SAE TECHNICAL PAPER SERIES

1999-01-1998

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The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

29th International Conference on Environmental Systems
Denver, Colorado
July 12-15, 1999

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

95-1826

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ABSTRACT

The Extravehicular Mobility Unit (EMU) used by astronauts during space walks is powered by an 11-cell, silver-zinc battery. The present battery is certified for 6 cycles with a minimum discharge requirement of 7 hours above 16.0 volts at a 3.8 Amp load. Its certified wet-life is 170 days. Operational requirements for the International Space Station (ISS) led to a design capable of 32 cycles over a 425 day wet-life. Other battery parameters including capacity, rate capability, weight, volume, safety and the need for continuing compatibility with the EMU and the Space Shuttle charger dictate that the new battery will also be silver-zinc.

INTRODUCTION

BACKGROUND. The space suit or Extravehicular Mobility Unit (EMU) worn by astronauts to perform space walks is powered by an 11-cell silver-zinc battery (Figure 1). The battery is located in the lower back portion of the Primary Life Support Subsystem (PLSS) as shown in Figure 2. The battery provides all the power for the Fan/Pump/Separator Assembly, which circulates oxygen and water through the EMU. It also powers the Display and Controls Module, the Caution and Warning System and the radio. The present battery has been in use with only minor design modifications for the entire 18 year history of the Space Shuttle Program. Despite changes to the Shuttle operating schedule, increases in nominal discharge requirements and space walks lasting up to 25% longer than the maximum design requirement, the battery has performed admirably. No Extravehicular Activity (EVA) has ever been cancelled or cut short because of a battery problem.

Figure 1. EMU Increased Capability Battery

The original requirements for the battery included supporting a 7-hour EVA with a nominal discharge rate of 3.5 Amps for a capacity of 24.5 AH (AH). The minimum voltage requirement was 16.0 volts. Weight and volume of the battery were critical requirements. Although the astronaut and the EMU are “weightless” in space, they still have mass and inertia. Minimizing weight and volume, as well as controlling the center of gravity of the suit was critical to maintaining astronauts' mobility and capacity to perform useful work in space. For this reason a high energy density battery was required. Because multiple EVA’s per mission were anticipated, including unscheduled contingency EVA’s, a rechargeable battery was essential to avoid the weight and volume penalties associated with manifesting multiple sets of batteries.

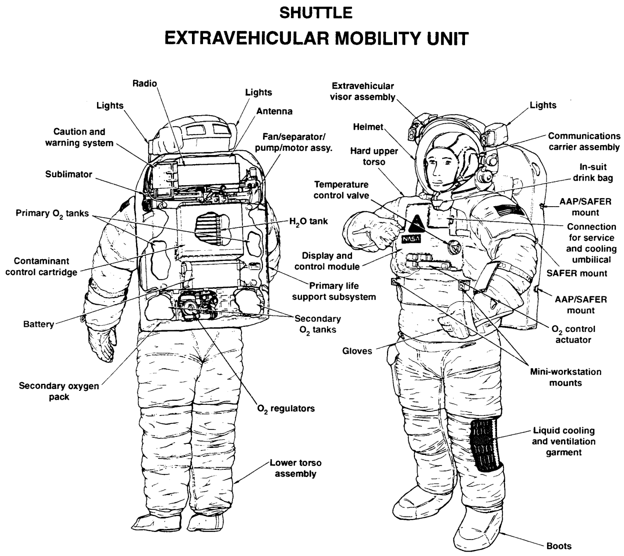

Figure 2. Extravehicular Mobility Unit

The original operating scenario for the Shuttle called for launches approximately once every two weeks and EVA's on almost every flight. Since a high rate of EVA's was anticipated, the very high energy density of the silver-zinc (Ag-Zn) battery outweighed its relatively short wet-life in the selection process. The battery was designed for 12 charge/discharge cycles with a wet-life of 90 days. The cost of the battery per EVA was expected to be low.

