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Report on Lithium Ion Battery Trade Studies to Support the Exploration Technology Development Program (ETDP) Energy Storage Project

Robert D. Green and Barbara I. McKissock
Glenn Research Center, Cleveland, Ohio

William R. Bennett
ASRC Aerospace Corporation, Cleveland, Ohio

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Robert D. Green and Barbara I. McKissock
Glenn Research Center, Cleveland, Ohio

William R. Bennett
ASRC Aerospace Corporation, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Robert D. Green and Barbara I. McKissock
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

William R. Bennett
ASRC Aerospace Corporation
Cleveland, Ohio 44135

Summary

This report documents the results of two system related analyses to support the Exploration Technology Development Program (ETDP) Energy Storage Project. These analyses were originally documented separately as unpublished reports to quickly and informally provide their results to the Energy Storage Project team. A brief description of both of these reports along with the rationale for performing them is given below:

1.0 Trade Study to Determine the Optimum Cell Capacity for the Altair 120 V Ascent Stage Battery

This study looked at the ideal or optimum cell capacity, from a minimum battery mass perspective, for the Altair lunar lander ascent stage battery. The battery cell capacity for the Ultra High Energy (UHE) Li-ion battery initially chosen as the target for development was 35 A-hr, based on the EVA suit battery design and the initial 28 V ascent stage battery design. But for design reasons, it would be advantageous to go to a 120 V power system for Altair, increasing the number of cells in the battery. Given the need for string redundancy internal to the battery to meet loss of crew (LOC) and loss of mission (LOM) requirements, the battery capacity becomes a key parameter in minimizing total battery mass.

2.0 Preliminary Assessment of a Lower Li-Ion Battery Operating Temperature Limit for Lunar Rover Applications

The second study in this report is a assessment of the low temperature battery cell performance data to determine whether lowering the operating temperature range of the Li-ion battery could save overall system mass by eliminating the Thermal Control System (TCS) specifically designed to maintain battery temperatures and rely on the wider temperature range thermal control system for electronics and other ancillary systems for the lunar rover application. But the lower battery operating temperature will reduce battery performance and capacity that must be compensated by increasing the battery size/mass to meet rover power requirements.

The first study used the best estimates of the UHE cell mass and performance based on William Bennett's most recent cell spreadsheet models, as of May 2009. The second study used the most recent available test cell data from the NASA Jet Propulsion Laboratory (JPL) Li-ion low temperature cell development program, as of March 2009. But the methodology of these studies should be applicable for similar future analyses utilizing applicable Li-ion or other cell chemistry test data.

1.0 Trade Study to Determine the Optimum Cell Capacity for the Altair 120 V Ascent Stage Battery

Robert D. Green and Barbara I. McKissock
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

William R. Bennett
ASRC Aerospace Corporation
Cleveland, Ohio 44135

1.1 Introduction

The ascent stage to the Altair lunar lander requires an energy storage system to provide power for the ascent, docking to Orion, and finally the disposal portions of the mission. In the present design, this is a single 28 V primary (i.e., single discharge) battery. This energy storage trade study is to assess the effect on battery cell capacity sizing for changing the battery voltage for the Altair ascent stage power system to 120 V from the baseline 28 V bus. The battery cell assumed for this study is the UHE Li-ion cell presently under development as part of the ETDP.

In addition to the optimum cell capacity trade study, two brief separate analyses were also performed. One is to assess any potential mass savings if the lower limit of the 120 V bus voltage range was decreased 108 to 96 V, and the other analysis assesses the battery mass if internal battery redundancy requirements were eliminated.

1.2 Background

The present Altair lunar lander power system design uses a single 28 V bus. The 28 V ascent stage battery design to accommodate this bus utilizes a Lithium-MnO$_2$ 33 A-hr primary cell (FRiWO M62); the battery consists of 20 strings with 11 cells in each string, which includes two redundant strings to meet LOC and LOM requirements (see Ref. 1.1).

For several reasons, including compatibility with Orion and to reduce cable losses in the Altair primary power system, it would be advantageous to change the ascent stage bus to 120 V.

Also, the Altair project desires a secondary battery, instead of the baseline primary battery, to add function and flexibility in providing power to Altair during the trans-lunar coast phase of a lunar mission, and other operational scenarios, which a single use non-rechargeable battery does not accommodate.

1.3 Assumptions for the 120 V Altair Battery Cell Capacity Trade Study

The assumptions in this trade study on UHE cell performance, Altair power loads, cell and battery mass estimation, are as follows:

A Microsoft Excel spreadsheet model, developed by W. Bennett for the Li-ion ETDP UHE cell, was used to estimate the battery voltage versus SOC for the assumed power load profile. This model uses the ETDP Key Performance Parameter (KPP) estimates for the UHE cell anode and cathode. Details of the model assumptions can be found in Reference 1.2.

