IN-SITU PROPELLANT PRODUCTION TECHNOLOGY AT KENNEDY SPACE CENTER.

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Introduction: The capability to produce propellant In-Situ is critical to NASA's exploration goals. With approximately 90% of a rocket's take-off weight being attributed to propellant [1], it would be unsustainable and inefficient to rely on resupply missions for all off-planet propellant needs. Whether to Earth orbit, the Moon, Mars, or deep space, the propellant demands of NASA and the commercial space industry will continue to expand beyond what current methods and infrastructure can supply. In-Situ propellant production is not only a possible solution, but a necessary requirement.

Recent advancements have brought In-Situ Propellant Production (ISPP) from an "attractive alternative" as first explored by Ash, Dowler and Varsi, to a fully demonstrated technology [2]. The most notable advancement towards ISPP was the MOXIE demonstration on Mars, where NASA and MIT successfully extracted oxygen from the Mar's atmosphere on board the Perseverance Rover through solid oxide electrolysis [3]. Electrolysis is just one example of the many possible methods to create propellant in-situ, and researchers at Kennedy Space Center have been working to advance and expand ISPP technology. Kennedy Space Center has a history of performing ISRU based research, from lunar dust work in the Swamp Works lab to chemical processes in the Applied Chemistry Lab. More notably, KSC is known as the world's leading spaceport, meaning KSC has the infrastructure, safety measures, and experience to handle rocket propellants on small and large scales. This combination of capabilities qualifies KSC to serve a supporting role for In-Situ Propellants and Consumable Production according to the most recent NASA STMD center roles. This paper will give an overview of the current ISPP efforts underway at KSC, including lunar and Martian ISPP, and touch upon the future work that is possible within the capabilities of KSC research and technology.

Sabatier Reactor: One of the legacy ISPP technologies at KSC has been the Sabatier system, the system that was previously on board the ISS to recycle CO_2 as part of life support systems. The current Sabatier assembly at KSC was first reported in 2014 and assembled based on a design developed at Pioneer Astronautics. The assembly at KSC has been shown to produce pure methane and water products from CO_2 and H_2 with near 100% conversion [4]. There is an availability of CO_2 in the Martian atmosphere (95.3% CO_2) as well as an availability of CO_2 wherever there are astronauts present (producing an average of 1.08 kg of CO_2 per day per person) [5]. The main challenges in implementing this technology lie in the thermal management systems. Researchers at KSC have investigated the thermal management systems on the Sabatier assembly through experimental and modeling methods, with the guiding goal of producing 6978 kg of methane over 428 days as necessary for a human Mars return method utilizing "methalox" propulsion [6].

Oxygen from Regolith: When it comes to lunar ISPP, the main resource available is lunar regolith. Lunar regolith contains about 45% oxygen by mass, which can be extracted and utilized for propellant applications. There are two main oxygen-from-regolith (O2FR) technologies under development at KSC, Molten Regolith Electrolysis (MRE) and Carbothermal Reduction. The CaRD (Carbo-thermal reduction demonstration) project is being led out of JSC through an SBIR with Sierra Space, but the team at KSC is providing support in gas analysis and avionics. Carbothermal Reduction is an attractive ISPP technology because it has been demonstrated at a relevant scale for terrestrial processes and it can be compatible with a ride range of regolith, including lunar and Martian, although it requires multiple steps to result in oxygen [7]. The goal of this effort is to raise the technology readiness level by demonstrating carbothermal reduction in a relevant environment, working towards demonstrating the technology on the moon. Since the labs at KSC have experience developing advanced, flight ready gas-analysis technology through the M-SOLO instrument (Mass Spectrometer observing lunar operations), they were chosen to design a flight forward analytical instrument for the quantification of CO and CO_2 gases produced in the demonstration . In 2023, the teams came together at JSC to successfully demonstrate carbo-thermal reduction in a vacuum environment for the first time [8]. Work is still underway at KSC to finalize avionics in order to integrate a full system.

The other O2FR technology underway at KSC is MRE. Early work focused on characterizing volatiles emitted from regolith melts, increasing understanding of regolith melting under high vacuum, and down selecting a heating method for future scaling [9]. The main challenge of MRE is the high temperatures necessary, at least 1600 °C, to keep regolith and metal products in a molten state, but the benefit is the production of O_2 in two steps. Previous testing was done on a laboratory scale, and recently KSC partnered with Lunar Resources Inc. through an SBIR and the Game Changing Development (GCD) program with the goal of raising the technology readiness level and reducing the risks associated with scaling MRE [10]. This required the ability to detect and quantify pure oxygen, leading to the development of VMOMS (Volatile Monitoring and Oxygen Measurement System). The successful development of VMOMS now gives KSC the capability to monitor ISRU process gases. MRE work is underway, with the scaled reactor being tested under vacuum and results in the process of being analyzed.

