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THE ELECTRICAL PERFORMANCE OF Ag Zn BATTERIES FOR THE VENUS MULTI-PROBE MISSION

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THE ELECTRICAL PERFORMANCE OF Ag Zn BATTERIES FOR THE VENUS MULTI-PROBE MISSION

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ABSTRACT

An evaluation of 5 Ah and 21 Ah Silver-Zinc batteries was made to determine their suitability to meet the energy storage requirements of the Bus vehicle, 3 Small probes and Large probe for the Venus Multi-probe mission. The evaluation included a 5 Ah battery for the small probe, a 21 Ah battery for the large probe, one battery of each size for the bus vehicle power, a periodic cycling test on each size battery and a wet stand test of charged and discharged cells of both cell designs. The study on the probe batteries and bus vehicle batteries included both electrical and thermal simulation for the entire mission as defined in the GSFC Phase A report of May 1971. The effects on silver migration and zinc penetration of the cellophane separators caused by the various test parameters were determined by visual and x-ray fluorescence analysis.

The 5 Ah batteries supported the power requirements for the bus vehicle and small probe. The 21 Ah large probe battery supplied the required mission power. Both probe batteries delivered in excess of 132 percent of rated capacity at the completion of the mission simulation. Both battery designs which were subjected to periodic cycling demonstrated their feasibility to support extensive spacecraft testing prior to installing the "flight" batteries. Results of the wet stand test showed the design(s) were capable of pro-long charge stands without severe capacity degradation. Charge stand, charge/float and temperature had the greatest effect of silver migration; whereas temperature and discharge stand caused the greatest amount of zinc diffusion.

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SUMMARY

Performance studies of the 5 and 21 ampere-hour batteries, selected for the Venus Multi-probe Mission, have been completed at GSFC. The battery tests have simulated both the electrical and thermal "flight" profiles for the Small probe, Large probe and Bus vehicle batteries.

The 5 Ah small probe and 21 Ah large probe batteries were subjected to environmental temperatures of -55° centigrade to 10° centigrade during the Cruise mode. The batteries performed satisfactorily during the 30 minute Separation phase; and 2 hour Entry to Impact phase at 10°C to 62°C. Cell out-gassing pressures at the high temperature were less than 1.5 atmospheres. The batteries were capable of delivering ≥1.5 times the ampere-hour capacity required for the mission.

Both battery designs were tested for the Bus vehicle profile which included a 1 hour pre-launch and 90 minute launch phase. These batteries were also capable of delivering power during the three Trajectory Correction maneuvers and Probe-Separation at day 148. The batteries were recharged after each operation and then-floated-at their open circuit potential. The charge/float method kept the batteries at their maximum capacity level without causing severe gas evolution within the individual cells. At the end of the five month flight profile, the 5 Ah battery delivered 160 percent of "rated capacity" whereas the larger battery delivered 135 percent of rated capacity.

Although the "flight" Bus batteries will only be recharged once during the mission, and the Probe batteries will receiving a "topping" charge before separation; the batteries used for subsystems and spacecraft tests will require numerous recharges. Thirteen cells of each ampere-hour size were periodically charge/discharge (100% depth) cycled at room temperature to determine the amount of capacity degradation caused by this regime. The 5 Ah cell capacities degraded by 5 to 11 percent after 20 cycles whereas the 21 Ah cell capacities degraded approximately 33 percent within 12 cycles. The "average" cell capacities for both designs at the end of the cycling regime were 7.5 and 20.0 ampere-hours as compared to 8.3 and 29.8 ampere-hours obtained at the beginning of the test.

THE ELECTRICAL PERFORMANCE OF Ag Zn BATTERIES FOR THE VENUS MULTI-PROBE MISSION

BACKGROUND

Early in 1972 a study was initiated at GSFC to determine the suitability of 5 and 21 ampere-hour silver zinc (Ag Zn) cells for a 1977 and 1980 Venus Multi-probe mission. Five ampere-hour batteries were selected to provide electrical power for the Bus vehicle and the three small probes. One 21 Ah battery was selected to supply the electrical power for the large probe. Each battery was comprised of 13 cells connected in series (GSFC Phase A Report, May 1971).

During entry into the Venus atmosphere the probes are decelerated by releasing drogue chutes, in order to obtain a 90 minute profile of the planet's atmosphere. The probe batteries during deceleration will be subjected to forces of 500 to 550 g's.

Acceleration tests were performed during 1972 on both cell designs, at the "flight" level of 550 g's (QEEL/C 72-274) and "prototype" level of 825 g's (GSFC/X-761-73-56). The "Epoxy" plate lock system which was used in both cell designs was capable of preventing severe damage to the internal cell components. Although both cell designs were able to meet the high "g" requirements for the mission, an additional study was required to determine the effects from the 158 day journey at the simulated electrical and thermal parameters. The Bus vehicle, Small probe and Large probe battery performance study was completed in 1973.

TEST PHILOSOPHY

Eighteen cells were activated for each battery. The cells were charge/discharge cycled three times during the Formation process and then recharged. The 13 cells whose ampere-hour input capacities were comparatively equal during the final recharge were selected for the battery. Two of the remaining five cells were discharged to a 100 percent depth (1.00 volts) to obtain the ampere-hour capability of the cells. These two reference cells were then placed on wet stand storage with the three charged cells, at room ambient temperature.

Two of the charged cells and five cells in the battery were fitted with pressure transducers or gauges (Figure 10) to obtain the cell gassing characteristics caused by the simulated battery test as compared to room temperature storage.

At completion of the simulated battery test, the three "charged" cells stored at room temperature and the 13 cells in the battery were discharged to 1.00 volts to compare their ampere-hour capabilities with respect to the two reference cells which had been discharged prior to initiating the simulated battery test.

Three 5 Ah batteries were studied. One battery was tested at the Bus vehicle profile and another at the Small probe parameters. The third battery was subjected to a periodic cycle test. All cells in this battery were discharged to a 100 percent D.O.D. (1.00 volts) and recharged to 1.98 volts to determine the loss of cell capacity caused by cycling.

Three 21 Ah batteries were also studied. One battery was tested at the Large probe parameters and another was also subjected to a periodic cycle test. Although the 21 Ah battery is only used in the Large probe, the third battery of this ampere-hour design was tested at four times the power levels required for the 5 Ah Bus battery to compare the effects of the charge/float method used to maintain the Bus vehicle battery at its maximum charge level throughout the 158 day mission.

NOTE

> Both battery designs were charged the Modified Constant Potential method with a 25.74 volt limit. The maximum charge current was 0.50 amperes for the 5 Ah battery and 2.1 amperes for the 21 Ah battery. When the current decreased to 50 milliamps for the 5 Ah battery and 210 milliamps for the 21 Ah battery, each battery charger was automatically tripped to the open circuit potential - Float Mode - of 24.18 volts (1.86 v per cell).

Several cells from each battery and some of the charged and reference cells which had been stored at room temperature were dissected at the conclusion of all the electrical tests. All separators and electrodes were visually examined to compare the amount of Silver migration and the loss of Zinc material caused by the different electrical and thermal parameters required for the Bus, Small probe, Large probe and Periodical Cycling tests. Samples of the cellophane separators were analyzed by x-ray fluorescence spectroscopy to determine the concentration of Silver and Zinc.

TEST PROCEDURES

A. Activation

Fifty-four cells of each design (5 Ah, 21 Ah) were activated in groups of eighteen cells. The height, width and thickness of each cell was measured prior to filling the cells with electrolyte. Cell thickness measurements were also obtained immediately after activation and prior to sealing the cells. The cells were reweighed after activation, at the end of the formation procedures and after the cells were sealed. The maximum and minimum dimensions of the sealed cells are shown in Table 1.

The 5 ampere-hour cells were filled with 19.5 cc of Potassium Hydroxide (44% KOH) and the 21 ampere-hour cells were activated with 53 cc. During activation the cells were placed in a vacuum of 20 to 25 inches of Hg to remove the air from the cells. Removing the vacuum forced the electrolyte into the cells.

Immediately after activation groups of 8 to 10 cells were restrained with end plates to prevent expansion of the cell cases. An overflow tube was then placed into each cell's vent spout to prevent the electrolyte from spilling over the top of the cells during formation.

B. Formation

The formation sequence consisted of 3 charge/discharge cycles and a final recharge using the manufacturer's recommended current and voltage parameters. A formation cycler was used to cycle each group of 18 cells at the specified constant current limits. Each cell was automatically removed from the series circuit at the required voltage limit (1.00 volts during discharge and 2.05 volts during charge). An ampere-hour integrator in each series group of 18 cells

Table 1

Sealed Cell Dimensions

	Height (Inches)	Width (Inches)	Thickness (Inches)	Weight (Grams)
HR5(S)-1				
Minimum	2.868	2.067	0.797	130.3
Maximum	2.881	2.076	0.803	132.3
HR21(S)-1				
Minimum	4.864	2.300	0.996	356.9
Maximum	4.878	2.303	1.000	361.2

recorded the ampere-hours of each cell whenever its charge or discharge was terminated. The current and cell voltages were monitored with an automated data acquisition system (Dymec 2010C).

At the end of each charge the 5 Ah cells had a substantial amount of electrolyte in the overflow tubes whereas the larger cells had little or no electrolyte in the overflow tubes. The larger quantity of electrolyte in the overflow tubes in the 5 Ah cells was attributed to the vent spouts which protruded below the bottom of the cell case covers, allowing the electrolyte to creep up into the overflow tubes. The lower portion of the vent spout was removed in the 21 Ah cells and therefore the electrolyte level had to reach the cell case cover in order for the electrolyte to creep up in the overflow tube. Removing the lower portion of the vent spout in the 5 Ah cells should substantially reduce the amount of electrolyte in the overflow tubes at the end of each formation charge.

At the completion of the three formation cycles, the cells were recharged, purged (20-25 inches Hg) and placed on stand for 24 hours. The electrolyte level of each cell was then examined and adjusted (removed KOH), where required, to assure the level of the KOH was below the top of the separator system. The amount of electrolyte removed from the 5 Ah cells ranged from 0.0 to 1.0 cc. No electrolyte was removed from the 21 Ah cells. The vent holes were then sealed with plastic disks and plexiglass cement (PS-18). Epoxy (Delta Cast 153) was used to seal the cells which were fitted with pressure gauges or transducers. Epoxy was also applied to the top of the cell case covers where the terminals are located to prevent possible leakage at the terminals during the long term study program.*

The 18 cells were leak checked with phenolpthalein prior to fabricating the battery.

The 13 cells with ampere-hour input capacities comparatively equal during the final recharge were selected for the battery since all cell voltages were similar throughout the "formation" cycling regime. Two of the five remaining cells were discharged to 1.00 volt to obtain the ampere-hour capability, which would be used as a reference for evaluating the cells at the end of the battery test. The three remaining charged cells were placed on open circuit stand at room temperature ambient and then discharged at the end of the study with the 13 cells in the battery.

*The batteries are incapsulated with an Epon epoxy for aero-space application whereas these test batteries and additional test cells were not potted. Incapsulating the cells with epoxy would have created problems for the "Cell Dissection and Separator Analyses."

Three batteries for each of the two type ampere-hour cells were tested during the study. The ampere-hour discharge capacities of the cells from each battery were compared to the three charged cells stored at room temperature and the two reference cells to determine the effects from the various battery tests. The 54 cells of both ampere-hour sizes are illustrated in Table 2.

