# BATTERY RECONDITIONING, SUMMARY OF TRW EXPERIENCE

W. Scott
TRW

I would like to present a summary of data that relates to the results of reconditioning that we have accumulated from three different spacecraft programs at TRW. I hope that most of this data will be new to you so that it will be of considerable interest.

I think it will add significantly to the engineering data base for reconditioning and hopefully increase the level of credibility of this process for general use.

(Figure 4-55)

First, I would like to show the basic design characteristics of the three programs that I am going to talk about.

First, all three are 24-hour synchronous orbit applications: Program A, 24 ampere-hour cells, GE, 22 cells in series. Program B, 12 ampere-hours, Gulton cells, manufactured approximately 1970, 1971, 22 in series. The third, fleet Satcom program which you have heard about, 24-ampere hour cells, GE, 24 cells in series. Each of these spacecraft has three batteries operating parallel, more or less, directly connected to the bus. The first two operating approximately over the same temperature range, 60 to 80 to 85°F. The fleet Satcom operates at a significantly lower temperature range. Also, the first two are operating at a designed maximum DOD 35 to 40 percent. Fleet Satcom is a designed maximum of 75.

As to reconditioning parameters, I showed two different reconditioning load resistors from the programs A and B because until recently the batteries had 44-ohm resistors used for reconditioning discharge.

Recently we have started to install higher load resistances, as indicated by B under each of those two. Fleet Satcom has about an 85-ohm resistance across 24 cells.

There is also a difference in the end voltage used to terminate the reconditioning discharge. These numbers you see here are the numbers presently used in flight. There is some difference right now in the way in which some of these programs are being tested on the ground and the way they are being actually operated in flight.

As you see here, the minimum voltage per cell that we are using is with the fleet Satcom program, which in flight has the highest resistance per cell. The 44 ohms for the programs A and B apply to the spacecraft, to the older spacecraft in flight, and they are going down to 0.9 and 1 volt per cell respectively.

(Figure 4-56)

I am going to show both ground test and flight data for two out of the three programs. I am going to show ground test data only for program A because it was just too much of a hassle to get the right kind of comparable flight data for program A. But we have quite a bit of ground test information.

This is the 24-ampere-hour GE cell discharged for reconditioning purposes into the 44-ohm resistor to approximately 1 volt per cell, 0.9 to 1 volt per cell.

What I have shown here is the data for actually three life tests conducted over a period of several years in connection with a long-term storage effects test that was completed a year or so ago. Battery serial number 13 was tested after 4 years of ground storage; battery 15 after 5 years; and 15X after 6 years.

On the first line I show the capacities actually taken out during the reconditioning discharge to 20 volts, which is about 0.9 volt per cell. You can see they are all roughly about the same and fall within a rather narrow range. What you are actually seeing there is the range for a 10-eclipse season test where we actually did a reconditioning discharge between each eclipse season.

Actually, that means that there were nine such discharges done during each of these life tests, and that is the range we obtained for all nine such discharges in each of those life tests. And you can see that the range is quite narrow.

To compare with that, the next line shows the range of end of discharge, minimum seen during each eclipse season, at the middle of the eclipse season, after 1.2-hours discharge.

Here again the range is very narrow. There was very little trend if any. If you look at the whole curve, you see a slight drop after the first eclipse season, but no significant change after that. I didn't plot any of these because the plots are rather dull. It looks like a flat, straight line, which isn't too interesting.

Some full load capacity data is at the bottom. All this testing was done using constant power loads for load discharge, and the capacity measurements were also measured on the constant power load, which were 300 watts for the 22-cell battery. Capacities to 25.5 volts of the battery were shown before each life test, 29.4, 28.7, and 27.9.

After the completion of each life test and a final reconditioning cycle, you can see that the capacities are a little bit less where we measured them on batteries 13 and 15. For some reason or other, it didn't get measured on the last one.

