ORBITING ASTRONOMICAL OBSERVATORY BATTERY AND POWER SYSTEM DESIGN

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

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

(Figure 42)

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

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

(Figure 43)

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

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

(Figure 44)

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

(Figure 45)

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

(Figure 46)

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

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

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

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

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

(Figure 47)

In talking this presentation over with Harry Wajgras, we realized that with 27,000 orbits you have a lot of data. So you have to be somewhat selective in what you are going to present and what you are going to discuss. What we chose to put forth was not the early orbit characteristics but the more recent because that is really where the degradation has come to be observed.

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

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

(Figure 48)

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

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

Another reason for showing this to you is it also emphasizes the consistency in battery temperature. And this spacecraft probably has one of the most solid thermals on it as far as keeping that battery cool as any one we have worked with in a long time. But I might also point out that this is being enhanced because we are not overcharging the battery a lot.

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

(Figure 49)

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

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

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

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

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

DISCUSSION

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

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

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

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

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

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

FORD: You can, yes.

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

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

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

FORD: In the former, yes.

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

FORD: You have got interacting effects.

RITTERMAN: Yes, and counteracting also.

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

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

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

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

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

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

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

FORD: Right.

UCHIYAMA: Floyd, I wonder if you could put up your slide (Figure 47), where you had the discharge -- In that curve there, are you suggesting that you are seeing that the whole plateau on discharge? As I understand the curve there, you seem to have taken out 3.2 ampere hours out of the total. What is that? About 40 percent?

FORD: It is about 20 ampere hour cell rated.

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

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

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

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

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

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

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

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

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

OAO-C BATTERY DESIGN SUMMARY

- 20 AH NICKEL-CADMIUM CELLS (GULTON)
- 22 SERIES CONNECTED CELLS PER BATTERY

THREE BATTERIES PER SPACECRAFT

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

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

Figure 42

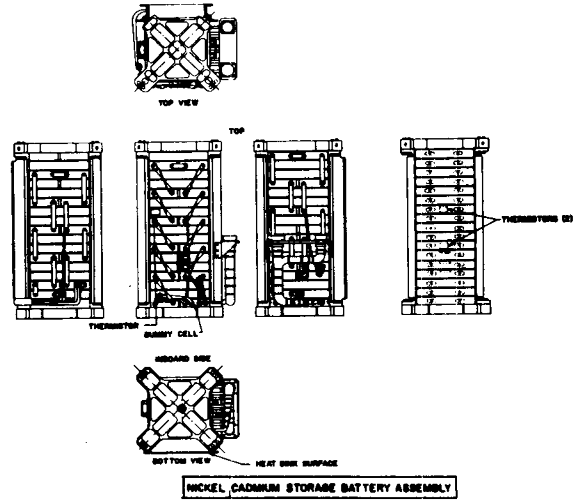
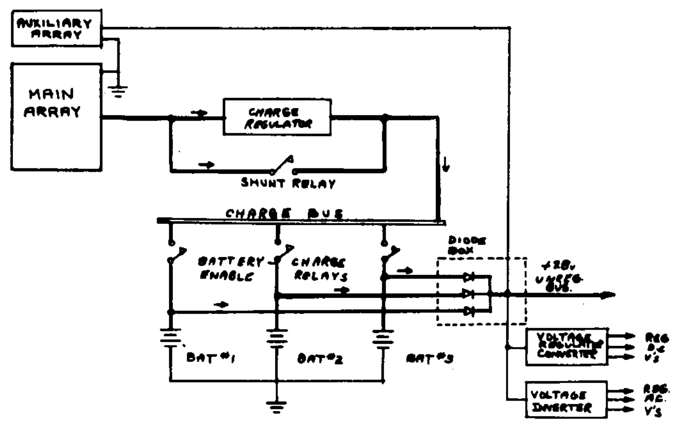


