCHARGE MAXIMUM
REAL TIME SYNCHRONOUS LOAD PROFILE
1 WEEK RECONDITIONING BETWEEN ECLIPSE SEASONS
TEST OBJECTIVE: VERIFY THE EFFECTS OF TEFLONATION ON CADMIUM PLATE
THEORETICAL EFFECTS OF TEFLONATION.
A BETTER BALANCED ELECTROLYTE DISTRIBUTION WHICH CAN REDUCE CADMIUM MIGRATION.
REDUCTION IN VOLTAGE FADING DUE TO BETTER SEPARATOR WETTING.
TWO SIMILAR BATTERY CELLS WITH TEFLONATED CADMIUM ELECTRODES WERE SELECTED FOR ANALYSIS AFTER FOUR ECLIPSE SEASONS.

Figure 48. Deep depth of discharge test program

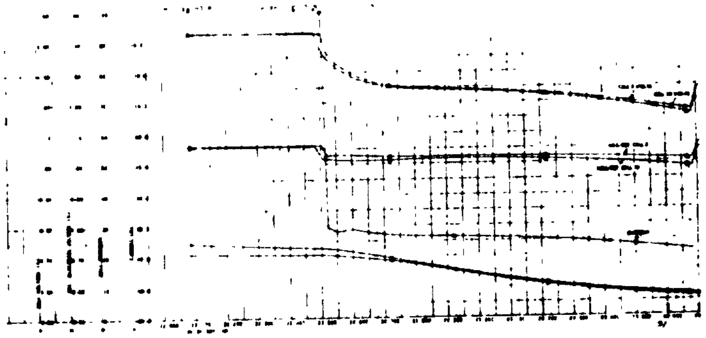


Figure 50

RESULTS:

TEFLONATED ELECTRODES HAD 50% LESS ELECTROLYTE THAN PREVIOUSLY ANALYZED CELLS WITH NON-TEFLONATED ELECTRODES.

THE SEPARATOR HAD TWO TO THREE TIMES MORE ELECTROLYTE THAN CELLS FROM SIMILAR TESTS HAVING NON TEFLONATED ELECTRODES.

CADMIUM MIGRATION WAS NEGLIGIBLE

END OF DISCHARGE VOLTAGE AT MAXIMUM DEPTH OF DISCHARGE WAS 10-15 MILLIVOLTS HIGHER THAN SIMILAR CELLS IN THE SAME TEST WITHOUT TEFLONATED ELECTRODES.

Figure 49. Deep depth of discharge test program

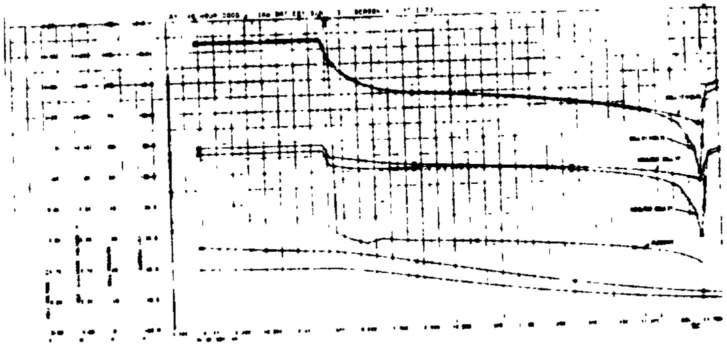


Figure 51

	ECLIPSE SEASON NO. 1			ECLIPSE SEASON NO. 5 (NOTE 1)			ECLIPSE SEASON NO. 8 (NOTE 2)		
LOT NO.	MINIMUM	MAXIMUM	MEAN	MINIMUM	MAXIMUM	MEAN	MINIMUM	MAXIMUM	MEAN
7B	1.161 (6)	1.166 (2)	1.164	1.086 (6)	1.116 (2)	1.107	1.103 (6)	1.118 (2)	1.111
8B	1.156 (8,9,11)	1.159 (7)	1.157	1.095 (10)	1.111 (7)	1.102	1.104 (11)	1.114 (7)	1.108
10	1.156 (12)	1.160 (15,17)	1.158	1.082 (14)	1.115 (17)	1.095	1.078 (14)	1.115 (17)	1.095
11	1.153 (18)	1.158 (23)	1.155	0.813 (21)	1.083 (23)	1.003	1.085 (21)	1.114 (22)	1.096

( ) = CELL POSITION NUMBER

NOTE 1: BEFORE RECONDITIONING TO LOW VOLTAGE

NOTE 2: TWO ECLIPSE SEASONS AFTER RECONDITIONING

Figure 52. Cell lot end-of-discharge voltage performance on life test

LOT NO.	CALC. FLOODED CAP. (Ah dm^{-2})	NET ELECTROLYTE WEIGHT (g)	FINAL STEADY-STATE OVERCHARGE PRESSURE (psig)	NUMBER OF ELECTROLYTE ADJUSTMENTS REQUIRED	CAPACITY AT SUPPLIER (Ah to 1 V)	CAPACITY AT TRW 3RD CYCLE (Ah to 1.1 V)	CAPACITY AFTER 30 CYCLE BURN-IN (Ah to 1.1 V)
7B	P: 3.50 N: 5.30	164.5	22	1	58.5	63.8	63.1
8B	P: 3.50 N: 5.29	179.0	30	1	58.1	62.3	58.7
10	P: 3.50 N: 5.27	161.3	31	2	57.1	59.5	60.2
11	P: 3.51 N: 5.31	162.5	59	2-3	54.1	59.6	56.7

Figure 53. Cell manufacturing and test data by lot numbers

Figure 54

SEALED NiCd CELL IDENTIFICATION	CELL SIZE	TERMINAL TESTED	PHENOPTHALEIN TEST RESULTS	POTASSIUM CONCENTRATION PPM	REMARKS
EAGLE PITCHER NO 0173	10 A H	NEGATIVE	NO LEAK	0.80	
GENERAL ELECTRIC 83-15	12 A H	NEGATIVE	SMALL LEAK	237	TEST SETUP USED HAD 3.0 TIMES THE STANDARD WATER VOLUME
GENERAL ELECTRIC 3C 37	12 A H	NEGATIVE	LEAK	580	IMMEDIATELY AFTER TWO SUBSEQUENT WASHES NO LEAK WITH PHENOLPHTHALEIN BUT OBTAINED 1.38 PPM BY ATOMIC ABSORPTION TEST
GULTON VO6-HS NO [illegible]	6 A H	NEGATIVE	SMALL LEAK	285	IMMEDIATELY AFTER ONE SUBSEQUENT WASH NO LEAK WITH PHENOLPHTHALEIN, BUT OBTAINED 1.38 PPM BY ATOMIC ABSORPTION
EAGLE PITCHER NO 46	3 A H	NEGATIVE	LEAK	414	
GENERAL ELECTRIC, BATTERY NO 2 CELL 4	10 A H	POSITIVE	NO LEAK	11.8	VERY NOTICEABLE ARC DAMAGE EVIDENT TO METAL DISC THAT IS BRAZED TO CERAMIC
GENERAL ELECTRIC BATTERY NO 2 CELL 9	13 A H	NEGATIVE	NO LEAK	341	MINOR ARC DAMAGE EVIDENT TO DISC THAT IS BRAZED TO CERAMIC
PURE WATER DOUBLE DISTILLED				0.16	

Figure 55. Seal leakage test summary

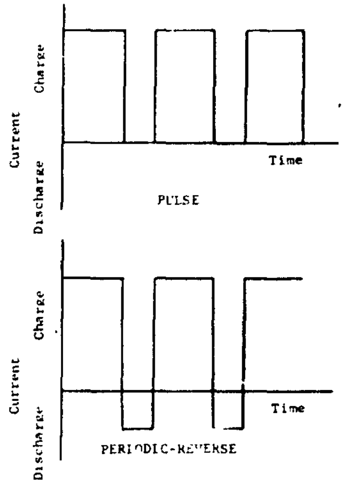


Figure 56

MASS TRANSFER CONSIDERATIONS

I. Reduction of Concentration Overpotential

II. Reduction of Gas Evolution

III. Power Saving

KINETIC CONSIDERATIONS

I. Influence of Nonfaradaic Process

II. Modification of Electrode Kinetics

STRUCTURAL CONSIDERATIONS

I. Composition of Active Materials

II. Crystalline Size and Structure

Figure 57

APPROACH OF PULSE CHARGING PROJECT

I. Half-Cell Studies

II. Theoretical Investigation

III. Battery Testing

Figure 58

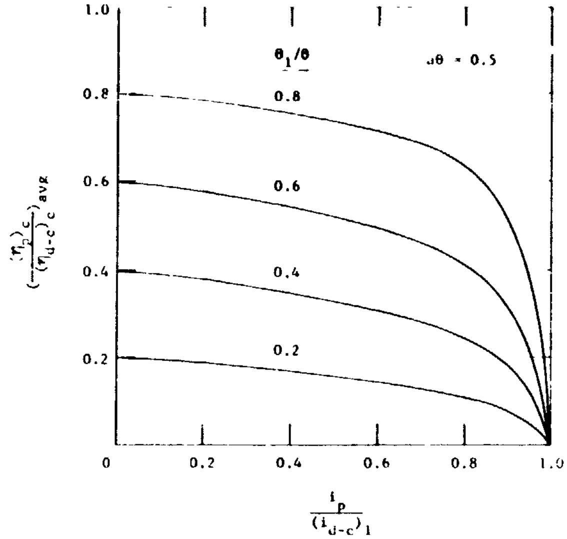


Figure 60

BASIC ASPECTS OF BATTERY CHARGING

I. Mass Transfer

II. Electrode Kinetics

III. Structure of Electrodes

Figure 59

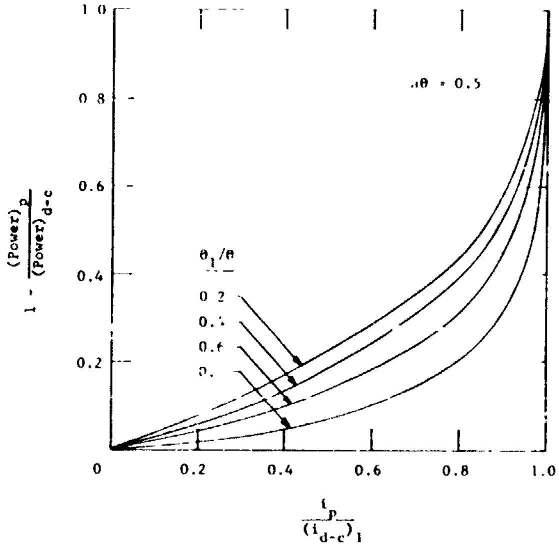


Figure 61

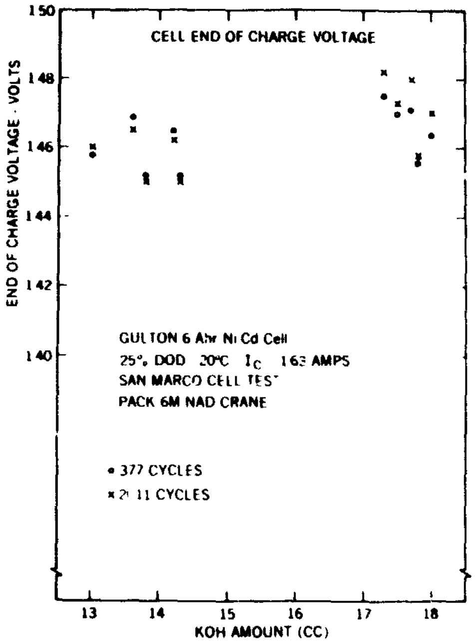


Figure 62

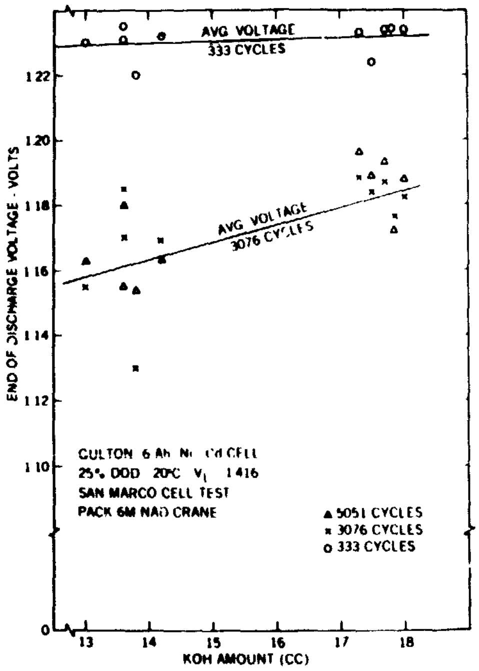


Figure 63

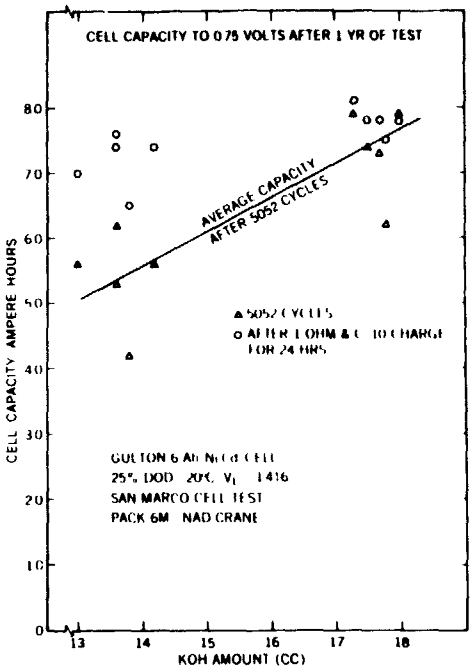


Figure 64

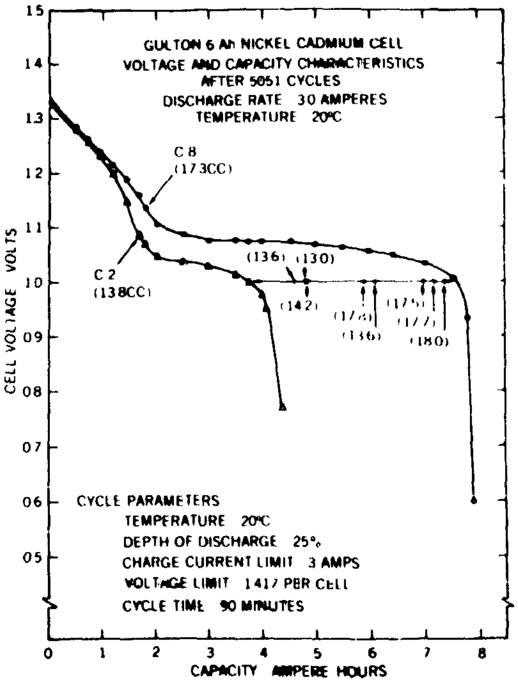


Figure 65

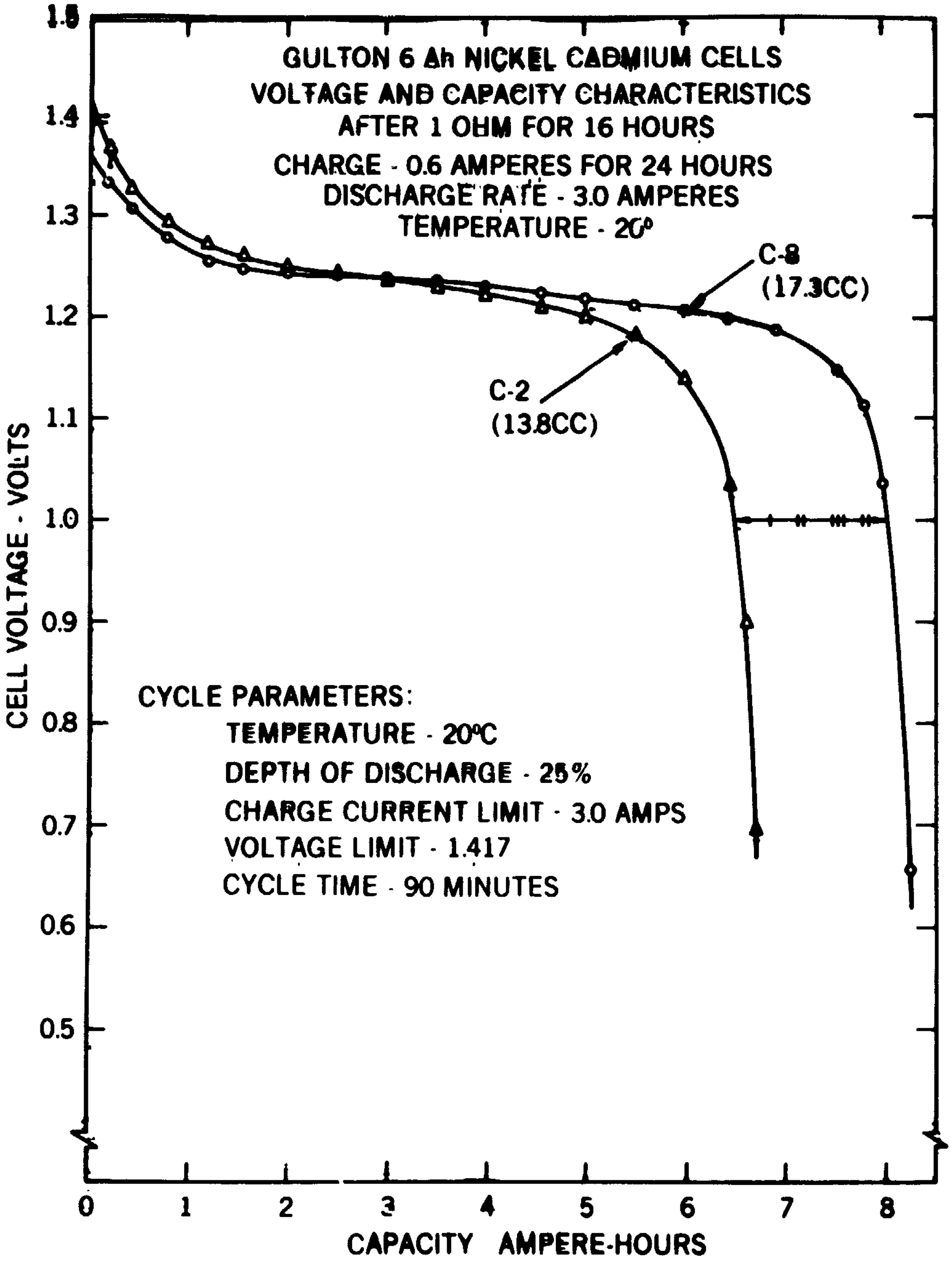

GULTON 6 Ah NICKEL CADMIUM CELLS
VOLTAGE AND CAPACITY CHARACTERISTICS
AFTER 1 OHM FOR 16 HOURS
CHARGE - 0.6 AMPERES FOR 24 HOURS
DISCHARGE RATE - 3.0 AMPERES
TEMPERATURE - 20°
C-8
(17.3CC)
C-2
(13.8CC)
CYCLE PARAMETERS:
TEMPERATURE - 20°C
DEPTH OF DISCHARGE - 25%
CHARGE CURRENT LIMIT - 3.0 AMPS
VOLTAGE LIMIT - 1.417
CYCLE TIME - 90 MINUTES
CELL VOLTAGE - VOLTS
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
1
2
3
4
5
6
7
8
CAPACITY AMPERE-HOURS

Figure 66

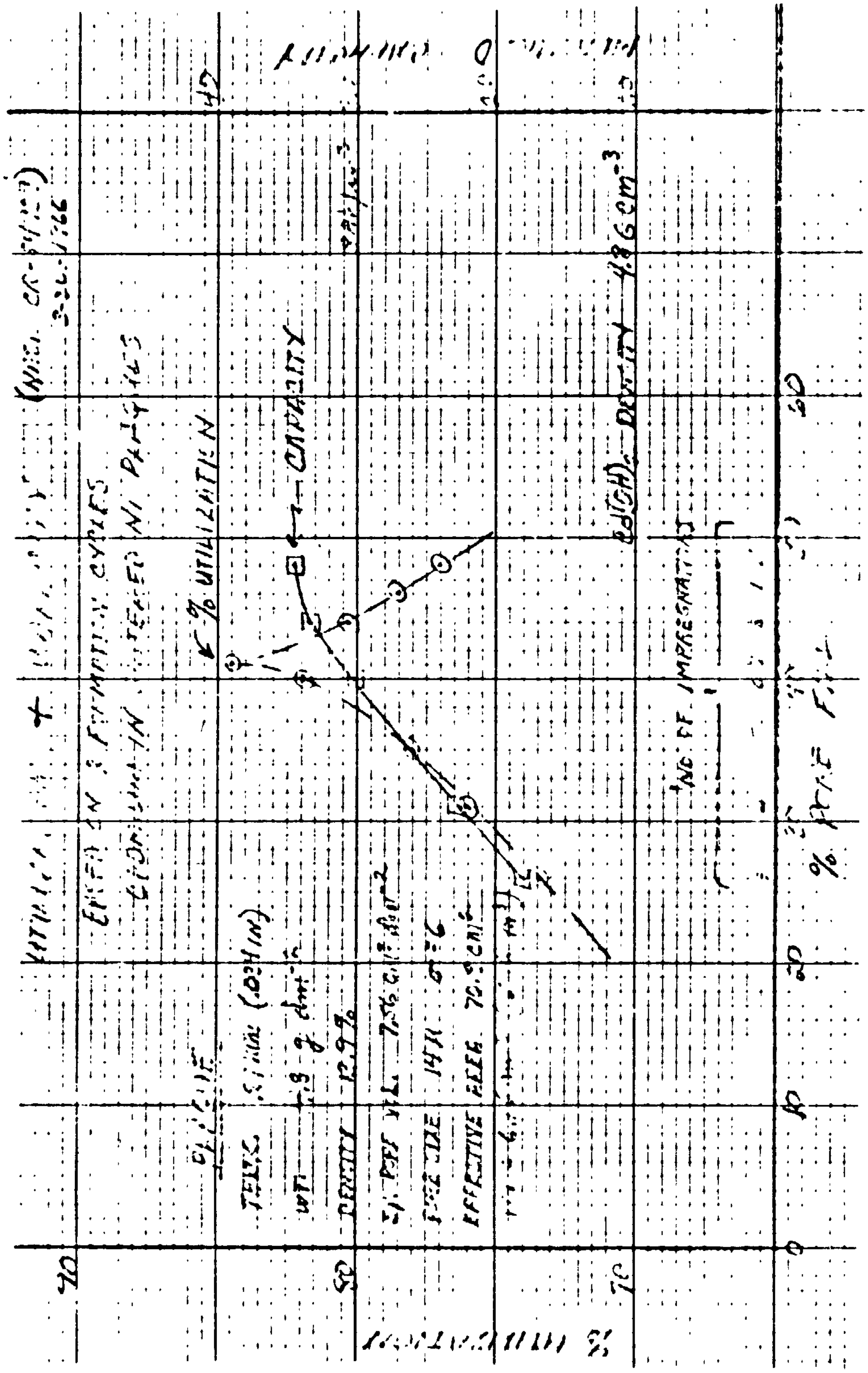
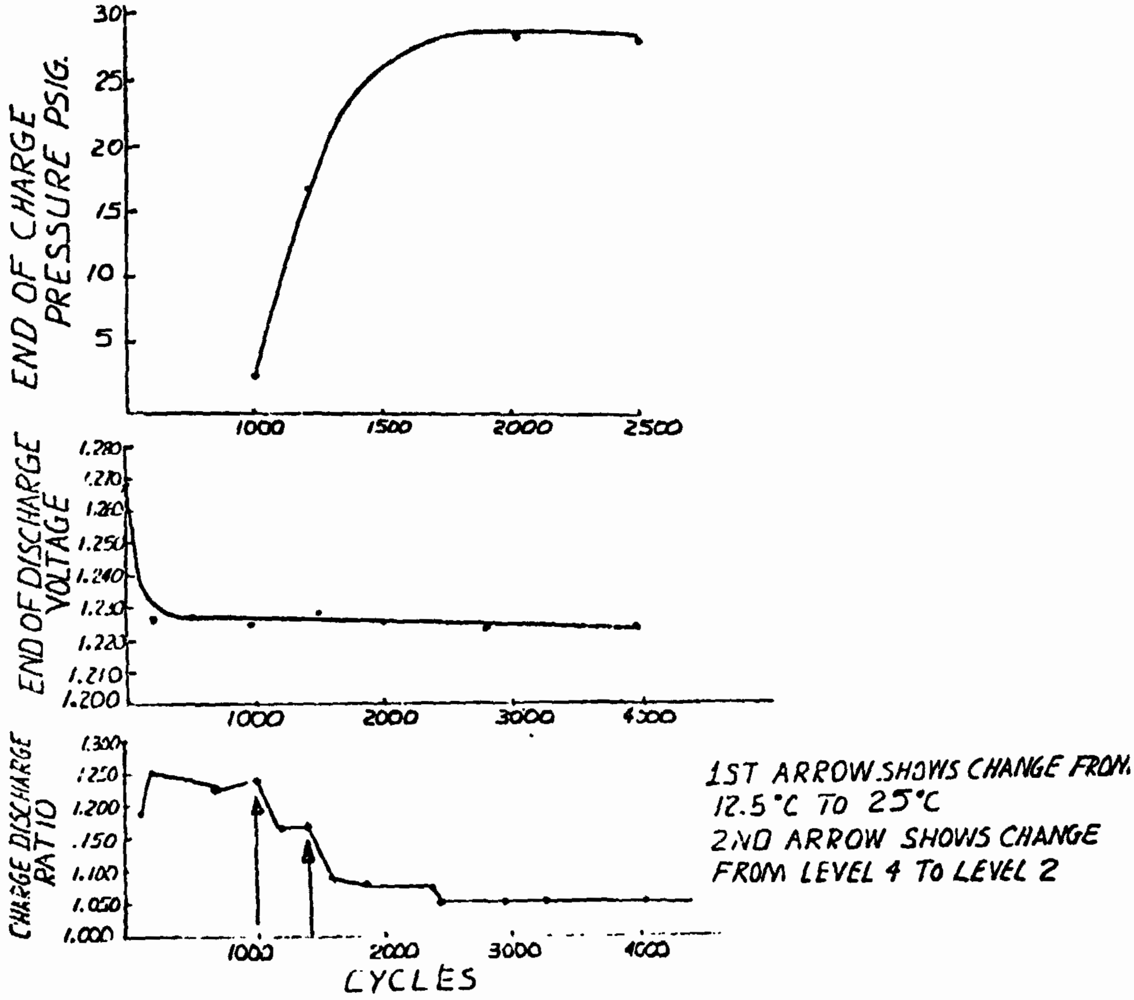