Now, in the middle of the final life test on serial number 15X, we did a power discharge after completion of season number 6 and before we did the reconditioning. We got 20 ampere-hours.

Then, we did the reconditioning and then did another 300-watt constant power discharge, and we got 25.4. So this indicates the mid-test response to reconditioning that we have attained.

(Figure 4-57)

For program B, we have both ground test and actual flight data. Although in this case, that data are not on the same type of cell, unfortunately.

You may have noted on the first graph that earlier spacecraft were made with Gulton cells. The more recent ones are being made with General Electric cells.

This data I have here for ground testing is for General Electric cells, and it shows the results over five eclipse seasons of accelerated testing on the ground with two different sizes of reconditioning resistors.

Again, I have left the data in the form of digital data so that it makes it easy to compare numerically with other data that you might have available.

I want to point out that again, after a slight adjustment during the very beginning of the test, there appears to be no trend either upward or downward in the end of discharge, minimum end-of-discharge capacity during mid season throughout the tests to date. Now, in addition to that, we have some of the actual reconditioning capacity data such as I showed on the previous graph.

For the 44-ohm resistance case, we take the battery to 19 volts. And the only data I could come up with was 14.5 ampere-hours. These are 12-ampere-hour rated cells, we call them for this program.

For the discharge into 167 ohms, we go down to 12 volts in this case for this ground test. We started out at 19 ampere-hours. There has been a small change down here, but it is hanging right in there.

(Figure 4-58)

This is flight data for two spacecraft of the B program. These are data for Gulton cells. These cells, as I indicated, were made around 1970, using SAFT plate material.

Again, we are getting very constant results after the first eclipse season. But notice also that we show what kind of a program of reconditioning we are carrying out in this particular case.

We had no reconditioning for the first two eclipse seasons, one cycle after the next one, and two cycles from there on for flight B2. Flight B1 had some operational problems after the sixth eclipse season, and the data is not comparable.

Incidentally, the reason we are doing two cycles on this spacecraft is that we found with the 44-ohm resistor the first discharge curve sometimes looks rather limp after an eclipse season, particularly after 3 or 4 eclipse seasons have passed. But the second one looks much better, and we get considerably more capacity out. So we have sort of got in the habit of doing two reconditioning cycles when we use the lower resistor for discharge.

(Figure 4-59)

The third program is fleet Satcom. Now I don't want to bore you with old data, but I want to show you the final outcome of the fleet Satcom cell pack life test. I don't believe some of you have seen the data right up to the very end of the test. Ed said that this test had gone for 42 seasons. As a matter of fact, it went for 44.

(Figure 4-60)

There are the results in terms of end of discharge voltage. This stuff down here has been reported on earler. I think the last report on this program carried the data out into here somewhere. Now, this carries the data out to the last eclipse season that was performed on this test before it was terminated.

I will talk a little bit about this part of the behavior in just a moment. But as you may recall, a different method of reconditioning discharge was used from here on in which a very low rate was used to take the battery down to a very low battery voltage.

During this part, the battery indicated by the triangles was discharged at a full load rate down to 1 volt, and then down to 1 volt again on a 25-ohm resistor for 12-cell pack. And the battery looked pretty bad after approximately 12 eclipse seasons with that type of reconditioning. So that was why we went over to the much lower rate with the results that you see here.

(Figure 4-61)

Now, again, this is not particularly new data, but I do want to emphasize that we have a record of the capacity withdrawn on these reconditioning discharges as the test proceeds. In this case up to season 30 where the capacity more or less leveled off and remained constant for the rest of the tests.

You can see that during that period of the test where the end-of-discharge voltage during regular eclipse season declined rapidly, we also got a rapid decline in the available capacity on reconditioning discharge.

Incidentally, all the capacities are measured to 1 volt per cell, even though the reconditioning discharge was taken down to a lower voltage than that.

After we reduced the rate and began taking the battery down to a lower voltage, the capacities recovered to essentially where they were when the cell was new, and it remained there throughout the rest of the test.

