20 WATT-HOUR PER KILOGRAM NICKEL CADMIUM ENERGY STORAGE FOR INTELSAT V

J. Armantrout
Ford

I would like to talk today about the nickel-cadmium battery that we have on the I-V program. We are speaking in terms of 20 watt-hours per kilogram usable energy density. If we go to 100 percent DOD, we have a system that is probably around 40 watt-hours per kilogram. We are talking in terms of a 7-year battery, and that is the reason for the use of the 20 watt-hours per kilogram.

(Figure 4-1)

This is the battery assembly. The cells are on their sides. It is the T-rib. We have the T-ribs, four cells on one T-rib. The T-rib is the heat sink to the baseplate.

(Figure 4-2)

With this next slide, we can see the end-view. We have heaters on every four cells, 28 watts of heaters. We have a power connector and a cell sense. We have a capability in orbit of monitoring and cell voltages. That's a nice feature we have.

(Figure 4-3)

On our battery configuration performance characteristics, we have a nominal battery load we are showing here, of 504 watts. That's now about 465 watts. Our nominal discharge current at 33.6 volts was 15 amperes. At the beginning of life, we will probably have about 34.2 volts, and that would be about 13.6 amperes.

Rated cell capacity is 34 ampere-hours, and our maximum design DOD is 55 percent. Right now, the actual depth is about 51, and with one cell failed with our diode bypasser, that drops down to about 48. Or rather, we are at 48-percent DOD, and with one cell failed we will go to 51.

Typical synchronous orbit maximum discharge is 1.2 hours, and our peak discharge current is 45 amperes. We are recommending bisequence charging. Our full charge rate that we are looking at right now is in the range of 2.26 to 2.86 amperes. We have a capability of going to higher charge rates or lower.

Trickle charge is in 0.73 to 0.95 range. We are looking at a 7-year life, 616 cycles. We also have electrothermal thrust of firing that occurs during the sunlight periods, which could add a potential 175 cycles to that number which would be 791 cycles in 7 years.

Our allowable temperature range is 1 to 25°C. Right now, our thermal predictions are that we will be operating at 1 to 16°C.

(Figure 4-4)

Some of the design characteristics of the cell are positive electrode, 13 plates, and loading of about 13.4; negative electrode, 14 plates with a loading of about 15.7. These are GE cells. Separator materials, nylon 2505. Our electrolyte is 31 percent by weight. KOH approximately 90 milliliters.

Our cell container is 304L stainless steel, 0.03 centimeters. Our negative electrodes are impregnated with TFE.

(Figure 4-5)

The weight of the case is approximately 80 grams. Positive and negative electrodes are 767, separator 17, KOH about 114. We got about 1025 grams. This is the cell weight. This is a nominal 34 ampere-hour. We are getting about 37 out of it.

(Figure 4-6)

The total weight on the engineering model battery, 28 cells, was about 31.6. Now, that was without our diode bypass. Diode bypass circuitry, which I will show in a later picture, adds about 0.9 kilogram so that number comes up to around 32.5 kilograms for the battery weight. This is the number that we use when we come up with a 20-watt-hours per kilogram usable energy density and 40-watt-hours per kilogram actual.

We are indicating corner blocks here, and I will show you in a minute, those corner blocks are not on the assembly now.

(Figure 4-7)

Our designs traditionally had a corner block that was epoxied on in this area of each four-cell group. These are now machined into the T-ribs, and it's an integral part of the T-rib.

Here you can see the diode assemblies which are mounted – actually they are part – the bolts that bolt the T-ribs into the platform also hold down the diode bracket. And we have protection in both the charging direction and the discharging direction. So, if we have an open cell failure for any reason, we can continue to operate.

(Figure 4-8)

Some of our flight battery test summary data is here. This is our initial reconditioning, or actually our first capacity test after our initial reconditioning cycles. We were getting around 37 ampere-hours, peak battery voltage around 41.2, or thereabouts. Our maximum cell voltages are as shown here. Our zero-degree capacity is about 33 on this particular cell lot and is running a little better here, about 35, 36.

These are our flight 1 batteries, and these are our flight 2 batteries. Vibration voltage stability running around 0.2 volt.

This is thermal vacuum. This is just a functional test during thermal vacuum. It is not a capacity test or anything of that sort.

We do a pulse load test which is 45 amperes, and this is the voltage performance we are getting, about 33-1/4 volts.

Then, after we have done all of our battery environmental tests, we turn around and do another room-temperature capacity. You can see the capacity is improving with time. This appears to be a characteristic of the teflonated negatives. As you begin to cycle these cells and get some life on them, the capacity is improving.

We have life testing underway. We have three batteries and have an accelerated life test, three cycles a day, a maximum eclipse 1.2 hours at 15 amperes. We recharge at 6.8 hours, about 3.2 amperes, 120 percent energy return.

We have completed 14 seasons on that particular test. We are not seeing any voltage degradation, except for when we do our capacity measurements after every second season. There is some tailoff of the voltage as you are about 90 percent into the discharge of a battery. Otherwise, the voltage is flat. It looks the same as it did at the beginning of life.

Our semiaccelerated test has got four eclipse seasons completed. That consists of a real-time eclipse profile, 2 weeks of sunlight simulation, and then our real-time test. We have completed two eclipse seasons, and we are into the second solstice, which is a 135-day simulation.

That pretty much concludes the status of where we are at on this program right now. We have, in fact, a replacement system that we are looking at, which will be the nickel hydrogen. Gert Van Ommering will be talking about that tomorrow.

We are going both ways. We have an option to go either nickel cadmium or nickel hydrogen. The first four flights will be nickel cadmium. Flights five through eight right now can be either nickel cadmium or nickel hydrogen.

