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Research into In-Situ Propellant Methods and Applications

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HONORS PROGRAM DIRECTED STUDY: IN-SITU PROPELLANTS

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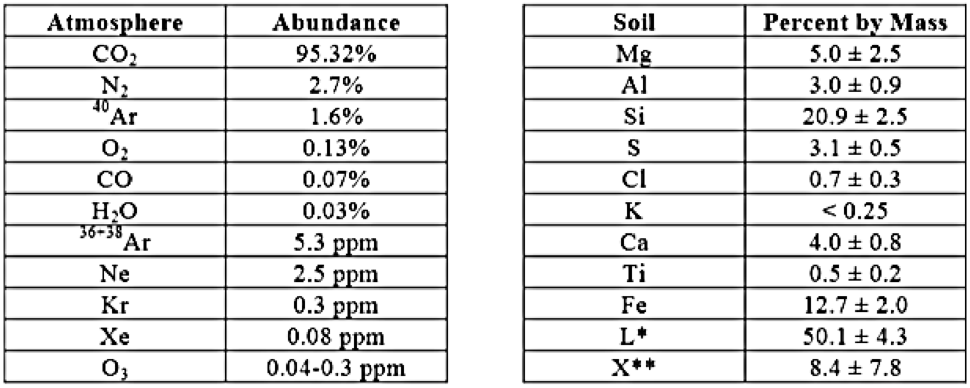
The topic of In-Situ propellants involves the study of how to use a planet's resources to create propellants for future space exploration. In-Situ propellant is part of the broader umbrella of In-Situ Resource Utilization (ISRU), but whereas ISRU focuses on using the available resources for purposes ranging from building materials to sustaining colonies, In-Situ propellant focuses on the production of propellants themselves. As organizations such as NASA and SpaceX continue to look at Mars and mankind's future in space, In-Situ propellant will play a key role in those plans. By utilizing In-Situ propellant methods, the mass requirements of missions launched from Earth will be reduced thus decreasing the cost and increasing the allowable payload mass. In addition to producing propellants, In-Situ propellant production (ISPP) will also lead to technologies that will support ISRU and possible involvement from the commercial industry. This papers provides an overview of In-Situ propellants, explores and evaluates five possible methods for production on Mars, highlights the benefits and difficulties of ISPP, and discusses how In-Situ propellant may impact other topics involved with space exploration.

As discussed above In-Situ propellant is a topic that explores how the available resources on a planet can be utilized to create propellants to help further space exploration. The "resources" mentioned above could be regolith, ice, atmosphere, thermal gradients, sunlight, and even discarded or waste materials generated by the mission itself (Simon 2007). The aforementioned resources are either directly used to generate the propellant or they are used in the process. Before determining the type of propellants that can be produced on Mars, the soil and atmosphere were analyzed. The following table was generated based off the results gathered by NASA's Viking program.



Atmosphere	Abundance
CO_2	95.32%
N_2	2.7%
^{40}Ar	1.6%
O_2	0.13%
CO	0.07%
H_2O	0.03%
$^{36-38}Ar$	5.3 ppm
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.04-0.3 ppm

Soil	Percent by Mass
Mg	5.0 ± 2.5
Al	3.0 ± 0.9
Si	20.9 ± 2.5
S	3.1 ± 0.5
Cl	0.7 ± 0.3
K	< 0.25
Ca	4.0 ± 0.8
Ti	0.5 ± 0.2
Fe	12.7 ± 2.0
L*	50.1 ± 4.3
X**	8.4 ± 7.8

Table 1: Atmospheric and Soil Resources on Mars
(Source: Boiron 2013)

As shown in the above table, CO_2 is the most abundant atmospheric resource and Si is the most abundant element found in the soil (L* represents the all of the elements not directly determined and X** represents all of the compounds not directly detected). While there are traces of naturally occurring propellants (CO and O_2) on Mars, they occur in such small quantities that harvesting them would be more difficult than producing fuel from the other resources (Clark 2008). Carbon dioxide would not be a good option as an oxidizer for rocket propellants as it is a low performance oxidizer. In this paper carbon dioxide is used in four of the five methods, but it is used to produce higher performance propellants using different reactions. A table displaying liquefaction temperatures, liquefaction energy, oxidizer/fuel ratio, combined average density, and specific impulse for oxygen and six different possible fuels can be seen below in Table 2: Propellant Data:

Constituent	Liquefaction Temperature (°K)	Liquefaction Energy (kJ/kg)	Oxidizer/Fuel Ratio	Combined Average Density (kg/m^3)	Specific Impulse (kN-sec/kg)
O_2	90.2	310	--	--	--
H_2	20.4	5900	5.0	324	4.18
CO	81.6	390	0.5	997	2.54
CH_4	111.4	460	3.4	812	3.35
C_3H_8	230.6	0	3.6	940	3.22
C_4H_{10}	273.6	0	1.7	852	3.09
CH_3OH	337.7	0	1.45	963	3.06

Table 2: Propellant Data
(Source: Ash 1978)

Looking at the above table, the oxygen would serve as an oxidizer while the rest of the constituents are possible fuels. From the data presented above, methane (CH_4) appears to be the best option for a fuel. Methane's liquefaction temperature is relatively close to that of Mar's ambient air (about 200°K) and the specific impulse for methane is the second best out of the possible fuels listed. In addition, methane's oxidizer to fuel ratio is the fourth smallest, methane's combined average density is the second smallest, and the energy required to liquefy methane is relatively small. Hydrogen as a fuel has the best specific impulse however the liquefaction energy is significantly larger than methane's and the oxidizer to fuel ratio is also larger than methane's. Having a large oxidizer to fuel ratio means that a propulsion system would have to carry a much larger supply of oxidizer compared to fuel and this would increase the total mass of the propellant required. The five methods examined in this paper focus on the generation of oxygen, hydrogen, carbon monoxide, and methane from the naturally occurring resources on Mars.

The first method looks at the production of oxygen and hydrogen from water. In order to obtain the necessary water for the reaction, the water can be collected from the atmosphere, the soil, and the polar ice on Mars. The Viking mission demonstrated that H_20 vapor could be released from Mars regolith by simply heating the regolith. Water can also be "mined" from the atmosphere, however, the limited availability of water in the atmosphere would make the process expensive in terms of energy (Clark 2008). Using the ice at the poles of Mars means the propellant production area would be limited to the poles of Mars. Once the water is obtained the direct electrolysis of the water molecules results in the following reaction occurring:

$$2\,H_2O \rightarrow 2\,H_2 + O_2$$

[1]**Equation 1**

Both the hydrogen and oxygen generated from the above reactions can be used as propellants. However, the energy required for the electrolysis method will be about 5.3 kWe-hr kg^{-1} of H_2O making this method expensive in terms of energy (Clark 2008).

The second method looks at the production of oxygen from the CO_2 found in the atmosphere on Mars. Carbon dioxide is the most abundant molecule found in the atmosphere on

Mars with an abundance of 95.32% as shown in Table 1: Atmospheric and Soil Resources on Mars. Having the ability to harvest the carbon dioxide from the atmosphere would allow propellant production to occur anywhere on Mars and would not limit the process to specific regions. To harvest and compress the carbon dioxide from the atmosphere a sorption compressor could be used. A sorption compressor works using a sorbent (a material that gathers a substance through absorption) bed that is alternately heated and cooled. The cooling process allows the sorbent bed material to absorb low pressure gas at a low temperature. The heating process of the sorbent bed works the opposite way of the cooling process; heating the sorbent bed allows the bed material to desorb high pressure gas at a high temperature. To cool the sorbent bed, the nighttime atmosphere on Mars will be used as temperatures typically reach about 200°K. Heating the sorbent bed would have to use artificial methods such as an electrical resistance heating element. After the sorption compressor desorbs the carbon dioxide, a zirconia solid-oxide generator could be used to strip the oxygen ion from the carbon dioxide molecule. To strip the oxygen ion the zirconia solid-oxide generator would work using electrolysis at elevated temperatures (about 750°C). In addition to stripping the oxygen ion, the generator could also separate the oxygen by applying a voltage to the zirconia crystal lattice which would allow only the oxygen molecules to pass through the lattice (Kaplan 2001). To test this method NASA's Johnson Space Center, the Jet Propulsion Laboratory, and the Glenn Research Center collaborated on a Mars ISPP Precursor (MIP) flight demonstration. A picture of what the MIP was designed as can be seen below in Figure 1: MIP Flight Demonstration Model:

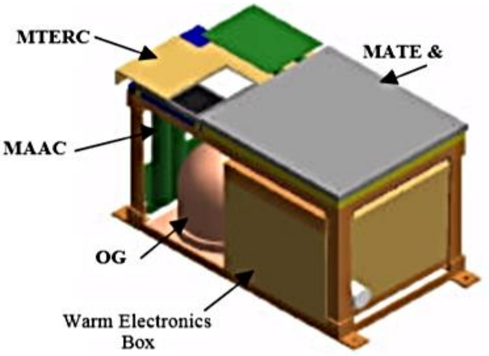


Figure 1: MIP Flight Demonstration Model
(Source: Kaplan 2001)

In the above figure, the MAAC stands for Mars Atmospheric Acquisition and Compression and OG stands for Oxygen Generator Subsystem. The MAAC would be used to absorb and compress the carbon dioxide from the atmosphere. The OG would be used to produce the required propellant grade oxygen. The initial predictions for the system was 0.5 standard cubic centimeters of carbon dioxide per a minute while operating (Kaplan 2001). The MIP was scheduled to launch in 2001 as a payload on the Mars Surveyor Lander, but the mission was canceled and the device was never tested.

The third propellant production method uses carbon dioxide found in the atmosphere on Mars and water found in the soil to produce methane and more water. The water used in this reaction can be extracted from the regolith on Mars using heat. After the water is extracted, electrolysis can be used to separate the hydrogen molecule from the oxygen atom and the following reaction takes place:

$$4H_2O \rightarrow 2O_2 + 4H_2$$

[2]**Equation 2**

Then the carbon dioxide collected from the atmosphere can be reacted with the hydrogen to produce methane and more water molecules using the Sabatier reaction as shown in Equation 3:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

[1]**Equation 3**

Not only does this reaction produce methane for propellant, but oxygen is also a byproduct of the first reaction with the water extracted from the regolith. Using electrolysis and then the Sabatier reaction a cycle can be created for propellant production as shown in Figure 2: Carbon Dioxide and Water Propellant Production Cycle:

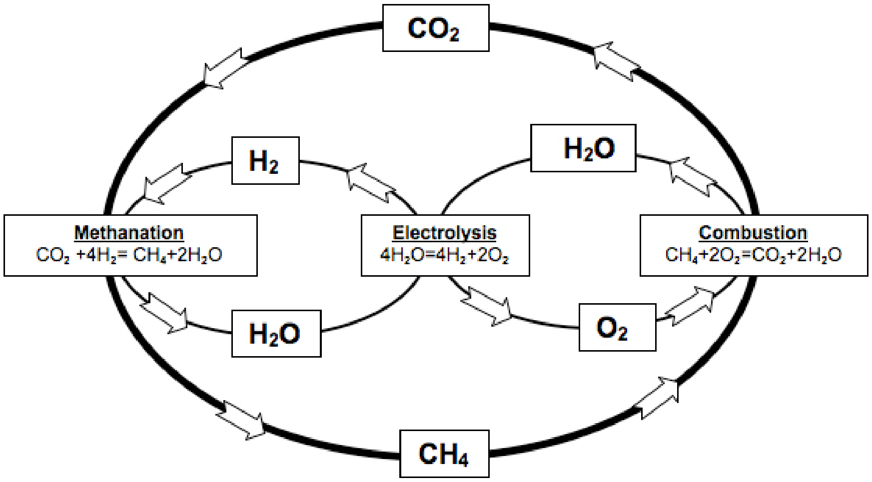


Figure 2: Carbon Dioxide and Water Propellant Production Cycle (Source: Barbarossa 2011)

In the cycle above, the water extracted from the regolith undergoes electrolysis which produces oxygen molecules and hydrogen molecules. The hydrogen then undergoes the Sabatier reaction using carbon dioxide from the atmosphere on Mars to produce methane and water molecules. The water molecules are then returned to the electrolysis process while the methane is used in a combustion process with the oxygen produced from the electrolysis process. The water produced by the combustion process is passed back into the electrolysis process and the carbon dioxide produced is passed into the Sabatier reaction. Theoretically once supplied with the initial reactants the cycle should be self-sustaining, however the cycle will not be perfectly efficient and isentropic so losses will occur. The cycle will have to be continually supplied with carbon dioxide and water to keep the propellant production cycle running. This process was originally suggested by Professor R.L. Ash in an article published in *Acta Astronautica* and he estimated that in order to produce propellant from 9 kg of water a day, a continuous power level of 1.875 kW must be supplied if an efficiency of 44.7 KWh/kg H_2 was assumed for the electrolysis cells (Ash 1978).

