DISCUSSION OF THE SAGE ANOMALY

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We could also call this the demise of a battery. Two almost identical spacecraft are HCMM and SAGE. They both have cells from the same manufacturing lot. It was an Eagle Picher 9-ampere hour cell. Eagle Picher was also the battery manufacturer, and Boeing was the prime contractor.

SAGE was selected for this presentation because it had the most severe and the most rapid degradation, plus it was documented a little better because it had a tape recorder on board, and HCMM did not.

(Figure 3-40)

This will give you a little bit of background. Here is a block diagram of the power system. It's a two-panel solar array that can be rotated plus or minus 80 degrees about the spacecraft X-axis, plus X is the velocity direction of the spacecraft.

The main bus voltage was specified at 28 plus or minus 4 volts, and the regulator bus was 28 volts plus or minus a percent. The loads are connected through a relay box for both the instrument module and the space module loads. There is undervoltage detector set at 23.5 volts and also an overload sensor.

There were some thermostats on the battery for overtemperature, and they were set at 33 plus or minus 2 degrees, although actually we ended up a little higher, something like 38 degrees where they tripped it. When they were tripped, they forced the battery to go to voltage level. It is a temperature compensated voltage limit, charge control and there were two limiters. The battery was 21 series connector cells divided into three packs.

(Figure 3-41)

This vugraph shows the voltage levels. The two limiters worked in tandem. The way it worked, when the voltage came up, the level B would clamp. When those transistors began to saturate at about 4 amperes, then the voltage would be clamped at the A limiter, at the higher curve.

These curves are very similar to the curves used in the MMS spacecraft, or in the standard battery spec. The A limiter is level 6. They are the same curves. The only difference between these is a little bit more space between the AEM voltage limits, about levels 5 and levels 6.

(Figure 3-42)

Here's a little more background. This curve shows the same SAGE sunlight duration, and you can see how it varies. Sunlight duration is as little as 61 minutes and as much as 97 minutes, which is the orbit period.

The spacecraft is in full sunlight every couple of months from 7 to 10 days. For most part, it is between 61- and 70-minute sunlight duration. However, the solar arrays are now illuminated when the spacecraft is in the sunlight, which may be another 10 minutes or so before the solar arrays are illuminated.

Therefore, the battery discharge periods can be as long as 59 minutes—45 minutes full loads, and load shares with solar array for about 14 minutes. So that only allows 38 minutes for charging. This and the HCMM spacecraft are the only spacecraft I am aware of that have a longer discharge period than they do a sunlight period.

(Figure 3-43)

This vugraph shows the beta angle, which is the angle the Sun makes when normal to the orbital plane. That is what determines the sunlight duration.

Here are battery average dissipation and battery temperatures, which are the diamonds and the squares. The circles are the panel 1 temperature, which is where the battery is mounted.

Through the first 800 orbits, the solar input was pretty much due to the variation because the battery dissipation was over 5 watts. But one part was under 5 watts. As you can see, at beta of 90 degrees when you have the longest arc period, the batteries are coolest. When the sunlight period is increased, then the temperature comes up.

But around orbit 800 or a little bit after, you can see some changes starting to take place. That is a delta between the battery panels, and the battery temperatures are beginning to increase along with the battery dissipation. And that is when the problems started to occur. That will probably be illustrated in some of the later vugraphs.

(Figure 3-44)

This is the percent recharge versus orbit. It varied anywhere from 95 percent to about 104 percent through the first 800 orbits, or slightly after 800. Then they began to climb.

Even though the voltage on the level was lower, it went from 7 to 6, then 5, 4, and then 5 again. The first undervoltage occurred on orbit 1277 right after this data point was taken. These data points are full orbit per course, so we don't have it every orbit.

Even though we were recharging batteries about 112 percent, we still have that undervoltage condition. After that point, the temperatures really started to take off as well as the percent return.

