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

ICES Paper 2019-077

Carolina Franco Ph.D. – AECOM

Sarah J. Snyder M.S. – AECOM

Elspeth M. Petersen M.S. – NASA

Paul E. Hintze Ph.D. – NASA

Robert W. DeVor Ph.D.

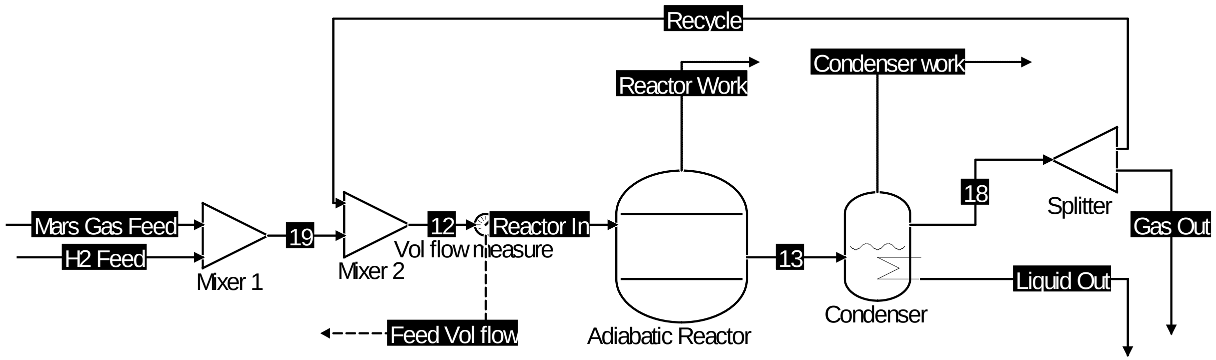
International Conference on Environmental Systems,
Boston, MA 2019

Background

- CO_2 gas from Mars atmospheric simulant gas was taken and condensed in a cryocooler (Muscatello et al.)
  - Condensed CO_2 was allowed to sublime and used as feed gas for the reaction
  - 7 hour runs for 4 days
  - Obtained reaction efficiency with nickel-based catalyst
- New Ru/Al_2O_3 catalyst was used (Meier et al.)
  - Reactant rates and temperature were increased to characterize reactor design and to determine catalyst performance limits and durability
  - Unable to run at off-nominal conditions – catalyst damaged

Background

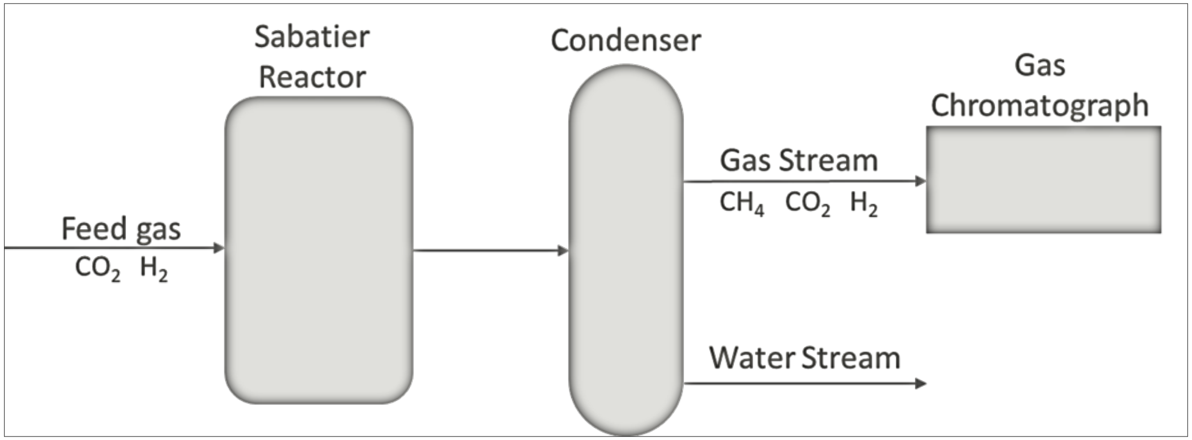
- Different Sabatier designs and configuration to maximize CH_4 while meeting purity requirements for a Mars ISRU Propellant Production Plant (Hintze et al.)
  - None met purity requirements
  - Advantages of adiabatic vs. isothermal systems
  - Optimization of reactors and condensers



