High Specific Energy Lithium Primary Batteries as Power Sources for Deep Space Exploration

Frederick C. Krause,1 John-Paul Jones,1,* Simon C. Jones,1 Jasmina Pasalic,1 Keith J. Billings,1 William C. West,1 Marshall C. Smart,1,∗ Ratnakumar V. Bugga,1,* Erik J. Brandon,1,∗,z and Mario Destephen2

1Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA
2EaglePicher Technologies, Joplin, Missouri 64801, USA

Abstract

Exploration missions to the moons of the outer planets (such as Europa) pose unique challenges regarding the design of the spacecraft power source. Current aerospace qualified primary battery technologies cannot adequately meet the mass and volume requirements of proposed missions. Although they have not been used in prior deep space landed missions, lithium carbon-fluoride (Li/CFx) technologies were identified as a potentially viable option, both with and without blends of manganese dioxide (MnO2). To meet the performance requirements over the intended operating conditions of future NASA missions requires further development of this technology, in particular in the delivery of a high specific energy at moderate to low temperatures, and low discharge rates. A cell development effort was therefore pursued with an industrial battery cell manufacturer. Low (50 mA) and medium (250 mA) discharge rates were used to assess the performance of D-size cells under mission relevant conditions, between 0 °C and −40 °C. Select AA-size and C-size cells were also evaluated using similar rates scaled to the lower cell capacities. Developmental Li/CFx-MnO2 D-size cells designed for higher specific energy over these conditions were fabricated and tested, targeting operation between 0 and −40 °C and a 50 mA constant discharge current, as the baseline operating condition.

© The Author(s) 2018. Published by ECS. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 License (CC BY, http://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse of the work in any medium, provided the original work is properly cited. [DOI:10.1149/2.1061810jes]

There is increasing interest in the exploration of the moons of the outer planets known as “Ocean Worlds,” where significant quantities of subsurface liquid water exist beyond Earth.1 Of particular interest are Jupiter’s moon Europa and Saturn’s moons Enceladus and Titan. Recent mission concept studies performed by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have focused on landed missions to Europa. There is a significant motivation to conduct in situ science on this moon, in particular sampling of the surface and sub-surface ice with subsequent analysis for habitability, bio-signatures and even extant life. Supporting the desired sampling and analysis activities would require significant levels of energy.

Due to Europa’s significant distance from the Sun (∼780 x 10^6 km), photovoltaic-based power generation is not feasible for current surface mission concepts. In addition, radioisotope power systems are difficult to implement in the currently planned mission architecture, due to constraints imposed by the baseline lander design and the high radiation environments prevalent on Europa. Given these limitations, the only viable power source of sufficient maturity is a primary battery. Primary batteries have been used in previous in situ exploration missions to Jupiter in 1995 (Galileo Probe),2 Mars in 1999 (Deep Space 2 Microprobes)3 and Saturn in 2005 (Huygens Probe).4

However, unlike these past missions which were required to operate for <24 hours, future missions (such as a proposed Europa Lander) could require surface operations to be conducted for several weeks (∼480 hours). Different lander mission architectures are under investigation, some requiring cold operations (∼−40 °C) and others operating closer to Earth ambient (+20 °C) conditions. Common spacecraft designs place the batteries in thermal contact with the cruise stage propellant loop, enabling battery storage and initial operating temperatures of approximately 0 °C.

Recent projections of the total energy required to perform an adequate science mission are in the range of 35–45 kWh. Peak power demands are anticipated at 500–600 W (during telecommunications events), with quiescent periods requiring 30 W or lower, and average power levels of approximately 60 W. These emerging requirements highlight the fact that many mission concepts would be constrained by available energy, and not power levels. A high specific energy (>700 Wh/kg) primary power source is needed, due to the high sensitivity of lander designs (500–600 kg total) to added mass.

New high specific energy primary battery cell designs based on the Li/CFx-MnO2 chemistry have recently been reported, specifically designed for improved low temperature performance.5 Efforts were initiated to select and benchmark existing and emerging primary battery chemistries from several different vendors, and to develop energy storage options needed to fill identified technology gaps. As mission success hinges on the ability to deliver adequate energy and power to support the key science objectives, significant efforts were expended in identifying appropriate technology options. Current tentative plans propose the launch of a landed mission to Europa in the mid-2020s timeframe, followed by a landing in the early 2030s. Initial battery cell options were identified, based on vendor-reported values and their potential to support the emerging architectures for this planned mission. A summary of their reported capabilities are listed in Table I.