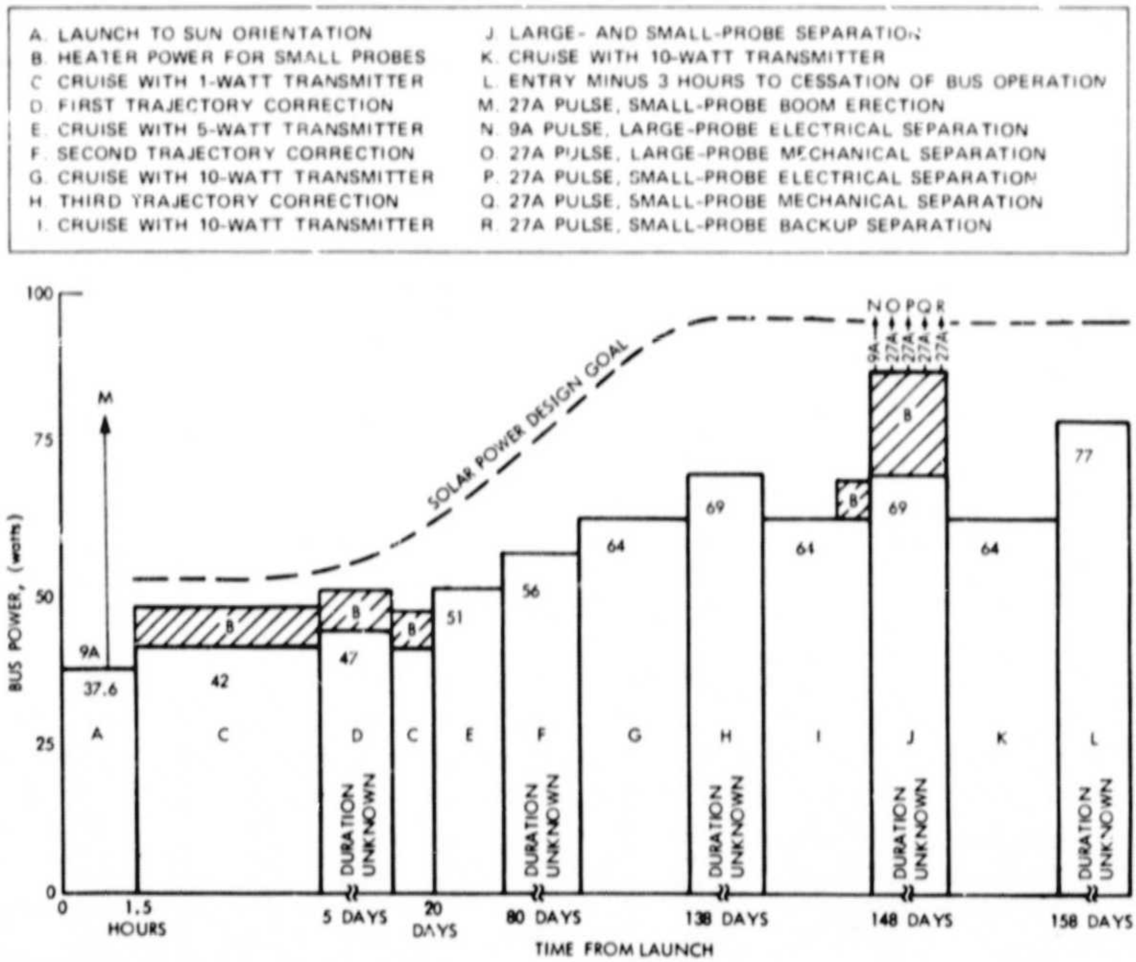
Table 2

Cell Test — Battery Program Outline

Batteries	HR5(S)-1 Cells			HR21(S)-1 Cells		
	Small Probe	Bus	Periodic Cycling	Large Probe	Bus	Periodic Cycling
	S/N	S/N	S/N	S/N	S/N	S/N
	28	45	63	28	45	63
	29	46	64	29	46	64
	31	47	65	30	47	65
	32	48	66	31	48	66
	34	49	67	32	51	67
	35	50	68	33	53	68
	36	51	69	36	54	69
	37	52	70	37	55	70
	38	53	71	38	56	71
	41	55	72	40	58	72
	42	56	73	41	59	73
	43	59	74	42	61	74
	44	61	75	43	62	75
Reference Cells	39	60	76	39	57	76
	40	62	77	44	60	77
Room Temperature Storage	30	54	78	27	49	78
	33	57	79	34	50	79
	37	58	80	35	52	80

C. Bus Vehicle Battery (HR5(S)-1 Cell)

Two batteries comprised of thirteen 5 Ah cells supply electrical power for the Bus vehicle. One battery is used for the "average" power requirements during pre-launch and the first 90 minutes of the launch phase when the spacecraft is without solar-array power. The second battery is used to fire the pyrotechnics (peak power requirements) during the launch phase and again during separation of the 4 probes. In case of a failure of either battery, the other can be switched in as a back-up. The solar-array supplies the electrical power to operate the spacecraft and recharge the batteries during the cruise to Venus (Figure 1).



NOTE: The 21Ah battery was tested at four times the power levels indicated in this profile.

Figure 1. Bus Battery Power Profile (5 Ah Battery)

The performance study of the 5 Ah battery included five pulses of 27 to 33 amperes for 5-second durations, at 1 minute intervals. The battery was then discharged at 2.1 amperes (≥38 watts) for 2.5 hours, simulating a 1-hour prelaunch and 90-minute launch phase. The battery was then recharged and floated at the open circuit potential of 24.18 (1.86 volts per cell).

Although the solar array supplies the required power (51, 69, and 77 watts) for the three trajectory correction maneuvers on days 5, 80, and 138, respectively, the battery was tested at these power levels for 30 minutes per correction maneuver (to represent a worst-case simulation). The battery was charge/floated after each maneuver.

A pulse test similar to the one performed during the launch phase was also conducted on day 148 when simultaneous separation (27 amperes, peak current) of the three small probes is required. The lowest battery voltage was 13.81 volts at the start of the second pulse (32.5 amperes).

A "Post Mission" evaluation of the battery was then performed by conducting a capacity test at the 69-watt power level for 30 minutes. The test was then continued at the 37-watt "launch phase" power level to compare the voltage characteristics with those obtained on day one. At 5.2 ampere hours out, the battery's voltage was [illegible] volts as compared with 19.85 volts at the start of the discharge. The test was terminated when the battery voltage decreased to 18.0 volts (<1.40 volts per cell). The capacity output was 8.3 ampere-hours. Each cell was then individually discharged to 1.00 volt. The total capacity output for the thirteen cells ranged from 8.3 to 8.9 ampere-hours. The capacity inputs for these cells prior to the start of the 148 day mission had ranged from 9.1 to 9.6 ampere-hours. This battery was capable of delivering the various power requirements (Figure 2) throughout the study.

During the first recharge the battery received 7.8 ampere-hours, which was 2.6 ampere-hours more than it delivered during the launch-phase simulation. Cell voltages ranged from 1.951 to 2.030 volts at the end of charge. The five cell pressures ranged from 12 to 44 psig whereas they had ranged from 6 to 8 psig at the start of the recharge. The cell which was 1.951 volts increased 6 psig and the cell which was 2.030 volts increased 36 psig. The severe voltage unbalance between the cells and high increase in cell pressures were indications that the battery had been overcharged.

A review of the data indicated the charge voltage characteristics of these 5 and 21 Ah cells were slightly different than 5 and 16 Ah cells previously tested at GSFC which contained the same sized Ag and Zn electrodes. An inquiry to the manufacturer revealed that the manufacturing process for the silver particles

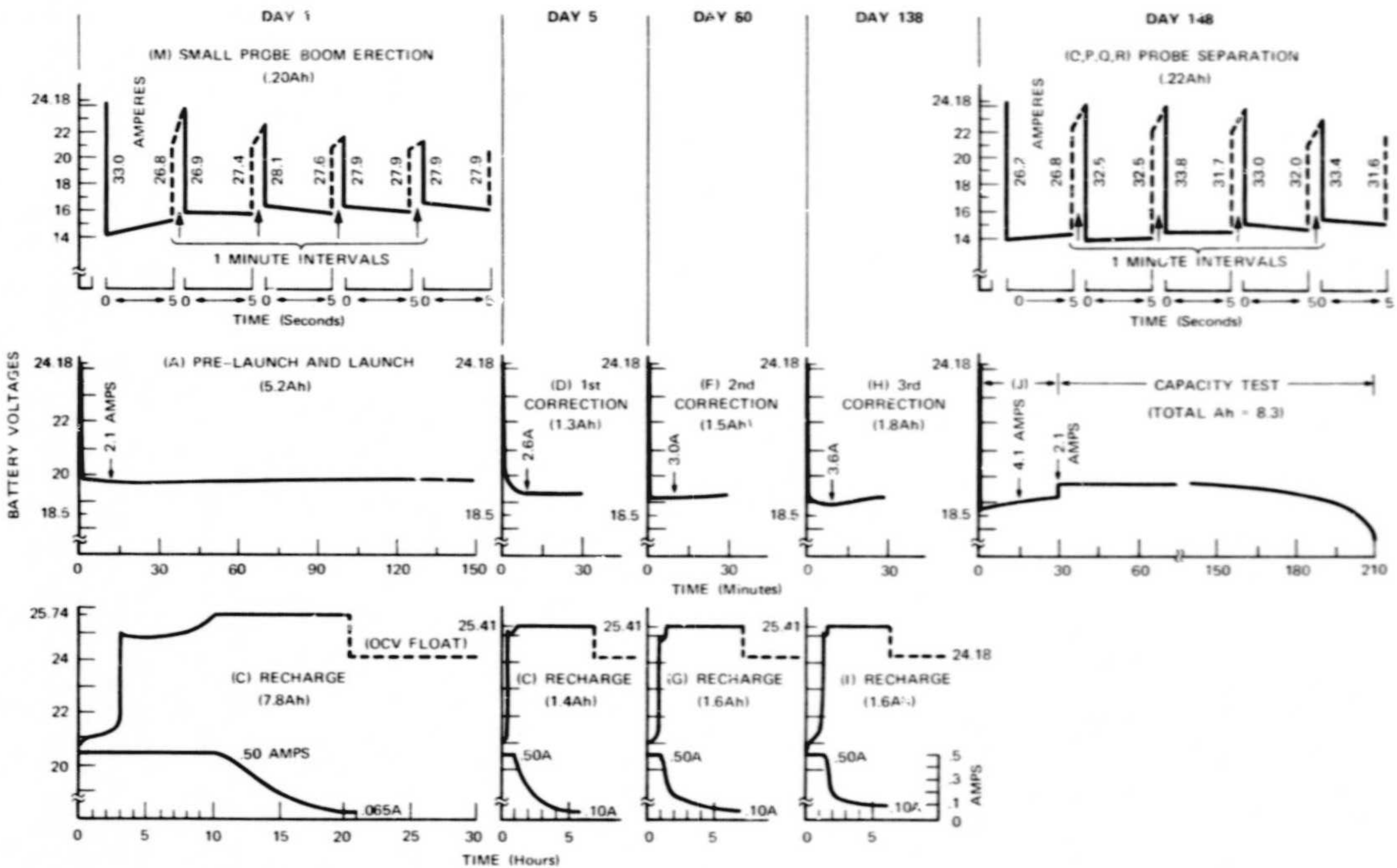


Figure 2. Bus Battery Voltage Profile (13 x HR5(S)-1 Cells)

used in sintering the Ag electrode had been improved. The average size of the Ag particles were smaller and resulted in the different charge voltage characteristics.

The battery charge voltage limit was lowered to 25.41 volts (1.955 volts per cell) and the current trip point was raised from 65 ma to 100 ma for all subsequent recharges. The cell voltages never exceeded 1.98 volts and cell pressures gradually decreased whenever the battery was "floated" at 24.18 volts (≃142 days total time). Cell pressures ranged from 4 to 10 psig at the end of the capacity test on day 148 (Table 3). All cells passed the leak check at the end of the study. The gradual decrease in cell pressures can be attributed to the recombination of the gasses (oxygen and/or hydrogen), that had developed during the overcharge on day 1.

D. Bus Battery Study (HR21(S)-1 Cells)

A substantial increase in the average power requirements for the Bus vehicle and/or Small probes would necessitate the selection of a cell with a nominal ampere-hour capacity greater than the 5 Ah cells. A substantial reduction in the average power requirements for the Large probe would necessitate the selection of a cell with a nominal ampere-hour capacity less than the 21 Ah cells which contain seventeen (9 Zn, 8 Ag) electrodes. A 16 Ah cell which contained thirteen (7 Zn, 6 Ag) of the same size electrodes had been previously tested at GSFC. A 10 Ah cell could be designed by using nine (5 Zn, 4 Ag) electrodes of the same size. The electrodes would fit into the manufacturer's 10 Ah cell case used for vented cells. The engineering costs to design a 10 Ah and 16 Ah cell would be minimized because the electrodes and cell cases have been designed and tested.

Since the 10 Ah and 16 Ah cells would contain the same sized electrodes as the 21 Ah cells, a 21 Ah battery was also tested at the Bus vehicle profile to obtain the voltage and pressure characteristics during the various discharges and charge/float modes. The average power levels (37 to 69 watts) were increased by a factor of four, similar to the capacity ratio of the two battery designs (21 Ah/5 Ah). The peak current level (27 to 33 amperes) for firing the pyrotechnics was not increased. The 21 Ah battery was capable of performing at the different power levels throughout the study as illustrated in Figure 3.