Overview

- Catalyst Screening: Catalysts tested in their capacity for continuous production of CH_4 gas via the Sabatier reaction and possible effects of:
  - Launch vibration loads
  - Liquid water
  - Particulate contamination
  - Chemical contamination

Testing Method



Testing Method

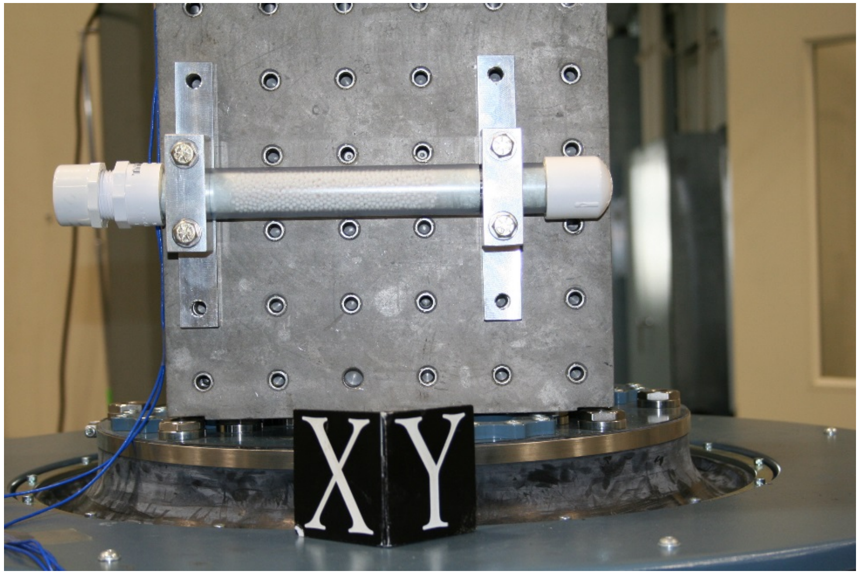
- Catalysts used
  - Clariant® (Nickel monoxide, impregnated through Al_2O_3 base)
  - 0.5% Ru coating on Al_2O_3 base
  - 2% Ru coating on Al_2O_3 base

	Clariant® (g)	0.5% Ru (g)	2.0% Ru (g)
Mass (g)	27.9 ± 0.5	20.0 ± 0.6	14.3 ± 0.3

- Clamshell heater, with CO_2 and H_2 gas feeds supplied through flow controllers connected on top of reactor
- Condenser cooled to 3°C
- Water collected at exit of reactor as byproduct

Vibration Test

- Background run for each reactor to determine baseline performance
- Reactors were affixed to shaker table and exposed to vibration profile – simulated launch environment (20 Hz – 2000 Hz, overall vibration force of 14.1 g_{rms})
- Vibration tests using clear plastic tubes were carried out to evaluate packing methods



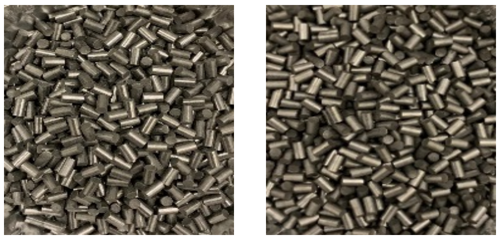
Vibration Test

- Performance of reactors measured after exposure to vibrational forces
- Test data compared before and after exposure to launch vibration to determine impact of vibration on each catalysts used

Preliminary vibration testing took place in plastic tubes. Data presented here used reactor configuration - 1” SS packed-bed reactor.