Figure 67. Effect on pore fill on material



1ST ARROW SHOWS CHANGE FROM 12.5°C TO 25°C
2ND ARROW SHOWS CHANGE FROM LEVEL 4 TO LEVEL 2

Figure 68. Low Earth orbit battery life test

GULTON IND. 15 AH (MFG. 71)

DRY STORED IN ARGON

FLIGHT CELLS ACTIVATED APRIL, 1973

LAUNCH MAY, 1974

NEG. TO POS. RATIO 1.40 MIN.

EXCESS NEG. 5AH MIN.

PRECHARGE 1 AH

ELECTROLYTE 43 cc.

Figure 69. ATS-6 cell background

ECLIPSE	END OF DISCHG E	END OF CHARGE I	Ah RETURNED	CAPACITY Ah
3	1.215 v	.45 to .69a.	10 0 to 19 5	20 0
4	1.182 v.	.40 to .63a	10.0 to 18 3	18.1*
5	1.181 v	.40 to .87a	12 0 to 22.9	18 8
6	1.179 v	39 to .75a	7 2 to 20 0	18 6
7	1 178 v			18.8

Figure 70. ATS-6 engineering cells Pack 226 A

ECLIPSE	END OF DISCHG E	END OF CHARGE I	Ah RETURNED	CAPACITY Ah
1	1.204 v.	.38 to .58a.	11.6 to 18.1	19.3
2	1.186 v.	.49 to .56a	11.6 to 19.0	18.9
3	1 192 v.			17.2

Figure 71. ATS-6 flight cells Pack 226 B

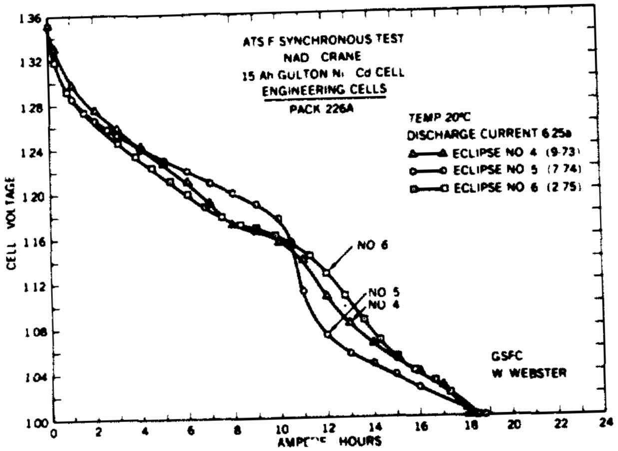


Figure 72

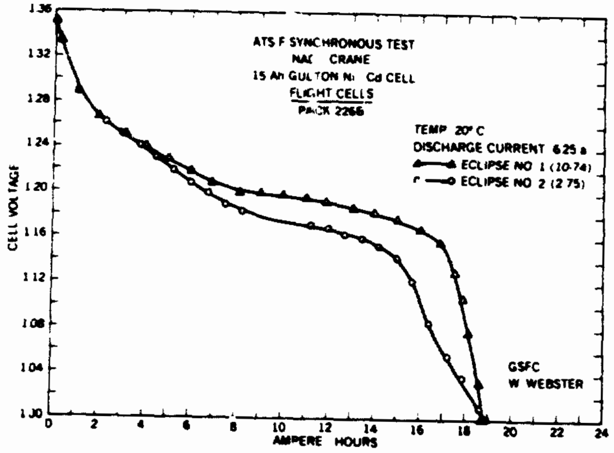


Figure 73

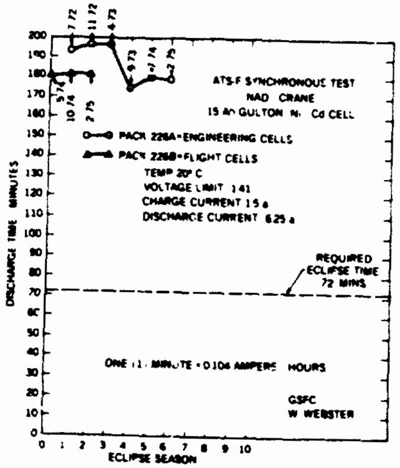


Figure 74

GENERAL ELECTRIC 12 AH (MFG. 72)

DRY STORED IN NITROGEN

FLIGHT CELLS ACTIVATED MARCH, 1974

LAUNCH JUNE, 1975

NEG. TO POS. RATIO 1.50 MIN.

EXCESS NEG. 11 TO 9.3 AH

PRECHARGE 3.3 AH

ELECTROLYTE 35 cc.

Figure 75. OSO-8 cell background

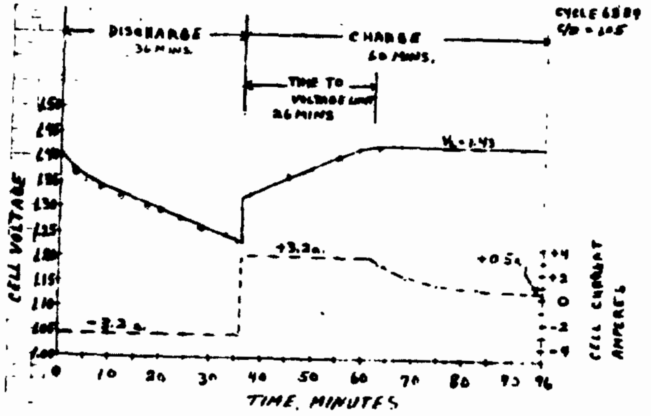


Figure 76. OSO-I life cycle test @ 10°C charger level 2

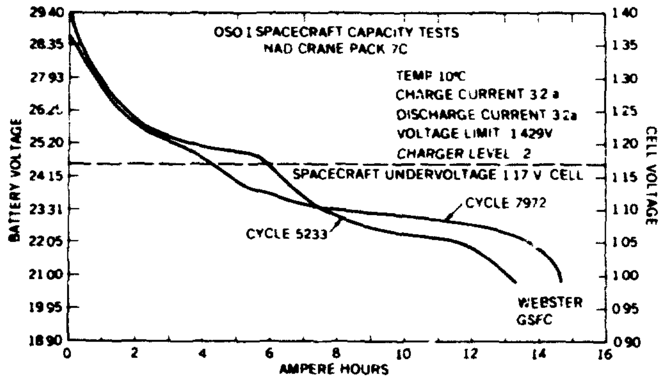


Figure 77

- SPIN STABILIZED SATELLITE 75 INCHES IN DIAMETER WITH AN ON-ORBIT LENGTH OF 102 6 INCHES AND WEIGHT OF 64[illegible] POUNDS
- SATELLITE SPINNING PROVIDES LINE SCAN IN A WEST-TO EAST DIRECTION WITH NORTH-SOUTH TRACING BY A VISIBLE INFRARED SPIN-SCAN RADIOMETER (VISSR)
- SATELLITE COMMUNICATION SYSTEM HAS THREE FREQUENCY BANDS HIGH RATE DIGITAL S-BAND, UHF AND VHF WITH ADEQUATE POWER [illegible] AND INTERIOR VOLUME TO ADAPT TO A VARIETY OF FUTURE MIS[illegible]
- SATELLITE POWER FOR MORE THAN [illegible] PR[illegible] [illegible]INDRICAL SOLAR ARRAY AND TWO PARALLEL [illegible] BATTERIES

Figure 78. SMS [illegible]tures

Figure 79. Synchronous meteorological satellite

DESIGNATED GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE (GOES)

DEVELOPED BY AERONUTRONIC FORD AND NASA FOR THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA) TO ADVANCE THE SCIENCE OF ENVIRONMENTAL MONITORING, INCLUDING WEATHER FORECASTING

- CONTINUOUS STORM TRACKING
- CLOUD ANALYSIS - DENSITY, TEMPERATURE, HEIGHT, WIND VELOCITY
- SURFACE TEMPERATURE MAPPING
- SPACE ENVIRONMENT SUN/EARTH INTERACTION
- REMOTE SENSOR DATA RELAY - FLOOD, RAIN, SNOW TSUNAMI, EARTHQUAKE, AIR WATER POLLUTION MONITORING

Figure 80. Synchronous meteorological satellite (SMS)

Figure 81. SMS/GEOS weather picture (NOAA)

NORMAL MAIN BUS BATTERY LOAD	5 A BATTERY
BATTERY DISCHARGE VOLTAGE RANGE	[illegible] TO [illegible] V
MAXIMUM DEPTH OF DISCHARGE	[illegible] RATED CAPACITY
BOOST CONVERTER EFFICIENCY	85% DESIGN MINIMUM
PEAK DISCHARGE RATE (SEE [illegible])	[illegible] A
MAXIMUM DISCHARGE TIME	1.2 H
MAXIMUM ALLOWABLE CHARGE TIME	[illegible] H
TOTAL CYCLES AT ECLIPSE (5 YEARS)	440 CYCLES
CYCLE REPETITION RATE	24 H
OPERATING TEMPERATURE	[illegible]
TRICKLE CHARGE PERIODS	[illegible] DAYS BETWEEN CYCLING PERIODS
ORBITAL LIFETIME	5 YEARS MINIMUM
BATTERY SYSTEM	TWO 10-CELL ASSEMBLIES
WEIGHT BATTERY	[illegible] LB. MAXIMUM
LOCATION OF C.G. (FROM BASE)	[illegible] INCH
MAXIMUM THERMAL LOAD BATTERY	[illegible]

Figure 82. SMS battery performance requirements

Figure 83. SMS battery assembly

SUMMARY OF DESIGN STRESSES AND FACTORS OF SAFETY

LOCATION	ULTIMATE		YIELD	
	(KSI)	F.S.	(KSI)	F.S.
CELL SUPPORT RIB				
WEB SHEAR	0 9	23.35	0 6	20.00
WEB TENSION	[illegible]	8 46	2 6	6 92
FLANGE SHEAR	1 3	14.15	0 9	13 35
FLANGE BENDING	[illegible]	40	15 8	1 14
FLANGE BEARING	[illegible]	05	2 4	12 10
END PLATE				
MAIN SUPPORT [illegible] SHEAR	[illegible]	12	5 4	2.22
MAIN SUPPORT [illegible]	[illegible]	24	1. 9	1 51
SIDE WEB SHEAR	[illegible]	[illegible]	10 1	1 19
THROUGH BOLT TENSION	[illegible]	1 14	15 5	2 58
TIE DOWN BOLT TENSION	[illegible]	[illegible] 45	1 3	13 85
TIE-DOWN BOLT SHEAR	[illegible]	10 00	1 4	8 58

Figure 84. SMS battery structural analysis

ORIGINAL PAGE IS
OF POOR QUALITY

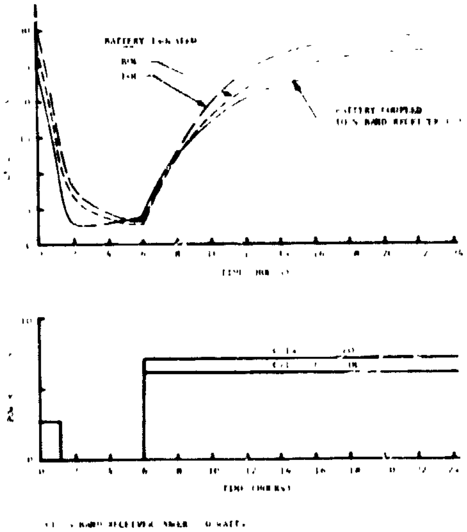


Figure 85 SMS battery temperature profile for a typical 24 hour equinox period

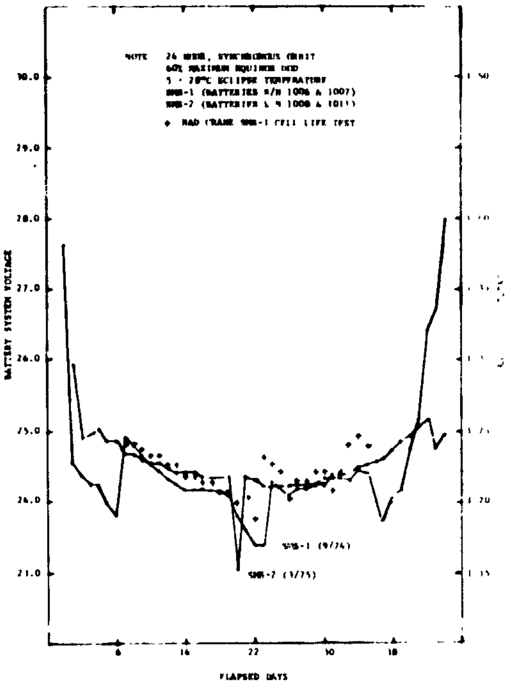


Figure 87. SMS orbital eclipse season 1 - battery voltage

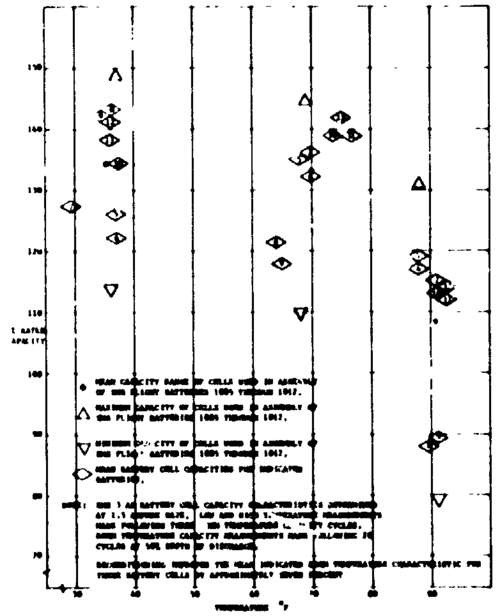


Figure 86. Summary of SMS battery cell capacity characteristics

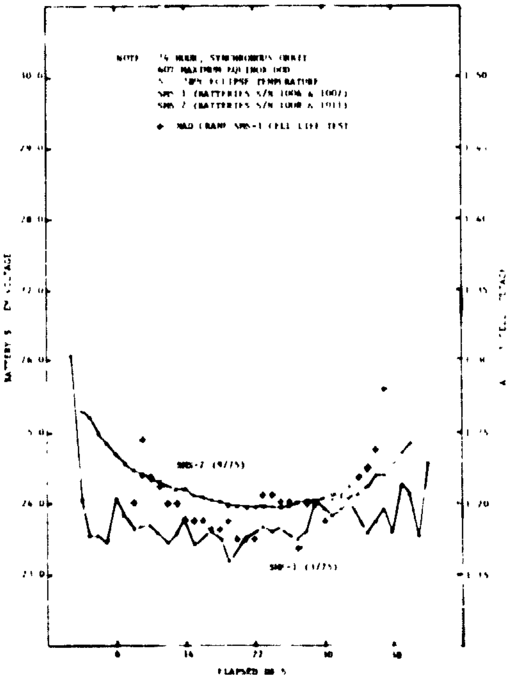


Figure 88. SMS orbital eclipse season 2 - battery voltage

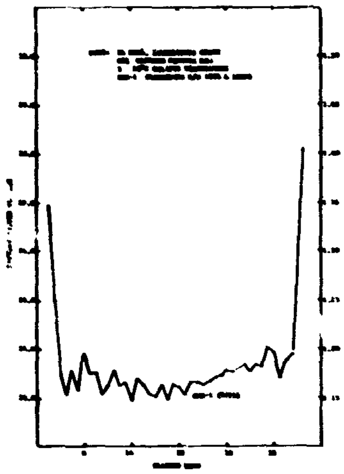


Figure 89. SMS orbital eclipse season 3 - battery voltage

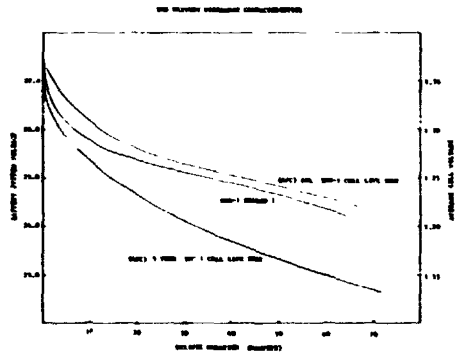
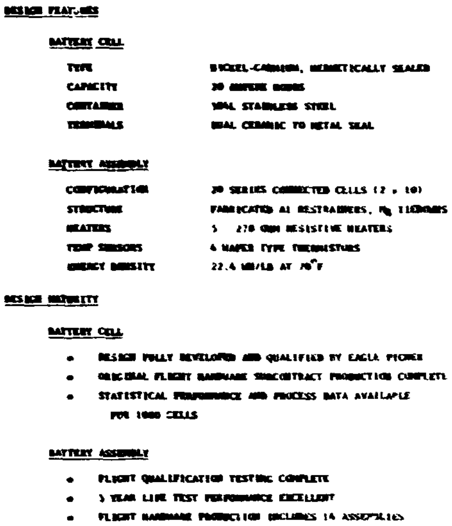


Figure 90. SMS battery discharge characteristics

Figure 91. NATO IV spacecraft battery assembly (22.4 WH/L6 energy storage)



DESIGN FEATURES

BATTERY CELL

TYPE	NICKEL-CADMIUM, HERMETICALLY SEALED
CAPACITY	30 AMPERE HOURS
CONTAINER	304L STAINLESS STEEL
TERMINALS	DUAL CERAMIC TO METAL SEAL

BATTERY ASSEMBLY

CONFIGURATION	20 SERIES CONNECTED CELLS (2 x 10)
STRUCTURE	FABRICATED Al RESTRAINERS, Mg [illegible]
HEATERS	5 - 270 OHM RESISTIVE HEATERS
TEMP SENSORS	6 WAFER TYPE THERMISTORS
ENERGY DENSITY	22.4 WH/LB AT 70°F

DESIGN MATURITY

BATTERY CELL

- DESIGN FULLY DEVELOPED AND QUALIFIED BY EAGLE PICHER
- ORIGINAL FLIGHT HARDWARE SUBCONTRACT PRODUCTION COMPLETE
- STATISTICAL PERFORMANCE AND PROCESS DATA AVAILABLE FOR 1000 CELLS

BATTERY ASSEMBLY

- FLIGHT QUALIFICATION TESTING COMPLETE
- 3 YEAR LIFE TEST PERFORMANCE EXCELLENT
- FLIGHT HARDWARE PRODUCTION INCLUDES 14 ASSEMBLIES

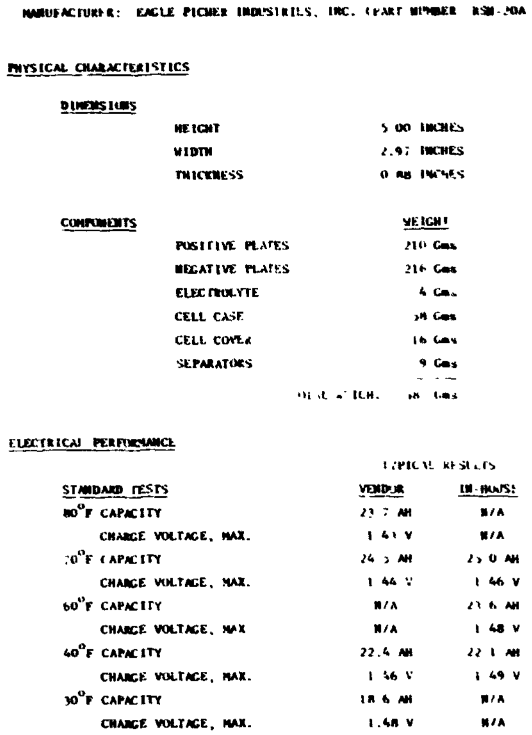
Figure 92. NATO III battery assembly

Figure 93. Design evolution (background)

