Lunar South Pole Regenerative Fuel Cell System Efficiency Analysis

Phillip J. Smith, Kerrigan P. Cain, Ryan P. Gilligan, and Ian J. Jakupca
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

It is expected that future NASA mission energy storage needs can be adequately met by regenerative fuel cells (RFCs). Aerospace RFCs package proton exchange membrane (PEM) electrochemical conversion devices based on hydrogen, oxygen, and water. To optimize system designs and direct further development, the most useful system metric is round-trip efficiency (RTE). Improving RTE generally increases specific energy and reduces system mass. The following analysis models the impact of several factors on RTE for RFCs scaling from 0.1 to 50 kW at the lunar south pole. The analysis demonstrates that higher electrolyzer (EZ) operational pressure most negatively impacts both RFC RTE and specific energy. Optimal EZ membrane thickness is evaluated as a function of operational current density and pressure. Reactant storage heating and power management losses are significant for RFCs of any scale but are reduced in impact at the south pole compared to colder equator applications. Solenoid valve power remains a noticeable parasitic load for smaller RFCs. Larger EZs enable higher peak theoretical efficiencies when recharging at higher rates, if the RFC can be coupled with a corresponding higher power source. Reduced EZ operational temperature improves efficiency at the expense of increased radiator size. The relative impacts were compared for improving EZ thermodynamic and Coulombic efficiency, showing that Coulombic efficiency improvements are more impactful at higher pressure, especially at reducing required RFC charge power. RFC design is a compromise of many interrelated factors, but this analysis provides a starting point for difficult decisions that must be made when designing a lunar south pole RFC.

Acronyms

BoP	balance-of-plant
DC	direct current
EZ	electrolyzer
FC	fuel cell
NASA	National Aeronautics and Space Administration
PEM	proton exchange membrane
PMAD	power management and distribution
PV	photovoltaic
RFC	regenerative fuel cell
RTE	round-trip efficiency

1.0 Introduction

Long-term lunar missions require energy storage systems capable of collecting electrical power during periods of sunlight and providing electrical power during times of eclipse. For most space missions with access to sunlight and comparatively low energy demands, photovoltaic (PV) systems convert sunlight into electricity and are typically coupled with an energy storage system such as a battery. Because of the long eclipse periods encountered on the Moon, the very high energy requirements render battery storage systems prohibitively massive and impractical for extended-duration surface operation missions. Although nuclear power systems operate independently of sunlight and are a viable lunar application power source, regulatory concerns and oversight significantly increase the required resources to implement nuclear power systems. Regenerative fuel cells (RFCs) offer a feasible solution to meet the energy storage needs of NASA lunar surface payloads from landers to rovers and stationary power systems.

A discrete RFC consists of a fuel cell (FC) and an electrolyzer (EZ) combined with a gas storage system. FCs are energy conversion devices that convert chemical potential energy into electrical energy. Proton exchange membrane (PEM) FCs consume hydrogen and oxygen gas to produce electricity, heat, and water. EZs produce hydrogen and oxygen gas by splitting water when supplied with electricity. RFCs must couple with a suitable external power supply, such as PV arrays or nuclear power systems, to provide power when the FC is not operating. All nonnuclear options will be comparatively high mass (Ref. 1), but RFCs are desirable for missions where nuclear power options are not practicable.

Of all system-level performance metrics, round-trip efficiency (RTE) is potentially the most useful to evaluate and compare systems. The theoretical maximum RFC RTE is only ~80 percent, but the potential specific energy is higher for RFCs than for batteries (Ref. 2). Improving efficiency is often secondary to reducing mass in flight systems (Ref. 3), but the two are not exclusive entities in RFC design. A past RFC design study noted conflicting design criteria in that the highest efficiency comes from highest temperature, low pressure, and lowest current density, whereas the lowest mass comes from highest temperature, lowest pressure, and highest current density and the best reliability comes from minimizing all three of those properties (Ref. 4). This makes it difficult to optimize an RFC for both RTE and mass in all scenarios.

NASA engineers in the 1970s promoted efficiency as the main priority for advancing electrolysis (Ref. 5). An efficiency improvement produces corresponding benefits elsewhere in the system. For example, reduced parasitic power consumption results in less reactant that must be stored and regenerated. As a result, the storage vessels could be smaller (i.e., lower mass and volume) and require less thermal power during a lunar night. In addition, the electrochemical stacks could be reduced in size or be able to operate at a more efficient and reliable level. Smaller or more-efficient stacks would generate less waste heat, corresponding to lower coolant flow rates and smaller radiators. Furthermore, less power would be transferred in and out of the boundary separating the energy storage system and the initial power source, or "customer," reducing absolute power conversion losses and solar array size.

It has been suggested that EZ stack, FC stack, and reactant storage improvements should be the focus for further improving RTE and specific energy (Ref. 2). Regardless of where the initial efficiency improvement originates (e.g., electrochemical stacks, fluidic components, or other hardware), the described cascading effects occur in every case. This RFC efficiency analysis is intended to inform potential flight system designers on the major factors affecting round-trip energy efficiency for a lunar south pole RFC application using a selfcontained, non-integrated design. As a result, a common ground will be established for comprehending these elements as well as what can realistically be accomplished to optimize RFCs for flight utilization.

The presented results incorporate electrochemical, fluidic, power management and distribution (PMAD), and thermal considerations for operation in a lunar south pole environment based on the Shackleton Crater. It is desirable to have a single study that evaluates a range of RFC power scales, optimizing for each level to evaluate what is possible rather than simply assuming modularity and adding complete units together. Like other recent NASA trade studies (Refs. 6 to 10), the assumed RFC system architecture is based on utilization of hydrogen-oxygen PEM technology for the discrete FC and EZ stacks. Unitized RFC concepts are still not advanced enough for flight consideration and may make it difficult to maximize RTE if charge and discharge rates are not aligned (Ref. 2).

Previous modeling was completed for a discrete PEM RFC on the lunar equator, and many of the conclusions regarding RFC performance are applicable to other lunar locations as well (Ref. 11). As such, certain topics are not repeated for this analysis of south pole RFCs. These include (1) fuel cell sizing decisions, such as active area and current density design point; (2) component decisions, such as reactant storage vessel configuration, solenoid valve operation and type, and voltage converters; and (3) reactant storage decisions, such as storage vessel temperature and gas versus cryogenic storage.

FC operation is generally less impactful on RTE than are EZ factors. At all RFC scales, FC efficiency is maximized by sizing the FCs relatively large and keeping current density low. This provides an added benefit in that maximum possible discharge power is also increased and total RFC mass (and thus specific energy) is not greatly affected by stack sizing (Ref. 12). Aligning stack voltages and customer bus voltages eliminates the voltage regulation losses that can consume 5 to 10 percent of charge and discharge power. In reactant storage subsystem design, because of improved volume-to-surface-area ratios, spherical gas-storage vessels benefit RTE by 2 to 3 percentage points and increase specific energy by ~50 percent. For the lunar equator location, cryogenic reactant storage was shown to diminish RTE to below 15 percent in all cases and is unlikely to be practical for any lunar RFC applications. For small-scale RFCs, solenoid valve operation consumes a surprisingly high parasitic power load. It is therefore desirable to incorporate latching valves or reduce steady-state power consumption through spike-and-hold-style voltage manipulation.

The purpose of this analysis is not to cover every single factor that influences RTE. All RFC design decisions may be critical for optimizing RTE, depending upon the mission application. For a lunar south pole application, the parasitic load impacts are discussed for RFCs of various size scales, and multiple significant design decisions are evaluated and compared with previously modeled and demonstrated results with a focus on electrolyzer design decisions, such as active area, theoretical performance improvements, membrane thickness, operational pressure and temperature, and charge duration.

2.0 Approach

Figure 1 shows the primary subsections and interconnections that form the RFC system for this analysis. All components and the electrochemical performance are based upon specifications and data for existing and available hardware. The FC has a non-flow-through design incorporating passive internal water separation. The EZ is a liquid anode feed unit requiring external water separation for both hydrogen and oxygen product gases. The fluidic balance-of-plant (BoP) consists of all storage vessels, valves, regulators, heaters, pumps, and sensors required to supply and store hydrogen, oxygen, water, and coolant, as needed. The power management and distribution (PMAD) subsystem includes voltage converters required for internal power management and integration with a customer. Reported system metrics do not include solar array physical sizing estimates, but solar array considerations are discussed as part of the EZ design.

