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Energy Storage: Batteries and Fuel Cells for Exploration

Michelle A. Manzo, Thomas B. Miller, Mark A. Hoberecht, and Eric D. Baumann
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Abstract

NASA's Vision for Exploration requires safe, human-rated, energy storage technologies with high energy density, high specific energy and the ability to perform in a variety of unique environments. The Exploration Technology Development Program is currently supporting the development of battery and fuel cell systems that address these critical technology areas. Specific technology efforts that advance these systems and optimize their operation in various space environments are addressed in this overview of the Energy Storage Technology Development Project. These technologies will support a new generation of more affordable, more reliable, and more effective space systems.

Nomenclature

AFC	alkaline fuel cell
CaLV	Cargo Launch Vehicle
CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle
ETDP	Exploration Technology Development Program
FC	fuel cell
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
kW	kilowatt
Li-ion	Lithium-ion
$LiPF_6$	Lithium hexafluorophosphate
LFP	Lithium iron phosphate
LPRP	Lunar Precursor and Robotic Program
LSAM	Lunar Surface Access Module
MEA	Membrane Electrode Assembly
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
PDR	preliminary design review
RATS	Research and Technology studies
RFC	regenerative fuel cell
SBIR	Small Business Innovative Research
TRL	technology readiness level

Introduction

The Energy Storage Project is one of twenty-one technology development efforts being implemented as part of the NASA Exploration Technology Development Program (ETDP). The Energy Storage Project is a focused technology development effort to advance Lithium-Ion (Li-ion) Battery and Proton Exchange Membrane (PEM) Fuel Cell (FC) technologies to meet the specific needs of NASA Exploration Mission needs including Orion (Crew Exploration Vehicle, CEV), Ares I (Crew Launch Vehicle, CLV), Ares V (Cargo Launch Vehicle, CaLV), Lunar Precursor and Robotic Program (LPRP), Lunar Surface Access Module (LSAM), rovers, and habitats. The project is led by the NASA Glenn Research Center in partnership with JPL, JSC, MSFC, KSC, GSFC, academia and industrial partners. The energy storage technology development effort addresses current energy storage technology limitations by reducing mass, volume and life-cycle-costs while increasing performance capabilities, reliability and human-rated safety.

All Exploration missions require electrical power and a means of storing energy to support loads on demand. Electrochemical systems, specifically Li-ion batteries, fuel cells and regenerative fuel cells are excellent candidates to store and provide the needed energy for a wide variety of applications. Technology development efforts are directed at addressing gaps between state-of-the-art capabilities and the most critical Exploration mission requirements. Technology development efforts will address:

(1) Affordability—The use of common, building block systems and components across multiple vehicles and platforms to reduce recurring and non-recurring costs.
(2) Flexibility—The use of modular “plug and play” components to permit reconfiguration of energy storage systems for multiple platforms and missions, and enable upward integration into existing systems.
(3) Effectiveness—Reduction in maintenance and logistics costs across Exploration missions using common power systems and components will enhance effectiveness.
(4) Reusability—The development of standards based on open architecture power systems will facilitate their reuse across all Exploration missions.
(5) Modularity—Intelligent power components and systems are modular to facilitate their use in multiple applications and enable sharing of resources between various systems platforms.

The Energy Storage Project reports to the Technology Development Program Office (level II) located at the Langley Research Center. Funding is provided by NASA Headquarters (level I), Advanced Capabilities Division of the Exploration Systems Mission Directorate.

Exploration Mission Energy Storage Requirements and Trade Studies

Mission requirements will dictate the salient characteristics of the energy storage subsystem. An overarching task within the Energy Storage Project involves the analysis and assessment of the available mission power profiles to identify and define energy storage requirements to properly define where a specific technology, (i.e., fuel cells or lithium-ion batteries) applies, and to then properly size and design the energy storage system to meet those requirements. Gaps between the performance capabilities and the mission requirements will be identified and used to direct specific technology development efforts. Figures 1 and 2 outline the need dates for batteries and fuel cells based on the current understanding of Exploration mission energy storage requirements (ref. 1).