The cell mass for various cell capacities was estimated using this same spreadsheet model performing a point design mass estimate for several different cell capacities. The cell was assumed to be prismatic design using best estimates of the UHE cell cover, structure, electrical connectors, terminals, etc. The cell mass values as a function of cell capacity are shown in Figure 1.1. For this study, the cell mass for intermediate capacities was estimated by linear interpolation between these values.
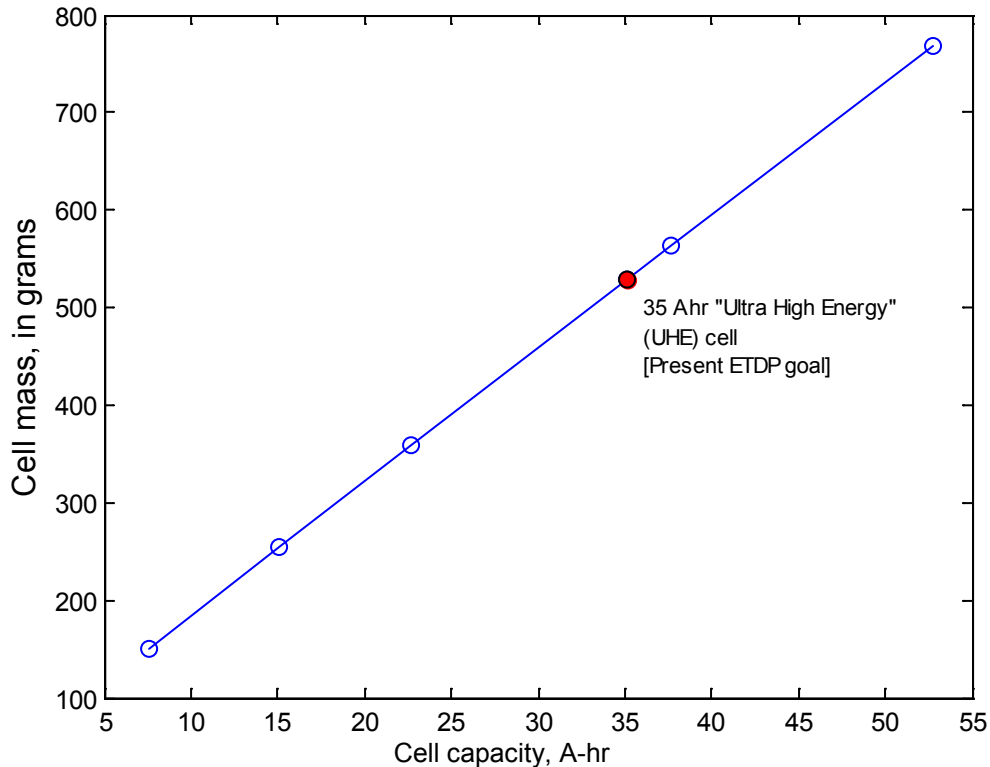
Figure 1.1.—Estimated UHE ETDP cell mass as a function of cell capacity.

The bus voltage range for the battery was assumed to be 108 to 136 V, based on the Constellation Systems 120 V Volume 3 Power Quality Specification (CxP 70050–03).

The cells-per-string in the battery was set to 29; which is driven by the upper voltage limit of 136 V. Two redundant strings were assumed, based on the 28 V baseline design, to meet LOC/LOM requirements.

The battery was assumed not to exceed a Depth of Discharge (DOD) of 90 percent. Note that for the baseline primary battery, the battery DOD was limited to ~87 percent DOD in order to meet the lower bus voltage limit of 108 V, i.e., the primary battery does not require a boost converter.

A boost converter mass was included in the battery mass for all the ETDP cases performed. A mass estimate of 7.2 kg was assumed for the boost converter, based on the estimate for a 28 V boost converter with a 3 kW load capability (see Chart 22 of Ref. 1.1). The booster power efficiency was assumed to be 94 percent. The baseline primary cell battery case does not include this extra mass, as a sizing analysis for a 120 V battery design using this cell indicates it can meet the required voltage range without a boost converter.

A battery charger mass was not included in the battery mass for any of the ETDP cases performed. Although a charger would be necessary to add the flexibility and advantages of a secondary battery choice, it was deemed not applicable for this trade study as this component adds extra functionality over the baseline primary battery. An estimate of the charger mass for the 28 V case was estimated at 1.5 kg, which has a small impact and would not change any conclusions in this trade study.

A factor of 1.3 was applied to the battery cell mass to account for incorporating the cells into a battery. This factor is based on a detailed battery design and packaging analysis performed by Brent Gardner on the baseline Altair 28 V Li-ion primary battery. It includes the baseplate, busbar, battery

cable, connectors, case, and miscellaneous components (fuses, diodes, sensors, and wiring). A summary of this design and mass breakdown is contained in Chart 14 of Reference 1.1.

As input, the "ascent stage underburn" power profile was utilized as battery load for sizing the capacity of the ascent stage battery. This is an off-nominal case that is presently the worst case for battery capacity sizing. The profile is shown in Figure 1.2. A 20 percent margin was applied to the power load profile to account for growth in power loads as the Altair design matures.

For the trade study, the number of strings was varied and then the cell capacity was optimized by adjusting the cell capacity value such that the load could be met at a DOD of 90 percent; the UHE cell voltage corresponding to this DOD is 3.140 V. The boost converter typically was activated about 5.6 hr in the power profile timeline.

