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Power System Trade Studies for the Lunar Surface Access Module

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Abstract

A Lunar Lander Preparatory Study (LLPS) was undertaken for NASA's Lunar Lander Pre-Project in 2006 to explore a wide breadth of conceptual lunar lander designs. Civil servant teams from nearly every NASA center responded with dozens of innovative designs that addressed one or more specific lander technical challenges. Although none of the conceptual lander designs sought to solve every technical design issue, each added significantly to the technical database available to the Lunar Lander Project Office as it began operations in 2007. As part of the LLPS, a first order analysis was performed to identify candidate power systems for the ascent and descent stages of the Lunar Surface Access Module (LSAM). A power profile by mission phase was established based on LSAM subsystem power requirements. Using this power profile, battery and fuel cell systems were modeled to determine overall mass and volume. Fuel cell systems were chosen for both the descent and ascent stages due to their low mass. While fuel cells looked promising based on these initial results, several areas have been identified for further investigation in subsequent studies, including the identification and incorporation of peak power requirements into the analysis, refinement of the fuel cell models to improve fidelity and incorporate ongoing technology developments, and broadening the study to include solar power.

Background

Power system trade studies were performed as part of the Lunar Lander Preparatory Study (LLPS), which was sponsored by the NASA Constellation Program Office (CxPO), Advanced Projects Office. The LLPS consisted of multiple parallel teams from various NASA centers investigating creative design solutions for the Lunar Surface Access Module (LSAM). The LSAM consists of a descent stage to take a crew of four to the lunar surface and an ascent stage to return the crew to the Crew Exploration Vehicle (CEV) in low lunar orbit. Each team was tasked to pursue lander designs using the Exploration Systems Architecture Study (ESAS) LSAM design as a point of departure and investigating the widest possible tradespace using a given set of fixed requirements, bounded trades, and "desirements" presented by the CxPO. As part of a NASA Marshall Space Flight Center-led team consisting of Marshall Space Flight Center, Johnson Space Center, and Glenn Research Center personnel, power system trade studies were performed. The work presented here represents one concept that was explored as part of the multi-team effort.

ESAS Power System Results

The ESAS report was used as the point of departure for the LLPS. The ESAS descent stage power system consisted of three Proton Exchange Membrane (PEM) fuel cells. Each fuel cell was sized to generate the LSAM peak power requirement of 5.6 kW at 28 VDC before losses, or 5.0 kW after losses, based on a 90 percent Power Management and Distribution (PMAD) efficiency. The LSAM average power for the mission was determined to be 4.5 kW. The hydrogen and oxygen reactants for the fuel cells were drawn from the main propellant tanks.

Four lithium-ion batteries provided power to the ascent stage. The total ascent stage energy storage requirement was 4.0 kW (average) for 3 hours or 12 kWh. Three batteries were sized to meet the 12.0 kWh requirement, each providing 4.0 kWh with a fourth included for redundancy. With a PMAD

efficiency of 90 percent and a battery depth-of-discharge of 80 percent, each of the four batteries was sized to store 198.4 Ah at 28 VDC (ref. 1).

Power Profile

The baseline mission profile and anticipated power needs by mission phase for the LLPS are shown in table 1. The numbers are based on the average power required by each of the subsystems and include 15 percent Electrical Power Distribution and Control (EPD&C) margin and 10 percent power growth margin. The mission begins when the LSAM and the Earth Departure Stage (EDS) are launched into low earth orbit (LEO). The LSAM/EDS loiters in LEO up to 95 days until the CEV arrives with the crew and docks with the LSAM. Once docked, a trans-lunar injection (TLI) burn is initiated to send the LSAM/CEV on a trajectory to the moon. A lunar orbital insertion burn (LOI) sends the vehicle into a low lunar orbit (LLO). After a brief pre-descent loiter, the LSAM, with the crew inside, undocks from the CEV and descends to the lunar surface for a 7-day sortie mission. Upon completion of the mission, the ascent stage carries the astronauts to LLO to rendezvous with the CEV. Once the crew has entered the CEV, the ascent stage is jettisoned and the CEV begins the journey back to earth. During the time that the LSAM is docked with the CEV, the CEV provides power to the LSAM. For the purposes of this study, it was assumed that 1.5 kW is available from the CEV during all phases to power various LSAM subsystems.