Current baseline energy storage systems for Orion and Ares I, specify the use of battery systems. Mission requirements are being assessed to identify common battery requirements to provide the basis for the identification of a common battery module that can service multiple missions. The module under development in Li-ion portion of the Energy Storage Project is scheduled to be at technology readiness level (TRL) 5 by the CEV, CLV Preliminary Design Review in the third quarter of FY2008. Fuel cells and regenerative fuel cells are enabling for many aspects of lunar surface operations. Development efforts are designed to meet TRL 6 with advanced concept passive fuel cell systems by 2011, PDR for the LSAM

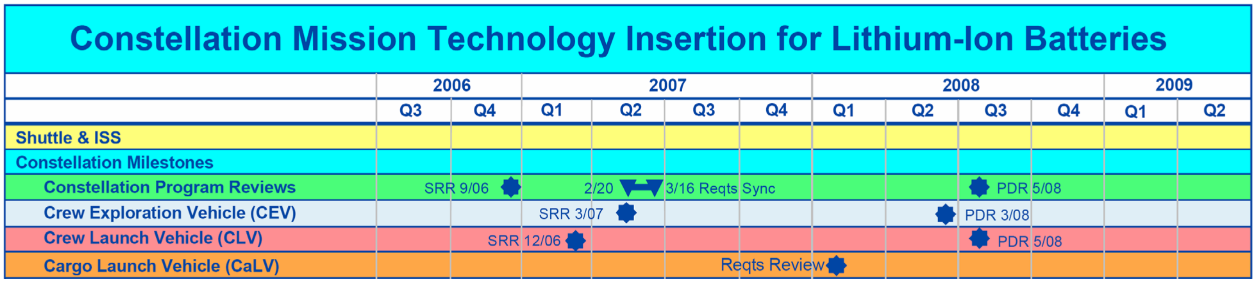

Figure 1.—Lithium-ion battery technology insertion schedule.

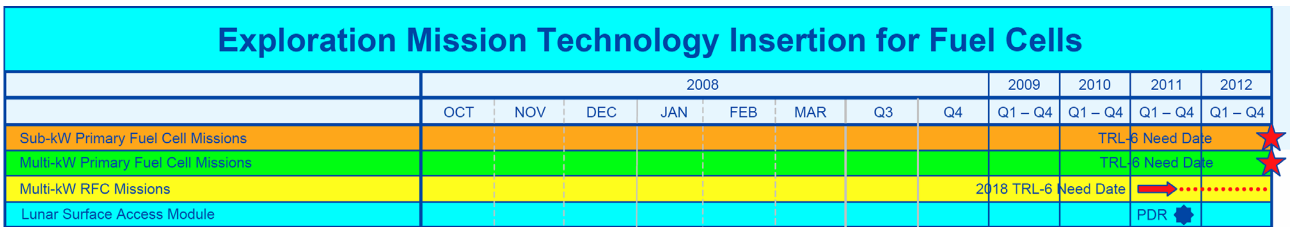

Figure 2.—Fuel cell technology insertion schedule.

mission, for flow-through fuel cell systems and by 2018 for regenerative fuel cell systems. TRL 6 indicates that a system or subsystem model or prototype has been demonstrated in a relevant environment (ground or space).

Continued battery and fuel cell development are required to meet the challenges of NASA’s Exploration missions. Travel to the moon and lunar surface operations will provide stressful environments for the energy storage subsystems. During this phase of the exploration initiative, the energy storage systems may be required to operate after relatively long periods of inactivity, or to operate at both high and low temperature extremes 400 to 100K, and/or operate in multiple gravity environments. Current system studies are showing that mass and volume continue to be critical characteristics that must be minimized.

Exploration energy storage requirements will be reviewed and assessed regularly. Gap analyses will be updated as needed to capture revised mission profiles and determine the impact on the battery module and fuel cell system designs. Within each specific battery and fuel cell technology area, lower level trades will be conducted to define the best approaches to specifically address and guide further developments.