(Figure 4-62)

This is flight data for fleet Satcom, which I don't believe many of you have seen yet. For the one flight that has completed four eclipse seasons to date, this data shows that we did not recondition prior to the first season, but have done one cycle of discharging on 85 ohms to approximately 3/4 volt per cell prior to each season after the first.

The capacities obtained on this reconditioning discharge for the three batteries on the spacecraft are indicated here. They are very, very even.

Minimal voltage during the season is battery voltage, range of the three batteries. I didn't even bother to calculate the difference between maximum and minimum to within the accuracy allowed by the telemetry system. There has been no change whatsoever in the minimum end of discharge voltage seen on this spacecraft to date.

In summary, what we are seeing is that the effects of reconditioning, when they are beneficial, are correlated best, of all the different variables that we looked at, and are correlated best with the capacity that we obtained during the reconditioning discharge. In this case, usually measured to 1 volt per cell.

You can discharge at a higher rate, you can discharge at a lower rate, and you can discharge to various end voltages. But as long as you get some minimum capacity out – and we don't know exactly what that minimum is, but, in all cases, it was something of the order of 10 percent greater than the rated capacity of the cell – as long as you can maintain that lowest capacity numbers, you can expect that you can get good results from your reconditioning discharge.

So we submit that possibly that capacity might be a more basic criterion to use to judge when you have completed reconditioning than the other variables you might think about.

## DISCUSSION

LEAR: Dr. Scott, on your B test, you said that you did two cycles; the first cycle was bumpy – and it's a two-part question – did you have individual cell control on that?

SCOTT: You mean individual cell voltage monitoring? No. That data that I referred to is flight data.

LEAR: Then you might attribute the bumps to be the cells reversing as you got down close to the . . . .

SCOTT: That's a good question. It's always difficult to interpret bumps on discharge curves in flight without individual cell data. It's a judgment call.

We believe that if the rate of change of voltage with time or with capacity is less than a certain number, then it probably isn't a cell reversal. It's usually a transition between plateaus or other things.

Usually, by looking, comparing that flight, some of that flight data with some of the things we have seen during ground tests where we have occasionally got cell reversals during discharge, we see a much sharper dropoff in voltage. A sharp dropoff in voltage is necessary to indicate a cell that might be reversing. I won't say that we have never seen that in flight, but we have not seen it on any of the examples I am giving here, any of these programs.

NAPOLI: Dr. Scott, on that one chart that you showed where you had the fleet Satcom craft test, at one point you changed the reconditioning discharge rate. Is that when you went down to lower levels than 1 volt per pack?

SCOTT: Right. We changed the rate and simultaneously allowed the pack to go down to something around 1 volt at the pack level.

NAPOLI: At the pack level. So basically you brought the cells down to zero?

SCOTT: Well, there were cells reversed during most of those discharges.

Yes, in the past, I believe we have indicated the kind of reversal behavior in general that we have seen and indicated that we have not seen any significant increase in pressure in those cells and that there is no sign of any problems throughout that test.

As a matter of fact, I recently looked at that data again and found that after the second or third such low discharge, that we had reversed 8 of the 12 cells in the pack every single time that we did that discharge. So that must have occurred for at least 30 different times before that test was terminated with no ill effects at all.

NAPOLI: Are you making any conclusion or recommendation on your opinion, or TRW's opinion of reconditioning, how beneficial is it, and down to what level would you recommend doing it on an operational satellite?

SCOTT: Well, I don't know that we are ready to make an official recommendation. But, unofficially, from an operational standpoint, we believe that the lower the discharge rate the better, because if it is low enough, you don't have to worry if you might reverse a few cells.

The operational problems of operating a battery under those conditions in orbit are much less than those if you are discharging at a higher rate where you have to worry about reversing cells.

