Study of Sabatier Catalyst Performance for a Mars ISRU Propellant Production Plant

Carolina Franco Ph.D.[1]
AECOM, John F. Kennedy Space Center, FL 32899

Robert W. Devor Ph.D.[2]
Southeastern Universities Research Association, John F. Kennedy Space Center, FL 32899

Sarah J. Snyder M.S.[3]
AECOM, John F. Kennedy Space Center, FL 32899

Elspeth Petersen M.S.[4]
and

Paul E. Hintze Ph.D[5]
National Aeronautics Space Administration, John F. Kennedy Space Center, FL 32899

NASA is currently developing technologies for use in the field of in-situ resource utilization (ISRU). One of the technologies being advanced is the Sabatier, or methanation, reactor which converts carbon dioxide and hydrogen into methane gas and water at high temperatures. This paper discusses the catalyst life and performance issues for these reactors that would be expected on Mars and describes the test methods employed and observed results. The various catalysts were tested in their capacity for the continuous production of methane gas via the Sabatier reaction and the possible effects of launch vibration loads, exposure to liquid water, particulate contamination, and chemical contamination to the overall observed reaction efficacy of the catalysts evaluated.

Nomenclature

ISRU = in-situ resource utilization
APU = atmospheric processing unit
CO_2 = carbon dioxide
CO = carbon monoxide
H_2 = hydrogen
H_2O = water
CH_4 = methane
Al_2O_3 = aluminum oxide
Ru = ruthenium
SLPM = standard liter per minute
APU = Atmospheric Processing Unit
KSC = Kennedy Space Center
Hz = hertz
GC = gas chromatogram
KSC = Kennedy Space Center

[1] Scientist 3, Laboratory Support Services and Operations, KSC-LASSO 6720
[2] Subject Matter Expert, Laboratory Support Services and Operations, KSC-LASSO 6720
[3] Scientist 2, Laboratory Support Services and Operations, KSC-LASSO 6720
[4] Aerospace Polymeric Materials, Exploration Research and Technology Programs, KSC-UB R30
[5] Science Project Management, Exploration Research and Technology Programs, KSC-UB R30

I. Introduction

OR the past several decades, the concept of in-situ resource utilization (ISRU) has received increased attention as it Fhas become the most effective method of reducing the total mass of cargo and cost of several space exploration activities. ISRU has increased the possibility for humans to be successful not only in the strategic journey to Mars but also in many other aspects of space exploration, as the use of on-site resources is of vital importance. NASA and many other agencies continue in the search and implementation of various ISRU technologies applicable in human missions beyond earth orbit. The atmosphere of Mars is especially suitable for the implementation of ISRU technologies, as it is primarily composed of carbon dioxide (CO_2) which can be converted to oxygen (O_2) and methane (CH_4). Although there are several technologies capable of processing the available CO_2 into useful consumables, this paper will focus on the Sabatier reaction. The Sabatier reaction uses transition metal catalysts (such as ruthenium or nickel) to catalyze the methanation of carbon dioxide (CO2) and hydrogen (H_2) (Equation 1). This research studied three different catalysts before and after being exposed to different conditions likely found in a long duration flight to Mars and once in use on the surface of the planet itself: the possible effects of launch vibration loads, exposure from liquid water, particulate contamination, and chemical contamination to the overall observed reaction efficacy.

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \tag{1}$$

The Sabatier reaction is a well-known process which is capable of producing CH_4. Additionally, the secondary product of water (H_2O) can by converted via electrolysis to oxygen and hydrogen, both of which can be utilized as well. It has a $\Delta_r H_{298K}° = -165$ kJ•mol^{-1} and it is typically operated at temperatures between 200ºC and 550ºC, depending on the catalyst used[1]. The optimal temperature for the conversion of CO_2 into CH_4 is found at the lower end of spectrum (resulting in almost 100% conversion); however, the reaction rate itself increases with a corresponding increase in temperature. This increase in temperature requires an increase in catalyst stability, as it can result in carbon deposition and catalyst fouling. Because of this, a significant effort has been made to find a catalyst for CO_2 methanation that would optimize the reaction for space use without losing catalyst stability under extreme conditions[2, 3, and 4].

In 2016, Muscatello et al. presented research on the Sabatier reaction specifically in the use of the Atmospheric Processing Unit (APU) developed at Kennedy Space Center (KSC), where CO_2 gas from a Mars atmospheric simulant gas was taken and condensed in a cryocooler. This condensed CO_2 was then allowed to sublime and used as feed gas for the reaction. Utilizing this configuration, the APU system was capable of performing up to seven-hour runs for four consecutive days and obtained a reaction efficiency for CH_4 production using a nickel-based catalyst[5 and 6].

After several months of successful nominal testing in 2017, Meier et al. performed a study using a new Ru/Al_2O_3 based catalyst. The reactant rates and temperature were purposely increased in order to characterize the reactor design and to determine the catalyst performance limits and durability. Testing showed that the Sabatier reaction was unable to run at nominal conditions after this more extreme testing was complete. The believed working hypothesis was that the catalyst itself had been damaged[7].

Hintze et al. also studied different Sabatier designs and configuration in order to maximize CH_4 production while meeting the purity requirements for a Mars ISRU Propellant Production Plant; however, none of the tested configurations produced the purity necessary for the CH_4 product. Additionally, Hintze et al. studied the advantages and disadvantages of using an adiabatic vs. isothermal system as well as the optimization of the number of reactors and condensers used within the system architecture itself[8].

For the work presented in this paper, three catalysts were tested to determine if the catalyst would be susceptible to damage during the flight or once on the surface of the red planet itself.

