

**Paper Title:** Liquid Oxygen / Liquid Methane Integrated Power and Propulsion

The proposed paper will cover ongoing work at the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) on integrated power and propulsion for advanced human exploration. Specifically, it will present findings of the integrated design, testing, and operational challenges of a liquid oxygen / liquid methane (LOx/LCH<sub>4</sub>) propulsion brassboard and Solid Oxide Fuel Cell (SOFC) system.

Human-Mars architectures point to an oxygen-methane economy utilizing common commodities, scavenged from the planetary atmosphere and soil via In-Situ Resource Utilization (ISRU), and common commodities across sub-systems. Due to the enormous mass gear-ratio required for human exploration beyond low-earth orbit, (for every 1 kg of payload landed on Mars, 226 kg will be required on Earth) increasing commonality between spacecraft subsystems such as power and propulsion can result in tremendous launch mass and volume savings.

Historically, propulsion and fuel cell power subsystems have had little interaction outside of the generation (fuel cell) and consumption (propulsion) of electrical power. This was largely due to a mismatch in preferred commodities (hypergolics for propulsion; oxygen & hydrogen for fuel cells). Although this stove-piped approach benefits from simplicity in the design process, it means each subsystem has its own tanks, pressurization system, fluid feed system, etc. increasing overall spacecraft mass and volume. A liquid oxygen / liquid methane commodities architecture across propulsion and power subsystems would enable the use of common tankage and associated pressurization and commodity delivery hardware for both. Furthermore, a spacecraft utilizing integrated power and propulsion could use propellant residuals – propellant which could not be expelled from the tank near depletion due to hydrodynamic considerations caused by large flow demands of a rocket engine – to generate power after all propulsive maneuvers are complete thus utilizing previously wasted mass. Such is the case for human and robotic planetary landers.

Although many potential benefits through integrated power & propulsion exist, integrated operations have yet to be successfully demonstrated and many challenges have already been identified the most obvious of which is the large temperature gradient. SOFC chemistry is exothermic with operating temperatures in excess of 1,000 K; however, any shared commodities will be undoubtedly stored at cryogenic temperatures (90-112 K) for mass efficiency reasons. Spacecraft packaging will drive these two subsystems in close proximity thus heat leak into the commodity tankage must be minimized and/or mitigated. Furthermore, commodities must be gasified prior to consumption by the SOFC. Excess heat generated by the SOFC could be used to perform this phase change; however, this has yet to be demonstrated. A further identified challenge is the ability of the SOFC to handle the sudden power spikes created by the propulsion system. A power accumulator (battery) will likely be necessary to handle these sudden demands while the SOFC thermally adjusts.

JSC's current SOFC test system consists of a 1 kW fuel cell designed by Delphi. The fuel cell is currently undergoing characterization testing at the NASA JSC Energy Systems Test Area (ESTA) after which a Steam Methane Reformer (SMR) will be integrated and the combined system tested in closed-loop. The propulsion brassboard is approximately the size of what could be flown on a sounding rocket. It consists of one 100 lbf thrust "main" engine developed for NASA by Aerojet and two 10 lbf thrusters to simulate a reaction control system developed at NASA JSC. This system is also under development and initial testing at ESTA. After initial testing, combined testing will occur which will provide data on the fuel cell's

ability to sufficiently handle the power spikes created by the propulsion system. These two systems will also be modeled using General-Use Nodal Network Solver (GUNNS) software. Once anchored with test data, this model will be used to extrapolate onto other firing profiles and used to size the power accumulator.