(Figure 3-45)

This vugraph is a typical early orbit where we had a 38-minute charge period and 59-minute discharge period, which resulted in a 21-percent DOD.

If you notice, we had only a 95-percent return when we were at level 7. We had the main bus voltage that is relatively flat until it reaches a clamp. The battery is running fairly cold, around 8 degrees. There isn't much of a delta between the panel and the battery pack.

There is a nice taper on the charge current. These humps are when the experiment is on, and it is being used. I will just move this slide over here so you can take a look at at, and I will show you one of the later orbits.

(Figure 3-46)

As you can see, there have been quite a bit of changes. On this one the DOD is a little lighter; it's a little shorter dark period. We are only running 19 percent, but it is 157-percent recharge, even though at this one we are at level 6.

If you notice the discharge voltage profile, this is dipping down to 24.8 volts, where on the early orbit 59596. The end-of-discharge was a little above 26 volts. The charge profiles also changed where the charge voltage seems to follow the charging current.

The battery temperature is now descreasing during discharge, and when we get to the overcharge region, there is a rapid increase in battery temperature. Battery temperature is now up in the neighborhood of 25 to 26 degrees.

There is a big delta between the panel 1 temperature and the battery pack temperatures. There is a very little taper where it drops off here. It is solar array limited. This was the last full orbit record we could get. The next time we tried, it was around orbit 1685, and we get undervoltage after about 127 ampere-hours out.

We continued bouncing around between 100 voltages and high battery temperatures by playing with the charge voltage limit until about over 2110 and 2120 when two cells, apparently, shorted.

At this point the voltage would no longer come up to level 1, so we could no longer use the charge control, the voltage limiter charge control. So the only charge control we had left was to rotate the arrays and try to limit the amount of current going into the battery in that fashion.

Also, we had to disconnect the intervoltage circuit, and the only indication we had of low voltages was when the clock stopped. The spacecraft clock was stopped at around 26 volts.

We are still operating. We are up to orbit 4000 continuous Sun now. We are not taking any signs. But I estimate the capacity of the battery is now in the neighborhood of 0.9 ampere-hour. And there was another cell shorted at orbit 2530.

(Figure 3-47)

This is rather an interesting curve. This is kind of Sid Gross' idea. He started to plot this on HCMM. This is what I call a zero-current voltage. This is at the transition point between charge and discharge. When you get on the edge of the orbiter records, you take a voltage point.

See, early in life if anything, it was going up. Then there again, around orbit 800 it started to fall off a little bit. Then, by orbit 900, it was downhill and never really recovered.

Back in here we are playing around with the different voltage limits, and it had a little bit of effect, but not very much.

(Figure 3-48)

We did some teardown analysis. These pictures are from a cell that was torn down after 2264 cycles. These results were very similar to a cell that was opened after about 2 years of tests at Crane. What I want to point out here is the way the separator is sticking to the neck of the plate.

When the cell was opened and we tried to get the separator off, it just kind of layered. And what would happen, one-half would stick to the plate, and the other half would come into your hand. Even when we went to the SOXIC extraction, we still couldn't get the separator off the negative plate.

(Figure 3-49)

I am not going to go over this whole chart. Since some of the analysis work was done, a little bit of clarification is needed.

Lot 1 on HCMM was flown on both spacecraft. On the SAGE lot, as you recall last year, Floyd made a presentation of some of the test data we got on the ground. The SAGE performance was so poor that we decided not to fly it. But, since they are both supposedly made the same, it is good for comparison.

As you can see, there is some plate expansion, both positive and negative. This first column is uncycled cells, and the other one is after 2 years of tests. The negative utilization isn't too good, about 55 percent in this particular cell, anyway.

I think what is important is the carbonate content of the uncycled cell. This is in percent mil equivalent of potassium carbonate in the electrolyte. A little different way than we usually report it.