As the Shuttle program evolved, the mission scenario changed. The number of Shuttle flights per year was reduced to seven or eight and until recently, EVA's were rare. This situation caused many batteries to exceed their certified wet-life without ever having been used in flight. Changes in the EMU also produced changes to battery usage. At present, the nominal discharge current is 3.8 Amps resulting in a minimum capacity requirement of 26.6 AH for a seven hour EVA.

Since none of the batteries were exceeding their certified cycle life, the battery was recertified several times to extend the wet-life while reducing the cycle life through a combination of test and statistical analysis of existing data. This was accomplished without actually changing the design of the battery itself. The battery presently flying is essentially the same one which first flew 18 years ago, but it is now certified for six charge/discharge cycles and a 170 day wet-life.

INTERNATIONAL SPACE STATION – The International Space Station (ISS) currently under construction will be one of the most complicated assembly projects ever attempted. Certainly it will be the most complicated task ever performed in space. Building and maintaining the ISS will involve more EVA's than have been performed previously by all nations in the 35 year history of space flight. It will involve 128 2-person EVA's, including those performed by Russian cosmonauts in NASA EMU's. This tremendous increase in space walks has come to be known as the "Wall of EVA's" and is illustrated in Figure 3.

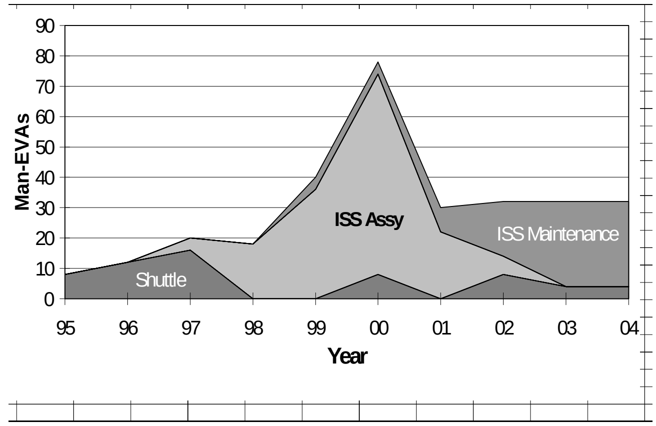

Figure 3. The "Wall of EVA's" required for the ISS

In addition to supporting many more EVA's than previously, batteries to be used on ISS have an additional requirement. The short wet-life of the present Ag-Zn Battery has not been a concern for NASA other than the cost of replacing them, since the longest Shuttle mission to date has been 16 days. Batteries left on board the ISS will need to have a considerably longer wet-life to support even the minimum logistics requirements of the ISS. The minimum wet-life required to support EVA's originating on board the ISS is 240 days, including a potential "skip cycle", a period when the Shuttle might be grounded for some reason. That duration is derived from Table 1, shown below.

Table 1. ISS Minimum Battery Wet-Life Requirement

	Days
Battery Formation/Launch Preparation	30
Launch Delay	30
Nominal Resupply Schedule	90
Skip Cycle	90
Total	**240**

This represents a 40% increase in wet-life above the duration presently certified. Moreover, since the cycle life of a battery is now likely to be exceeded during a supply cycle, several sets of batteries would be required even if their wet-life could be extended to 240 days.

In addition to the cost of the extra batteries, the logistics cost of getting them to the ISS must also be considered. The cost of launching a pound of payload into low earth orbit is variously quoted as $9000 to $12,000. Since the present battery weighs approximately 10 pounds, taking even one extra battery to the ISS would cost up to $120,000 just for transportation. The space needed to store extra batteries on orbit would also have a cost associated with it and would displace scientific experiments or some other essential piece of equipment. Clearly a new battery is required.

