NATO – IN-ORBIT EXPERIENCE

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My presentation is on the NATO III satellite battery, on the experience we have had. Primarily I will concentrate on NATO III-A and NATO III-B.

The NATO III satellite system is the latest in a series of NATO communication satellites contracted to Ford Aerospace Communications Corporation.

Before I go on, I have two coauthors; that is, John Armantrout of Ford and Wayne Stafford of Aerospace Corporation.

These satellites were contracted to Ford Aerospace. They are managed by the Space and Missile organization. The cells were subcontracted to Eagle Picher, and the battery was fabricated and put together by Ford.

NATO III-A was launched in April 1976; III-B in January 1977; and III-C in November 1978. The satellites are in synchronous orbits and experience two 45-day eclipse seasons per year with the longest eclipse being 72 minutes.

(Figure 3-1)

Briefly, I will go over the electrical power subsystem. They are spinning satellites, and we have about 533 watts at the beginning of life on our solar reactor. We have three 20-ampere hour NiCad batteries with an orbital life of 7 years. This battery weighs approximately 26 pounds.

We have a power-control unit that regulates the batteries. In sunlight we are regulated by partial shunt regulator, and we use a booster.

(Figure 3-2)

Our charge or discharge characteristics are such that we have a ½-ampere and 1-ampere array. When in a full charge mode, we go 1½ amperes. We charge for 5 minutes on battery 1. We put on open circuit for 10 minutes and go to the next two batteries. We are tri-sequenced.

When we are on full charge, we put both arrays in series. Trickle charge is approximately C/4 with a full charge array of about C/13.

That is incorrect where it says both arrays are in parallel. As I said before, we try to sequence the batteries and have had a lot of success handling batteries in that mode.

Next, I will talk about the cell and assembly. Our NATO III battery is a basic type design, lightweight with two end plates and two through-bolts. We have a thermal control on each group of four cells.

(Figure 3-3)

This gives you basically the characteristics. In orbit load is approximately 4 amperes and voltage limit of 30.8 volts. We cut back our charge. There is a little bit more description at the bottom on the type of materials we used on the battery pack.

If we hit a temperature of 85 degrees, we will limit back to trickle charge. We have a heater that is actuated at 40 degrees.

(Figure 3-4)

As far as our reconditioning design philosophy is concerned, we have a 16-ohm resistor which turns out to be reconditioned discharge current of approximately 1.6 amperes. We undervoltage whenever a group of five cells hits 5 plus 1/4 volt.

(Figure 3-5)

To give you a brief understanding of the kind of testing we put the batteries through, at the vendor we have starved and flooded electrode capacity tests. The flooded is when we fill electrode with electrolyte; the starved is as designed.

Factory testing at Ford, at the cell level, we have 20 burn-in cycles and capacity tests at 40, 60, and 70. We have very stringent requirements at the vendors and at the factory. As far as the battery level is concerned, we have vibration and thermal vacuum testing and a capacity test at 40, 60, and 70. And we have several tests at 40, 60, and 70. Those are the basic temperatures that we test at.

(Figure 3-6)

Now, what I am going to try to do is take you through NATO III-A, NATO III-B, and the engineering model or life test battery to give you an idea. You can look at some of these results that we have at the vendor. Keep those in mind whenever we look at the orbital experience that we buy. I guess the key would be a precharge and the negative deposited ratio.

NATO III-As is a bit greater than NATO III-Bs, which is an engineering model. The pickup is the loading. The amount of the electrolyte is listed on the far right.

(Figure 3-7)

We had some slight differences between NATO III-A and NATO III-B, despite handling almost exactly the same with identical thermal environment. We try and figure out why there is a difference in performance. As you have seen, the NATO III-A batteries tended to have a little bit better factory testing and vendor results than those of NATO III-B. However, NATO III-B has performed better in space.

This indicates our reconditioning. Our capacity cycle is on the far right. On the left side I put 3-hour, 60-degree capacity tests that we had at the battery level.

It will somewhat indicate to you, as we were cycling the batteries, we don't really tend to get a trend at the beginning of life. However, as we go on in life, we tend to get a trend. You can see that the III-A results are slightly less than those of III-B.

I did put capacity for the entire system and not for each individual battery. So you might justify that by three.