To give you an idea, 31 percent is rather high, maybe just a little bit high for a cell to cycle like this—58 percent, and 52 percent, and 48 percent are very high numbers.

What we concluded to date is that the anomaly is essentially a bunch of soft shorts which is probably caused by cadmium vibration, and in some cases soft shorts developing hard shorts, we have lost three cells.

Why it happened so quickly results in several debates and discussion: Perhaps high carbonate content across it, plate expansion, heavy loading, or maybe a combination of several things.

I might want to add that the problem did not show up in any ground tests. The cells have flown and they look fine. Although there was quite a bit of voltage diversion on charge and discharge and it was a little hard to control the percent of return, the cells on test at Crane did not show a great deal of capacity loss after a 2-year capacity check.

This is rather from memory, but it was something on the order of 7.5- or 8-ampere hours. So it wasn't too terrible. These cells were also bought to the 1974 15,000 spec or a similar type of spec.

DISCUSSION

MILLER: Dave, I am sure you are aware that NASA was kind enough to furnish us the reports, data, and analysis of your efforts in this problem. I guess probably we, better than anybody else, really appreciate just how much work you guys did in this area, and I think you should be commended on this. I would like to take this opportunity to do that.

We also appreciate your suggestions with respect to our manufacturing changes that you have brought out. In the paper we will present tomorrow, we will cover some of these areas. Using this data, we had several meetings back at Eagle Picher to see what we could contribute to the investigation.

Although we are certainly not impartial observers in this matter, we probably look at your data from the respect of trying to defend the matter. However, I think there were some valid questions brought up in our meetings. When we looked at the thermal design of the spacecraft, we noticed several comments in the reports. The thermal environment of the battery was very marginal in the thermal design so that some equipment would have to be turned off and equipment would have to be used at different times to stop from overloading, evaluating the cause of the thermal problem.

We noticed that as the battery was just approaching its maximum thermal input from the Sun, as the vehicle rotated and the Sun was shining directly on the panel to which the battery was mounted, there was a decision to go to a higher voltage cutoff level, which may not have been a really appropriate way to use the battery. There was also apparently a thermal abnormality associated with some adjacent panels on the batteries prior to battery mount.

We looked at the carbonate which you pointed out in there. If you would back those figures back to the specification level, you will find that 40 or 50 percent level as you expressed it in milliequivalents for actual free hydroxide ions. That translates into less than 2 percent carbonate per plate weight, and that was the specification limit for the program.

If you looked at some of the thermal data on there, as I am sure everyone realizes, the HCMM/SAGE battery is not really a 21-cell battery. It is three 7-cell batteries, and they are physically separated. However, the two battery temperature profiles track very well.

The problems you perceive are cell problems, let's say, individual cell problems and still allow these two values to subtract --

I guess I won't take up any more time of your meeting, but I think there is sufficient evidence to indicate that batteries shouldn't take full blame. I think there are some areas and some questions to be answered, and let me just stop there.

BAER: You brought up several points, and I will try to address them, if I can remember them.

I think thermal design did leave something to be desired, and certainly contributed after the problem developed into making it hard to control. Because with the 5-watt design for battery thermal dissipation, we could dissipate slightly more than that during the longer eclipses, just in the eclipse part. So that allowed nothing for recharge. It should have run a little warmer than what was predicted anyway. However, I wouldn't expect to be able to control this by using a different voltage level which we tried.

In regard to your comment about going to level 7, that was done because on one of the previous orbits, we weren't getting a full-percent return in the spacecraft. So we went to level 7 for a while. At that point in the game the thing was running cool, and we were worried about the battery running down.

If you looked at the one chart I read up there, the orbit 596, we had only 95-percent return.

To back that up, the temperature didn't rise at all during the charge period. So that certainly indicated that at a beta 90 during the longer dark periods, you were not getting the batteries fully charged. You weren't in energy belts.

So we did go to level 7 for a few orbits, and when we knew the dark periods were getting shorter again, then we went back to our level 6.