The initial assessment of available primary battery cell technology options focused on selection of both liquid cathode (Li/SO2 and Li/SOCl2) and solid cathode (Li/MnO2, Li/CFx, Li/CFx-MnO2, and Li/FeS2) systems. Specific cells evaluated as part of this study are listed in Table I. The critical temperature range of interest was identified as 0 to −40 °C. Although several cell formats were investigated based on available chemistries from various vendors, D-size cells were found to offer the best combination of commercial availability, high specific energy and optimal cell geometry to support battery pack designs. Using notional pack designs featuring the D-size cell format, coupled with assumed peak power levels to estimate maximum current levels per cell, a baseline operating condition at the cell level of 0 °C and 50 mA was identified. Testing was ultimately performed on D-size cells between 0 and −40 °C and 50 mA to 250 mA, to encompass a comprehensive range of potential operating conditions.

**Experimental**

A range of available cells representing a cross-section of chemistries (Table I) were procured from vendors. Wires were soldered to the terminals or tabs (whichever was provided by the vendor), and each cell was placed into a holding fixture. A J-type thermocouple was affixed to the surface of each cell using Kapton tape. Electrical leads were interfaced to a Maccor 4000 automated battery test unit (5V and 7.5 A maximum current per channel). Each cell was placed in a thermally controlled chamber (ESPEC Platinous EPZ-2H) and the...
carbon fluoride (CFx)-based cells, in particular the observed voltage cathode formulation to address some of the historical limitations of corresponding to the open circuit voltage. The cells were maintained at potentiostat/frequency response analyzer at the DC potential corresponding to the excitation voltage using a Princeton Applied Research VersaSTAT data were collected over the range of 1 MHz to 125 mHz with 5 mV discharge voltage and the delivered capacity, typically averaged from primary chemistries). The specific energy was determined from the size format and Li/FeS₂ in an AA-size cell format were discharged to generate the desired polymorph. The CFx-MnO₂ hybrid electrodes CFx (x = 1) and electrolytic MnO₂ were used. The MnO₂ was heat treated at temperatures between 350 and 400°C prior to use, in order to generate the desired polymorph. The CFx-MnO₂ hybrid electrodes were prepared using a web coating process similar to that used for Li-ion battery electrodes. The web coating process enables the production of very thin electrodes for improved rate capability and low temperature performance. The two active materials were mixed with carbon black, graphite and poly(vinylidene difluoride) binder to form a slurry that was then coated on an aluminum current collector. The cathode formulation was modified to achieve a high electrode density with enhanced rate capability. This included optimization of the particle size distribution of the active materials and the porosity of the electrode. The baseline particle size distribution was centered at approximately 38 μm, with the optimized particle size distribution centered at approximately 25 μm. The baseline cell available from the vendor featured a LiClO₄ salt in a solvent blend of propylene carbonate and 1,2-dimethoxyethane and tetrahydrofuran (PC:DME:THF), 1:1:1 by volume. For the first cell modification (2R), a reduced LiClO₄ salt concentration was used in the electrolyte formulation, relative to the baseline design. The second cell design modification (3R) combined this reduced salt concentration with a cathode that was thinner relative to the baseline design. The third design variant (4R) featured both of these cell modifications, along with a modified electrolyte solvent formulation using a mono-fluoroethylene carbonate additive (EC) in a blend of PC:DME:THF:FEC (15:40:40:5 by volume). The cell electrode assembly was prepared using the same automated winder used for the baseline cells. Aluminum hardware (can and header) were used in place of the traditional stainless steel can, to increase the cell-level specific energy. The use of aluminum hardware increased the specific energy by ~100 Wh/kg compared to cells using mild steel hardware. Laser welding was used to achieve optimal can-to-header welds for the aluminum cells. Following manufacture, the cells were pre-discharged and conditioned at 55°C. A final cell screening protocol (involving evaluation of cell mass, open circuit voltage, 1 kHz impedance, and a visual inspection) was performed after a two-week room temperature storage period.