(Figure 3-8)

This shows you each individual season that we have had in the battery and end of discharge voltage characteristics for each season, all the way through the season.

The first season is September 1976. Ignore the asterisk at the top. It is not applicable to life of the season. We didn't recondition after the first season. When we went to the second season, which was March 1977, we had a slight decrease in end of discharge voltages. I have that percentage here for you. It turned out to be about a 0.5 percent drop in the discharge voltage without reconditioning.

Then, we went to our third season and we did reconditioning. We lost 2 percent from the first one on the first and the second season. When we reconditioned, we gained back 1.3 percent of that end of discharge voltage. As we continued to see the results that we got in orbit, we were able to predict pretty much where we would be from year to year, in that we seemed to lose from one season to the next without reconditioning, approximately 0.6 percent and we gained back approximately 0.4 percent at the end-of-discharge voltage through reconditioning. Then we went on to our fourth season, and again we did not recondition. Our philosophy is to recondition every other season, which would put us in August just prior to the fall equinox. As you see, we dropped again. I believe we dropped here a little over 2 percent. We then reconditioned again for our fifth season.

Here comes the thing that makes it not apples and apples. As you get toward the end, what happened is that we lost one-half of our load that is a traveling-wave tube amplifier, and we lost that on September 17.

Up to the point halfway through the season, as you see, it really doesn't correlate after that. We went from approximately a 24-percent DOD for a maximum eclipse to what would be about a 16-percent DOD. But we did on that regain 0.4 volt.

(Figure 3-9)

Basically, this slide gives you the same information, except on NATO III-B. If you remember the type of results we got at the vendor and in the factory, it doesn't quite correlate as well as we would expect.

Here's our first season. No reconditioning.

We go to our second season, September 1977, with no reconditioning, and basically, the same discharge voltage characteristics.

Again, we went to the third season. We decided not to recondition for the third season. The third season was the same, and we never lost more than 0.8 percent from season to season without reconditioning for the first three seasons.

We decided to start reconditioning in the fourth season. We regained a little bit, but not much. We regained approximately 0.4 percent. So we are extremely happy with NATO III-B's performance on orbit, but we cannot really explain why it is that much better than that of NATO III-A.

(Figure 3-10)

This will give you an idea on pretty much what the individual discharge voltage curve was for each maximum eclipse. This is our first season maximum eclipse, approximately 70 minutes in October 1976.

This is again without reconditioning. Of course, we lost percentage.

With the third season we did recondition. You can see the shape of the curve flatten out a bit and raised up higher by a few tenths of a volt.

For our fourth season, again we did reconditioning at this point, and we got that dropped down to just a little bit above 23 volts.

Then we did reconditioning again for the September 28 season. We saw it jump up approximately 1 volt. So that reconditioning seemed to help us more as we got further down in the life on NATO III-A.

(Figure 3-11)

Basically, this gives the same information on NATO III-B. You will get an idea on how close these curves are and how we have been able to get pretty close repetitive characteristics on NATO III-B's discharge voltage.

This is our first season.

We go to our second season without reconditioning. Again, we didn't recondition for our first three seasons.

You can see that the first three seasons are almost identical. We have to rather ignore the end because all the equivalents we got were exactly the same as far as length, a few minutes off as far as the discharge curve. It was pretty much the same. We didn't really need to recondition, so we didn't.

Then, we reconditioned for the fourth season, and it gained us just a little bit, not too much.

(Figure 3-12)

We had Ford do a life test for us in which one-half of the battery was reconditioned approximately every other season. The other half of the battery was not reconditioned. This half was the unreconditioned-half of the battery. It did support high loads for 7 years, accelerated life test. However, the accelerated life test was almost down to a few tenths of a volt, approximately what we have seen in one of them. So it has been very well represented.

The other half of the battery was reconditioned. The circles denote where we reconditioned. We reconditioned every other season as we do in space.

Then, as you can see, we plotted the NATO III-A characteristics against the life test.

You see, we weren't quite as good on the reconditioned half as we had expected. As I said, after this one season, NATO III-A will operate at the maximum 16-percent depth of discharge.

(Figure 3-13)

Basically, the same information on NATO III-B. This is the same life test battery, our engineer-model batteries.

Again, we reconditioned halves; this is the reconditioned-half of the battery.

