

INTEGRATED MARS IN-SITU PROPELLANT PRODUCTION SYSTEM. Anthony Muscatello, Douwe Bruinsma, and Robert Zubrin, Pioneer Astronautics, 11111 W. 8th Ave., Unit A, Lakewood, CO 80215, tony.muscatello@pioneerastro.com.

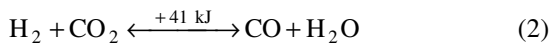
Introduction: Mars exploration can be greatly enhanced by the use of local resources to produce propellant. Producing rocket fuel for the return flight using *in-situ* resources greatly reduces the mass of the Mars lander. Combining the Sabatier reaction and the reverse water gas shift (RWGS) to convert hydrogen and carbon dioxide into oxygen and methane (with carbon monoxide as a waste product) provides a mass leverage ratio of 20:1. For example, a propellant payload of 500 kg on a Mars ascent vehicle delivered to the Martian surface as part of a Mars sample return mission can be replaced with 25 kg of hydrogen and an *in-situ* propellant production (ISPP) system. The goal of this phase II SBIR project is to develop such an ISPP system.

The Sabatier reaction converts hydrogen and carbon dioxide into methane and water according to the following reaction:



The water can be electrolyzed into hydrogen that can be recycled and oxygen that can be burned with the methane. The oxygen to methane weight ratio in equation (1) is 2:1, whereas stoichiometric combustion requires a ratio of 4:1 and optimum performance requires a ratio close to 3.5:1.

This problem can be resolved with the addition of the RWGS reaction:



To produce an oxygen to methane ratio of 4:1 twice as much carbon dioxide needs to be converted with the RWGS reaction than with the Sabatier reaction. This ratio leads to the following net exothermic conversion:



The goal of this project is to acquire carbon monoxide from a simulated Martian atmosphere and to convert it into rocket propellant according to equation (3) using an electrolyzer to convert the water into oxygen and hydrogen.

System design: The system was designed from the standpoint that the Sabatier and the RWGS reactions occur in a single reactor. This design maximizes heat conservation within the system and minimizes ancillary equipment. A single reactor design requires only one membrane separator, one condenser and one recycle pump whereas separate reactors would require two of each of these units. Hence the benefits of a single reactor are readily apparent.

A simplified schematic of the single reactor ISPP system is shown below with the omission of the carbon dioxide acquisition and the oxygen liquefaction systems.

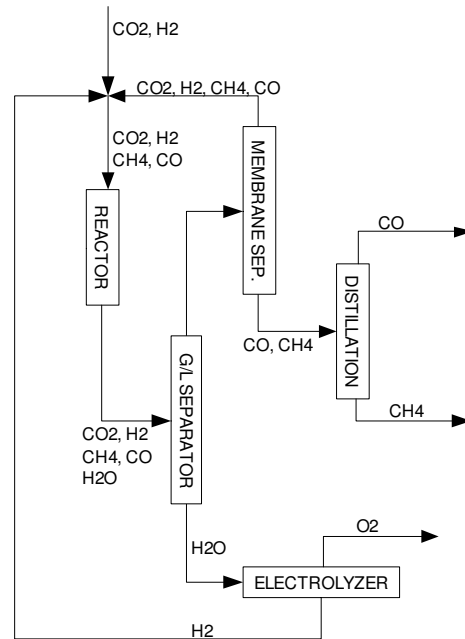


Figure 1: Schematic of ISPP system

Reactor optimization. Several reactor designs were tested with the most successful being a tube-in-tube reactor. A schematic of this the reactor is shown in Figure 2. The conversion of the Sabatier reaction was controlled by limiting the amount of catalyst in the reactor to 0.5 gram and sufficient catalyst (130 grams) was added to reach equilibrium conversion with the RWGS reaction. The Sabatier catalyst is 0.5 % ruthenium on alumina and the composition of the RWGS catalyst is CuO(57)/ZnO(31)/-Al₂O₃(11)/Promoter(1) where the values in parentheses are weight percentages.

Results: The system shown in Figure 1 was built excluding the distillation column. The distillation column and the oxygen liquefaction system will be integrated using a single cryocooler and this system is currently under construction. The system was built to produce about 1 kg of propellant per day.