A typical battery cell voltage and C rate profile is given in Figure 1.3. The Li-ion EDTP UHE cell model developed by W. Bennett assumes a constant C/10 profile in estimating the cell voltage versus A-hr discharged, hence there are no discontinuities (or "jumps") in the voltage profile to correspond with those in the current profile—in Figure 1.3(b)—at the elapsed times where the load profile changes. We feel this assumption is conservative, as the current discharge rate is below a C/10 rate except for a short period at beginning of the "ascent stage underburn" profile, which lasts approximately 7 min out of the total 12 hr power profile.
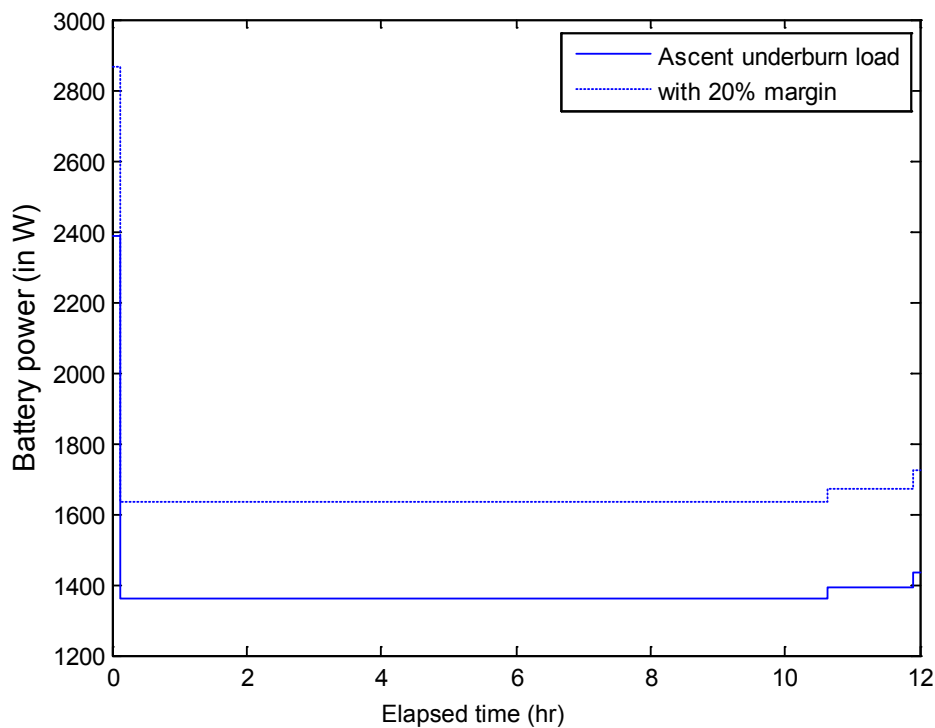

Figure 1.2.—Battery power profile used for 120 V battery trade study, and is based on the "ascent stage underburn" off-nominal operations case. A 20 percent margin was applied to the load profile (Altair project margin).
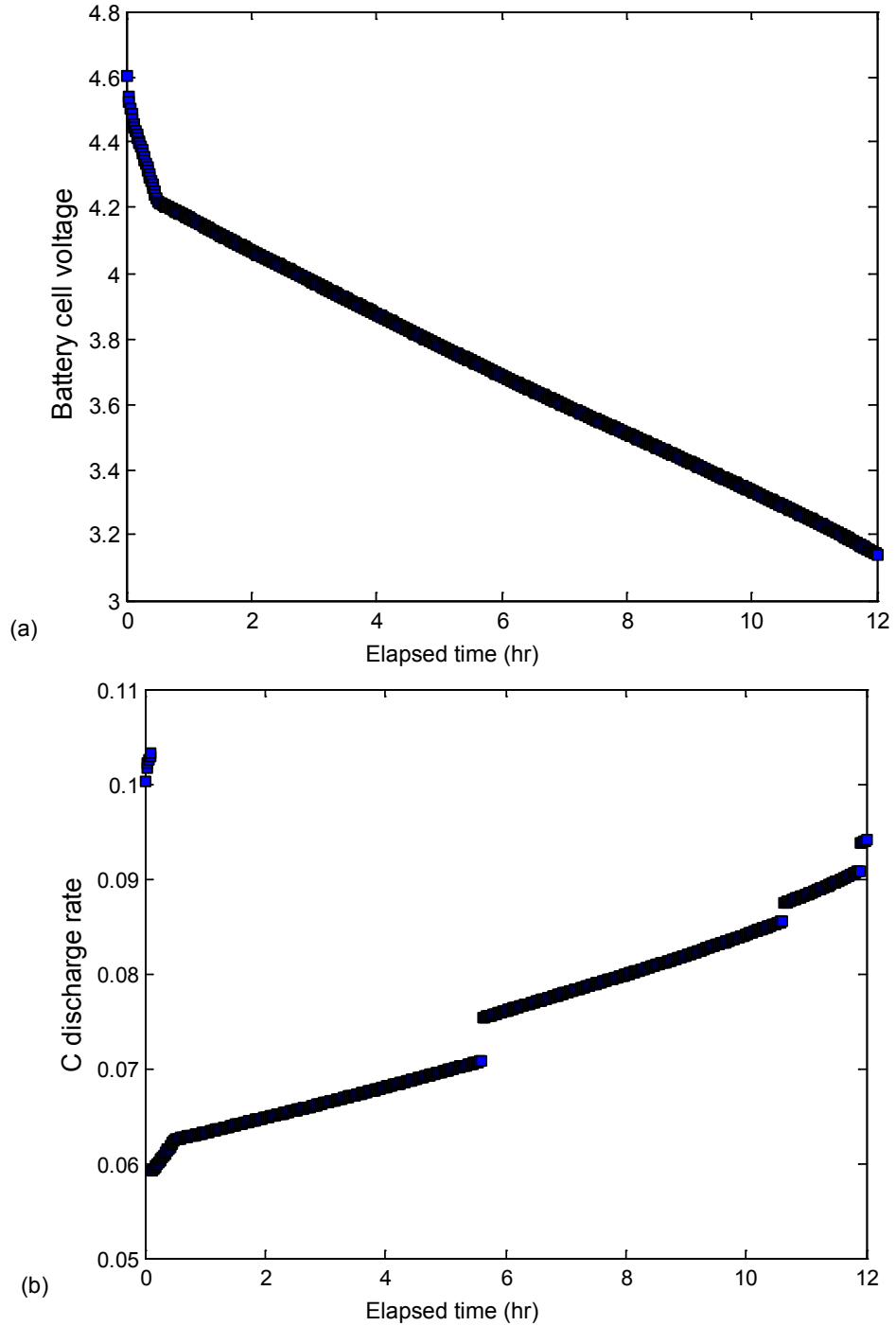
Figure 1.3.—Typical ETDP UHE cell voltage and current discharge rate profiles for 120 V ascent stage battery trade study.