Then, our results are better than the life tests. So, when we looked at all the data, it was hard for us to understand why III-B was that much better than III-A.

The last point on NATO III-B shows about 25.44 volts end-of-discharge volts. That is because we are now in orbital storage on both NATO III-B and NATO III-C. That is with a zero-degree Sun and the wind blows, which puts us about 8-percent DOD on batteries at maximum eclipse, and we will keep it that way until NATO needs to use one of the satellites off III-A.

DISCUSSION

GASTON: What is the minimum/maximum average temperature?

CAPULLI: During our winter solstice, we experienced very high temperatures and had to manage our batteries, both on NATO III-A and III-B. Those temperatures rose to between 70 and 80°F.

With charge management we cut back the charge, and we got that temperature to go down to the high 60s. That is in the winter solstice.

In summer solstice we are right around 40 degrees during both eclipse seasons—the eclipse seasons closest to the winter solstice. In other words, the tail end of the fall equinox and the beginning of the spring equinox we tend to see temperatures in the high 60s, between 60 and 70. However, whenever we are in the summer solstice, getting toward summer solstice, our equinox seasons, we tend to see temperatures between 40 and 50 degrees.

STOCKEL: Was this a constant current discharge?

CAPULLI: Yes. All three batteries are tied directly to the bus, which is one of the reasons I had only one voltage curve for all three batteires, because all three batteries have identically the same voltages as the discharges.

STOCKEL: I noticed on your accelerated test data, you only had it out to 7 years?

CAPULLI: Yes

STOCKEL: Would you say after 7 years you are getting marginal?

CAPULLI: Maybe I can get one of my coauthors to help me answer that one.

ARMANTROUT: We were beginning to see that at the end of 7 years, it was beginning to tail off on the data you saw up there. However, we believed that it was going to perhaps last for another 2 years if we had kept going, to the end of voltage, that is.

Now, if our end of voltage had been a little lower, these cells had a particularly low voltage plateau. But I believe they would have stabilized in another 2 years at probably about 115 or something like that. We experienced that on our other tests on SMS, about 115 was the number.

DeBAYLO: Can you describe your mechanism for reconditioning? Do you have a fixed resistor that you can put across all battery housings?

CAPULLI: Yes. We can put one battery across a 16-ohm resistor and discharge a battery across there to what turned out to be about 20 to 21 volts. We terminated at that point and recharged to approximately a 1.5- to 2.0-return. We did one battery and then did the next and the next.

DeBAYLO: Essentially to 1 volt per cell?

CAPULLI: Right. However, our undervoltage, as I stated, takes a group of five cells. When that group of five cells—that's five plus a quarter volt—any group of five cells automatically cuts off our reconditioning discharge.

FORD: In your life test cells, were they from NATO III-B or NATO III-A lot? Or was it a different lot?

CAPULLI: Our first lot was lot one.

FORD: Did it really show data on three lots of cells?

CAPULLI: Yes, it did.

GROSS: Could you repeat the DOD that you had in orbit?

CAPULLI: When we started, we were experiencing 24-percent DOD. When we lost three, we went to 16 percent, and orbital storages on III-B and III-C were operating at approximately 8-percent DOD.

GROSS: Do you have information on the current sharing between the three batteries in flight?

CAPULLI: I have that, but not with me. I know each battery has been about 4 amperes, with battery two on NATO III-A and NATO III-B appearing to take a little bit more of the load. Maybe about 4.0 to about 4.4 amperes on that battery with the lowest supporting about 3.8 amperes.

So that is about 0.6 ampere from time to time. Most of the time we were a little bit closer than that.

LACKNER: How many cells did you have in each group? 24?

CAPULLI: 20 cells per battery.

LACKNER: You got down to 23 volts?

CAPULLI: Yes, we got down to about 23 volts on NATO III-A only. We didn't get down that low on NATO III-B. As a matter of fact, I don't think we got below 24 volts on NATO III-B.

LACKNER: You were talking about something like 1.15 volts inthe longest eclipse?

CAPULLI: Something like that.