As far as the carbonate is concerned, I would have to pass my comment on that to Pat Montgomery, who is here today. I don't think Jerry has anything.

HALPERT: That was percent there, not milliequivalents, right?

BAER: Right. It was percent. Well, percent milliequivalents.

THIERFELDER: Dave, you showed a photograph and commented that the separator was sticking to the negative plate. What cells were they? Did you open other cells where it wasn't sticking? What point in life did the sticking to the negative plate start?

BAER: Well, it is rather like comparing apples and oranges. That was not the plate lot. That was after 2264 cycles of tests here on the SAGE lot cells. There were two cells opened. There was usually some dryness and a little bit of sticking. That was the most severe case of sticking.

THIERFELDER: At 2000 cycles they were sticking?

BAER: On that particular cell.

THIERFELDER: You don't have any number where they were not sticking?

BAER: As I said, some of the ones at about 2000 cycles weren't sticking very bad at all, just a little bit more of a dryness than a sticking.

LEAR: You had reference to the photographs, the sticking of the separator. What about positive plates, did you notice any of the bubbling or crystalizing?

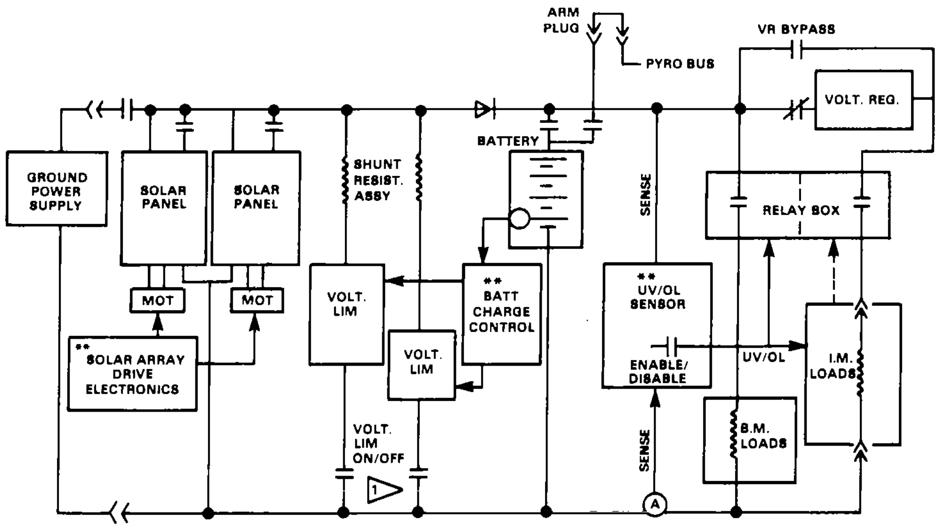
BAER: On the positive plates, you could see they looked as if they were under pressure and they were starting to deteriorate a little bit. I am addressing strictly the flight lot cells, the one that was opened at 10,000 cycles. So there was a little bit discoloration. It looked as if it had been under pressure.

WEBB: Was there a plate hold down or constraint?

BAER: I don't remember. Lee, do you remember?

MILLER: There's no hold down in the cell.

