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Mars In Situ Resource Utilization Technology Evaluation

Anthony Muscatello and
Edgardo Santiago-Maldonado

NASA – Kennedy Space Center

Outline

- Background
- Purpose
- Methodology
- CO_2 Capture and Buffer Gases
- Chemical Processes
- Recommendations
- Conclusions

Background – Our Changing View of Mars

- Mariners – dry, dusty, cold, Moon-like
  - Evidence for ancient water flow
- Vikings – dry, dusty, cold, but intermediate between Moon and Earth
  - RH ~100% (?)
  - Oxidizers in soil, no life (?)
- Pathfinder/Mars Global Surveyor – dry, dusty, cold, but interesting
  - Possible current liquid water flows
- Mars Odyssey – evidence for extensive water ice
- Mars Rovers – in situ proof of ancient, long duration surface water
- Mars Phoenix – in situ proof of near-surface water ice
  - Near neutral pH, perchlorate oxidizer

Purpose

- Update status of Mars ISRU technologies
- Provide guidance for future investments
- Provide basis for Mars ISRU planning

Methodology

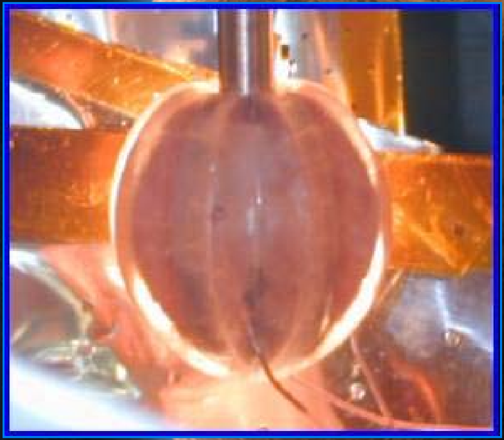
- Evaluated CO_2 capture and gas separation technologies
  - Included new options: ionic liquids, amine-based solvents, preparative GC
- Selected RWGS and Sabatier systems
  - Examined unit processes for TRL status
- Summarized results in a report to ISRU Program Manager Bill Larson
- Plan full paper for 50th AIAA ASM

CO_2 Capture Technologies

- CO_2 Freezers Look Promising
- CO_2 freezers have been tested by Pioneer Astronautics and Lockheed-Martin
- Results show accumulation rates of ~20, 13, and 80 g/hr using lab-scale systems (equiv. 5-30 g/hr CH_4)
- N_2/Ar was not measured or purified
- Rapp estimated a CO_2 freezer for 0.5 kg/hr needs ~1/3 the power and 11% the mass of a compression pump/membrane CO_2 purifier
- JPL investigated liquefaction of the Martian atmosphere, but power requirements are high
- Adsorption beds also rejected because of high mass, volume, and power