Space-Rated Li-ion Battery Development

The key deliverable end item for the Space-Rated Li-Ion Battery development effort is a NASA Standard Lithium-Ion Battery Module that incorporates safe, rugged cell designs based on components with enhanced capabilities designed to meet the specific needs of NASA’s Exploration missions. This standard battery module will serve as a common building block that can be configured to meet multiple Exploration mission battery requirements and improve overall reliability, reusability, commonality, effectiveness and flexibility for the energy storage subsystem. Cost reduction and an improved schedule for deliverables are realized through uniform voltage, ampere-hour capacity, and form, fit, and functional interfaces. This module development is being pursued in parallel with component development and test and demonstration efforts.

Cell/component technology development tasks are aimed at enhancing or enabling specific performance parameters and the test and demonstration tasks are focused on evaluating state-of-the-art capabilities and limitations as well as the capabilities of the technology advances pursued as part of the development effort. The general flow of the battery development effort is illustrated in figure 3.

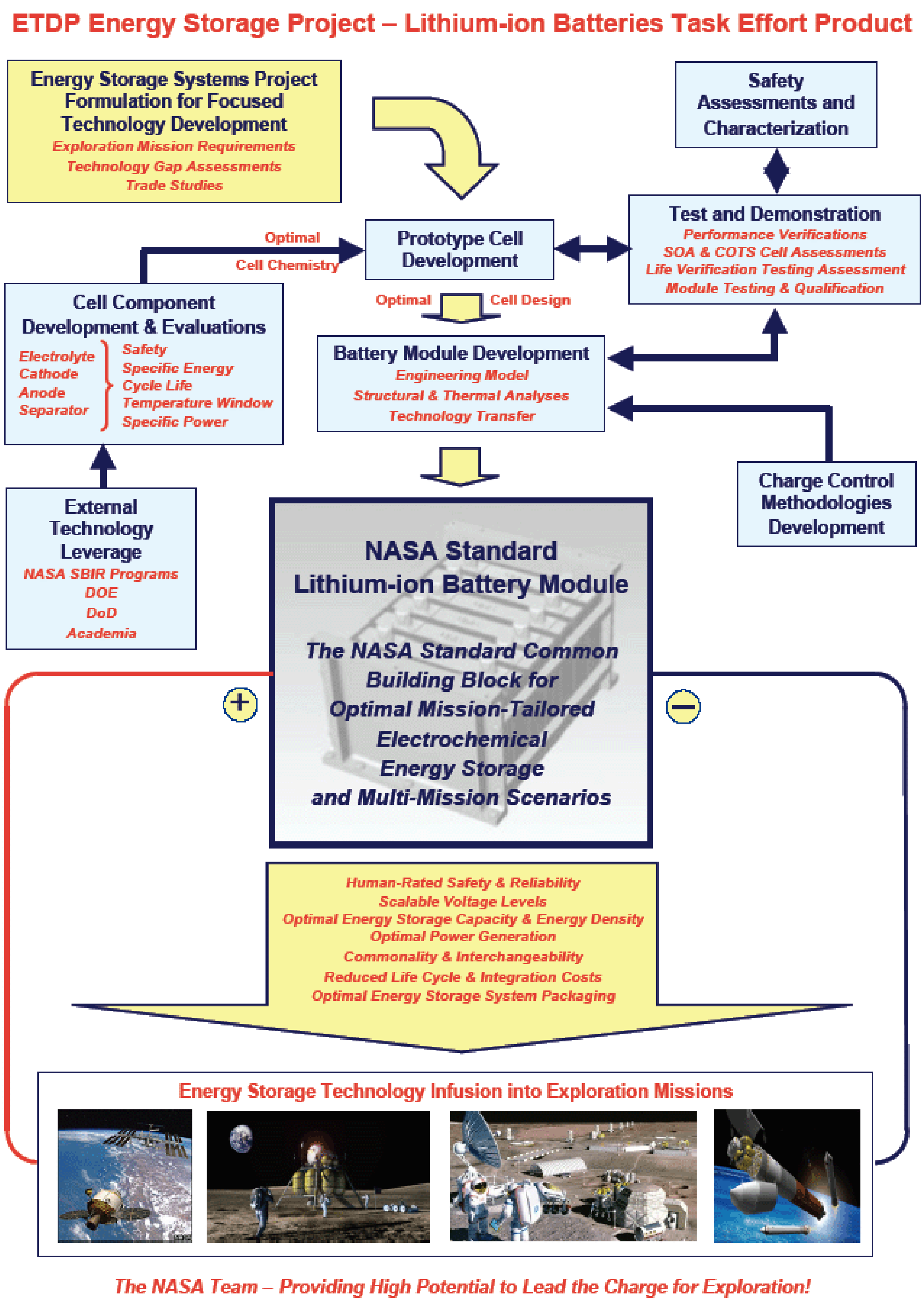

Figure 3.—Battery development flow diagram for exploration.

While lithium-ion batteries are currently used for some aerospace missions, none has been qualified for use as the main energy storage element for human-rated vehicles. As such, cell and component development efforts are directed toward improving the overall safety for Li-ion battery systems. In addition, Li-ion batteries require further development to improve performance at low and high temperatures to effectively operate in extreme Exploration mission environments. Future missions will also benefit from the efforts to achieve improved specific energy and energy density to reduce energy storage subsystem mass and volume. The near term emphasis in the test and demonstration area will focus on determining safety and performance characteristics for specific CEV and CLV mission type profiles.

Cell and Component Development

The achievement of high specific energy, high energy density, wide operational temperature limits, improved safety features, and high charge/discharge rates are predicated upon successful development of anode, cathode, electrolyte and separator elements with targeted characteristics. During FY2007, successful technology advances at the component level will be scaled-up and incorporated into Generation 1 prototype cells for evaluation as a working unit. These cells will incorporate the best materials developed to date. This will enable the characterization and evaluation of these materials in a relevant lithium-ion cell environment. Future technology advances will be demonstrated in subsequent generations of prototype cells.