Plasma Chemistry: The Applied Chemistry Lab at KSC is also working to develop plasma chemistry ISPP technology. This work is in its low technology readiness level and aims to use the highly energetic environment of plasma to induce chemical reactions and create hypergolic propellant products without traditional infrastructure. Plasma systems are advantageous due to their versatility and low temperatures compared to chemical or electrolysis processes. Recent advances to plasma power supplies have also allowed for low power requirements, and the team at KSC is utilizing these energy efficient systems. Previous efforts have demonstrated the production of dinitrogen tetroxide (N_2O_4) from air (O_2 and N_2) and simulated Martian atmosphere (95% CO_2, 3% N_2, 2% Ar). The team has also shown the production of hydrazine (N_2H_4) from nitrogen and hydrogen, with efforts still underway for optimization and scaling. The same experimental setup is also being utilized to explore the production of monomethyl hydrazine. *In-situ* application of this technology would require preprocessing to have the O_2, N_2, and H_2 necessary for these reactions, since those commodities are not readily available in a usable form off planet. This technology could also have applications in earth's orbit, where there are many spacecraft that utilize hypergolic propellants and could have extended lifespans with refueling capabilities.

Plasma technology can have a large number of ISPP applications. Plasma separation of CO_2 is a widely researched topic, with the guiding goal of creating oxygen from the Mars atmosphere at reduced temperatures and power requirements compared to electrolysis [11]. Another possibility is the creation of methane using hydrogen plasma with graphite electrodes. When it comes to lunar dust, the highly energetic environment of plasma can be an alternative O2FR method that avoids high temperatures. Positive hydrogen ions from hydrogen plasma can reduce silicates and create water from regolith [12]. Oxygen can then be extracted from this water via electrolysis. Each of these technologies has either been briefly investigated by or is within the capabilities of researchers at KSC.

Conclusions: Although some of the ISPP technologies described here are in further development stages than others, there is still much work to be done. None of these technologies produce oxygen, hydrogen, or methane in liquid form, the form necessary for propellant applications. There are constantly new off-planet resources being discovered and validated, bringing more possibilities to ISRU technology. Hopefully soon, there will be another demonstration similar to MOXIE, in which NASA can continue to prove ISRU, specifically ISPP, is the answer to long duration missions and continued planetary exploration. In the meantime, researchers at KSC will continue to serve the supporting role in for In-Situ Propellants and Consumable Production through work on the Sabatier reactor, oxygen from regolith, plasma based propellant production, and other emerging ISPP technologies.

References: [1] NASA Glenn Research Center. "Ideal Rocket Equation." 2023. [2] Ash, R.L., Dowler, W.L., Varsi, G., "Feasibility of rocket propellant production on Mars." *Acta Astronautica* Vol. 5, pp. 705-724. 1978. [3] NASA. "NASA's Oxygen-Generating Experiment MOXIE Completes Mars Mission." 2023. [4] Muscatello, A. C., Hintze, P.E., Gibson, T.L., et al. "Mars Atmospheric In Situ Resource Utilization Projects at Kennedy Space Center." *ASCE Earth & Space Conference*, Orlando, FL. 2016. [5] Ewet, M. K., Stromgren, C., "Astronaut Mass Balance for Long Duration Missions." *International Conference on Environmental Systems*, Boston, MA. 2019. [6] Hintze, P. E., Meier, A. J., Shah, M.G., DeVor, R., "Sabatier System Design Study for a Mars ISRU Propellant Production Plant." *International Conference on Environmental Systems*, Albuquerque, NM. 2018. [7] Gott, R.P., Olson, J. A., Azim, N., et.al. "Carbothermal Reduction Demonstration Gas Analysis Subsystem Development." *International Conference on Environmental Systems*, Louisville, KY. 2024. [8] NASA. "NASA Successfully Extracts Oxygen from Lunar Soil Simulant." 2023. [9] Engeling, K.W., Meier, A. J., Peterson, E., et al. "Characterization of Volatiles from Simulated Lunar Highland Melts Under Vacuum." *Lunar Polar Volatiles Conference*, Boulder, CO. 2022. [10] NASA Space Technology Mission Directorate. "Molten Regolith Electrolysis Annual Program Review." 2024. [11] McKinney, L., Pitts, R., Engeling, K., Guerra-Garcia, C. "Plasma Chemical Conversion and Resource Generation Beyond Low-Earth Orbit." *International Astronautical Conference*, Milan, Italy. 2025. [12] Gott, R., Peterson, E., Engeling, K., Azim, N., Franco, C., Olson, J. "Plasma Reduction of Regolith for Oxygen Liberation." *Gaseous Electronics Conference*, 2021.