MARS IN SITU RESOURCE UTILIZATION TECHNOLOGY EVALUATION. A. C. Muscatello[1] and E. Santiago-Maldonado[2], [1]National Aeronautics and Space Administration-Kennedy Space Center, Surface Systems Office, NE-S2, Kennedy Space Center, FL 32899, anthony.c.muscatello@nasa.gov, [2]National Aeronautics and Space Administration-Kennedy Space Center, Surface Systems Office, NE-S2, Kennedy Space Center, FL 32899, edgardo.santiago-maldonado-1@nasa.gov.

Introduction: We have examined the technologies required to enable Mars In-Situ Resource Utilization (ISRU) because our understanding of Mars resources has changed significantly in the last five years as a result of recent robotic missions to the red planet [1-4]. Two major developments, (1) confirmation of the presence of near-surface water in the form of ice in very large amounts at high latitudes by the Phoenix Lander and (2) the likely existence of water at lower latitudes in the form of hydrates or ice in the top one meter of the regolith, have the potential to change ISRU technology selection. A brief technology assessment was performed for the most promising Mars atmospheric gas processing techniques: Reverse Water Gas Shift (RWGS) and Methanation (aka Sabatier), as well as an overview of soil processing technology to extract water from Martian soil.

Results: We conclude that the basic technologies needed to (1) concentrate carbon dioxide, nitrogen, and argon on Mars, (2) separate them, (3) process them into oxygen, methane, and buffer gases, and (4) store them for use are available at a relatively high level of development (technology readiness level: TRL 4-5) at the component level. Future work should be focused on engineering development and field demonstrations of integrated systems of these processes. The effort of developing integrated systems, with a focus on operational life-cycle testing, will reveal further technology needs required to design and build a full-scale flight system. Advanced technologies that promise improvements in the performance of these subsystems, such as ionic liquids for carbon dioxide collection and electrolysis to oxygen, low temperature electrolysis of carbon dioxide and water to methane and oxygen, microchannel collectors and reactors, and advanced cryogenic liquefaction and storage, deserve closer scrutiny and require more development. These technologies, with a TRL range of 2-4, have the potential to significantly improve in the overall performance of the Mars ISRU system: reduce mass, power, and volume and increase reliability and operational life-cycle.

In addition, current lunar soil processing technologies (i.e. excavation, soil reactor, and fluid processing) have applicability to Mars soil processing to extract water and these efforts should continue further development. It is expected that these integrated system engineering units will also reveal remaining vulnerabilities caused by interactions of the various subsystems that are currently unknown, leading to new technological needs. Once satisfactory performance is demonstrated in the laboratory, oxygen, propellant, and buffer gas engineering units should be demonstrated at analog Mars sites along with other surface systems to demonstrate a full operational cycle (resource acquisition, processing, purification, storage, and utilization) to raise the TRLs to the 5-6 range. The time is right to push the development of these technologies to give mission planners the information and confidence they need to use Mars ISRU, which is a powerful tool for reducing costs and expanding exploration capabilities for Mars missions.

Moreover, we recommend that the decision on whether hydrogen for oxygen and propellant production on Mars should be imported from Earth or obtained from Martian water sources should be the use of Mars water resources. Years of debate on whether it is feasible to transport hydrogen in liquid or slush form to Mars is not likely to be resolved in the near future. The best strategy, which also enables future Mars ISRU, is to use the water resources that are already known by direct measurement to exist on Mars. The problem is then simplified to something we can address: the development and demonstration of efficient Mars water mining and refining technologies, which would also provide pure water, another extremely useful supply item for human missions for both drinking water and radiation shielding.

One other extremely important advantage of this strategy is that the amount of oxygen and propellant that could be produced would no longer be limited to the amount of hydrogen brought from the Earth; a virtually unlimited supply would become available, restricted by only the lifetime of the hardware needed and the energy supply. Looking to the more distant future, this strategy is precisely what needed for a Mars outpost and a future Martian civilization. The availability of local Martian water resources will limit landing sites somewhat to known locations, but this is a minor disadvantage because Mars is a large planet with the same surface area as the continents of Earth. Furthermore, exploring sites with water would enhance the possibilities of finding signs of past or current Martian lifeforms, a significant scientific goal for Mars exploration.

References:

[1] Boynton, W. V. et.al. (2009) *Science, 325*, 61-64. [2] Harvey, R. P. (2010) *Science 329*, 400-401. [3] Hecht, M. H., et.al. (2009) *Science 325*, 64-67. [4] Smith, P. H., et al. (2009) *Science 325*, 58-61.