II. Materials and Equipment

Reactors were built and assembled for each of the catalysts. Each reactor consisted of a stainless steel tube capped at both ends enclosing glass wool packing at each end with catalyst pellets in the center surrounded by Al_2O_3-coated pellets as shown in Figure 1a. The reactor housing was a 12-inch long 304/304L stainless steel tube 0.065 inches thick with 1-inch outer diameter threaded at both ends. The ends of the tube were capped with 1-inch to ¼-inch Swagelok fittings. Materials used inside of the reactor include:

- Outer packing material: Acros glass wool, part number 386060010, lot numbers A0318555 and A0388695.
- Inner packing material: Alfa-Aesar Al_2O_3 pellets, part number 43855, lot numbers W30B046 and T09E036.
- Catalysts:
  - Clariant SNG 8000 catalyst (nickel-based): part number SNG-FMC100

o 0.5% Ru catalyst: Aldrich part number 206199, lot numbers NMKCG055044575 and MKG0550.
o 0.5% Ru catalyst: Chemsavers, no part or lot number or part specified
o 2.0% Ru catalyst: Alfa-Aesar part number 44575, lot number H20Z013

The following gases, sourced from pressurized gas k-bottles, were used:

- Hydrogen: NexAir ultra-high purity, supplied to the reactor for catalyst activation
- Carbon dioxide: NexAir 99.8% pure, lot number 109303171223, supplied to the reactor for the Sabatier reaction
- Helium: NexAir 6.0 grade-99.9999% pure, lot number 3915918701, used as a carrier gas in the micro GC
- Argon: Bogg's Gases 99.997% pure, used as a carrier gas in the micro GC
- Methane: Praxair 99.999% pure, 5.0 research grade, used for calibration

Throughout each test, a Varian CP-4900 micro gas chromatograph was used to detect gases present in the reactor output stream. Measurements from the gas chromatograph were used to determine reaction efficiency and evaluate the overall efficacy of each catalyst. It was configured with three different channels, each of which was able to detect different gases:

- Channel one: hydrogen. Equipped with a 10 meter length M5A BF column with Serial #55176 and Part # CP740148. Column temperature was set to 80 °C and pressure to 150 kPa, and injector temperature was set to 110 °C
- Channel two: methane, oxygen, and nitrogen. Equipped with a 20 meter length M5A BF column with Serial #55175 and Part #CP740149. Column temperature was set to 60 °C and pressure to 190 kPa, and injector temperature was set to 109 °C
- Channel three: CO_2. Equipped with a 10 meter length PPU column with Serial #55184 and Part #CP740146. Column temperature was set to 80 °C and pressure to 130 kPa, and injector temperature was set to 110 °C

A commercially available Exergy 23 Series Shell and Tube Heat Exchanger cooled product gases as they exited the Sabatier reactor to condense and collect the water produced in the reaction. A Cole-Parmer Polystat chiller, set to 3 °C, was also used to cool the heat exchanger.

Gas flow into the reactor was controlled with two Alicat Scientific flow controllers. H_2 gas flow controller with Serial #139543 was set to a 0.280 slpm flow. CO_2 gas flow controller with Serial #139544 was set to 0.070 slpm flow for the duration of the reaction.

III. Methods

Three different catalysts: SNG 8000 catalyst, 0.5% Ru coating on Al_2O_3 base, and 2% Ru coating on Al_2O_3 base, were tested. Each of the three catalysts were evaluated under four different test conditions to simulate anticipated harsh environments: launch vibration loads, exposure to liquid water, particulate contamination, and chemical contamination.

Figure 1a shows a diagram of the reactor assembly, including the position and thickness of each of the reactor's constituents. From bottom to top, each reactor was packed with a 2.5-inch layer of tightly-packed glass wool followed by 2 inches of bare Al_2O_3 pellets, then 2 inches of the chosen catalyst pellets, another 2 inches of bare Al_2O_3 pellets, and finally another 2.5 inches of tightly-packed glass wool. The amount of glass wool, catalyst, and Al_2O_3 was weighed and recorded for each reactor. Table 1 lists the average amount of the different catalysts added when the reactors were built. Figure 1b shows a picture of an assembled reactor.

Tabe 1: Average amount of catalysts added to the reactors

	SNG 8000	**0.5% Ru**	**2.0% Ru**
mass (g)	27.89 ± 0.485	20.01 ± 0.557	14.30 ± 0.305

3

a)

Top Of Reactor

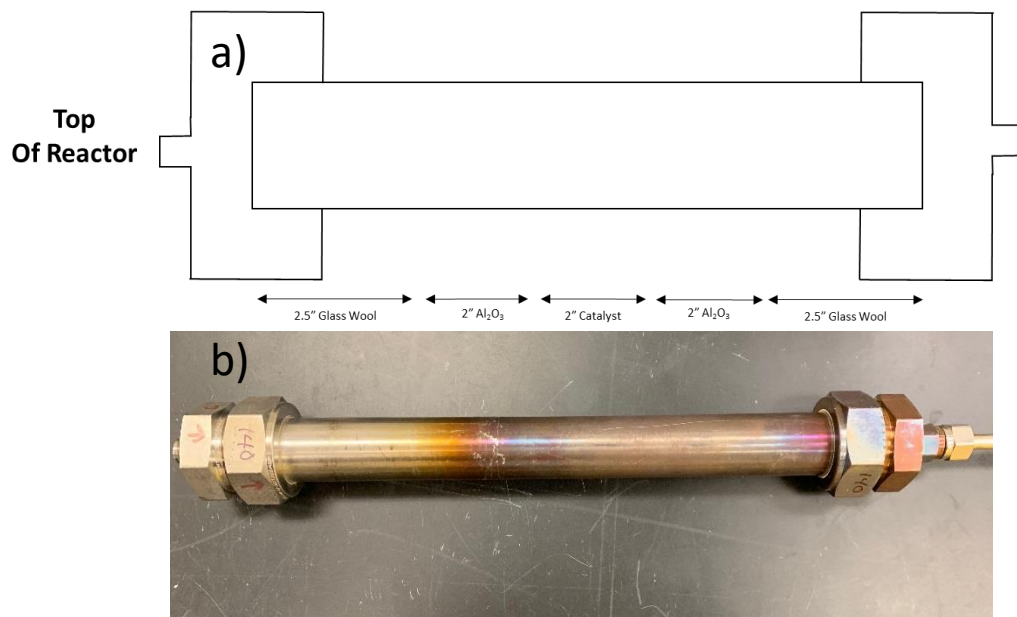2.5" Glass Wool   2" Al_2O_3 2" Catalyst   2" Al_2O_3 2.5" Glass Wool