So in addition, as the cells age, it appears that the amount of capacity that you can take out to any end voltage, decreases at any given rate. So that the lower the rate you start out with, the better chance you have of maximizing the output on a reconditioning discharge and therefore obtaining the maximum benefits. But exactly what voltage you have to go to, I don't think is the key factor right now. I think if you can get out some minimum number which is not yet really defined, some minimum fraction of the real capacity in the cell, you have done the job.

HENDEE: Perhaps you mentioned and I missed it, but if you had 44 seasons on your test, this is obviously an accelerated test?

SCOTT: That's correct.

HENDEE: That was on test C. Were A and B also accelerated?

SCOTT: Yes. The ground life tests that I have shown are all accelerated to the extent that the maximum between eclipse seasons time is of the order of 2 weeks.

HENDEE: That covers your reconditioning time plus a bit.

SCOTT: Right.

GASTON: One of your earlier slides showed that the ten eclipse seasons were conducted after 4, 5, and 6 years of ground storage.

Ground storage, first of all, I assume that is in a shorted state, cold temperature that the cell was kept at that condition. Second of all, I conclude from that that the cell performs perfectly well if kept up to 6 years in cold storage.

In other words, is the cell still flightworthy?

SCOTT: In this case, I would agree that the best known way of storing batteries is discharge shorted and at some low temperature. However, it is interesting that the three batteries that we put through this storage test were out of storage and at room temperature for significant periods of time.

So they do not represent, necessarily, a continuous period of low-temperature storage. Some of them were out doing other things for probably as much as half of their total storage time. But they were shorted essentially all that time.

GASTON: And yet their performance appears almost identical.

SCOTT: That's right.

One of several things that I believe is, of course, that the effect of proper reconditioning will overcome many of the problems associated with storage and improper handling that people have had in the past. I am convinced of that. That may have been what we were really doing here. I am not sure.

The other thing is that these were operated at a relatively mild depth of discharge, and I don't think that was particularly a severe type of test. The fleet Satcom test being at 70, 75 percent was considerably a more severe test.

HARKNESS: One more question. Joe?

LACKNER: I would like to make a comment on some of your findings. You note particularly after the reconditioning season, you went from 28 ampere-hours to 20 ampere-hours. After reconditioning you went back up to 25 ampere-hours.

Well, what we found on the CTS satellite, which is now in its fourth year of operation, as we go into the eclipse season for the first half of it, where we are actually increasing the ampere-hours out, we do get a recondition effect. In fact, it does improve.

It is during the second half of the eclipse season that there tends to be a slump. I think several people in their curves have noted that. So this past eclipse season we decided that what we would do is try to have a maximum load and increase the load throughout the eclipse season.

When we hit our peak eclipse day, instead of having a decreasing ampere-hour load, we had it on a ramp function and continued to increase the ampere-hour load out of it. What we found was that we didn't get a slump in the second half of the eclipse season, but it stayed relatively steady. And at the end of the eclipse season, we didn't get that dropoff that you noted.

So this may be a bit of a compromise for people who are sitting on the fence about reconditioning and nonreconditioning and need something on an operational basis.

# TRW SPACECRAFT BATTERY DESIGN SUMMARY

| | | | | | | | | RECONDITIONIG PARAMETERS | |
|---|---|---|---|---|---|---|---|---|---|
| PROGRAM DESIGNATION | ORBIT | CELL CAP. AH. RATED | CELL MFGR. | NO. OF IN SERIES | NO. OF BATTERIES PER S/C | OPER. TEMP ($^{0}$F) | NORMAL MAX. DOD (% OF RATED) | DISCHARGE LOAD RES. (Ω) | NORMAL DISCHARGE END VOLTAGE (V) |
| A | 24H SYNCH. | 24 | G.E. | 22 | 3 | 60-80 | 40 | A) 44<br>B)150 | 20(0.9V/CELL)<br>-- |
| B | 24H SYNCH. | 12 | GULTON (F.3 & 4)<br>G.E. SUBSEQ. | 22 | 3 | 60-85 | 35 | A) 44<br>B)167 | 22(1.0V/CELL)<br>-- |
| FLEETSATCOM | 24H SYNCH. | 24 | G.E. | 24 | 3 | 40-60 | 75 | 85 | 18(0.75V/CELL) |