DISCUSSION

NAPOLI: Can I ask some questions of Armantrout? Do you have constant power discharge on the batteries? I am talking about what's intended for the flight.

ARMANTROUT: The flight will be constant power, and 465 watts is the number right now. That has been varying as the loads – I believe that is the most current number. I showed 504 on the vugraph.

NAPOLI: Do you plan to do any reconditioning?

ARMANTROUT: We plan to recondition every eclipse season prior to it.

NAPOLI: To what level?

ARMANTROUT: Right now, we are in the life test. We are going down to the first cell, to 0.7 volt. Some of that it still being worked out. I don't know that we have a final plan there.

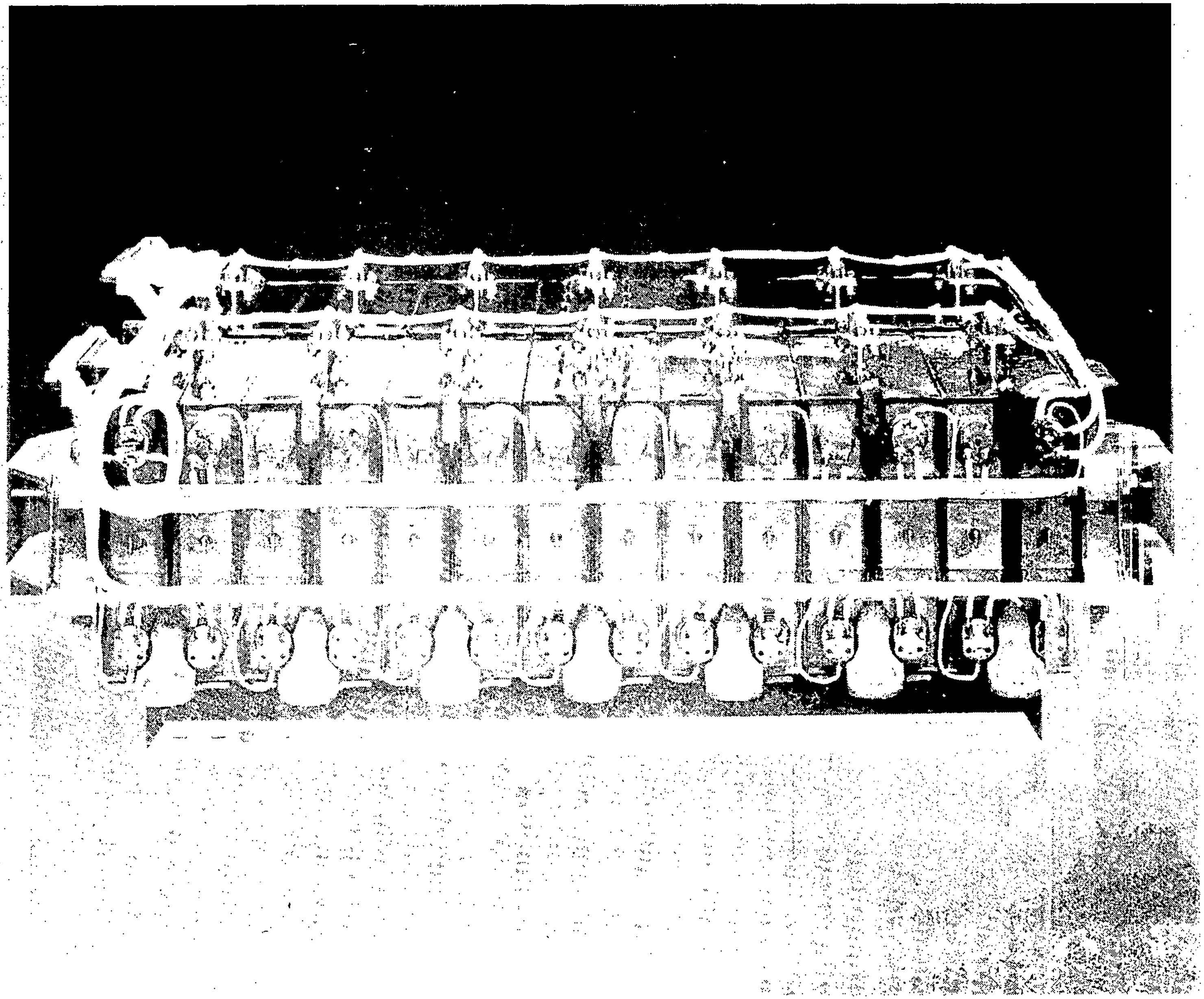

Figure 4-1

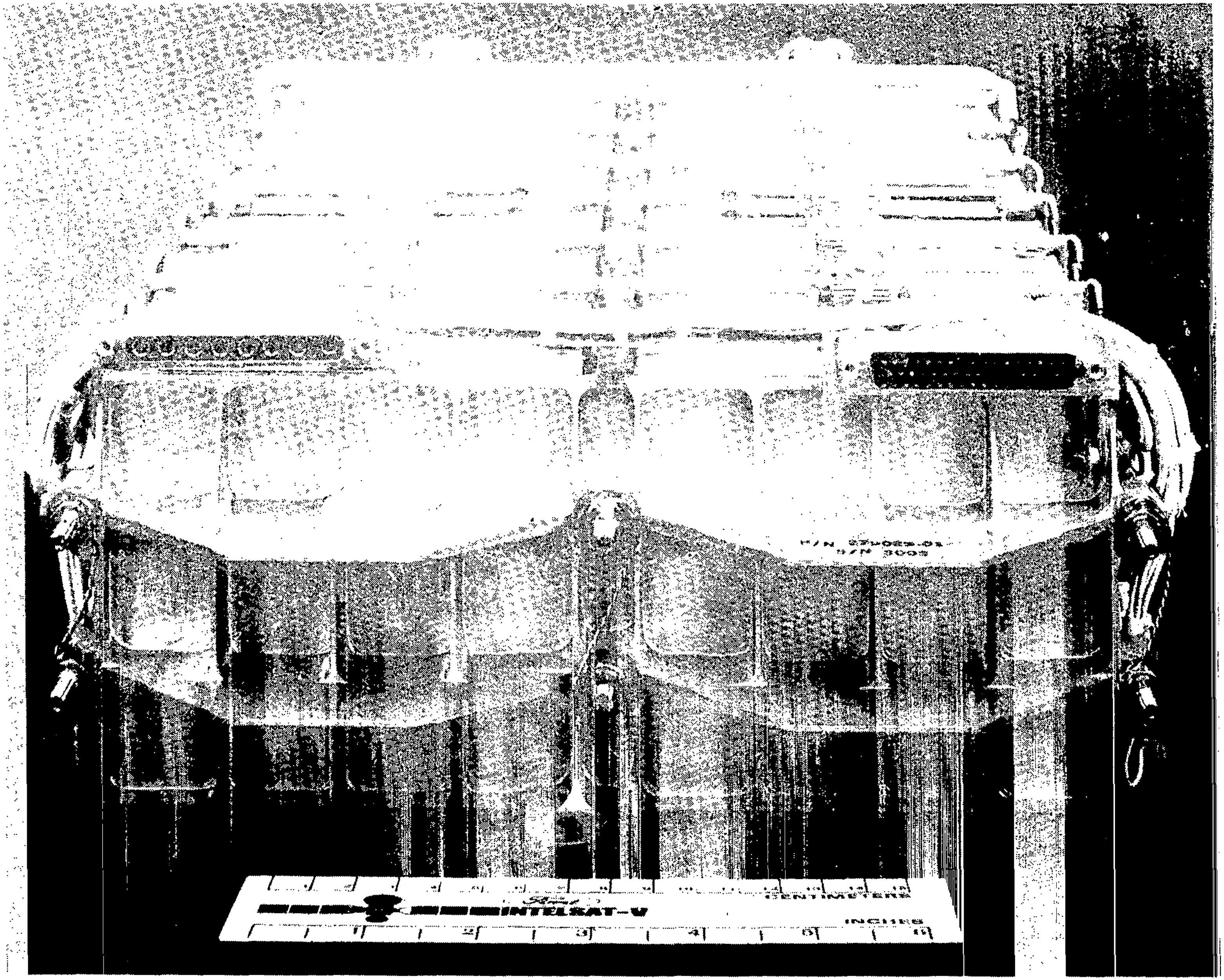

Figure 4-2

BATTERY CONFIGURATION PERFORMANCE CHARACTERISTICS

• NOMINAL BATTERY LOAD PER BATTERY	504 W
• NOMINAL DISCHARGE CURRENT AT 33.6 VOLTS	15.0 A
• RATED CELL CAPACITY	34.0 Ah
• MAXIMUM DEPTH OF DISCHARGE	55%
• MAXIMUM DISCHARGE TIME	1.2 h
• PEAK DISCHARGE CURRENT (10 SECOND PERIOD MAXIMUM)	45.0 A
• ALLOWABLE SEQUENCE CHARGING CURRENT RANGE (FULL)	2.26 TO 2.86 A