The charge voltage was limited at 25.74 volts (similar to the 5 Ah battery) for the first recharge. The current was limited at 2.1 amperes and the "trip" current level was set for 210 milliamperes. A severe unbalance between the cell voltages (1.940 to 2.039 volts) also occurred in this battery similar to the 5 Ah battery previously discussed. The recharge was manually stopped after the five cells with pressure gauges had exhibited pressure increases of 2 to 16 psig.

Table 3

"Bus Battery" Cell History

	Day 1		Day 5		Day 80		Day 138		Day 148
	Ah Out	Ah In	Ah Out	Ah In	Ah Out	Ah In	Ah Out	Ah In	Ah Out
HR5(S)-1 Cells	5.20	7.80*	1.31	1.40	1.45	1.57	1.80	1.61	8.3
Lowest Voltage	1.524	1.951	1.493	1.928	1.485	1.943	1.474	1.948	1.511
Average Voltage	1.527	1.980	1.497	1.956	1.487	1.955	1.477	1.954	1.515
Highest Voltage	1.528	2.030*	1.499	1.977	1.490	1.964	1.483	1.966	1.519
Lowest psig	6	12	13	13^-	6	6^+	3^+	3^+	4^-
Average psig	7^+	23^-	18^+	18	7^+	8^-	5^+	5^+	7
Highest psig	8.5	44*	27^+	26	10^+	10^+	8^+	8^+	10^-
HR21(S)-1 Cells	20.10	21.4**	5.16	5.38	5.80	6.08	7.10	6.90	28.60
Lowest Voltage	1.514	1.940	1.492	1.950	1.493	1.943	1.482	1.936	1.512
Average Voltage	1.524	1.981	1.500	1.956	1.499	1.952	1.491	1.956	1.522
Highest Voltage	1.527	2.035**	1.503	1.963	1.502	1.963	1.495	1.973	1.526
Lowest psig	4	6	3^-	3^-	2^+	2^+	1.5	2^-	2^+
Average psig	9^+	17	5^+	5^+	3^+	4^-	2^+	2^+	3^-
Highest psig	12	28**	20^-	19^-	4	4.5	2.5	4	3.5

NOTE: Average pressure calculated from 5 cell pressures.

*Charge Voltage Limit = 1.980/cell. Battery overcharged, automatically tripped to "Float" mode.

**Charge Voltage Limit = 1.981/cell. Battery overcharged, manually put into "Float" mode.

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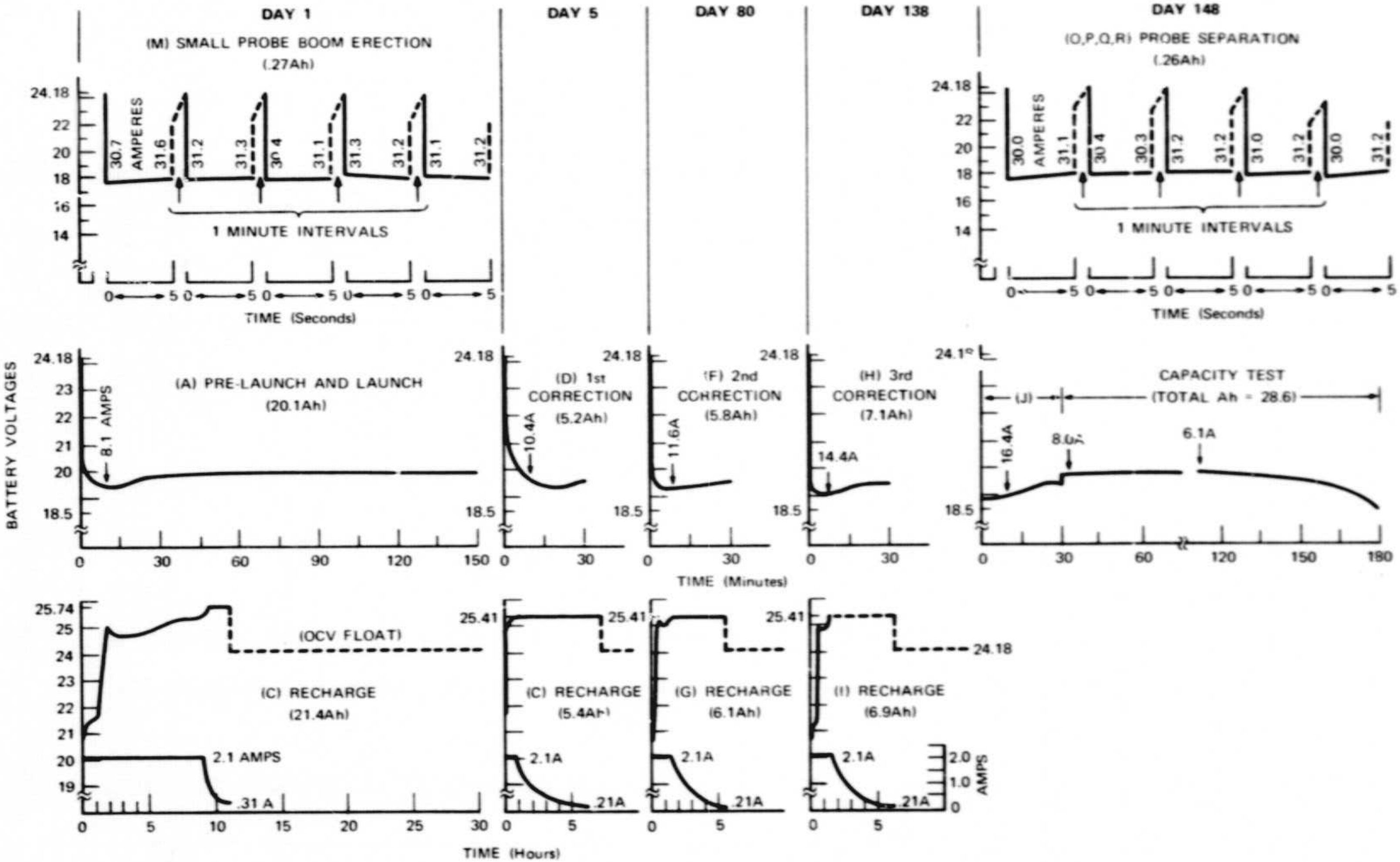

Figure 3. Bus Battery Voltage Profile (13 x HR21(S)-1 Cells)

The capacity input was 1.3 ampere-hours more than the output.

Lowering the battery "charge" voltage to 25.41 volts eliminated the severe cell voltage unbalance and high cell pressures during the remaining recharges (Table 3). Cell pressures ranged from 2 to 3.5 psig at the end of the capacity test on day 148. The battery's capacity output at 18.0 volts (~1.40 volts/cell average) was 28.6 ampere-hours. The individual cell capacities ranged from 28.6 to 29.9 ampere-hours. The capacity inputs for the cells had been 30.8 to 32.3 ampere-hours during the final formation recharge, prior to initiating the study.

E. Small Probe and Large Probe Batteries

Immediately after launch the ambient temperature of the three Small probe (5 Ah) batteries and the Large probe (21 Ah) battery will decrease to -45°C and -20°C respectively. Both battery designs were studied at the Small probe temperature profile because this battery experiences the greatest temperature change during the 158 day mission from Launch to Impact (Figure 4). The "flight" temperature as defined in the GSFC Study (Phase A Report, 5-71) range was exceeded by -10°C and +10°C to represent the prototype levels.

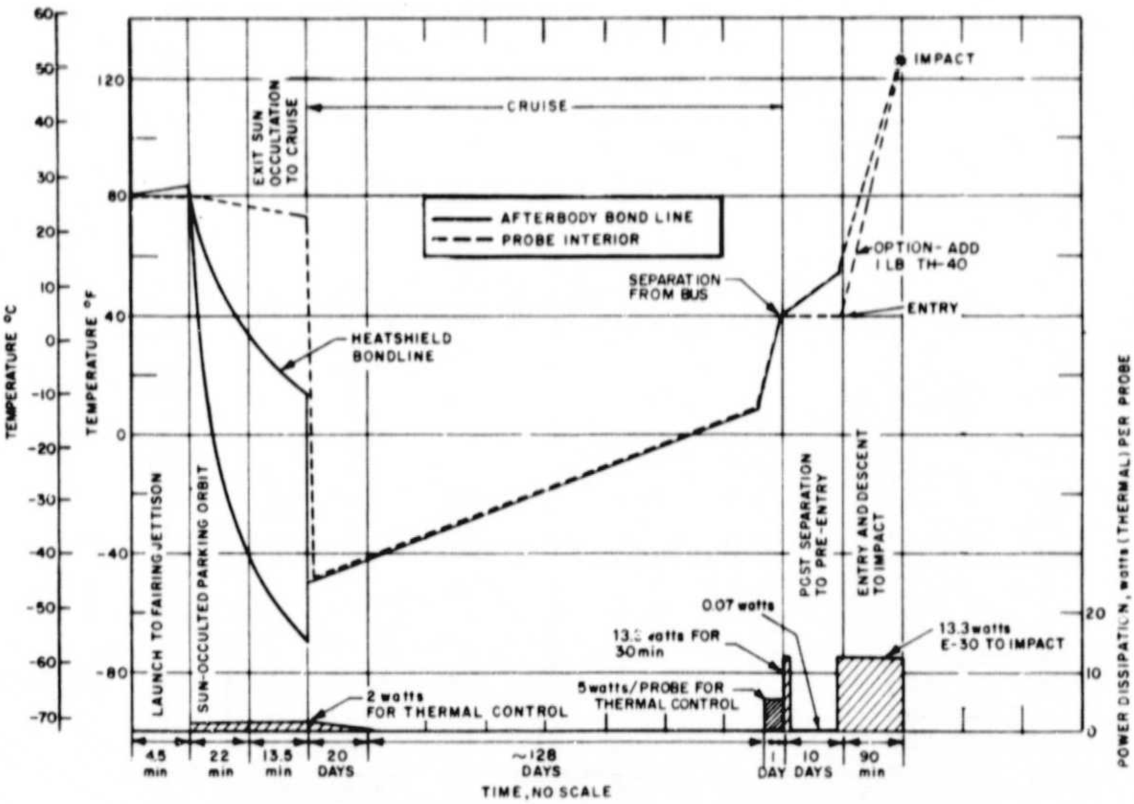

Figure 4. Small Probe Temperature and Power Profile

The ambient temperature was decreased from 24°C to -55°C during the first 2 hours of the test profile. During the following 21 weeks the temperature was increased at the rate of 2°C per week. Prior to simulating the "separation" of the probes from the Bus vehicle, the temperature was increased from -13°C to 5°C. The temperature profile is shown in Figure 5. The open circuit voltages of the cells in each battery remained stable (1.85 to 1.86 volts) throughout this period. The batteries were charged on day 148 at the same voltage and current parameters described for the Bus batteries. The (5 Ah) Small probe battery tripped into the float mode after 0.03 ampere-hours input. The (21 Ah) Large probe battery received 0.16 ampere-hours when it went into the float mode. Battery capacity did not appear to degrade during the five month storage at -55°C to 5°C.

The power levels used for testing each battery from Separation to Impact (day 148 through 158) are shown in Figures 6 and 7. Pulse testing (peak power) consisted of five pulses of 5 second durations, at one minute intervals. The ten day "Coast" period (0.07 watts) was not simulated since the current and capacity requirements were insignificant. The Entry to Impact phase (11°C to 62°C) of the test was simulated for an additional 30 minutes at 62°C.