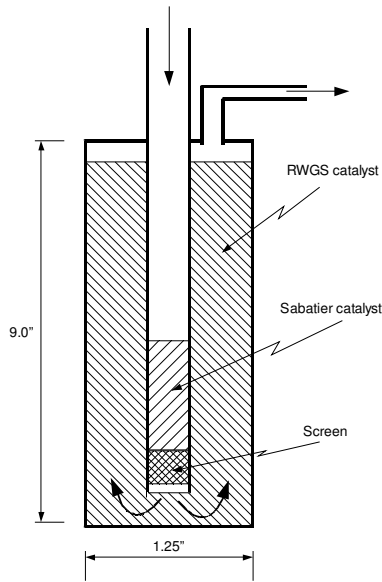


Figure 2: Schematic of tube-in-tube reactor.

Chemical conversion. Initial tests were performed with an electrolyzer integrated into the system to ensure that the hydrogen from the water could indeed be recycled back into the reactor. Some maintenance issues, however, prevented the integration of the electrolyzer for further testing.

The system was tested with a CO_2 feed of 0.63 SLPM and a H_2 feed of 1.26 SLPM. The outlet gas stream of the reactor was maintained at 3 bara and 375°C . And the recycle rate was set at 10 SLPM which produced a permeate pressure of 1.2 bara. The concentrations of the reactor feed, the dry reactor products, the membrane permeate and membrane retentate are presented below in mol fractions.

Table 1: Compositions in mol fractions of gas streams

	Reactor inlet	Reactor outlet	Permeate	Retentate (final product)
H_2	0.5834	0.5538	0.5917	0.0000
CO_2	0.2789	0.2316	0.2441	0.0015
CO	0.1000	0.1486	0.1188	0.6444
CH_4	0.0376	0.0661	0.0454	0.3541

These results reveal several important aspects about the operation of the ISPP system. First of all, the low concentrations of H_2 and CO_2 in the retentate show 100 % conversion of the hydrogen and 99.5 % conversion of CO_2 . Secondly, the ratio of CO to CH_4 is 1.8:1, which is close to the anticipated ratio of 2:1. The discrepancy is attributed to errors in the flow controllers. And third, the performance of the membrane separation is excellent. The permeate is enriched in H_2 and

CO_2 while the retentate consists of nearly pure CO and CH_4 .

Oxidizer:Fuel ratio control

An important aspect of an autonomous ISPP system is that the oxidizer to fuel ratio can be tightly controlled. Precise control of the oxidizer to fuel ratio was obtained by changing the feed $\text{H}_2:\text{CO}_2$ ratio as shown in Figure 3.

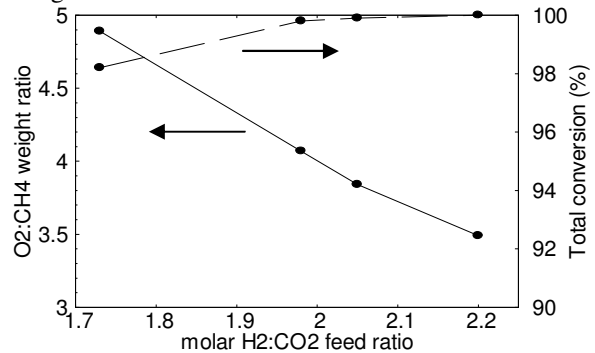


Figure 3: Oxidizer to fuel ratio vs. feed ratio

Energy usage. Through the use of regenerative heat exchangers, the energy consumption of the ISPP system was kept at a minimum. The chemical conversion process discussed above requires about 70 W to heat the reactor and about 10 W of cooling to cool the gas before the gas/ liquid separator. The net conversion in the reactor according to reaction (3) is exothermic and produces about 13 W, but this is not sufficient to account for the heat losses to the surroundings. Note that just preheating the gas going into the reactor requires 160 W, but most of this duty is provided by a regenerative heat exchanger.

The electrolysis of the water requires about 300 W and the recycle pump consumes 100 W of electrical power. This brings the total power consumption to 470 W for the chemical conversion process to produce 1 kg of propellant per day.

Conclusions: At this point we have demonstrated the feasibility of converting CO_2 and H_2 into CH_4 and O_2 with nearly 100% conversion in a single reactor. The chemical conversion process requires about 470 W of power to produce 1 kg of propellant per day.

During the remainder of this phase II SBIR project we will integrate a CO_2 acquisition system and a cryogenic distillation column. When a successful experimental system is developed the entire apparatus will be rebuilt into a complete end-to-end flight-like ISPP system.

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