POWER & DISTRIBUTION SUBSYSTEM V BLOCK DIAGRAM



1 NORMALLY BOTH ON: ONLY ONE CAN BE COMMANDED OFF AT A TIME

** LOCATED IN RELAY BOX

Figure 3-40

AEM VOLTAGE LIMIT

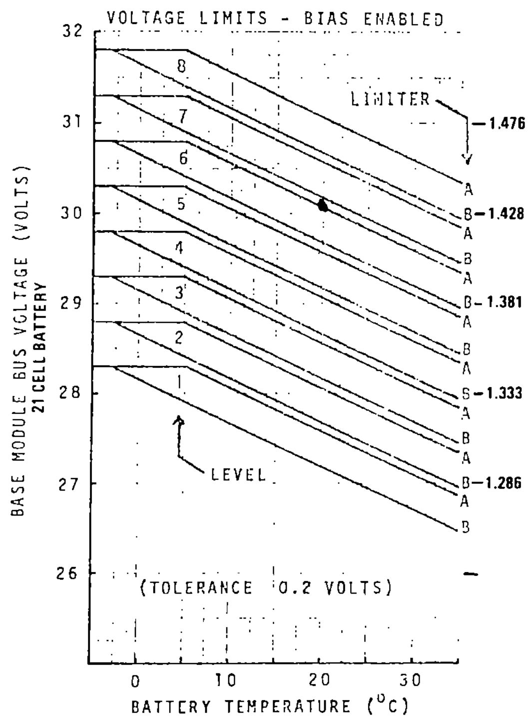