b)

Figure 1: a) Reactor assembly diagram and b) picture of assembled reactor

The apparatus used for this set of experiments was a reactor (Figure 2) kept at temperature using a clamshell heater, with CO_2 and H_2 gas feeds supplied through flow controllers connected at the top of the reactor. Pure CO_2 gas was chosen to simulate the Martian atmosphere, which is 95.7% CO_2, 2.7% N_2, and 1.6% Ar, for the purpose of this experiment. A condenser, cooled to 3 °C (using an external chiller) throughout each test run, was connected at the bottom of the reactor to collect water produced as a byproduct of the Sabatier reaction. Figure 3 shows a picture of the actual Sabatier system used through testing.
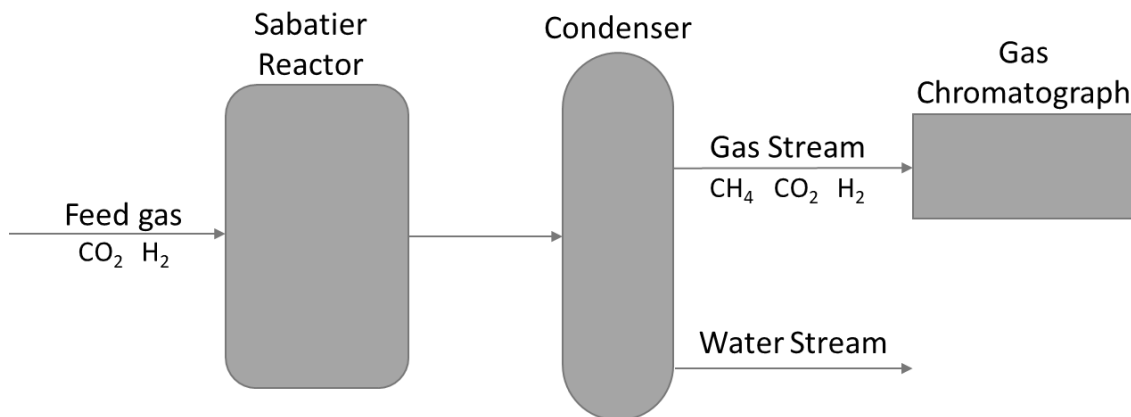

Sabatier Reactor

Condenser

Gas Chromatograph

Feed gas
CO_2 H_2

Gas Stream
CH_4 CO_2 H_2

Water Stream

Figure 2: Single isothermal Sabatier system design

At the start of each test, H_2 feed was set to 0.280 slpm gas flow, the heater was set to 200 °C, which is the activation temperature of the catalysts. When the temperature reached 200 °C, the temperature set point was changed to 400 °C and the H_2 gas was allowed to flow at 0.280 slpm through the reactor for one hour for SNG 8000 catalyst and 45 minutes for both Ru/Al_2O_3 based catalysts to ensure complete activation of the catalysts before continuing. The temperature was monitored using a thermocouple placed in contact on the outside of the reactor. Following the wait time for catalyst activation and temperature reaching the 400 °C set point, the CO_2 flow controller was set to 0.070 slpm and a one-hour test run was started. During each test run, the amount of CH_4 produced in volume percent was continuously determined by the micro GC software. At the conclusion of the one-hour test run time, CO_2 gas flow

International Conference on Environmental Systems

into the reactor was stopped. Data collection continued for one complete run after CO_2 peak dropped off the GC readings. At that time, the temperature for the unit was set to 10 °C and the unit was allowed to cool.

Figure 3: Sabatier assembly used during testing

Between consecutive runs for the same reactor, the unit was allowed to cool to 100 °C before starting the subsequent run. H_2 gas flow and chiller operation remained on between runs.

Each catalyst was evaluated in three different reactors. Following each set of tests, the reactors were disassembled. Pictures were taken of the catalyst and packing material removed from the reactor. All individual materials were saved in separate bags in the event that further analysis was needed following testing. A t-test was used to determine changes between baseline performance and performance after exposure to the challenge.

Vibration test: On a mission to Mars, all materials being transported will be subject to vibration loads during launch. Such conditions can cause damage to the catalysts, even prior to any use. In order to determine the effects that launch vibration may have on the catalysts' performance in the production of methane gas, each catalyst was subjected to launch vibration simulation testing.