### Results and Discussion

Li/CFx cells are typically chosen for applications requiring high power delivery at low temperatures, as the charge transfer kinetics for SO₂ dissolved in organic solvent are favorable for low temperature operation; Li/CFx cells offer higher specific energy but their temperature range and power capabilities are more limited due to the properties of the pure inorganic catholyte used. In contrast, the Li/CF₄ chemistry is selected where a very high specific energy is required, especially at low rates and moderate temperatures (~20°C). The kinetic limitations of the Li/CF₄ system relate largely to the nature of the solid cathode system (involving diffusion of the Li⁺ ion into the cathode, coupled with the breaking of the C-F bond and the passivation effects from the LiF formation). A number of previous attempts have focused on improving low temperature performance of this chemistry in laboratory cells.⁶⁻⁸ A summary of the specific energy determined for all cell types tested is given in Table II. The mean cell voltages during discharge under various conditions are also given in Figs. 1 and 2; voltage versus discharge capacity curves are shown in Figs. 3 and 4. The temperatures used for discharge, 0°C and ~40°C, encompass the range of anticipated low temperature operating conditions for the lander application. At 0°C, the highest specific energy observed was from the Rayovac Li/CF₄ cells, at both the low current (640 Wh/kg) and medium current (508 Wh/kg) conditions. At ~40°C,
Table II. Specific energy at relevant rates and temperatures for commercial and developmental cells (average of three cells per measurement condition at 1.5 V cutoff voltage). Error bars are expressed as $2\sigma$, with $n = 3$ unless otherwise noted.

| Cell Chemistry          | Specific Energy, Wh/kg | 0°C       | Medium Rate | Low Rate | Medium Rate |
|-------------------------|------------------------|-----------|-------------|----------|-------------|
| Li/SO₂ (Saft)           |                        | 281 ± 25  | 279 ± 26    | 264 ± 28 | 200 ± 7     |
| Li/SOCl₂ (Saft)         |                        | 377 ± 13  | 323 ± 1     | 229 ± 6  | 160 ± 4     |
| Li/MnO₂ (UltraLife)     |                        | 247 ± 5a  | 232 ± 6a    | 120 ± 9  | 46 ± 6      |
| Li/CF₅-MnO₂ (EaglePicher)|                        | 437 ± 14  | 418 ± 8     | 226 ± 11 | 131 ± 4     |
| Li/CF₅-MnO₂ (UltraLife) |                        | 358 ± 10  | 324 ± 3     | 205 ± 18 | 105 ± 9     |
| Li/CF₅ (Rayovac)        |                        | 640 ± 13a | 508 ± 9a    | NO       | NO          |
| Li/CF₅ (Panasonic)      |                        | 297 ± 10b | 251 ± 20b   | 135 ± 19b,14 | 14 ± 3d   |
| Li/FeS₂ (Energizer)     |                        | 318 ± 14b,c | 309 ± 29c,e | 276 ± 15b,c | 211 ± 9c,e |
| Li/CF₅-MnO₂ 2R (EaglePicher)|              | 494 ± 9   | 437f       | 219 ± 2  | 136 ± 4     |
| Li/CF₅-MnO₂ 3R (EaglePicher)|                  | 558 ± 19  | 512 ± 9     | 203 ± 3a | 160 ± 29    |
| Li/CF₅-MnO₂ 4R (EaglePicher)|                  | 564 ± 1a  | 515 ± 12a   | NO       | NO          |

Low rate: 50 mA (unless otherwise noted).
Medium rate: 250 mA (unless otherwise noted).
aaverage of 2 cells.
bat 20 mA.
cat 100 mA.
daverage of 4 cells.
e0.8V cutoff.
fdata from 1 cell.
NO: Non-operational.

Figure 1. Mean cell voltages during discharge at 0°C; top: low rate (50 mA for D cells or 20 mA for AA, C cells); bottom: medium rate (250 mA for D cells or 100 mA for AA, C cells). Cells are D-size except as noted.
the Li/FeS₂ cells provided the highest specific energy at the low current (276 Wh/kg) and medium current (210 Wh/kg) conditions. At this temperature, the Rayovac Li/CFₓ cell chemistry was no longer operational and was incapable of supporting these discharge currents, although they were not specifically optimized for low temperature operation. The Panasonic Li/CFₓ C cells, which likely do not employ sufficiently thin electrodes, provided a much lower specific energy relative to the Rayovac Li/CFₓ D cells at equivalent currents, and temperatures.