C.4

Figure 94. Background

Figure 95. Planned development



MANUFACTURER: EAGLE PICHER INDUSTRIES, INC. (PART NUMBER RSN-20A

PHYSICAL CHARACTERISTICS

DIMENSIONS

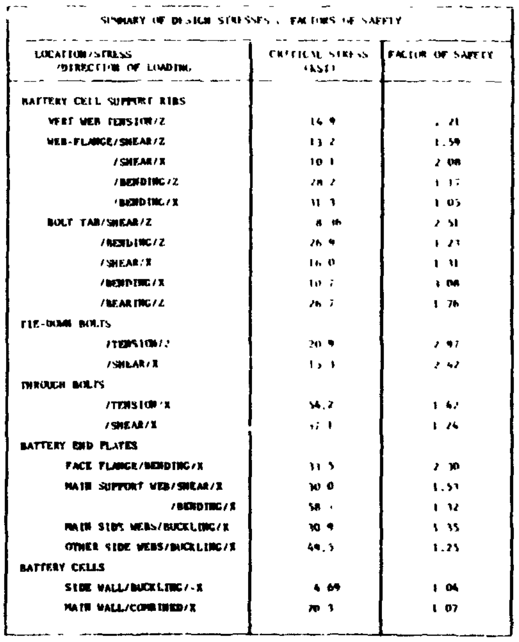
HEIGHT	5.00 INCHES
WIDTH	2.97 INCHES
THICKNESS	0.88 INCHES

COMPONENTS	WEIGHT
POSITIVE PLATES	210 Gms
NEGATIVE PLATES	216 Gms
ELECTROLYTE	4 Gms
CELL CASE	58 Gms
CELL COVER	16 Gms
SEPARATORS	9 Gms
TOTAL WEIGHT	[illegible] Gms

ELECTRICAL PERFORMANCE

	TYPICAL RESULTS	
STANDARD TESTS	VENDOR	IN-HOUSE
80°F CAPACITY	23.7 AH	N/A
CHARGE VOLTAGE, MAX.	1.43 V	N/A
70°F CAPACITY	24.5 AH	25.0 AH
CHARGE VOLTAGE, MAX.	1.44 V	1.46 V
60°F CAPACITY	N/A	23.6 AH
CHARGE VOLTAGE, MAX	N/A	1.48 V
40°F CAPACITY	22.4 AH	22.1 AH
CHARGE VOLTAGE, MAX.	1.46 V	1.49 V
30°F CAPACITY	18.6 AH	N/A
CHARGE VOLTAGE, MAX.	1.48 V	N/A

Figure 96. NATO III battery cell design



SUMMARY OF DESIGN STRESSES & FACTORS OF SAFETY

LOCATION/STRESS /DIRECTION OF LOADING	CRITICAL STRESS (KSI)	FACTOR OF SAFETY
BATTERY CELL SUPPORT RIBS		
VERT WEB TENSION/Z	14.9	1.21
WEB-FLANGE/SHEAR/Z	13.2	1.59
/SHEAR/X	10.1	2.08
/BENDING/Z	28.2	1.17
/BENDING/X	31.3	1.05
BOLT TAB/SHEAR/Z	8.06	2.51
/BENDING/Z	26.9	1.23
/SHEAR/X	16.0	1.31
/BENDING/X	10.7	1.08
/BEARING/Z	26.7	1.76
TIE-DOWN BOLTS		
/TENSION/Z	20.9	2.97
/SHEAR/X	15.3	2.42
THROUGH BOLTS		
/TENSION/X	56.2	1.62
/SHEAR/X	47.1	1.26
BATTERY END PLATES		
FACE FLANGE/BENDING/X	33.5	2.30
MAIN SUPPORT WEB/SHEAR/X	30.0	1.53
/BENDING/X	58.[illegible]	1.32
MAIN SIDE WEBS/BUCKLING/X	30.9	1.35
OTHER SIDE WEBS/BUCKLING/X	49.5	1.25
BATTERY CELLS		
SIDE WALL/BUCKLING/-X	4.69	1.04
MAIN WALL/COMBINED/X	70.3	1.07

Figure 97. NATO III Battery assembly

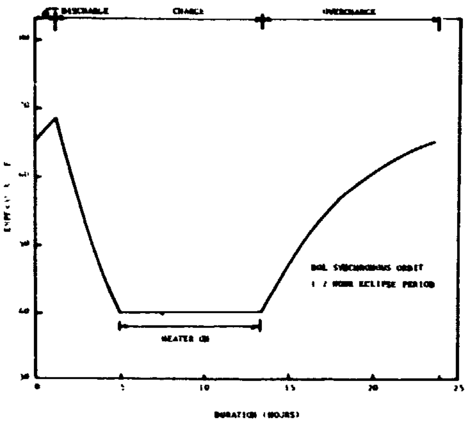
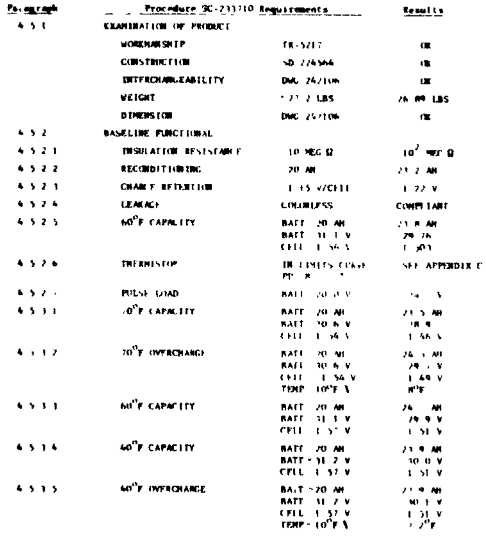
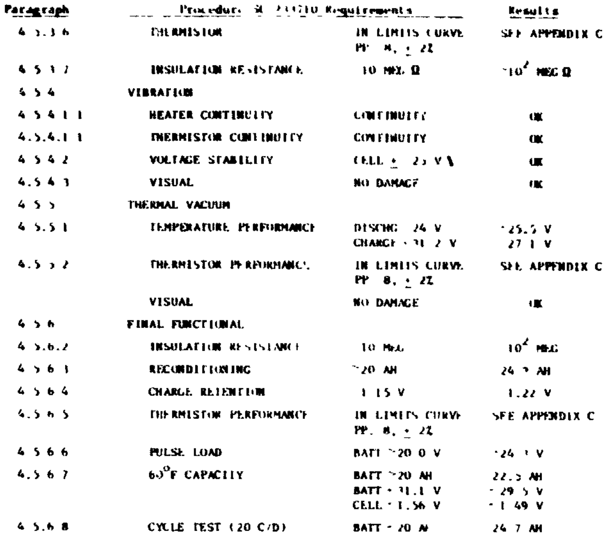


Figure 98. NATO III battery typical equinox temperature profile



Paragraph	Procedure SC-233710	Requirements	Results
4.5.1	EXAMINATION OF PRODUCT		
	WORKMANSHIP	TR-5217	OK
	CONSTRUCTION	SD 224566	OK
	INTERCHANGEABILITY	DWG 242106	OK
	WEIGHT	< 27.2 LBS	26.89 LBS
	DIMENSION	DWG 242106	OK
4.5.2	BASELINE FUNCTIONAL		
4.5.2.1	INSULATION RESISTANCE	10 MEG Ω	10^2 MEG Ω
4.5.2.2	RECONDITIONING	20 AH	23.2 AH
4.5.2.3	CHARGE RETENTION	1.15 V/CELL	1.22 V
4.5.2.4	LEAKAGE	COLORLESS	COMPLIANT
4.5.2.5	60°F CAPACITY	BATT 20 AH BATT 31.1 V CELL 1.56 V	23.8 AH 29.76 1.503
4.5.2.6	THERMISTOR	IN LIMITS CURVE PP 8	SEE APPENDIX C
4.5.2.7	PULSE LOAD	BATT 20.0 V	[illegible] V
4.5.3.1	70°F CAPACITY	BATT 20 AH BATT 30.6 V CELL 1.54 V	21.5 AH 28.9 1.46 V
4.5.3.2	70°F OVERCHARGE	BATT 20 AH BATT 30.6 V CELL 1.54 V TEMP 10°F Δ	24.[illegible] AH 29.[illegible] V 1.49 V 8°F
4.5.3.3	60°F CAPACITY	BATT 20 AH BATT 31.1 V CELL 1.57 V	24.[illegible] AH 29.9 V 1.51 V
4.5.3.4	40°F CAPACITY	BATT 20 AH BATT < 31.2 V CELL 1.57 V	23.9 AH 30.0 V 1.51 V
4.5.3.5	40°F OVERCHARGE	BATT > 20 AH BATT 31.2 V CELL 1.57 V TEMP < 10°F Δ	23.9 AH 30.1 V 1.51 V [illegible]2°F

Figure 99. NATO III battery assembly test summary



Paragraph	Procedure SC 233710	Requirements	Results
4.5.3.6	THERMISTOR	IN LIMITS CURVE PP 8, ± 2%	SEE APPENDIX C
4.5.3.7	INSULATION RESISTANCE	10 MEG Ω	$>10^4$ MEG Ω
4.5.4	VIBRATION		
4.5.4.1.1	HEATER CONTINUITY	CONTINUITY	OK
4.5.4.1.1	THERMISTOR CONTINUITY	CONTINUITY	OK
4.5.4.2	VOLTAGE STABILITY	CELL ± .25 V	OK
4.5.4.3	VISUAL	NO DAMAGE	OK
4.5.5	THERMAL VACUUM		
4.5.5.1	TEMPERATURE PERFORMANCE	DISCHG > 24 V CHARGE < 31.2 V	> 25.5 V 27.1 V
4.5.5.2	THERMISTOR PERFORMANCE	IN LIMITS CURVE PP 8, ± 2%	SEE APPENDIX C
	VISUAL	NO DAMAGE	OK
4.5.6	FINAL FUNCTIONAL		
4.5.6.2	INSULATION RESISTANCE	10 MEG	10^4 MEG
4.5.6.3	RECONDITIONING	> 20 AH	24.[illegible] AH
4.5.6.4	CHARGE RETENTION	1.15 V	1.22 V
4.5.6.5	THERMISTOR PERFORMANCE	IN LIMITS CURVE PP. 8, ± 2%	SEE APPENDIX C
4.5.6.6	PULSE LOAD	BATT > 20.0 V	> 24.[illegible] V
4.5.6.7	65°F CAPACITY	BATT > 20 AH BATT < 31.1 V CELL < 1.56 V	22.5 AH = 29.5 V = 1.49 V
4.5.6.8	CYCLE TEST (20 C/D)	BATT > 20 AH	24.7 AH

Figure 100. NATO III battery assembly test summary (cont'd)

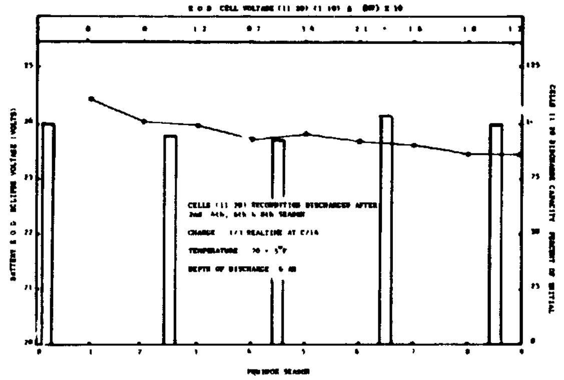


Figure 101. NATO III battery equinox season life test results

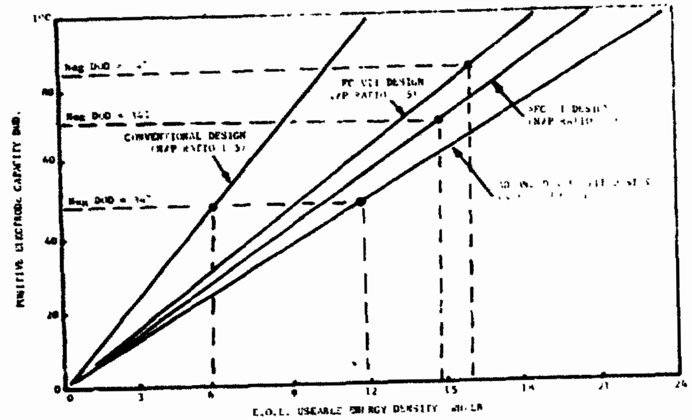


Figure 102. Comparative battery design charac- for long life synchronous orbit flight spacecraft

OBJECTIVES

- OPTIMIZE ENERGY STORAGE FOR SYNCHRONOUS ORBIT MISSIONS
- 7 TO 10 YEARS OPERATING LIFE AT TEMPERATURE
- IMPROVE COMPONENT RELIABILITY
- INCREASE ENERGY DENSITY [illegible] WH/LB OR EQUIVALENT)
- MAINTAIN LOW DEPTH OF DISCHARGE ON Cd ELECTRODE

DESIGN APPROACH

- SELECT POSITIVE ELECTRODE DOD IN 70 TO 80% RANGE - BASIS NASA REALTIME LIFE TESTS
- LIMIT NEGATIVE ELECTRODE DOD TO 35% (DEMONSTRATED CAPABILITY)
- INCREASE N P RATIO AND MAINTAIN STANDARD PLATE LOADINGS
- UTILIZE ULTRALIGHT WEIGHT CELL CONTAINER DESIGN TECHNOLOGY
- EVALUATE ELECTROCHEMICAL ELECTRODE LOADING PROCESSES

DESIGN CHARACTERISTICS

	STD DESIGN	AFL VI & VII DESIGNS
o N/P RATIO	1.5	2.0 - 2.5
o RATED ENERGY DENSITY	12 WH/LB	20 - 22 WH/LB
o DESIGN DOD, 7 YEARS	50%	70 - 80%
o EOL, BATTERY ENERGY DENSITY	5 WH/LB	15.2 WH/LB
o BOL, EQUIVALENT STD CELL ENERGY DENSITY	N/A	36.5 WH/LB*

*EQUIVALENT STD CELL RATED ENERGY DENSITY:

$$15.2 \text{ WH/LB} \times \frac{12 \text{ WH/LB (RATED)}}{5 \text{ WH/LB (EOL)}} = 36.5 \text{ WH/LB}$$

Figure 103. Advanced Ni-Cd cell design development

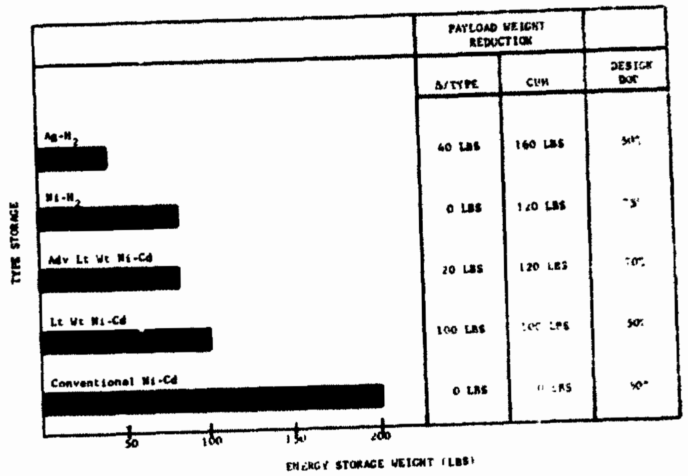


Figure 104. Synchronous orbit long life 1 KW battery comparative weight characteristics for flight spacecraft

ORIGINAL PAGE IS OF POOR QUALITY

- PROFILED TEMPERATURE TO SIMULATED SPACECRAFT ENVIRONMENT; NOMINAL 7 to 15°C ENVIRONMENT AT THE BASEPLATE.
- EARLY LIFE DEPTH OF DISCHARGE (63% DOD) AND CHARGE RATE (C/10) SIMULATED FOR 2-1/2 EQUIVALENT YEARS.
- LATE LIFE DEPTH OF DISCHARGE (75% DOD) AND CHARGE RATE (C/15) SIMULATED FOR 7-1/2 EQUIVALENT YEARS WITH ONE CELL FAILED IN ONE BATTERY.
- SUNLIGHT PERIODS NOT SIMULATED; NEGLECTED BECAUSE C/100 TRICKLE CHARGE RATE IS USED.
- CAPACITY MEASUREMENTS MADE DURING RECONDITIONING CYCLES AT END OF EACH SEASON.
- CHARGE CONTROL - CHARGE TO TEMPERATURE COMPENSATED VOLTAGE LIMIT ADJUSTABLE BY COMMAND OVER EIGHT LEVELS.
- TEST SAMPLE:
  - 12 CELL PACK, NO RECONDITIONING FOR 5 EQUIVALENT YEARS.
  - 12 CELL PACK, RECONDITIONED FOR 10 EQUIVALENT YEARS.

Figure 105. Fltsatcom accelerated life test description

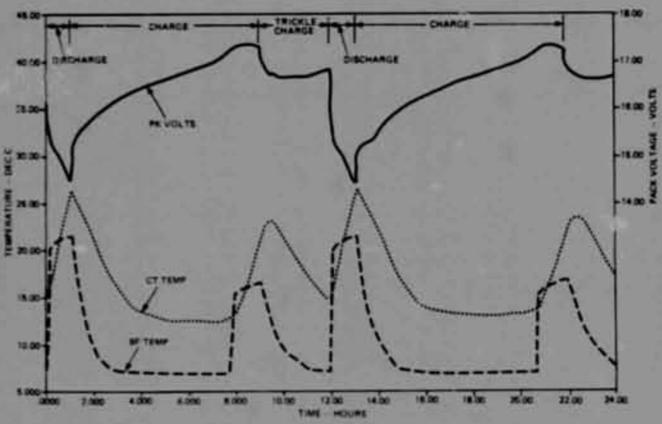


Figure 106. FSC pack B life cycles 13 + 14

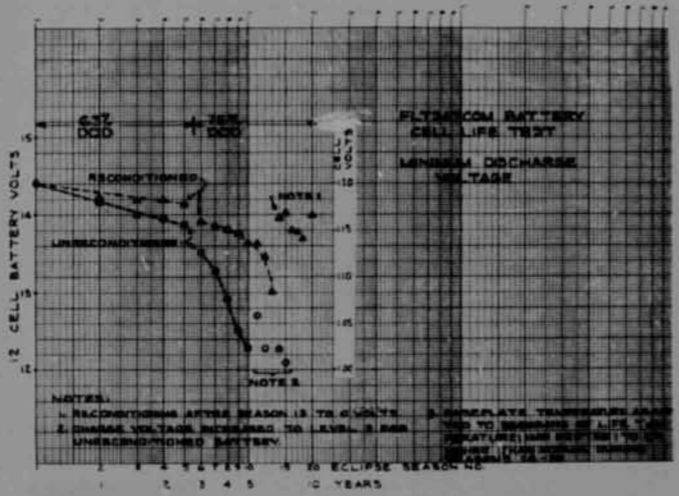


Figure 107

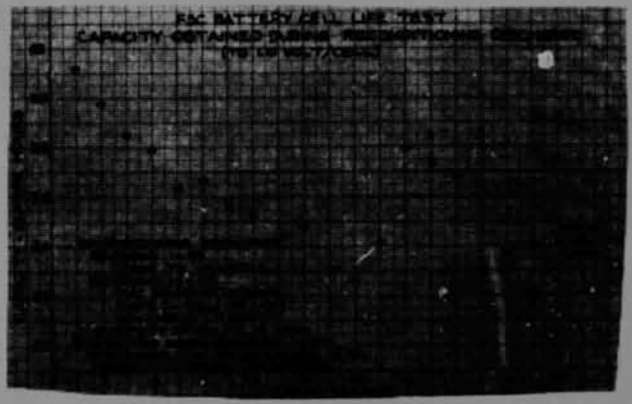


Figure 108

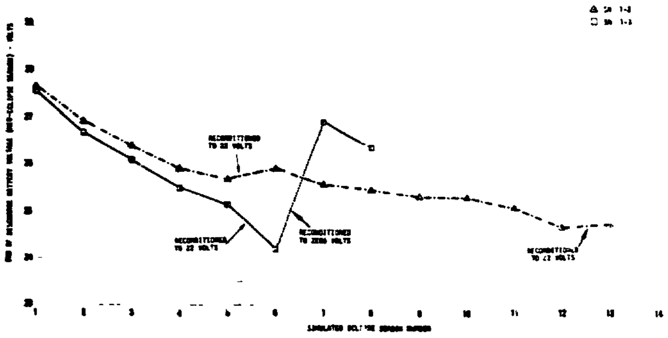


Figure 109. 1 KW battery system prototype accelerated life test performance

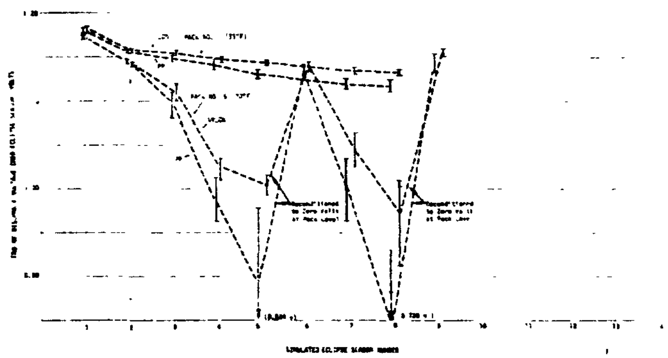
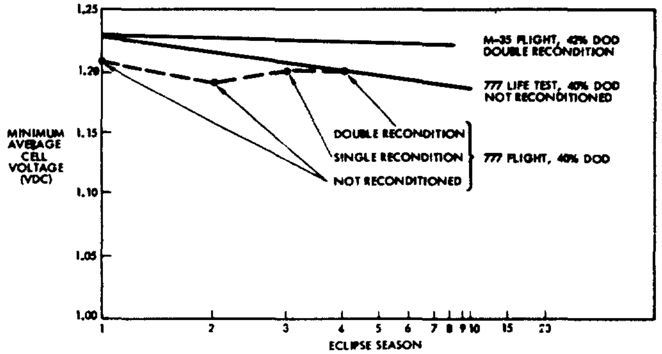


Figure 110. Cell pack accelerated life test performance



NOTE:
RECONDITIONING WAS A DISCHARGE INTO 44 OHM RESISTOR TO AN AVERAGE CELL VOLTAGE OF 0.9 TO 1.0 VOLTS

Figure 111. Battery life experience voltage degradation characteristics

	TRANSIT 12, 13 & 14	SAS-B	SAS-C
Launch Date	(12) 4/14/67 (13) 5/18/67 (14) 9/25/67	11/15/72	5/7/75
Orbit Type	Circular Polar	Circular Equatorial	Circular Equatorial
Altitude	600 nmi	300 nmi	300 nmi
No. of Orbits/Day	13.3	15	15
Orbit Time	108 Min.	96 Min.	96 Min.
Eclipse Time	0 to 35 Min.	36 Min.	36 Min.
Projected Cycle Life (Based on NASA SP-172, Pg. 102)	2×10^4	10^4	8×10^3
Projected Lifetime (months)	50	22	17

Figure 112. SAS transit orbital characteristics

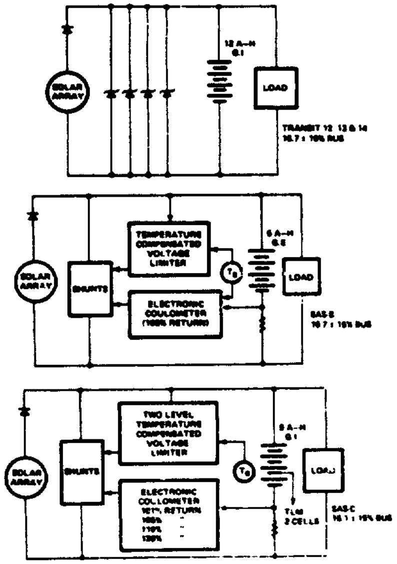


Figure 113.