JPL is the lead for efforts related to the synthesis and evaluation of advanced electrolytes for the lithium-ion cells that provide a wide operating temperature range and a non-flammable medium for safer human-rated applications. Low proportions of ethylene carbonate, high molecular weight esters, fluorinated esters, additives and new salts are being investigated to extend the performance of the traditional liquid electrolytes. New polymer electrolytes and ionic liquids are also being researched. To date, good low-temperature performance has been achieved in laboratory cells with liquid electrolytes with low proportions of ethylene carbonate and fluorinated and non-fluorinated ester co-solvents. Forty-five percent of room temperature capacity has been demonstrated at –60 °C at moderate rates (C/30). This is a significant improvement over the baseline standard electrolyte (1.0 Molar $LiPF_6$ in a 1:1:1 volume percent mixture of ethylene carbonate, diethyl carbonate and dimethyl carbonate) which delivers <1 percent of the room temperature capacity under similar conditions.

Cathode advances are being pursued to improve the specific energy and energy density of the Li-ion systems. Investigation of enhanced cathode materials with layered structures that facilitate rapid lithium ion intercalation at high cell voltages will continue. Oxide coatings designed to improve interfacial properties and intercalation kinetics are being pursued via a grant at the University of Texas, Austin. In addition to improved thermal stability, these materials under investigation have the potential for a 50 percent improvement in specific energy (at the component level) over state-of-the-art materials. Preliminary performance and safety assessments of electrodes and electrolytes will be completed in laboratory cells under representative operating conditions. Results will identify candidate materials with the greatest resistance to thermal runaway under abuse conditions.

Electrode/electrolyte combinations that can best achieve or exceed performance goals will be selected for scaled-up production and incorporated into Generation 1 cells. Manufacturability and chemical compatibility of components will be assessed. JPL, GRC, JSC and MSFC will be involved in testing the finished cells. Cell-level specific energy, energy density, specific power and cycle-life data will be collected. The cells will be evaluated for tolerance to ambient conditions, vibration and shock in this phase of testing. Results will confirm performance, reliability and safety characteristics and help to define optimum operating conditions.