Figure 4-55

TRW

### GROUND LIFE TEST DATA - PROGRAM A

Test Description: Simulated orbital life test - Flight config. Batteries
DOD 55% of rated capacity (13aH/24Ah cell)
10 Eclipse Seasons - Accelerated Schedule
Prior history - 4, 5 and 6 years of ground storage

| | Test Battery Serial Number | | |
|---|---|---|---|
| | s/n 13 (4 yrs.) | s/n 15 (5 yrs.) | s/n 15x (6 yrs. |
| Capacity on Reconditioning Discharge (Ah to 20 V) (44 ohms) | 31.25-31.50 | 31.00-31.82 | 31.90-32.60 |
| Range of Minimum EOD Voltage During Life Test (10 seasons) | 26.1-26.2<br>(1.190v/cell) | 26.2-26.6 | 26.2-26.5 |
| Full Load (300w) Capacity (Ah to 25.5V) | | | |
| Before Test | 29.4 | 28.7 | 27.9 |
| After Test | 27.9 | 27.6 | not measured |
| After Season 6 and: | | | |
| Before Recond. | ---------- | --------- | 20.00 |
| After Recond. | | | 25.4 |

Figure 4-56

TRW

### GROUND LIFE TEST DATA - PROGRAM B

| Eclipse Season No. | | Reconditioning Discharge Load Resistance | |
|---|---|---|---|
| | | 44 ohms<br>(S/N 3-6) | 167 ohms<br>(S/N 3-3) |
| 1 | Min. Voltage (v) | 26.82 (1.219 v/cell) | 27.00 (1.227 v/cell) |
| | Recond. Cap. (Ah) | | 19.0/12v |
| 2 | Min. Voltage (v) | 26.80 (1.218 v/cell) | 26.85 (1.220 v/cell) |
| | Recond. Cap. (Ah) | | 19.5/12v |
| 3 | Min. Voltage (v) | 26.70 (1.214 v/cell) | 26.90 (1.223 v/cell) |
| | Recond. Cap. (Ah) | | 19.3/12v |
| 4 | Min. Voltage (v) | 26.80 (1.218 v/cell) | 26.90 (1.223 v/cell) |
| | Recond. Cap. (Ah) | 14.5/19v | 19.4/12v |
| 5. | Min. Voltage (v) | | 26.85 (1.220 v/cell) |
| | Recond. Cap. (Ah) | | 18.5/12v<br>(18.0/22v) |

Figure 4-57

TRW

### MINIMUM VOLTAGE DATA IN FLIGHT - PROGRAM B

| Eclipse Season No. | Recond. Prior to Season | Minimum Voltage During Season | | | |
|---|---|---|---|---|---|
| | | Flight B1 | | Flight B2 | |
| | | Battery | V/Cell | Battery | V/Cell |
| 1 | None | 26.7 | 1.214 | 26.7 | 1.214 |
| 2 | None | 26.4 | 1.200 | 26.1 | 1.184 |
| 3 | One cycle | 26.5 | 1.206 | 26.2 | 1.189 |
| 4 | Two cycles | 26.5 | 1.206 | 26.3 | 1.195 |
| 5 | Two cycles | 26.4 | 1.198 | 26.3 | 1.190 |
| 6 | Two cycles | 26.4 | 1.200 | 26.2 | 1.190 |
| 7 | Two cycles(1) | NA | NA | 26.2 | 1.190 |
| 8 | Two cycles(1) | NA | NA | 26.2 | 1.190 |
| 9 | Two cycles(1) | NA | NA | 26.2 | 1.190 |
| 10 | Two cycles(1) | NA | NA | 26.2 | 1.190 |