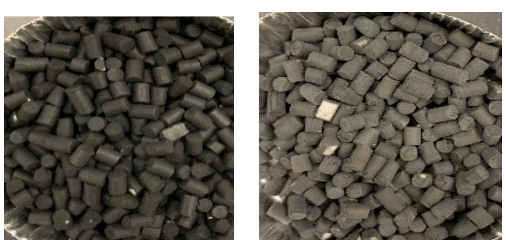
Vibration Test

Catalyst pellets before (left) and after (right) vibration tests

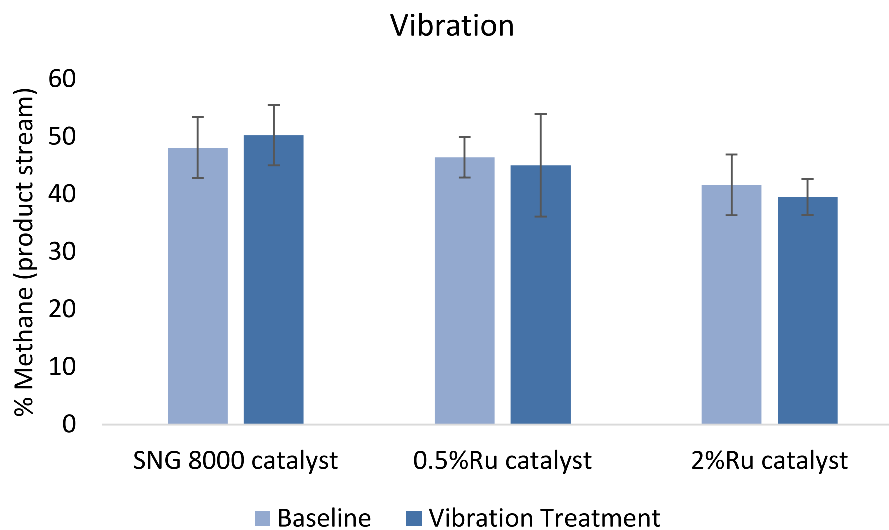


Clariant®

0.5% Ru



2.0% Ru

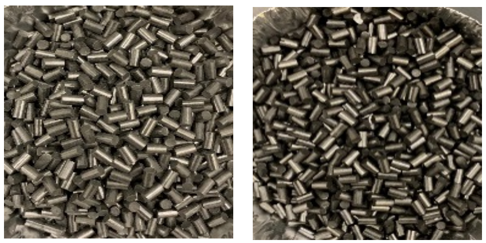


Liquid Water Test

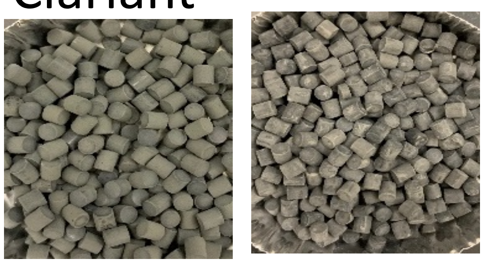
- Background run for each reactor to determine material's baseline performance
- Reactors were filled with water to maximum capacity through the top to ensure catalyst was completely submerged
- Water was left inside of reactors for a approximately 18 hours, emptied, and placed in a vacuum oven over night to ensure catalyst dried prior testing
- Measured production of CH_4 gas after catalyst was subjected to liquid water exposure
- Test data processed and compared before and after to determine impact of water exposure on each of the catalysts used

Liquid Water Test

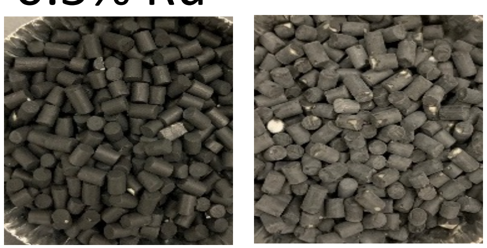
Catalyst pellets before (left) and after (right) liquid water tests