Figure 3-41

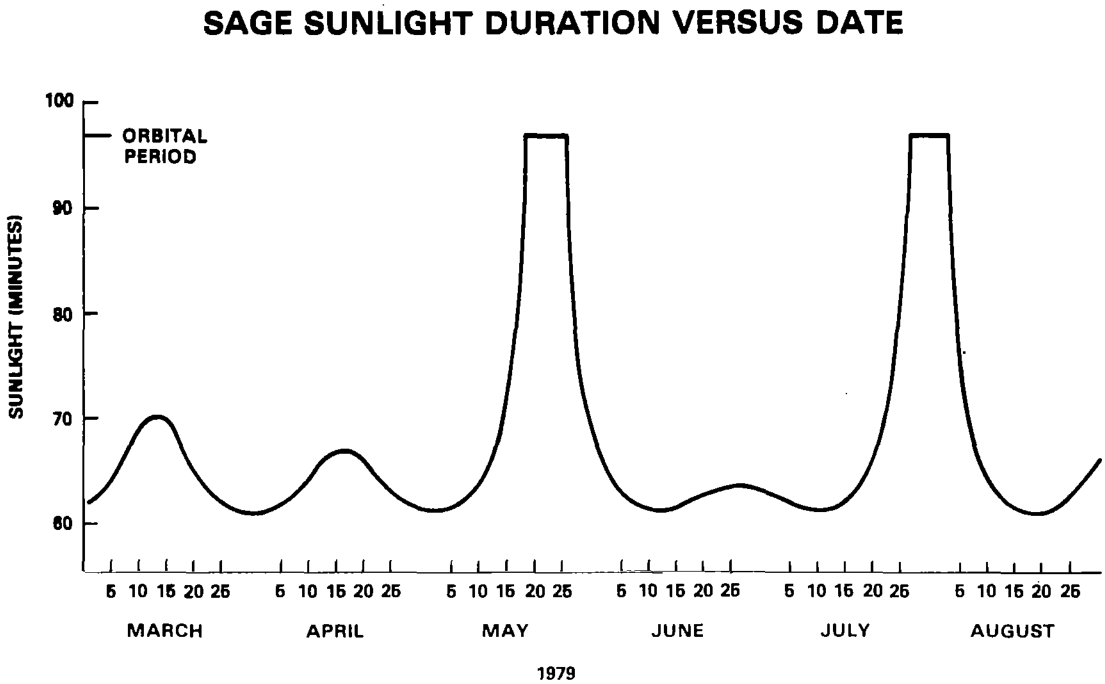


Figure 3-42

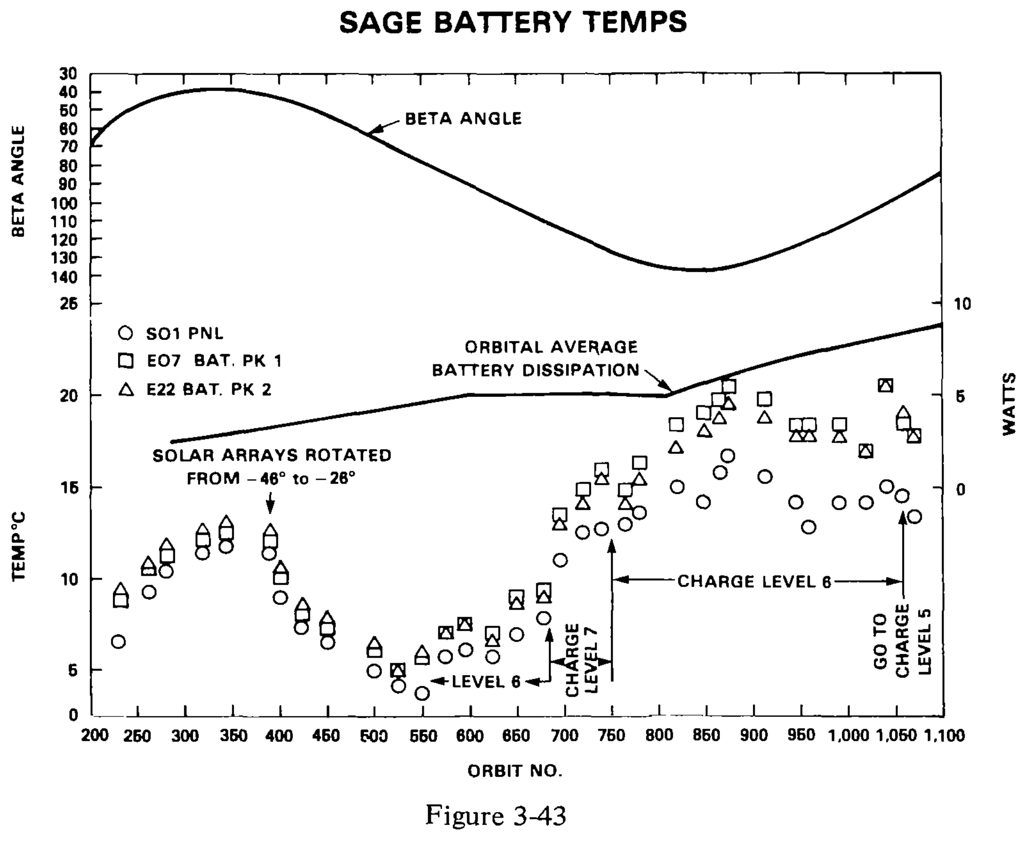


Figure 3-43

SAGE % RECHARGE VS ORBIT