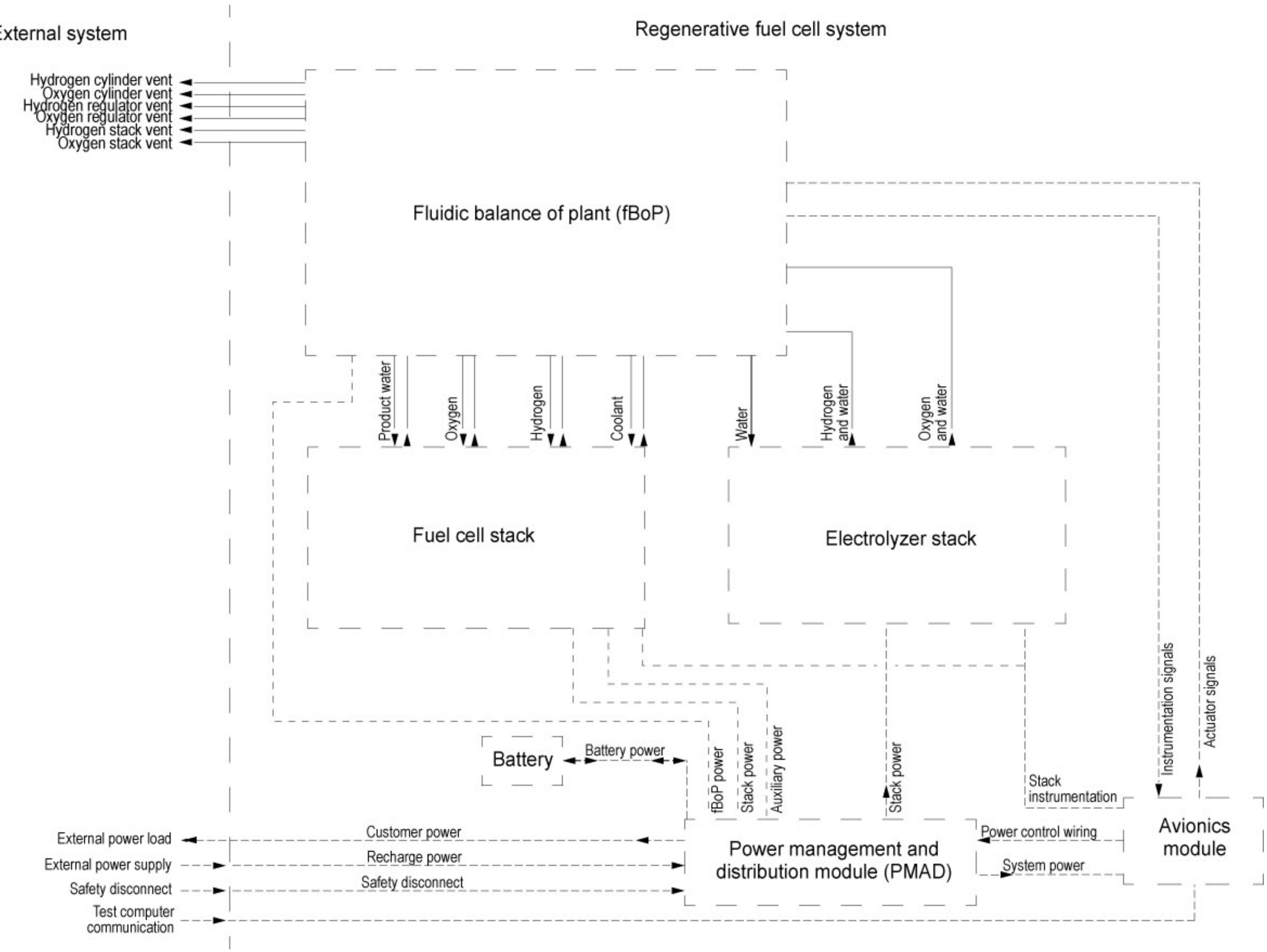

Figure 1.—Regenerative fuel cell system primary subsections and connections.

Model baseline input assumptions are listed in the Appendix. Net power is the electricity provided to a customer, whereas gross power includes all internal parasitic loads that the FC must supply. RFC gross input power, or charge power, includes all parasitic loads during EZ operation in addition to the power required to split water. RFC RTE is a function of the net power produced during lunar night phases and the gross input power.

A 0.1-kW-class RFC is among the lowest power levels practical for an RFC. Even with long lunar night durations of ~350 h, the comparative performance and simplicity of batteries are appealing at power levels 0.1 kW or less. At the south pole, where the shaded durations are likely to be shorter (nearer to 100 h), the RFC specific energy is further reduced. As such, lower power scales are not ideal for highlighting the specific energy potential of RFCs. Still, these are useful case studies to discuss relative impacts of system design selections, while representing an energy storage option suitable for integration into a midsize lander.

RFCs in this paper are modeled assuming constant required net power outputs of 0.1, 0.25, 0.5, 1, 5, 10, 25, and 50 kW. No variable profile was simulated for any case, but given the conservative FC stack sizing, it is realistic to assume maximum possible net power outputs of at least 4 times the nominal net power could be produced. Extended duration operation in such a condition would affect the absolute values of the reported system metrics and increase required reactant storage mass.

Any reported system metrics, such as specific energy, are for comparison purposes only and are not to be accepted as absolute values without context. The modeled systems are designed to function in assumed worst-case scenarios, defined as being a lunar cycle with the lowest available total solar energy. Unless otherwise noted, all modeled systems are designed to store enough energy to satisfy worst-case conditions without any power production compromises. No accommodation is made for any redundancy, and no metrics reported herein necessarily represent the absolute best-case results for any particular scenario. Mission risk tolerance (i.e., the need for redundancy and de-rating); exact mission location; electrical requirements; and other design constraints on mass, volume, or particular dimensions make it difficult to speculate on practical limits of RTE for a specific mission.

3.0 Results

3.1 Reactant Mass Change Due to RTE

In the previous NASA TM covering the design of an RFC for a lunar equator location (Ref. 11), it was shown that improving RTE benefits specific energy, reduces required charge energy, and reduces system mass. For example, a 1-percentage point improvement in RTE reduces total system mass by nearly 3 percentage points. Table I shows the effect of RFC RTE on required reactant mass and total system mass for a lunar south pole location. The baseline values represent the current model scenario

TABLE I.—ROUND-TRIP EFFECT ON REQUIRED SYSTEM MASS FOR 1-KW SYSTEM

Efficiency change, percentage points	Reactant mass, kg		Total system mass, kg	Mass change, percent
	Hydrogen	Oxygen		
–2	7.6	56.7	267.6	2.8
–1	7.5	55.7	264.3	1.5
Baseline	7.3	54.7	260.3	0.0
1	7.2	53.9	257.4	–1.1
2	7.1	53.0	253.9	–2.5

based on anticipated NASA requirements and preliminary electrochemical stack performance estimates. The baseline RTE is 31.7 percent for a 1-kW RFC. Improving RTE by 1 percentage point reduces the reactant mass by 0.4 percent. This reduction has carryover effects in that storage vessel mass and parasitic loads also decrease in magnitude, leading to a 1.1-percent reduction in total system mass. The absolute numbers are relatively small for a 1-kW-scale system, but this translates to a decrease in mass by tens of kilograms in a 10-kW system.

3.2 Parasitic Load Rankings During Fuel Cell Operation

There are two primary phases of RFC operation: when the FC provides system power and when the EZ consumes system power. Different sets of BoP components are operating during these two phases. The nominal FC parasitic loads are listed in Table II for three RFC scales. For small-scale RFCs, the second largest loss is from heating the reactant storage vessels, which are located outside of the thermal enclosure. In multikilowatt-class RFCs, reactant storage constitutes the majority of the mass and volume of the entire system. As described in previous reports, although it is not unreasonable to design a single thermal enclosure to contain a complete 0.1-kW-class RFC system that includes reactant storage, it does not scale up satisfactorily. If hydrogen and oxygen can be adequately separated from water after exiting the EZ, there is no need for the gases to be maintained in the relatively narrow thermal environment (i.e., between 0 and 100 °C) required by water-containing components. This remains an unknown in RFC design, and results shown here assume maintaining storage vessels above 4 °C, which is an impactful decision given the cold temperatures achieved during shaded periods. Heating of gas storage vessels is significant at all scales, as it remains the second largest parasitic load at 50 kW. This is likely to be because of the better volume-to-surface-area ratios that are achievable with larger vessels. Such a benefit may not be observed if larger storage volumes are obtained simply through addition of multiple smaller vessels instead of a single vessel of increased size.

Regardless of the RFC scale, the required quantity of solenoid valves is unlikely to change, so although larger valves tend to consume more power, it’s a minor increase compared to that of RFC scale. Without incorporation of spike-and-hold (i.e., reduced steady-state operational voltage) or latching valve concepts, solenoid valves are likely to be the largest periodic parasitic load during FC operation for small RFCs at the lunar south pole. In RFCs at the equator, storage vessel heating power is the greatest parasitic component for lower power RFCs and remains the second most significant even as scale increases. The solenoid valves become less impactful for larger RFCs in either location.