An alternate approach utilizing a potentially safer lithium iron phosphate (LFP) cathode material is being addressed via contract efforts with T/J Technologies, Inc. (T/J). This task involves the fabrication of lithium-ion cells employing LFP cathodes and carbon-based insertion anode material. T/J has recently applied nano-composite designs to lithium iron phosphate systems that show very good charge and discharge rate performance, good capacity, and long cycle-life. These attributes, along with the inherent safety of the phospho-olivines which curtail thermal runaway make these systems very attractive for CEV and CLV applications. Twenty prismatic 7 Ah cells will be fabricated and tested at T/J to confirm that they have a specific energy of at least 110 Wh/kg, and retain 80 percent of room temperature C/5 capacity at –20 °C.

T/J will also fabricate Li-LFP pouch cells using polymer-based electrolyte materials. Electrochemical performance and characterization testing on the pouch cells will be performed to assess the practical performance feasibility and to identify any technical barriers. The testing protocols include charge/discharge cycle life testing, rate capability as a function of temperature, electrolyte electrochemical stability and impedance studies.

Battery Module Definition and Development

As stated previously, the identification and development of a common battery module/building block that supports multiple Exploration missions is the major focus of the battery effort. GRC leads this task that specifically involves the identification of a common module in terms of form, fit, and functional integration. Thermal and structural analysis tasks will be performed to define and optimize the packaged battery module. This development will be initiated with state-of-the-art cells and cell components and conducted in a manner that will allow the incorporation of successful component developments as they mature.

Cell and Battery Test and Demonstration

NASA Exploration missions have operational requirements that differ significantly from the traditional low-Earth-orbit and geosynchronous-orbit satellite missions that commonly use batteries for energy storage. Evaluation of the performance of state-of-the-art Li-ion battery technology in the Exploration specific mission operational profiles is underway to fully understand the capabilities and limitations of this technology for those applications. Responsibility for this testing is distributed between GRC, JPL and JSC.

The FY07 effort will focus on the test and demonstration of the performance of candidate cells via Constellation mission profiles. Performance for the most challenging aspects of the projected profiles will be evaluated. Thermal characterization of cells and cell components via calorimetry will be used to assess safe operating temperature limits, quantify self-heating rates, to investigate new cathode and electrolyte interactions, and to ascertain lithium-ion failure modes at GRC. Specific evaluations include:

(1) Performance assessments to address safety and thermal characteristics of cells and cell components
(2) Performance assessments of state-of-the-art lithium-ion cells under Exploration mission conditions to expand the overall performance database on specific cell manufacturer’s designs.
(3) Performance assessments of Generation 1 cells incorporating enhanced components
(4) An investigation on pressure growth in lithium-ion pouch cells to quantify performance degradation and pressure growth as a function of operational conditions
(5) Continuation of the NASA Lithium-ion Verification Life Test program to evaluate domestic aerospace lithium-ion cell manufacturers and to develop a model that predicts cycle life based upon temperature, depth-of-discharge, and end-of-charge voltage limits. Test data will be used to generate a performance model that can be used to reliably predict performance for a given set of operating conditions.

In addition to the cell/battery level tests, demonstrator projects are planned to insert the new lithium-ion cell component advancements and the modular battery package into Constellation missions. This activity involves the deployment of a prototype Li-ion battery or battery module as the power system for a rover demonstration at GRC or JPL. Additional demonstrations in conjunction with Desert Research and Technology Studies (RATS) operations are under investigation. Desert RATS involves field demonstrations of developing technologies applicable to the manned exploration of a planetary surface (the Moon and Mars). The desert area near Meteor Crater, Arizona serves as a laboratory for learning how to live and work during a human and robotic surface exploration mission.

Multi-Mission Support

In addition to the battery module development which the cell development efforts and test and demonstration tasks feed, the battery portion of the energy storage project also addresses systems level management via a grant with the University of Akron. Lithium-ion cell testing efforts will continue to feed the development of a damage control model at the University of Akron. Here, the interactions between temperature, charge voltage limits, and depth-of-discharge are used to determine the instantaneous damage from life cycle data, and establish an optimal charging profile to minimize damage. This effort involves a demonstration of the real-time observers implemented on individual cell microcontrollers to manage the charge control of an 8-cell series connection of 18650 lithium-ion cells.