As indicated, Li/CFₓ cells typically cannot support modest to high currents at reduced temperatures, and often display a significant voltage delay during discharge. To overcome these limitations, several battery vendors have explored "hybrid" designs featuring a composite cathode of CFₓ and MnO₂ electrode materials. These cells display a characteristic two-plateau voltage profile during discharge, with the MnO₂ discharge occurring first at a slightly higher voltage, followed by a lower voltage CFₓ discharge plateau. Given the lower specific capacity of MnO₂ vs. CFₓ, this cell chemistry cannot match the higher specific energy of a pure Li/CFₓ cell. However, the composite electrode can impart the higher current/temperature capabilities of the Li/MnO₂ chemistry combined with a still very high specific energy enabled by the pure Li/CFₓ chemistry. Across the temperature range of 0 °C and −40 °C, the EaglePicher Li/CFₓ-MnO₂ hybrid cathode cells displayed the highest specific energy, providing 437 Wh/kg and 418 Wh/kg at the low and medium current conditions, respectively, at 0 °C. This cell chemistry also supported discharging down to −40 °C, where specific energies of 226 Wh/kg (low current) and 131 Wh/kg (medium current) were measured.

As indicated above, there was particular interest in improving the specific energy at the low current 0 °C condition, since the cells will likely need to support discharge under these conditions when lander surface operations are initiated. Following operation under this condition for some period, it is anticipated that the battery temperature would increase due to self-heating, bringing the cells into a warmer temperature regime where kinetic limitations are less of a concern. It is possible that the battery temperature will again approach the initial temperature (0 °C) during quiescent periods in the mission timeline. The EaglePicher Li/CFₓ-MnO₂ cell design provided a combination of adequate rate capability at moderate capacity over a range of temperatures, making it a suitable choice for operations in the 0 and −40 °C range.

Representative discharge data collected for the baseline EaglePicher Li/CFₓ-MnO₂ cells at various currents at −40 °C, and over a range of temperatures at 50 mA, are provided in Figs. 5 and 6,
Figure 3. Voltage vs. discharge capacity at 0°C; top: low rate (50 mA for D cells or 20 mA for AA, C cells); bottom: medium rate (250 mA for D cells or 100 mA for AA, C cells). Cells are D-size except as noted.

respectively. Fig. 5 illustrates the effect of temperature increase within the cell during high current discharge. Increasing the discharge current from 50 to 250 mA results in a significant loss of capacity, however increasing discharge current further to 600 mA, 2 A, or 3 A increases delivered capacity at −40°C. Although the cells were discharged in a convectively cooled chamber, their temperature still rose considerably during discharge, particularly for the 2 A and 3 A discharge conditions. Fig. 6 indicates that, while the cell can support discharge at −40°C, very little of the CF₃ portion of the cathode is actually utilized (no second plateau is visible) and the specific energy is approximately half of what is available at 0°C. Given these performance capabilities over a broad range of operating conditions, this cell chemistry and design was chosen for further development. The other hybrid cell variant (Ultralife) featured a lower specific energy under similar conditions (Table II) in spite of its higher delivered capacity (Figs. 3 and 4). This is primarily due to the mass of the stainless steel can used for the cell design. Use of aluminum cans offers a higher cell level specific energy due to its lower mass vs. stainless steel, but also entails more challenging sealing/welding operations. Several design features were therefore introduced into developmental EaglePicher test cells to optimize performance under the anticipated mission operating conditions, including the use of an aluminum can.
Figure 4. Voltage vs. discharge capacity at −40 °C; top: low rate (50 mA for D cells or 20 mA for AA, C cells); bottom: medium rate (250 mA for D cells or 100 mA for AA, C cells). Cells are D-size except as noted.