TABLE 1.—POWER PROFILE BY MISSION PHASE

	LSAM/ EDS launch	LSAM/ EDS loiter	LSAM/ EDS dock with CEV	TLI burn	Outbound coast	LOI burn	Pre-descent loiter	Undock and descent	Lunar stay	Ascent and dock with CEV
Power (W)	1006	1018	1021	869	1048	2283	2376	3345	3900	3218
Time	2 hr	95 days	48 hr	1 hr	72 hr	1 hr	24 hr	3 hr	7 days	3 hr

The LSAM itself carries two independent power systems—one on the descent stage and one on the ascent stage. The descent stage power system provides all power for undock and descent operations and the lunar surface stay, as well as additional power for the LOI and pre-descent loiter phases if the power required by the LSAM exceeds the 1.5 kW available from the CEV. The ascent stage power system delivers power for ascent operations until the vehicle docks with the CEV.

Descent Stage

A fuel cell powerplant is composed of a fuel cell stack and its associated ancillaries (pumps, valves, regulators, separators, etc.) and hydrogen and oxygen reactant tanks. For long storage durations, fuel cells exhibit higher specific energies (Wh/kg) than batteries due to the independent sizing of the power (stack) and energy (reactants and tanks) components. Given that the descent stage power system must provide power for the 3-hr descent and 7-day surface operations, fuel cells were chosen as the descent stage power source for the LLPS.

The power profile for the LLPS was worked in parallel with the descent stage subsystem sizing and was continuously updated and refined as the study progressed. Therefore, in order to determine a starting point for the power system calculations, the ESAS average power requirement of 4.5 kWe at 28 VDC was chosen as the LLPS baseline power output for the fuel cell powerplant. Assuming a 90 percent PMAD efficiency, which is representative of state-of-the-art systems, each fuel cell was sized to deliver 5 kWe before losses. It was determined that two fuel cell powerplants, one primary and one back-up, would be carried on the descent stage. The hydrogen and oxygen reactants were sized for 195 hr of fuel cell operation, which included the 3-hour undock/descent operation, 7-day surface operations, and 1-day

contingency. To reduce mass, hydrogen and oxygen was drawn from the main propellant tanks to feed the fuel cells, eliminating the need for dedicated tanks.

A PEM fuel cell stack model was developed to predict performance, mass, and volume based on an advanced technology concept under development by Teledyne Energy Systems (TES) as part of the Exploration Technology Development Program. To estimate the ancillary mass and volume, an algorithm was developed that predicted mass and volume as a function of reactant mass flow rate. The algorithm was based on ancillary size estimates for a TES flight hardware design (ref. 2) and an Environmental Research and Sensor Technology (ERAST) flight design (ref. 3).

The mass breakdown of the power system is shown in table 2. The fuel cell stack consisted of 40 cells, each with an active area of 302 cm^2, operating at 520 mA/cm^2 to achieve the 28±4VDC range required by the PMAD system.

TABLE 2.—DESCENT STAGE
MASS BREAKDOWN

Component	Mass, kg
Fuel cell powerplants	74
Reactants	412
PMAD	114
Total	600

Operating the fuel cell at a lower current density was considered during the course of this study. Lowering the current density of the fuel cell results in higher efficiency operation, thus decreasing fuel consumption (i.e., lower tank and reactant mass) at the expense of increasing powerplant mass. For long mission times, where reactant and tank mass dominates the total system mass, reducing the current density can lead to a lower system mass. Sizing the fuel cell to operate at 100 mA/cm^2 resulted in a mass increase of 36 kg for the fuel cell powerplant and a reduction in reactant mass of 41 kg, for a net overall decrease of 5 kg. Since the reactants were stored in the propellant tanks, additional savings in tank mass was negligible since the change in reactant mass represented less than 0.5 percent of the total propellant mass stored. In this scenario, the fuel cell stack was composed of 192 cells arranged in 6 parallel stacks of 32 cells to provide 5 kW at 28 VDC. Therefore, reducing the current density would have added additional complexity for minimal mass savings and was not pursued further in this study.

Table 3 shows the approximate dimensions of the major components and the associated volumes. The PMAD component mass and volume is representative of state-of-the-art 28V space systems.

TABLE 3.—DESCENT STAGE COMPONENT DIMENSIONS AND VOLUMES

Component	Approximate dimensions, cm	Volume, cm^3	Quantity	Total volume, cm^3
Fuel cell stack	24×36×33	28,512	2	57,024
Fuel cell ancillary section	43×43×43	79,507	2	159,014
PMAD distribution box	31×6×2.5	465	2	930
PMAD miscellaneous (wiring bundles, receptacle boxes, control panels, etc.)	N/A	52,328	1	52,328

As can be seen in table 1, the final power profile shows a maximum power requirement of 3.9 kWe (4.3 kW before losses), which occurs during the 7-day lunar stay, less than the 5.0 kW baseline powerplant. However, since the descent stage was designed to accommodate the mass and volume of the 5.0 kW powerplant, the decision was made to retain the larger powerplant rather than downsize it to allow for future mass and volume growth. In addition, the excess energy capacity of the larger system (i.e.,

excess reactants) was retained to augment the energy required during the LOI burn and pre-descent loiter when the power required exceeded that available from the CEV.