Results

The results of this trade study are shown in Figure 1.4 and Table 1.1. Figure 1.4 shows the variation in battery mass as a function of cell capacity; the number of strings required is noted for several calculated points. As the number of strings is increased, the optimum battery cell capacity decreases, resulting in a reduction in the cell mass associated with the two additional or redundant strings required in the design.
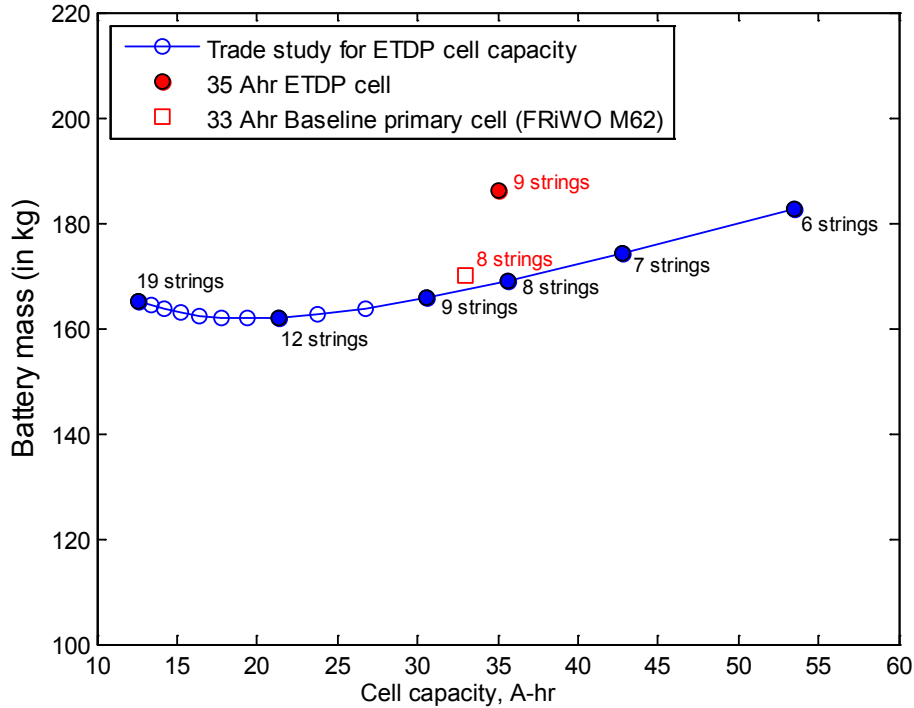
Figure 1.4.—Mass of Altair 120 V battery as a function of cell capacity. Required number of cell strings (includes two strings for redundancy) is given for several cell capacity values.

TABLE 1.1.—SEVERAL CELL CAPACITY AND BATTERY MASS
VALUES NEAR THE MINIMUM BATTERY
MASS POINT GIVEN IN FIGURE 1.4

Number of strings (includes two redundant)	Required cell capacity (A-hr)	Battery mass (kg)
12	21.4	163.5
13	19.4	163.3
14	17.8	163.4

This analysis indicates the minimum mass battery for this application has 13 strings with an optimum cell capacity of 19.4 A-hr. Figure 1.4 indicates that the optimum battery cell capacity is roughly 55 percent of the capacity of the present goal 35 A-hr ETDP UHE cell that is being developed for both the Constellation Systems second generation EVA suit battery pack, and Altair ascent stage applications. A change to a cell capacity in this range is projected to decrease the total battery mass by ~12 percent, compared to the 35 A-hr cell.

Table 1.1 lists several capacity and the associated battery mass values near the minimum battery mass point. The data indicate small deltas in additional mass savings for higher string value near this optimum mass point. Hence, the more optimum design may be a lower string value, e.g., 12 strings, to lower cell count and associated parts (wiring, connectors) in the battery.