Table III. Summary of cell designs and performance for developmental Li/CF_x-MnO_2 cells.

| Cell Design Parameter | Baseline | 2R | 3R | 4R |
|-----------------------|----------|----|----|----|
| Cathode Thickness     | Baseline | Baseline | Thin | Thin |
| Cathode composition (CF_x:MnO_2) | Baseline | Baseline | High CF_x content | High CF_x content |
| Separator type        | PP/PE/PP | PP/PE/PP | PP/PE/PP | PP/PE/PP |
| Separator thickness   | 25 µm    | 25 µm    | 25 µm     | 25 µm     |
| Salt Type             | LiClO_4  | LiClO_4  | LiClO_4   | LiClO_4   |
| Salt Concentration    | Low      | Low      | Low       | Low       |
| Solvent System        | PC:DME:THF (1:1:1) | PC:DME:THF (1:1:1) | PC:DME:THF (1:1:1) | PC:DME:THF: FEC (15:40:40:5) |
| Specific Energy, 50 mA and 0 °C (Wh/kg) | 437 | 494 | 558 | 564 |

PC: propylene carbonate.
DME: 1,2-dimethoxyethane.
FEC: fluoroethylene carbonate.
THF: tetrahydrofuran.
PE: poly(ethylene).
PP: poly(propylene).
One specific cell design variant featured a lower salt concentration (2R) to reduce solvent viscosity effects at lower temperatures and further improve electrolyte conductivity. A second cell variant featured a higher CF\textsubscript{x}:MnO\textsubscript{2} ratio along with a lower LiClO\textsubscript{4} salt concentration (3R), to increase the specific energy over a broad temperature range. A third cell design variant (4R) featured this higher CF\textsubscript{x}:MnO\textsubscript{2} ratio along with a modified solvent blend formulation using FEC as an additive to the standard PC, DME, and THF solvent blend. This modified solvent blend was selected based on earlier developmental studies using three-electrode laboratory cells\textsuperscript{7} which suggested that addition of FEC to the electrolyte improves the anode film properties (with a threefold decrease in resistance observed at lower temperatures). These cell design modifications are summarized in Table III, with the delivered specific energy given in Tables II and III.

Constant current discharge testing of these modified cells indicated improved specific energy at both 50 mA and 250 mA at 0 °C. In the case of the 4R cell design, the specific energy increased from 437 Wh/kg in the baseline cell to 564 Wh/kg for the advanced development cell at the baseline condition of 50 mA and 0 °C, and increased from 418 Wh/kg to 515 Wh/kg at 250 mA at the same temperature. At −40 °C, however, the same cell design failed to discharge at either rate. The 2R and 3R cell designs, on the other hand, were able to support discharging at both rates at −40 °C. The specific energy of the developmental cells at −40 °C was lower than the baseline version at 50 mA, but higher at 250 mA. The cell discharge voltage vs. specific energy data at 250 mA and 0 °C are given in Fig. 7.

The room temperature impedance of cells was evaluated at 1 kHz (Fig. 8). The baseline cells displayed the lowest average 1 kHz impedance of ∼58 mΩ, whereas the 4R variant was found to have the highest average value of >200 mΩ. The EIS responses for three of the EaglePicher Li/CF\textsubscript{x}-MnO\textsubscript{2} cell variants are shown in Fig. 9, along with a summary of the extracted impedance parameters in Table IV. The “series resistance” refers to the high frequency x-axis intercept (likely dominated by the lead resistance and electrolyte resistance), whereas the “film” resistance refers to the difference between the mid frequency x-axis intercept (inferred from the arc of the semicircle) and the series resistance, and is likely dominated by the film impedance on one of the electrodes (likely the Li anode, as in other Li primary cells). Given the complex nature of the cell chemistry and the limited access to individual cell components, a more sophisticated model is not presented here; detailed discussion can be found in the literature.\textsuperscript{8–11}

The 3R cells displayed a significantly higher series resistance relative to the baseline cell design (from 45 to 115 mΩ), whereas the

| Table IV. Summary of electrochemical impedance spectroscopy parameters for Li/CF\textsubscript{x}-MnO\textsubscript{2} cell types. |
|-----------------|-----------------|-----------------|
| Cell            | Series resistance (mΩ) | “Film” resistance (mΩ) |
|-----------------|-----------------|-----------------|
| Baseline        | 45          | 61          |
| 3R              | 115          | 58          |
| 4R              | 141          | 317         |
Figure 8. 1 kHz impedance at 20°C for multiple cells featuring the baseline Li/CFₓ-MnO₂ cell design (a) and two developmental cells: 3R (b) and 4R (c). Each bar represents a unique measured cell. The ±1σ standard deviation and mean value limits are included. The mean 1 kHz impedance values were 55 mΩ (baseline), 110 mΩ (3R) and 200 mΩ (4R).