Ascent Stage

Upon completion of the lunar stay, the ascent stage carries the astronauts from the lunar surface to low lunar orbit where it docks with the CEV. The crew transfers to the CEV for the return trip and the LSAM ascent stage is jettisoned. For the purposes of the LLPS, a three-hour ascent operation was assumed. Both lithium-ion batteries and PEM fuel cells were considered for the ascent stage power system. The fuel cell technology assumptions and sizing methodology were the same as for the descent stage.

For the battery sizing, a representative cell size was chosen with the weight and volume scaled from commercial lithium-ion cells. Series and parallel combinations of the cell were used to meet the mission power and energy requirements. The mass of the battery was determined by multiplying the individual cell mass with the total number of cells and then applying a mass packaging factor of 1.5 to account for packaging, structure, and thermal considerations. Similarly, the volume was determined by summing the cell volumes and applying a volume packaging factor of 2.2.

The ascent power requirement of 3.2 kW shown in table 1 is based on a fuel cell powerplant and includes a fuel cell ancillary load of 500 W. If a battery is used instead of a fuel cell, the total ascent power required would be decreased to 2.6 kW after removing the ancillary load and readjusting the EPD&C and power growth margin, resulting in 7.8 kWh delivered for the 3 hr operation. Due to the fact that the ascent batteries are only required to perform for one cycle, a high depth-of-discharge (DOD) was chosen to minimize battery mass. Assuming 90 percent PMAD efficiency and 90 percent DOD, the total stored energy was 9.6 kWh. The battery redundancy scheme was carried from the ESAS report where three battery modules supply full power with a fourth carried for redundancy. Each module is rated at 3.2 kWh. At 28 VDC, each module will need be sized to produce 115 Ah.

For the purposes of the trade, a 58 Ah cell with a specific energy of 125 Wh/kg at 100 percent DOD was assumed. Lithion produces a 55 Ah cell with this specific energy (ref. 4), and it was assumed that a 58Ah cell could be produced to meet the requirements of this application with a similar specific energy. Similarly, the energy density of the cell was assumed to be 277 Wh/l, similar to the 55 Ah cell, with cell dimensions of 13.8 by 3.4 by 16.6 cm. To meet the required 115 Ah, each LSAM module was comprised of sixteen 58 Ah cells (8 cells in series, 2 parallel strings) operating at a nominal 3.6 V/cell to provide 3.2 kWh at 28 VDC. A summary of the battery system mass is shown in table 4, while table 5 shows the volume and dimensions of the battery system components.

TABLE 4.—MASS SUMMARY FOR
ASCENT BATTERY OPTION

Battery	
Component	Mass, kg
Battery	160
PMAD	136
Total	296

TABLE 5.—DIMENSIONS AND VOLUMES FOR ASCENT STAGE BATTERY OPTION

Component	Approximate dimensions, cm	Volume, cm^3	Quantity	Total volume, cm^3
Battery module	34×33×25	28,050	4	112,200
PMAD distribution box	31×6×2.5	465	3	1,395
PMAD miscellaneous (wiring bundles, receptacle boxes, control panels, etc.)	N/A	76,445	1	76,445

The ascent fuel cells were configured to deliver 3.2 kW average to the loads (table 1). Assuming a three-hour ascent operation and 90 percent PMAD efficiency, the total energy stored is 10.7 kWh and the total power delivered is 3.5 kW. Two complete fuel cell powerplants were carried in this scenario to provide full redundancy. Each fuel cell stack consisted of 37 cells operating at 375 mA/cm^2 to achieve the 28±4VDC range required by the PMAD system.

The 375 mA/cm^2 current density represents the operating point that provided the minimum mass system for a 28VDC output given a fixed 302 cm^2 active area. Reducing the current density resulted in a higher system mass due to the relatively short mission time. For example, reducing the current density to 100 mA/cm^2 increased the powerplant mass by 22 kg while the reactant and tank mass was reduced by only 1 kg. Conversely, increasing the current density to 1000 mA/cm^2 and decreasing the cell active area to 175 cm^2 resulted in a 10 percent system mass reduction. The reduction in cell active area was required to maintain a 28VDC output from the powerplant. For this study, it was decided to select a 302 cm^2 active area to maintain consistency with the descent stage fuel cell and with the developmental hardware. In addition, the lower current density provided margin in the fuel cell operating range to meet peak loads that had not yet been defined.