Vibration testing was done by first performing a background run for each of the reactors to determine the material's baseline performance. Reactors were then affixed to a shaker table and exposed to a vibration profile which simulated that of a launch environment. This testing was conducted by the Vibration Laboratory located at KSC using the Unholtz-Dickie Model 2XSAI240-T-1000-32LH/ST Electrodynamic Shaker System utilizing a standard vibration profile for (20 Hz – 2000 Hz, for an overall vibration force of 14.1 g_{rms}). For flight hardware with no specific launch configuration, GSFC has a catch all vibration test at acceptance and qualification levels in GSFC-STD-7000. Vibration tests followed that standard and were performed with the following conditions given in Table 2.4-3 of that document. Following exposure to vibration, performance of the reactors was measured again. The test data were processed, and a comparison of performance before and after exposure to launch vibration was made in order to determine the impact of vibration on each of the catalysts used.

Liquid water test: Exposure to liquid water could occur during an unexpected shutdown of the reactor. If reactant flow to the reactor is stopped, the water produced during the reaction would condense and thus, catalysts need to be able to handle exposure to liquid water. The production of methane gas before and after the catalyst was subjected to liquid water exposure for approximately one day was measured. A background (pre water exposure) test was conducted for each reactor. After collecting background data, the reactors were filled with water to their maximum capacity through the top of the reactor to ensure the catalyst inside was completely submerged. Water was left inside

of the reactors for a period of approximately 18 hours, then dumped out. The reactors were then placed in a vacuum oven set to 30 °C over night to ensure that the catalyst was completely dried prior to post-exposure testing. After sufficiently drying the reactors, Sabatier testing was repeated (post water exposure). The data were processed and compared to determine the impact of water exposure on each of the catalysts used.

Particle contamination test: While care can be taken to minimize particulate contamination, the surface of Mars is covered in dust and some exposure is almost certain. In order to select a catalyst which will be least impacted by exposure to dust on the surface of Mars, particle contamination testing was conducted. For this specific test, no background was performed for any of the reactors, as the catalyst pellets had to be contaminated with particulates before the reactor was assembled. The performance of the reactors with particle contamination was compared to the average of the background runs taken during the liquid water and vibration tests.

Mars JSC-1 simulant, sieved to 5 µm was used for the particle contamination of the catalyst. Calculations were performed in order to determine the correct amount of particulate to be added to the catalysts, taking into consideration the requirements and constants shown in Table 2. Given a mission time and methane production requirement, the amount of Mars atmosphere that passes through the reactor can be calculated. After assuming a dust particle density and a filter efficiency, the total amount of particles that enter the reactor was estimated. The total scaling factor used was 1:60 for all calculations. Afterward, the reactors were assembled as previously described, using the contaminated catalyst pellets. Sabatier test runs were conducted, and the data was recorded and analyzed to determine the efficacy of each catalyst in the presence of Martian simulant dust.

Chemical contamination test: Chemical contamination is another concern to keep in consideration on the Mars surface since the dust contains chemicals which could be liberated when the dust enters the reactor. Leshin et al. reported chemicals present in the Mars regolith to be mainly sulfates and chlorides[9]. Therefore, HCl and $FeSO_4$ were used as surrogates and added to the reactor upstream, once the catalyst pellets were already added.

As with the particle contamination test, no backgrounds were performed and the performance after chemical contamination was compared to the average of the baseline runs performed during vibration and water testing. The reactor beds were packed with the contaminant chemicals placed upstream of the catalyst bed to allow for the contaminants to flow over the reactor bed during the reaction. The contaminants consisted of ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$) and hydrochloric acid (0.1M HCl) to account for the 4.2wt% sulfate and 0.6wt% chloride contaminants, respectively, found in the reactor Martian dust contaminants. Calculations were also performed in order to determine the correct amount of chemicals to be added to the catalysts, taking into consideration the requirements and constants shown in Table 2. Because background runs were unable to be performed for the chemical contamination test, data from previous trials were used as a reference to determine the possible impact of chemicals on catalyst performance. Sabatier test runs were conducted, and the data was recorded and analyzed to determine the efficacy of each catalyst in the presence of Martian contaminants.

Table 2: Particle and chemical contamination calculations

Requirements and constants	
6978	amount of CH_4 (kg)
434.7	production time (days)
0.5	fraction of production done by each module
6	number of particles/cm^3
0.9997	filter efficiency
273	atmosphere temperature (K)
598	atmosphere pressure (Pa)
Calculations	
8.03	kg CH_4/day
0.33	kg CH_4/hr
0.92	kg CO_2/hr

20.9	mol CO_2/hr
79306	liters CO_2/hr at Mars conditions
4.76E+08	particles/hr
142750	particles that pass thru/hr
1.49E+09	number of particles reaching the reactor during a production cycle
5	radius of a particle (μm)
5.23E-10	volume of a particle (cm^3)
0.78	volume particles during produciton (cm^3)
0.4550	volume particles to coat catalyst (cm^3)
0.0130	volume chemical (0.10 M HCl) to coat catalyst (cm^3)
0.0113	mass chemical ($FeSO_4 \cdot 7H_2O$) to coat catalyst (mg)