(TRICKLE)	0.73 TO 0.95 A
• TOTAL ECLIPSE CYCLES (7 YEARS)	616 CYCLES
• ORBITAL LIFE	7 YR
• ALLOWABLE BATTERY TEMPERATURE RANGE DURING ORBITAL OPERATION	+1 TO +25°C

Figure 4-3

CELL COMPONENT DESIGN CHARACTERISTICS

• POSITIVE ELECTRODE	13 PLATES, 10.4 cm x 9.8 cm x 0.69 mm
	LOADING: 13.40 ± 0.6g
• NEGATIVE ELECTRODE	14 PLATES, 10.4 cm x 9.8 cm x 0.74 mm
	LOADING: 15.70 ± 0.65g
• SEPARATOR MATERIAL	NYLON 2505 ml
• ELECTROLYTE	31% BY WEIGHT KOH SOLUTION.
	ELECTROLYTE QUANTITY: 88 – 90 ml
• CELL CONTAINER	304L STAINLESS STEEL SHEET: 0.030 cm THICK
• NEGATIVE ELECTRODE ADDITIVES	TFE: $0.35 g/dm^2$

Figure 4-4

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CELL COMPONENT WEIGHT CHARACTERISTICS

COMPONENT	WEIGHT
CASE	80.4 g
POSITIVE AND NEGATIVE ELECTRODES	767.4
SEPARATOR	17.6
WRAPPER	3.9
KOH	114.5
COVER	40.3
COMB INSULATOR	1.3
TOTAL	1025.4 g

Figure 4-5

ENGINEERING MODEL BATTERY WEIGHT BREAKDOWN

COMPONENT	WEIGHT
BATTERY CELLS (28 EACH)	28.71 kg
ENDPLATES (2 EACH)	0.54
TIE ROD ASSEMBLIES (6 EACH)	0.27
CELL SUPPORT RIBS (7 EACH)	1.19
CORNER BLOCKS	0.02
CONNECTORS, HEATERS, THERMISTORS	0.13
WIRE, EPOXY, SHRINK TUBING, AND MISCELLANEOUS	0.73
TOTAL	31.59 kg