The new battery will maintain the same requirements for high energy density and rechargeability as the present battery. The safety of the battery is, of course, a prerequisite. The Ag-Zn battery currently in use has demonstrated its safety and reliability throughout the Shuttle Program, now totaling almost 100 flights. A similar Ag-Zn battery was used for the Apollo moon landings. An alternative chemistry battery would have to be at least as safe as the flight proven Ag-Zn design. Capacity and rate capability would have to be the same or better. Finally, the battery would have to be compatible with the operating characteristics of the EMU and the Shuttle Air Lock Power Supply as well as the ISS Battery Charger Assembly and be transparent in use to the crew.

BATTERY OPTIONS – Prior to beginning the development of the new battery, a survey of battery chemistries and new developments was undertaken to evaluate alternatives to Ag-Zn. A number of technologies were evaluated, including the following:

- Nickel - Metal Hydride (Ni-MH)
- Silver - Metal Hydride (Ag-MH)
- Nickel - Cadmium (Ni-Cd)
- Lithium -Cobalt Oxide (Li-CoO)
- Lithium - Titanium Disulfide (Li- TiS_2)
- Lithium-Ion (Li-Ion) batteries

Each of the alternatives had favorable and unfavorable characteristics which are discussed below.

1. Ni-MH and Ni-Cd batteries are noted for performing hundreds of cycles and having wet-lives measured in years. However, their energy densities fall significantly short of Ag-Zn and their individual cell voltages are lower. The lower cell voltage would have required at least three additional cells per battery, resulting in a further decrease in energy density due to additional cell cases, terminals and connectors. Both Ni-MH and Ni-Cd suffer from rapid self discharge, requiring that they be maintained on trickle charge if they are to be ready for EVA on short notice.
2. Ag-MH should have an energy density close to that of Ag-Zn, but has received little development effort, because of its cost and limited market potential. Its lower cell voltage could be compensated by a much lower rate of capacity loss per cycle than Ag-Zn; however, in practice, the expected capabilities have not been demonstrated with any degree of reliability.
3. The Li-CoO, Li-TiS_2 and Li-Ion chemistries are theoretically capable of exceeding the energy density of Ag-Zn, but they are relatively new developments and have several limitations that prevent their use in an EMU battery. Not the least of these is safety. Batteries containing Lithium metal, such as the Li-CoO and Li-TiS_2 designs, are capable of failing explosively. Although Li-Ion cells are not fabricated with lithium metal, it is necessary to control each cell individually in order to prevent lithium metal from forming during recharge. At the time this survey was conducted, Li-Ion cells were being produced commercially only in the AA size. An EMU battery would have needed hundreds of cells and each of those cells would have required its own charge controller.

When all of the above issues were considered, as well as the desire to minimize the cost and risk of development, it became clear that the best choice for an increased capability EMU battery was an improved and slightly larger Ag-Zn design.

SPACE STATION REQUIREMENTS – Once the decision was made to continue with a Ag-Zn battery, several design goals were set to optimize the battery for use on the ISS. There had been discussion of increasing the end of life capacity of the battery to support the power draw of additional electrical devices which might be added to the EMU at a later date. However, no formal requirements for new devices had been defined. The other potential reason for increasing the capacity of the battery was to be able to perform longer EVA's. However, this would have required increasing the supply of expendables (e.g., oxygen and water) to support a longer EVA. In the end, a decision was made not to increase the capacity requirement of the battery. Should the battery be called upon in the future to provide additional capacity, it will be able to do so, but for a reduced number of cycles.

OPTIMIZING BATTERY CYCLE AND WET-LIFE – A 240 day wet-life was set as an absolute minimum for the battery, but the high logistics cost of replacing batteries on the ISS dictated that the longest practical wet-life was desired. It is only reasonable that the battery be capable of supporting all of the EVA's anticipated during that wet-life. The resupply schedule calls for a Shuttle flight to the ISS once every 90 days. The wet-life of the battery would, therefore, have to increase in increments of 90 days beyond the minimum 240 days.