TRL 3-4

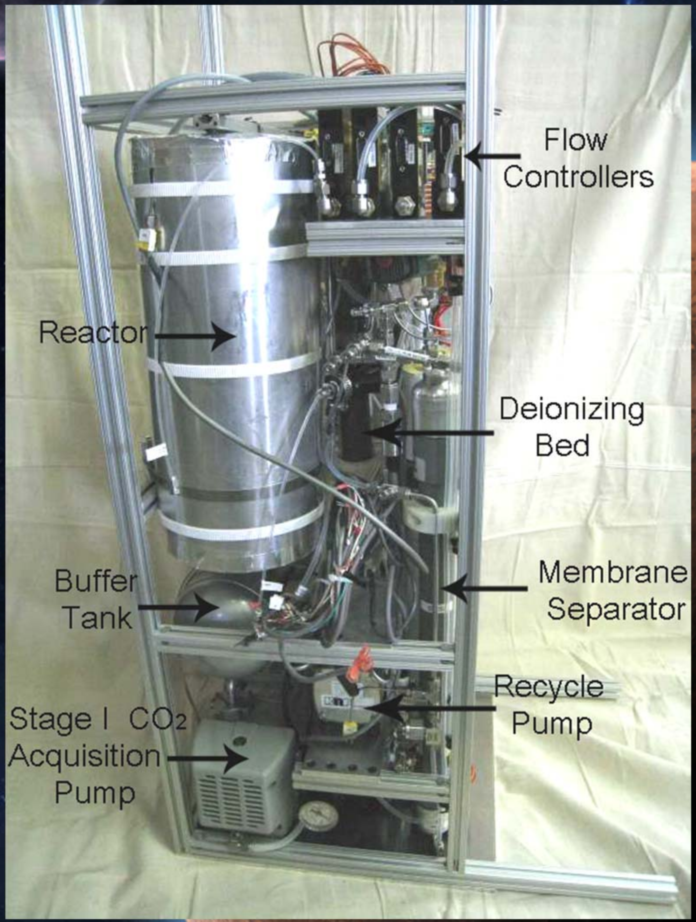
Pioneer MACDOF



Lockheed Cryocooler Freezer

Alternative Approach- Direct Mars Atmospheric Gas Processing

- ISRU processes (SOE, RWGS, Sabatier) may not require high purity CO_2.
- Pioneer Astronautics ran a combined RWGS-Sabatier process with $CO_2/N_2/Ar$ for 5-continuous days without degradation of catalyst.
- N_2 and Ar were not separated from feed, but were removed during condensation or cryodistillation of products
- Gas separation downstream from CO_2 reduction process may be easier and still provide useful buffer gases
- Mechanical compression is required, and may require more power but was claimed to be less complex.
- A mass comparison needs to be done, as well.



Pioneer IMISPPS

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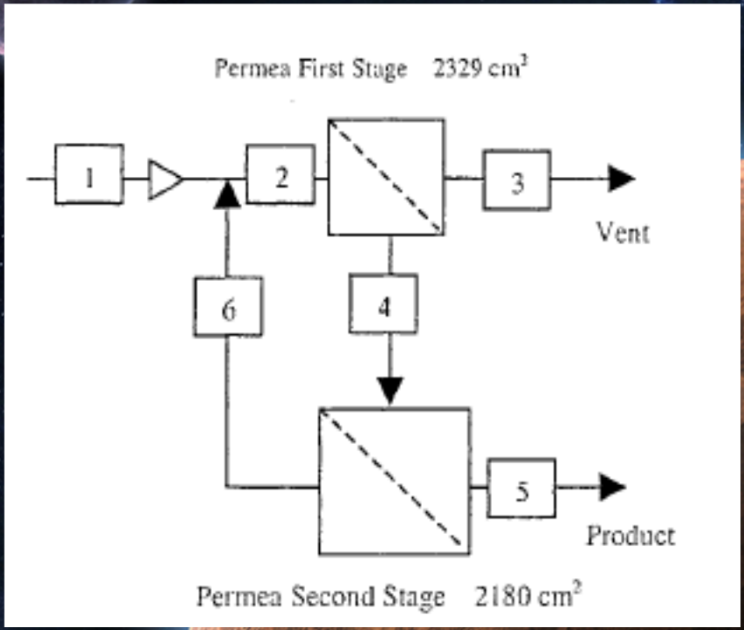
Buffer Gas Separation

- COTS Membrane Modules Are Adequate
- Parrish (KSC, 2002) performed a study of several commercial membranes:
  - Permea Prism® Alpha Separators PPA-20.
  - Neomecs GT #020101 .
  - Enerfex SS.
  - Enerfex SSP-M100C Membrane sheet.
- Temperatures = -45°C to +30°C.
- Variety of pressures.
- Designed a system that would operate at -44°C and 780 mm Hg (1.03 atm)
- Feed = 30% CO_2, 26% Ar, and 40% N_2.
- Predictied product = 6 lpm, 600 ppm CO_2, 38% Ar and 62% N_2.
- 47% recovery of the feed.
- Work is needed on Ar/N_2 separation.
  - Ar leads to potential bends issue.

TRL 3-4



Membrane purification of feed from the capture of CO_2 (Parrish, 2002)

Chemical Processes

- Solid Oxide Electrolysis:

  $2\ CO_2 \rightarrow 2\ CO + O_2$ (1)
- Sabatier:

  $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (2)
- RWGS:

  $CO_2 + H_2 \rightarrow CO + H_2O.$ (3)
- SOE: fragile ceramic membrane, but new developments at Bloom Energy
- RWGS: produces only oxygen, but recycles hydrogen many times
- Sabatier: well known, but need to take H_2 to Mars and makes only half the oxygen needed
- So?

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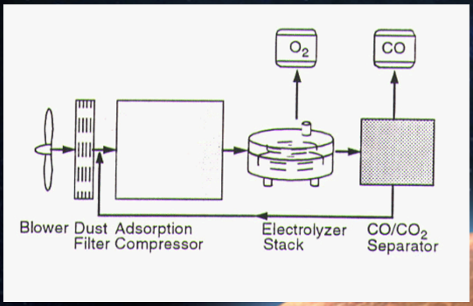
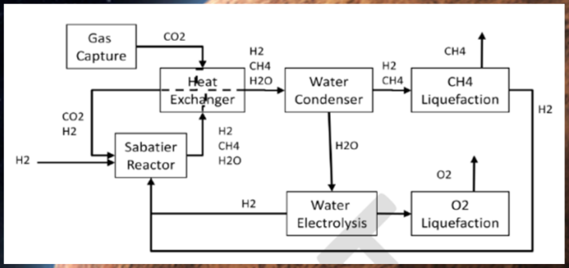
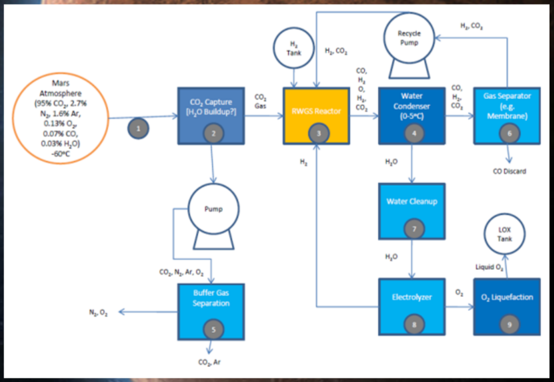