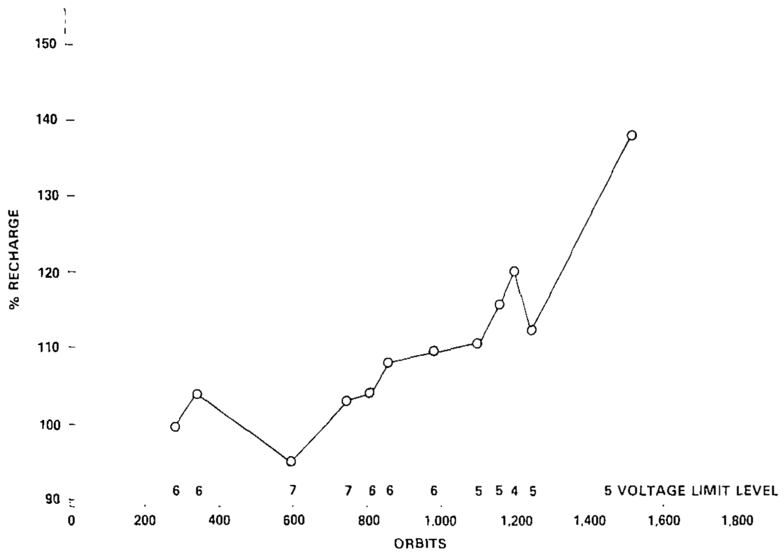


Figure 3-44

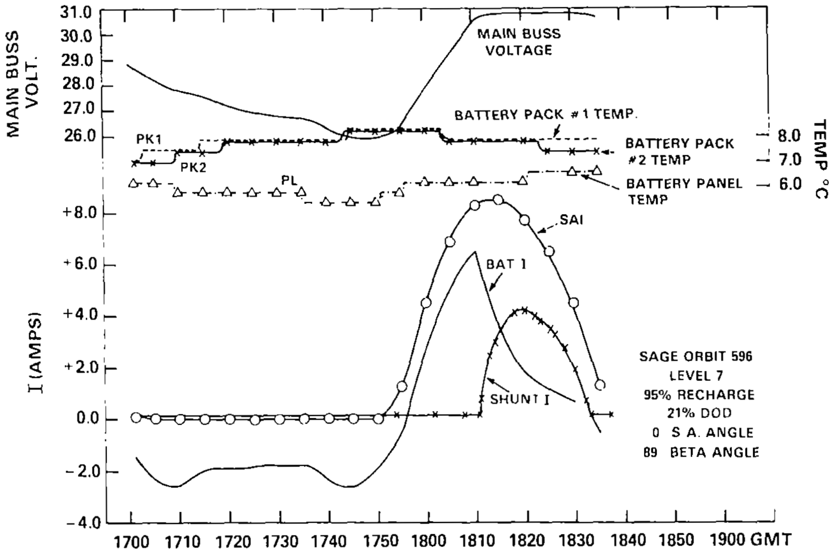


Figure 3-45

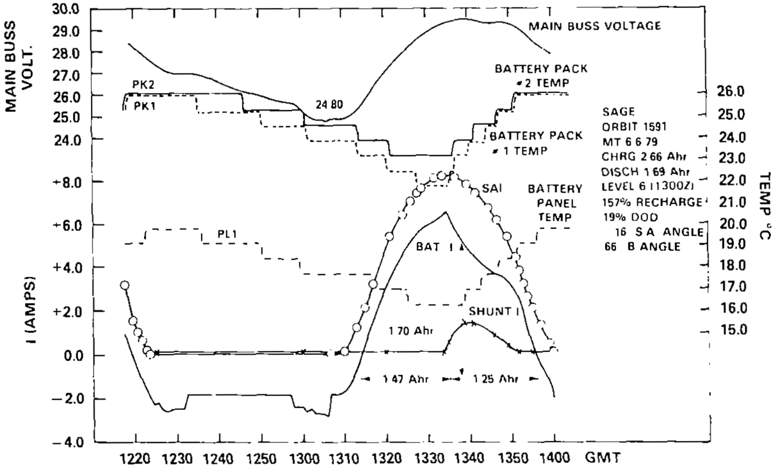


Figure 3-46

SAGE BATTERY "0" CURRENT VOLTAGE (EOC)