2nd Planetary & Terrestrial Mining Sciences Symposium
and Space Resources Roundtable Meeting
Ottawa, Ontario, Canada
June 19-22, 2011

Mars In Situ Resource Utilization Technology Evaluation

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Outline

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

Background – Our Changing View of Mars

- Mariners – dry, dusty, cold, Moon-like
  - Evidence for ancient water flow
- Vikings – dry, dusty, cold, but intermediate
  - 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

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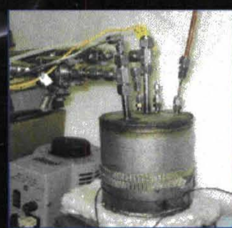
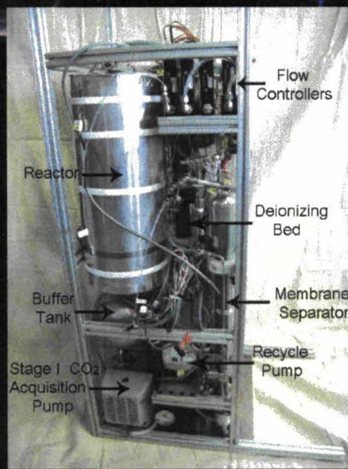


Pioneer MACDOF

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-countinuous days without degradation to 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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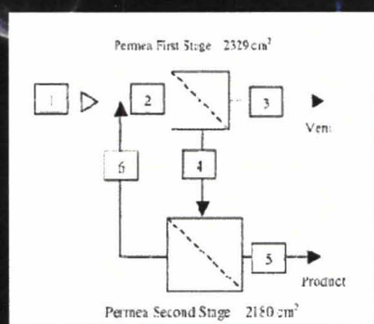
Buffer Gas Separation

- 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.



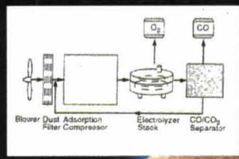
Membrane purification of feed from the capture of CO_2 (Parrish, 2002)

TRL 3-4

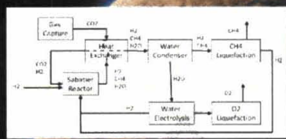
Chemical Processes

- 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?

TRL 3-4



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

TRL 3-4

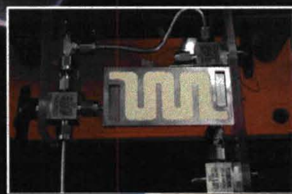
	Stream	Calculated H2 (slpm)	Measured H2 (slpm)	Calculated CO2 (slpm)	Measured CO2 (slpm)	Calculated CO (slpm)	Measured CO (slpm)
	Feed	16.825	16.861	7.56	7.522	2.114	2.116
Base Case	Permeate	16.812	16.812	7.547	7.547	1.126	1.126
	Reject	0.013	0.013	0.013	0.013	0.988	0.988
	Feed	26.265	25.333	7.265	8.126	1.793	1.864
Sim-1	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
	Feed	30.748	30.555	7.984	8.07	1.537	1.644
Sim-2	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
	Feed	29.552	29.428	8.605	8.696	2.028	2.047
Sim-3	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
	Feed	25.603	25.099	7.035	7.332	1.779	1.986
Sim-4	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
	Feed	16.507	17.248	8.921	8.323	2.47	2.327
Sim-5	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
	Feed	20.591	20.864	7.036	6.786	1.983	1.96
Sim-6	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