At the time, the design goals for the battery were being set, it was anticipated that up to 32 2-person EVA's would be conducted from the ISS each year spaced at relatively uniform intervals. Therefore, each 90 day resupply cycle for the ISS was assumed to be associated with eight EVA's. After evaluating a performance map that traded cycles against wet-life, a decision was made to set a design goal of being able to support 3, 90-day supply periods, plus a potential 90-day skip cycle (essentially a full, 365-day year) and the normal 60-day activation and launch/delay schedules. Since the battery could be on the ISS for up to a year, the design goal for cycle life was intended to support a minimum of 32 EVA's. If the battery were returned to Earth on schedule, it would still have plenty of cycle and wet-life to support one or more Shuttle missions.

The final design goals were derived from EMU requirements. It was possible to enlarge the battery, because the decision had been made that the Manned Maneuvering Unit (MMU) would not be flown again. The MMU mounted over the back of the PLSS and the width of the battery was limited by interference with the MMU. Once this potential interference was eliminated from consideration, the width of the battery was permitted to grow by 0.9 in.. This increase in width equated to approximately 34% more volume for the battery. Shorter relief valves are utilized for the new battery, permitting an 0.20 in. increase in height of the cell cases. This extra height is used to increase the head space (void volume) in the cell cases and is not filled with additional active material. The additional void volume helps to reduce the pressure build up in the cells from gas generation and minimizes the potential for cell venting. The envelope height of the complete battery was not increased. The weight of the battery is limited by the ability of the latching mechanisms in the PLSS to support it during 9g crash loads. The maximum weight permissible was calculated to be 18 pounds; the new battery comes in 3.5 pounds below that. The dimensions of the cell blocks for the old and new batteries are below:

	W	L	H
• Old Cell Block	2.64”	x 9.09”	x 4.00”
• New Cell Block	3.54”	x 9.09”	x 4.20”

Packaging, including an aluminum battery case, electrical connector, potting and latch pin, produces a final battery envelope of approximately 3.9” x 11.1” x 4.9” as shown in Figure 4. The differences between the present design and the new battery are compared in Table 2.

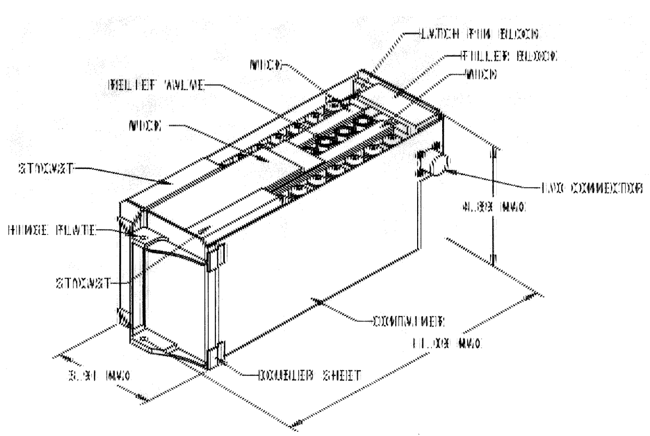

Figure 4. EMU Battery Showing Construction

Table 2. Comparison Between Old and New Battery

	Present Battery	New Battery
Cycles	6	32, min.
Wet-Life, days	170	425, min.
1st Cycle Capacity, AH.	33.5	45.0
End of Life Capacity, AH	26.6	26.6
Weight, lbs.	9.9	14.5

CELL DESIGN AND DEVELOPMENT TESTING

The Ag-Zn cells were designed to provide a minimum of 26.6 AH at the end of life. Although the operational capacity requirement remained the same from the present battery to the new, Increased Capability Battery, the degradation of battery capacity with cycling is such that the cells were designed with an initial capacity of approximately 45 AH. This compares to the 33.5 AH available on the first cycle with the present battery.