Figure 4-6

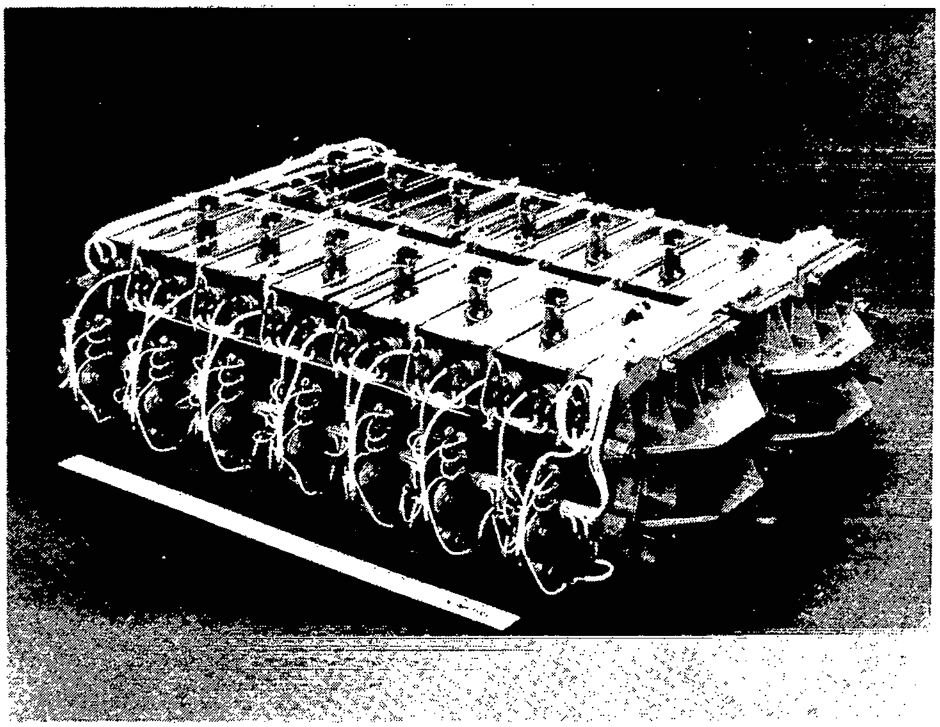


Figure 4-7

INTELSAT V FLIGHT BATTERY TEST SUMMARY

TEST \ BATTERIES	RESULTS 3006	3007	3008	3009
20°C CAPACITY	37.20 Ah	37.20 Ah	37.05 Ah	37.35 Ah
BATTERY VOLTAGE	41.27 V	41.20 V	41.61 V	41.67 V
MAX CELL VOLTAGE	1.476 V	1.476 V	1.478 V	1.484 V
0°C CAPACITY	33.30 Ah	33.00 Ah	36.15 Ah	35.85 Ah
BATTERY VOLTAGE	42.36 V	42.45 V	42.77 V	43.05 V
MAX CELL VOLTAGE	1.518 V	1.526 V	1.539 V	1.528 V
VIBRATION VOLTAGE STABILITY	0.23 V MAX	0.16 V MAX	0.10 V MAX	0.28 V MAX
THERMAL VACUUM				
20°C DISCHARGE BATTERY VOLTAGE	35.65 V	35.57 V	35.71 V	36.15 V
20°C CHARGE BATTERY VOLTAGE	38.42 V	38.25 V	38.11 V	38.61 V
PULSE LOAD BATTERY VOLTAGE	33.25 V	33.15 V	33.84 V	33.88 V
20°C CAPACITY	39.00 Ah	38.40 Ah	40.35 Ah	40.35 Ah
BATTERY VOLTAGE	42.00 V	41.54 V	42.04 V	41.73 V
MAX CELL VOLTAGE	1.496 V	1.485 V	1.504 V	1.494 V
CHARGE RETENTION (MINIMUM CELL VOLTAGE)	1.213 V	1.221 V	1.203 V	1.212 V

Figure 4-8

MULTIMISSION MODULAR SPACECRAFT PARALLEL BATTERY TEST

M. Tasevoli
NASA/GSFC

For the past two workshops, Charlie Palandati has been presenting the results of the engineering evaluation of the multimission modular spacecraft performed by the Power Applications Branch at NASA.

(Figure 4-9)

Today I will present additional test data on the results of several simulations which were repeated after approximately 10,000 orbits to further characterize the operating stability of the power battery operation.

(Figure 4-10)

The multimission spacecraft power system employs a standard power regulated unit with eight commandable voltage temperature levels charging up to three standard 20- and 50-ampere hour batteries in parallel. The mission requires a depth of discharge of 25 percent per battery in the near-Earth orbit of 100 minutes; 36 shadow, 64 sunlight.

The 12-ampere hour batteries used for the simulation utilize a standard electrical approach of 22 cells in series and a thermal design which is an extension of the IUE spacecraft battery and which has been further instrumented to record cell pressures and temperatures. Both batteries are mounted on a thermal cooling plate with a circulating refrigerant and are installed in two separate forced air chambers.

(Figure 4-11)

The first test performed within the first 2000 cycles was an evaluation of four of the eight VT levels. In particular, we were evaluating the battery charge response within the design temperature range of 0 to 20°C.

Based on those results at that time, level 5 supported both batteries with nominal depth of discharge of 25 percent with a percent recharge between 101 and 105 percent within the design temperature range of the module. Based on those results, level 5 was chosen as a baseline level for the entire program when not in a test simulation.

This test was repeated at level 5 after 11,000 orbits at those three temperatures. Of particular significance is, there is very little difference in percent recharge and load sharing between the batteries when comparing the two results.

Cell pressures have approximately doubled during the period as a result of this cycling. There is a slight increase in the end of charge current, but, on the whole, the batteries continue to share the load quite evenly.

(Figure 4-12)

One of the power system design criteria is that the battery cable harness shall be less than 150 milliohms. However, there is no specification on mismatch.