SOE Process



Sabatier Process


RWGS Process

Major Recommendation – Use Mars Surface Water Resources

- Considered by DRA 5.0
- We know where the water (ice) is and how much (Phoenix and Mars Odyssey)
- Combined with Sabatier, we can make H_2 on Mars and get the right ratio of CH_4/O_2 with surplus O_2 for life support
- Avoids difficulty of LH_2 storage
- Requires surface mining
  - Base on lunar mining technologies
- Provides a path forward for human exploration and settlement
  - i.e. water for life support and shielding

Other Chemical Processes

- Electrolysis of CO_2 in ionic liquids
  - – Low TRL, low priority
  - – Good topic for academic R&D
- Electrocatalylic reduction of CO_2 and H_2O to CH_4 and O_2
  - – Room temperature, low voltage
  - – Also low TRL, but very promising
  - – Eltron Research for JSC for ISS application

Chemical Processes - Membrane Separations

- Permea modules have been tested by LMA, Pioneer Astronautics and KSC
  - KSC results are good with minor H_2 losses (0.26% average)
- 28 other candidate membrane materials evaluated
  - Top 10 identified
- Selectivity and permeability are inversely related
- Pressurization is required (1-10 atm)
- Synthesis required in some cases

	Stream	Calculated H2 (slpm)	Measured H2 (slpm)	Calculated CO2 (slpm)	Measured CO2 (slpm)	Calculated CO (slpm)	Measured CO (slpm)
Base Case	Feed	16.825	16.861	7.56	7.522	2.114	2.116
	Permeate	16.812	16.812	7.547	7.547	1.126	1.126
	Reject	0.013	0.013	0.013	0.013	0.988	0.988
Sim-1	Feed	26.265	25.333	7.265	8.126	1.793	1.864
	Permeate	26.058	26.205	7.162	7.189	0.64	0.65
	Reject	0.207	0.059	0.103	0.076	1.153	1.144
Sim-2	Feed	30.748	30.555	7.984	8.07	1.537	1.644
	Permeate	30.011	30.48	7.681	7.801	0.3831	0.541
	Reject	0.737	0.267	0.303	0.184	1.154	0.996
Sim-3	Feed	29.552	29.428	8.605	8.696	2.028	2.047
	Permeate	29.324	29.463	8.486	8.523	0.723	0.834
	Reject	0.228	0.09	0.119	0.082	1.305	1.194
Sim-4	Feed	25.603	25.099	7.035	7.332	1.779	1.986
	Permeate	25.515	25.563	6.987	6.96	0.753	0.747
	Reject	0.088	0.04	0.048	0.076	1.026	1.032
Sim-5	Feed	16.507	17.248	8.921	8.323	2.47	2.327
	Permeate	16.43	16.5	8.843	8.909	1.032	1.384
	Reject	0.077	0.007	0.078	0.012	1.438	1.086
Sim-6	Feed	20.591	20.864	7.036	6.786	1.983	1.96
	Permeate	20.552	20.564	7.008	7.007	0.952	1.024
	Reject	0.039	0.026	0.028	0.029	1.031	0.959

KSC RWGS Membrane Results

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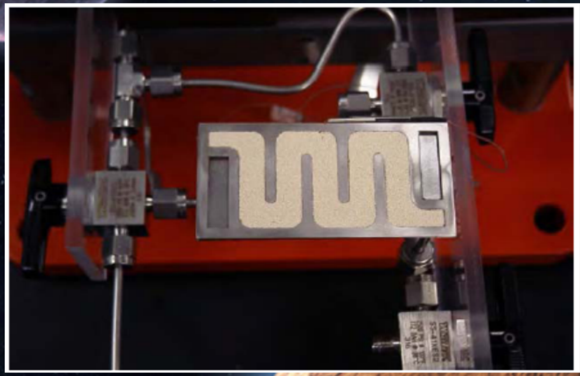
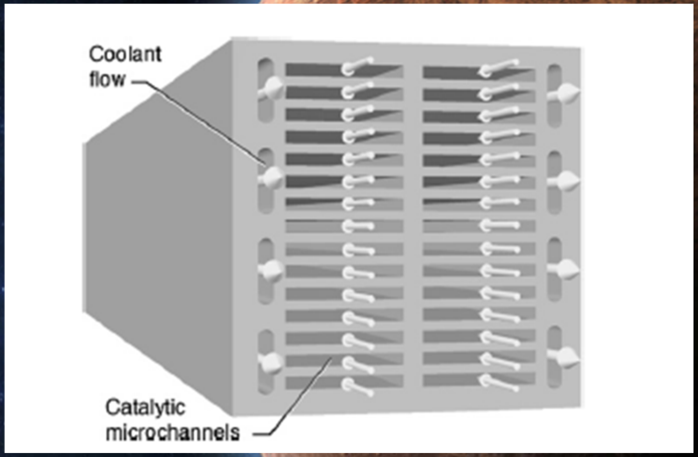
Microchannel Technologies