IV.   Results and Discussion

A. Vibration Test

Once the baseline reactor tests were completed, the reactors were taken to a test facility where they were subjected to vibration forces that simulated those felt during a launch. Then, the reactors were tested once again to determine if the catalyst had been affected. Once the post-vibration tests were finished, the reactors were disassembled, and the catalysts were observed in order to determine any apparent degradation. The collected data were analyzed and plotted to compare pre- and post-vibration test Sabatier runs. Figure 4 shows the physical appearance of the catalyst before and after the test. Although a few of the Ru/Al_2O_3 pellets split open, the overall catalyst performance was not affected. Figure 5 shows catalyst performance before and after vibration exposure with the error bars representing the standard deviation over three reactors with three runs each for all catalysts. The variation denoted by the error bars can be largely attributed to temperature variation from one run to the next. Small changes in the placement of the thermocouple at the outer wall of the reactor resulted in changes in the reactor operating temperature. Even small temperature differences affect the rate and equilibrium of the reaction. While great effort was made to maintain consistent operating conditions for each reactor and run, temperature variations were observed. The production of CH_4 gas after vibration was very similar to the reactor's baseline data for all of the catalysts tested. A t-test showed that there was no stastical difference in the performance of any catalyst after it was subject to vibration.
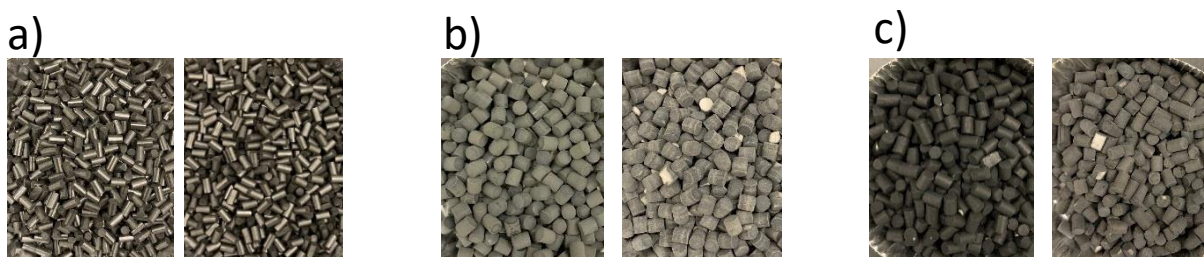

Figure 4: Catalyst pellets before (left) and after (right) vibration tests for a) SNG 8000 catalyst, b) 0.5% Ru catalyst, and c) 2.0% Ru catalyst
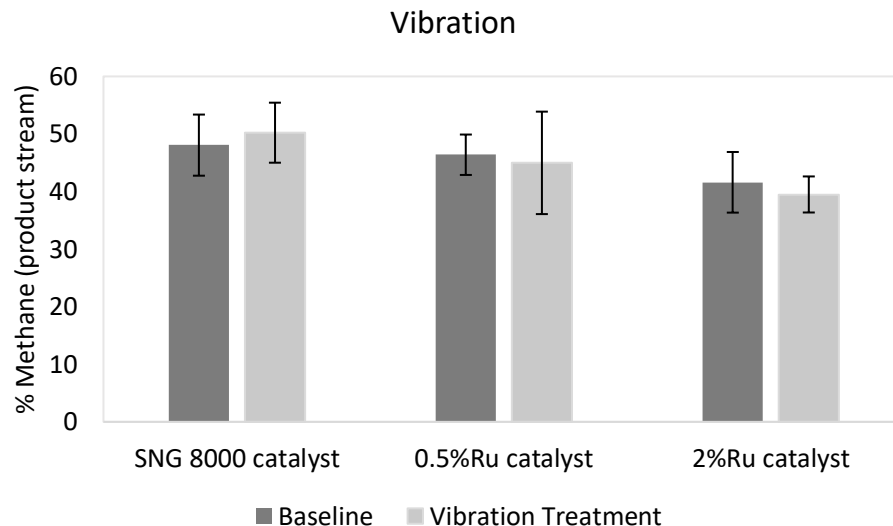
7

Figure 5: CH₄ production before and after vibration test for a) SNG 8000 catalyst, b) 0.5% Ru catalyst and c) 2.0% Ru catalyst

B. Liquid Water Test

Once all the background data were collected, the reactors were filled with room-temperature deionized water to soak the catalyst and left overnight, then dried inside the vacuum oven, and cooled at room temperature. The reactors were tested again to evaluate any degradation in performance following extended exposure to liquid water. Data were analyzed and plotted comparing catalyst performance before and after liquid water exposure. Figure 6 shows the different catalysts before and after liquid water exposure, and Figure 7 illustrates the performance of the catalysts before and after water contact. The appearance of the catalyst pellets after water exposure was relatively dramatic with both Ru catalysts lightening significantly to lighter grey indicating the amount of ruthenium mon the surface had decreased. Despite this altered appearance, the water treatment did not show a negative effect on the performance of the reactors. The t-test completed for this series of experiments showed a statistical difference between the baseline and post-contamination performance for the 2.0% Ru catalyst only. While previous literature has shown that water can activate the catalytic sites, it is unlikely this effect was observed in only one of the catalysts tested. We do see, however, that the variation among the 2.0% Ru catalyst baseline data is much smaller than the other two catlalysts, which could explain why the difference before and after treatment results in a positive t-test for that catalyst alone.
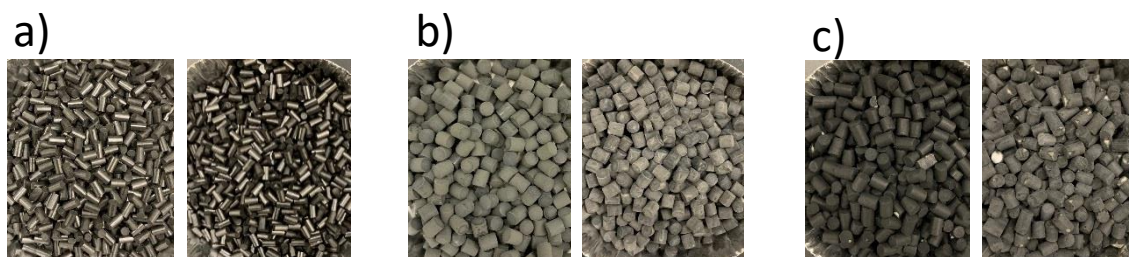