Note that in Figure 1.4, the battery mass is also given for the 35 A-hr ETDP cell design; the mass is significantly higher than the "trade study" curve since the 35 A-hr cell just misses meeting the power load for an eight string battery design. As such, it requires nine strings, making it substantially heavier for this application. If this estimate is used, the mass reduction is ~20 percent for a change to the lower cell capacity range listed in the previous paragraph. Also note, the design point for the baseline primary cell capacity has not been optimized for the 120 V battery; it uses the identical 33 A-hr cell chosen for the 28 V baseline Altair ascent stage battery.

1.4 Analysis of a Wider Bus Voltage Range Without Boost Converter

A separate analysis of a proposed wider voltage range for the 120 V bus was performed to see if a lower battery mass could be obtained without a boost converter. The revised voltage range proposed is 96 to 136 V (March 10, 2009, e-mail to B. McKissock from J. Soltis). The minimum cell voltage required to meet the 96 V minimum bus voltage is 3.310 V and corresponds to a DOD of 75 percent. Several cases were run near the optimum capacity for the previous analysis, and the resulting battery mass values are given in Table 1.2. The resulting battery mass was approximately 11 kg heavier for each of these cases, compared to the analysis presented in the previous section, that required a boost converter.

TABLE 1.2.—BATTERY MASSES AND CELL CAPACITIES FOR
96 V LOWER BUS VOLTAGE LIMIT WITH NO BOOST CONVERTER

Number of strings (includes two redundant)	Required cell capacity (A-hr)	Battery mass for 96 V lower limit (kg)
12	24.4	174.6
13	22.2	174.4
14	20.3	174.2

1.5 Analysis of the Optimum Cell Capacity for a Battery Without Internal String Redundancy

A separate analysis was performed to assess the optimum cell capacity for a 120 V battery that does not have a redundancy requirement. A potential example of this would be if Altair changes to a dual (or multiple) bus power system for the ascent stage, where the systems redundancy would most likely negate the need for string redundancy internal to the battery. As such, the optimum capacity would be for a single string, and would exceed 210 A-hr, which may be impractical for a Li-ion cell. Table 1.3 lists the battery mass for several larger cell capacities corresponding to low string numbers and no string redundancy. For a four string battery, the optimum capacity is 53.4 A-hr cell and for a three string battery, the optimum capacity is 71.3 A-hr, which brackets the 60 A-hr battery pack that presently is optimum for the EVA application, according to W. Bennett and L. Kohout's latest assessment (Ref. 1.3).

TABLE 1.3.—BATTERY MASS AND ASSOCIATED CELL CAPACITY
FOR A NO STRING REDUNDANCY BATTERY DESIGN FOR
THE ALTAIR ASCENT STAGE

Number of strings (no redundancy)	Required capacity (A-hr)	Battery mass (kg)
2	106.9	120.0
3	71.3	122.2
4	53.4	124.2

1.6 Conclusions and Recommendations

The preliminary conclusion of this report is that the 35 A-hr ETDP UHE cell can be utilized in the 120 V Altair ascent stage, but based on the present best estimate of the Altair ascent stage power profile, the Altair battery mass could be reduced by 12 percent to as much as 20 percent if an ETDP UHE cell of lower capacity (19.4 A-hr) is developed.

A battery with 13 strings and cells with 19.4 A-hr capacity would save approximately 8 kg, or about 5 percent, compared to the baseline 33 A-hr primary cell battery. This reduced cell capacity would decrease the battery mass by 24.1 kg, or about 13 percent, compared to the 35 A-hr capacity for the ETDP UHE cell presently being developed for both Altair and EVA applications. Although this analysis indicates the 19.4 A-hr cell is the optimum from a minimum mass perspective, it may more advantageous to select a design with a fewer number of strings. For example, a 12 string battery with a 21.4 cell capacity would lower the total cell count by 29, with less than a 0.5 kg increase in battery mass.

If the 35 A-hr cell capacity is increased to 35.6 A-hr, it would meet the eight string criteria. This could be done either by increasing the capacity, or increasing the maximum DOD to 92 percent. The resulting mass of a 35.6 A-hr battery is approximately 7 kg, or 4 percent heavier than the optimum 19.4 A-hr cell capacity battery.

Altair bus voltage range was assumed to be 108 to 136 V, based on the CX power quality specification. Potential revisions to this document may change the low voltage cutoff to 96 V. An analysis using the lower limit voltage and eliminating the boost converter increases the battery mass by 11kg, negating any benefit to decreasing the voltage to 96 V.

A separate analysis was performed to determine the optimum cell capacity for a 120 V battery without any string redundancy. Although a single string battery would provide the minimum mass, the cell capacity required would exceed 200 A-hr. A two or three string battery design with capacities of 71.3 or 53.4 A-hr respectively, would provide a mass saving of ~40 kg or 25 percent less than the two string redundancy minimum mass battery.

With these preliminary conclusions and recommendations, there are a few caveats to be considered given some of assumptions made for this trade study:

The present LOC/LOM estimates for the Altair ascent stage battery were performed on the 28 V baseline battery, which has a total cell count of 264. The 120 V battery using this same 33 A-hr baseline primary cell increases the cell count to 328 cells. The optimum 19.4 A-hr cell capacity for the ETDP UHE cell increases the cell count to 377 cells. This is a significantly higher cell count and revised LOC/LOM estimates should be performed to reassess whether the two redundant strings assumption remains valid.

The Altair ascent stage power profiles lack the fidelity of peak power loads, and therefore, the significantly lower cell capacities that this study indicates would be more optimum for mass considerations, but may not be adequate to meet peak power loads.

