The Technology and Future of In-Situ Resource Utilization (ISRU)

The University of Central Florida

Mars Atmospheric Capture [and Processing]

Presented by Dr. Tony Muscatello

NASA Applied Chemistry Laboratory

Kennedy Space Center

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Outline

- Martian resources
- Introduction
- Why Mars ISRU?
- Dust removal
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- CO_2 Freezing/Liquefaction
- Direct compression
- Membranes
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- Buffer gas capture and separation
- Microchannel technologies
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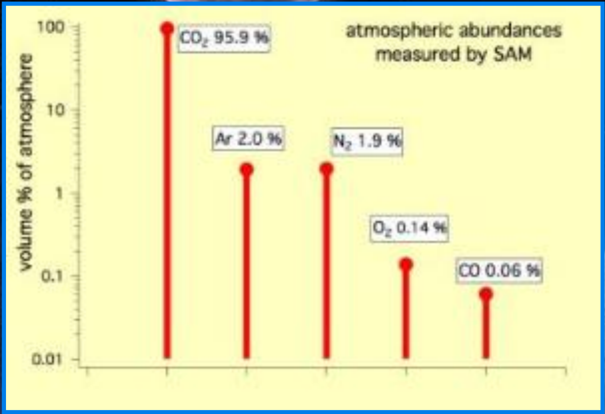
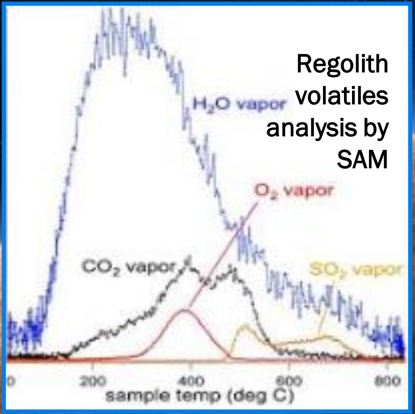
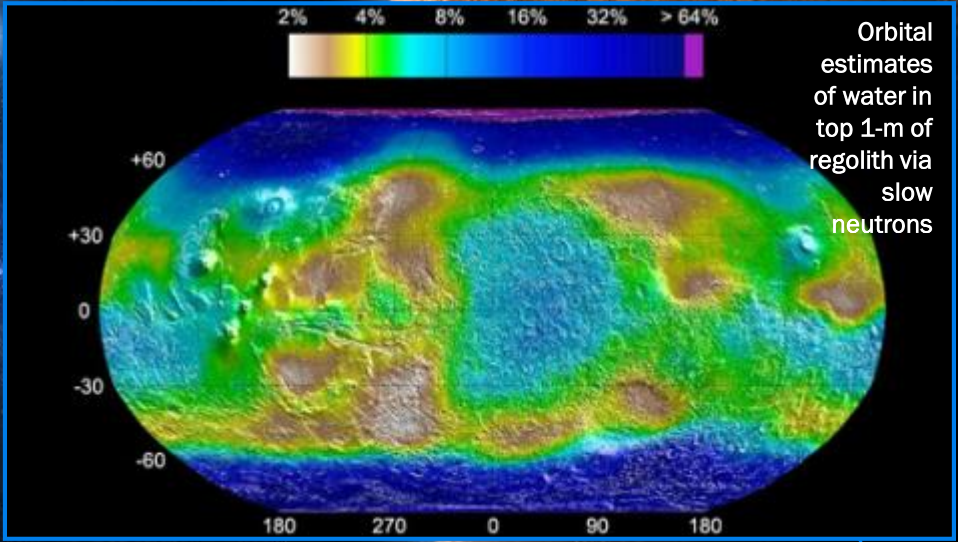
Martian Resources

- Atmosphere of Mars
  - 95.9% CO_2
  - 2% Ar, 1.9% N_2
  - <1% pressure of Earth's atmosphere (~7 mbar)
- Significant Amounts of Water in the Top 1-Meter of Regolith
  - Water ice caps at the poles
  - ~2% at least everywhere else
  - ~10% even at equatorial regions
  - <u>Curiosity rover ground truth:</u>
  - 1.5-3% water in surface regolith (SAM)
  - Average 2.9% water (DAN), up to 7% in top 60 cm of regolith in some locations-seasonal variation
  - Transient liquid water at night in the top 5 cm of regolith