Figure 6: Catalyst pellets before (left) and after (right) liquid water exposure tests for a) SNG 8000 catalyst, b) 0.5% Ru catalyst, and c) 2.0% Ru catalyst test.
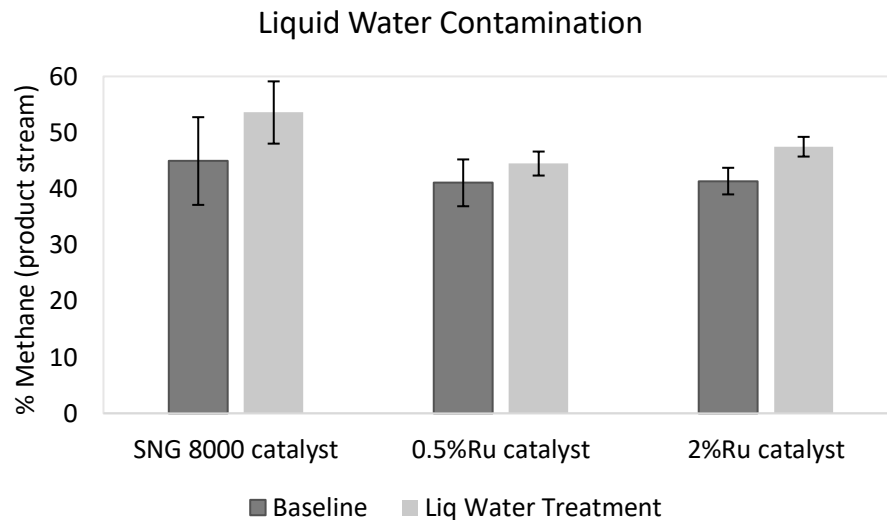
International Conference on Environmental Systems

Figure 7: CH$_4$ production before and after liquid water exposure for a) SNG 8000 catalyst, b) 0.5% Ru catalyst and c) 2.0% Ru catalyst

C. Particle Contamination Test

This test differed from the vibration and water tests as the reactors had to be assembled with the catalyst already contaminated; therefore, the baseline had to be evaluated differently. The average of all baseline data from previous trials was used as a reference to determine the possible impact of particle contamination on catalyst performance. As was observed in the previous test scenarios, the catalyst performance was minimally affected by particle contamination. Figure 8 shows a picture of the different catalysts before and after particulate contamination exposure, and Figure 9 illustrates the performance of the catalysts before and after particulate exposure. The t-tests showed a positive result for both the Ruthenium-based catalysts. A gap in the testing schedule existed between the baseline and the contaminated catalyst tests for those two catalysts, which appears to play a role in the trend seen. As with all the tests, the reactor temperature control also likely played a significant role in performance variation.
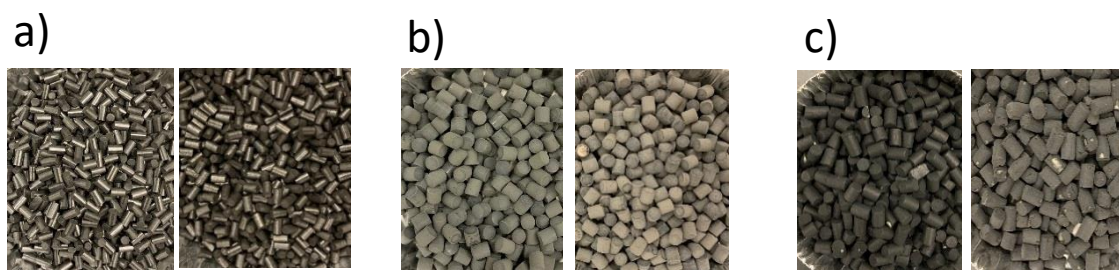

Figure 8: Catalyst pellets before (left) and after (right) particle contamination test for a) SNG 8000 catalyst, b) 0.5% Ru catalyst, and c) 2.0% Ru catalyst
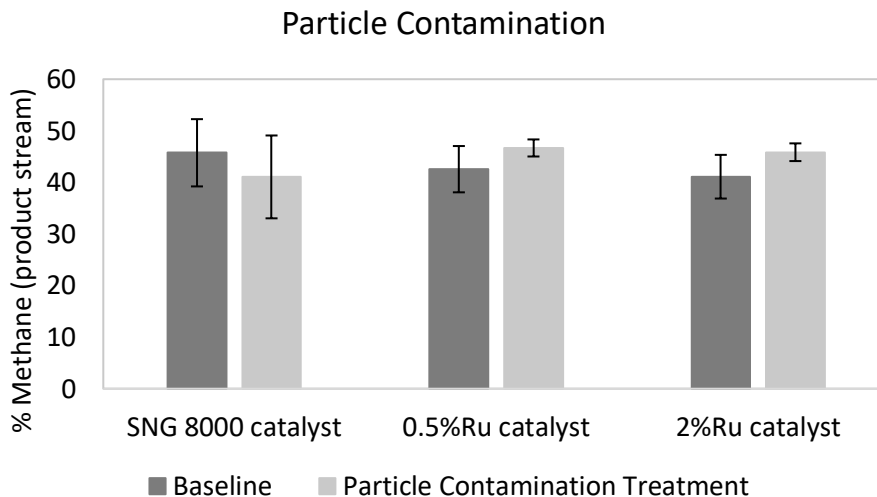
International Conference on Environmental Systems