This project will continue to sponsor the NASA Battery Workshop, managed and hosted by MSFC. The workshop provides for an open forum to cover current topics of interest to the battery community. Recent developments in cell designs and capabilities, battery performance from both ground and flight data, as well as testing standards are addressed in the annual three-day Battery Workshop.

Summary of Battery Development Efforts

The Space-Rated Li-Ion battery development effort incorporates elements of basic component technology development and advancement that will extend operational parameters for Exploration missions. The development is conducted in parallel with battery module development efforts that will lead to the production of a multi-use battery element that will standardize and streamline battery replacement units across Exploration mission elements. These efforts are complimented by test and demonstration tasks that will serve to quantify and identify capabilities and limitations of not only current batteries but also technology advances pursued as part of this project.

Fuel Cells for Surface Power Development

Fuel cells and regenerative fuel cells are enabling technologies for many aspects of lunar surface operations. In many cases, they offer significant mass and/or cost advantages over nuclear and/or battery options for some long-duration missions. Fuel cells also have the unique advantage of providing a source of potable water for manned missions as water is a byproduct of the fuel cell operation. Alkaline fuel cells (AFCs) are a space-qualified technology in use on the Shuttle, but PEMFC technology promises many advantages over existing AFC technology for space applications. In contrast to the early days of PEMFC technology development when NASA-pioneered fuel cells during the Gemini and Apollo eras, NASA is now able to leverage technology advances from the commercial sector in developing PEMFC technology. This has allowed recent NASA PEMFC development efforts to focus on the unique aspects of fuel cell system operation in the space environment, specifically operation with pure oxygen as the oxidant instead of air, and water management in multiple gravity environments (from zero-gravity to several times that of Earth’s gravity).

Because pure oxygen is much more corrosive than air, PEMFC operation in pure oxygen dictates that cell materials of construction be very corrosion resistant, and that specific catalyst formulations be utilized to achieve long life. It also requires that individual cell flow channels be sized appropriately to achieve sufficient gas velocities within the channels to entrain and remove product water. With air as the oxidant, only 20 percent of the recirculating gas stream is oxygen as compared to 100 percent in a pure oxygen gas stream. Therefore in a PEMFC operating on pure oxygen, individual cell flow channels must be proportionately smaller than flow channels in a PEMFC operating on air in order to achieve the same gas velocities.

PEMFC product water removal in the multiple gravity environments of space missions is much more challenging than product water removal on Earth. As mentioned previously, the velocity of the recirculating gas stream within the individual cell flow channels provides the necessary force to entrain and remove product water. The design of these flow channels becomes even more critical when gravitational forces are not available to help direct the flow of product water toward the cell outlets. Cross-sectional area, drag coefficients, and pressure drop are several of the important parameters to be considered in design of the flow channels.

Once the product water leaves the PEMFC stack with the recirculating gas stream, it must be separated from the gas before reentering the stack. In a gravity environment, the liquid water can simply flow to the bottom of a collection chamber with the gas passing through the top of the chamber. In a space environment, the separation becomes much more challenging. Options include mechanical devices that apply centrifugal forces to the gas/water stream, combinations of hydrophobic and hydrophilic membranes, and wicking devices.

PEMFC Development Effort

These aerospace specific challenges were the primary focus of NASA's recently completed, 5-year PEMFC development effort (ref. 2). In the first phase of the effort, two competing vendors, ElectroChem, Inc. and Teledyne Energy Systems, Inc. were contracted by NASA to develop breadboard hardware in the 1 to 5 kW power range. The second phase of the effort, to develop Engineering Model hardware at the 10 kW power level, was conducted by the winning vendor from the Phase I, Teledyne Energy Systems. Both breadboard power plants and the single engineering model power plant were delivered to NASA for independent testing. Table 1 summarizes the key Engineering Model system parameters and goals.

TABLE 1.—ENGINEERING MODEL POWER PLANT KEY PARAMETERS AND GOALS

Parameter	Goal
Nominal power, kW	7 to 10
Voltage regulation, V	30±10 percent
Voltage response time, sec	<0.2
Operating life, hr	10,000
Operating temperature, °C	60 to 80
Operating pressure, kPa	<690
Power plant weight, kg	<140
Power plant volume, m^3	<0.2

The engineering model power plant as delivered to NASA fully met all of the program goals, except for a 25 percent excess in power plant weight. In addition, it incorporated design features to accommodate operation in pure oxygen and water removal in multiple gravity environments.