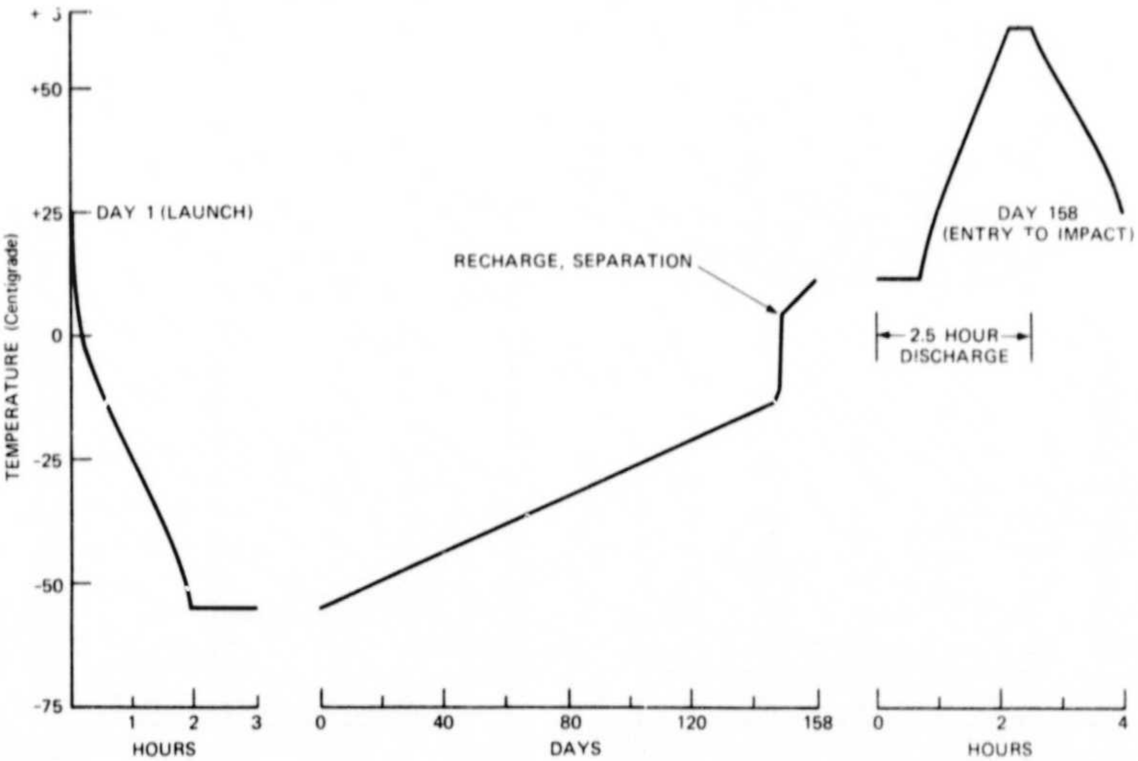

Figure 5. Temperature Profile of Small and Large Probe Battery Studies

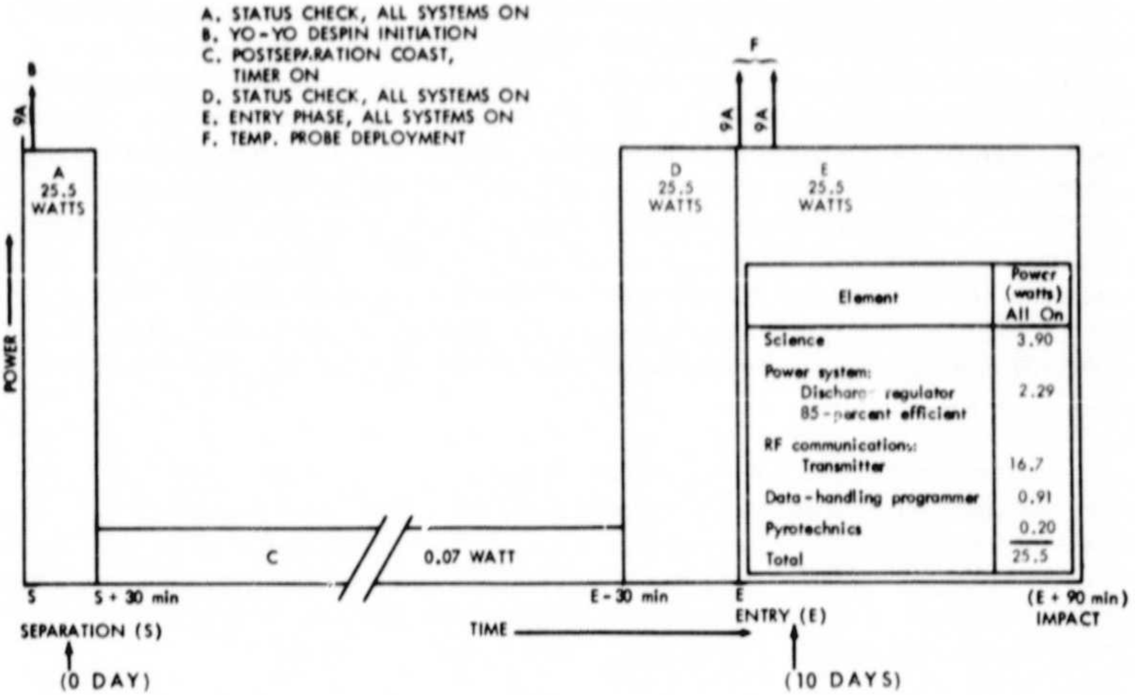

Figure 6. Small Probe Power Profile

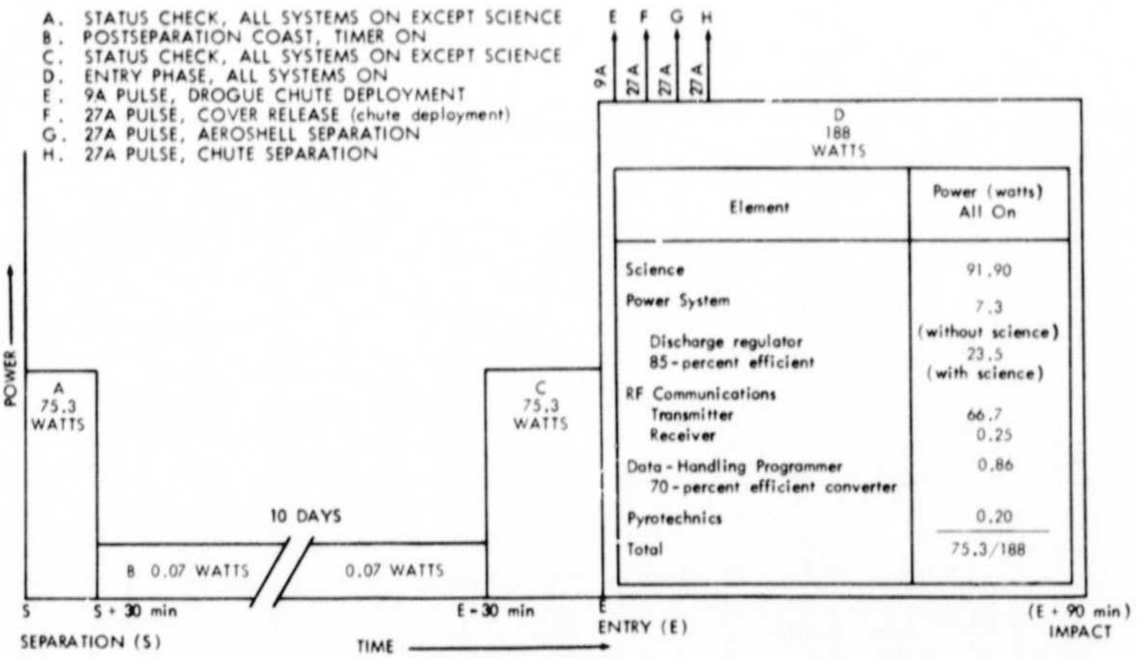

Figure 7. Large Probe Power Profile

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E1. Small Probe Battery Discussion and Results—The small probe batteries' lowest voltage was 19.40 volts at 1.3 amperes (25.5 watts average power) during the thirty minute "separation phase." The battery voltage decreased to 16.41 volts during the pulse test simulating "Yo-Yo despin." Similar voltages were observed 10 days later during the 30-minute preentry phase and pulse test (Temperature Probe Deployment, Figure 6). Battery voltage increased from 19.55 to 20.86 volts during the 2-hour Entry to Impact phase when the ambient temperature was increased from 11°C to 62°C. The complete voltage and temperature profile is depicted in Figure 8.

The five cells with pressure transducers increased 3.3 to 4.5 psia during this portion of the test. Cell pressures at the end of this period ranged from 16.7 to 18.8 psia (Table 4).

The battery was dismantled and each cell was discharged to 1.00 volts at room temperature ambient on day 175.

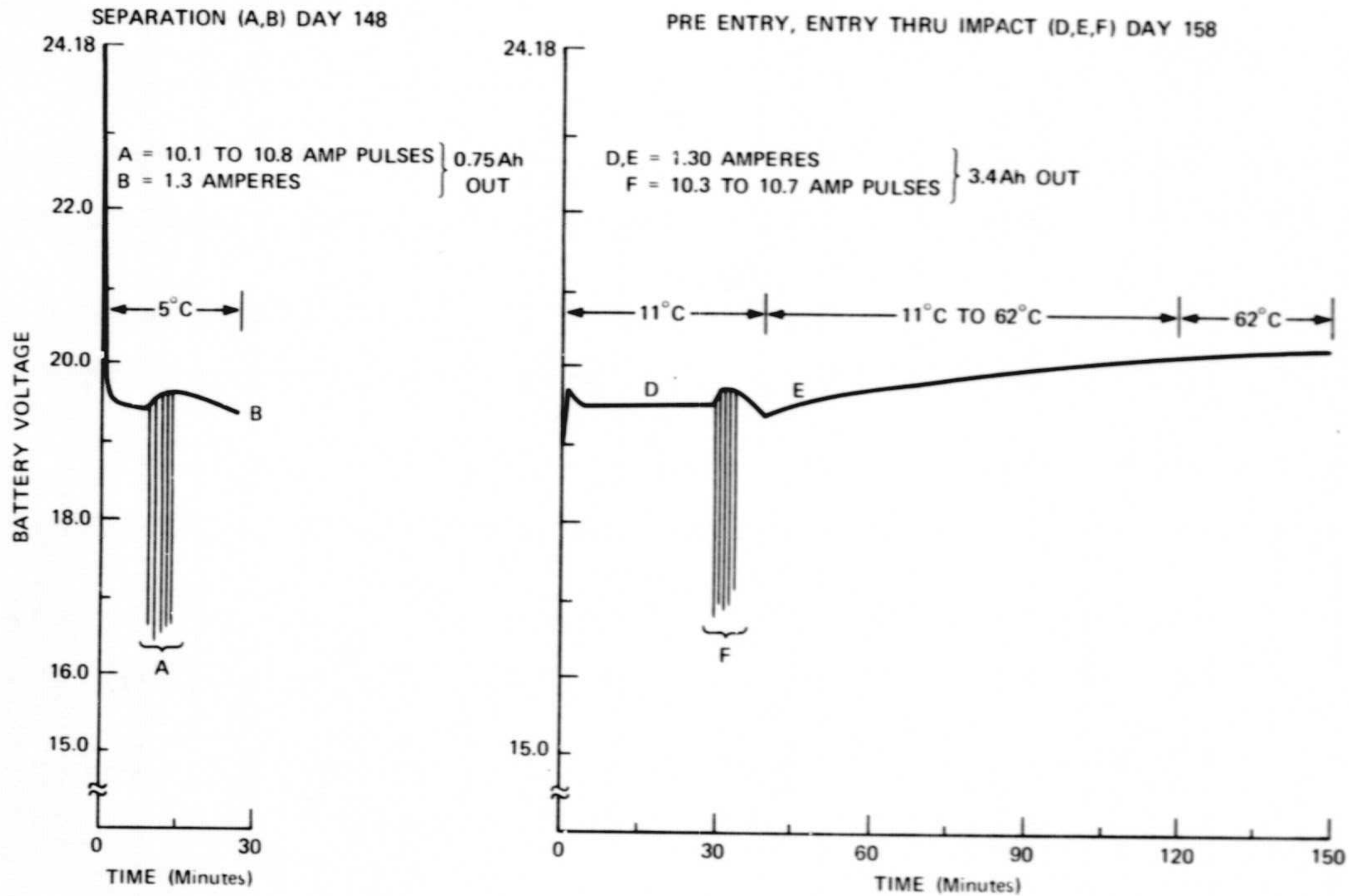
Total cell capacities ranged from 8.0 to 8.3 ampere-hours out, whereas the capacity inputs had ranged from 8.6 to 9.3 ampere-hours prior to initiating the study. Similar discharge capacities were recorded during the third Formation cycle which had preceded this study.

Table 4

Small Probe Battery "Cell Pressure and Temperature" During Mission Simulation

Test Day	1	1	31	62	93	124	146	148	148*	158	158**
Ambient Temp. (°C)	24	-55	-47	-37	-29	-19	-13	05	05	11	62
Lowest Pressure (psia)	15.4	10.6	10.9	10.2	9.5	9.6	9.8	11.1	11.6	13.0	16.7
Average Pressure (psia)	17.7	12.1	11.6	11.0	10.7	10.8	11.0	12.3	12.7	13.5	17.9
Highest Pressure (psia)	19.1	13.0	12.7	11.8	12.4	12.9	13.3	14.4	14.4	14.9	18.8

NOTE: Average pressure calculated from 5 cell pressures.
*Pressures at end of 30 minute "Separation" Test.
**Pressures at end of 150 minute "Preentry" through "Impact" Test.