The purpose of this test was to simulate an ohm-resistance mismatch between cables and to determine the effect of load sharing on the parallel battery configuration. Every effort initially was made to ensure that the in-cell connections and the power cables were properly matched. In particular, the battery impedance was determined by assuming approximately 3 milliohms per cell and calculating 9 milliohms for all the in-cell connections up the battery post, here represented by 75 milliohms for A and B.

The measured A and B cable resistances, which included not only the wiring harness but the connectors and the shunts, were measured at 76 and 77 milliohms, respectively, up to the parallel tie point. Cable mismatches will be simulated now by inserting a nonresistive shunt in the B circuit leg.

(Figure 4-13)

These results are tabulated here, highlighting the individual battery C/D ratio and the depth of discharge. Notice that the increasing resistance of one leg resulting in a divergence of the depth of discharge with the battery, in this case battery B, with the longer path length supporting less of the load on discharge. In contrast, the battery C/D ratios remain essentially unchanged.

(Figure 4-14)

The simulation was again repeated after the cable resistances were lowered by approximately 87 percent from 77 to 10 milliohms. Here again the battery impedance was assumed to remain the same, 75 milliohms, and the cables were lowered to 10 milliohms each.

As before, I have gone ahead and compared again individual C/D ratios and depths of discharges for both batteries. I have gone one extra step by comparing the results at similar mismatches for both the high- and the low-cable resistances.

Notice that in the last three trials performed with the lower cable resistance, the effect of the cable mismatch has rather a negligible effect on the depth of discharge while the C/D ratio again remains unchanged.

The results also seem to indicate that as the battery impedance becomes a greater portion of the circuit resistance, cable mismatches become less significant.

(Figure 4-15)

The last simulation performed was that of simulating one shorted cell in one battery. The simulation was conducted in basically two stages.

The first stage found one cell in Battery B would have a 1-ohm resistant load placed across it, while the parallel batteries continued to cycle. In the second stage, as the cell voltage dropped to below 0.5 volt, the resistive load would be replaced with a hard short, as the batteries are allowed to continue to cycle. In the interim, all battery characteristics are monitored to observe system stability.

It should be pointed out that during that first stage with the resistive load across the cell, as long as the cell supported some voltage on discharge and charge, it was very nearly impossible to identify any system anomaly throughout the period where the cell supported some voltage on charge and discharge.

(Figure 4-16)

The most dramatic change occurred when the resistive load was replaced with the hard short here at the end of the discharge cycle, here numbered at cycle 1.

Within less than one orbit, the recharge ratio on the shorted cell battery increased from a nominal 1.05 to 1.7 as cell pressures increased from 30 to approximately 75 psi, as the end of charge current increased from a nominal 0.5 ampere to slightly less than 3 amperes.

After an additional orbit, you will notice that the battery B remains in the sump state of condition experiencing a possible thermal voltage instability. In contrast, battery A is experiencing normal, near-normal recharge as the end of charge current tapers off normally while sharing approximately 60 percent of the load on discharge.

(Figure 4-17)

This is a comparison plot of cell characteristics, most notably voltage, current, and pressure as a function of time, approximately 40 orbits after lowering the charge level from 5 to 3. You will see that for the shorted cell, battery, the recharge ratio dropped considerably from 1.6 to 1.15 as the cell pressures dropped from 90 to 95 range down to below 50 psi. In contrast, battery A with 22 normal cells is experiencing a recharge ratio of 0.99 while supporting approximately 60 percent of the load on discharge.

Notice that while the individual battery voltages are tracking very nicely on discharge and charge, the individual battery currents are diverging quite noticeably.

(Figure 4-18)

A simulation at level 3 was continued for approximately 440 orbits and was extended another 250 orbits at level 2.

What I wish to highlight in particular is a comparison of load sharing and percent recharge at this lower level. In particular, as highlighted before, Battery A is supporting approximately 60 percent of the load on discharge, whereas battery B has a significantly low amount.

Battery A throughout that first 400 orbits is experiencing approximately a recharge ratio of 0.99. Battery B with the shorted cell supporting less of a load has its percent recharge increase quite dramatically from 1.15 up to nearly 1.5. This is the second time that the shorted cell battery has experienced some type of thermal voltage instability. Additionally, the pressures on battery B also increase with the increasing C/D as was the end of charge currents.

In response to this unstable condition of battery B, the charger level was further reduced from three to two, resulting in a lower recharge ratio for both batteries. Now, the shorted cell battery experienced a gradual decreasing C/D ratio while battery A was at approximately 97.5 percent recharge.

It is also interesting to note that there is a reversal in the load sharing after switching from level 3 to level 2. Prior to this time, the 22-cell battery was supporting most of the load. After switching from 3 to 2, now the shorted cell battery is experiencing the greater depth of discharge.

(Figure 4-19)

The test was terminated arbitrarily by extending the discharge cycle to simulate an extended eclipse to determine the actual capacity available to the load. Highlighting battery voltage and battery current as a function of time in orbit, you will see that battery A running down, the state of charge delivered approximately 8.6 ampere-hours when its lowest cell dropped below 0.5 volt.

At that time, battery B delivered approximately 9.4 ampere-hours and was further discharged to 11 ampere-hours when battery A was removed from the line. The uneven load current is a clear indication of the two battery imbalances that were simulated during this extended period. That is a cell imbalance between the batteries and also a capacity imbalance with the 22-cell battery at below 100-percent recharge, essentially running down the state of charge.

(Figure 4-20)

After the shorted cell simulation, the hard short was removed, and the cell voltage recovered quite normally. As in all our tests, we immediately reestablish the baseline cycling at level 5 and 25 percent of discharge. Almost immediately the batteries began to share the load unevenly, favoring battery A at 26 and battery B at 24.