ELECTRICAL POWER SUBSYSTEM

- SOLAR ARRAY PANEL (upper and lower right circular cylinder)
  - 85 in. DIAMETER BY 88.7 in. HEIGHT
  - 21,256 SILICON SOLAR CELLS
  - PROVIDES 533 W BEGINNING OF LIFE, 421 W END OF LIFE EQUINOX
- THREE 20 amp-hr NICKEL-CADMIUM BATTERIES
  - EACH BATTERY CONSISTS OF 20 CELLS IN SERIES
  - EACH BATTERY WEIGHS 26 lb
  - BATTERIES PROVIDE 304 W IN PARALLEL DISCHARGE FOR 1.2 hr
  - CELL BASED ON EXISTING SMS DESIGN
  - ORBITAL LIFE: 7 yr
- POWER CONTROL UNIT
  - PROVIDES MAIN BUS VOLTAGE REGULATION (29.6 to 28.4 V)
  - PROVIDES THE ELECTRICAL INTERFACE BETWEEN SOLAR ARRAYS, THE BATTERIES, AND THE SPACECRAFT ELECTRICAL LOAD
  - CONTROLS BATTERY CHARGE, DISCHARGE AND RECONDITIONING

Figure 3-1

CHARGE/DISCHARGE CHARACTERISTIC

DEDICATED CHARGE ARRAY

- 0.5A ARRAY
- 1.0A ARRAY
- ARRAYS IN SERIES WITH MAIN BUS
- 0.5A TRICKLE CHARGE (C/40)
- 1.5A FULL CHARGE (C/13) BOTH ARRAYS IN PARALLEL

TRI-SEQUENCE

- 2 REDUNDANT CHARGE SEQUENCERS
- 5 MIN ON CHARGE
- 10 MIN OPEN CIRCUIT

Figure 3-2

BATTERY ASSEMBLY CHARACTERISTICS

CONFIGURATION	20 SERIES CONNECTED NICKEL CADMIUM CELLS
LOAD	5 TO 7.5 AMPS
DURATION	1.2 HRS MAX (ECLIPSE)
LIFE	7 YR ON ORBIT (600 CYCLES)
CHARGE CURRENT	1.24 TO 1.48 AMP (HIGH)
	0.35 TO 0.44 AMP (LOW)
CHARGE DUTY CYCLE	1/3 (1/2 OR CONTINUOUS BY COMMAND)
TEMPERATURE	40F TO 70F (85F RESET TO LOW CHARGE)
	(40F MIN BY ACTIVE HEATER CONTROL)
VOLTAGE LIMITS	30.8 VOLTS MAX/5 VOLTS PER FOUR CELLS
	(CONTROLLED BY PCU)
WEIGHT	27.03 LB MAX (EP) 30.4 LB MAX (GE)
MATERIALS	MAGNESIUM SUPPORT RIBS AND END PLATES (HM21A.T8)
	ALUMINUM TIEDOWN AND THROUGH BOLTS (2024.T4)

Figure 3-3

NATO III RECONDITIONING DESIGN

- 16 OHM RESISTOR
- C/12 DISCHARGE RATE
- UNDERVOLTAGE
  - GROUP OF 5 CELLS REACHES 5.00 + .25V

Figure 3-4

NATO III Battery Testing

VENDOR TESTING

- STARVED AND FLOODED ELECTRODE CAPACITY TESTS
- CAPACITY TEST (30°, 40°, 70°, 80°F)

FACTORY TESTING

- CELL LEVEL
  - 20 BURN-IN CYCLES
  - CAPACITY TESTS (40, 60, 70°F)
- BATTERY LEVEL
  - VIBRATION AND THERMAL VACUUM TESTING
  - CAPACITY TESTS (40, 60, 70°F)

Figure 3-5

Battery Cell Electrode Characteristics

	PRE CHARGE (AH)	FLOODED ECT (AH)			PICKUP (g/dm^2)		POROSITY (%)		KOH (g)
		POS	NEG	RATIO	POS	NEG	POS	NEG	
NATO IIIA	3.6	23.0	33.6	1.45	13.34	15.79	84.6	83.7	74
NATO IIIB	3.2	24.4	31.1	1.27	13.25	15.70	85.3	85.0	77
E.M.	5.8	23.0	43.3	1.88	13.52	15.42	83.3	83.3	74