NOTE: A-F are defined in Figure 6.

Figure 8. Small Probe Battery Voltage Profile (13 x HR5(S)-1 Cells)

E2. Large Probe Battery Performance—The lowest battery voltage during the separation and preentry phases was 19.36 volts at the average power level of 75.0 watts. Battery voltage decreased to 16.27 volts during the pulse test (37.3 amperes). The voltage increased from 18.99 volts to 19.78 volts at the 188 watt "average" power level as the ambient temperature was increased from 11°C to 62°C during the entry through impact phases (Figure 9). Cell pressures increased approximately 8psia during this period (Table 5).

The capacity output of the cells ranged from 27.9 to 29.3 ampere-hours at the end of the study. The average cell capacities were 1.5ah less than those obtained during the final Formation cycle discharge.

Table 5

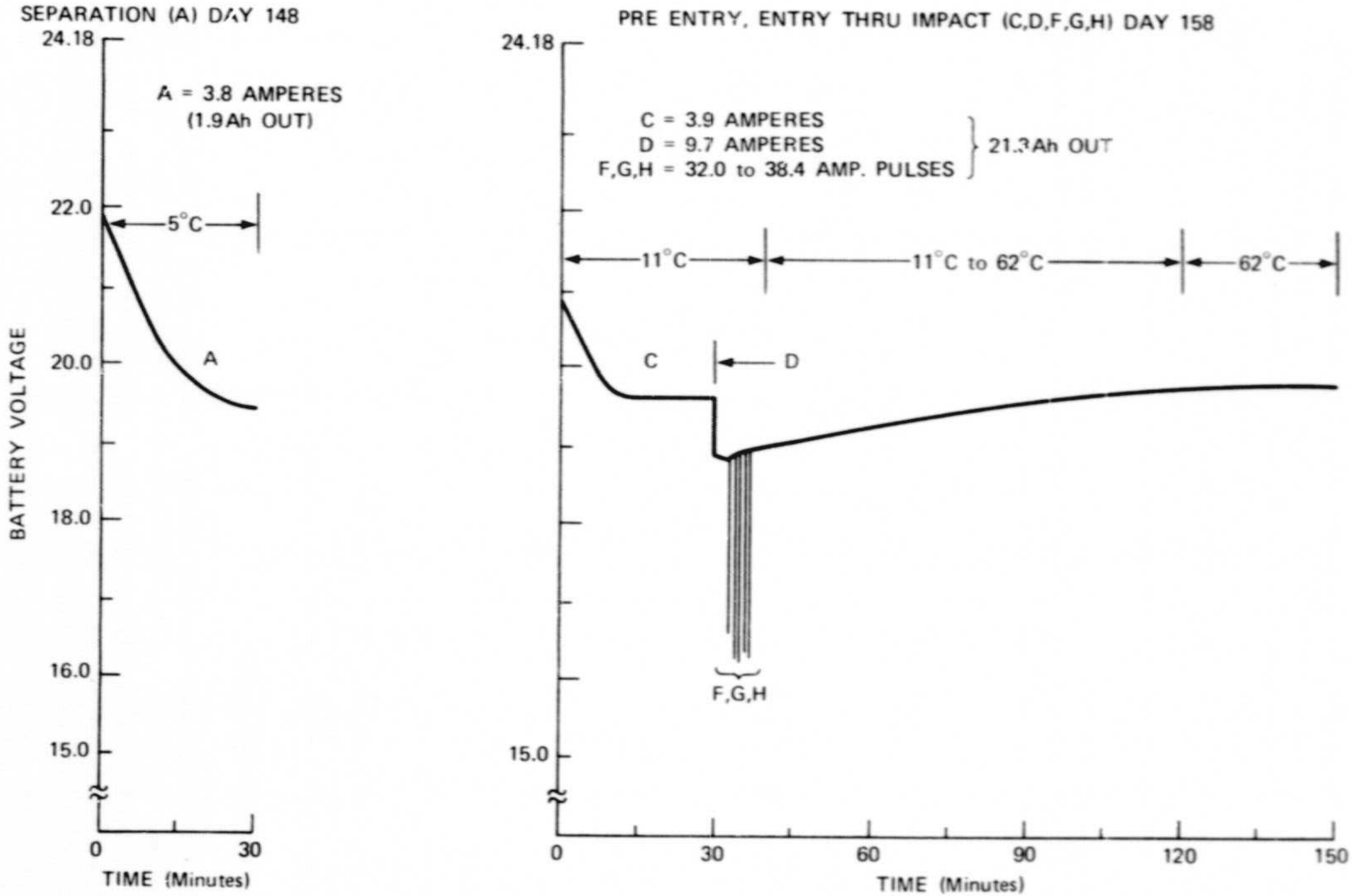
Large Probe Battery "Cell Pressure and Temperature" During Mission Simulation

Test Day	1	1	31	62	93	124	146	148	148*	158	158**
Ambient Temp. (°C)	24	-55	-47	-37	-29	-19	-13	05	05	11	62
Lowest Pressure (psia)	17.8	12.1	10.4	9.6	9.2	9.1	9.3	10.7	11.3	11.8	19.7
Average Pressure (psia)	18.3	12.5	11.0	10.2	9.7	9.4	9.7	11.1	11.7	12.3	20.1
Highest Pressure (psia)	19.0	13.0	11.4	10.7	10.0	9.8	10.0	11.5	12.2	12.7	20.5

NOTE: Average pressure calculated from 5 cell pressures.
*Pressure at end of 30 minute "Separation" Test.
**Pressure at end of 150 minute "Preentry" through "Impact" Test.

F. Periodic Cycling Tests

Although the "flight" batteries are not subjected to a severe charge/discharge cycle regime, the test batteries which will be used for the extensive subsystem and spacecraft tests will require numerous charge/discharge cycles. The depth of discharge may change from cycle to cycle due to the various subsystem and spacecraft test schedules. Battery capacity will degrade during the cycling regime, particularly at deep depths of discharge.



NOTE: A-H are defined in Figure 7

Figure 9. Large Probe Battery Voltage Profile (13 x HR21(S)-1 Cells)

A battery of each Ah design was subjected to a "cycle" test to determine the amount of capacity degradation for the test batteries. The 13 cells in each battery were individually discharged to a 100 percent depth (1.00 volts) each cycle. The 5 Ah cells were discharged at the current drain of 1.3 amperes (small probe) and the larger cells at 10.0 amperes (large probe).

Each cell was recharged at a constant current of 0.5 and 2.1 amperes for the 5 Ah and 21 Ah respectively, to a voltage limit of 1.98 volts. Since each cell was automatically disconnected from the charge circuit, the individual cell voltage limit was (1.98 volts), which was slightly higher than the "battery" voltage limit of 1.955 volts/cell used to charge the Bus and probe batteries.

After completing 20 charge/discharge cycles during a span of 3 months, the cell capacities of the 5 Ah battery ranged from 7.3 to 7.7 ampere-hours which is approximately 150 percent of the nominal rated capacity. Cell capacities only degraded 5 to 11 percent during the 20 charge/discharge cycles (Table 6).

The 21 Ah cells were cycled at the same intervals as the smaller cells. This test was prematurely terminated during the thirteenth cycle charge. All cells were ruptured due to an overcharge of approximately 13 ampere-hours, caused by a malfunction of test equipment.

Table 6

Ampere-Hour Discharge Capacities of Periodic Cycling Tests

13 HR5(S)-1 Cells								
Cycle	F1	F3	1	4	8	12	16	20
Date	2-13-73	2-22	3-9	3-23	4-12	4-26	5-10	5-24
Lowest Ah	8.3	8.4	7.7	8.4	7.9	7.3	7.1	7.3
Average Ah	8.7	8.9	8.3	8.5	8.0	7.4	7.3	7.5
Highest Ah	8.8	9.2	8.8	8.6	8.1	7.6	7.5	7.7
13 HR21(S)-1 Cells								
Cycle	F1	F3	1	4	8	12		
Date	2-13-73	2-22	3-9	3-23	4-12	4-26		
Lowest Ah	27.9	28.3	28.3	26.8	21.7	19.3		
Average Ah	29.8	29.4	29.8	27.4	22.5	20.0		
Highest Ah	30.6	30.3	31.0	28.5	22.9	20.6		

NOTES: (A) F1 and F3 were Formation cycles; (B) Cells charged to 2.05 volts during Formation and first cycle: (C) Cells charged to 1.98 volts during cycles 2-20.

Cell capacities had degraded 9 to 10.5 ampere-hours at the end of the twelfth cycle discharge. The average cell capacity was 95 percent of the nominal 21 Ah rating as compared to 142 percent at the end of the final formation cycle. Charge/discharge cycling had a more detrimental effect on the ampere-hour capacity of the 21 Ah cells than on the 5 Ah cells.

G. Wet Stand Test

Silver-zinc cells are known to be adversely affected by the length of wet stand (storage time) and temperature. The decomposition of the electrode's active material and silver migration through the separator system also depends on the cell's "state-of-charge" during storage. Data obtained throughout the years have shown that Ag Zn cells and batteries should be stored in a "discharged" condition at cold temperatures.

Three charged cells were stored at room ambient temperature for each battery test. This was done to compare the effects of the sub-zero temperatures on the probe battery cells and the effects of "charge/float" on the Bus battery cells. The storage periods varied from 115 days to 190 days whereas the probe and Bus batteries were on test for 175 and 172 days, respectively.

The results of the capacity tests which are illustrated in Tables 7 and 8 showed that the capacity output of the cells decreased as wet storage time increased (i.e., Table 7, Group A's wet stand periods were 3, 115, and 190 days). The effects of the various storage periods at the different temperature parameters were determined by comparing the "average" charge efficiencies Ah out/Ah in of the reference cells with the cells placed on charge stand (groups A, B, C) and the cells in each of the batteries listed in Table 9.

The ratio of the Ah out/Ah in of the 21 ampere-hour reference cells were greater than the 5 ampere-hour reference cells and therefore the larger cells should have had higher charge retention for all test conditions.

The 5 Ah cell's "charge" retention was lower for all test conditions except the small and large probe batteries which were 3.9% and 4.1% respectively. The cells in the probe batteries which had been tested at sub-zero temperatures for 148 days of the 175 day test program were least affected by the long wet stand regime as compared to the cells stored at room temperature.

The cells in the Bus batteries which had been on charge/float at room ambient temperature for 143 days of the 172 day test program had a slight decrease in charge retention as compared to the reference cells stored at room ambient temperature for 160 days.

Table 7

HR5(S)-1 Wet Stand Capacity

Room Temperature Stand

	S/N	Ah In	Days on Stand	Ah Out
A	39R	9.2	3	8.8
A	40R	9.5	3	8.9
A	30	9.4	115	8.2
A	33	8.9	115	8.1
A	27	9.1	190	7.7
B	60R	9.0	4	8.5
B	62R	9.2	4	8.6
B	54	9.0	160	7.6
B	57	9.2	160	7.8
B	58	9.1	160	8.1
C	76R	8.8	14	8.3
C	77R	9.1	14	8.4
C	78	9.2	117	7.7
C	79	8.2	117	7.4
C	80	8.8	117	7.6

Small Probe Battery

S/N	Ah In	Days on Stand	Ah Out
28	8.9	175	8.1
29	8.8	↑	8.0
31	8.8		8.1
32	9.3		8.2
34	9.3		8.2
35	8.7	Sub-Zero	8.0
36	9.1	Storage	8.2
37	8.9	(148 Days)	8.2
38	9.1		8.2
41	9.2		8.3
42	9.3		8.2
43	8.6	↓	8.0
44	9.0	175	8.2

Bus Battery

S/N	Ah In*	Days on Stand	Ah Out**
45	9.5	172	8.5
46	9.6	↑	8.6
47	9.6		8.7
48	9.5		8.9
49	9.4		8.7
50	9.5	Charge/Float	8.8
51	9.4	at Room	8.8
52	9.1	Temperature (143 Days)	8.5
53	9.3		8.3
55	9.3		8.8
56	9.6		8.6
59	9.2	↓	8.8
61	9.3	172	8.5

A - Extra (Small Probe Battery) Cells

B - Extra (Bus Battery) Cells

C - Extra (Periodic Cycling Battery) Cells

R - Reference Cells

*Prior to Launch Phase Simulation

**Probe Separation and Capacity Test

Table 8

HR21(S)-1 Wet Stand Capacity

Room Temperature Stand

	S/N	Ah In	Days on Stand	Ah Out
A	39R	31.4	3	30.9
A	44R	29.9	3	28.7
A	27	30.3	190	27.0
A	34	31.3	190	28.2
A	35	30.2	190	27.3
B	57R	31.6	4	29.4
B	60R	32.3	4	30.8
B	49	31.9	160	28.0
B	50	32.1	160	29.0
B	52	32.0	160	28.7
C	76R	31.2	14	30.0
C	77R	31.2	14	29.4
C	78	31.2	117	28.6
C	79	30.9	117	28.5
C	80	30.8	117	27.9