Figure 2 reiterates that as the power level increases, PMAD losses become the greatest parasitic source, just as in equator RFC systems. There is no size benefit to PMAD components as RFC increases in power output, and the power loss simply scales with RFC power output. This results from the assumption of 95 percent voltage regulation efficiency. If a power customer were able to accept a floating

TABLE II.—PARASITIC LOADS DURING FC OPERATION

Component	Power consumption, W		
	0.1-kW RFC	1-kW RFC	50-kW RFC
Gas storage heater power	16	55	695
Solenoid valves	57	60	230
PMAD	5	50	2,500
Coolant pump	2	14	377
Product water degassing	1	10	100

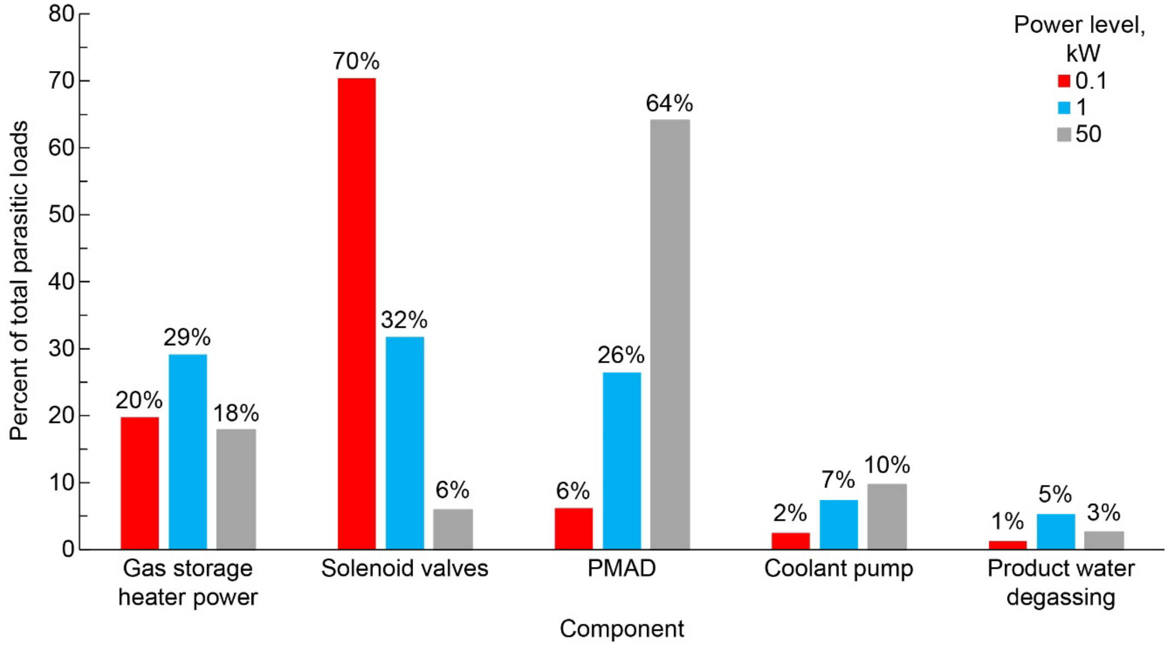

Figure 2.—The percentage of each nominal parasitic load relative to the parasitic load total during fuel cell operation for regenerative fuel cells at different nominal power levels.

voltage in the event of a variable load profile or if a FC were perfectly designed to a nominal steady-state power level (i.e., size active area and number of cells to match current and voltage needs), this loss could be significantly reduced. That outcome would be highly desirable for high-power systems.

The remaining parasitic loads are smaller in magnitude. The continuously operating coolant pump provides flow through the FC, heat exchangers for PMAD components, the EZ, and radiator. Coolant pump power also nearly scales with RFC power level but becomes a greater fraction of the total parasitic load at larger scales. FC product water is likely to contain dissolved oxygen gas. Therefore, product water degassing is accomplished in a FC stack auxiliary cell, and this places a relatively small load on the rest of the stack.

3.3 Parasitic Loads During Electrolyzer Operation

The nominal EZ parasitic loads are listed in Table III for multiple RFC scales. Note that the nominal power levels represent the RFC net power output and not the EZ charge rate. Because of the inefficiencies inherent in an RFC, electrolysis must proceed at a higher rate relative to the FC. Maximum electrical input power to the EZ is more than double the maximum power produced by the FC. As shown in Figure 3, during EZ operation, PMAD becomes the most significant loss at the larger RFC scale without aligning the EZ stack operational voltage range to the PMAD bus voltage range.

There are fewer solenoid valves in continuous operation during electrolysis mode compared to FC mode, resulting in lower power consumption. The modeled RFC design also includes continuous circulation from the coolant pump and two pumps for pressurizing and then recirculating water to supply and cool the EZ stack. Coolant pump power is approximately the same percentage at all modeled RFC scales, and there is only a small power increase for larger solenoid valves.

TABLE III.—PARASITIC LOADS DURING ELECTROLYZER OPERATION

Component	Power consumption, W		
	0.1-kW RFC	1-kW RFC	50-kW RFC
PMAD	25	155	7,020
Solenoid valves	49	52	61
High-pressure pump	0.5	5	145
Coolant pump	2	14	377

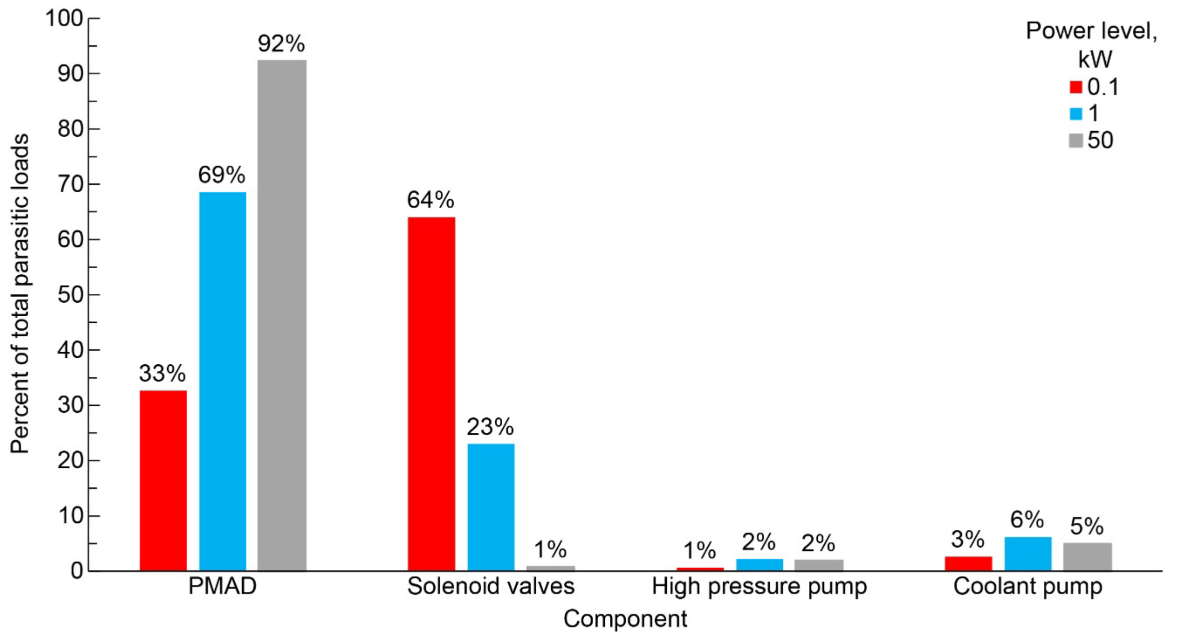

Figure 3.—The percentage of each average parasitic load relative to the parasitic load total during electrolyzer operation for regenerative fuel cells at different nominal power levels.

3.4 Electrolyzer Considerations

In the following sections, RFCs are modeled to consider the effects of varying EZ operational pressure, membrane thickness, temperature, and current density, as well as to evaluate the potential benefits of theoretical EZ performance improvements.

3.4.1 Reactant Storage Pressure

In RFC applications with short cycle durations, reactant storage mass (i.e., reactant plus storage vessels) may be only about 25 percent of the total system mass (Ref. 13). For the 0.1 kW lunar south pole cases here, reactant storage is ~30 percent of the total RFC mass. This percentage increases to nearly 60 percent for 50-kW systems, making reactant storage important for overall RFC system metrics. The most important reactant storage design decision is the storage pressure. In the absence of additional compressors, the EZ operational pressure effectively determines reactant storage pressure. When studying alkaline RFCs, Chang assumed pressure effects on stack performance to be negligible between 135 and 565 psia (Ref. 4). A practical PEM system is likely to store gases at higher pressure. The general design principle is to operate at the highest pressure that still allows for an acceptable RTE (Ref. 14).