Note (1) Flight 4 only

Figure 4-58

TRW

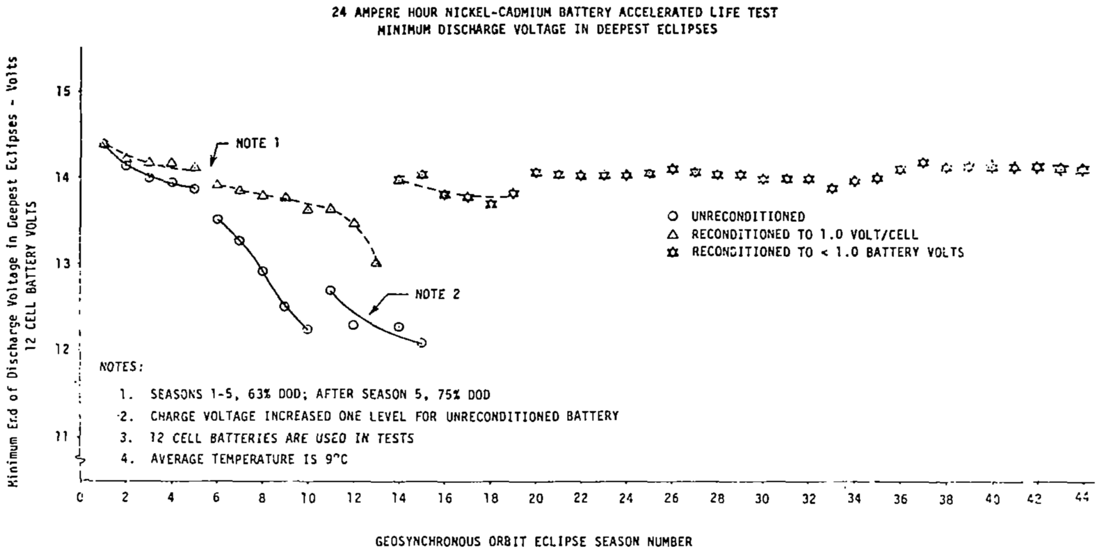
### FLEETSATCOM CELL PACK LIFE TEST RESULTS

CELL REVERSAL DATA SUMMARY

| Eclipse Season No. | Cell No. First to Reverse | Time on Recond. Discharge to First Reversal (hrs.) | Current at First Reversal (A) | 12-Cell Pack Voltage (v) | No. of Cells Reversed at EOD (~0.1v/cell) |
|---|---|---|---|---|---|
| 15 | 11 | 79 | 0.132<br>(C/180) | 4.31<br>(0.36v/cell) | 9 |
| 23 | 1 | 77 | 0.277<br>(C/87) | 8.10<br>(0.68v/cell) | 8 |
| 29 | 1 | 77 | 0.289<br>(C/83) | 10.75<br>(0.90v/cell) | 8 |
| 33 | 1 | 69 | 0.285<br>(C/84) | 11.35<br>(0.95v/cell) | 8 |

Figure 4-59

## FLEETSATCOM CELL PACK LIFE TEST RESULTS



NOTES:

1. SEASONS 1-5, 63% DOD; AFTER SEASON 5, 75% DOD
2. CHARGE VOLTAGE INCREASED ONE LEVEL FOR UNRECONDITIONED BATTERY
3. 12 CELL BATTERIES ARE USED IN TESTS
4. AVERAGE TEMPERATURE IS 9°C

Figure 4-60

## MINIMUM VOLTAGE DATA IN FLIGHT - PROGRAM FLEETSATCOM

| Eclipse Season No. | Recond. Prior to Season | Cap. on Recond. Discharge (1) (AH to 18V) | Minimum Voltage During Season | | |
|---|---|---|---|---|---|
| | | | Batteries | V/cell | Max. Temp. (°F) |
| 1 | None | ----- | 27.8-27.9 | 1.158 | 63 |
| 2 | One cycle | 33.77-34.30 | 27.8-27.9 | 1.158 | 65 |
| 3 | One cycle | 34.10-34.72 | 27.8 | 1.158 | 65 |
| 4 | One cycle | 34.36-34.43 | 27.8 | 1.158 | 65 |