Prototype cells were first tested in available cell cases that differed dimensionally from the eventual flight configuration. The current during discharge was increased slightly to compensate for a larger cross-sectional area by adjusting the current density (Amps/ cm^2) to that expected in the final design. The internal volume was adjusted to that of the flight configuration by means of spacers.

CYCLE TESTING – Rapid cycle testing of the prototype cell design was extremely promising. Five cells were tested in 7 hour discharges intended to simulate a nominal EVA. The first of the five cells failed after achieving 71 cycles above the cut-off voltage (1.454 V/ cell) as shown in Figure 5. The remaining four cells all failed due to insufficient capacity within the next five cycles. This test demonstrated that the design provided more than adequate volume for the active materials and separator necessary to reliably achieve the goal of 32 cycles. Importantly, none of the cells failed due to shorts through the separator.

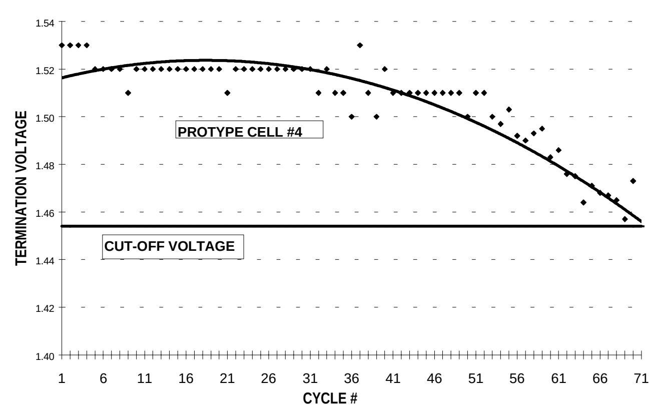

Figure 5. Prototype Cell First Failure at Cycle 71

Next, 18 cells were fabricated as a batch lot and tested in the appropriate configuration. They were tested in nine sets of two, series connected cells to evaluate different aspects of performance and also to check the uniformity of performance of the cells. It is important for the cells in a battery to be well matched to avoid the risk of a weak cell in a battery being driven into reverse by the other cells in the series. The average voltage of the two cells at cut-off was graphed to produce the curve seen in Figure 6. The cells were considered to have failed when the average voltage at the end of 7 hours dropped below

1.454 V/cell, the equivalent of 16.0 volts in an 11-cell battery. The first set, Group A, was rapid cycled with a 3.8 Amps discharge for 7 hours/cycle (26.6 AH). These cells achieved 48 cycles, well above the 32 cycle minimum.