The cell-to-battery factor of 1.3 used for this analysis is based on a detailed conservative estimate of the Altair 28V battery design with the baseline primary cells. Still, as the Altair design matures, this factor may increase. For example, the more mature Orion battery design utilizing secondary Li-ion cells, has a cell-to-battery factor of 1.7. It should be noted that Orion does have several unique requirements (i.e., such as a waterproof battery enclosure) that are not anticipated for the Altair ascent stage battery.

1.7   Future Work

This trade study will be updated as part of the next design analysis cycle for Altair if the decision is made to change to a 120 V bus.

1.8   References

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2.0 Report on a Preliminary Assessment of a Lower Li-Ion Battery Operating Temperature Limit for Lunar Rover Applications

Robert D. Green
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

2.1 Introduction

This report documents a preliminary look at whether lowering the operating temperature Li-ion battery, to reducing the thermal control system mass, could potentially reduce the overall system mass on a lunar rover. This assessment utilizes data from the low temperature battery development work at JPL. The unmanned Mars Exploration Rover (MER) thermal control system (TCS) is used as a "point design" for estimating the TCS mass savings.

2.2 Background

The Lunar Surface Systems (LSS) Project, under the Exploration Systems Management Directorate (ESMD) is tasked with development of the lunar surface architecture, including development of manned rovers. The present prototype rover vehicle being developed by LSS is the Lunar Electric Rover (LER) that consists of two functional elements, a six double-wheeled mobility platform, referred to as Chariot, and a pressurized cabin; total mass of the vehicle is approximately 4200 kg (Ref. 2.1). The LER will require 90 kW-hr of energy storage capability for an anticipated 3 day (2 night) mission. In addition, the LER will have the capability to perform longer missions, 14 days or potentially longer, with the addition of a Portable Utility Platform (PUP) carried on the back of the LER. The PUP will contain an additional 90 kW-hr of energy storage capability, along with solar arrays to provide supplemental power and provide up to 2 kW to recharge the energy storage system during vehicle stops, such as sleep and overhead periods (Ref. 2.2). Based on a 3 day analog test of a LER prototype in the Arizona desert, the average power levels expected for the LER is 5 kW, with peak power levels up to 29 kW (Ref. 2.1). The LSS project is planning to use the High Energy (HE) Li-ion cell being developed under the ETDP, for the energy storage system. Batteries comprised of the high energy cells are projected to meet a performance goal of 150 W-hr/kg in the temperature range at 0 °C.

One of the minimum surface temperatures during the lunar night are expected to be in the range of –180 to –60 °C for lunar surface operations; temperatures as low as 40 K (–233 °C) are possible during excursions into permanently dark craters. During a lunar day, the average temperature is around 100 °C, but maximum temperatures can reach 120 °C at the lunar equator. Given that for many aerospace spacecraft, the batteries often have the tightest temperature control requirements; this typically results in a larger mass thermal control system to accommodate these tighter temperature requirements. A more robust wide temperature battery would be of interest to designers of lunar rovers and associated surface systems to potentially reduce the thermal control system mass.

2.3 Preliminary Assessment of Battery Thermal Control System Trade

A first order assessment was made to determine if decreasing the low temperature limit of the temperature range of a Li-ion battery could eliminate the battery thermal control system and result in a net mass reduction of the rover. Novak (Ref. 2.3) suggested this for the Mars Exploration Rover (MER) battery and determined a potential 22 percent mass reduction if the battery thermal control system could be eliminated, and battery temperatures be maintained within the wider range of –40 to 50 °C that MER electronics and other systems are maintained.
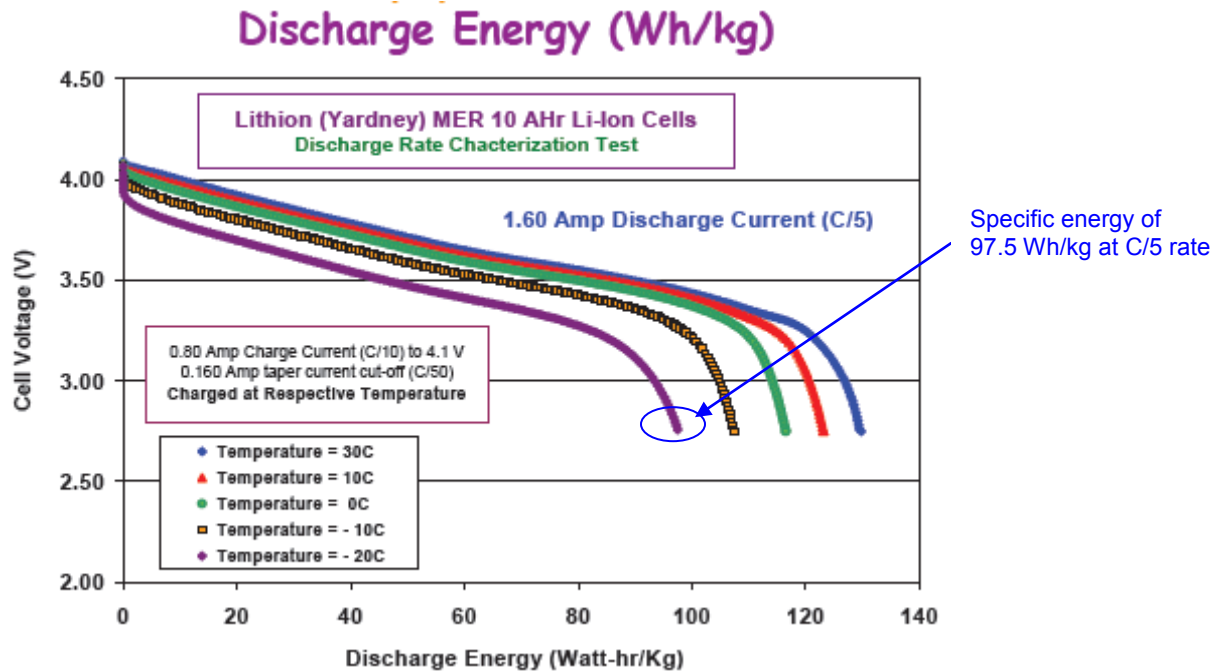
Figure 2.1.—Specific Energy performance for an 8 A-hr nameplate capacity MER Lithion cell at T = –20 °C (Ref. 2.4). [Note that the 10 A-hr capacity value in title of plot refers to the actual capacity, as opposed to the 8 A-hr nameplate value.]