In Figure 4 and Figure 5, RFC net specific energy and RTE, respectively, are presented for EZ operation at 500, 1,500, 2,000, 2,500, and 4,000 psia. Operation at higher pressure increases the mass of the gas storage vessels, EZ stack hardware, and BoP components to generate and isolate the greater pressures. Reactant storage at 4,000 psia results in the lowest specific energy for all calculated power levels. There is also a penalty to low-pressure operation at small scales. For RFCs smaller than 1 kW, 500 psia storage is worse than the 1,500- and 2,000-psia cases, but it provides a benefit at 10 kW and greater. Below 1 kW, specific energy is maximized at 1,500 psia storage pressure. These results all align with the trends and magnitude of impact modeled for the equator, but the specific energy values all tend to be lower for the south pole because of the lower total energy storage quantity.

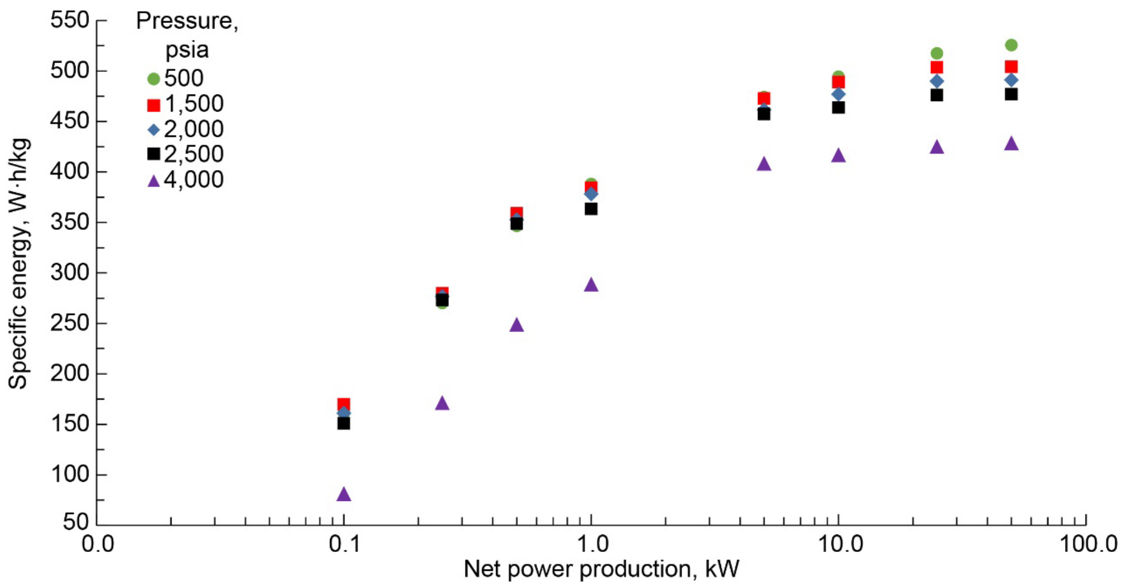

Figure 4.—Effect of electrolyzer operational pressure on regenerative fuel cell net specific energy at various power production levels.

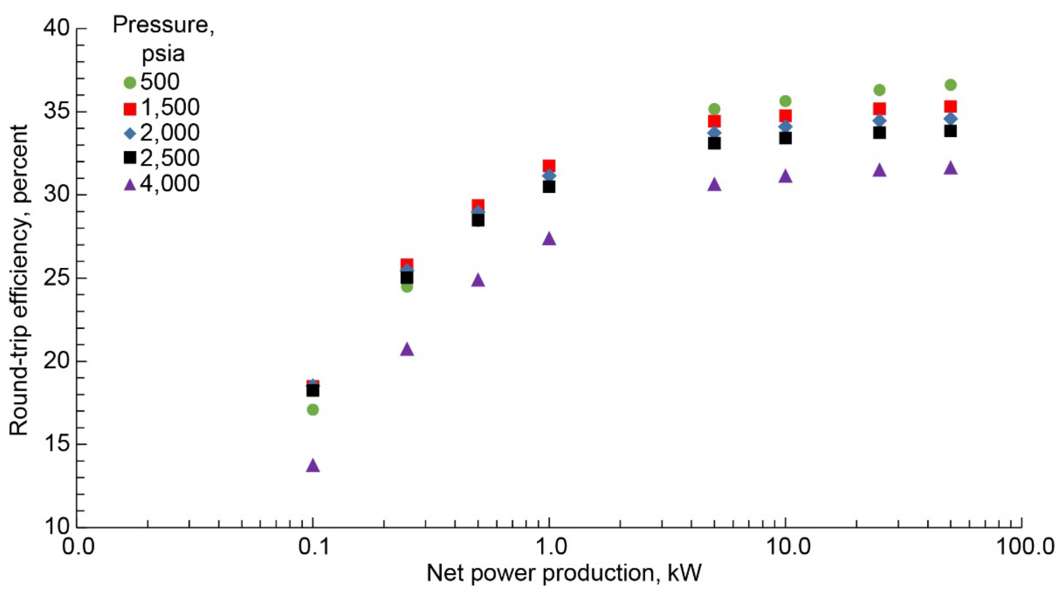

Figure 5.—Effect of electrolyzer operational pressure on regenerative fuel cell round-trip efficiency at various power production levels.

The RTE results are similar to the specific energy results. Lowering operational pressure from 4,000 to 1,500 psia improves efficiency in all cases. Reducing the pressure from 4,000 to 2,000 psia provides a 3- to 5-percentage point increase in RTE. Further reducing pressure from 1,500 to 500 psia improves efficiency for RFCs ≥1 kW, but for RFCs <1 kW it provides only equivalent or even slightly worse performance.

RTE improvement as pressure decreases is mostly a result of reduced pressure-driven back diffusion, or crossover, losses in the EZ. In terms of current density, these diffusion losses equate to 18 mA/cm^2 at 500 psia and 142 mA/cm^2 at 4,000 psia for a 0.25-mm-thick membrane based on equations sourced from the Handbook of Fuel Cells (Ref. 15). Operating such an EZ at a design maximum current density of 1000 mA/cm^2, 4,000 psia operation automatically results in at least a ~15-percent efficiency reduction during electrolysis. Without improved membrane technology, operation at such high pressures is impractical unless system volume becomes the primary performance metric (where doubling reactant storage pressure effectively equates to halving the RFC volume). Section 3.4.2 further investigates the impact of EZ membrane thickness on reactant crossover and EZ efficiency.

In designing power generation and energy storage systems, it is also useful to note cases where there are decreasing or few benefits to increasing system scale. It is at such a point where an RFC designer may wish to separate the system into modular blocks to improve reliability. This can be seen where the rate of increase in RTE or specific energy diminishes in size as RFC power level increases. For example, in Figure 5, the RTE for a 10-kW RFC is 34.8 percent, but it increases to only 36.3 percent at 25 kW and 36.6 percent at 50 kW. Past design studies have selected modular units to meet up to 75 kW of electrical power demands (Ref. 4). If there is minimal mass or efficiency benefit to a 50-kW RFC over a 25-kW unit, two 25-kW units provide at least one level of redundancy by conservatively sizing electrochemical stacks. Even better would be five 10-kW units. Wynveen presented a baseline design that consisted of four modular units and recommended focusing on enabling improved reliability as opposed to prioritizing improved performance (Ref. 16). Given the scope of RFC reliability unknowns, multiple parallel RFCs is perhaps the only way to meet the 5- to 10-year mission life requirements (Ref. 17). The results demonstrated here indicate that modular RFC units may still be the best option to meet mission requirements.