---

(1) 85 ohms/24 cells

Figure 4-61

# FLEETSATCOM CELL PACK LIFE TEST RESULTS

## CAPACITY (AH TO 1V/CELL) ON RECONDITIONING DISCHARGES

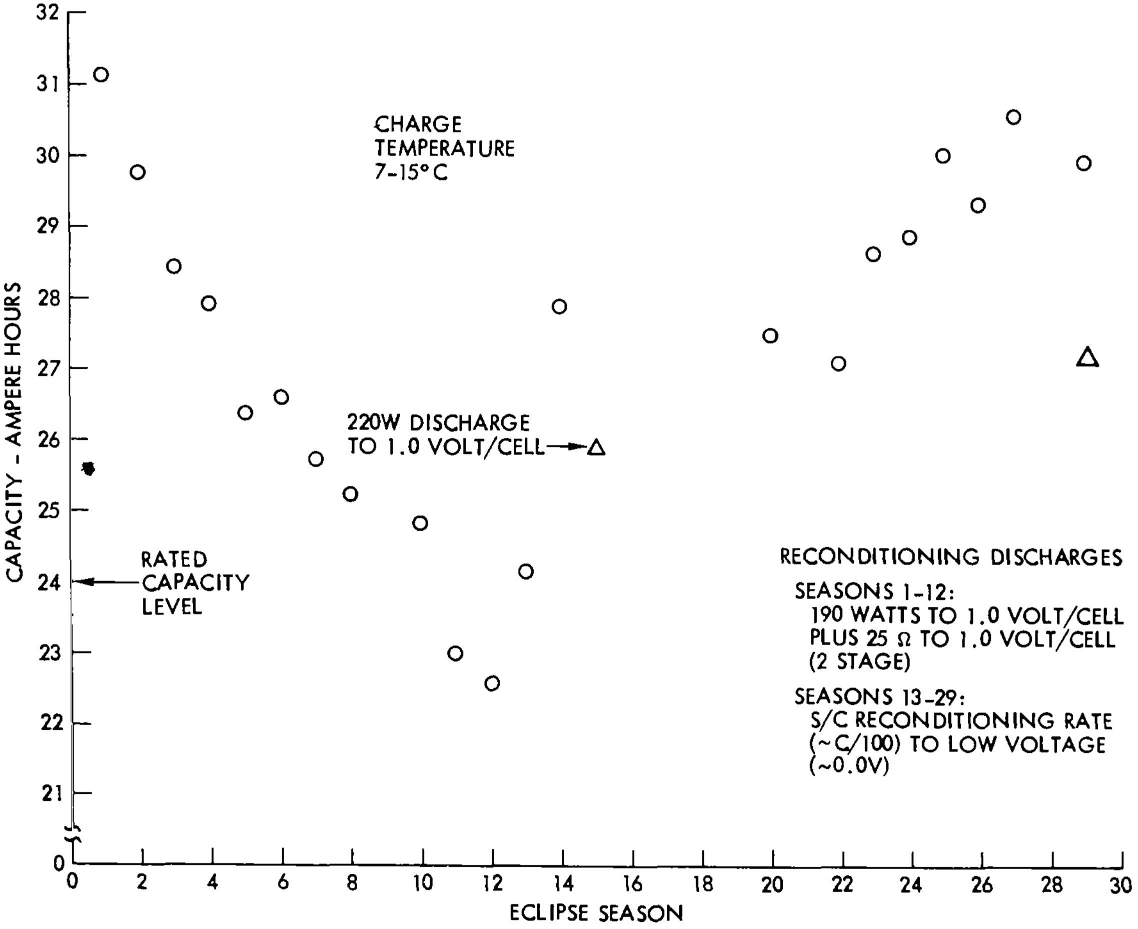


Figure 4-62