	TRANSIT 12, 13 & 14	SAS-B	SAS-C
Cell Type (Rectang. NiCd)	12 A-H	6 A-H	9 A-H
Cell Manufacturer	Gulton (SAFT America)	G.E.	Gulton (SAFT America)
Teflon Coated Plates	No	Yes	No
Typical Depth of Discharge	0 to 11%	21	25
Torquing Depth of Discharge	No Torquing	32%	30%
Charge-Discharge Profile	Variable	Nearly Constant	Nearly Constant
Initial Recharge Rate	Variable	C/1.5	C/1.5
Temperature	15 to 32°C 59 to 90°F	3 to 28°C 37 to 82°F	13.5 to 28°C 56 to 82°F
No. Cells/Battery	8	8	12

Figure 114. SAS and transit battery characteristics

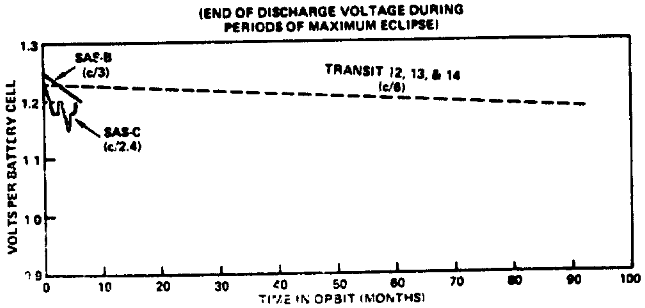


Figure 115. Comparison of transit and SAS battery performance

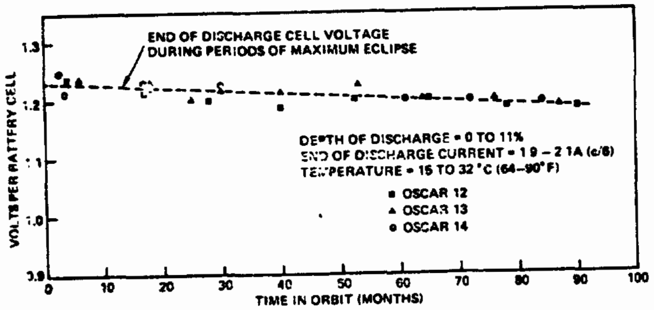


Figure 116. Battery orbital performance of transit 12, 13 and 14

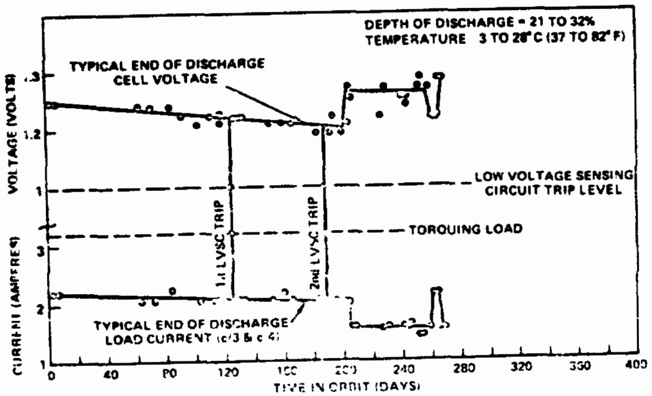


Figure 117. Battery orbital performance, SAS-B

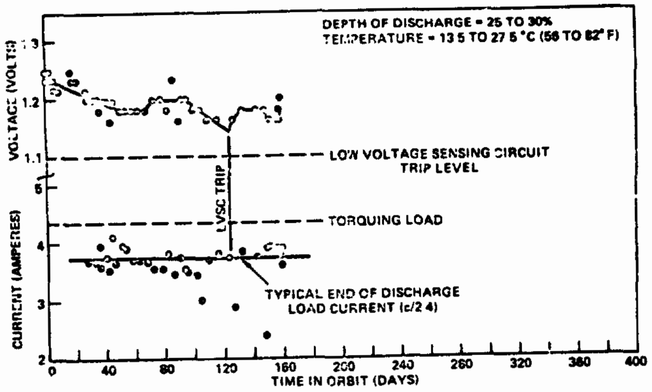


Figure 118. Battery orbital performance, SAS-C

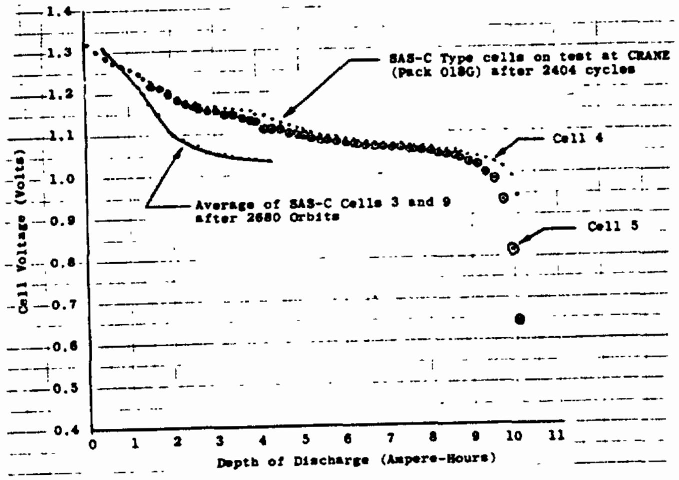


Figure 119. Comparison of SAS-C cells in orbit with those at CRANE

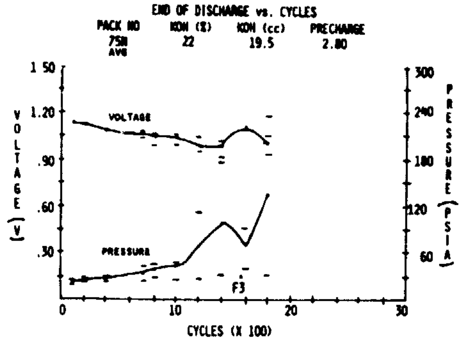


Figure 120

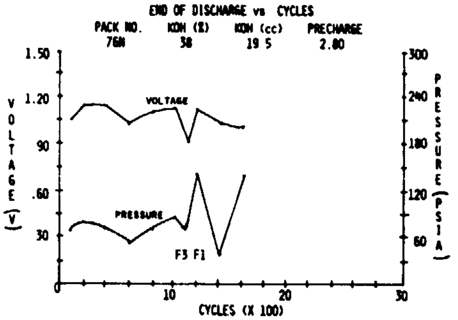


Figure 121

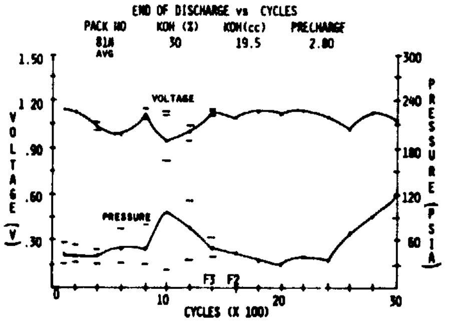


Figure 122

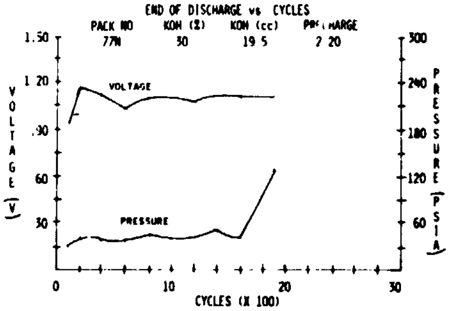


Figure 123

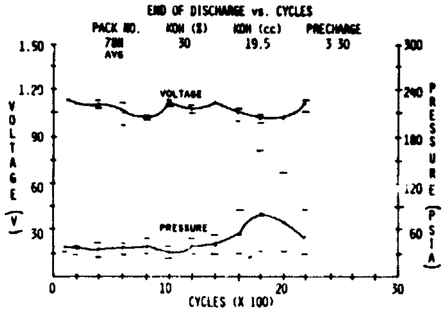


Figure 124

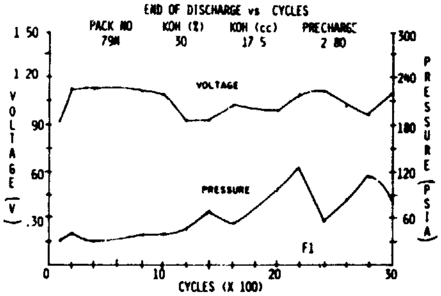


Figure 125

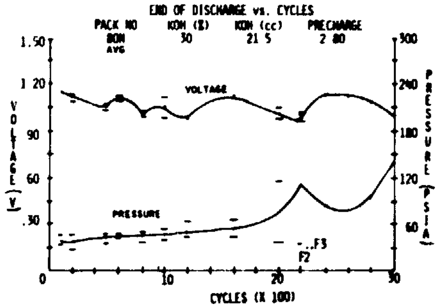


Figure 126

PACK NUMBER	11/[illegible]/7[illegible] CYCLES TO DATE
1N	1430
5N	842
11N	527
15N	618
1[illegible]N	922
22N	522
28N	111[illegible]
32N	3
36N	44[illegible]
40N	90
42N	345
4[illegible]N	50[illegible]
55N	5[illegible]
57N	113
61N	9[illegible]
65N	405[illegible]
67N	1048[illegible]
71N	156[illegible]
83N	48[illegible]7
84N	4017
85N	519[illegible]
86N	40[illegible]

Figure 127

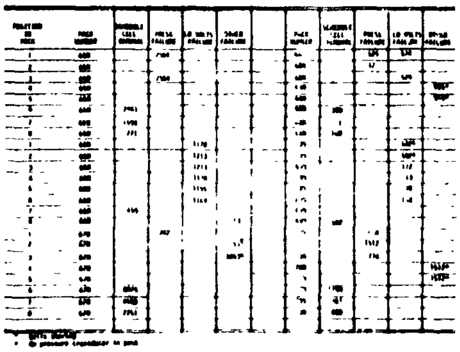


Figure 128

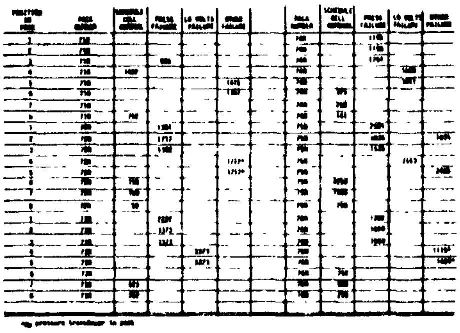


Figure 129

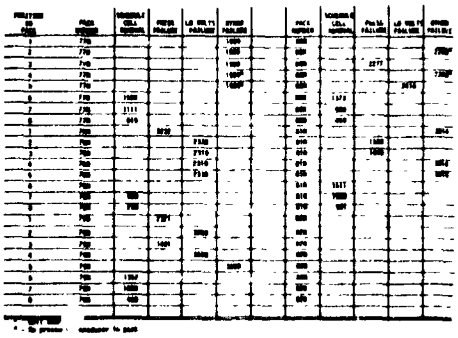


Figure 130

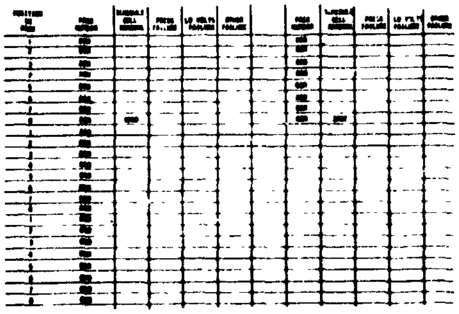


Figure 131

Figure 132

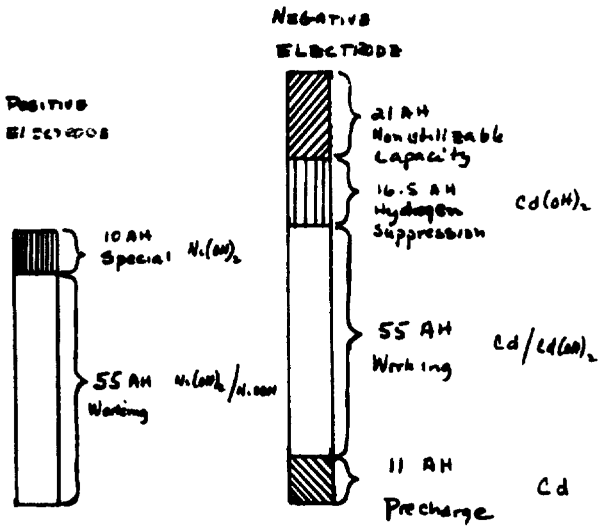


Figure 133. Capacity distribution for performance and overcharge

DESIGN NR.	POSITIVE ELECTRODE THICKNESS (INCHES)	POSITIVE ELECTRODE SINTER POROSITY (%)	POSITIVE ELECTRODE NR. OF PLATES	NEGATIVE ELECTRODE THICKNESS (INCHES)	NEGATIVE ELECTRODE SINTER POROSITY (%)	NEGATIVE ELECTRODE NR. OF PLATES	CELL WEIGHT (GRAMS)
6	0.036	82	14	0.036	90	15	1486
11	0.032	84	16	0.032	90	17	1478
15	0.036	84	14	0.038	90	15	1475

Figure 134. Electrode designs for 20 W-H/LB nickel-cadmium cell

Design	S/N	Weight Dry	(Grams) Activated	Electrolyte Wt	C/2 Cap. (AH)	W-H/LB	Midpt. Voltage	EOCU (Volts)	EOCP (PSIA)
15	14	1192	1390	198	49.6	20	1.21	1.437	15
	15	1194	1392	198	51.7	20	1.21	1.435	15
	16	1191	1398	207	51.2	20	1.21	1.436	15
	17	1186	1386	200	50.0	20	1.20	1.435	15
	18	1182	1381	199	50.8	20	1.21	1.436	15
	19	1178	1377	199	50.4	20	1.21	1.438	11
	20	1186	1377	191	48.8	19	1.20	1.434	10
	21	1189	1380	191	48.8	19	1.21	1.433	15
	$\bar{X}$	1187±6	1385±8	198±5	50.2±1.1			1.436±.002	14±2

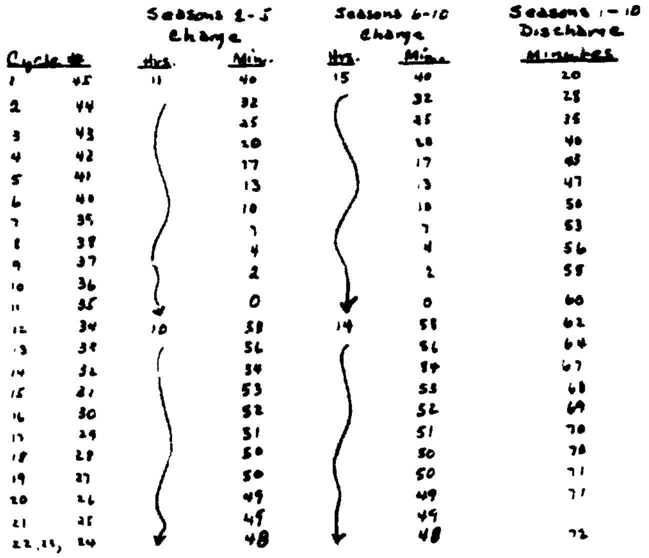
Figure 135. Phase I cell data

Design	S/N	Weight Dry	(Grams) Activated	Electro-lyte Wt	C/2 Cap. (AH)	M-H LB	Midpt. Voltage	EOCU (Volts)	EOCP (PSIA)
11	02	1241	1427	186	54.6	21	1.20	1.442	11
	03	1216	1408	192	50.8	20	1.21	1.437	9
	04	1224	1406	182	50.8	20	1.21	1.434	11
	05	1235	1414	179	50.0	19	1.21	1.438	12
	06	1233	1418	185	50.8	20	1.21	1.434	15
	07	1217	1407	190	50.0	20	1.21	1.435	13
	08	1224	1404	180	50.4	20	1.21	1.433	11
	09	1223	1414	191	49.6	19	1.21	1.424	13
	$\bar{X}$	1227±3	1412±8	186±5	50.9±1.2			1.435±.004	12±2
06	10	1200	1396	196	45.0	18	1.20	1.427	21
	11	1208	1405	197	47.9	19	1.20	1.455	23
	12	1216	1402	186	51.7	20	1.21	1.446	15
	13	1212	1395	183	50.0	20	1.21	1.458	10
	$\bar{X}$	1209±7	1400±5	190±7	48.6±2.1			1.446±.014	17±6

Figure 136. Phase I cell data

Design	S/N	Weight Dry	(Grams) Activated	Electro-lyte Wt	C/2 Cap. (AH)	M-H LB	Midpt. Voltage	EOCU (Volts)	EOCP (PSIA)
11	22	1188	1384	196	50.0	20	1.21	1.434	10
	23	1181	1380	199	50.8	20	1.21	1.430	11
	24	1179	1372	193	50.6	20	1.20	1.434	9
	25	1187	1377	191	50.0	20	1.21	1.426	8
	26	1182	1376	194	51.3	20	1.21	1.425	8
	27	1188	1383	195	51.8	20	1.21	1.425	10
	28	1187	1379	195	51.1	20	1.21	1.426	10
	29	1188	1379	191	51.5	20	1.21	1.424	9
	30	1187	1371	184	51.5	21	1.21	1.424	9
	31	1202	1395	193	52.1	21	1.22	1.427	10
	32	1188	1389	201	50 1	20	1.22	1.428	9
	33	1178	1370	192	51.1	20	1.22	1.419	10
	34	1189	1386	197	52.0	21	1.21	1.424	9
	35	1195	1385	190	51.5	20	1.21	1.425	8
	36	1185	1375	190	51.7	21	1.21	1.430	10
	37	1179	1378	193	48.0	19	1.21	1.423	10
		1186.±6	1380±7	194±4	50.9±1.1	20	1.21	1.426±.004	9

Figure 137. Phase II cell data



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

Figure 138. WU.31452272 - Cell life test procedure (discharge periods for 12 & 16 hour orbits versus cycle number)

OBJECTIVES

- INVESTIGATE SINGLE CELL LEVEL AND BATTERY LEVEL CHARGE/DISCHARGE CONTROL IN EXTENDING BATTERY LIFE IN THE RANGE OF 13,000 TO 20,000 CYCLES IN LOW EARTH ORBIT (3 TO 5 YRS).
- DETERMINE THE EXTENT OF CHARGE CONTROL FLEXIBILITY REQUIRED FOR THE FLEXIBLE CHARGE DISCHARGE CONTROLLER (FCDC).

Figure 139. Investigations of charge control parameters affecting the cycle life of Ni-Cd batteries

- PERFORM SIMULATED LOW EARTH ORBIT TESTS ON TWO (2) BATTERY PACKS, EACH CONTAINING 24 8-AMP-HOUR CELLS.
  - BATTERY LEVEL CONTROL PACK - NO CELL VOLTAGE MONITORING OR CELL BYPASS CAPABILITY ASSUMED.
  - CELL LEVEL CONTROL PACK - CELL VOLTAGE MONITORING AND CELL BYPASS CAPABILITY PROVIDED.
- SUBJECT BATTERIES TO DIFFERENT OVERCHARGE LEVELS AT VARIOUS TEMPERATURES TO DETERMINE DESIRABLE CHARGE CONTROL METHODS.

Figure 140. Approach

RATED CAPACITY:	8 AH
MANUFACTURER:	GENERAL ELECTRIC (GAINESVILLE)
SEPARATOR:	POLYPROPYLENE
NO. POSITIVE PLATES:	11
NO. NEGATIVE PLATES:	12

Figure 141. NiCd cell description

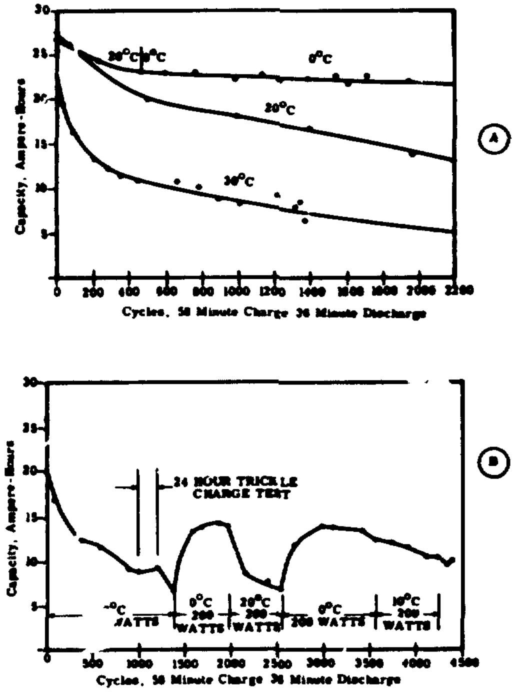


Figure 142. Effects of temperatures A and changes in temperature B on battery capacity

CYCLE NUMBER	CONDITION TEMPERATURE	RECHARGE FRACTION
0-5000	40°C	1.10
5001-5230	40°C	1.60
5230-5350	40°C	1.17
5400-5550	40°C	1.30
5550-5650	25°C	1.17
5650-5730	0°C	1.17
5800-6000	0°C	1.05
6000-6150	0°C	1.10
6150-6300	0°C	1.02
6300-6450	20°C	1.02
6450-6600	20°C	1.10
6600-6750	20°C	1.20
6750-6900	20°C	1.06