The C/D ratio of the shorted cell battery increased steadily for approximately 250 cycles as the recharge ratio increased from 1.07 to 1.15.

At approximately 250 cycles, several cells in battery B exceeded the software limit established for the test. The software limit at 10°C was 1.51 volts per cell. At this point and without changing the loads on the system, the charger level was reduced from 5 to 3.

Cycling has continued for approximately 1200 orbits now as both batteries are experiencing approximately 99 percent recharge.

(Figure 4-21)

In conclusion, the voltage versus temperature levels that are built into the MPS system has sufficient versatility to accommodate a wide range of abnormal conditions. In particular, during the shorted cell simulation, it was impossible to identify the partially shorted cell condition from telemetry data.

In contrast, for the hard-cell short level 5, the shorted cell battery experienced a severe overcharge exceeding the high end of charge currents, while supporting less of a load on discharge.

In an actual spacecraft environment, the battery temperature would increase quite rapidly and probably trip the overtemperature thermostat.

With the added versatility of additional lower levels, it was demonstrated that, indeed, a short-term stable operation could be sustained for several hundred orbits without changing load currents.

Increasing the impedance mismatch between battery harness cables resulted in a divergence in the depth of discharge while the recharge ratio remained unchanged.

Cable mismatch has a less significant effect on parallel battery performance, as the battery impedance becomes a more dominant or predominant part of the circuit leg impedance.

DISCUSSION

LEAR: With the 1200 cycles continuing running at less than 100-percent state of charge, how long do you expect to run that test before you deplete all the energy in the batteries?

TASEVOLI: I would like to answer the question this way: Although a percent recharge was below 100 percent, the watt-hour efficiency was greater than 100 percent. In particular, at 99-percent recharge, the watt-hour efficiency was approximately 108 percent.

And at the lower percent recharge, 97.5 at level 2, the watt-hour efficiency was again greater than 100 percent. I think it was approximately 104 percent.

I would like to answer that question specifically. I had the same question in mind, too. I attempted to determine the actual capacity lost if the battery is experiencing a 99-percent recharge.

In particular, I went ahead and I plotted orbits on the X-axis, and what I will term here as just cumulative lost ampere-hours.

The solid lines represent three different trials where we purposely placed the battery in such a condition as the percent recharge was below 100 percent. For these three trials, the percent recharge was 99 percent. These solid lines then will represent the cumulative lost ampere-hours as simply the difference between ampere-hours in the ampere-hours out at each cycle and summed over several hundred cycles.

In particular, these two small lines show that the battery was run at 99 percent recharge, and the test was terminated with an extended discharge after about 240 orbits. The capacity lost based on the rated capacity was almost 2 ampere-hours.

The same analysis could be done during the 800 orbits in the shorted cell simulation where, for the first 440 orbits, battery A was experiencing a percent recharge of 99 and when switched over to level 2, considerably less, approximately 97. That point then is right here, 8.6 minus 12 or slightly under 4 ampere-hours lost. Based on these calculations then, it could be possible that we could be in this particular mode for several thousand cycles.

PALANDATI: I would like to clarify one thing right now. These tests started last November. The purpose of the tests are for the fact that actually there were certain conditions in a spacecraft, at that point the voltage level would automatically decrease. Should the temperatures get to a certain point you would automatically drop down to these lower levels.

Of course, the first question was: Could you maintain the two batteries or three batteries in a parallel application at the lower level?

We ran a test for approximately 1 1/2 months, and as we added the ampere-hours in versus the ampere-hours out, nice numbers, we suddenly said we shouldn't have more than 3 ampere-hours left in any one of the two batteries. We ran a CAP test and said the CAP test told us we had better than 8 ampere-hours.

There is no definite explanation of it other than the fact that we looked at the watt-hour relationships, the energy that does go into a battery and comes out of the battery, we were always on the plus side.

Mike continued on again in January and February running some more tests, and the longer he ran it the longer the batteries continued to go, even though our numbers said we have two dead batteries. We still had power. That was basically the reason for the test to start with, to see whether we could definitely operate two batteries at the low level, particularly if you did have one, say, with a shorted cell.

THIERFELDER: On the hard short case you showed after two cycles, you were up charging at 3 amperes, on a C/4 rate, and the pressure was up to 95 pounds. Suppose you hadn't switched to level 3 at that point? Would the cell have blown up?

TASEVOLI: Remember in an actual spacecraft environment, in the thermal vacuum conditions, at this particular C/D ratio of over 1.5, I suspect that the battery temperature would exceed the overtrip temperature.

THIERFELDER: You are gambling on what comes first, the temperature rise or the pressure rise.

TASEVOLI: The test condition, the limits on a test condition, was to take some type of action. If the cell pressure went above 100 psi, that was our governing factor during this isothermal test, to do something. Either lower the loads, or in this particular case, we decided to lower the charger level.

THIERFELDER: So, in orbit, someone would have to be watching every orbit to do the same thing. To do what you did on your test in orbit, someone would have to change from level 5 to level 3.

TASEVOLI: I was under the impression that the overtemperature demand was built into the MPS.

THIERFELDER: But you don't know if it is going to go overtemperature.

TASEVOLI: At this C/D ratio and in a thermal vacuum condition, I would think so.

Remember, in this thermal vacuum condition, we purposely kept the thermal condition of the battery at 10°C so that the end-of-charge currents in the C/D ratios here are probably low for the type of condition that we are running.