3.4.2 Electrolyzer Membrane Thickness

There are alternative membranes that are known to reduce gas crossover, improve mechanical and thermal stability, and improve operational efficiency relative to the current industry standard solid polymer electrolytes (Refs. 18 and 19) but none are readily commercially available for high-balanced-pressure PEM EZs. It is expected that near-term technological advances will change this scenario. EZ efficiency was evaluated as a function of pressure for sulfonated fluoropolymer membrane thicknesses of 178 μm (0.007 in.), 254 μm (0.010 in.), and 508 μm (0.020 in.). The results are shown in Figure 6 for operational pressures ranging from 100 to 10,000 psia for membrane thicknesses of 178, 254, and 508 μm. The relatively high ohmic resistance of the 508-μm membrane slightly impairs cell voltage performance versus thinner membranes at lower pressures. However, the thicker membranes do provide a benefit compared to the 178 μm membrane as crossover losses become more significant with increasing pressure. At 2,500 psia, the crossover current density is 45, 89, and 127 mA/cm^2 for 178-, 254-, and 508-μm membranes, respectively. In previous modeling efforts, 178-μm EZ membranes enabled EZ efficiency approaching a maximum of 75 percent at 3,000 psig, 78 percent at 2,000 psig, and 89 percent at 200 psig (Ref. 2). Grigoriev reported a mean stack efficiency of 85 percent (not including reactant crossover) when operating 178-μm reinforced membranes at 500 mA/cm^2 and pressures up to 1900 psia (Ref. 20). The values reported from this work are slightly lower, near 71percent, in the conditions that

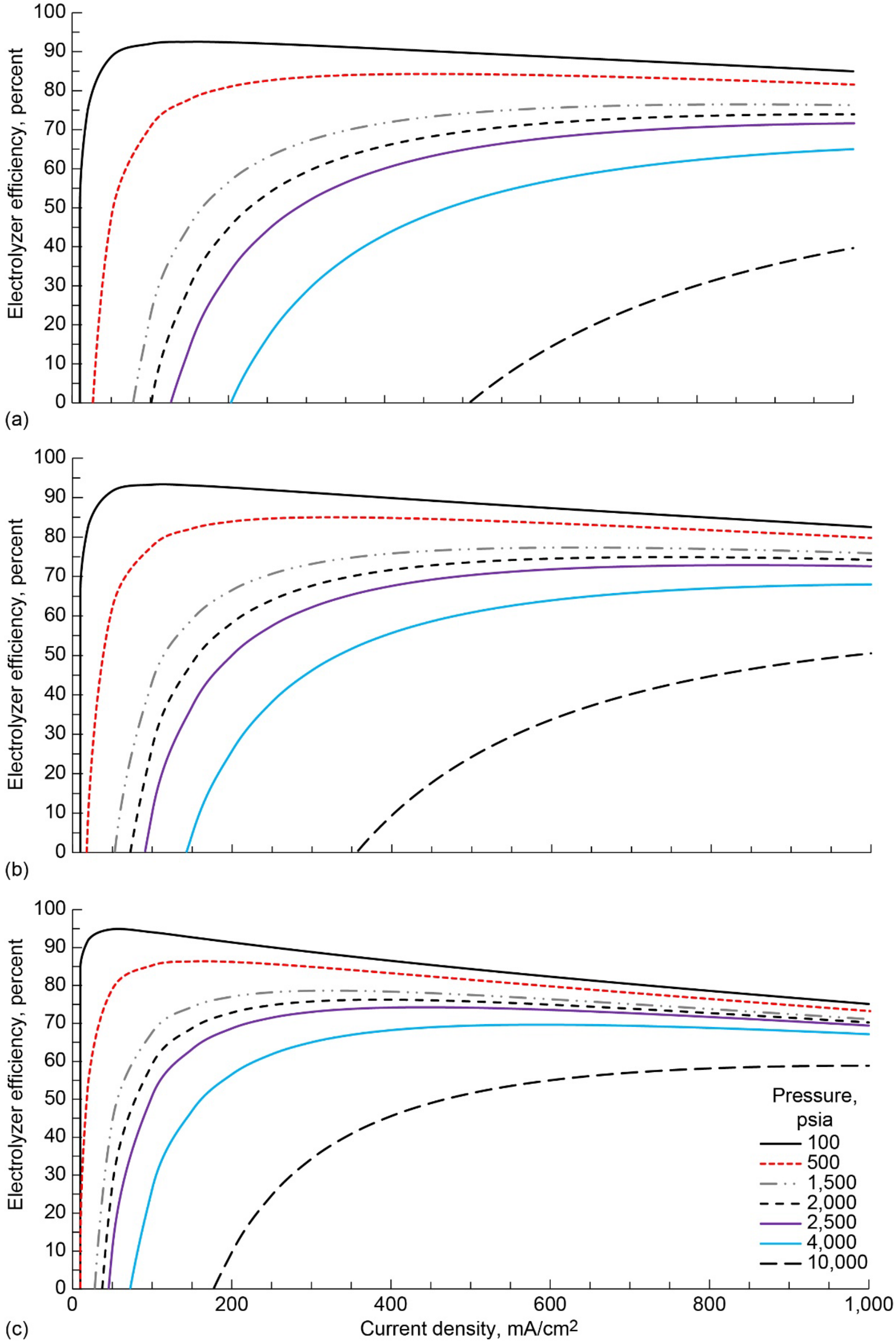

Figure 6.—Modeled electrolyzer efficiency as function of current density for range of operational pressures at different membrane thicknesses. (a) 178-μm- (0.007-in.-) thick membrane. (b) 254-μm- (0.010-in.-) thick membrane. (c) 508-μm- (0.020-in.-) thick membrane.

most closely approximate Grigoriev, because of the inclusion of more conservative estimates of reactant crossover. Still, the permeabilities used in this modeling effort to determine crossover rates are very similar to the values in Reference 21 (e.g., at 55 °C, 3.0 mol H_2/(cm·s·atm) and 1.6 mol O_2/(cm·s·atm) for the current model versus 3.2 mol H_2/(cm·s·atm) and 1.6 mol O_2/(cm·s·atm) in Ref. 21). In reality, exact cell design, operational procedures, and resulting membrane hydration levels are going to greatly impact the results.

Thicker membranes allow for much lower practical operating current densities, because of the trade-off between back-diffusion and ionic conductivity in liquid-fed EZs. Operation at low current density and high pressure with a thin membrane can produce effective efficiencies below 0 percent where the reactant crossover is greater than the operational current density. Maximum efficiencies are generally achieved at lower pressures and current densities in combination with a thicker membrane. For many cases, EZ efficiency is less sensitive to current density for thinner membranes (i.e., the slopes after achieving the maximum efficiency are smaller for the remainder of the current densities). This suggests that if an EZ must be produced well before the recharge load profile is firmly established and operating pressure is not expected to be too high, a thinner membrane might be a worthwhile selection. Thicker membranes are expected to be more efficient at low current density, but thinner membranes are potentially more efficient throughout the moderate current density range and possibly enable higher current density operation (Ref. 2). The analysis here shows that such a statement regarding thicker membranes is true at lower pressures and current densities, but with the assumed EZ performance, 1 A/cm^2 remains too low a current density to fully realize most benefits. Afshari evaluated unbalanced pressure (i.e., atmospheric-pressure H_2) EZ performance up to 10 A/cm^2 and then concluded that thinner membranes were a necessity because of reduced concentration and ohmic losses (Ref. 22).

For 1,500-psia operation, Figure 7 shows that the 508-µm membrane enables the highest efficiency at 550 mA/cm^2 or less, the 254-µm-thick membrane provides the highest efficiency when operating at pressures between 550 and 950 mA/cm^2, and the 178-µm membrane is best at 950 mA/cm^2 and beyond. Increasing pressure further to 2,500 psia, as presented in Figure 8, the 504-µm membrane produces the

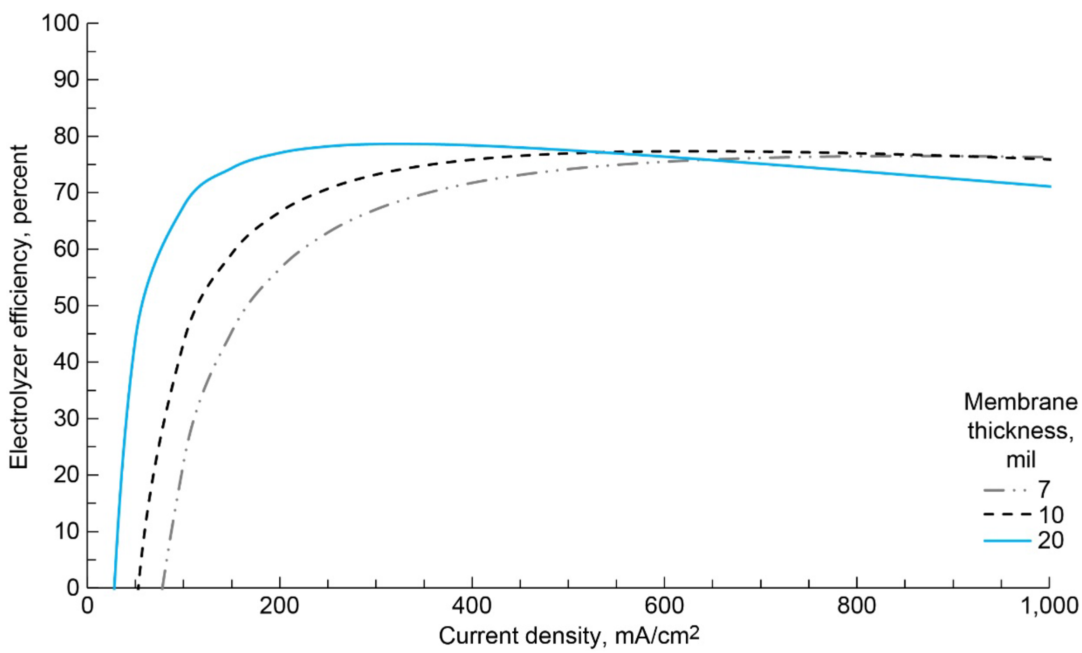

Figure 7.—Electrolyzer efficiency at 1,500 psia as function of current density for varying membrane thicknesses.