OTHER CONDITIONS

ORBIT DURATION:
84 MINUTES (54-MINUTE DAY, 30-MINUTE DARK)
DEPTH OF DISCHARGE:
25%

Figure 143. Histogram of test conditions

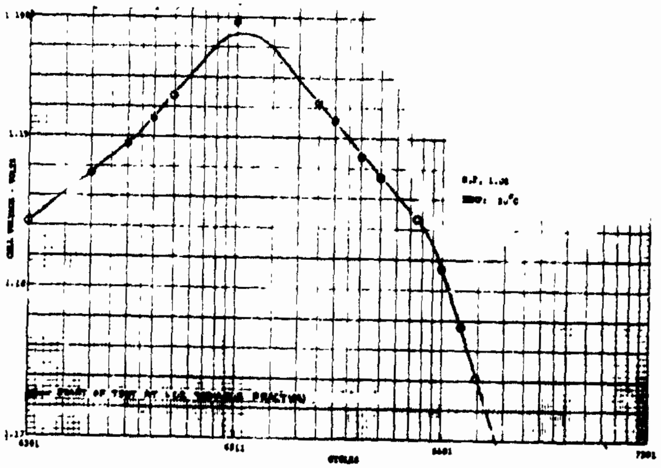


Figure 145. Average end of discharge voltage

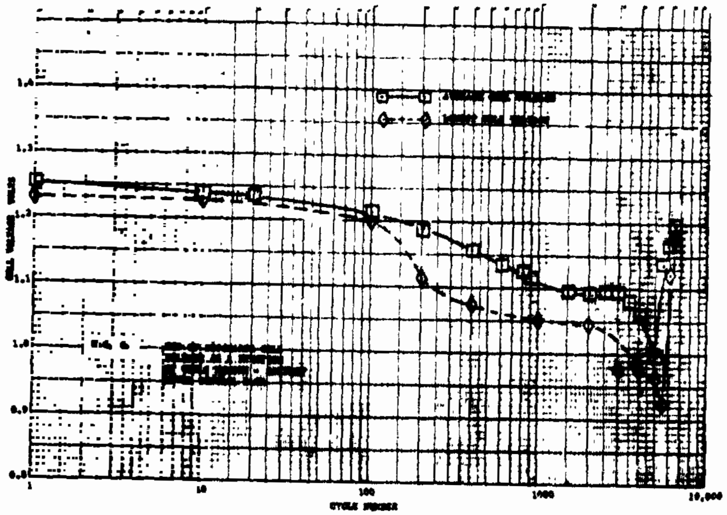


Figure 144

Figure 146. No slide required

Figure 146

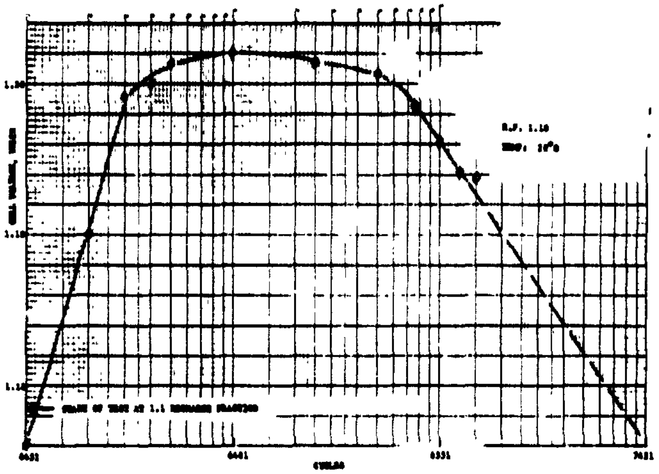


Figure 147. Average end of discharge voltage

Figure 149. No slide required

Figure 149

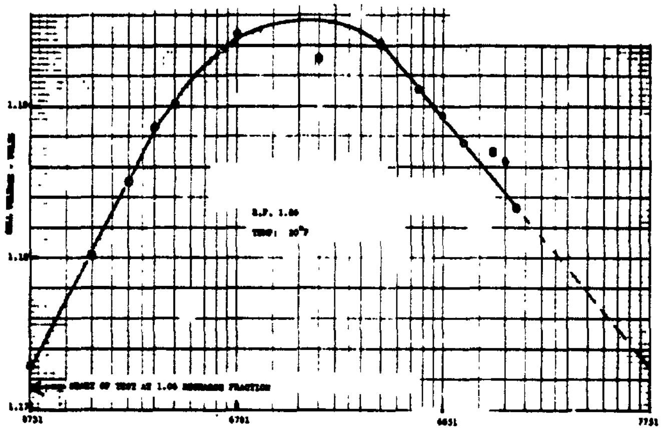


Figure 148. Average end of discharge voltage

Figure 150. No slide required

Figure 150

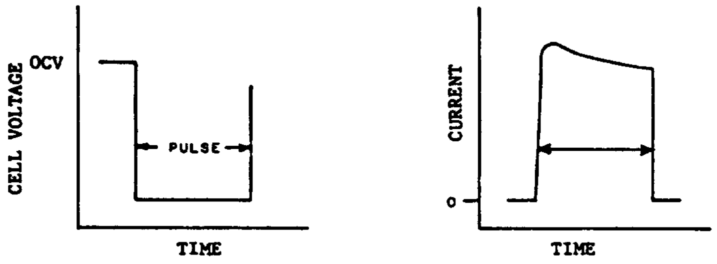


Figure 151. Constant voltage discharge pulse and the response current behavior

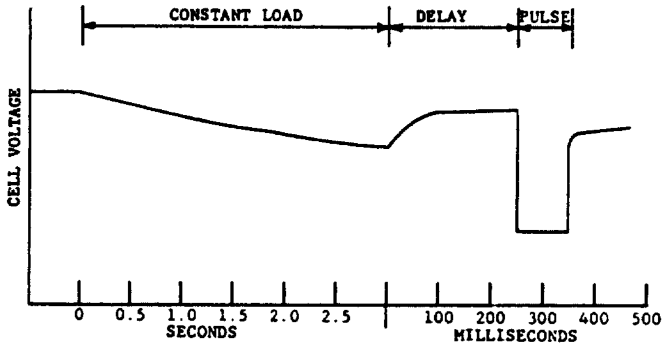


Figure 153. Voltage behavior of nickel-cadmium cell undergoing three-step constant voltage discharge test

The most successful test developed for vented nickel-cadmium cells consists of the following steps

(1) a constant load discharge for 3 seconds across a 0.011 ohm resistor,

(2) a 0.25 second delay (open circuit), and

(3) a constant voltage discharge pulse to 1.050 volts.

The constant load discharge cycle removes only about 0.03A-hr. of charge from the cell. The response current measured at either 100 or 120 msec after the initiation of the pulse is a good state-of-charge indicator

Figure 152

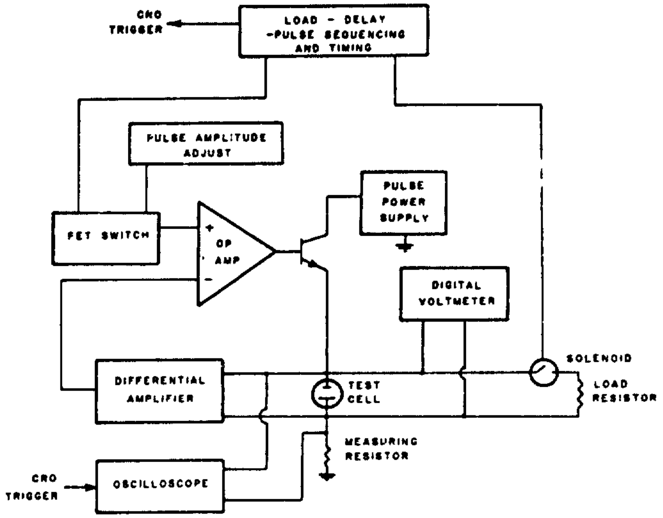


Figure 154. Complete test schematic in constant voltage discharge mode

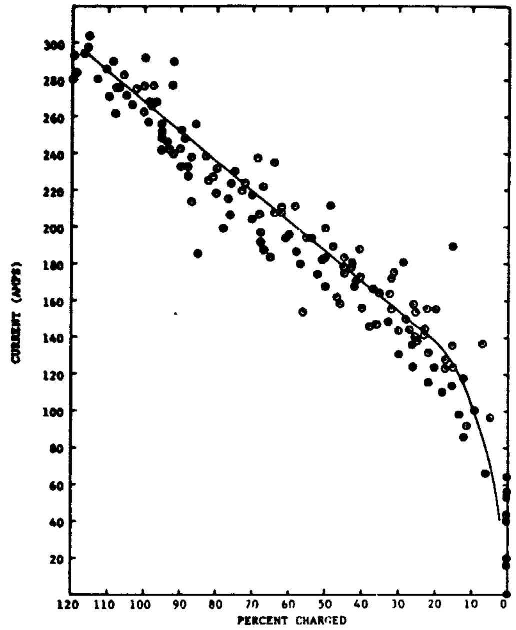


Figure 155. Ni-Cd single cells at 75°F

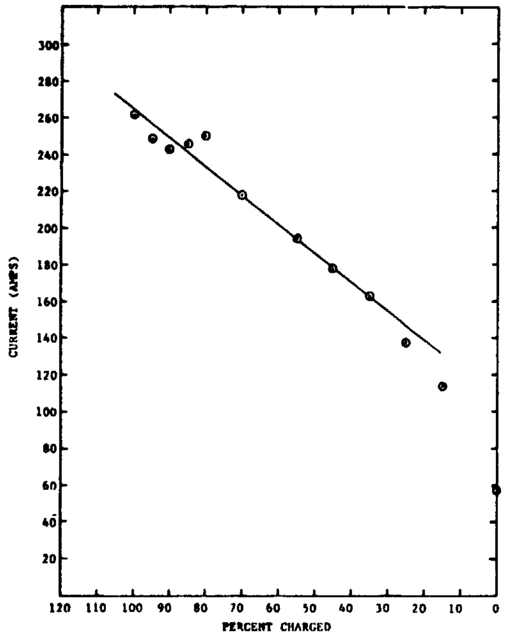


Figure 156. Single Ni-Cd cell at 75°C

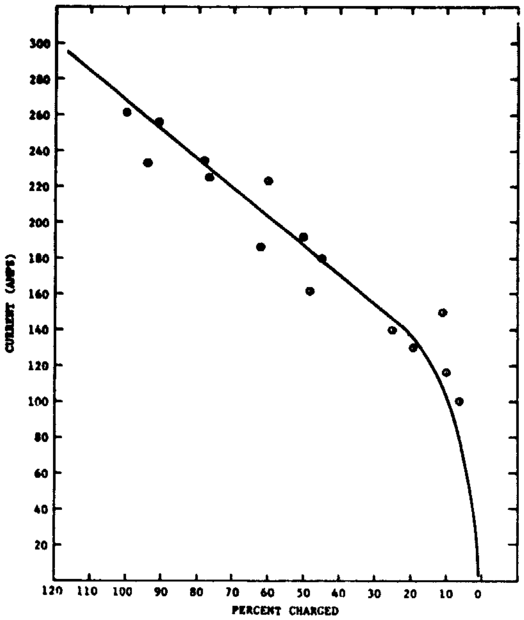


Figure 157. Used and defective Ni-Cd cells at 75°C (solid line represents results of good cells given)

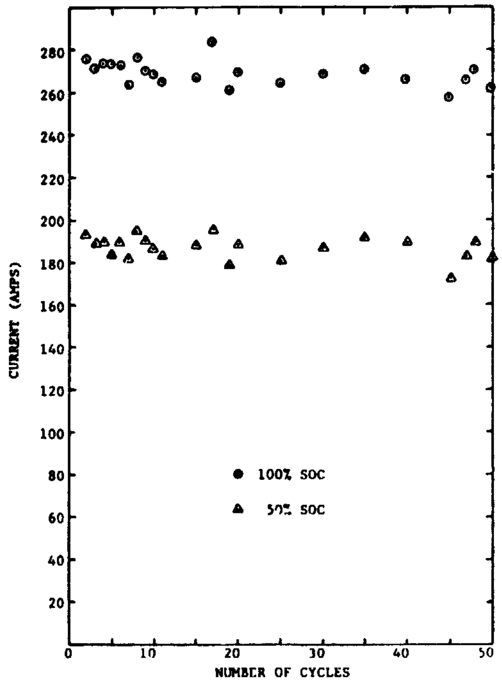


Figure 158. Effect of charge-discharge cycles on response current of nickel-cadmium cells

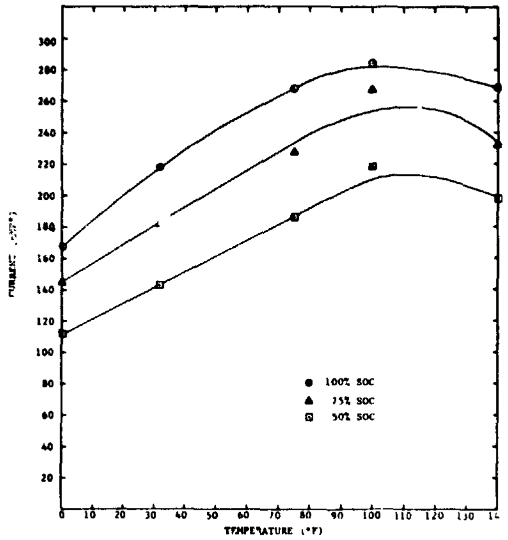


Figure 159. Response current versus temperature for different state of charge

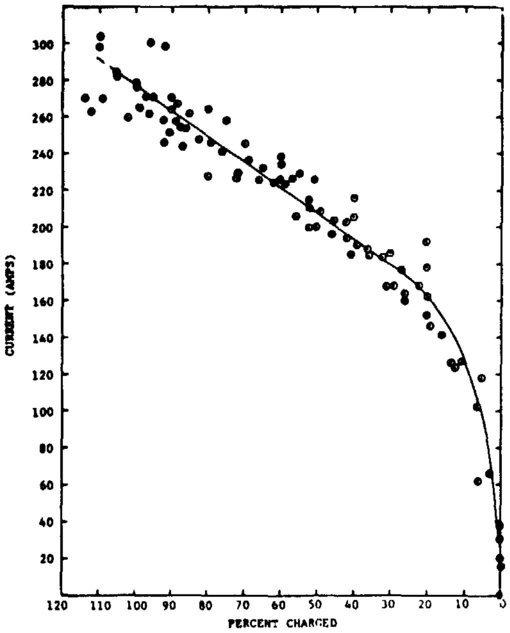


Figure 161. Four-cell nickel-cadmium batteries at 75°F

The test procedure for the four-cell batteries consisted of the following steps

(1) a 3.0 second constant load discharge across a 0.04[illegible] ohm resistor,

(2) a 0.25 second delay, and

(3) a constant voltage discharge pulse to 4.20 volts

The response current was measured at 100 to 120 msec

Figure 160

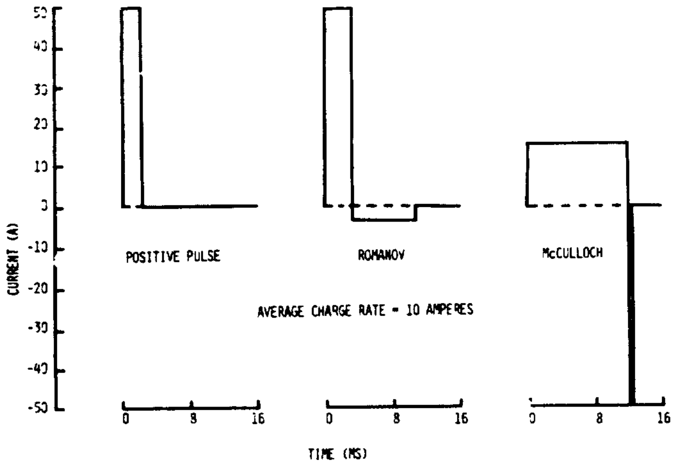


Figure 162

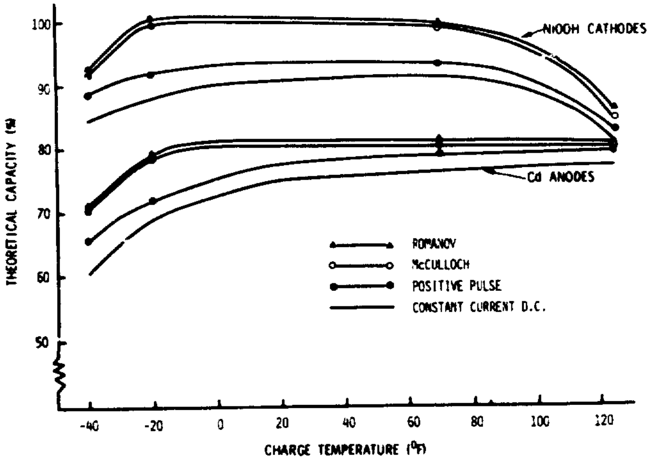


Figure 163

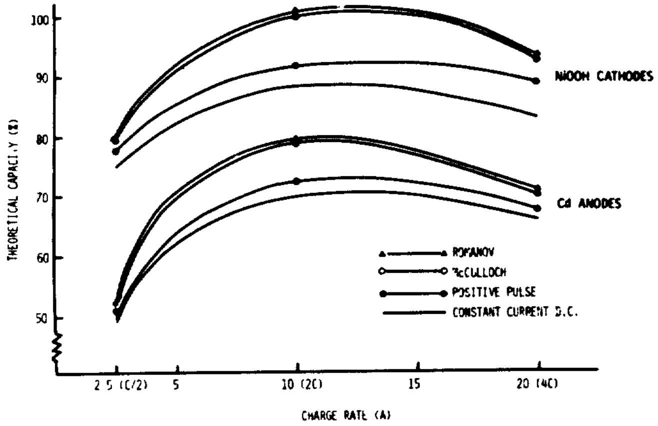


Figure 164

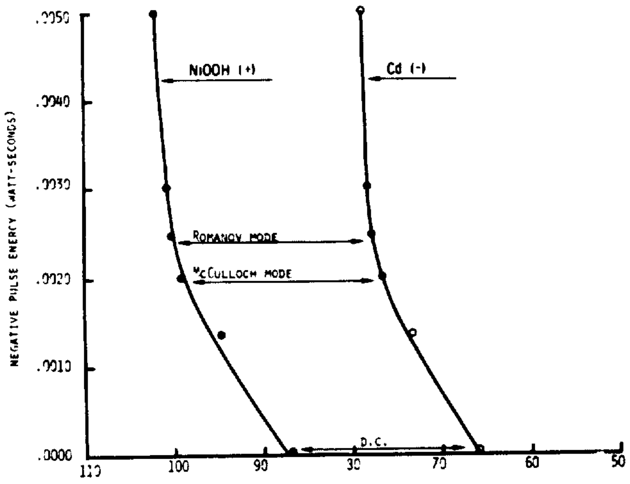


Figure 165

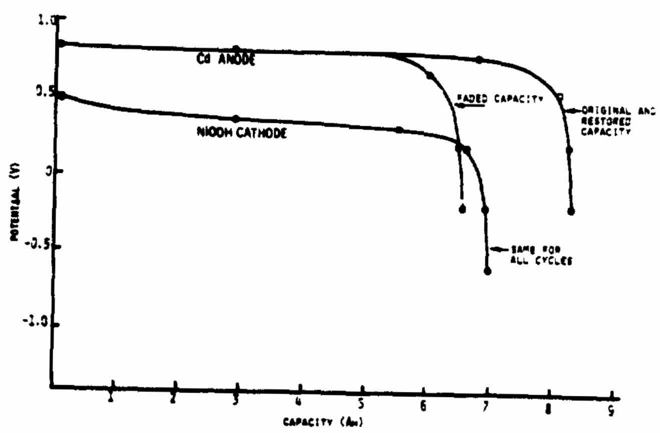


Figure 166. Capacity lost by fadeout and restored by pulse charging

Figure 167

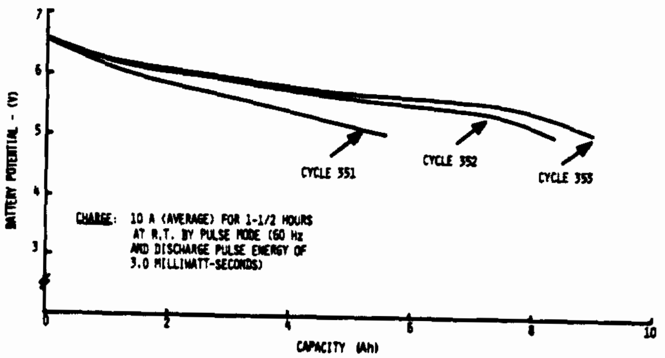


Figure 168. Deep discharge of a vented cell battery on cycles 351, 352 and 353

Figure 169

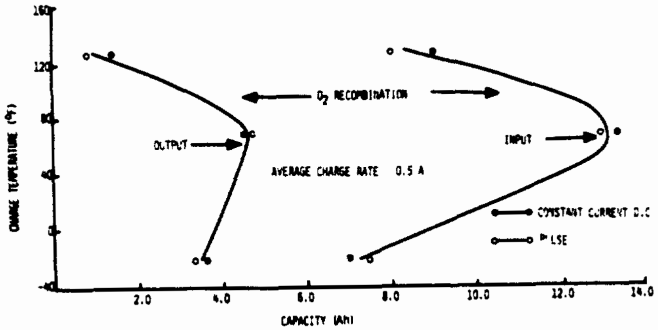


Figure 170

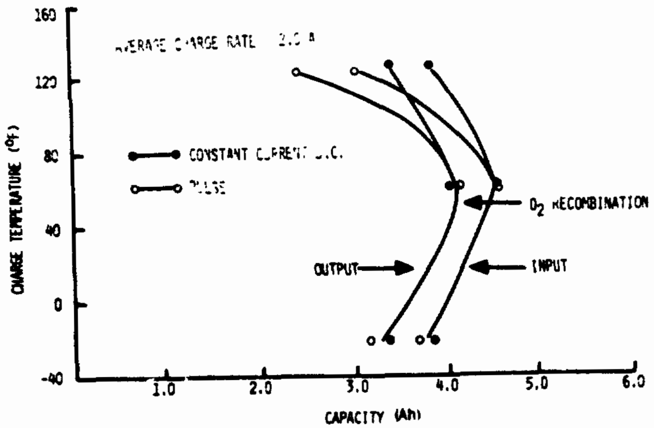


Figure 171

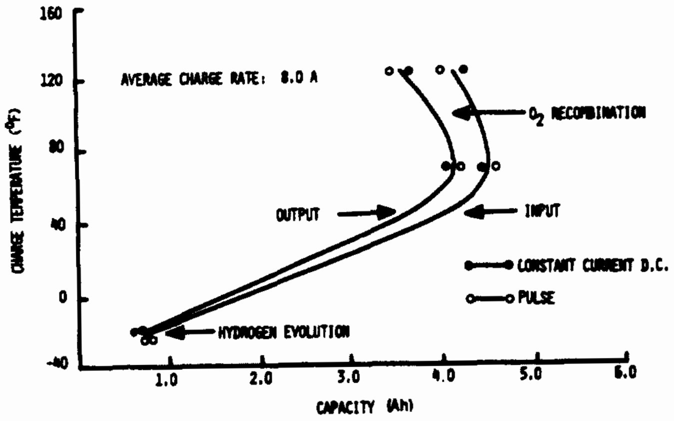


Figure 172

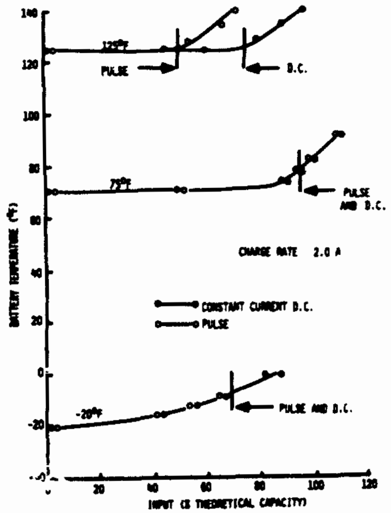
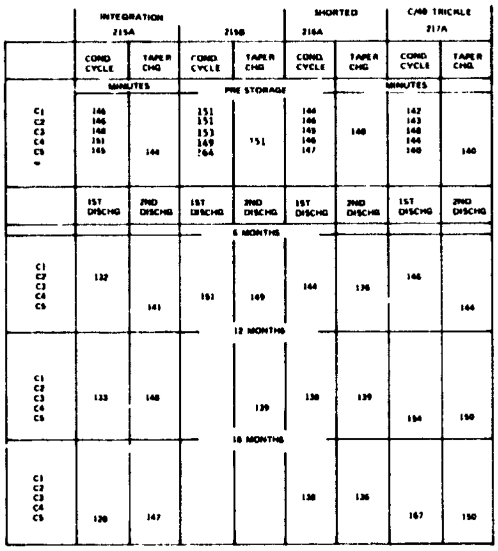
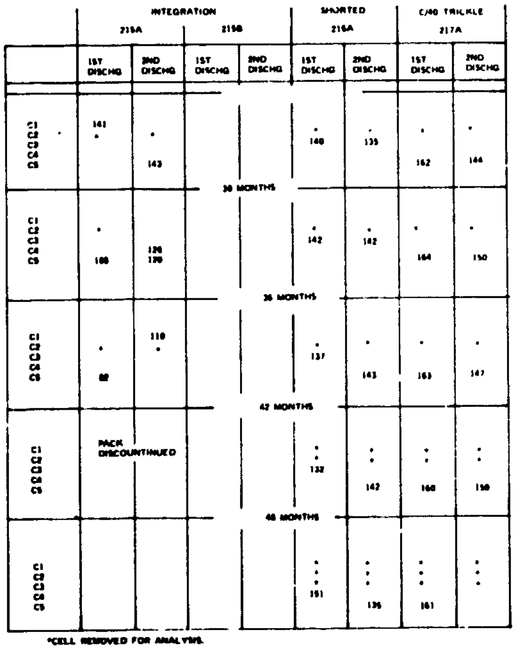


Figure 173



	INTEGRATION				SHORTED		C/40 TRICKLE	
	215A		215B		216A		217A	
	COND CYCLE	TAPER CHG	COND CYCLE	TAPER CHG	COND CYCLE	TAPER CHG	COND CYCLE	TAPER CHG
	MINUTES		PRE STORAGE				MINUTES	
C1 C2 C3 C4 C5 *	146 146 148 151 145	144	151 151 153 149 164	151	144 146 145 146 147	140	142 143 148 144 140	140
	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG
				6 MONTHS				
C1 C2 C3 C4 C5	132	141	151	149	144	136	146	144
				12 MONTHS				
C1 C2 C3 C4 C5	133	148		139	130	139	154	150
				18 MONTHS				
C1 C2 C3 C4 C5	120	147			138	136	167	150

Figure 174. Naval weapons support center crane OAO storage test 10 ampere discharge to 0.5 volts



	INTEGRATION				SHORTED		C/40 TRICKLE	
	215A		215B		216A		217A	
	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG	1ST DISCHG	2ND DISCHG
C1 C2 C3 C4 C5	141 *	* 143			* 140	* 135	* 162	* 144
				30 MONTHS				
C1 C2 C3 C4 C5	* 100	126 129			* 142	* 142	* 164	* 150
				36 MONTHS				
C1 C2 C3 C4 C5	* 82	110 *			* 137	* 143	* 163	* 147
				42 MONTHS				
C1 C2 C3 C4 C5	PACK DISCOUNTINUED				* * 132	* * 142	* * 160	* * 150
				48 MONTHS				
C1 C2 C3 C4 C5					* * * 151	* * * 136	* * * 161	* * *

*CELL REMOVED FOR ANALYSIS.