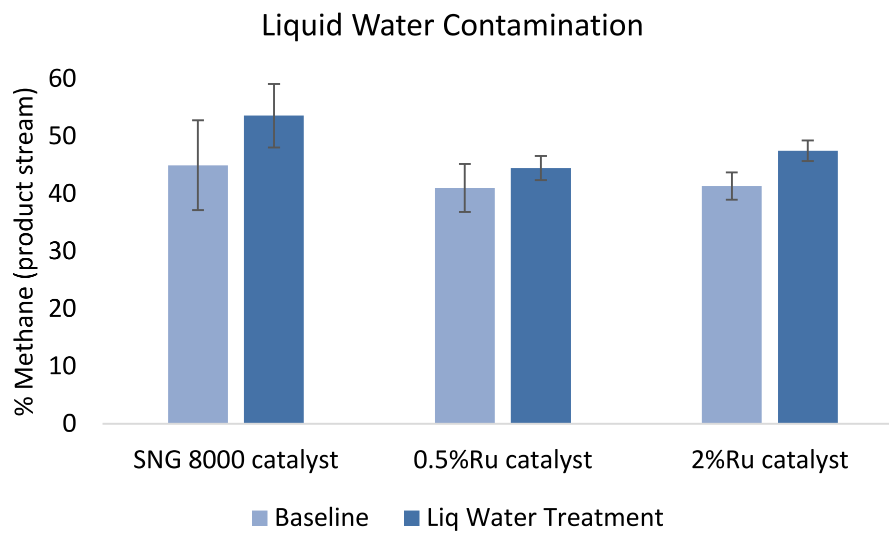
Clariant®



0.5% Ru



2.0% Ru



Particle Contamination Test

- No backgrounds performed
- Performance of reactors compared to average of previous background runs
- Mars JSC-1 simulant sieved to 5 µm used for particle contamination of catalysts
- Amount of particulate to be added determined, taking into consideration total flow and filtration efficiency
- Test data compared to determine impact of dust particles on each catalyst used

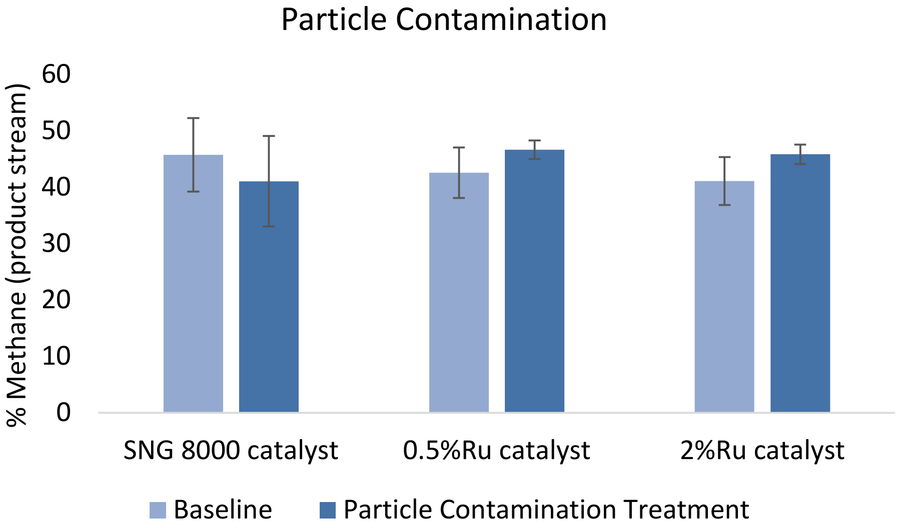
Particle Contamination Test

Catalyst pellets before (left) and after (right) particle contamination tests


Clariant®


0.5% Ru


2.0% Ru



Chemical Contamination Test

- No backgrounds performed
- Performance of reactors compared to average of previous background runs
- HCl and $FeSO_4$ used as surrogates; added to reactor upstream to allow contaminants to flow over reactor bed during reaction
- Calculations performed to determine amount of chemicals to be added
  - ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), 4.2wt%
  - hydrochloric acid (0.1M HCl), 0.6wt%
- Test data compared to determine impact of chemicals on each catalysts used