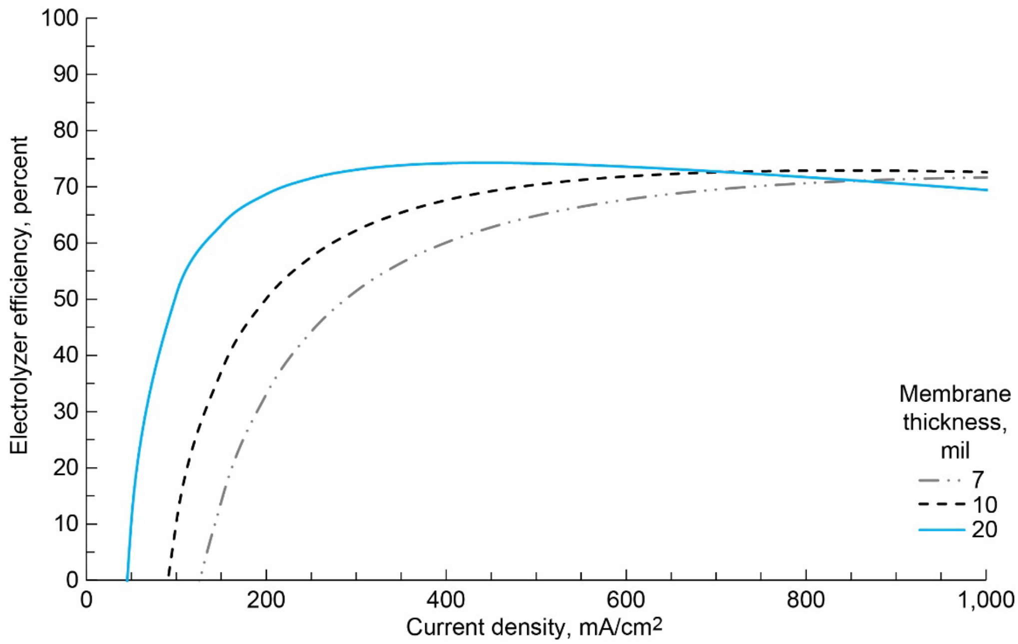

Figure 8.—Electrolyzer efficiency at 2,500 psia as function of current density for varying membrane thicknesses.

highest efficiency up through 700 mA/cm^2 and the 254-µm-thick membrane provides the highest efficiency beyond that point. Within the set operational current density limit, the thinnest membrane never equates to the highest efficiency.

3.4.3 Theoretical electrolyzer performance improvement

NASA has long aimed for an RFC RTE goal of 55 percent (Ref. 23), which stills aligns with current targets, but the realistic specific energy goal has advanced considerably (from 110 to 550 W·h/kg). This modeling shows that the specific energy target is nearly achievable at larger scales, but the RTE goal is a challenge for any lunar location. Although it is possible to approach 50 percent RTE in demonstration when considering only stack efficiencies, accounting for parasitic losses seems likely to drop efficiency into the 30 to 40 percent range, assuming the current mission parameters and assumptions. Improving practical RTE values requires further development of BoP components and high-balanced-pressure EZ performance, specifically reducing reactant crossover.

Since EZ efficiency is one of the most impactful factors in overall RFC performance and sets the ultimate limit on RTE, it is desirable to know how much potential EZ improvements could carry over to complete RFC system metrics. EZ efficiency can be improved in two ways. One, cell voltage could be reduced to improve thermodynamic efficiency. Second, reactant crossover could be reduced to improve Coulombic efficiency. These improvements could be achieved through further development of catalyst or membrane materials.

Table IV presents the EZ efficiency improvement impacts on overall EZ efficiency, RFC charge power, total system mass, and RTE, each at two different operational pressure levels. Pressure is not known to impact cell voltage (Ref. 20), but it is significant since reactant crossover is primarily a function of pressure once the EZ stack design is settled. Modeled cases include cell voltage improvements of up to 10 percent, meaning 10 percent reduction in the absolute value of the average cell voltage for a stack. Reactant crossover reductions consist of cases up to a 100 percent reduction, equating to no reactant crossover at all. The baseline cases using existing state-of-the-art performance estimates are presented as 0 percent improvements or reductions.

TABLE IV.—RFC PERFORMANCE BENEFITS FROM ELECTROLYZER EFFICIENCY IMPROVEMENTS

Pressure, psia	Voltage efficiency improvement, percent	Crossover reduction, percent	Electrolyzer efficiency, percent	Charge power, kW	System mass, kg	Round-trip efficiency, percent	Charge power reduction, percent	System mass reduction, percent	Round-trip efficiency improvement over baseline, percent
1500	0	0	75.4	1.95	238.9	32.1	-----	-----	-----
	1	0	76.1	1.93	238.7	32.4	–1.0	–0.1	1.0
	5	0	79.2	1.85	238.0	33.7	–5.0	–0.4	5.1
	10	0	83.5	1.76	237.0	35.5	–10.0	–0.8	10.8
	0	1	75.4	1.95	238.9	32.1	–0.1	0.0	0.1
	0	5	75.7	1.94	238.8	32.2	–0.4	0.0	0.4
	0	10	76.0	1.93	238.8	32.4	–0.9	–0.1	0.9
	0	50	78.7	1.87	238.0	33.5	–4.3	–0.4	4.5
	0	100	82.4	1.78	231.4	35.1	–8.6	–3.2	9.3
	10	10	84.2	1.74	236.8	35.8	–10.8	–0.9	11.8
4000	0	0	64.2	2.29	307.9	27.0	-----	-----	-----
	1	0	64.9	2.27	307.7	27.3	–1.0	–0.1	1.0
	5	0	67.5	2.18	306.8	28.4	–5.0	–0.4	5.1
	10	0	71.1	2.06	305.6	29.9	–10.0	–0.7	10.7
	0	1	64.4	2.29	307.8	27.0	–0.2	0.0	0.2
	0	5	64.9	2.27	307.6	27.3	–1.0	–0.1	1.0
	0	10	65.6	2.24	307.3	27.5	–2.0	–0.2	2.0
	0	50	71.3	2.06	304.8	30.0	–10.2	–1.0	11.0
	0	100	80.0	1.83	295.9	33.6	–20.1	–3.9	24.5
	10	10	72.6	2.02	305.0	30.5	–11.8	–0.9	12.9

Cell voltage efficiency improvements equate directly to reductions in required charge power. For crossover current reductions, charge power is reduced by the approximate reduction in total current density, the applied current density plus the crossover current. Stacks sized to operate at higher current densities are less affected by crossover. More conservatively sizing EZs or selecting reactant feed types that must operate at lower current densities will cause the crossover current to be more influential in this sort of analysis. Crossover reductions are more than twice as impactful on charge power and RTE for the 4,000 psia cases compared to the 1,500 psia cases. For a given membrane and operational temperature, crossover rate is primarily a function of pressure. A greater percentage of the charge power is productively used if there is less crossover. At 4,000 psia, eliminating half of the reactant crossover could improve RTE by 11 percent. By percentage, much smaller reductions in system mass are achievable as a result of EZ efficiency increases. Overall, thermodynamic improvements appear more impactful than Coulombic efficiency.

Past and current PEM research has often focused on reducing costs, usually in catalyst materials and quantities (Ref. 24). NASA applications are much more sensitive to improvements in performance, durability, predictability, and scalability. In the short term, it might be simpler to reduce reactant crossover by making design decisions such as selecting a thicker conventional membrane, although that also impacts thermodynamic performance, as opposed to pursuing more fundamental development that could in theory provide large reductions in operational cell voltage. Reference 22 stated, however, that there is a point of diminishing returns for further increasing membrane thickness to reduce crossover at a given pressure. As always, every design factor introduces various tradeoffs that must be considered, and it is likely that many methods to reduce crossover will impair cell efficiency (Refs. 20 and 24) or increase cost, limit operational ranges, and reduce life (Ref. 24). One should also note that the relative impacts of various losses (both reactant crossover and cell voltage consisting of various diffusion, ohmic, concentration, and activation losses) change with current density (Ref. 22), so different stack operating points will produce slightly modified results. Lastly, while this paper is focused on performance, reactant crossover is a significant safety issue that must be addressed (Refs. 20, 25, and 26). Grigoriev (Ref. 20) noted that product hydrogen purity decreases approximately linearly with increasing pressure, approaching the flammability limit as pressure exceeds 2,000 psia. Reference 22 predicted H_2 in O_2 concentrations well in excess of the flammability limits at pressures less than 40 bar (600 psia). These conditions would necessitate internal gas recombiners or external units as described in Reference 25.