Figure 3-6

Capacity Measurements

FROM CELL ACTIVATION

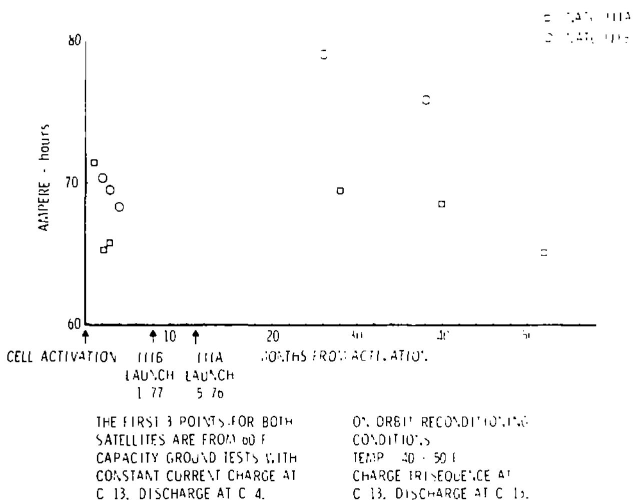

Figure 3-7

NATO IIIA Comparison of First 5 Seasons Battery Eclipse Voltages (End of discharge)

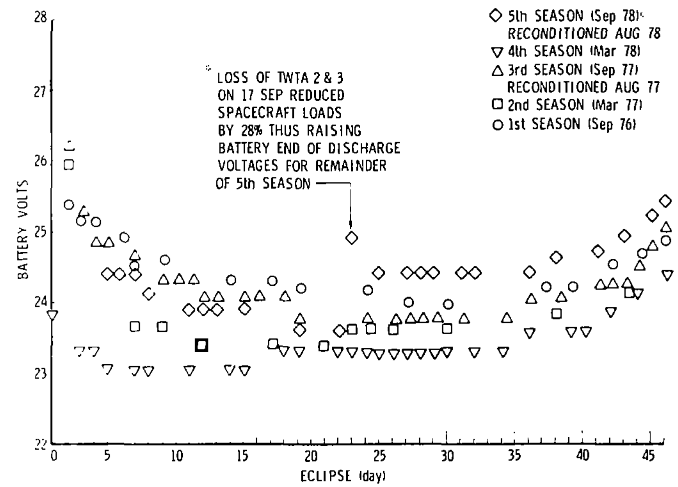

Figure 3-8

NATO IIIB Comparison of First 4 Seasons Battery Eclipse Voltages (End of discharge)

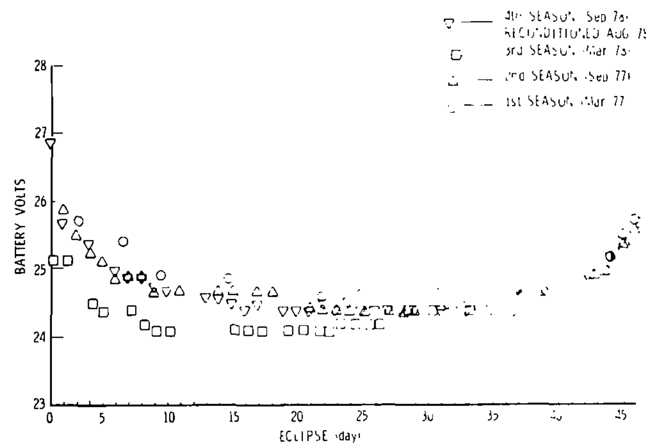

Figure 3-9

NATO IIIA Max Eclipse Battery Parameters

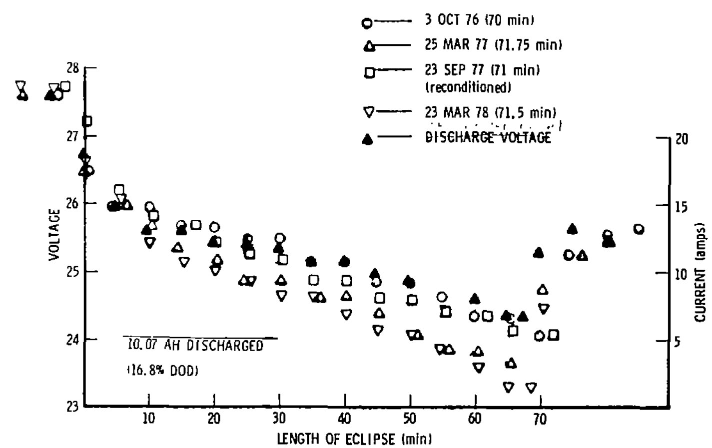

Figure 3-10

Comparison of NATO IIIB Max Eclipse Battery Parameters - Voltage for First 4 Seasons

