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.
- Kennedy Space Center (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.
- 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.

NASA KSC Research & Technology supporting role: "*In-Situ* Propellants and Consumable Production"

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. The assembly at KSC has been shown to produce pure methane and water products from CO_2 and H_2 with near 100% conversion [2]. The system has been continuously used for experimentation from the lens of Martian ISPP since then, including the investigation of catalyst material, heat exchange configurations, and the recycling of hydrogen.
- The main challenges in implementing this technology for ISPP applications lies in the thermal management systems. The Sabatier process is exothermic, meaning it releases excess heat as part of its chemical reactions. 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 [3].

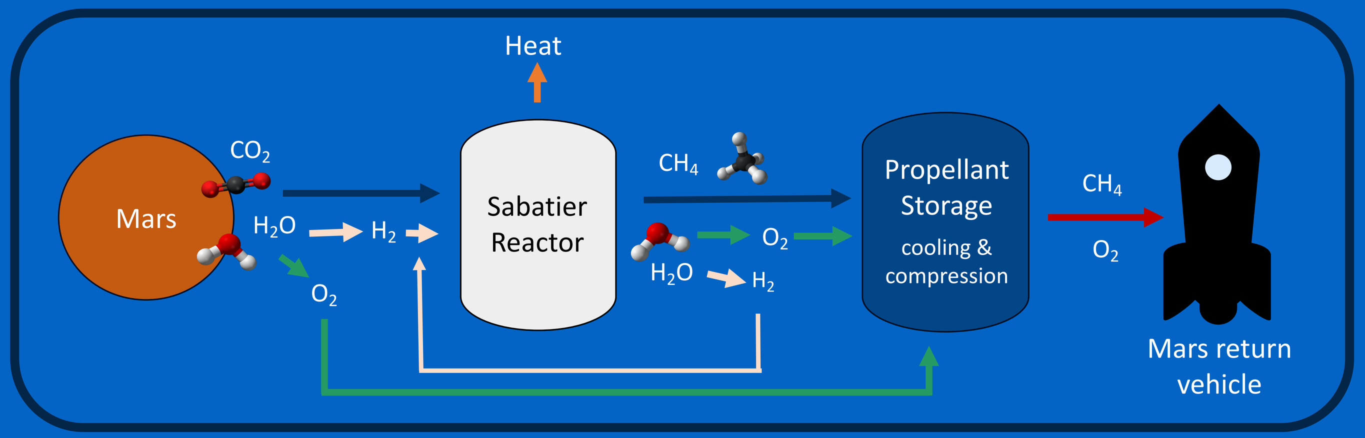


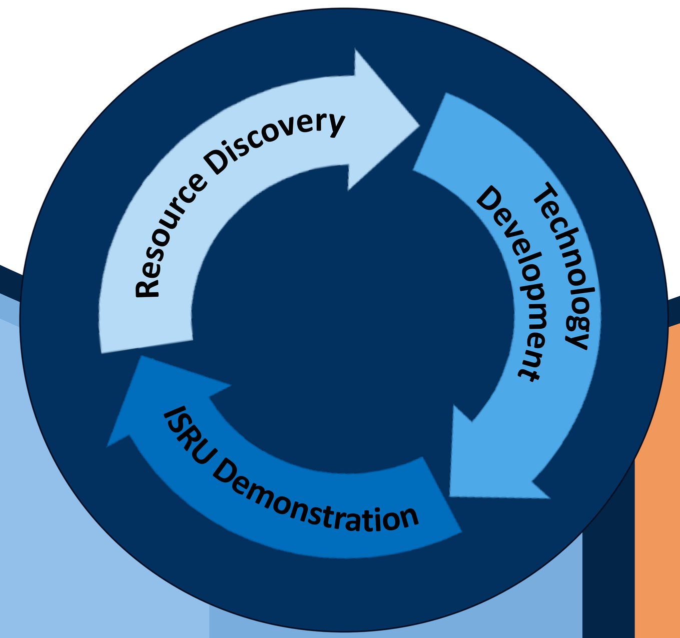
Figure 1: Overview of the Sabatier reaction for Martian ISPP applications

Researchers at KSC have been working to develop several ISPP technologies:

- the Sabatier reactor for methane & oxygen production on Mars
- molten regolith electrolysis and carbo-thermal reduction for oxygen production from lunar regolith
- plasma production of hydrazine, MMH, and dinitrogen tetroxide for off-planet hypergolic propellant production

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 propellants in liquid form, the form necessary for propellant applications.

There are constantly new off-planet resources being discovered and validated, requiring new technology development and bringing more possibilities to ISRU technology.



Plasma Chemistry

- Researchers at KSC aim to use the highly energetic environment of plasma to perform chemical synthesis.
- Plasma systems are advantageous due to their versatility, low power requirements, and low temperatures compared to chemical or electrolysis processes.
- Previous efforts have demonstrated the production of dinitrogen tetroxide (N_2O_4) from air (O_2 and N_2) as well as simulated Martian atmosphere (95% CO_2, 3% N_2, 2% Ar at Earth's atmospheric pressure).
- 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 monomethylhydrazine (MMH). Both are useful propellants for small spacecraft and satellites, with hydrazine, MMH and N_2O_4 fueling the Orion spacecraft.
- Plasma systems would likely need be paired with complimentary ISRU technology or require the transport of some reactants from earth.
- There are several other plasma based ISRU technologies that have already been demonstrated by researches at KSC or are within the scope of future work for KSC, shown in Table 1.