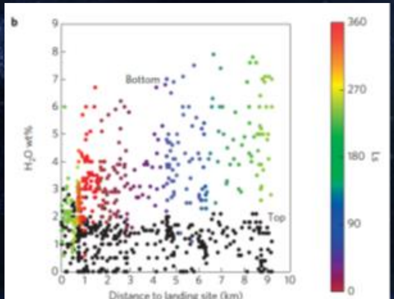




Regolith volatiles analysis by SAM



Orbital estimates of water in top 1-m of regolith via slow neutrons



Water content of regolith vs. distance by DAN on Curiosity Rover

Introduction

- In 1976, Robert Ash at Old Dominion U. initiated idea of Mars ISRU using CO_2 from the atmosphere & water from regolith
- Concept: make methane and oxygen via the Sabatier reaction and water electrolysis:
  - $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$
  - $2\ H_2O \rightarrow 2\ H_2 + O_2$
  - Freezing using liquid methane for CO_2 collection
- First demonstrated by Zubrin, Clark *et al.* at Lockheed Martin Astronautics in early '90s, but w/H_2 from Earth
  - Used zeolite sorption/desorption for CO_2 collection
  - Leverage: 12:1, but 10.3:1 after discarding excess CH_4
  - Supplement w/RWGS or CO_2 electrolysis $\rightarrow O_2$
  - Raises leverage to 18:1
- Main issue w/imported H_2: size of H_2 tanks
  - Low density/high boil-off
  - Too large for practical shrouds & heat shields

- R. Ash, W. Dowler, and G. Varsi, "Feasibility of Rocket Propellant Production on Mars," Acta Astronautica, Vol 5, pp. 705-724, 1978
- R. Zubrin, S. Price, L. Mason, and L. Clark, "Mars Sample Return with In-Situ Resource Utilization: An End to End Demonstration of a Full Scale Mars In-Situ Propellant Production Unit," NASA Contract No. NAS 9-19145. Presented to NASA JSC Jan. 13, 1995.

Why Mars ISRU?

- "Gear ratio" = mass in LEO/landed mass on Mars surface = ~10
- 10 kg IMLEO/1 kg on Mars surface
- Example: MAV (Mars Ascent Vehicle) = ~6 tons dry mass
- Propellant
  - 7 tons CH_4 + 23 tons O_2
  - 5 tons life support O_2
  - Total = 35 tons
- IMLEO ~ 300 tons or ~several HLLVs (saves $billions)
- Mars atmosphere/water ISRU system ~1.7 tons (regolith)
  - ~2.2 tons w/life support water product
- Reduces landing mass by ~30 tons or ~60%!
- Power ~40 kW, but also needed for crewed phase
  - Not counted against ISRU system mass

Kleinhenz, Julie E., and Aaron Paz. "An ISRU propellant production system for a fully fueled Mars Ascent Vehicle." 10th Symposium on Space Resource Utilization. 2017.

Dust Removal

- Martian atmosphere contains significant amounts of dust, especially during dust storms
- Can interfere with valves, catalysts, pumps, etc.
- NASA developing three approaches
  - Cyclone separator and HEPA filters (Juan Agui at GRC)
  - Electrostatic dust removal (Carlos Calle at KSC)

Cyclone separator prototype. 10” tall, 2.4” inner diameter. Smaller prototypes were built.