The Engineering Model unit underwent extensive independent testing by NASA. The test regime included routine tests such as polarization curves, a variety of performance tests under multiple load profiles, specialty tests such as rapid start-up and loss-of-coolant tests, and environmental tests such as thermal vacuum and vibration tests. Tests were also conducted in three different spatial orientations in order to evaluate the gravity independence of the power plant.

At the present time, PEMFC stack electrical performance is excellent, but overall system complexity, weight, and reliability are major limiting factors when compared to existing AFC technology. This is because of the limitations of the existing active mechanical ancillary components in the system. PEMFC balance-of-plant deficiencies must be addressed for PEMFC technology to be the superior fuel cell option by equaling, and then exceeding, all of the attributes of AFC technology. The major efforts in this technology development project have shifted to focus on balance-of-plant issues in general, and ancillary components in particular. In spite of much progress, PEMFC system technology still requires significant development if all its promised advantages over AFC technology are to be realized.

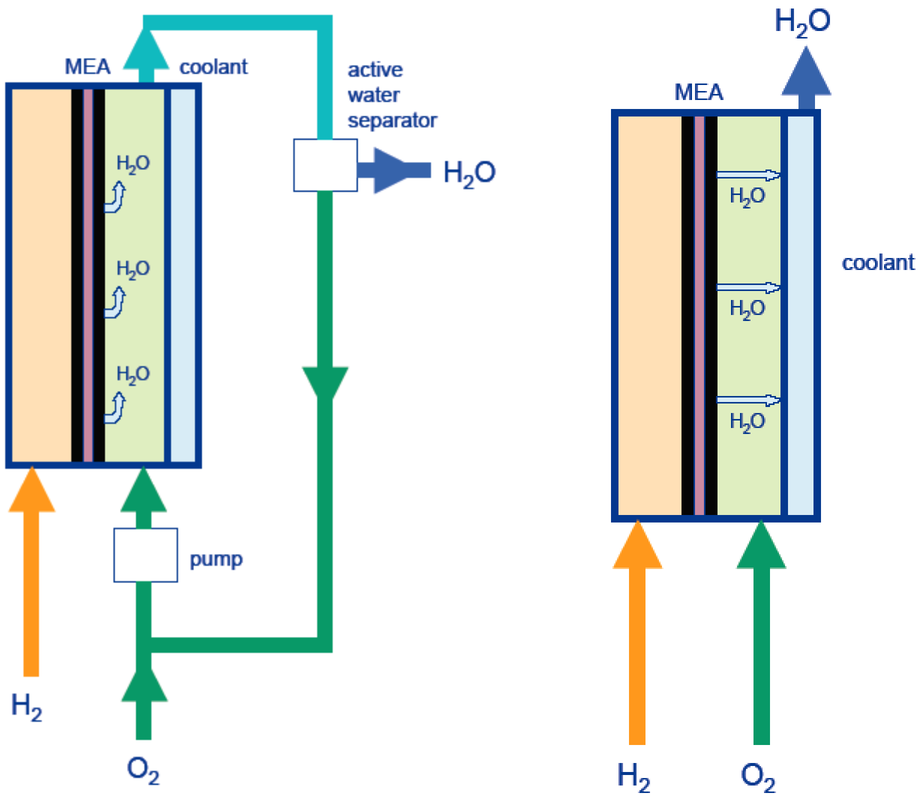

Figure 4.—Flow-through and non-flow-through fuel cell technology diagrams.

In the current phase of the project, two basic fuel cell technology design concepts are being pursued in parallel. They are characterized by the management of the reactant gases as “flow-through” and “non-flow-through” systems. The system concepts are illustrated in figure 4.