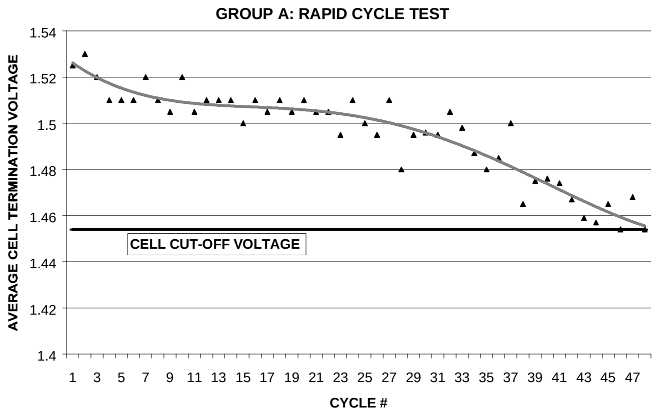

Figure 6. Group A: Rapid Cycle Test

The second set of cells, Group B, were tested at 100% Depth of Discharge (DOD). For purposes of the EMU Battery, 100% DOD means that the cells were discharged on each cycle until the average cell voltage dropped to 1.454 volts. The last full discharge would, therefore, produce at least the minimum required 26.6 AH capacity, while all previous cycles would be greater than 26.6 AH. In the past, the EMU Battery has been tested to 100% DOD as the simplest measure of capacity and to indicate the longest duration for which an EVA could be supported. With the new battery, however, the capacity early in life is equivalent to a 12 to 13 hour EVA at nominal conditions. Since this is far greater than would be permitted by other expendables, the 100% DOD test is not really relevant for evaluating the ability to support EVA's with the EMU as presently configured. It also accelerates the degradation of the battery separator unnecessarily. 100% DOD does provide a clear measure for comparison to the existing test database. It is also an indicator of the degree to which a "growth version" of the EMU or additional electrical hardware can be supported. Figure 7 shows the capacity of the new battery plotted versus cycle number. The graph shows that these two cells achieved almost 50 AH capacity on the second cycle and did not drop to the minimum 26.6 AH capacity until the 39th cycle. Even when tested at 100% DOD, the design was capable of exceeding the 32 cycle minimum. The capability of the battery to support additional loads is even greater than this test might indicate. Although 3.8 Amps is the nominal load used for test purposes, that figure already includes a safety margin. The current drain during actual EVA's is typically in the range of 3.3 to 3.4 Amps. Figure 8 shows the additional capacity available in the battery if the discharge current is assumed to be a more realistic 3.4 Amps. The capacity in Amp-hours is shown on the right side of the y-axis. The vertical bars illustrate the number of hours of EVA that could be supported, as measured against the left side of the y-axis. The light colored bars represent a 3.4 amp load and the dark bars represent the 3.8 Amp nominal load. Early in life, it might be possible to perform back-to-back 7-hour EVA's without recharging the battery if it became necessary to do so. The graph could also be used to determine the ability of the battery to operate a power tool with a higher current drain than the EMU.

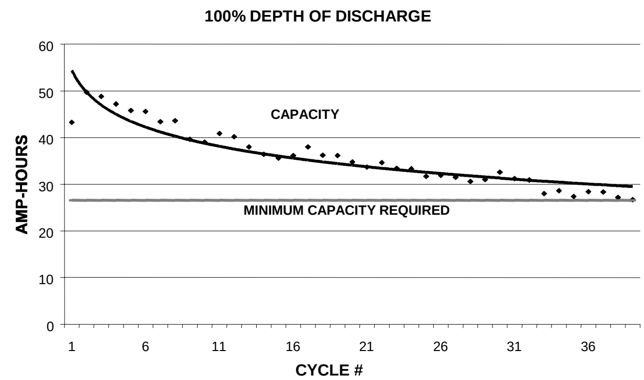

Figure 7. 100% Depth of Discharge Test

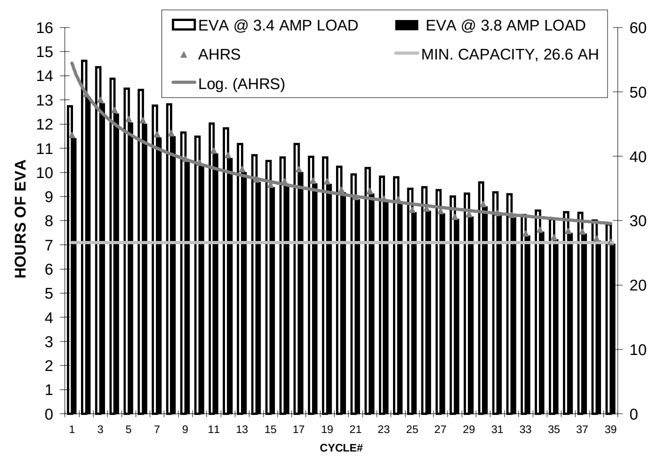

Figure 8. Capacity Margin for new EMU Battery

WET-LIFE PERFORMANCE – While the rapid cycle testing of the battery has always resulted in far more cycles than the design goal, the second design iteration demonstrated a problem in achieving the desired wet-life. Groups C, D and E were cycled approximately once every two weeks after varying initial stand times to simulate possible mission scenarios (activate and launch, launch delay, Space Station spares). In each case the cells were left on charged stand between cycles. Although charged stand is known to be deleterious to the performance and life of the battery, it has always been the normal practice because of the Shuttle operational requirement to be ready to perform a contingency EVA on short notice. Charged stand will be a requirement for at least some of the batteries to be kept on Space Station.