Particle Contamination

Figure 9: CH$_4$ production before and after particle contamination exposure for a) SNG 8000 catalyst, b) 0.5% Ru catalyst and c) 2.0% Ru catalyst

D. Chemical Contamination Test:

Similar to the particle contamination test, the chemical contamination experiment results were compared to baseline data collected during the vibration and liquid water contamination tests. The reactors were assembled with the chemical contaminants added upstream of the catalyst bed. In this test, ferrous sulfate heptahydrate (FeSO$_4$.7H$_2$O) and hydrochloric acid (0.06M HCl) were used as surrogates to account for the chemicals contained within Martian dust contaminants in the reactor. After the catalyst was added inside the reactor, FeSO$_4$·7H$_2$O was added, followed by the diluted HCl so that they were located upstream of the catalyst bed during gas flow; the reactors were then finished and run. As it was observed in the previous test scenarios, the catalyst performance was not significantly affected by chemical contamination. Figure 10 shows a picture of the different catalysts before and after chemical contamination exposure, and Figure 11 illustrates the performance of the catalysts before and after chemical exposure. Figure 11 shows a slight increase in the performance of the catalyst. For this particular test, we find that all the catalysts show a statistical improvement in performance following the chemical contamination. While all the tests showed variation, this one has other factors that likely contributed to the variation in results other than the actual catalyst performance. The baseline and contamination tests were performed several months apart. During that time, a new operator joined the group, and the GC underwent maintenance.

Even with these inconsistencies, it has been shown that chemical contaminations on this scale does not adversely affect catalyst performance.
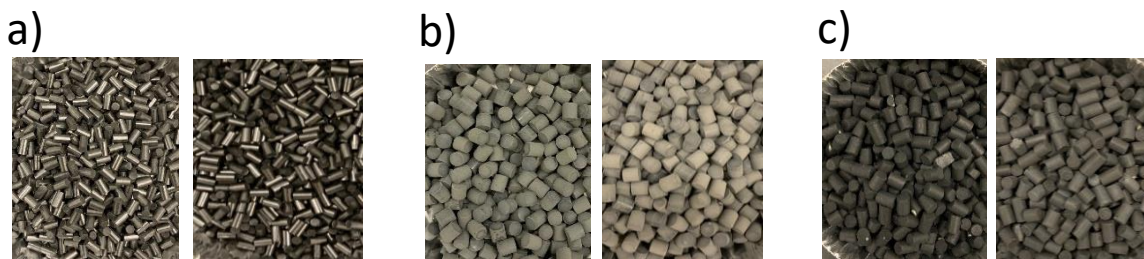

Figure 10: Catalyst pellets before (left) and after (right) chemical contamination test for a) SNG 8000 catalyst, b) 0.5% Ru catalyst, and c) 2.0% Ru catalyst
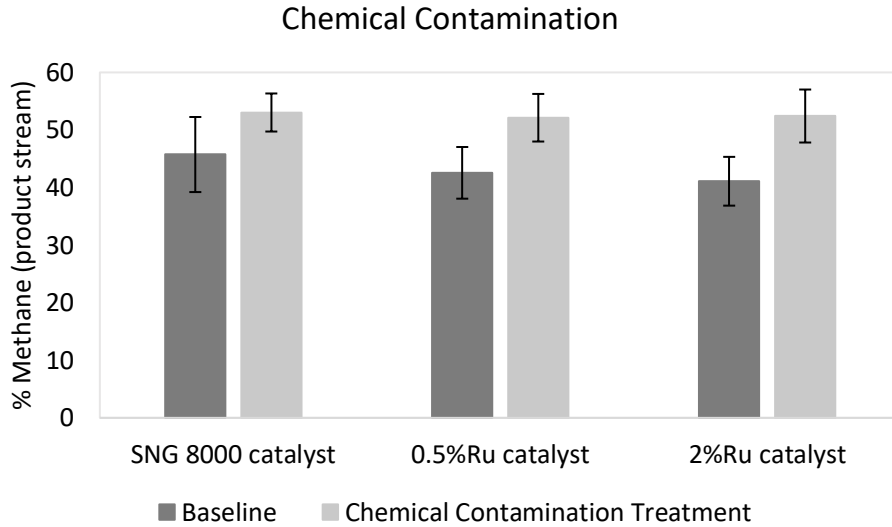
International Conference on Environmental Systems

Chemical Contamination

Figure 11: CH$_4$ production before and after chemical contamination exposure for a) SNG 8000 catalyst, b) 0.5% Ru catalyst and c) 2.0% Ru catalyst

V. Conclusion

Three different catalysts: SNG 8000, 0.5% Ru coating on Al$_2$O$_3$, and 2.0% Ru coating on Al$_2$O$_3$, were tested to evaluate their capacity for the continuous production of methane gas via the Sabatier reaction and the possible effects of harsh conditions that may be encountered on a Mars mission on their performance.

Vibrational forces did not have an effect on the catalyst performance. After evaluating CH$_4$ production before and after this type of forces, it could be determined that the percent difference in performance did not exceed the expected change from run to run. Liquid water exposure may have slightly enhanced the formation of CH$_4$ due to activation of reaction sites. Particulate contamination or chemical contamination exposure did not have a great influence on the catalysts' capacity to produce methane gas. This determination was made based on previous baselines as no baseline runs on the same reactors were possible for these two specific tests.