Large Probe Battery

S/N	Ah In	Days on Stand	Ah Out
28	30.8	175	28.7
29	31.1	↑	28.7
30	31.2		29.3
31	31.4		28.5
32	31.2		27.9
33	31.0	Sub-Zero	29.2
36	30.6	Storage	28.8
37	30.8	(148 Days)	28.7
38	31.1		28.9
40	30.9		28.2
41	31.2		28.6
42	30.8	↓	28.8
43	30.7	175	28.5

Bus Battery

S/N	Ah In*	Days on Stand	Ah Out**
45	30.8	172	28.6
46	31.2	↑	29.2
47	31.8		29.6
48	32.0		29.9
51	32.1		29.9
53	31.3	Charge/Float	29.2
54	31.2	at Room Temperature	29.3
55	31.5	(143 Days)	29.5
56	31.9		29.7
58	31.9		29.7
59	32.1		29.8
61	31.6	↓	29.4
62	30.8	172	28.6

A - Extra (Large Probe Battery) Cells

B - Extra (Bus Battery) Cells

C - Extra (Periodic Cycling Battery) Cells

R - Reference Cells

*Prior to Launch Phase Simulation

**Probe Separation and Capacity Test

Table 9

Average Charge Efficiencies

HR5(S)-1				HR21(S)-1			
Group	Days on Stand	Eff. (%)	Loss (%)	Group	Days on Stand	Eff. (%)	Loss (%)
A	3 115 190	94.5* 89.0 84.6	— 5.5 9.9	A	3 190	97.2* 90.0	— 7.2
B	4 160	94.0** 84.6	— 9.4	B	4 160	94.1** 89.3	— 4.8
C	14 117	93.3*** 86.7	— 6.6	C	14 117	95.2*** 91.5	— 3.7
Small Probe	175	90.6	3.9	Large Probe	175	93.1	4.1
Bus	172	91.8	2.2	Bus	172	93.2	0.9

*(Small Probe Battery) Reference Cells
**(Bus Battery) Reference Cells
***(Periodic Cycling Battery) Reference Cells

*(Large Probe Battery) Reference Cells
**(Bus Battery) Reference Cells
***(Periodic Cycling Battery) Reference Cells

H. Examination of Electrodes and Cellophane Separators

H1. Electrodes (Visual)—One reference cell and one test cell for each storage period listed under Room Temperature Stand (Groups A, B, C) in Tables 7 and 8 were dissected at the conclusion of the electrical tests. Several cells from each one of the six batteries were also dissected after being discharged to 1.00 volt.*

The silver electrodes in the reference cells had a small trace of AgO on the top edges. The cells which had been on charge stand for 117 to 190 days had traces of AgO on the entire surface area. The amount of AgO increased with storage time.

The 5 Ah electrodes (Figure 11) and 21 Ah electrodes (Figure 12) from the cells in the test batteries showed a substantial variation in the quantity and pattern of AgO which was directly related to the "state of charge" and environmental temperatures.

The Ag electrodes in the 21 Ah cells which had been periodically charge/discharge cycled had a heavy concentration of AgO at the top edges. The pattern was similar to the severe change in the shape of active zinc material in the top of negative electrodes.

The 5 Ah cell (S/N 33) that had been on charge stand for 14 weeks and then was included in the periodic cycle test also had a heavy concentration of AgO on the top edges of the silver electrodes. S/N 68 which had been cycled immediately after "formation" had a slight trace of AgO on the top edges of the electrodes.

The silver electrodes in the cells from the probe batteries stored at sub-zero temperatures had slight traces of AgO on the entire surface area. The greatest amount of AgO was on the electrodes from the Bus Battery cells which had been on charge/float.

H2. Cellophane Separators (Visual)—Each pair of Ag electrodes in the HR5 cells was covered with one wrap of woven nylon. The HR21 cells had one wrap of non-woven nylon on each pair of Ag electrodes. Both designs had four wraps of cellophane on each pair of Ag electrodes. Visual examination of the cellophane separators showed a substantial variation of silver migration for the various test conditions. The penetration of silver migration through the four wraps of cellophane were as follows:

---

*The corners of some electrodes were damaged while removing the Epoxy which incapsulated the electrode leads soldered to the terminal posts.

(a) Heavy concentration through the first inner wrap and some buildup on second wrap in the cells stored in a "discharged" condition at sub-zero temperatures (S/N 39, Figures 13, 17).

(b) Cells which were stored "charged" at sub-zero temperatures (Probe Batteries) had a heavier deposit of silver on the second inner wrap as compared to the discharged cells (Figures 13, 17).

(c) All the cells stored "discharged" at room temperature had a heavy penetration through the first wrap and some migration through the second wrap, whereas all the cells stored "charged" had a heavy penetration through the two inner wraps and some penetration through the third and fourth wraps which increased with the increase in storage time (Figures 14, 15, 18, 19).

(d) All the cells which were cycled immediately after "formation" had a heavy penetration through the first wrap and some migration through the second wrap whereas the 5 Ah cell (S/N 33) which had been stored charged for 14 weeks prior to cycling, had silver migration through the third wrap. Silver migration in these cells did not appear to be as severe as in the cells stored "charged" at room temperature (Figures 15, 16, 19).

(e) Cells which were on a "charge/float" at room temperature (Bus batteries) had a heavy penetration through two wraps and some penetration (S/N 50, Figure 14) or deposit (S/N 53, Figure 18) on the third wrap.

(f) The cells in the Probe Batteries (Figures 13, 17) had a heavy penetration through the first wrap, the cells in the Periodic Cycling tests (Figures 15, 19) had silver migration through the second wrap and the Bus Battery cells (Figures 14, 18) had the greatest penetration of silver, through the third wrap (Figures 16, 20). Silver migrated* up to or through all four wraps in the cells which were stored "charged" at room temperature for the duration of these battery tests.

H3. Cellophane Separators (X-ray Fluorescence)—The cellophane separators (Figures 13-20) were also analyzed by x-ray fluorescence to determine the concentration of silver and zinc for each wrap. A 15 x 25 mm sample was removed from each wrap (near the "U" fold) that covered one of the Ag electrodes.

*Silver migration was determined by examining the "colored" photographs. The white background appears as silver in the third wrap of cellophane in the black and white photographs of the "Probe battery" cells and cells stored at room temperature.

The silver and zinc counts (determined over a period of one minute) were obtained by using a chromium target, Li F crystal and flow proportional counter.

Five measurements were taken for each sample and the counts were averaged. The analyses for all eight layers (2 layers/wrap) were also averaged. The results are listed in Tables 9 and 10. No corrections were made for background noise since it remained the same for all measurements (Ag - 14.3×10^3, Zn = 91×10^3).

Although the visual observations for silver migration were similar to the results obtained in the x-ray fluorescence analyses, selecting the particular test conditions which had the greatest effect upon the silver contents for each wrap of cellophane could only be determined by analyzing the results of Tables 10 and 11. The test conditions which had the greatest effect on the silver content for each wrap (two layers/wrap) were as follows:

a. First inner wrap (layers 1 and 2) (highest silver content, regardless of test condition)

    1. Temperature (appreciably higher at room temperature as compared to sub-zero)

    2. Wet stand

b. Second inner wrap (layers 3 and 4) (significantly lower than first wrap for all test conditions)

    1. Charge stand

    2. Bus battery tests (charge/float)

    3. Battery cycling tests (100% DOD)

    4. Temperature (higher at room temperature)

c. Third inner wrap (5, 6) (significantly less than second wrap for all test conditions)

    1. Charge stand (HR5 cell only)

    2. Bus battery test (HR5 cell only)

d. Fourth wrap (7, 8) (similar silver contents as third wrap, slightly higher than background counts)

    1. Formation cycling (3 charge/discharge cycles and recharge)

Temperature, charge stand and charge/float appear to have had the greatest effect on silver migration throughout the four wraps of cellophane, whereas discharge stand and charge/discharge cycling had the least effect.

Table 10

Analyses of HR5(S)-1 Cellophane Separators

Test Conditions		Chrg. Stnd.	Dschrg. Stnd.	Small Probe Battery	Chrg. Stnd.	Dschrg. Stnd.	Bus Battery	Chrg. Stnd.	Dschrg. Stnd.	20 Cycles	Chrg. Stnd. 15 Cycles
Temperature		Room	Sub-zero to 65°C	Sub-zero to 65°C	Room	Room	Room	Room	Room	Room	Room
Days		190	190	175	160	160	168	117	117	85	115
S/N		27	39	35	54	60	50	78	76	68	33
Silver (Ag) — Average Counts per Minute x 10^3 (5 Measurements/Layer)											
Layers (2 Layers/Wrap)	1-2	68	63	71	80	87	89	64	73	75	63
	3-4	53	18	20	55	19	58	47	26	41	51
	5-6	28	16	17	22	16	20	19	16	17	26
	7-8	18	18	19	17	16	16	16	17	16	22
Zinc (Zn) — Average Counts per Minute x 10^3 (5 Measurements/Layer)											
Layers (2 Layers/Wrap)	1-2	275	354	379	265	187	250	297	230	238	247
	3-4	346	725	710	343	351	233	374	388	285	230
	5-6	349	637	674	482	301	340	345	385	354	250
	7-8	469	95[illegible]	955	613	343	405	406	528	362	399

NOTES: 1. Each Ag electrode has four wraps of cellophane.
2. Area of cellophane sample analyzed was 15 x 25 mm.
3. Ag background = 14.3×10^3.
4. Zn background = 91×10^3.

Table 11

Analyses of HR21(S)-1 Cellophane Separators

Test Conditions			Chrg. Stnd.	Dschrg. Stnd.	Large Probe Battery	Chrg. Stnd.	Dschrg. Stnd.	Bus Battery	Chrg. Stnd.	Dschrg. Stnd.	12 Cycles
Temperature			Room	Sub-zero to 65°C	Sub-zero to 65°C	Room	Room	Room	Room	Room	Room
Days			190	190	175	160	160	168	117	117	57
S/N			27	39	33	49	57	53	78	76	68
Silver (Ag)											
Layers (2 Layers/Wrap)	1-2	Average Counts per Minute x 10^3 (5 Measurements/Layer)	65	40	51	72	89	85	74	77	65
	3-4		50	17	17	57	25	55	45	20	23
	5-6		18	16	16	17	16	18	16	16	16
	7-8		17	17	16	17	16	17	17	16	16
Zinc (Zn)											
Layers (2 Layers/Wrap)	1-2		283	511	449	242	200	228	283	240	221
	3-4		342	590	445	227	402	235	390	381	382
	5-6		553	628	444	409	282	433	365	427	395
	7-8		602	745	540	590	317	508	591	515	474

NOTES: 1. Each Ag electrode has four wraps of cellophane.
2. Area of cellophane sample analyzed was 15 x 25 mm.
3. Ag background = 14.3×10^3.
4. Zn background = 91×10^3.

The zinc electrodes are adjacent to the fourth wrap (layers 7 and 8) of cellophane, and therefore the highest concentration of zinc always appeared to be in the outer wrap. The test conditions which had the greatest effect on zinc penetration of the cellophane separator system was as follows:

a. Fourth wrap (7, 8) (highest zinc counts for all test conditions)

   1. Temperature (discharged cells stored at sub-zero to 65°C and Small probe cell)

   2. Wet stand

b. Third wrap (5, 6) (less concentration than outer wrap for all test conditions)

   1. Temperature (discharged cells stored at sub-zero to 65°C and Small probe cell)

   2. Wet stand

c. Second wrap (3, 4) (some samples had a higher concentration and others had a lower concentration in comparison to the third wrap)

   1. Temperature (discharge stand at sub-zero to 65°C, Small and Large probe cells)

   2. Wet stand (cell stored discharged at room temperature)

d. First wrap (1, 2) (concentrations varied between samples as compared to the second wrap)

   1. Temperature (sub-zero to 65°C)

   2. Wet stand

The two HR5 and one HR21 cells which were analyzed from the periodic cycle test showed a gradual decrease in zinc concentration from the outer wrap to the inner wrap whereas zinc concentration appeared to randomly vary for the other test modes. Although there was a substantial loss of active zinc material in the negative electrodes of the cells which had been periodically cycled (12, 15, 20 cycles), the ionic diffusion through the cellophane separator system did not appear to be significantly greater than the diffusion resulting from the other test conditions.