This preliminary low temperature assessment a Li-ion battery in a rover application, utilized C/5 discharge rate performance data for a state-of-the-art MER battery cell (Lithion, 8 A-hr) at the minimum –20° C temperature requirement for the MER program as a baseline. As shown in Figure 2.1, the specific energy of this cell under these discharge conditions is 97.5 W-hr/kg. This baseline was compared with cell performance data at –40 °C, i.e., compatible with the low temperature limit for electronic components on the MER rover. The Li-ion battery cell performance data for the JPL low temperature Li-ion development program (Ref. 2.4) does show significant improvement in low temperature capacity/specific energy but there is still is significant capacity loss for temperatures below –20 °C. Of the data reviewed, an advanced development Yardney 7 A-hr cell using a methyl propionate (MP) based low temperature electrolyte was chosen as a close match in capacity to the MER baseline cell. The discharge energy data for this Yardney cell is shown in Figure 2.2, and shows a specific energy value of 76 W-hr/kg at a C/5 discharge rate at –40 °C. The resulting 22 percent reduction in the specific energy of this cell compared to the baseline MER cell would require a corresponding increase in battery mass, essentially negating the thermal control mass savings in the MER design.

Note that the normal cell voltage cutoff for Li-ion batteries in many present spacecraft applications, including the MER rover, is 3.0 V. But the cell voltage data for temperatures below –20 °C indicates a significant amount of A-hr capacity is available below 3.0 V. For the JPL low temperature Li-ion cell development work discussed in the previous paragraph, a cutoff voltage of 2.0 V was utilized for performance and capacity measurements. For rovers utilizing these low temperature cells, the power systems will have to tolerate a wider battery voltage range (2.0 to 4.1 V per cell) which may require a boost converter, resulting in additional mass to the vehicle.

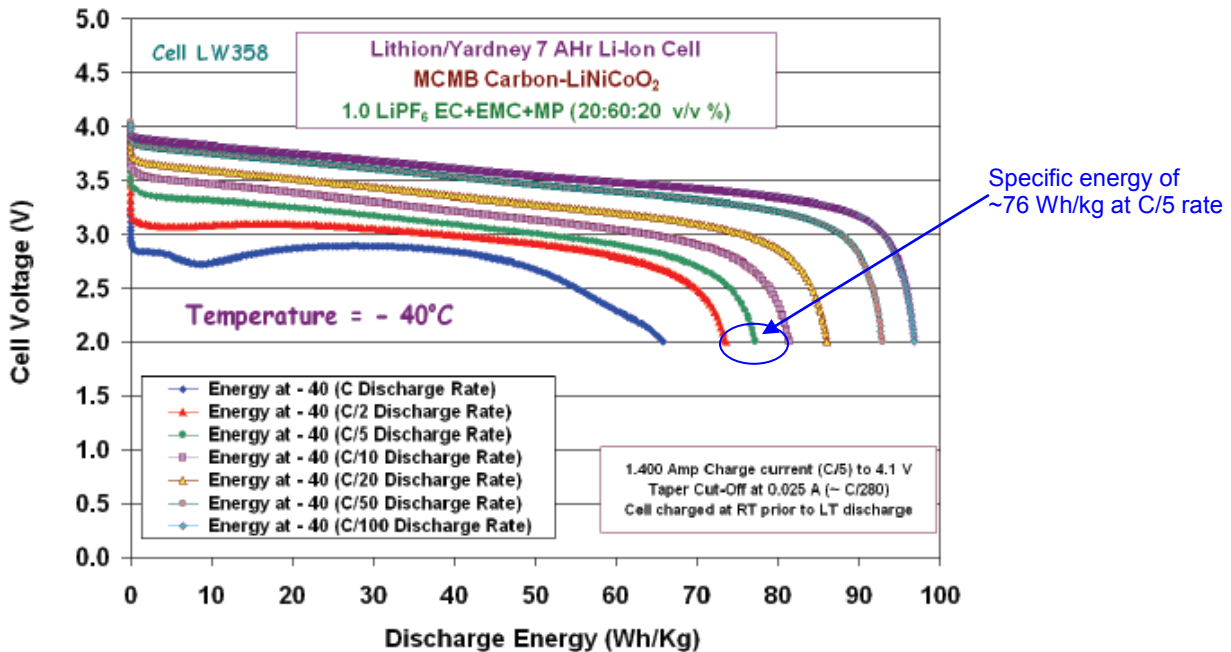Figure 2.2.—Specific Energy performance for a 7 A-hr prototype cell with advanced MP-based electrolyte at T = –40 °C (Ref. 2.4).