Groups C, D and E were able to perform only 17 to 26 cycles over wet-lives of 355 to 383 days (Figure 9). In each case failure was caused by low capacity above the cut-off voltage. There were no indications of separator failure. Dissection and analysis of the cell data indicated the problems were related to the zinc electrode. In addition to the expected shape change of the zinc electrode, there appeared to be problems with adhesion of the zinc to the current collector resulting in inefficient utilization of the zinc that was available as well as increased internal resistance. Furthermore, it became apparent that the change from the prototype cell configuration to the flight-like cell configuration had permitted process changes to occur that resulted in decreases in the weight and density of the zinc electrode.

As a result of the above problem analysis, several changes were made. The number of perforations in the current collector was increased to ensure adequate adhesion of the two zinc plates that are pressed together on opposite sides of the current collector to form the zinc electrode. The improved adhesion should, in turn, provide better contact to the current collector, better zinc utilization and reduced internal resistance. The manufacturing process was revised to increase the amount of zinc by approximately 11% and the density of the zinc by almost 9% in order to achieve adequate capacity at the end of life.

Another iteration of cells were assembled and activated. The rapidly cycled cells improved over their previous excellent performance. Group J completed 59 cycles above the minimum cut-off voltage. Group K was rapidly cycled at 100 % DOD and achieved 45 cycles with greater than 26.6 AH capacity. Despite the outstanding performance of the rapidly cycled cells, the wet-life cells were once again disappointing. It became obvious early in the test program that the wet-life cells were not going to achieve their design goal. Group L eventually completed 16 cycles in 185 days, worse performance than the previous iteration.

Dissection and analysis of the cell components indicated that once again the problem was in the zinc electrode. There were no problems with the separator and testing of the silver electrode demonstrated more than adequate capacity. Sections of the zinc electrode appeared to be excessively dry. The zinc in the dry sections was approximately the same thickness as when the electrode had been made. It had neither swelled with electrolyte, nor been depleted by cycling. The areas of the electrode where the zinc appeared to be wet, had been severely depleted by cycling, far more than would be expected for the number of cycles performed. It was apparent that only part of each electrode had been involved in the reaction, resulting in a higher current density in those areas, depressed cell voltage and localized depletion of active material. Since the rapidly cycled cells had performed so well, it was felt that the density of the zinc had been increased too much. There was far more zinc than necessary to achieve the design goal cycle life, but increasing its density to the extent of this iteration had made its wettability marginal. During discharge the potassium hydroxide electrolyte is "used up" by the reaction which forms a zincate ion. During the subsequent recharge, the electrolyte is reconstituted into potassium hydroxide solution. The fluxing of the electrolyte in the rapidly cycled cells was evidently enough to keep the zinc electrodes wet. The long stand time between cycles in the wet-life test cells may have permitted the zinc electrodes to partially dry out. Once dry, the dense zinc had little tendency to wick electrolyte.