ENGINEERING EVALUATION OF MMS POWER SYSTEM

OBJECTIVE

- o DETERMINE ENGINEERING LIMITATIONS ON PARALLEL BATTERY OPERATION BY SIMULATING BOTH NORMAL AND ABNORMAL FLIGHT CONDITIONS
- o RECOGNIZE SIGNIFICANT CHANGES OR TRENDS IN BATTERY OPERATING CHARACTERISTICS DURING EACH SIMULATION

Figure 4-9

BLOCK DIAGRAM OF PARALLEL BATTERY CABLE CONFIGURATION

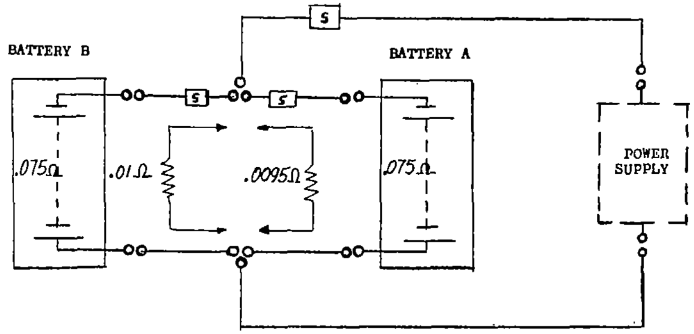


Figure 4-10

BLOCK DIAGRAM OF PARALLEL BATTERY CABLE CONFIGURATION

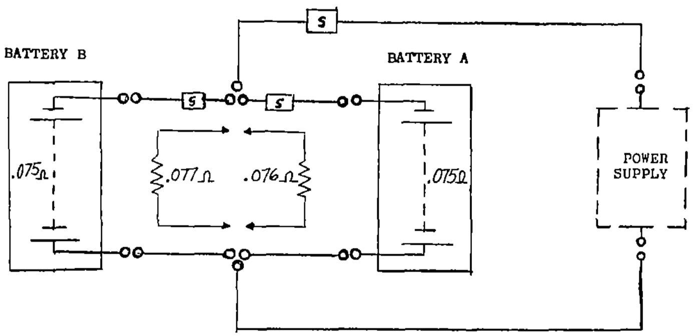


Figure 4-11

COMPARISON OF BATTERY CHARGE RESPONSE AT LEVEL 5 AND 0° 10° AND 20°C

ORBIT	TEMP (°C)	EOD VOLTAGE	EOD PRESSURE (PSIA)	EOC PRESSURE (PSIA)	EOC CURRENT (AMP)	C/D
<1000	0	26.84	12.7	13.2	0.56	1.02
	10	27.06	13.6	14.5	0.52	1.03
	20	27.23	11.1	11.6	0.51	1.05
~11500	0	26.53	25.0	26.2	0.66	1.01
	10	26.66	27.5	29.8	0.62	1.03
	20	27.77	28.7	31.9	0.61	1.05

Figure 4-12

EFFECT OF CABLE MISMATCH ON LOAD SHARING AND C/D RATIO AT V.L.5

% MISMATCH	BATTERY A C/D	BATTERY A DEPTH OF DISCHARGE (%)	BATTERY B DEPTH OF DISCHARGE (%)	BATTERY B C/D
0	1.04	24.8	25.3	1.02
14.5	1.04	25.2	25.0	1.03
27.6	1.05	25.5	24.7	1.02
40.8	1.05	25.8	24.3	1.03
53.9	1.04	26.2	24.0	1.03
67.1	1.04	26.6	23.6	1.02
132.8	1.04	28.2	21.9	1.02

Figure 4-13

COMPARISON OF CABLE MISMATCH VS BATTERY CABLE RESISTANCE AT V.L.5

% MISMATCH	BATTERY A POWER CABLE RESISTANCES	BATTERY B POWER CABLE RESISTANCES	BATTERY A C/D	BATTERY A DOD %	BATTERY B DOD %	BATTERY B C/D
0	76	77	1.04	24.8	25.3	1.02
53.9		117	1.04	26.2	24.0	1.03
132.9		177	1.04	28.2	21.9	1.03
0	9.5	10	1.03	25.0	25.3	1.03
57.9		15	1.03	25.1	25.2	1.03
105.3		20	1.03	25.3	25.0	1.03

Figure 4-14

PROCEDURE FOR SHORTED CELL IN ONE BATTERY SIMULATION

- VERIFY STABLE PARALLEL BATTERY CYCLING AT LEVEL 5 AND 25% DOD
- CONNECT 1.0 OHM RESISTOR ACROSS ONE CELL IN BATTERY B
- CONTINUE TO CYCLE AT THE BASELINE OPERATING MODE
- MONITOR BATTERY CHARACTERISTICS DURING CELL DECAY PERIOD
- WHEN CELL VOLTAGE DROPS BELOW 0.5 VOLTS REPLACE 1.0 OHM LOAD WITH HARD SHORT AND CONTINUE TO CYCLE
- OBSERVE LONG TERM CHARACTERISTICS