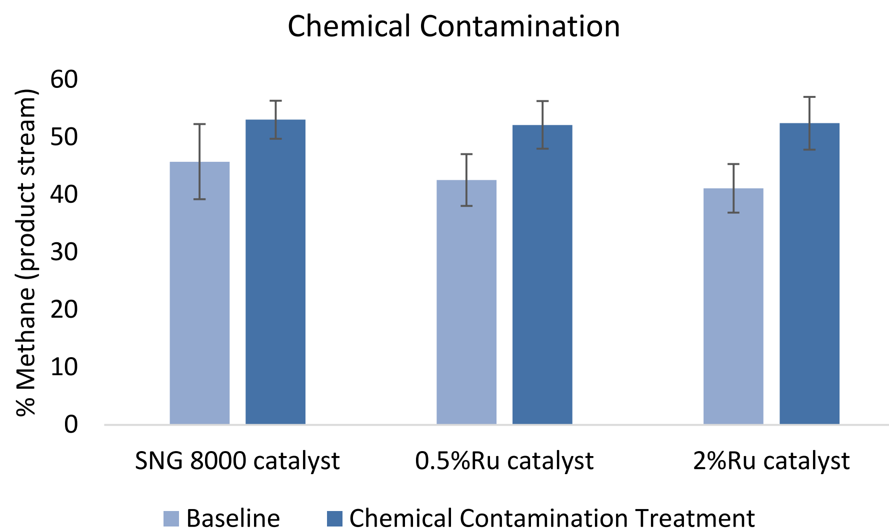
Chemical Contamination Test

Catalyst pellets before (left) and after (right) chemical contamination tests


Clariant®


0.5% Ru


2.0% Ru



Conclusion

- Clariant®, 0.5% Ru/Al_2O_3, and 2.0% Ru/Al_2O_3 catalysts tested to evaluate capacity for production of CH_4 gas via Sabatier reaction and possible effects of harsh conditions encountered on a Mars mission
  - Vibrational forces did not have a significant effect on the catalyst performance
  - Liquid water exposure appears to have slightly increased CH_4 formation for the 2% catalyst but otherwise did not show significant effects
  - Particulate and Chemical contamination exposure did not have a significant effect on the catalyst performance. (Vibration and Liquid water baselines were used)

Conclusion

- All catalysts continued to perform, with minimal change, regardless of circumstances; none were largely affected either physically or chemically
- Disparities in testing results likely stem from variation in thermocouple placement from one test to the next – causing inconsistencies in reactor operating temperature
- Any of these catalysts will be an adequate choice for the overall design study of the Mars IRSU Propellant Production Plant

Future Work

- Effective size and mass scaling for the reactor and product separation required for a successful system
- Determine how the water condenser will perform in a reduced gravity environment
- Sabatier reaction is also being targeted for lunar oxygen liberation via the carbothermal route
  - Volatile separation to avoid poisoning Sabatier catalyst
  - Operating conditions to meet reactant and product requirements
    - Carbon monoxide as key reactant
    - Minimize CH_4 loss and carbon deposition in reactor system

Acknowledgements

The team appreciates the funding for this project from the following sources: Advanced Exploration Systems (AES) and Space Technology Mission Directorate (STMD) ISRU Technology Project

THANK YOU!

References

1. T. Schaaf, J. Grünig, M. R. Schuster and T. R. e. A. Orth, "Methanation of CO2 - 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, "CO2 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 CO2-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, "CO2 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/Al2O3 for Long Duration Use on Mars," 47th International Conference on Environmental Systems, Charleston, SC, 2017.

References

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 CO2 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 CO2 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.