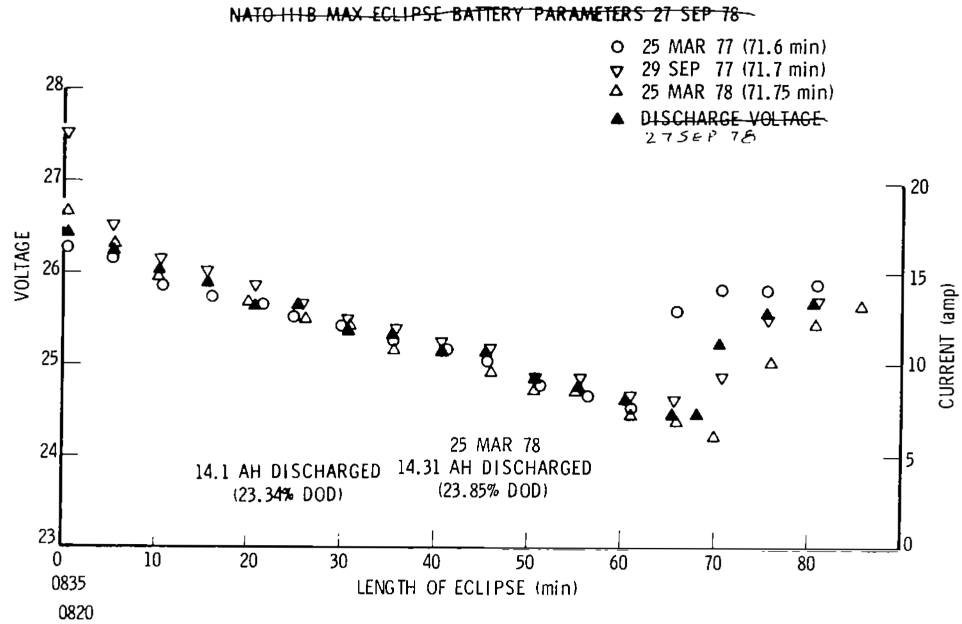

Figure 3-11

NATO IIIA End of Discharge Voltages

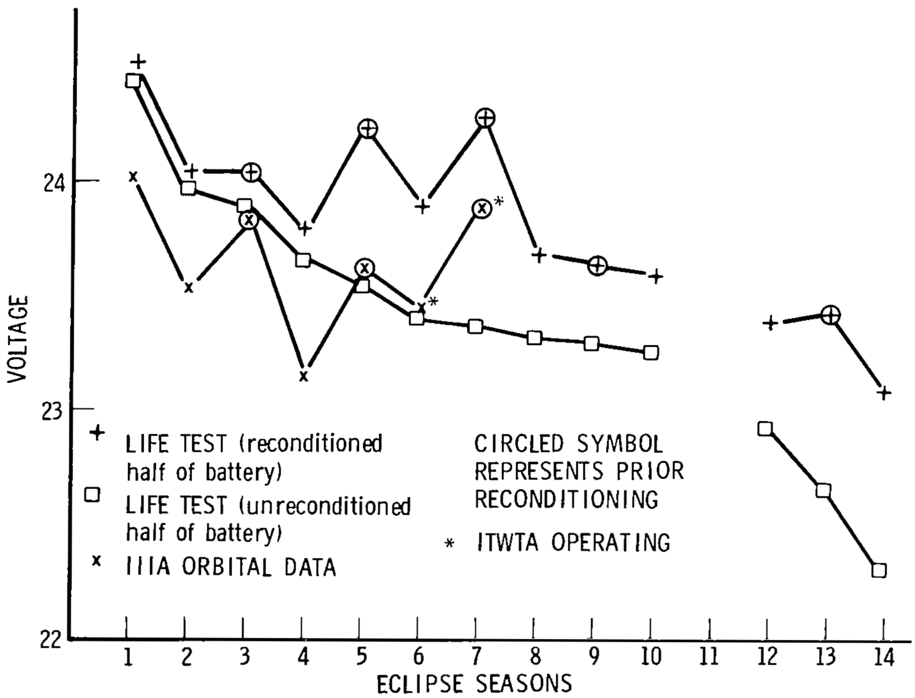