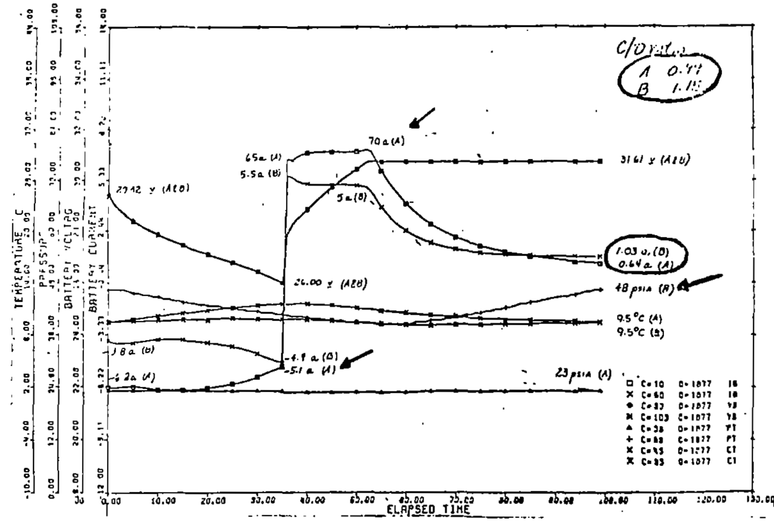
Figure 4-15

BATTERY COMPARISON CHARACTERISTICS DURING HARD CELL SHORT PERIOD AT VL5

	BATTERY A					BATTERY B				
CYCLE	END OF DISCH CURRENT (AMP)	Ahr OUT	C/D	END OF CHARGE CURRENT (AMP)	END OF CHARGE PRESSURE (PSIA)	END OF DISCH CURRENT (AMP)	Ahr OUT	C/D	END OF CHARGE CURRENT (AMP)	END OF CHARGE PRESSURE (PSIA)
1	-7.6	3.3	1.02	0.66	30	-2.4	2.5	1.7	2.9	75
2	-4.9	3.5	1.00	0.75	30	-5.1	2.5	1.6	3.0	90

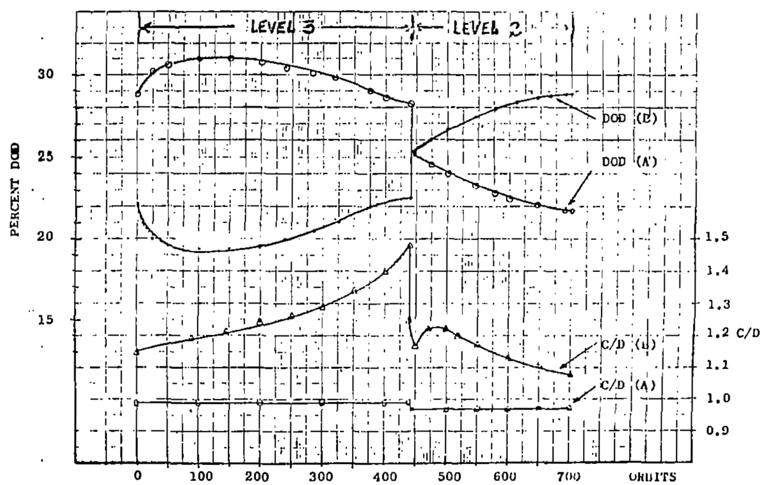
NOTE: AT THE END OF THE DISCHARGE PERIOD ON CYCLE 1, THE RESISTIVE LOAD WAS REPLACED WITH A HARD SHORT

Figure 4-16



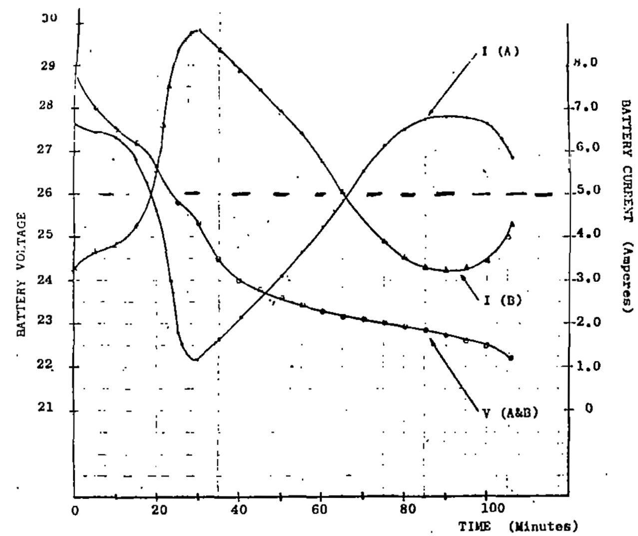
BATTERY CHARACTERISTICS DURING HARD CELL
SHORT PERIOD at level 3

Figure 4-17



BATTERY DOD AND C/D TREND DURING HARD CELL
SHORT PERIOD AT LEVELS 3 and 2

Figure 4-18



DISCHARGE CHARACTERISTICS DURING CAPACITY TEST
SHORTED CELL EVALUATION

Figure 4-19

CURRENT UPDATE ON PARALLEL BATTERY CYCLING

- o RE-ESTABLISHED NORMAL BASELINE CYCLING AT LEVEL 5 AND 25% DOD
- o C/D RATIO OF BATTERY B INCREASING DURING CYCLING
- o **BATTERIES SHARING LOAD UNEVENLY, BATTERY A 26% AND BATTERY B 24%**
- o SEVERAL CELLS IN BATTERY B EXCEED SOFTWARE VOLTAGE LIMIT ON CHARGE AFTER 250 CYCLES
- o LOWER CHARGER LEVEL FROM LEVEL 5 TO LEVEL 3
- o CYCLING CONTINUES FOR 1200 ORBITS AS BOTH BATTERIES EXPERIENCING 99% RECHARGE
- o MISSION DOD REMAINS UNCHANGED THROUGHOUT TEST

Figure 4-20

CONCLUSIONS

- o VOLTAGE VS TEMPERATURE LEVELS OF THE CHARGER HAS SUFFICENT VERSATILITY TO ACCOMMODATE A WIDE RANGE ABNORMAL CONDITIONS
  - o ACCOMMODATE BATTERY WITH A SHORTED CELL
- o INCREASING IMPEDANCE MISMATCH BETWEEN BATTERY HARNESS CABLES RESULTED IN DIVERGENCE OF DOD WHILE RECHARGE RATIO REMAINED UNCHANGED LOWERING THE CABLE IMPEDANCE RESULTED IN NEGLIGIBLE CHANGE IN DOD AND RECHARGE RATIO

Figure 4-21