Figure 175. 10 ampere discharge to 0.5 volts - cont.

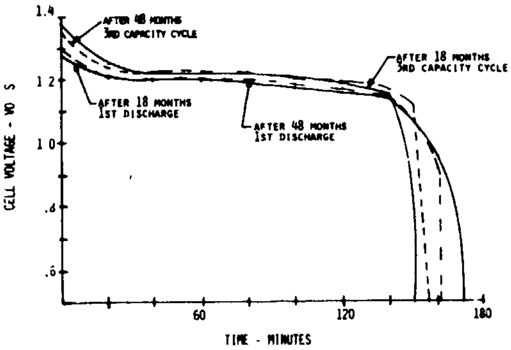


Figure 176. OAO storage test pack 217A C/20 trickle charge voltage profile for 10 ampere (C/2) discharge. Temperature — 25°C

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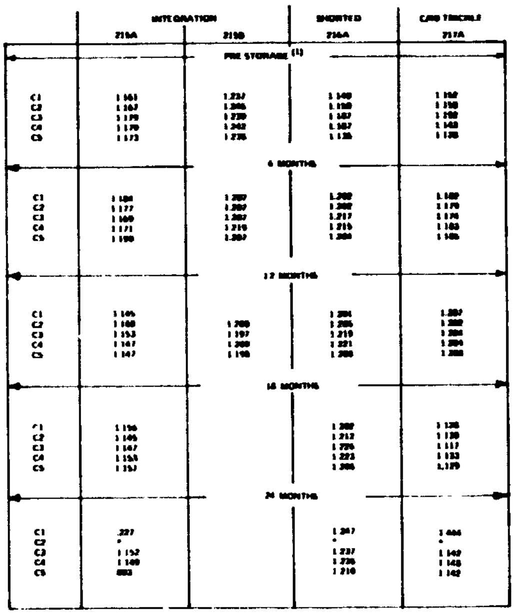
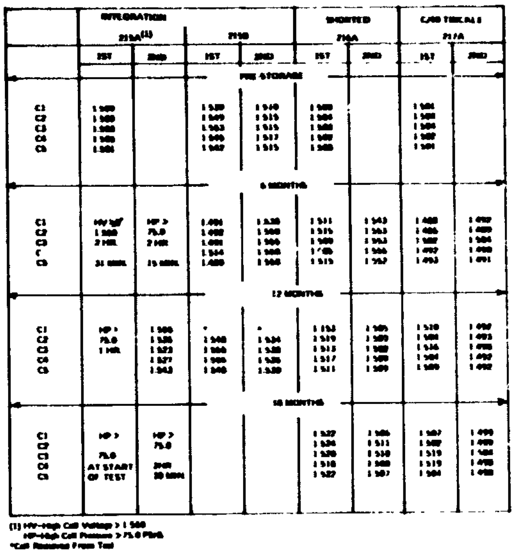


Figure 177. Naval weapons support center, Crane OAO storage test open circuit voltage recovery



(1) HV-High Cell Voltage > 1.500
HP-High Cell Pressure > 75.0 PSIA
*Cell Removed From Test

Figure 179. Naval weapons support center, Crane OAO storage test overcharge voltage @ 0°C - C/20 for 5 Hrs

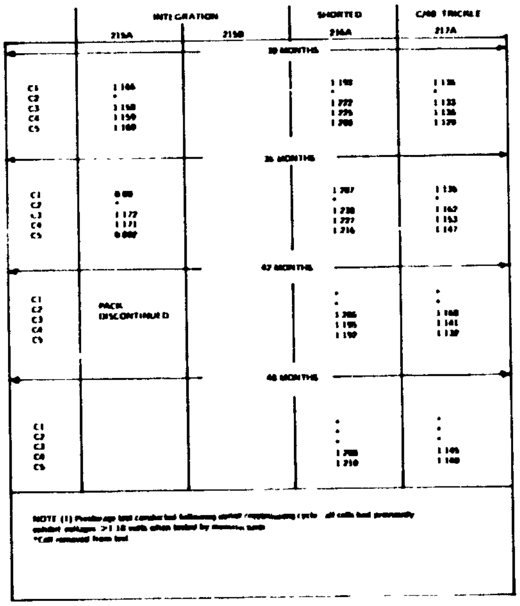


Figure 178. Open circuit voltage recovery — Cont.

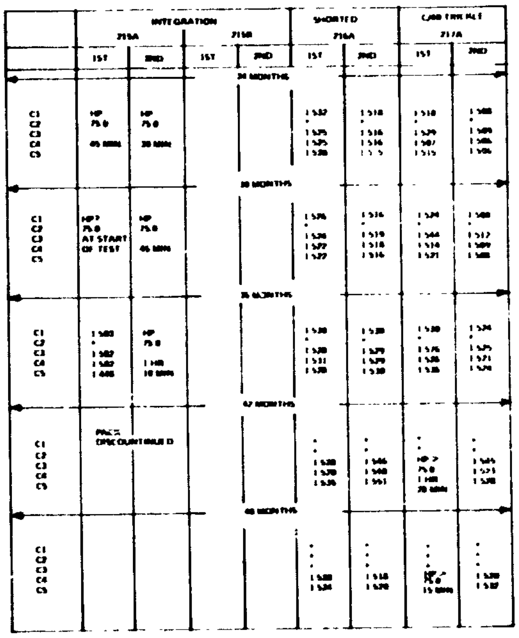


Figure 180. Overcharge voltage @0°C - C/20 for 5 hrs.

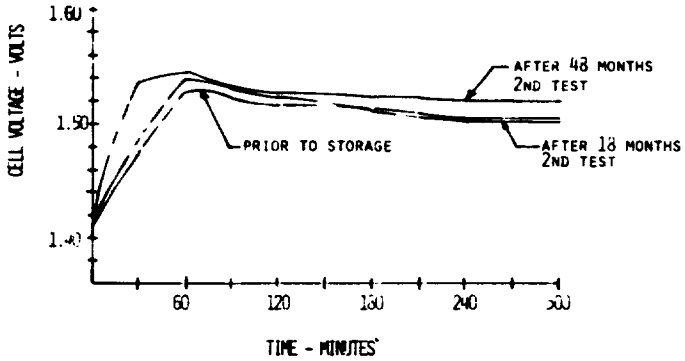


Figure 181. OAO storage test overcharge voltage at 0°C C/20 charge pack 216A - discharge and shorted

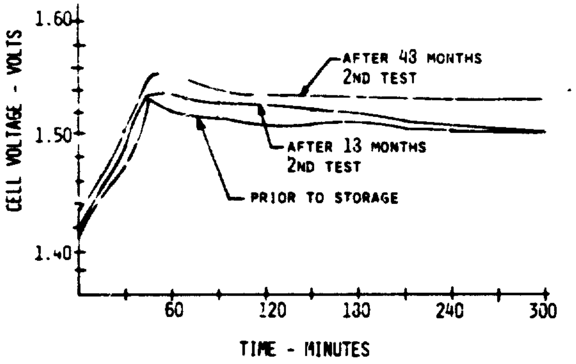


Figure 182. OAO storage tests overcharge voltage at 0°C C/20 charge pack 217A - C/40 trickle charge

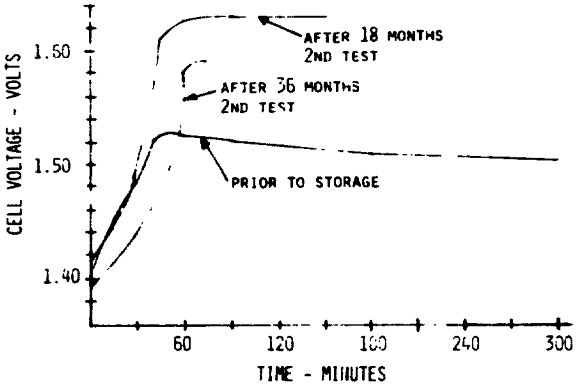


Figure 183. OAO storage test overcharge test at 0°C C/20 charge pack 215 A - integration

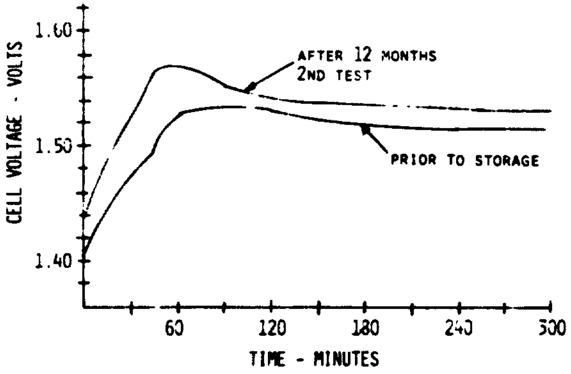


Figure 184. OAO storage test overcharge voltage at 0°C pack 215 B - discharge O.C.V.

TEST ITEMS	TESTS PERF ̓ED	RESULTS
THREE FLIGHT BATTERIES FROM STORED SPACECRAFT (22 x 24-AH CELLS EACH)	ELECTROLYTE LEAKAGE CONDITIONING CYCLE THERMAL-VACUUM THREE SYSTEM- ORIENTED CYCLES	NO LEAKAGE NO CHANGE SAME THERMAL PERFORMANCE CAPACITIES WITHIN 3 OF NEW
FOUR CELLS EACH FROM THREE BATTERIES	THREE CONTROLLED CYCLES	3RD CYCLE EOCV 1 450 - 1 456 (WAS 1 444 - 1.454) CAP TO 1-V 29 2 - 29 8 AH (WAS 27 4 - 30 0-AH)
SIX CELLS FROM SHORTED STORAGE	CONDITIONING CYCLE THREE 24-HOUR CYCLES LOW TEMPERATURE OVERCHARGE	NORMAL CAP 27 1 - 29.0 AH TO 1 V EOCV BELOW 1 ʼ2 V EOCP BELOW 65 PSIG VOLTAGES AND PRESSURES CONSTANT 4.4 - 6 8 AH AT C/2 FROM 0 TO -1 V 100 HYDROGEN BY ANALYSIS

Figure 185. Electrical test summary

ITEM NO.	DESCRIPTION	NUMBER ANALYZED	NUMBER OF LOTS
1.	NEGATIVE PLATES, AFTER FORMATION	12	3
2.	CELLS, AS RECE VEC AT TRW	1	1
3.	CELLS, AFTER ACCEPTANCE TESTING AT TRW*	5	3
4.	CELLS, STORED SHORTED 2-3 YEARS AFTER ACCEPTANCE TEST	7	3
5.	CELLS, STORED SHORTED 4-5 YEARS AFTER ACCEPTANCE TEST	6	2
6	CELLS, STORED SHORTED 2 YEARS AFTER ACCEPTANCE TEST AND SPACECRAFT INTEGRATION TESTING	4	2

* INCLUDES A 30-CYCLE BURN-IN

Figure 186. Summary of plates and cells analyzed

		CELLS AS RECEIVED	AFTER ACC. TEST	AFTER ACCEPTANCE TESTING PLUS:		
				2 YRS SSU	I&T + 2 YRS SS	4 YRS SSO
WEIGHT LOSS GDM^{-2}	SEPARATORS	1.34	1.21	-	0.6	-
	POS PLATES	2 13	2.66	-	3.0	-
	NEG PLATES	2.87	3.31	-	4.1	-
TOTAL ALKALINITY MEGS DM^{-2}	SEPARATORS	7.8	7 2	6.0	3.0/3 7	3.0
	POS. PLATES	17.0	19 4	-	20.7/16.4	21.0
	NEG. PLATES	17 2	21.8	-	- /24 8	19.5

Figure 187. Electrolyte analysis data-I

		CELLS AS RECEIVED		AFTER ACCEPTANCE TEST		AFTER ACCEPT. TEST, I&T TEST, & 2 YRS SS	
		GDM^{-2}	WS	GDM^{-2}	WS	GDM^{-2}	WS
KOH	SEPARATORS	0.30	22.0	0 20	16.0	0.078	13.0
	POS. PLATES	0.37	17.5	0.31	11.7	0.63	21.0
	NEG. PLATES	0.56	19.5	0.54	16.3	0.65	16.0
K_2CO_3	SEPARATORS	0.17	12 7	0.26	21.5	0.15	25.0
	POS PLATES	0 71	33.3	0.95	35.8	0.43	14.2
	NEG. PLATES	0.50	17.3	0.835	25.2	0.89	21.7

Figure 188. Electrolyte analysis data-II

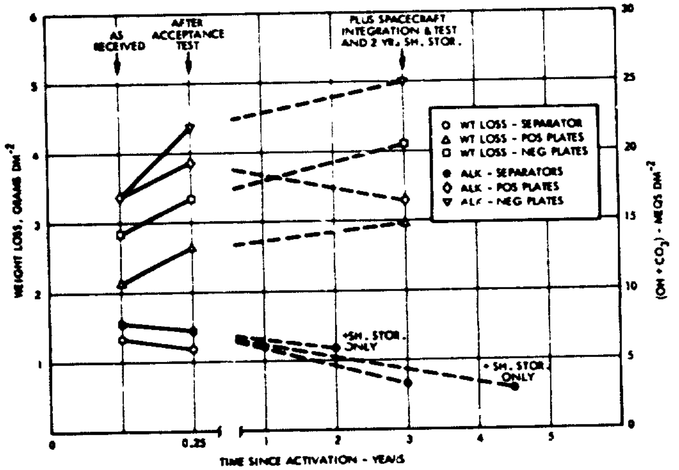


Figure 189. Electrolyte distribution vs usage

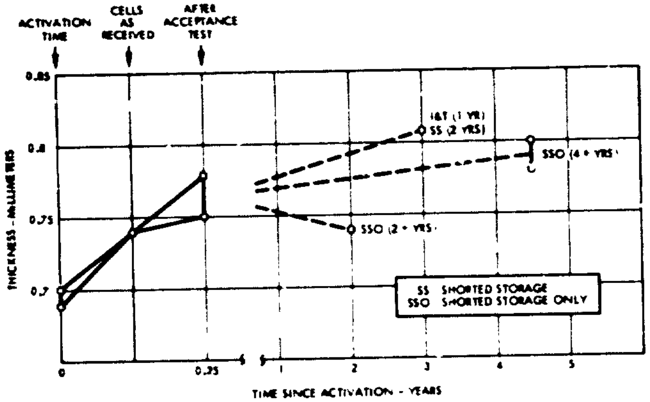


Figure 190. Positive plate thickness data

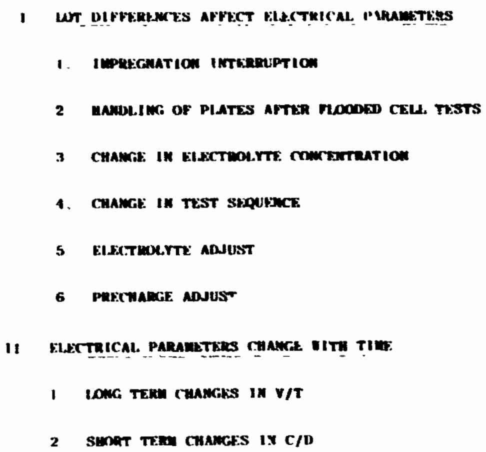
Figure 191. Cadmium plate surface after acceptance testing

Figure 192. Cadmium plate surafce after removal of adhering separator layer

CELL S/N	HYDROGEN FREE CHARGE ACCEPTANCE (AMPERE-HOURS)		DISCHARGE CAPACITY (AMPERE-HOURS)	
	SINGLE PLATE	12 PLATE EQUIVALENT	SINGLE PLATE	12 PLATE EQUIVALENT
033-L01	5.9	71	3.5	42
040-L02	4.5	54	3.4	41
041-L02	4.5	54	3.4	41
042-L02	5.0	60	3.5	42
AVERAGES	4.67*	57*	3.45	41.5

* AVERAGE OF 040,041, AND 042 ONLY

Figure 193. Flooded electrochemical capacities for negative plate



I LOT DIFFERENCES AFFECT ELECTRICAL PARAMETERS

1. IMPREGNATION INTERRUPTION
2. HANDLING OF PLATES AFTER FLOODED CELL TESTS
3. CHANGE IN ELECTROLYTE CONCENTRATION
4. CHANGE IN TEST SEQUENCE
5. ELECTROLYTE ADJUST
6. PRECHARGE ADJUST

II ELECTRICAL PARAMETERS CHANGE WITH TIME

1. LONG TERM CHANGES IN V/T
2. SHORT TERM CHANGES IN C/D

Figure 194. Atmospheric explorer/ ITOS experience

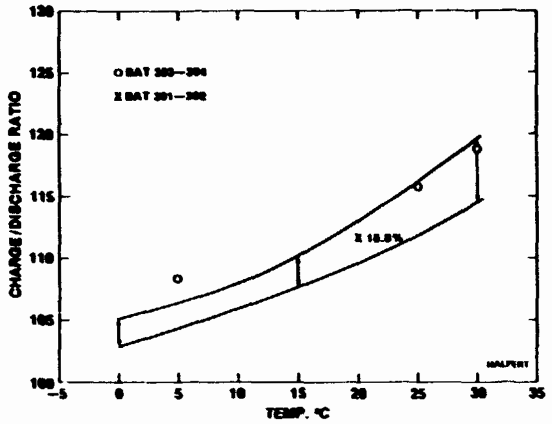


Figure 196. C/D ratio vs temperature ITOS

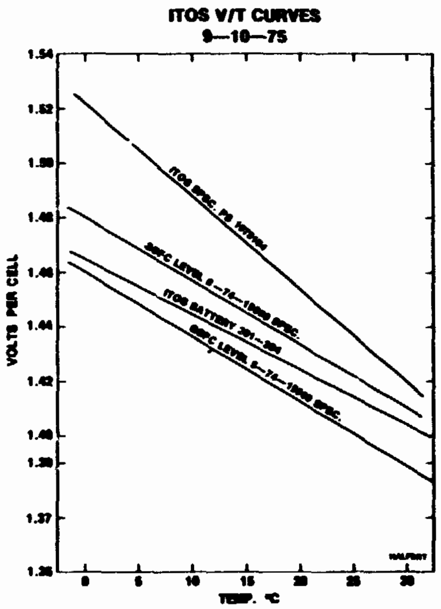


Figure 195. ITOS V/T curves 9-10-75

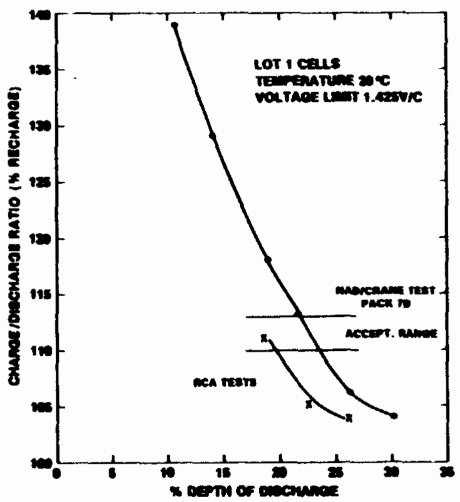


Figure 197. C/D ratio vs % DOD

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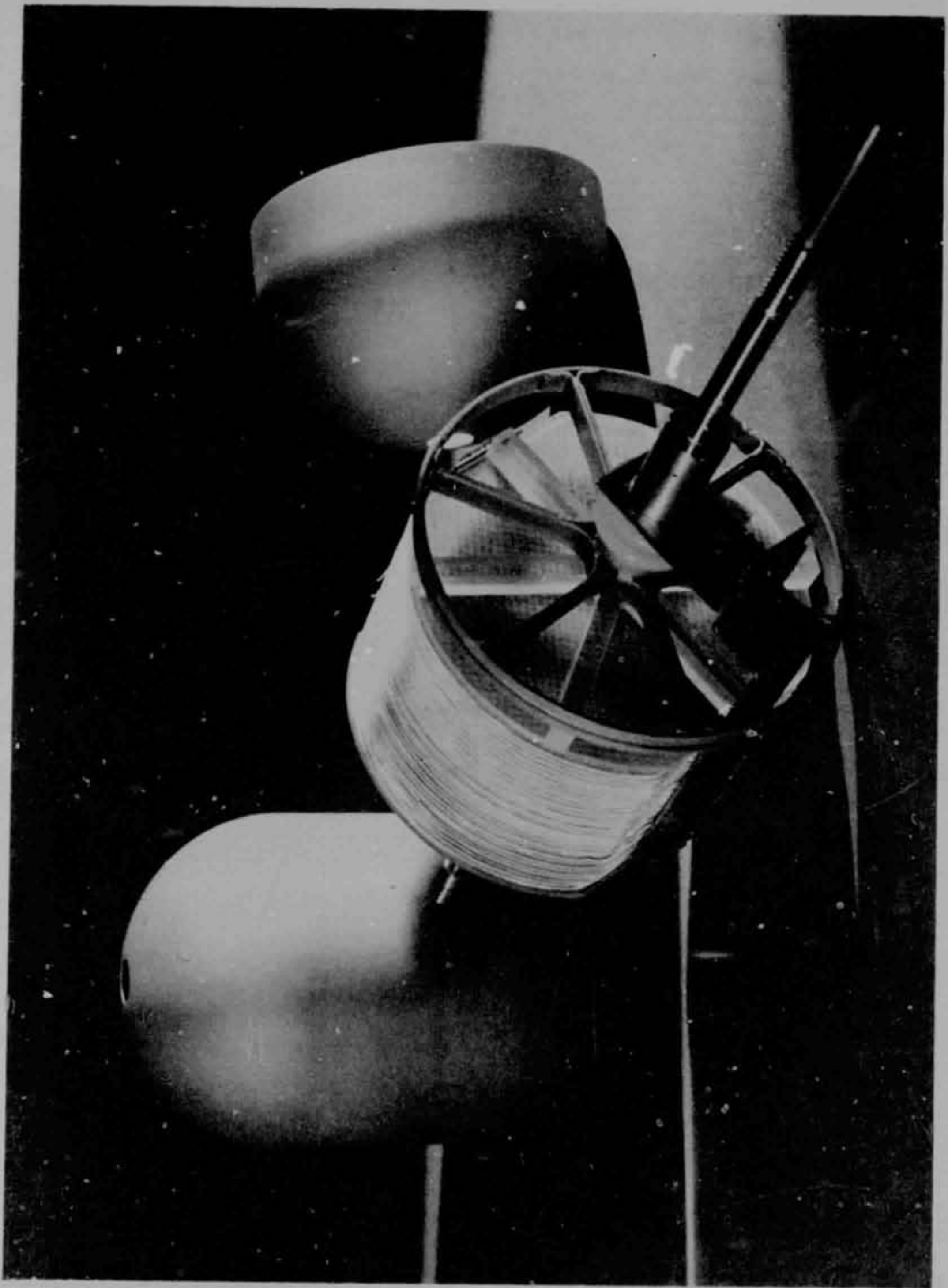