“film” resistance remains essentially constant at about 60 mΩ. Comparison of the 4R cells to the baseline cells reveals that both series resistance and “film” resistance are substantially greater in the 4R variant. These data indicate that the new electrolyte in the 4R cells has resulted in a significantly more resistive film on one or both electrodes. Investigation of the discharge profile for the 3R and 4R cells (Fig. 7) reveals this presumed electrode film effect in the 4R cells does not significantly affect the cell voltage under dynamic conditions (during discharge) and is likely removed early in discharge. Although electrochemical impedance spectroscopy (EIS) provides a more complete understanding of the impedance properties of the cell by separating out high and low frequency contributions to the signal, a single 1 kHz point can also be used as an efficient screening tool for large quantities of primary cells. Based on our analysis, the 1 kHz impedance data point correlates with both the “series” and “film” resistances measured by EIS.

The hybrid cell design offers improved performance relative to a pure Li/CFₓ design over a wider temperature range, resulting from the combination of improvements in materials and electrode properties. As noted earlier, the use of an aluminum can leads to further increases in specific energy, relative to cells using a stainless steel design. The ~10% higher capacity and minor voltage advantages of the Ultralife hybrid cells were transformed into a nearly 20% specific energy deficit relative to EaglePicher at 50 mA and 0°C, mainly due to this difference in cell hardware. Increases in the amount of CFₓ in the cathode (for the developmental cells, relative to baseline designs), combined with the use of the FEC additive, were also found to improve the specific energy of these cells under certain low rate/low temperature conditions.

The Li/FeS₂ cells appear to provide the highest specific energy at low temperature (as seen in Table II), although given the sample size and the standard deviation of the data, the performance is comparable to that of Li/SO₂ cells. Recent vendor changes include modifications to the electrolyte, to improve conductivity over a wide temperature range. Electrolytes used in this cell design are typically a mixture of 1,3-dioxolane and 1,2-dimethoxyethane, resulting in formation of...
a high conductivity and a thin, stable anode film suited to low temperature discharge over a range of rates.

Conclusions

Prior deep space probes into the atmosphere of Jupiter (Galileo Probe) and to Saturn/Titan (Huygens Probe) featured Li/SO2 cells as the sole power source. Given the emerging mission requirements for a planned Europa lander requiring weeks (rather than hours) of continuous operation, the specific energy of this battery chemistry option is too low to support a viable landed vehicle design. At anticipated operational temperatures centered at ~0°C, these cells deliver a specific energy of approximately 280 Wh/kg. Given a mission energy requirement of approximately 25 kWh, this would lead to a full battery mass (with packaging) exceeding 100 kg, which is too large for emerging lander designs. Therefore, despite the flight heritage of this battery chemistry, new cell designs are needed to support the challenging mission power requirements posed by future lander mission concepts.

New cell designs were developed targeting the baseline operating condition of 50 mA and 0°C, with one of the developmental Li/CFx-MnO2 cell variants (4R) delivering 564 Wh/kg. This represents a twofold improvement relative to the heritage Li/CFx-MnO2 cell chemistry and a nearly 30% improvement relative to the baseline Li/CFx-MnO2 cell design under the same conditions. Although not specifically designed for lower temperature operation, two available Li/CFx cell designs were evaluated as part of this study, given the need for a very high specific energy. A Rayovac pure Li/CFx D-size cell provided an even higher specific energy (640 Wh/kg) relative to Li/CFx-MnO2 cells, although a Panasonic C-size Li/CFx cell provided a much lower specific energy (297 Wh/kg). Vendor-provided data indicates the Rayovac cells feature an electrolyte comprising LiBF4 in PC and DME. No specific cell design data is available for the Panasonic cell, therefore it is difficult to discern the nature of the observed differences in specific energy. Neither the high energy developmental EaglePicher Li/CFx-MnO2 cell (4R variant) nor the Rayovac Li/CFx cell were functional at ~40°C, which may be required of future surface mission spacecraft designs. Other cell designs operated over the full range of temperatures as noted above, albeit with a lower specific energy. These findings suggest future approaches for cell development, particularly focusing on improved pure Li/CFx cell chemistries (where high specific energy at 0°C is required) and even Li/FeS2 (where extended operation at ~40°C is critical).