Figure 43



POWER FLOW
(FUNCTIONAL

Figure 44

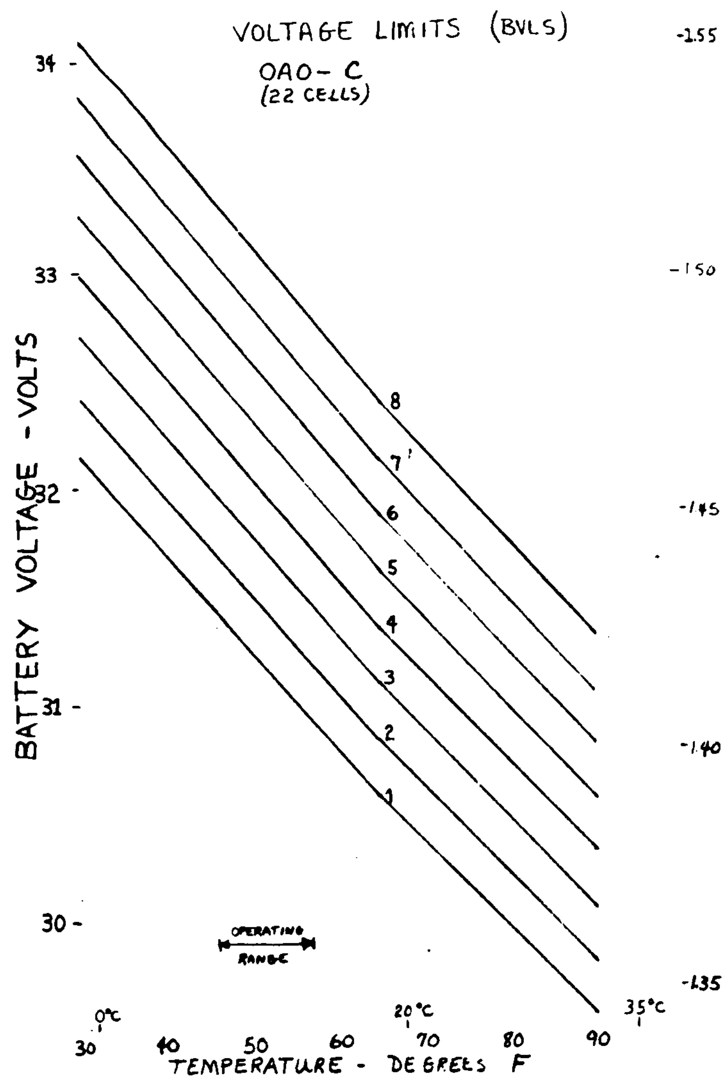


Figure 45

SUMMARY OF OAO-C BATTERY PERFORMANCE

OPERATING LIFE AS OF NOVEMBER 1977	63 MONTHS, 27,620 ORBITS
BVLS LEVELS USED	NORMAL OPERATION - 1 OR 2 LOW ARRAY POWER - 3 OR 4
TYPICAL DISCHARGE CAPACITY	2 8 TO 3.2 AH PER BATTERY 4.0 AH PEAK PER BATTERY
BATTERY TEMPERATURE	AVERAGE OF 50 F RANGE OF 46 TO 52 F
RECHARGE RATIO	TYPICALLY - 105% MINIMUM - 103%
BATTERY CURRENT SHARING	WITHIN RESOLUTION OF TELEMETRY
BUS UNDERVOLTAGE SETTING	FIRST SIX MONTHS - 26.4 VOLTS INCREMENTALLY REDUCED TO 23.3 VOLTS
SOCU FAILURE	21,050 ORBITS
SOLAR ARRAY DEGRADATION	APPROXIMATELY 20%

Figure 46

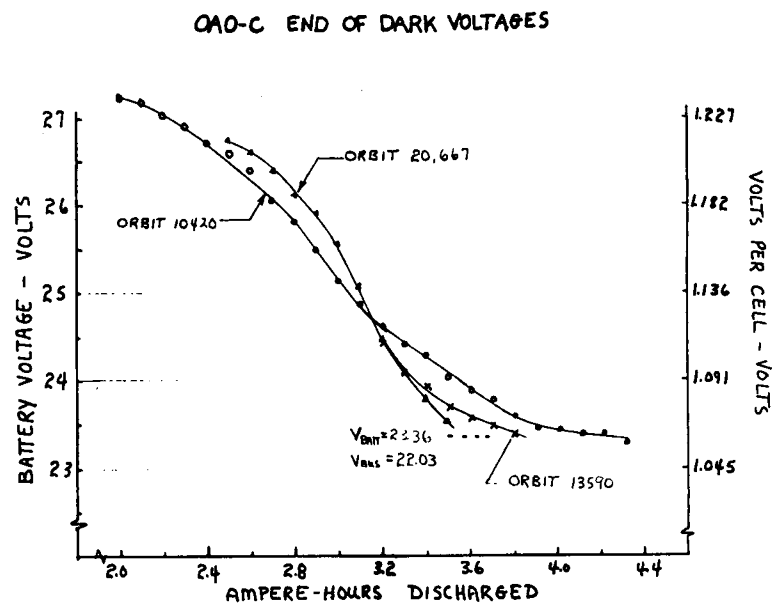


Figure 47

SUMMARY OF BATTERY PERFORMANCE

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

* (EOL) END OF LIGHT

Figure 48

COMPARISON OF OAO-C WITH OAO A-2

- BVLS RANGE EXPANDED (LOWER LEVELS) FOR OAO-C
  - LOWEST A-2 LEVELS NOT ADEQUATE TO LIMIT OVERCHARGE AFTER TWO YEARS
- OVERCHARGE OF A-2 BATTERIES HIGHER DURING LIFE
- A-2 BATTERIES OPERATED AT HIGHER TEMPERATURE DURING LIFE
- BOTH BATTERIES EXHIBITED DECREASE IN THIRD ELECTRODE SIGNAL
- DEPTH-OF-DISHCARGE FOR OAO-C GREATER THAN A-2
- BATTERY END-OF-DARK VOLTAGE DEGRADATION APPEARED GREATER FOR OAO-C
- A-2 BATTERIES EXHIBITED SYMPTOMS OF NEGATIVE LIMITING ON CHARGE
- KNOWN MANUFACTURING DIFFERENCES

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

Figure 49