Since the ascent vehicle did not utilize hydrogen and oxygen propellants, dedicated reactants tanks were needed to supply the fuel cell. Reactants were stored in the gaseous state at 5000 psi in carbon fiber tanks with titanium liners. Gaseous reactant storage was chosen to eliminate the complexity of storing cryogenic reactants during the two-week lunar stay. Two sets of tanks were carried, one for each powerplant, to provide redundancy. Reactants were sized for the three-hour ascent with 5 percent residuals. Table 6 shows the mass breakdown of the fuel cell system option for the ascent stage, while Table 7 shows the component dimensions and volume.

A comparison of the battery and fuel cell ascent options shows that, while the battery system had a 20 percent lower volume than the fuel cell system, the fuel cell option resulted in a mass reduction of approximately 26 percent. Since the ascent vehicle was mass constrained, fuel cells were chosen as the baseline power system for the ascent stage.

TABLE 6.—MASS SUMMARY FOR
ASCENT FUEL CELL OPTION

Fuel cell	
Component	Mass, kg
Fuel cell powerplants	56
Reactants	9
Tanks	17
PMAD	136
Total	218

TABLE 7.—DIMENSIONS AND VOLUMES FOR ASCENT STAGE FUEL CELL OPTION

Component	Approximate dimensions, cm	Volume, cm^3	Quantity	Total volume, cm^3
Fuel cell stack	22×34×30	22,440	2	44,880
Fuel cell ancillary section	38×38×38	54,872	2	109,744
PMAD distribution box	31×6×2.5	465	3	1,395
PMAD miscellaneous (wiring bundles, receptacle boxes, control panels, etc.)	N/A	76,445	1	76,445

Future Work

The work presented here is a first order analysis to meet the LSAM mission requirements. While fuel cells look promising based on these initial results, several areas have been identified for consideration in subsequent studies. The first among these is the refinement of the power profile to include peak power requirements, which will have an effect on both battery and fuel cell sizing. The increased discharge rates associated with peak power will influence battery cell selection and could potentially add parallel strings to the battery module to meet the higher discharge current without exceeding cell discharge rate capability. On the fuel cell side, nominal operational current densities may need to be lowered so as not to exceed the stack current density limits during peaking, resulting in the addition of cells, and mass, to the fuel cell stack. Fuel cell ancillary equipment must also be sized to accommodate increased reactant flow rates associated with higher power output.

The impact of storing the descent stage fuel cell reactants in the propellant tanks should also be addressed in greater detail through a trade of the mass reduction benefits of this approach versus the added complexity. If a decision is made to carry dedicated reactant tanks on the descent stage, the effect of raising the descent stage fuel cell efficiency should be considered to minimize the reactant and tank mass.

Follow-on studies should also consider other power sources such as solar arrays in addition to batteries and fuel cells. The use of solar arrays for lunar surface power was touched on during the LLPS, but time constraints prohibited an in-depth analysis. Preliminary results showed that for sortie locations that have adequate solar illumination, solar arrays may be a viable option for producing some or all of the power required during the lunar surface stay, resulting in potential mass reductions by significantly decreasing the fuel cell reactant mass.

Finally, lithium-ion cells are commercially available and lithium-ion batteries have flown on various space missions. Although batteries are tailored to each mission application, there is sufficient design heritage and data available to produce fairly high fidelity mass and volume models. PEM fuel cells, on the other hand, are still under development and have not reached the level of maturity of battery systems. While the models used for this analysis have drawn on flight designs and engineering data, the fidelity of the fuel cell model is considered to be at a lower level than the battery model, primarily due to the lack of full system validation through flight-like hardware. As such, it would be prudent to review and update the model prior to any follow-on studies to incorporate future technology developments.

Appendix A—Acronyms

CEV Crew Exploration Vehicle
CxPO Constellation Project Office
DOD Depth of Discharge
EDS Earth Departure Stage
EPD&C Electrical Power Distribution and Control
ERAST Environmental Research and Sensor Technology
ESAS Exploration Systems Architecture Study
LEO Low Earth Orbit
LLO Low Lunar Orbit
LLPS Lunar Lander Preparatory Study
LOI Lunar Orbital Insertion
LSAM Lunar Surface Access Module
PEM Proton Exchange Membrane
PMAD Power Management and Distribution
TES Teledyne Energy Systems
TLI Trans-Lunar Injection

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
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