CONCLUSIONS

The 5 ampere-hour battery for the Bus vehicle is capable of supplying electric power for one hour prior to launch and 90 minutes after launch when the solar array is shadowed from the sun. The battery can be maintained at its maximum capacity level without causing severe pressure buildup within the sealed cells by "charge/floating" the battery. The battery will also deliver the 27 ampere pulses required for simultaneously separating the three Small probes from the Bus vehicle.

The 5 ampere-hour Small probe battery and 21 ampere-hour Large probe battery were not adversely affected by the -55°C to 65°C "proto-type" thermal profile simulated during the 158 day program. Cell pressures in both batteries were less than 1.5 atmospheres. The Small probe battery was capable of delivering 4.2 ampere-hours during the simulated mission profile and each cell delivered an additional 3.8 ampere-hours or greater when they were discharged to 1.00 volt at the conclusion of the test. The cells in the Large probe battery delivered 28.6 to 29.7 ampere-hours, of which 23.2 ah was removed during the simulated mission profile.

Both cell designs were periodically charge/discharge (100% depth) cycled during a 3-month period. The 5 Ah cells were capable of delivering 7.1 to 7.5 ampere-hours at the end of 20 cycles as compared to 7.7 to 8.8 ah during the first cycle. The larger cells delivered 19.3 to 20.6 ampere-hours at the end of only 12 cycles as compared to 28.3 to 31.0 ah during the first cycle. The average cell capacity degraded 33 percent for the larger cells as compared to 14 percent for the 5 Ah cells. A record should be maintained for each battery used for the various "sub-system" and "spacecraft integration" tests. The record should list the dates of activation, formation cycles and various charge/discharge cycles performed during the spacecraft tests. The ampere-hour inputs and outputs should also be listed in order to establish the usable capacity in the test batteries.

The high "g" acceleration tests performed at the "flight" level (QEEL/C 72-274) and "prototype" level (X761-73-56) and this battery performance study have qualified both battery designs for the Venus multi-probe mission described in the GSFC "Phase A" report of May 1971.