Flow-Through PEMFC System Technology

Nearly all commercial PEMFC technology is characterized as flow-through fuel cell technology. This includes the shuttle alkaline fuel cell technology and the Teledyne Engineering Model PEMFC system described above. In this type of system, mechanical pumps are used to circulate the pure hydrogen and oxygen reactant gases through the fuel cell stack, and mechanical water separators are used to separate the product water from the recirculating reactant streams. These active motorized mechanical components are a major contributing factor to the overall system complexity, weight, and reliability of any fuel cell system, and are a key deficiency of existing PEMFC technology for space applications. To address this deficiency, this project will pursue the development of passive components to perform both the reactant recirculation and product water separation functions. During 2007, three reactant recirculation methods and four water separation devices will be evaluated. Replacement of active mechanical ancillary components with passive components is the most critical step in addressing the deficiencies of existing flow-through PEMFC system technology. These passive ancillary components also have direct application to regenerative fuel cell energy storage systems.

The flow-through fuel cell technology development effort addresses sub-kW and multi-kW Exploration mission applications. Multi-kW PEMFC stack technology is very mature, with excellent electrical performance. During 2007, optimization of multi-kW stack technology will continue with reductions in stack weight and increases in electrical performance. This optimized stack technology will then be down-sized for sub-kW mission applications, and subsequently combined with passive ancillary components to form a complete flow-through sub-kW PEMFC system. Present plans call for a demonstration test of this sub-kW PEMFC system on a small rover in 2008.

Non-Flow-Through PEMFC System Technology

A revolutionary non-flow-through PEMFC system concept is being addressed via an existing NASA Phase II SBIR with Infinity Fuel Cell and Hydrogen. In this system, reactants enter the fuel cell stack directly and are consumed, with no reactant exit. Product water is wicked to a reservoir internally within the stack. By eliminating the need for reactant recirculation and external product water separation, this non flow-through system eliminates most, if not all, of the ancillary components in a fuel cell system, whether they be active or passive. The resulting system approaches the simplicity of a primary battery system, and if successful, would allow NASA to pursue a radically different approach to PEMFC development—one that has the potential to far exceed the attributes of existing flight-proven AFC technology, as well as any PEMFC technology presently under development. This SBIR effort concludes in 2007 with the delivery to NASA of a small stack.

To complement the stack development effort, NASA’s plans include the development of a non-flow-through balance-of-plant, which when teamed with the small stack, will form a complete non-flow-through PEMFC system. The balance-of-plant will be totally autonomous and include all mechanical and electrical functions. Present plans call for a demonstration test of this non-flow-through system, also on a small rover, in 2008.

Generic PEMFC Technology Development

A series of generic PEMFC technology development tasks are also planned for 2007. Two of the tasks address performance limitations of flow-through and non-flow-through primary fuel cell systems, as well as regenerative fuel cell systems. These performance-specific tasks include development of high-performance membrane-electrode-assemblies (MEAs) and several passive thermal management techniques. In particular, high-performance MEAs have the potential to dramatically improve PEMFC electrical performance and perhaps even exceed AFC performance, based on results to date. Another generic task that helps augment the 2008 rover demonstration tests of both flow-through and non-flow-through PEMFC systems is the development of a hydrogen/oxygen fuel system specific to the rover demonstration hardware. A final generic task is the initiation of an advanced RFC conceptual design that will lead to fabrication of a small RFC system in 2008, and demonstration on a rover in 2009.

Fuel Cell Development Effort Summary

NASA’s recent fuel cell development efforts have resulted in excellent fuel cell stack performance. Current system limitations are in the balance-of-plant and ancillary components. NASA is addressing these limitations by developing passive ancillary components to replace active components, and by conducting parallel flow-through and non-flow-through technology development efforts directed at simplifying the overall PEMFC system. By reducing weight and improving performance and overall reliability, these developments will be critical to the successful deployment of fuel cell and regenerative fuel cell systems for long-term NASA Exploration missions.

Conclusion

Electrochemical energy storage is critical to the success of NASA’s Exploration missions. The Energy Storage Project is focused on addressing the gaps between current fuel cell and battery technology capabilities and the projected requirements for future Exploration missions. Technology developments and advancements afforded by this project will ensure the availability of optimized energy storage systems for NASA’s Exploration missions.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
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