3.4.4 Electrolyzer sizing and operational duration

The rate at which RFC recharge must proceed and the size of the EZ stack greatly impact efficiency. As previously shown for multiple lunar locations, from most starting points EZ efficiency can be improved by increasing the operational current density. This results from making the constant crossover current density smaller in comparison. Still, a system designer should not pursue an extremely oversized EZ stack and minimize the recharge time. This is complicated because of high efficiency not directly leading to the lowest stack mass and highest specific energy (Refs. 2, 13, and 27). Maximizing RTE can increase total stack masses by 2 to 5 times (Ref. 13), but stack mass is not the biggest factor for a lunar RFC where reactant storage dominates total system mass and volume. Higher charge rates also require higher charge power.

In Figure 9, an example 1-kW RFC system is modeled to show EZ efficiency for three different cell active areas as the goal recharge duration is varied. The cutoff point for minimum recharge time is set by the 1,000 mA/cm^2 maximum expected operational current density for the chosen EZ technology. Efficiency rapidly decreases at this point because of cell voltage losses. Elsewhere, the results are primarily dominated by reactant crossover. For a given goal recharge time, it is best to use the smaller stacks that minimize the total active area for crossover. To achieve the absolute highest efficiency values, increasing stack size offers the potential for improved efficiency.

Obtaining higher efficiency by increasing stack size is not possible without correspondingly increasing available recharge power. Although highest efficiency and specific energy are generally in agreement throughout this publication, the two are not always equivalent as design metrics, especially when considering the solar array power source in conjunction with the RFC. Solar array mass may make up ~70 percent of total system mass when considering an RFC plus PV array, so a designer must consider the complete system (Ref. 2).

Figure 10 demonstrates that all three stack sizes require similar power inputs of 1 to 3 kW throughout the common operational time ranges. Operating below 100 h requires the 100 or 150 cm^2 stacks and more than 3 kW input power. To shorten recharge to 50 h or less demands at least a 150 cm^2 active area and 6.5 kW input power. This is a significant change in demand on the whole power system. Whereas improving efficiency provides the opportunity to reduce solar array size, improving EZ efficiency only partially counteracts the large power increase required to operate an oversized EZ at higher rates. A system designer must balance the desire to improve efficiency with the charge power level, as the mass of an oversized solar array could negate the efficiency improvement benefits.

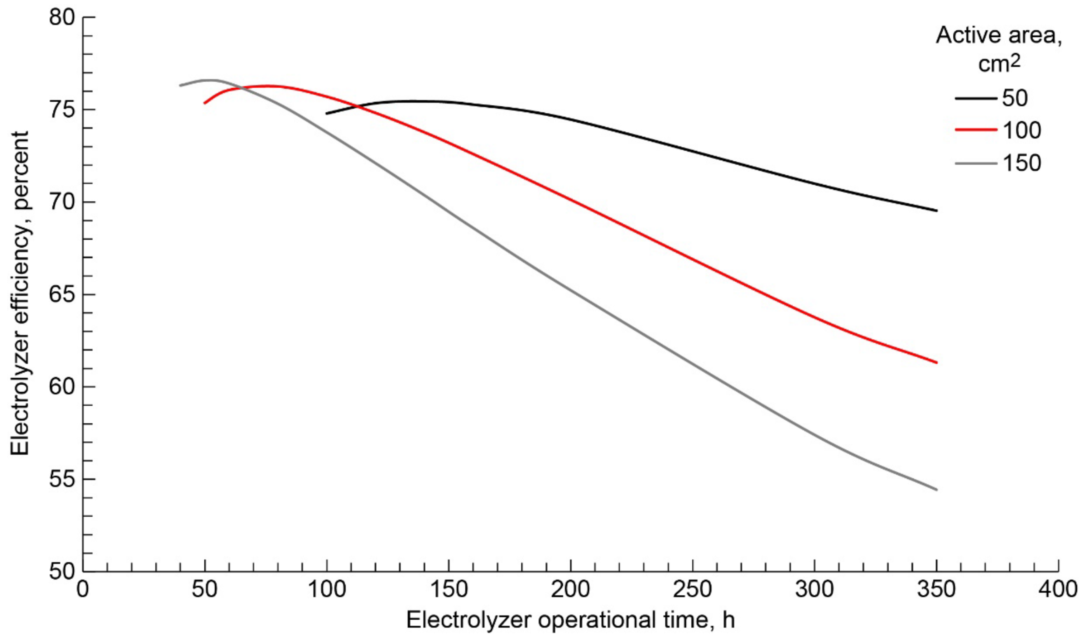

Figure 9.—Electrolyzer overall efficiency at various electrolyzer operational times for 33-cell electrolyzers operating at 1 A/cm^2 with either 50, 100, or 150 cm^2 active area per cell.

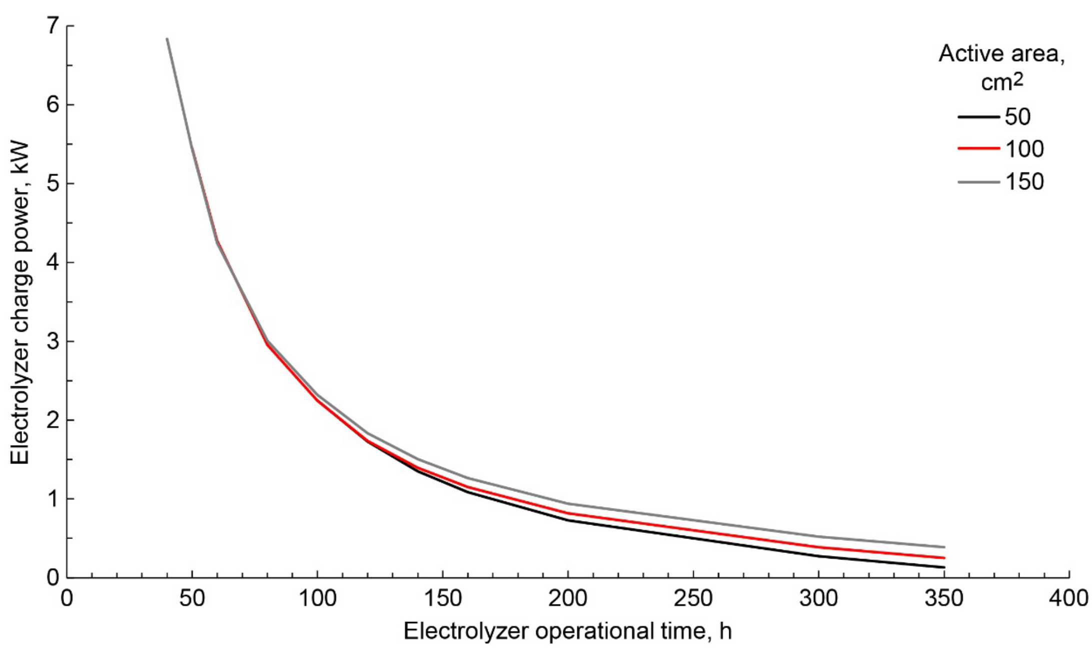

Figure 10.—Maximum regenerative fuel cell input power required from solar array to complete electrolysis cycle in various operational times for 15-cell electrolyzers with either 50, 100, or 150 cm^2 active area per cell.

3.4.5 Operational Temperatures

Historical data suggest that the optimum temperature for high-pressure operation (>400 psia) is somewhere between 45 and 65 °C. Manufacturers often specify different ideal operating temperatures for distinct cell designs and stack sizes. This suggests there are design-specific factors not captured by single-cell testing. For RFC systems, the EZ operational temperature is a tradeoff among:

- System-level RTE
    - Electrochemical efficiency
    - Compression or pumping
    - Thermal (parasitic loads)
    - PMAD (parasitic loads)
- Operational life
    - Stack
    - Thermal system
- Mass
    - Reactant
    - Thermal system (to operate the EZ at such a low temperature during the lunar day)
    - PMAD system (particularly DC/DC converters)

Because of these additional considerations included at the system level, it is probable that the EZ may not necessarily be optimized at the stack level because of benefits gained at the system level. This analysis prioritizes complete system RTE.