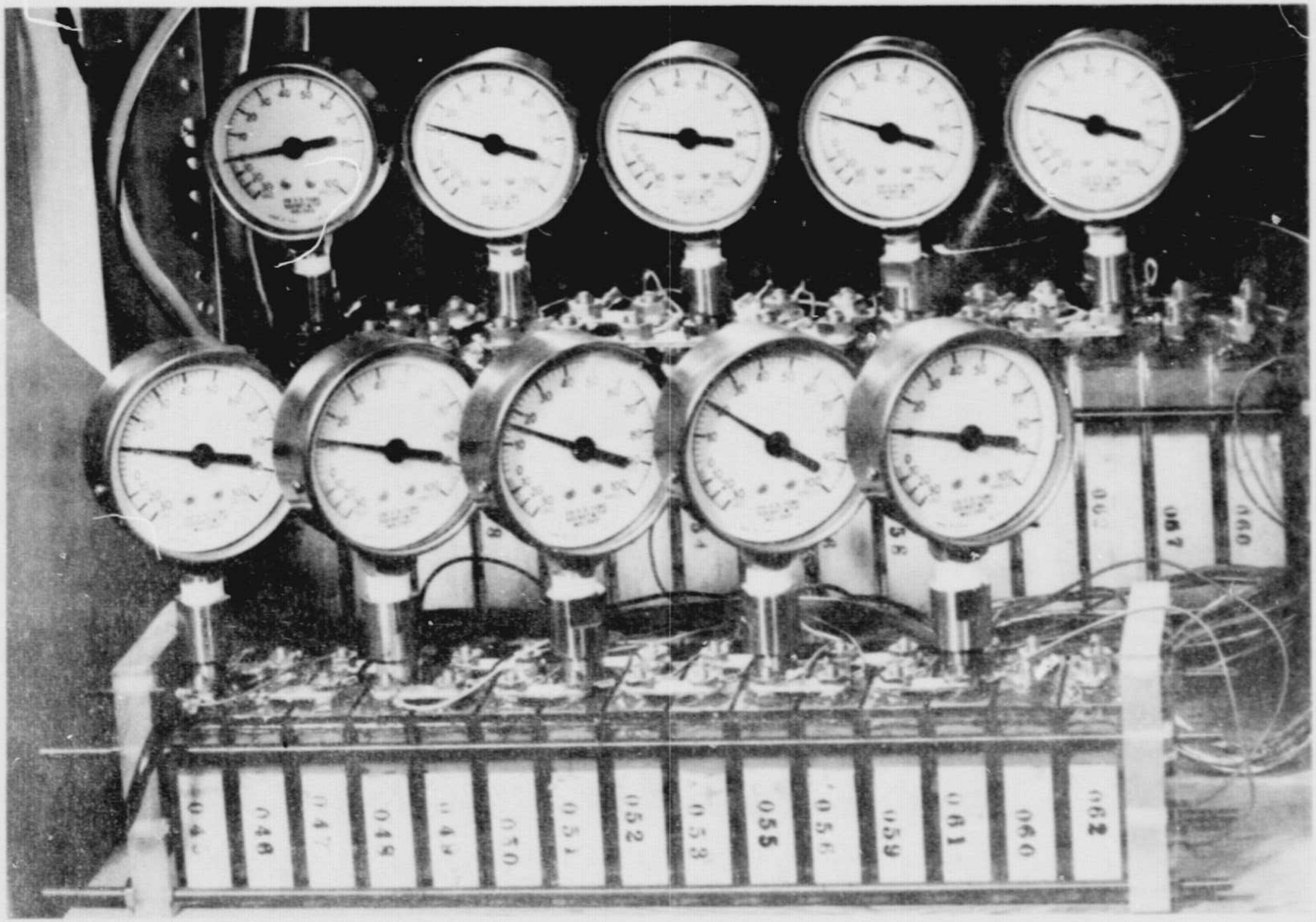


Figure 10. 5 Ah and 21 Ah Bus Batteries

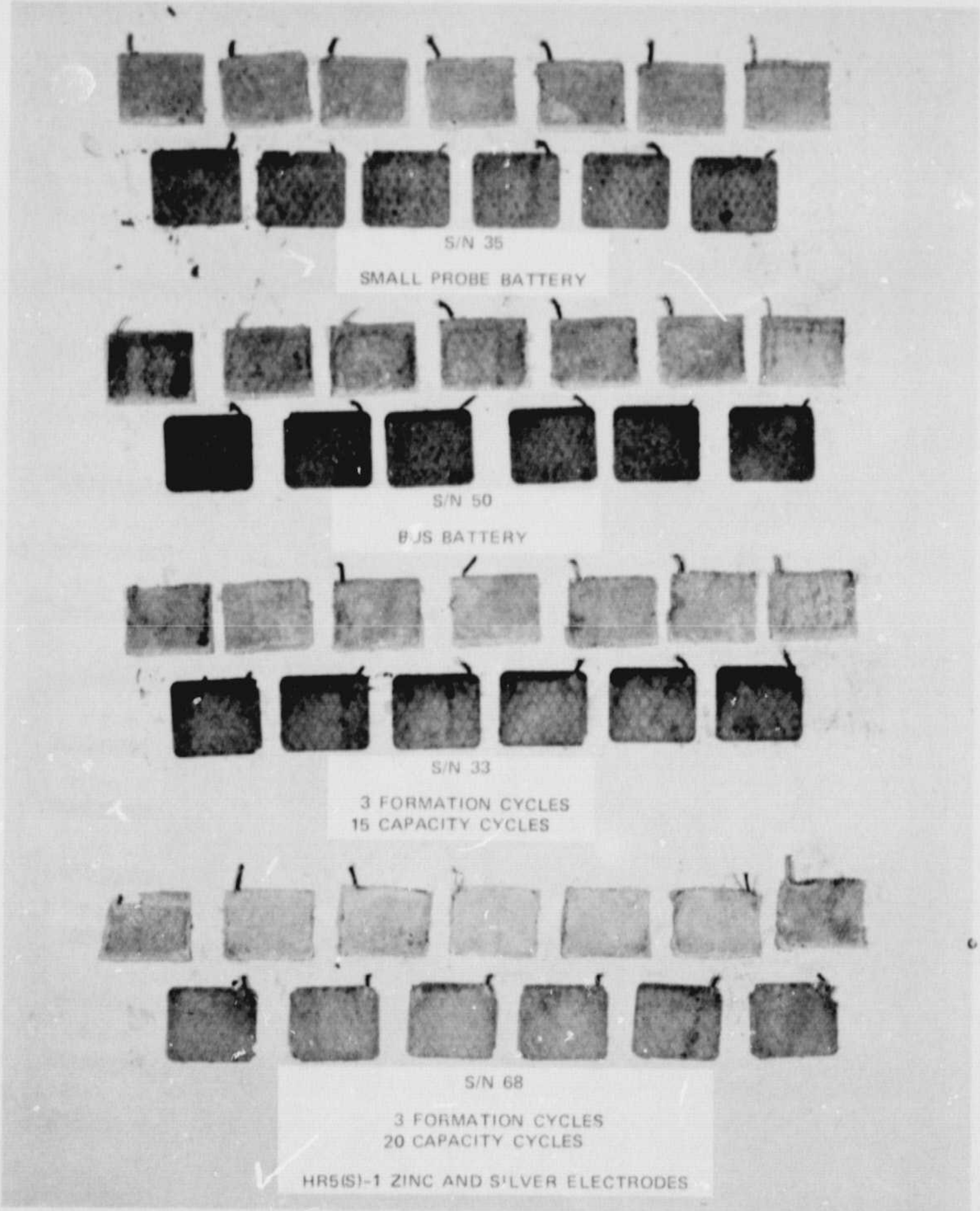


Figure 11. Five Ampere-Hour Ag and Zn Electrodes

Figure 12. Twenty-one Ampere-Hour Ag and Zn Electrodes

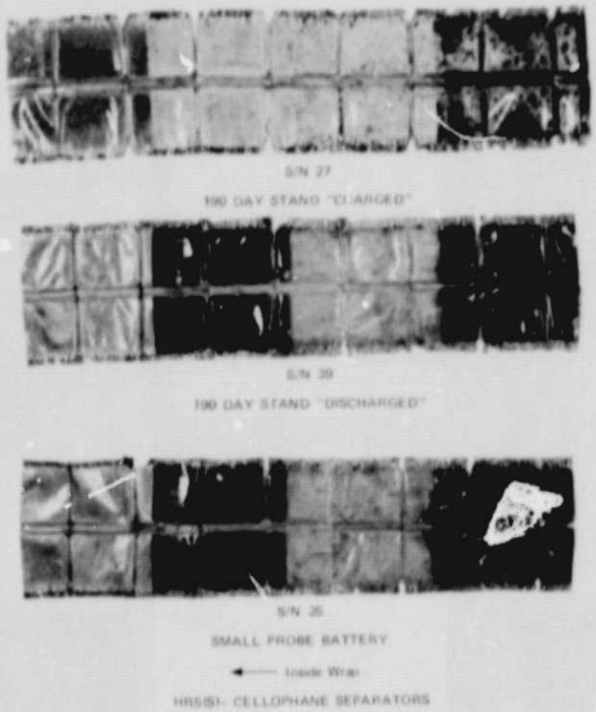


Figure 13. Ag Migration of 5 Ah Small Probe Battery Study

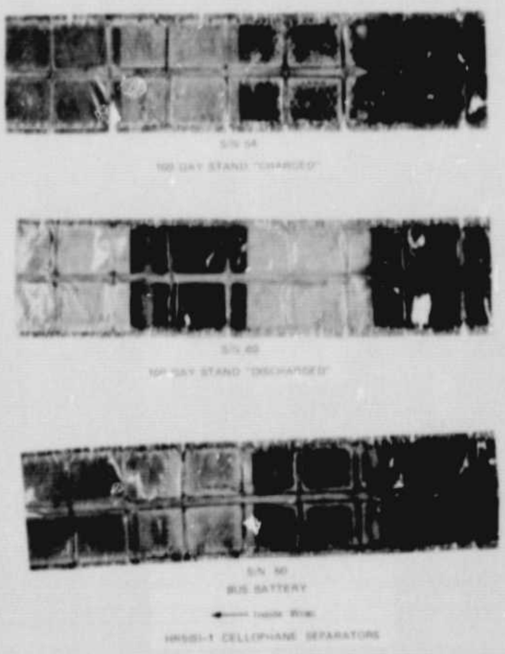


Figure 14. Ag Migration of 5 Ah Bus Battery Study

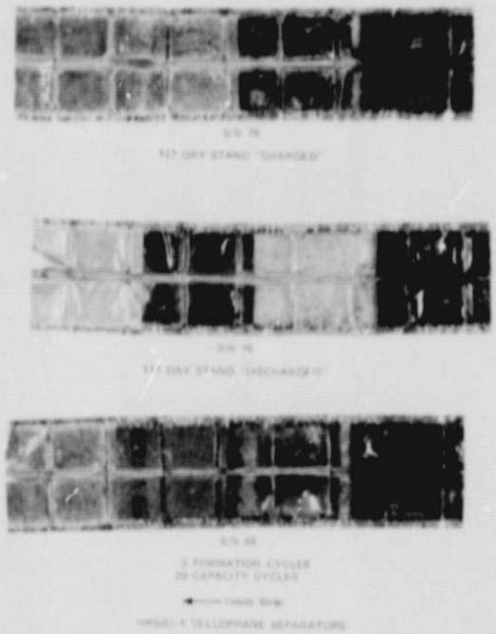


Figure 15. Ag Migration of 5 Ah Periodic Battery Cycling Study

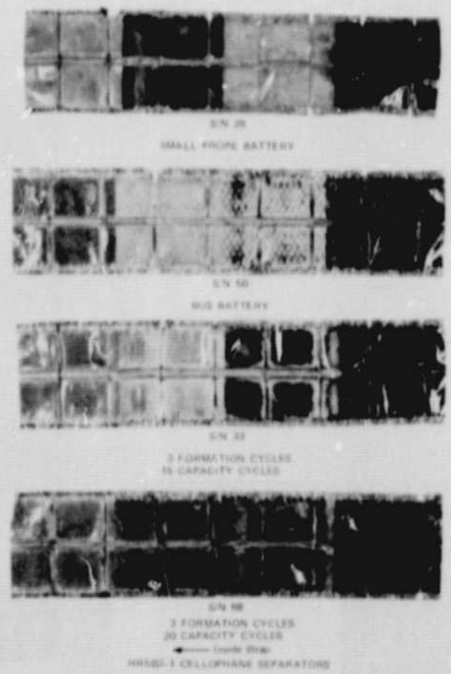


Figure 16. Ag Migration of the Three 5 Ah Battery Studies

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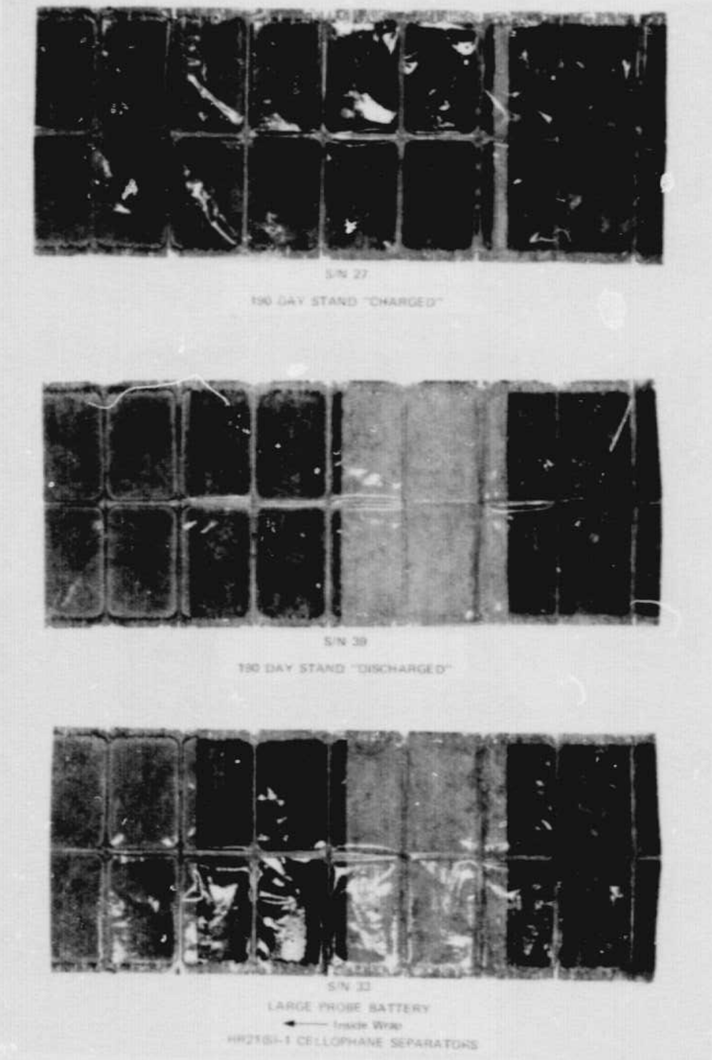

Figure 17. Ag Migration of 21 Ah Large Probe Battery Study

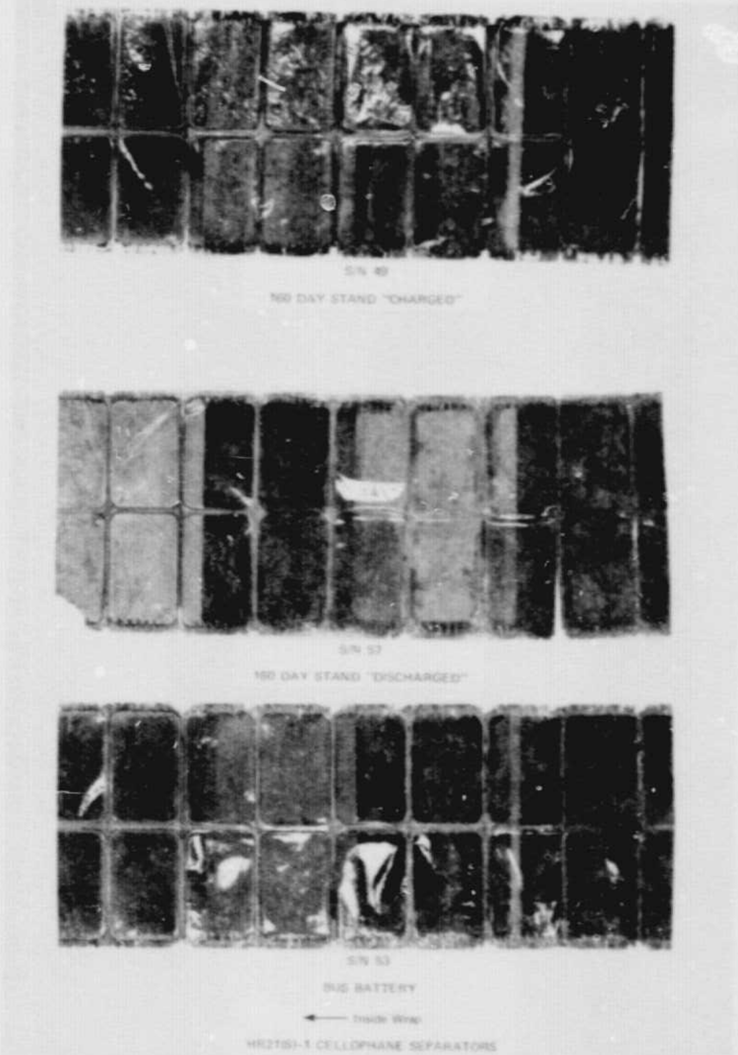

Figure 18. Ag Migration of 21 Ah Bus Battery Study

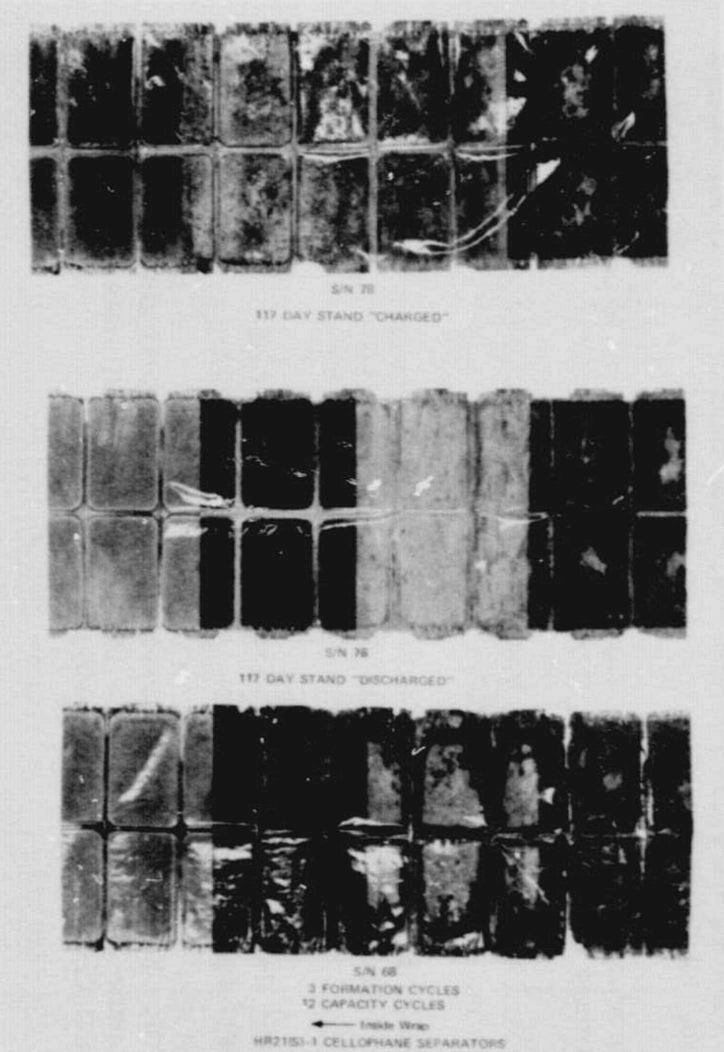

Figure 19. Ag Migration of 21 Ah Periodic Battery Cycling Study

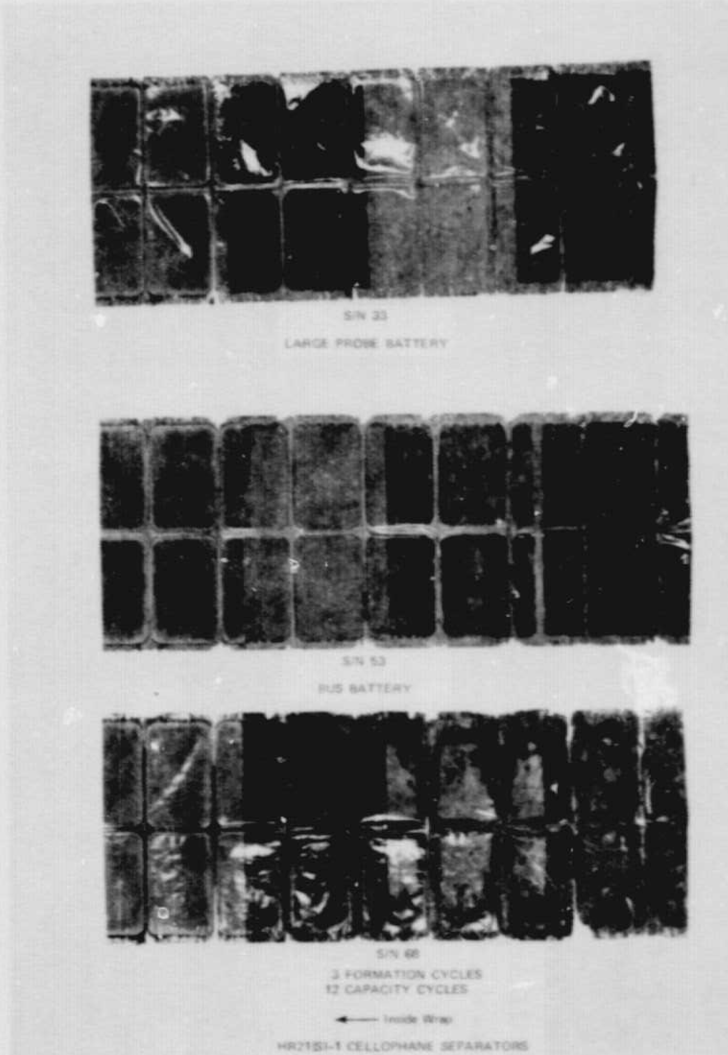

Figure 20. Ag Migration of the Three 21 Ah Battery Studies

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