Several cell options were identified to meet operational requirements over this full temperature range, including both currently available and developmental Li/CFx-MnO2 cells. In addition, commercially available cells featuring the solid cathode Li/FeS2 cell chemistry were observed to deliver a high specific energy at ~40°C, comparable to that of the liquid cathode Li/SO2 system. As the mission operating profiles continue to evolve, cell designs will be further developed and optimized to meet the specific energy and power needs. Future cell performance parameters requiring further investigation include estimation of self-discharge during the very long interplanetary cruise times (5–8 years) and tolerance to radiation, which will be discussed in future publications. The results of this study, however, confirm that developmental Li/CFx-based cell chemistries can exceed the performance of technologies used in prior deep space missions. They have the potential to provide significant benefits to future missions, with respect to supporting much longer mission durations.

Acknowledgments

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was supported by the NASA Science Mission Directorate. The information presented about future NASA mission concepts is pre-decisional and is provided for planning and discussion purposes only.

ORCID

Erik J. Brandon https://orcid.org/0000-0001-6106-7645

References

1. J. L. Lune, “Ocean worlds exploration,” Acta Astronautica, 131, 123 (2017).
2. B. Dagarin, R. Taenaka, and E. Stofel, “Galileo Probe Battery System,” IEEE Aerospace and Electronic Systems Magazine, 11(6), 6 (1996).
3. P. Russell, D. Carnen, C. Marsh, T. Reddy, R. Bugga, F. Deligiannis, and H. Frank, “Development of a Lithium/Thionyl Chloride Battery for the Mars Microprobe Program,” in Proceedings of The Thirteenth Annual Battery Conference on Applications and Advances, Long Beach, CA, 1998.
4. K. Clausen, H. Hassan, M. Verdiant, P. Couzin, G. Huttin, M. Brisson, C. Sollazzon, and J. P. Lebreton, “The Huygens Probe System Design,” Space Science Review, 104, 155 (2002).
5. M. Destephen, D. Zhang, E. Listerud, and U. Viswanathan, “Advanced Li/CFx Technologies - An Opportunity for Space Applications,” in Proceedings of the Space Power Workshop, Manhattan Beach, CA, 2015.
6. J. Whitacre, W. West, M. Smart, R. Yazami, G. S. Prakash, A. Hamwi, and B. Ratnakumar, “Enhanced Low- Temperature Performance of Li-CFx Batteries,” Electrochemical and Solid-State Letters, 10(7), A166 (2007).
7. S. S. Zhang, D. Foster, and J. Read, “A low temperature electrolyte for primary Li/CFx batteries,” Journal of Power Sources, 188, 532 (2009).
8. J. P. Jones, S. C. Jones, F. C. Krause, J. Pasalic, M. C. Smart, R. V. Bugga, E. J. Brandon, and W. C. West, “Additive Effects on Li/CFx and Li/CFx-MnO2 Primary Cells at Low Temperature,” Journal of Electrochemical Society, 164(13), A3109 (2017).
9. V. Leger, Pat. U.S. Pat, 4,327,166, April 1982.
10. Y. Li and W. Feng, “The tunable electrochemical performances of carbon fluorides/manganese dioxide hybrid cathodes by their arrangements,” Journal of Power Sources, 274, 1292 (2015).
11. Y. R. Li, A. M. Bruck, A. B. Brady, D. Bock, K. J. Takeuchi, E. S. Takeuchi, and A. C. Marschilok, “Hybrid Ag2VO2PO4/CFx, as a High Capacity and Energy Cathode for Primary Batteries,” Journal of The Electrochemical Society, 164(12), A2457 (2017).
12. X. Yin, Y. Li, Y. Feng, and W. Feng, “Polythiophene/graphite fluoride composites cathode for high power and energy densities lithium primary batteries,” Synthetic Metals, 220, 560 (2016).
13. S. S. Zhang, K. Xu, and T. R. Jow, “Understanding Formation of Solid Electrolyte Interface Film,” Journal of The Electrochemical Society, 149(12), A1521 (2002).
14. J. Marple and A. Webber, “Improvements in Energizer’s L91 LiFeS2 AA Cells,” in Proceedings of the 41st Power Sources Conference, Philadelphia, PA, 2004.
15. Rayovac Safety Data Sheet, Lithium Carbon Monofluoride Battery BR.