Also, a discharge rate of C/5 was chosen for this assessment as it provided an "apples-to-apples" comparison of the baseline MER battery cell discharge data for its required low temperature limit of –20 °C limit with available data from the JPL low temperature battery cell development program. But the discharge rate for the HE ETDP cell is a C/10 rate, to meet the 150 W-hr/kg specific energy goal. A comparison of a baseline Li-ion cell data from the low temperature battery development program at the lower C/10 rate would be a more accurate projection for mass saving for the LSS rover.

Finally, this initial assessment does not consider the high temperature limit for a wider temperature range Li-ion battery. In general, for Li-ion battery chemistries, performance typically does improve with increased operating temperature, up to 50 °C or so. But sustained operating temperatures above 30 °C can reduce the cycle life of the battery and, there is some evidence that storage at temperatures above 50 °C can reduce Li-ion cell performance (Ref. 2.5).

2.4   Conclusions and Recommendations

From this preliminary look at battery performance at low temperature, there appears to be no mass advantage to utilizing a battery with current low-temperature electrolytes as the thermal control system mass savings is negated by the increased battery mass required to compensate for the reduced battery W-hr capacity at low temperatures. Significant improvements in low-temperature performance are needed to enable elimination of the thermal control system. Since maximizing the specific energy of rover batteries while maintaining safe operation is the top priority for LSS, the Energy Storage Project recommends that NASA's priority remain focused on improving specific energy and safety in the narrow temperature range of 0 to 30 °C.

We would note that certainly there are advantages to pursuing development of a wider temperature range battery, despite minimal system mass savings. For example, a wider temperature battery may potentially increase reliability of a rover with a less complex TCS, i.e., the battery may not require liquid

cooling or extra heaters, which may reduce parts count and eliminate components with moving parts like pumps. Another advantage is a low temperature tolerant battery could potentially provide capability for off-nominal situations, for example, start-up of the rover after a cold soak condition due to a TCS failure or extended non-operational period. If these advantages are potential needs for the LSS rovers or other systems, it would be prudent to initiate a wide temperature Li-ion development program. At present, the U.S. Department of Energy (DOE) is ramping up their work in low temperature Li-ion battery development; NASA will leverage the results of this DOE effort as much as possible.

2.5   Future Work

The following studies would be helpful to further clarify battery thermal management requirements for lunar mobility systems applications:

This initial assessment did not attempt to estimate potential improvements in low temperature Li-ion cell performance. There is a need to develop conservative projections of performance and capacity improvements that could be obtained with an initiation (or restart) of a low temperature development program to enhance the low temperature performance of the High Energy Li-ion battery cell.

This assessment did not evaluate any potential TCS savings due to increasing the high operating temperature limit of the battery. There is a need to develop projections of battery cell performance at the high end of the temperature range—and assess the trade between thermal mass to maintain the higher temperature with the improved performance (at the expense of life).

This initial assessment only considered a "point design", namely the MER design, and whether or not a change in the low battery operating temperature limit from –20 to –40 °C could reduce overall system mass. A more detailed and expanded trade study needs to be performed to determine thermal control system mass vs. battery mass for a wider range of low temperatures (i.e., –20 to –60 °C). LSS would need to provide a methodology for estimating rover TCS mass to perform this trade study.

Development of thermal model(s) of the High Energy Li-ion battery cell may be advantageous to better estimate operating cell temperature in the lunar environment, under cold temperature soak conditions, and assess effect of insulation (aerogel or other high performance thermal insulation material) on minimum heater power during non-operational periods.

Finally, it may be helpful to provide battery packaging and design options to LSS to improve heat transfer to the TCS under high temperature operating conditions or limit heat loss under cold temperature conditions.

2.6   References

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Green, Robert, D.; McKissock, Barbara, I.; Bennett, William, R.

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14. ABSTRACT
This report documents the results of two system related analyses to support the Exploration Technology Development Program (ETDP) Energy Storage Project. The first study documents a trade study to determine the optimum Li-ion battery cell capacity for the ascent stage battery for the Altair lunar lander being developed under the Constellation Systems program. The battery cell capacity for the Ultra High Energy (UHE) Li-ion battery initially chosen as the target for development was 35 A-hr; this study concludes that a 19.4 A-hr cell capacity would be more optimum from a minimum battery mass perspective. The second study in this report is an assessment of available low temperature Li-ion battery cell performance data to determine whether lowering the operating temperature range of the Li-ion battery, in a rover application, could save overall system mass by eliminating thermal control system mass normally needed to maintain battery temperature within a tighter temperature limit than electronics or other less temperature sensitive components. The preliminary assessment for this second study indicates that the reduction in the thermal control system mass is negated by an increase in battery mass to compensate for the loss in battery capacity due to lower temperature operating conditions.

15. SUBJECT TERMS
Energy storage; Electric batteries; Lithium ion battery; Electric cells; Spacecraft power supplies

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