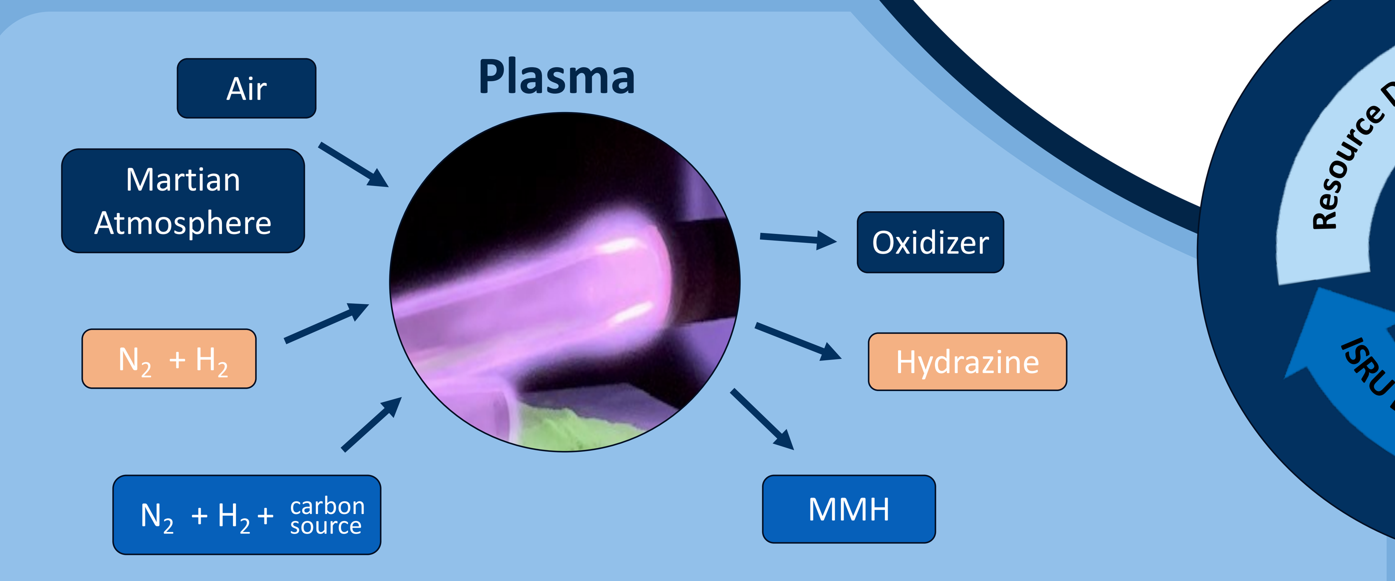


Figure 2: Reactants and products of the plasma propellant production processes being developed at KSC.

Application	Description	Goal/Outcome	Notes
Plasma Dissociation of CO_2	Using specific plasma conditions to perform carbon dioxide dissociation into carbon monoxide and oxygen.	Creating oxygen from the Mars atmosphere at lower temp-eratures and power requirements compared to electrolysis.	This is a widely researched topic [4], with the main challenge of preventing recombination of CO and O_2.
Plasma Production of CH_4	Using a hydrogen plasma with a graphite electrode to produce methane.	An alternative methane production method at lower power requirements than the Sabatier reaction.	This technology was briefly demonstrated at KSC.
Plasma Regolith Reduction	Positive hydrogen ions from hydrogen plasma can reduce silicates and create water from regolith [5].	An alternative O2FR technology that operates at lower temperatures and power requirements.	To produce O_2, this would be a multi-step process. This technology has been demonstrated at KSC.

Table 1: Overview of additional plasma based ISRU technologies.

Oxygen from 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 (CaRD).

Figure 3: Lab testing of regolith melts for off-gassing characteristics under high vacuum.

	CaRD: Carbo-thermal Reduction Demonstration	MRE: Molten Regolith Electrolysis
Description	• The CaRD (Carbo-thermal reduction demonstration) project is being led out of JSC partnered with Sierra Space, with the goal of raising the TRL through relevant environment testing and eventually a lunar surface demonstration. • In 2023, NASA performed the successful demonstration of carbon monoxide extraction from regolith in a vacuum environment for the first time [6].	• Early work focused on characterizing volatiles emitted from regolith melts, increasing understanding of regolith melting under high vacuum [8]. • KSC partnered with Lunar Resources Inc. with the goal of raising the technology readiness level and reducing the risks associated with scaling MRE [9]. • In 2024, NASA performed the successful extraction of molecular oxygen from regolith in a vacuum environment.
Challenges	• Requires multiple steps to result in oxygen. • Consumes a carbon source. • Requires high temperatures, at least 1500C.	• Requires high temperatures, at least 1600C, to keep regolith and metal products in a molten state.
Advantages	• Has been demonstrated at a relevant scale for terrestrial processes. • Can be compatibility with a ride range of regolith, including lunar and Martian.	• Production of oxygen in a 2-step process. • Produces metals as a bi-product which can be utilized for other ISRU applications.
KSC Role	• KSC was chosen to design a flight forward analytical instrument for the quantification of CO and CO_2 gases produced in the demonstration [7]. • KSC is providing support in avionics development for a full, flight ready system.	• KSC is the primary NASA center for regolith operations and performed the MRE scaled demonstration using the ASSIST (Atmosphere-to-Vacuum Simulated Space Test) chamber. • KSC developed VMOMS (Volatile Monitoring and Oxygen Measurement System) for quantification of O_2 during the MRE demonstration.

Table 2: Summary of oxygen from regolith technology development at KSC.

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Space Resources Round Table
June 2025