Figure 3-12

NATO IIIB End of Discharge Voltages

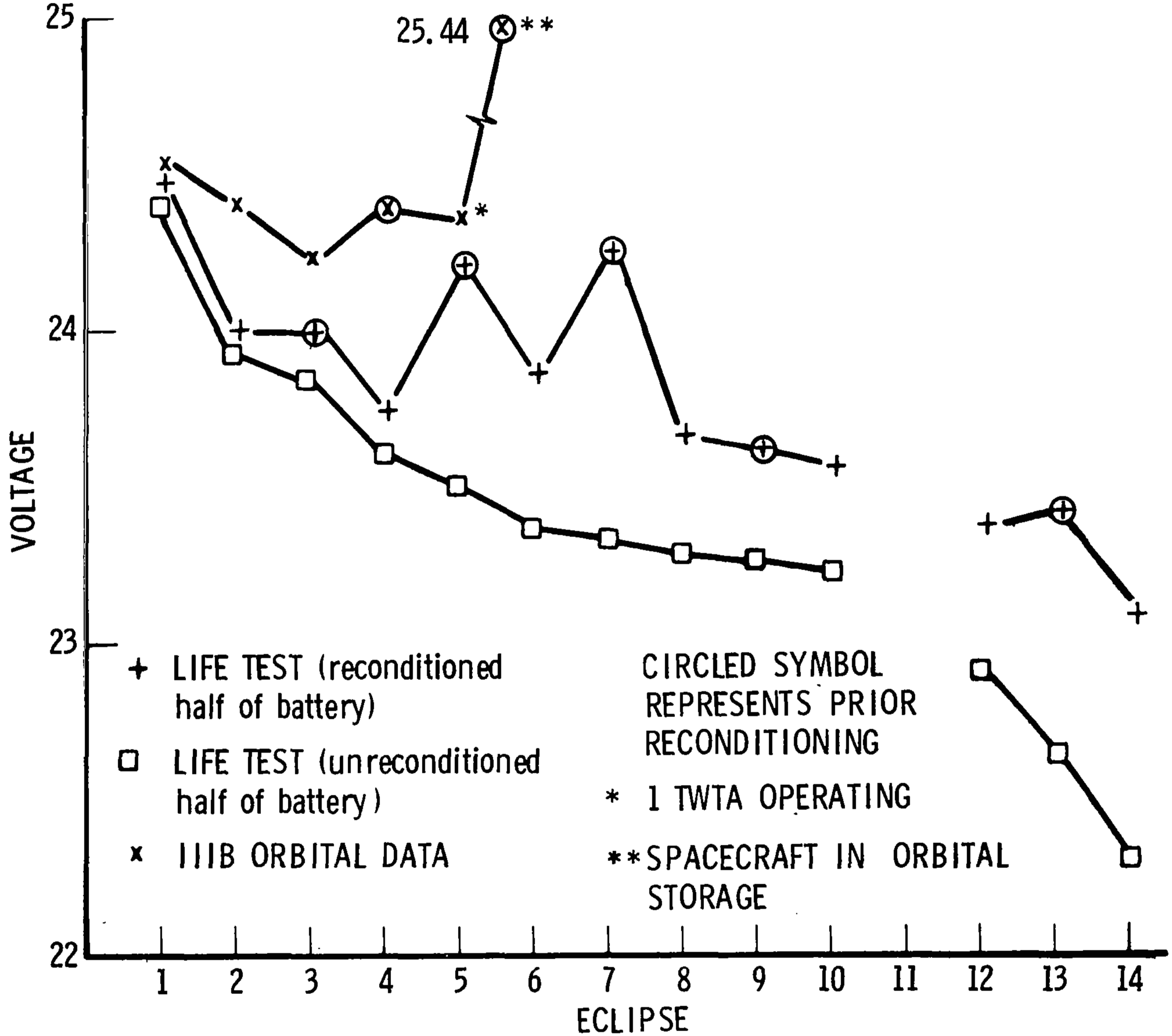

Figure 3-13