The fourth method examined in this paper uses the atmospheric carbon dioxide to produce carbon monoxide and oxygen. The carbon dioxide would be collected from the atmosphere on Mars and through thermal decomposition, carbon monoxide and oxygen could be produced as shown below in Equation 4:

$$2CO_2 \rightarrow 2CO + O_2$$ [1]**Equation 4**

To separate the oxygen and carbon monoxide produced in the above reaction, a zirconia membrane could be used as discussed in the second method with the MIP flight demonstration. While this method would eliminate the need for water and the possible location limitations, the propellants produced (the carbon monoxide and the oxygen) have lower performance than the propellants generated using the other methods (Clark 2008).

The fifth and final method explored in this paper is the production of hydrazines and oxidizers. The elements required to produce hydrazines and oxidizers (nitrogen, hydrogen, oxygen, and carbon) can all be found in the atmosphere on Mars and can be obtained through either reactions or harvesting them straight from the atmosphere as shown in Table 1: Atmospheric and Soil Resources on Mars. A propellant currently being investigated is nitrogen tetroxide and the required nitrogen and oxygen can be collected from the atmosphere. The main benefit to using this method versus the previous four methods is that the compounds produced would not need to be cryogenically stored. This would eliminate a part of the propellant production process that would require a lot of energy. However, the specific impulses of these propellants are lower than that of the earlier discussed propellants and the method to produce them are very complex (Clark 2008).

Using In-Situ propellant production methods would help several topics related to space exploration and not just the propulsion aspect. For instance, for space exploration to be plausible, methods to sustain mankind while out in space must be discovered. Space exploration is not feasible if humans would have to bring all their supplies for the whole trip from Earth. One large concern in space for long term manned missions is oxygen. Four out of the five methods discussed in this paper create oxygen from the natural resources found on Mars. The oxygen produced in these processes could be used for both propellant and as a sustained air supply for humans on long term missions. Water is also involved with two of the five methods and this could also be used as a resource by humans exploring space or living in a space colony. In addition to producing air and water, a significant amount of research must go into building materials and power supplies for the propellant production process. The research done in these fields can be translated into building materials for space colonies and for power supplies for those colonies. Finally, ISPP could help encourage the commercial industry to get involved with space exploration. Many of the methods mentioned above involved collecting resources from the regolith on Mars. The research involved with that collection process could possibly be applied to mining operations in space.

The three biggest difficulties involved with the ISPP methods discussed in this paper are the liquefaction of the propellants, the storage of the propellants, and the collection of water on Mars. As shown in Table 1 for the first four production methods, the propellants produced (oxygen, carbon monoxide, methane, and hydrogen) have a liquefaction temperature below the ambient temperature on Mars. This means that a method must be devised to cool the propellants to their liquefaction temperature after production. Once the propellants have undergone the phase change from a gas to liquid, the propellants must be stored in such a way that they remain liquids. The propellants will have to be insulated and refrigeration systems will have to be used. For both the liquefaction process and the storage process, additional power will be required to run the phase change process and the refrigeration system. Along with needing more systems and a larger power supply, the water extraction process may be difficult due to the variations in water availability from site to site. Water can be obtained by heating the regolith on Mars but there could be locations where there is very little water in the regolith. If a propellant production site is established at a site with minimal water resources, the process would either have to be moved or it would be forced to shut down.

The ISPP methods examined in this paper were specific for Mars and involved the production of oxygen, hydrogen, carbon monoxide, and methane. In-Situ propellant production is important to furthering space exploration as it not only provides a way for space ships to get propellants outside of Earth, but ISPP also furthers technology and industry participation. Having the ability to produce propellant outside of Earth will allow for long-term missions and will reduce the total propellant mass at launch. The technology that will be developed for ISPP can also be used to produce necessary resources, such as oxygen and water, for explorers. The research into building materials and power supplies for the propellant production process can also be applied to space colony developments. Overall In-Situ propellant production would not only assist space exploration, but also the space industry on a whole and continued development of these methods should be encouraged.

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