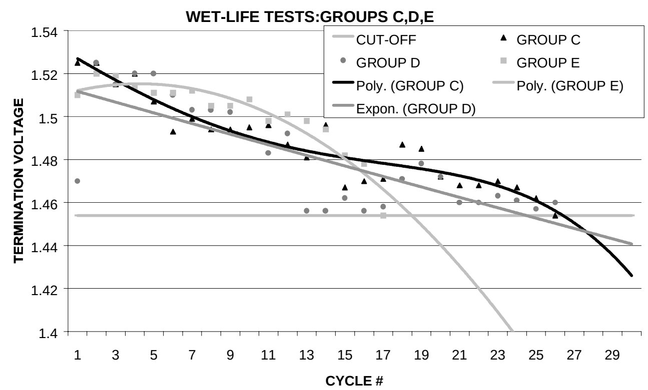

Figure 9. Wet-Life Tests: Groups C, D, E

The solution to this problem was threefold. First, the density of the zinc electrode was reduced to slightly less than that of the baseline first iteration. Second, the amount of zinc was reduced from that of the second iteration, but was still almost 8% more than that of the baseline. Third, the cell activation process was revised. Ag-Zn cells are typically filled with electrolyte and then vacuumed to remove trapped air bubbles and to aid in wetting the electrodes and separators. The activation process was revised to increase the number and duration of the vacuum cycles. The soak time in between evacuations was also increased. These steps were taken to ensure that all areas of the zinc electrodes would be thoroughly wet during activation and would remain wet throughout the life of the cells. Furthermore, the amount of electrolyte added to each cell was increased by 8cc. The changes in the design of the Ag-Zn cells are summarized in the table below.

Table 3. Cell Design Changes

	Group 1	Group 2	Group 3 Certification Battery
Zn Density	B	+ 8.68%	- 1.68%
Zn Weight	B	+ 11.40	+ 7.80%
Zn Thickness	B	+ 1.96%	+ 1.96%
KOH Electrolyte	B	B	+ 7.81%

B = Baseline

CERTIFICATION TESTING – The Group 3 configuration has been incorporated into the Certification Test Batteries. Wet-Life Certification Testing is currently underway with two fully packaged, 11-cell batteries. As of this date, the batteries have completed 21 cycles and 320 days of wet-life. Performance has been excellent and regression analysis trendlines which proved accurate during cell testing indicate that the full scale battery will easily exceed the design goals for cycles and wet-life (Figure 10). The Increased Capability EMU Battery will be able to support EVA's on board the ISS and the Shuttle for the expected lifetimes of those programs.

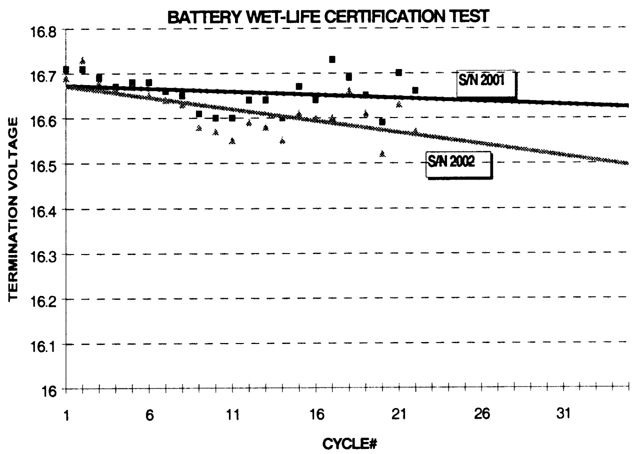

Figure 10. Certification Batteries Wet-Life Tests

CONCLUSIONS

- The Increased Capability EMU Battery will safely support all of NASA's EVA requirements for the International Space Station and the Shuttle Program.
- The Increased Capacity EMU Battery is sized for an on-orbit life of one year and 32 EVA's.
- The reduction in launch weights made possible by the need for fewer batteries will save NASA millions of dollars in logistics and resupply costs over the life of the ISS.
- The high initial capacity of the battery makes it capable of supporting additional electrical equipment or a "growth" version of the EMU by reducing cycle life.
- Making batteries is still an art as much as a science.

ACKNOWLEDGMENTS

- Development of the Increased Capability Battery has been funded by the NASA Johnson Space Center under contracts NAS9-17873 and NAS9-97150.
- Information on the history and changing requirements of the battery was summarized from the "Evolution of the EMU", an internal document prepared by Bob Balinskas and Ed Tepper of Hamilton Standard Space Systems International, Inc.