Figure 198

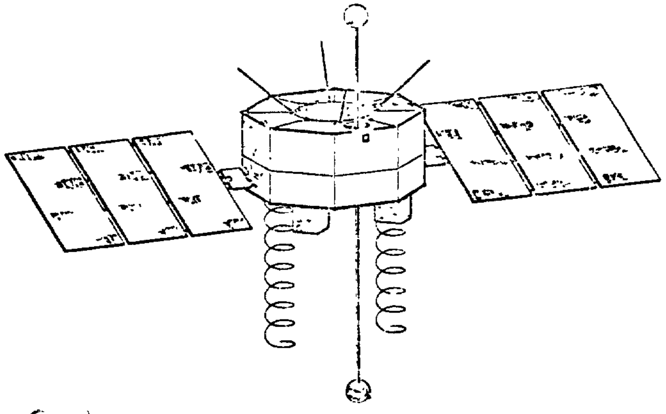


Figure 199

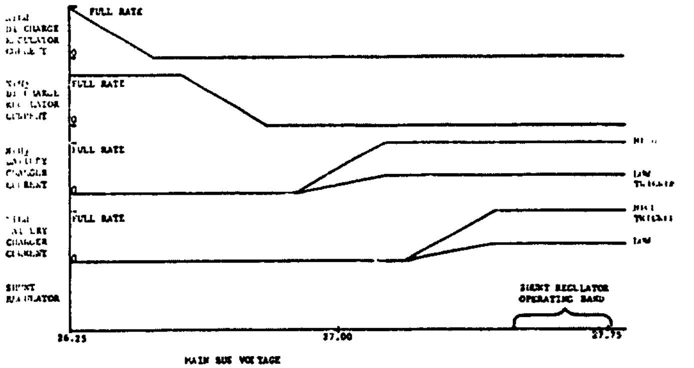


Figure 201. DETS operating characteristics

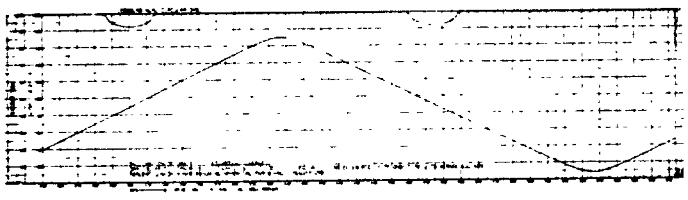


Figure 200

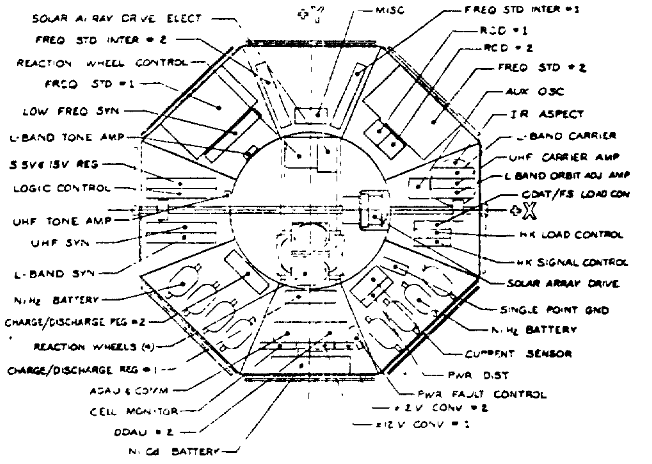


Figure 202

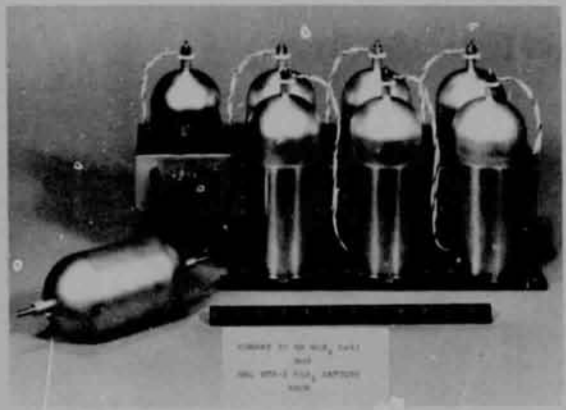


Figure 203. Comsat 35 Ah and NiH cell
NRL NTS-2 NiH battery pack

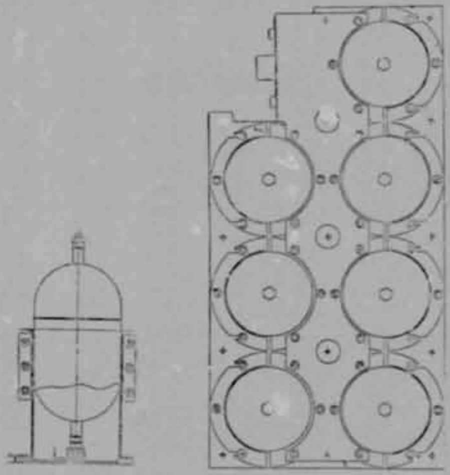


Figure 204

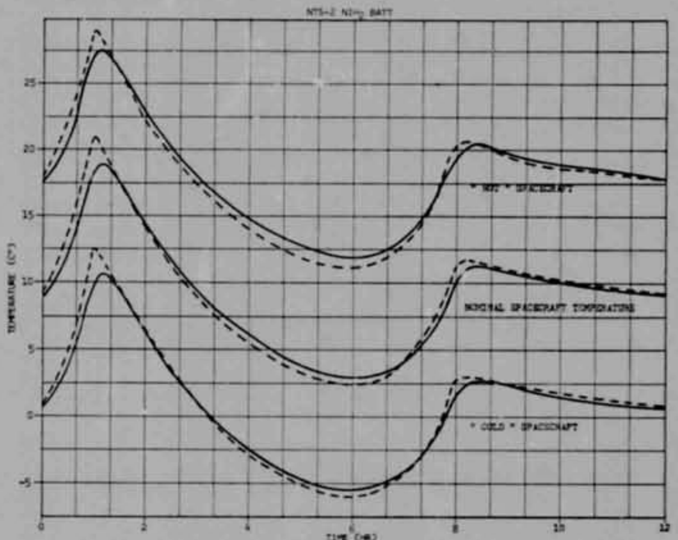


Figure 205

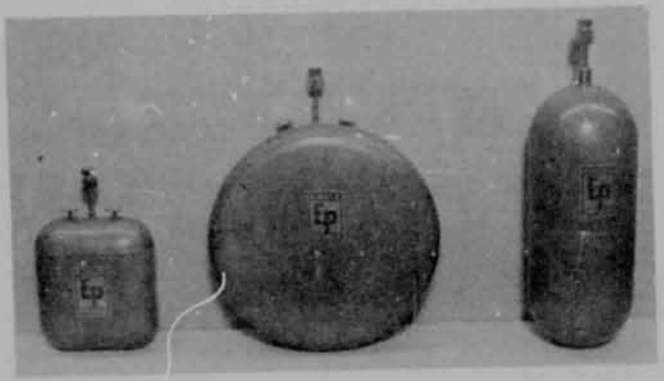
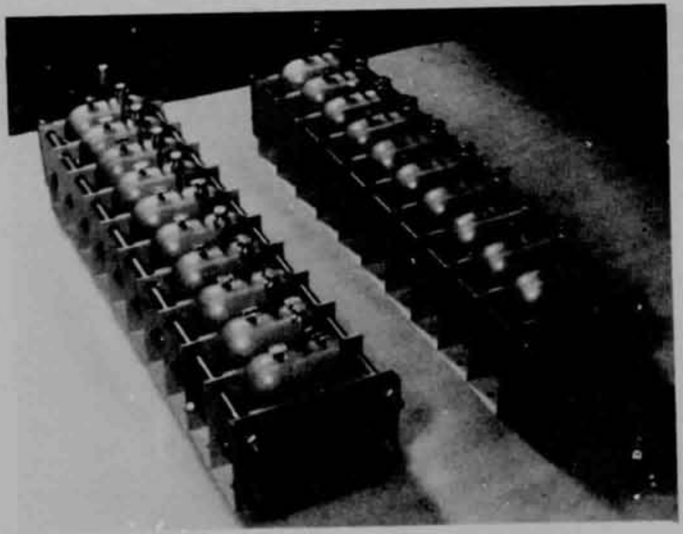


Figure 206



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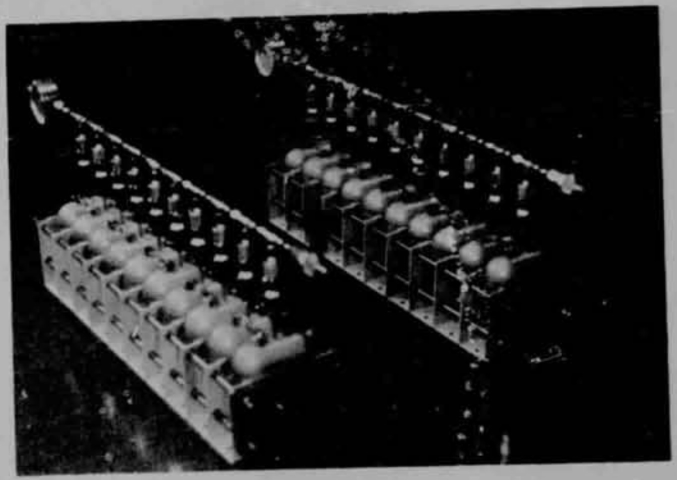

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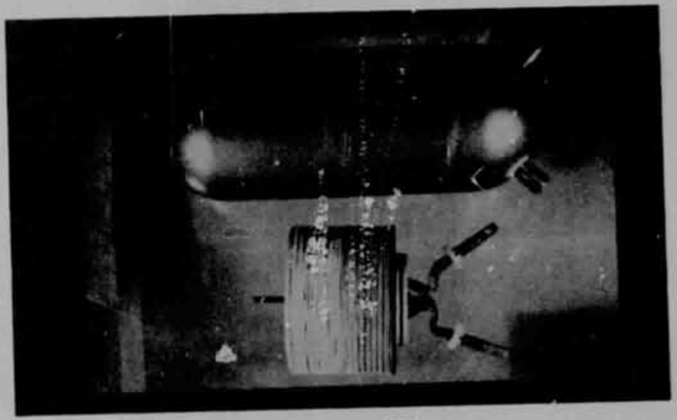

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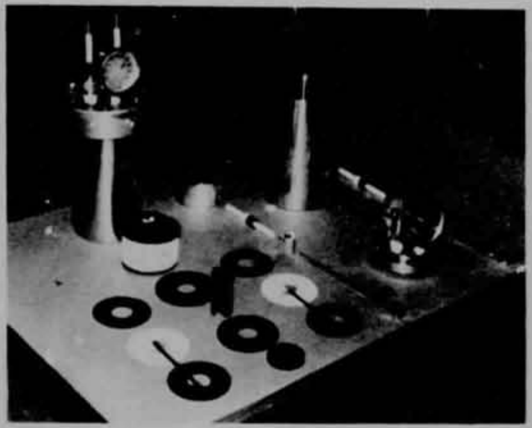

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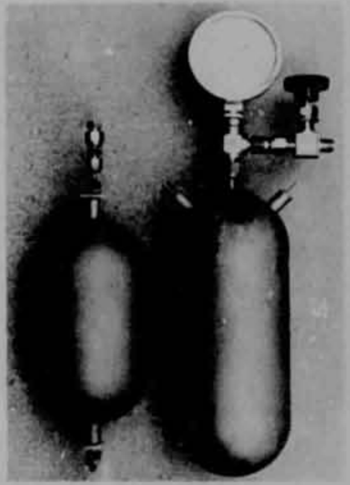

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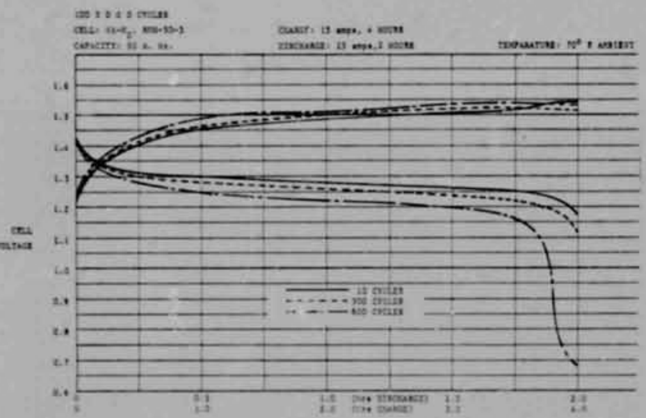

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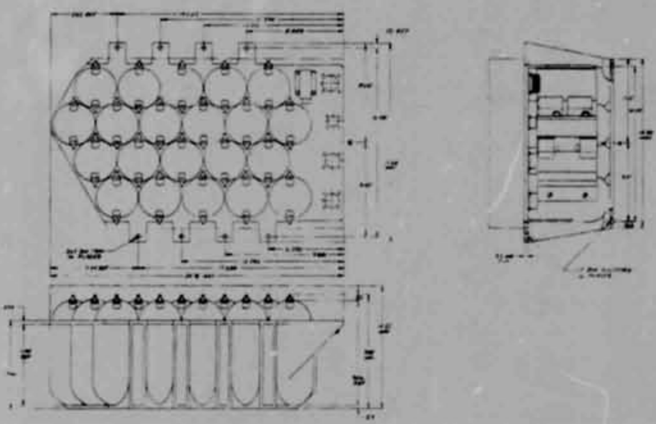

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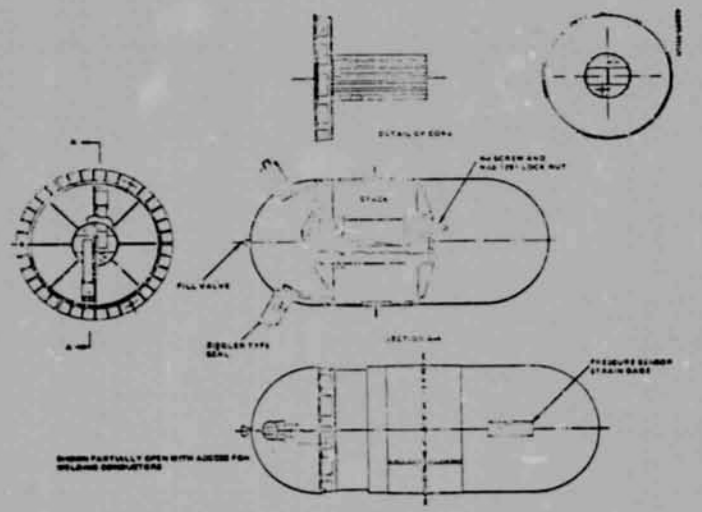

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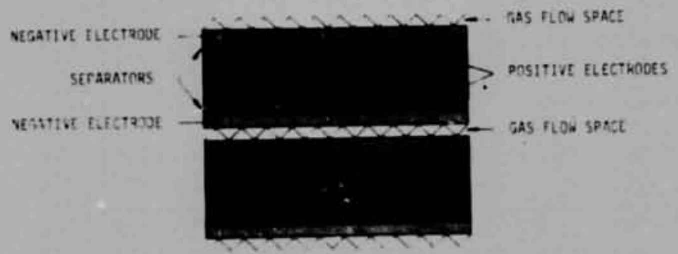


Figure 215. Conventional nickel-hydrogen cell stack

Figure 216. Nickel-hydrogen cell stack

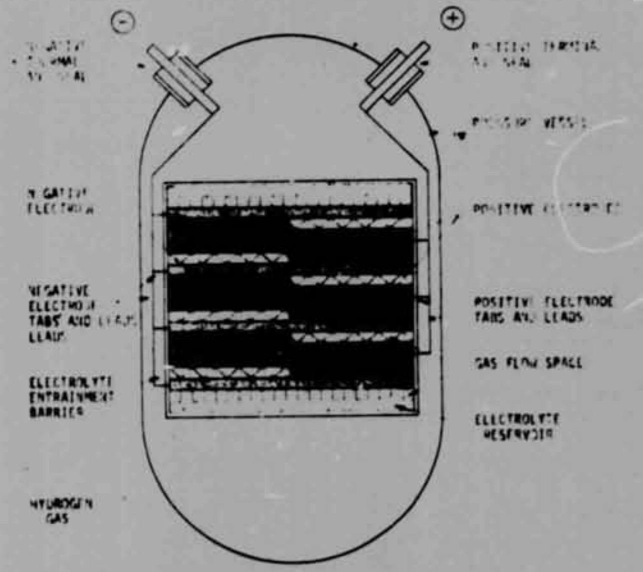
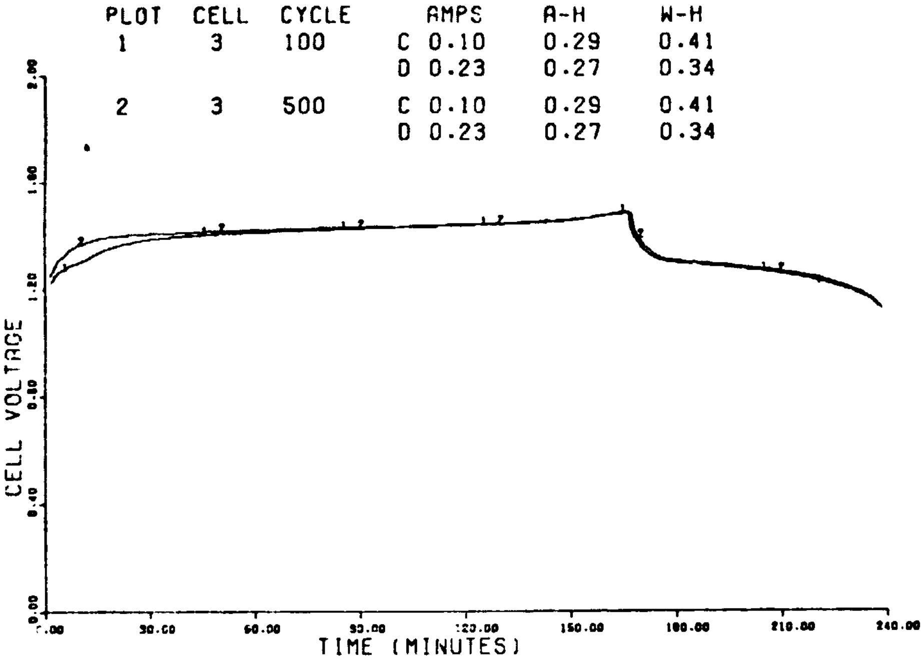


Figure 217. An electrochemical cell design for balanced distribution of oxgen and electrolyte



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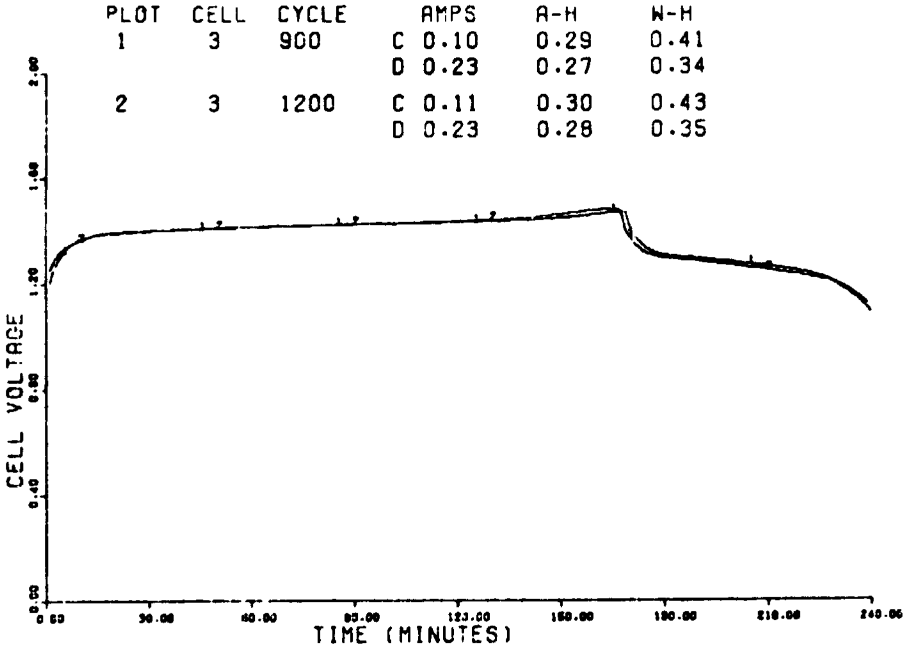


Figure 219

SCOPE OF COMSAT PROGRAM INCLUDES PRESSURE VESSEL AND BATTERY DEVELOPMENT

- PRESSURE VESSEL DEVELOPMENT
  - MATERIAL & WELD STUDIES
  - STRESS & THERMAL ANALYSES
  - MANUFACTURING
- BATTERY DEVELOPMENT
  - MOUNTING HARDWARE DESIGN
  - CHARGE CONTROL & BYPASS ELECTRONICS
  - STRESS & THERMAL ANALYSES
  - BATTERY FABRICATION AND TEST

Figure 220

OBJECTIVE OF COMSAT PROGRAM IS TO DEVELOP A NICKEL-HYDROGEN BATTERY PACKAGE WITH THE FOLLOWING DESIGN REQUIREMENTS:

- 50 Wh/kg ENERGY DENSITY (100% DOD) EXCLUSIVE OF CHARGE CONTROL AND BYPASS ELECTRONICS
- 1000 SYNCHRONOUS ORBIT CYCLES AT 60%DOD

Figure 221

MATERIAL STUDY BASED ON FRACTURE MECHANICS ANALYSIS

- THREE CANDIDATE MATERIALS SELECTED (316 STAINLESS, INCONEL 718, Ti 5 Al-2.5 Sn)
- STATIC STRESS, FRACTURE TOUGHNESS, SUSTAINED LOAD, CYCLIC LOAD TESTS CONDUCTED
- FLAW DEPTH VERSUS CYCLES TO FAILURE CURVES PRODUCED FROM TEST DATA
- EMBRITTLEMENT CHARACTERISTICS DETERMINED

Figure 222

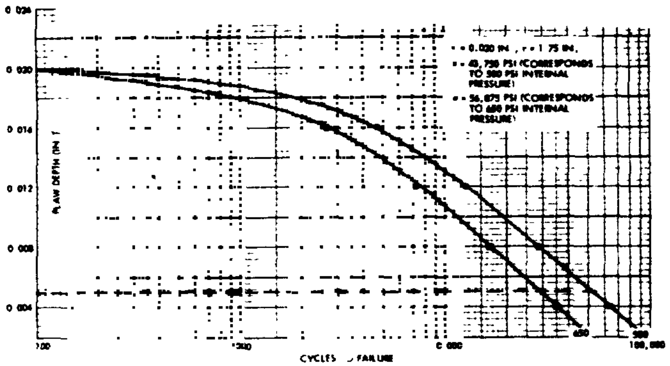


Figure 223. Flaw depth versus cycles to failure for Titanium 5A1-2.5Sn with 0.020-inch thickness