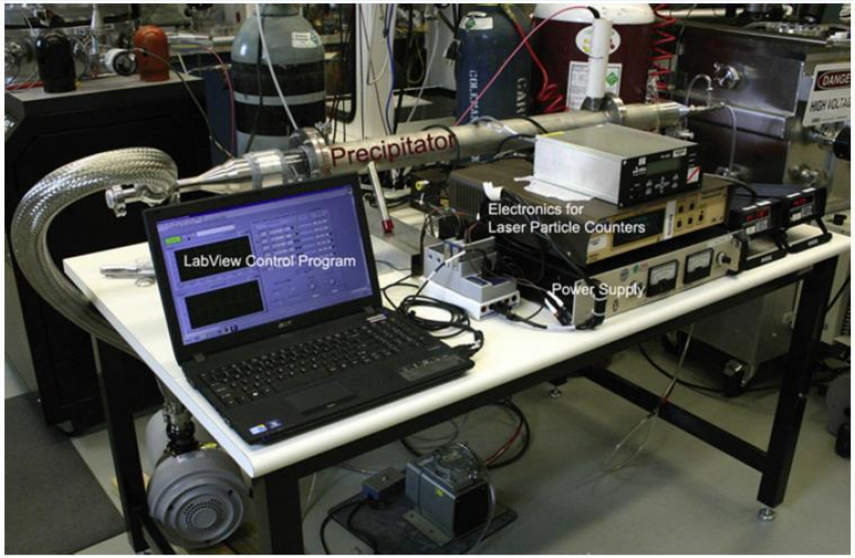


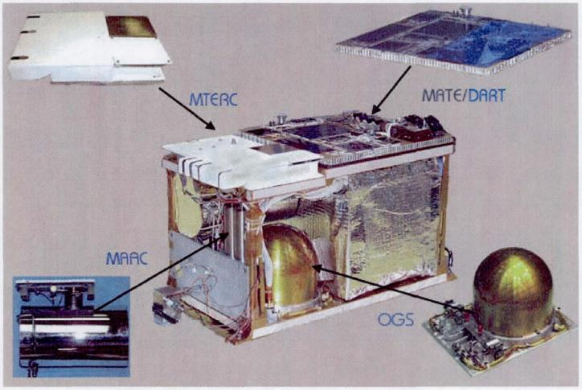
Fig. 2. Electrostatic precipitator in a flow through configuration.

Adsorption/Desorption - MIP

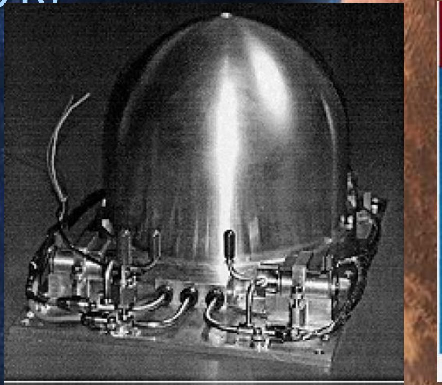
- MIP: Mars In-situ Propellant Production Precursor planned for the canceled Mars Surveyor 2001 Lander
- Led by David Kaplan at JSC
- Mass = 8.5 kg, Power (avg) = 16.0 W
- 40 cm x 24 cm x 25 cm box
- Oxygen Generator Assembly (OGA) Electrolyzes CO_2 to oxygen (~10 g/h) and carbon monoxide
- Used zeolite sorption/desorption (13X) (MAAC from JPL) with night/day cycle (200 K – 450 K)
  - 4.5 g CO_2/6 h at 0.58 atm pressure
- Designed to run for 300 Mars days (sols).

TRL 6

"Mars In-situ Propellant Production Precursor (MIP)"
http://nssdc.gsfc.nasa.gov/nmc/experimentDisplay.do?id=MS2001L%20%20-06