Figure 11 shows the effect of EZ average cell operating temperature on RTE. EZ operating temperature was set to 50, 60, 70, and 80 °C. Increasing temperature generally improves cell voltage performance (i.e., increasing efficiency) (Ref. 14). There is a converse effect, however, in that membrane permeability also increases with temperature. At 1,500 psia balanced pressure operation with a 0.010-in.-thick membrane, there is gas crossover equivalent to 79 mA/cm^2 at 80 °C, but only 44 mA/cm^2 at 50 °C. Others have found that temperature had no impact on hydrogen concentration on the anode side (Ref. 22), but this does not necessarily mean crossover rate did not change with temperature, only that the same balance was maintained for crossover and recombination. This crossover impairs EZ efficiency enough to reduce RTE with increasing EZ temperature at any power level. Across the evaluated power levels, there is a decrease in RTE of 1 to 2 percentage-points when raising temperature from 50 to 80 °C. Lower operating temperature is also known to reduce membrane degradation (Refs. 28 to 31), so lower operational temperature is clearly preferred if other compromises can be accepted.

The primary reason to increase EZ operating temperature is that radiator size reduces with high EZ operating temperature. Levy noted that higher stack operational temperature improves stack voltage performance and eases radiative heat rejection (Ref. 23). For an RFC in a lunar environment where there are extreme temperature changes between day and night periods, the system radiator is most likely to be sized based off of the daytime operation. Because it takes more power to charge an RFC than the FC produces and there are much cooler environmental temperatures during FC operation, an RFC must reject more heat during times when it also happens to be hottest. Therefore, a warmer EZ stack gives a greater temperature difference to the sink temperature, reducing the required radiator surface area. If a lander design is particularly volume constrained, this may become a primary design factor. Unfortunately, there is a relatively narrow thermal operational range for PEMs: at certain locations daytime lunar sink temperatures may approach the typical operational temperatures, and increased gas crossover counteracts the cell voltage efficiency gains. When optimizing the system design, there must be consideration of all these issues.

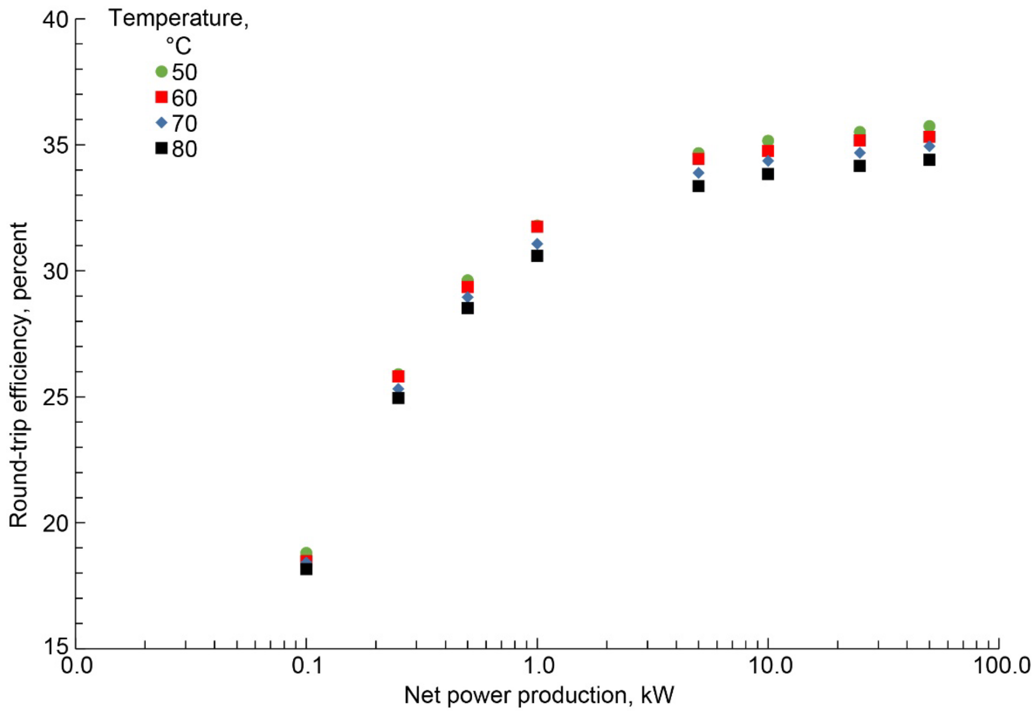

Figure 11.—Round-trip efficiency over a range of regenerative fuel cell scales when varying electrolyzer average cell operational temperature and maintaining 1,500 psia balanced pressure operation.

4.0 Conclusions

To design regenerative fuel cell (RFC) systems for anticipated NASA lunar south pole missions, it is best to optimize all possible aspects to maximize round-trip efficiency (RTE). Improving RTE benefits specific energy, reduces required charge energy, and reduces system mass. A 1-percentage point improvement in RTE reduces total system mass for a lunar south pole RFC by 1.1 percent. For RFCs scaled from 0.1 to 50 kW nominal net power output, the effects were evaluated for various operational setpoints, and component design and selection and parasitic power loads were ranked during fuel cell and electrolyzer operation. For a small-scale RFC, such as the 0.1-kW-class unit, the primary parasitic loads are related to solenoid valves, power management voltage converters, and reactant storage vessel heating. As RFC power increases, voltage conversion losses dominate, but the valves become much less impactful.

EZ operation was discussed to inform design decisions related to operating pressure and load profile. These are influential parameters in the resulting electrolysis efficiency and required charge power. Higher EZ operational pressure most negatively impacts both RFC RTE and specific energy. Thinner EZ membranes benefit efficiency at lower pressures, but the increased reactant crossover at higher pressure must be negated by use of thicker membranes to maximize efficiency and make operation practical. The relative impacts were compared for improving EZ thermodynamic and Coulombic efficiency, showing that Coulombic efficiency improvements are more impactful at higher pressure, especially at reducing required RFC charge power. Reduced EZ operational temperature improves efficiency at the expense of increased radiator size. For a given RFC scale, there is an RTE benefit to specifying larger EZs and recharging at higher rates, but only if the RFC can be coupled with a corresponding power source. Whenever possible, RFC energy storage systems should be designed in conjunction with the power source and customer. This is particularly necessary in cases where there are specific constraints on total volume or packaging specific components such as radiators and solar arrays.

Appendix

Regenerative Fuel Cell Design Assumptions

The design assumptions presented in Table V form the basis of the regenerative fuel cell (RFC) model inputs used throughout the report, unless evaluating a specific factor discussed in the text such as electrolyzer membrane thickness. This includes mission information (i.e., fuel cell (FC), electrolyzer (EZ), and photovoltaic (PV) array inputs) and reactant storage vessel design information such as that based on American Society of Mechanical Engineers (ASME) code.

TABLE V.—REGENERATIVE FUEL CELL (RFC) DESIGN ASSUMPTIONS

Input	Value	Units	Explanation
Location	Lunar south pole	----	Solar power profile and environmental temperature based on Shackleton Crater location.
Mission duration	1	yr	Used to estimate leak and vent rate of reactants over time to ensure adequate excess reactant capacity.
Mission case	Worst	----	Lunar day cycle with either the most total available solar energy (Best) or least (Worst). Best case for south pole assumes continuous solar power.
FC power load profile	Constant	----	Assume constant net power requirement.
Design FC current density	200	mA/cm^2	For sizing needed FC active area at nominal gross power output. Provides cell voltage of 0.84 Vdc and 54.5 percent efficiency.
Nominal system potential	28 to 120	Vdc	28 to 36 Vdc FC and electrolyzer (EZ) stack voltages for RFCs ≤1 kW. 120 Vdc for all larger RFCs.
FC internal cell temperature	70	°C	Affects reactant crossover calculation, thermodynamic properties, and thermal calculations.
Number of FCs in parallel	1 to 7	----	Additional FCs are assumed if needed cell active area is unrealistically large for one stack to produce enough power.
Percentage of excess reactant stored in vessels	20	%	--
Storage vessel types	Spherical	----	Steel-lined carbon composite pressure vessels
Number of reactant storage vessels	1	Each	--
Storage vessel design safety factor	6	----	Based on ASME Boiler and Pressure Vessel Code Section VIII Division I Rules For Construction of Pressure Vessels. UG-27. A conservative value. Flight missions may opt for a type III vessel that under AIAA S-081B requires a minimum of 1.5× safety factor, or a type III or V vessel where ISO 11119-2/3 requires a minimum of 2× safety factor.
Product water storage	N/A	----	Ideal-sized (calculated for exact model volume of product water) cylindrical carbon composite pressure vessel.
FC operating pressure	45	psia	--
FC membrane thickness	0.178	mm	--
EZ recharge time per cycle	100	h	--
EZ current density limit	1,000	mA/cm^2	--
Voltage regulation efficiency	95	%	--

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