- Microchannel reactors offer:
  - Better temperature control of the catalyst bed
  - Reduce temperature gradients and localized “hot spots”
  - Prevent sintering of a packed bed catalyst
  - Large mass savings over the traditional packed bed reactor design,
  - Penalty of increased pressure drop and increased probability of complete catalyst deactivation.
- Potentially improved CO_2 absorption for concentration
  - Lower mass, volume, and power
- Further development is justified



PNNL Microchannel Zeolite CO2 Absorber



TRL 3

PNNL illustration of a section of microchannel reactor.

Recommendations

1. Mars Atmospheric Gas Processing: Select Sabatier (Methanation) Process for Fuel Production

   Research and Technology:

   - Lifetime of COTS catalyst
   - Efficient thermal control
   - Effect of pure CO_2 versus raw atmospheric gas on catalyst
   - Alternatives (for dissimilar redundancy): microchannel reactors (poison resistant/regenerable), ionic liquid electrolysis of CO_2, combined electrolysis of CO_2 and H_2O, improved SOE subsystems (ruggedized)

   Rationale:

   - Given the recent robotic mission findings, significant water is available on the surface of Mars
   - Water mining-Sabatier Process provides oxygen:methane in a ratio appropriate for propulsion
   - This approach will reduce Earth departure mass (no hydrogen logistics)

2. Mining Water: Continue soil excavation system and soil processing reactor development

   Research and Technology:

   - High temperature seals, valves, sensors/instrumentation, gas pumps, auxiliary equipment
   - Efficient thermal design
   - Excavation systems: reliable, long life
   - Dust tolerant mechanisms

   Rationale:

   - Martian water provides a better architecture for ISRU (i.e. eliminates Earth-supplied hydrogen logistics)

Recommendations

3. Mars Atmospheric Gas Capture: Parallel developmental effort for CO_2 freezer and mechanical compression:

   Research and Technology:

   - High efficiency (freezer/compressor)
   - Efficient thermal design (freezer)
   - Long life (cryocooler compressor)
   - Improvements in microchannel absorbers and new approaches

   Rationale:

   - The gas capture technique downstream of CO_2 reduction unit depends on the gas capture technique employed to capture atmospheric CO_2

4. Water Condenser: Engineering design to take place during integrated system development effort

   Research and Technology:

   - None

   Rationale:

   - This is an engineering effort, not a technology development task

Recommendations

5. Gas Separation: Parallel effort of cryogenic condensation and membrane separation

   Research and Technology:

   - PEM-based membranes
   - Efficient cryogenic system (combine with cryocooler development above)
   - Solubility of gases in cryogenic liquids

   Rationale:

   - Methane purity and atmospheric gas capture selection will drive the final selection of the gas separation (separation of CH_4-H_2 or N_2-Ar-H_2-CH_4)

6. Water Cleanup: Continue regenerable water cleanup

   Research and Technology:

   - Regenerable water cleanup to meet electrolysis grade

   Rationale:

   - Clean water is required for electrolysis

Recommendations

7. Electrolyzer: Continue SBIR and collaboration with ELS and Power; encourage industry development

   Research and Technology:
   - Contaminant resistant electrolysis

   Rationale:
   - Electrolysis is a common sub-system for various surface system elements.
   - Continue team collaboration and SBIR hardware.

8. Cryogenic Liquefaction and Storage: Continue collaboration with CFM.

   Research and Technology:
   - Zero boil-off storage
   - High efficiency and reliable cryocooler

   Rationale:
   - Cryogenic storage is needed to provide methane and oxygen from propellant
   - Cryogenic storage provides high density storage of consumables.

Conclusions

- Most of the technology needed for an integrated Mars ISRU demonstration is at a high enough TRL
- Further development is required on more efficient and high-reliability options for a large-scale, fully operational system for human missions
  - Microchannel devices
  - Catalysts