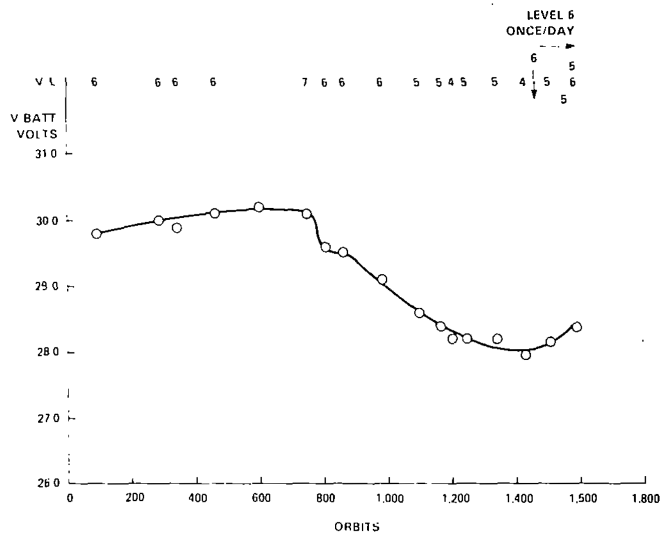


Figure 3-47

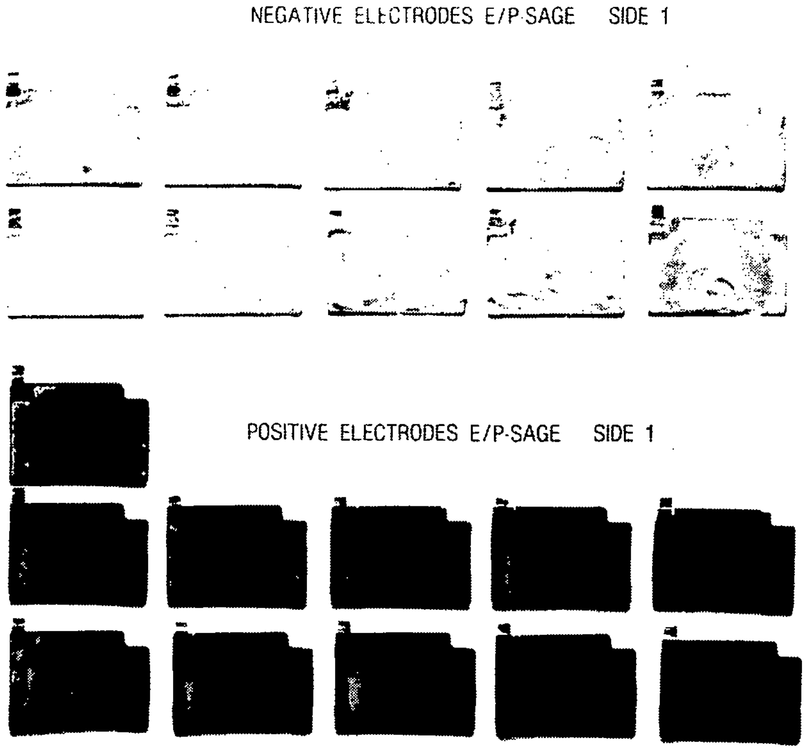


Figure 3-48

ANALYSIS OF NICKEL-CADMIUM CELLS FROM THE HCMM AND SAGE FLIGHT LOTS

	LOT 1 (HCMM)		LOT 2 (SAGE)	
	S/N #214 Uncycled	S/N #256 Life Test (10 K Cycles)	S/N #291 Parametric Test	S/N #318 Uncycled
Pos. Pl. Wt.	8.24 g	8.60 g	8.62 g	8.89 g
Neg. Pl. Wt.	10.60 g	9.76 g	9.83 g	10.29 g
Pos. Thick.	29.10 mils	31.58 mils	28.84 mils	28.27 mils
Neg. Thick.	32.60 mils	33.50 mils	31.16 mils	31.70 mils
Pos. Chem. Cap.	14.30 Ah	15.00 Ah	12.94 Ah	12.12 Ah
Neg. Chem. Cap.	30.37 Ah	26.38 Ah	20.52 Ah	23.26 Ah
Pos. E Chem. Cap.	11.67 Ah	**	13.75 Ah	11.25 Ah
Neg. E Chem. Cap.	16.82 Ah	**	15.60 Ah	18.24 Ah
Electrolyte OH^-	100.79 meq.	162.11 meq.	101.79 meq.	98.10 meq.
Electrolyte $CO_3^=$	138.28 meq.	74.18 meq.	108.28 meq.	90.60 meq.
Total meq.	239.07 meq.	236.29 meq.	210.07 meq.	198.70 meq.
Electrolyte as OH^-	42%	69%	48%	52%
Electrolyte as $CO_3^=$	58%	31%	52%	48%

** These tests have not yet been performed.

Figure 3-49