Five of the six tests that had baselines that immediately preceded the challenge experiment did not show a statistical difference between the baseline and treated catalysts shown by t-test analysis. The testing schedule appears to have influenced results. Tests that were carried out with a significant gap between the baseline and contaminated reactor showed test result disparities. Overall, it appears the four test cases were not detrimental to catalyst performance as none of the tests showed a negative correlation between the baseline catalyst performance and the reactors exposed to contamination and vibration forces. The variation within the test data can be attributed to reactor temperature variation due to thermocouple placement, the test schedule, and inconsistencies between operators. Due to these circumstances, it is unlikely that the minor dispartities observed before and after contamination is the result of true differences in performance.

Testing showed that all of the catalysts continued to perform, with minimal change, regardless of circumstances: none were largely affected either physically or chemically in their capacity to catalyze the conversion of CO$_2$ and H$_2$ into CH$_4$. Any of these catalysts will be an adequate choice for the overall design study of the Mars ISRU Propellant Production Plant.

VI. Future Work

For the application of rocket fuel production on Mars, this and previous work has shown that a number of catalysts and reactors work to produce high conversion and selectivity for the Sabatier reaction. Therefore, future work will focus on effective size and mass scaling for the reactor and the other components required for a successful system. Other considerations for the system include how the water condenser will perform in a reduced gravity environment,

International Conference on Environmental Systems

what are the propellant methane purity requirements, and how much power will be required for a gas separation system.

In addition to the Martian fuel production application, the Sabatier reaction is also being targeted for lunar oxygen liberation via the carbothermal route. This new focus brings up several more issues to investigate. The carbothermal process will release a large quantity of volatiles, including sulfur-containing compounds, chlorides, and hydrogen fluoride that will poison the Sabatier catalysts unless dealt with. Another key difference is that the reactants will consist primarily of hydrogen and carbon monoxide, which will necessitate adjusting the operating conditions, namely the CO to hydrogen feed ratio and reactor temperature. Lastly, for carbothermal, both methane and hydrogen play a role in reducing the lunar minerals, so reactor outlet separation will play a less important role but still requires analysis. All these considerations will continue to be explored as the Sabatier system moves closer to implementation.

Acknowledgments

References

[1]T. Schaaf, J. Grünig, M. R. Schuster and T. R. e. A. Orth, "Methanation of CO_2 - storage of renewable energy in a gas distribution system," *Energy, Sustainability and Society*, Dec. 2014.

[2]C. Junaedi, K. Hawley, D. Walsh, S. Roychoudhury, M. Abney and J. Perry, "CO_2 Reduction Assembly Prototype using Microlith-based Sabatier Reactor for Ground Demonstration," *44th International Conference on Environmental Systems*, Tucson,
AZ, 2014.

[3]K. Müller, M. Fleige, F. Rachow and D. Schmeißer, "Sabatier based CO_2-methanation of flue gas emitted by conventional power plants," *Energy Procedia*, 2013, pp. 240-248.

[4]K. Stangeland, D. Kalai, H. Li and Z. Yu, "CO_2 methanation: the effect of catalysts and reaction conditions," *Energy Procedia*, 2016, pp. 2022-2027.

[5]A. C. Muscatello and E. Santiago-Maldonado, "Mars In Situ Resource Utilization Technology Evaluation," *50th AIAA Aerospace Sciences Meeting*, Nashville, TN, 2012.

[6]A. C. Muscatello, P. E. Hintze, A. J. Meier, J. A. Bayliss, L. J. Karr, M. S. Paley, M. J. Marone, T. L. Gibson, J. M. Surma, J. M. Mansell, G. M. Lunn, R. W. Devor, J. G. Captain and M. Berggren, "Mars Atmospheric In Situ Resource Utilization Projects at the Kennedy Space Center," *Earth and Space*, 2016, pp. 449-460.

[7]A. J. Meier, M. G. Shah, P. E. Hintze and A. C. Muscatello, "Mars Atmospheric Conversion to Methane and Water: An Engineering Model of the Sabatier Reactor with Characterization of Ru/Al_2O_3 for Long Duration Use on Mars," *47th International Conference on Environmental Systems*, Charleston, SC, 2017.

[8]P. E. Hintze, A. J. Meier, M. G. Shah and R. W. Devor, "Sabatier System Design Study for a Mars ISRU Propellant," *48th International Conference on Environmental Systems*, Albuquerque, NM, 2018.

[9]L. A. Leshin, P. R. Mahaffy, C. R. Webster, M. Cabane, P. Coll, P. G. Conrad, P. D. A. Jr., S. K. Atreya, A. E. Brunner, A. Buch, J. L. Eigenbrode, G. J. Flesch, H. B. Franz, C. Freissinet, D. P. Glavin, A. C. McAdam, K. E. Miller, D. W. Ming and R. Nava, "Volatile, Isotope, and Organic Analysis of Martian Fines with the Mars Curiosity Rover," *Science*, Vol 341, Issue 6153
27 Sept. 2013

[10]R. S. Amaral and S. Thomas. "Kinetics of CO_2 methanation over a Ni/alumina industrial catalyst." (2016).

[11]D. Samplatsky, K. Grohs, M. Edeen, J. Crusan and R. Burkey, "Development and Integration of the Flight Sabatier Assembly on the ISS," *41st International Conference on Environmental Systems*, Portland, OR, 2011.

[12]G. Alptekin, B. Hitch, M. Dubovik, J. Lind and F. Smith, "Prototype Demonstration of the Advanced CO_2 Removal and Reduction System," *35th International Conference on Environmental Systems*, Rome, Italy, 2005.

[13]K. P. Brooks, J. Hu, H. Zhu and R. J. Kee, "Methanation of carbon dioxide by hydrogen reduction using the Sabatier process in microchannel reactors," *Chemical Engineering Science*, 2007, pp. 1161-1170.