MATERIAL STUDY RESULTS CONFIRMED THAT ALL THREE MATERIALS ARE SATISFACTORY FOR USE IN $Ni-H_2$ PRESSURE VESSELS

- 4000 PRESSURE CYCLE REQUIREMENT MET
- NO STRESS CORROSION IN BATTERY ENVIRONMENT

Figure 224

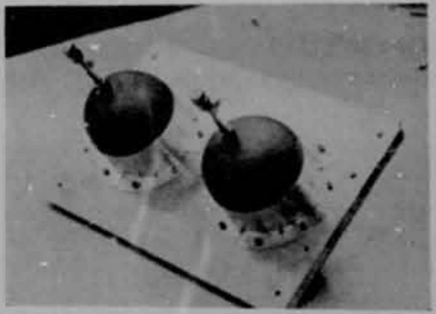


Figure 226. Two-cell 35-Ah nickel hydrogen test battery showing cell mounting bracket design

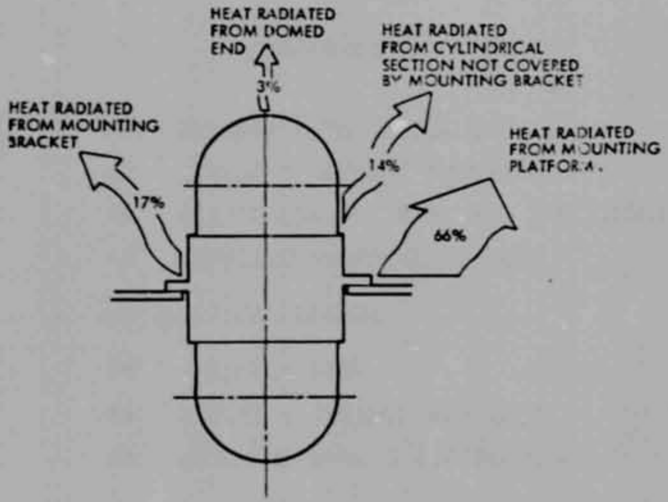


Figure 225. Thermal design required detail understanding of heat flow

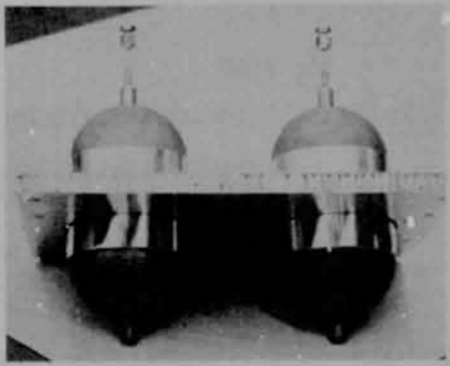


Figure 227. Two-cell 35-Ah nickel-hydrogen test battery showing bulkhead feedthrough cell mounting

Figure 228. Ten-cell 35-Ah nickel-hydrogen battery model used for wiring layout

MASS PROPERTIES ANALYSIS VERIFIED 11-16WH/LB ESTIMATE FOR A 10-CELL 50-AH BATTERY SYSTEM

• BATTERY CELL MASS	25.0 LB
• PACKAGING AND WIRING MASS	2.2 LB
• BYPASS ELECTRONICS MASS	2.5 LB
• CHARGE CONTROL MASS	3.0 LB
• TOTAL BATTERY SYSTEM MASS	32.7 LB
• BATTERY SYSTEM ENERGY (75% DOD)	504 WH
• ENERGY DENSITY (75% DOD)	15.4 WH/LB

Figure 229

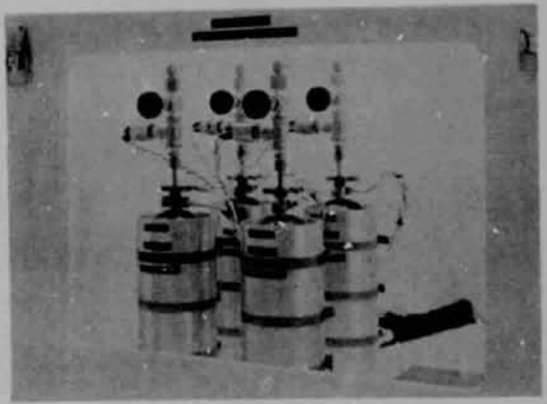


Figure 230. Nickel-hydrogen cell test set-up for accelerated cycle life test

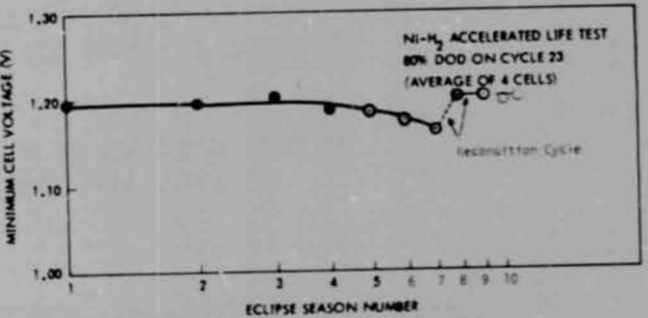


Figure 231. Accelerated life tests show excellent performance through 11 eclipse seasons at 80% DOD

TRW's IR&D PROGRAM HAS AND WILL CONTINUE TO PROVIDE SUPPORTING TECHNOLOGY FOR NICKEL-HYDROGEN BATTERY DEVELOPMENT

- PARAMETRIC ELECTRICAL PERFORMANCE DATA INDICATE THAT NO SIGNIFICANT DEPARTURE FROM CONVENTIONAL POWER SYSTEM DESIGN IS REQUIRED
- ACCELERATED LIFE TESTS SHOW EXCELLENT PERFORMANCE THROUGH 11 SIMULATED SYNCHRONOUS ECLIPSE SEASONS AT 80% DEPTH-OF-DISCHARGE (TEST CONTINUING)
- OVER 1000 LOW-EARTH ORBIT CYCLES AT 80% DEPTH-OF-DISCHARGE HAVE BEEN PERFORMED
- CELLS APPEAR SAFE AGAINST HYDROGEN LEAKAGE FAILURE MODE
- CELLS ARE TOLERANT TO OVERCHARGE AND OVERDISCHARGE WHICH SIMPLIFIES CHARGE CONTROL AND PROTECTION ELECTRONICS REQUIREMENTS
- LIGHTWEIGHT BYPASS CIRCUIT DESIGNS HAVE BEEN ACHIEVED
- $Ni-H_2$ BATTERY SYSTEM ENERGY DENSITIES OF 11-15 Wh/lb FOR SYNCHRONOUS ORBIT AND 6-9 Wh/lb FOR LOW EARTH ORBIT ARE FEASIBLE

Figure 232

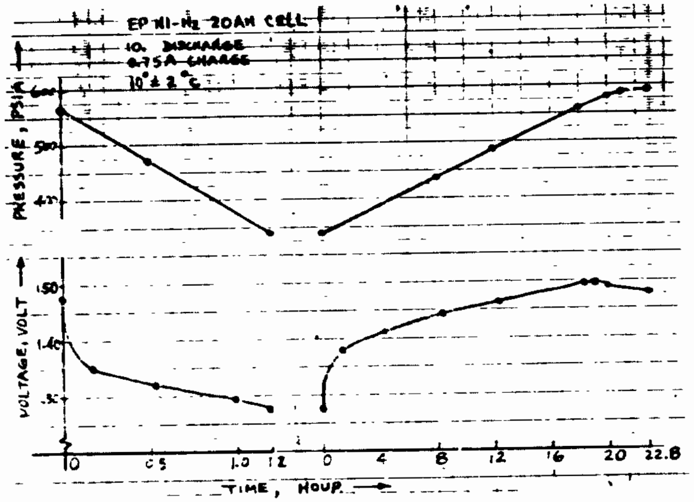
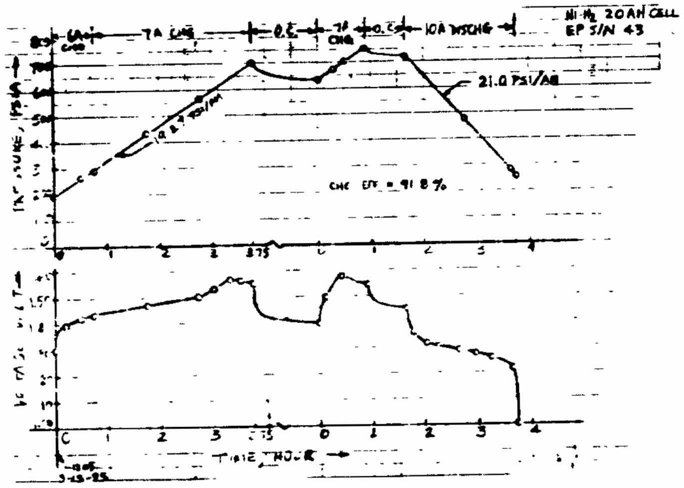


Figure 233



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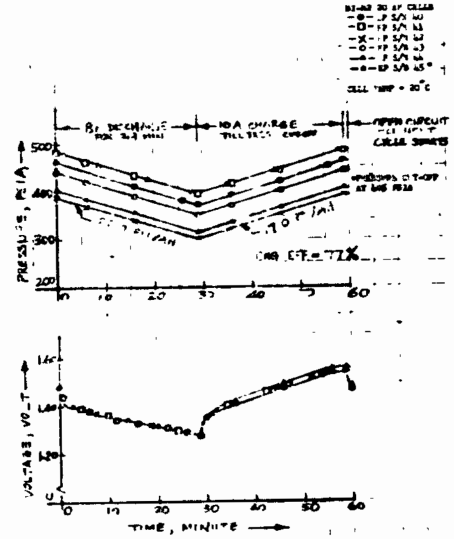

Figure 235

TEMP / CHG RATE	0°C	10°C	20°C	30°C
C	--	57	77	--
C/2	--	168	1286	--
C/3	--	250	--	--
C 4	--	95	142	145
C 10	250	46	47	--

NOTE ABOVE DATA COLLECTED ON SIX EP 20AH PRISMATIC CELLS

TOTAL CYCLES = 2633

Figure 236. Accelerated low Earth orbit test cycles completed

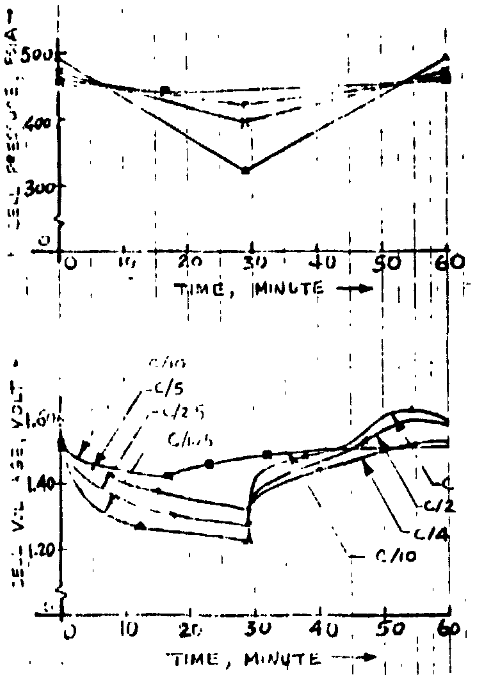

Figure 237. Chg/dischg regimes for 10°C accelerated low Earth orbit cycling

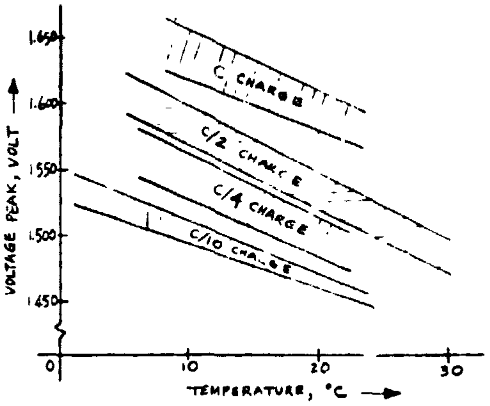

Figure 239. EP 20 AH Ni-H_2 cells

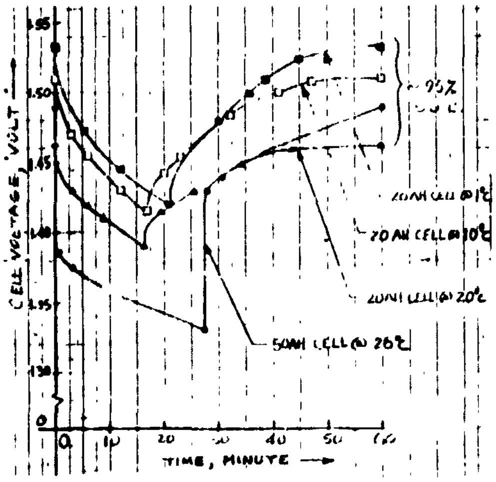

Figure 238. C/10 rate charge/discharge

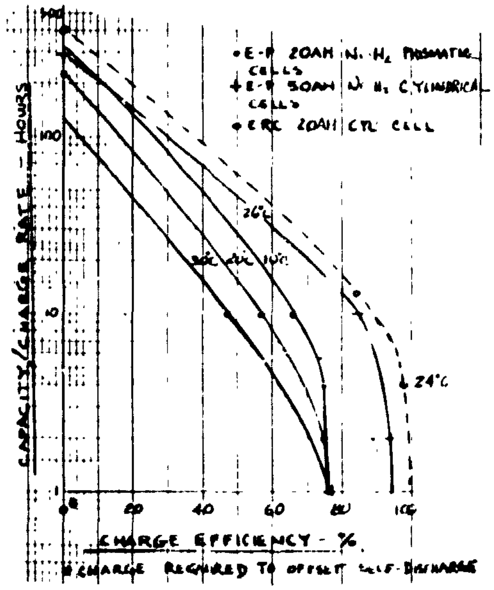

Figure 240

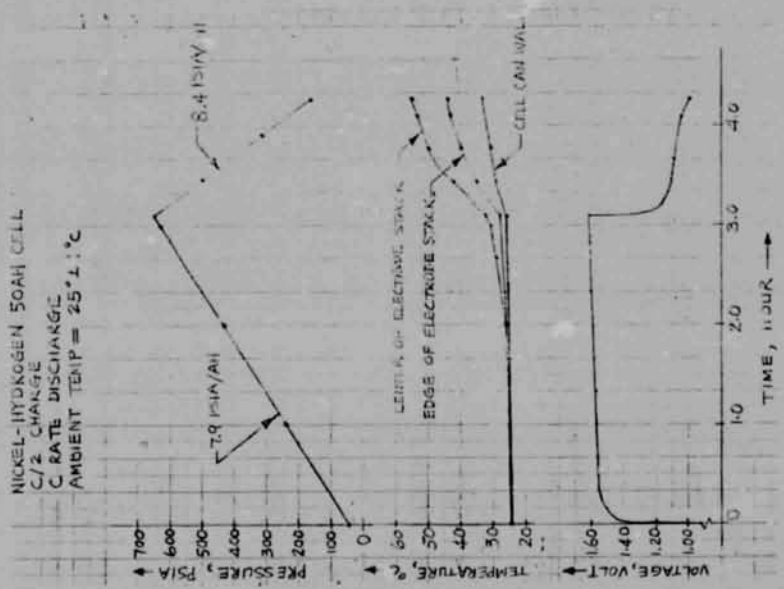

Figure 241

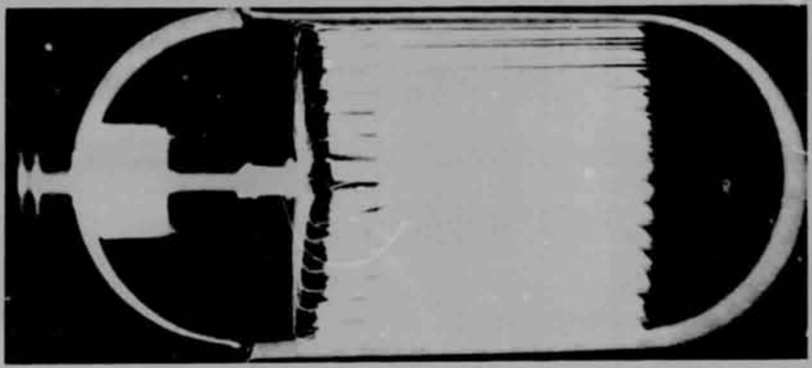

Figure 242

WORK DONE UNDER CONTRACT NO. F33615-75-C-2025, AIR FORCE AERO PROPULSION LABORATORY, AIR FORCE PROJECT ENGINEER, IRVIN LUKE.

OBJECTIVES OF THIS TASK

- MEASURE DEGRADATION RATE OF BASELINE NICKEL-HYDROGEN CELL UNDER LOW EARTH ORBIT CONDITIONS
- MONITOR ELECTROLYTE LOSS DURING OPERATION
- MEASURE AMOUNT OF OXYGEN GENERATED UNDER VARIOUS CONDITIONS OF CHARGE

Figure 243. Low Earth orbit testing of a nickel-hydrogen cell-status report

PINEAPPLE SLICE DESIGN

TYCO ELECTROCHEMICALLY IMPREGNATED POSITIVES (TWO)

BACK-TO-BACK POSITIVES

EMC NEGATIVES (TWO)

JOHNS-MANVILLE FUEL CELL GRADE 10 MIL ASBESTOS SEPARATORS (TWO)

DU PONT VEXAR POLYPROPYLENE GAS DIFFUSION SCREENS (TWO)
(0.024 INCH THICK, EACH)

ELECTROLYTE - 31 PERCENT, WT., KOH

LEADS, EACH PLATE 0.032 INCH NICKEL 200 WIRE, APPROXIMATELY 6 INCHES LONG

Figure 244. Asbestos separator cell stack description (baseline stack design)

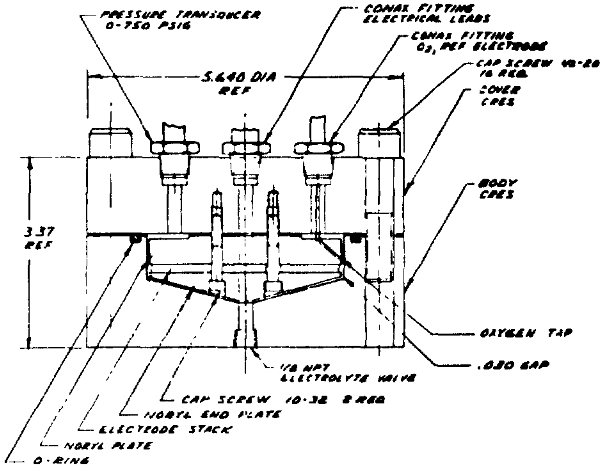

Figure 245. Nickel-hydrogen research cell

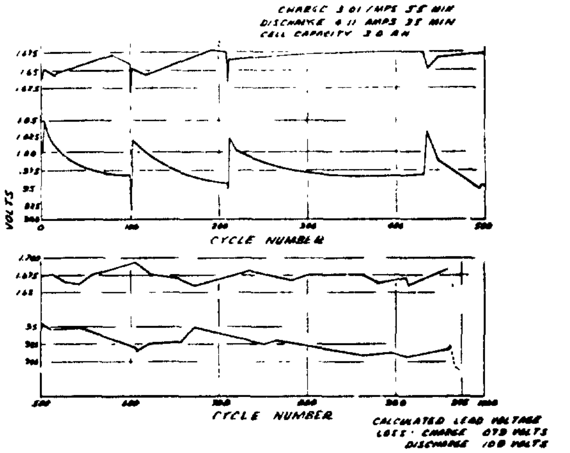

Figure 246. Asbestos separator, research cell, cycle data

CELL CAPACITY, VACUUM FILL 16.7 CC

INITIAL LOSS (RUN 1-5) 0.45 CC (2.7%)

DURING CYCLING

CYCLE NO.	LOSS CC	PERCENT	CAPACITY TEST RUN NO.
100	0.07	0.42	6
210	0.20	1.2	7
320	0.15	0.90	NONE
432	0.06	0.36	8
432	0.78	4.7	9*
607	0.10	0.60	NONE
798	0.002	0.01	NONE
975	NONE	NONE	10
TOTAL	1.81	10.9	

*SPECIAL TEST C/2 CHARGE FOR 4 HOURS

Figure 247. Electrolyte loss

RUN NO.	CHARGE RATE AMPS	TIME HRS.	OPEN CKT. TIME HRS.	OXYGEN PERCENT EOC	EO-OC
2	1.375	4.0	1.8	10.8	5.0
3	0.34	15.3	1.4	4.7	2.6
5	3.00	1.5	1.0	6.9	3.7
6	0.34	15.7	1.0	2.5	1.7
7	0.34	15.8	1.0	2.2	1.0
8	0.34	15.8	1.0	1.7	0.9
9	1.375	4.0	2.0	3.8	0.4
10	0.34	15.3	1.0	1.3	0.6

CYCLE #627, END OF CHARGE, 1.8% (3.01 AMPS)

Figure 248. Oxygen generation in a 3 A-HR nickel-hydrogen cell

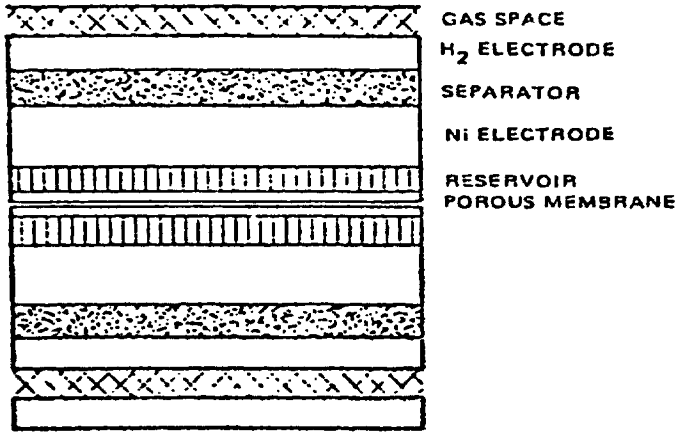

Figure 249. Design I: Back-to-back positives a) gas permeable separator, b) gas impermeable separator (dimension of gas space critical)

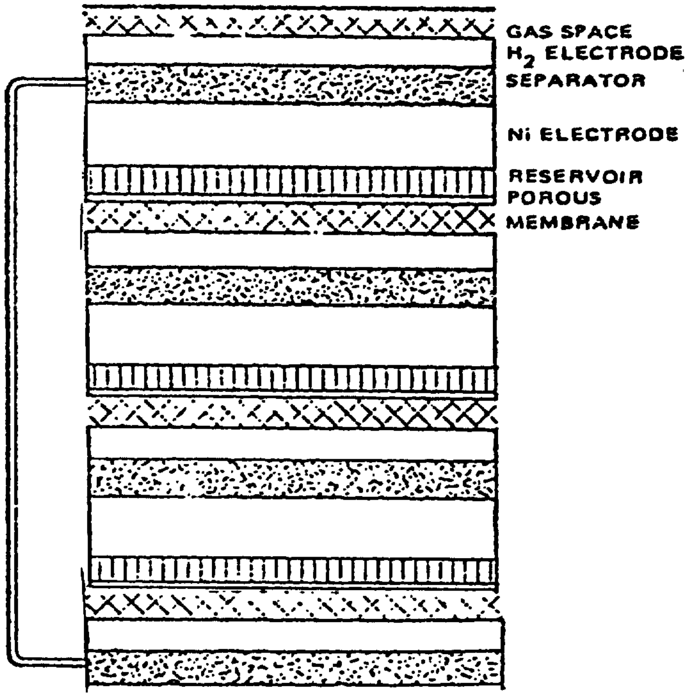

Figure 250. Design II: Single positives, gas impermeable separator

APPENDIX A

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