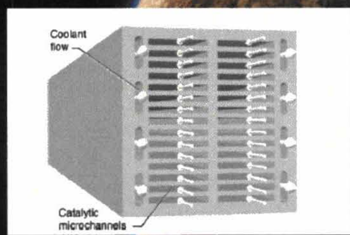
Microchannel Technologies

- 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

TRL 3



PNNL Microchannel Zeolite CO2 Absorber



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

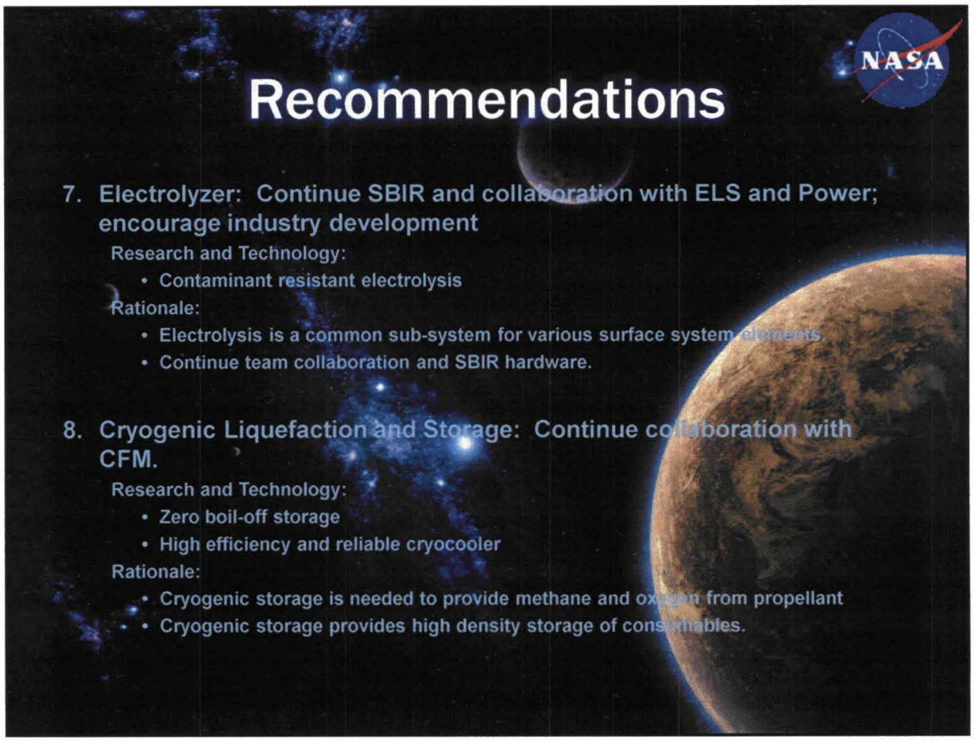
Research and Technology:
- PEM-based membranes
- Efficient cryogenic system (combine with cryocooler development above)
- Solubility of gases in cryogenic liquids

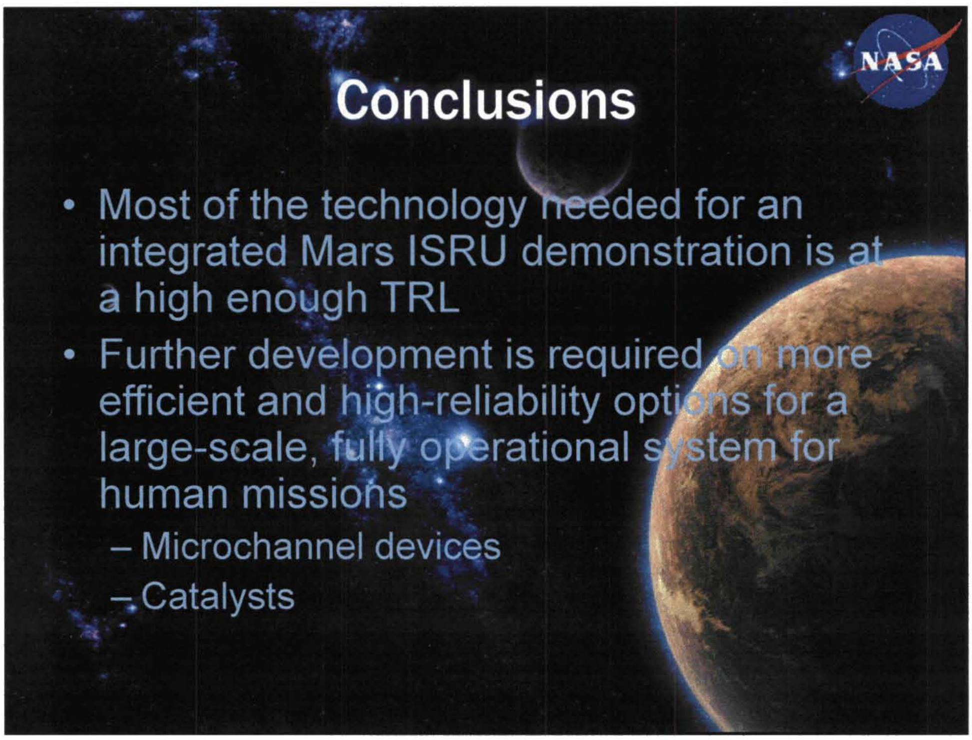
Rationale:
- Methane purity and atmospheric gas capture selection will drive the final selection of the gas separation (separation of CH_4-H_2 or N_2-Ar-H_2-CH_4)

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
NASA
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
NASA
• 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