Photograph of integrated MIP Development Unit



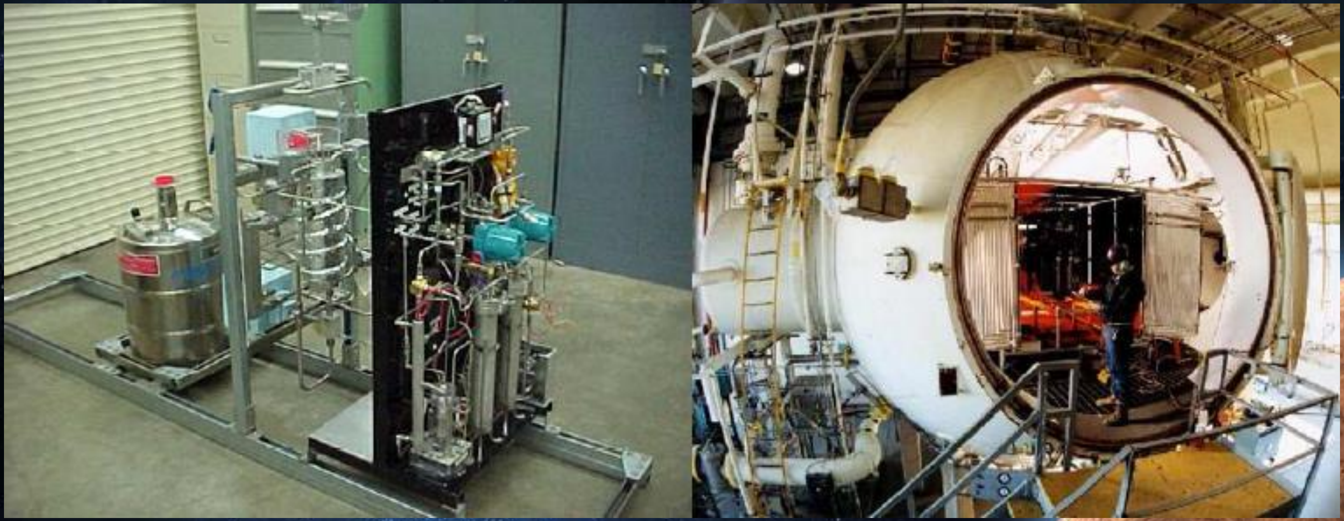
Photograph of OGS Qualification Unit

OGS DU Hardware

OGS Flight Design

OGS (Oxygen Generation System)

Adsorption/Desorption



LMA/JSC Mars ISRU System (left); JSC Mars 20 ft. Dia.Environment Chamber (right)

“The end-to-end test started with the adsorption bed removing carbon dioxide from the simulated Mars atmosphere. The bed was then heated to transfer CO2 to the Sabatier reactor with H2 gas which was catalytically converted to CH4 and H2O. The H2O vapor is condensed and delivered to the H2O electrolysis unit where it is electrolyzed into H2, which is recycled back to the Sabatier reactor, and O2, which is dried and delivered to the liquefaction and storage system. The CH4 stream from the Sabatier reactor contains residual H2 since the process is run H2 rich to maximize the conversion of CO2. The CH4 stream is passed through an electrochemical membrane to recover the H2 (and a good portion of the water) and recycle it back to the Sabatier reactor. Finally, the CH4 is passed through a drier and then routed to the liquefaction and storage system. In initial tests, the methane was simply vented overboard, since only one cryocooler was available for the system (used for O2 liquefaction). The test was run under simulated Mars conditions for 9 days, and test results were favorable, with almost complete conversion of the CO2, maximized usage of the H2, and smooth operation of the integrated breadboard13. Figure 11 depicts the end-to-end Mars ISRU test article and the Mars environment simulation chamber at JSC.”

TRL 6

Sanders, G. B., et al. Development of in-situ consumable production (ISCP) for Mars Robotic and Human Exploration at the NASA/Johnson Space Center. No. 2000-01-2240. SAE Technical Paper, 2000.

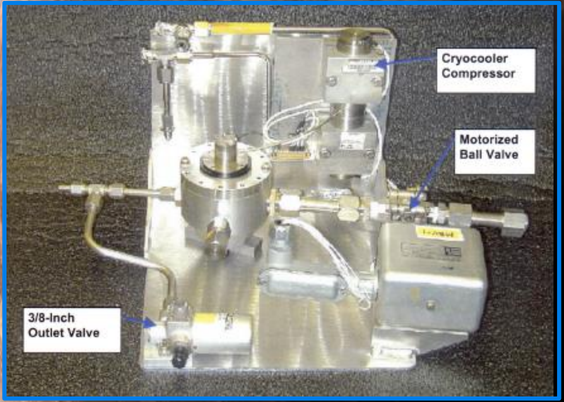
Freezing/Sublimation

- CO$_2$ Freezers Look Promising
- CO$_2$ freezers tested by Pioneer Astronautics, Lockheed-Martin (two scales), and KSC
- Results: ~20, 13, 80, and 100 g/hr using lab-scale systems
  - (equiv. 5-32 g/hr CH$_4$)
- Thickness up to 1 cm
- N$_2$/Ar was not measured or purified
- CO$_2$ self-pressurizes via sublimation
- Don Rapp (JPL) 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

TRL 3-6

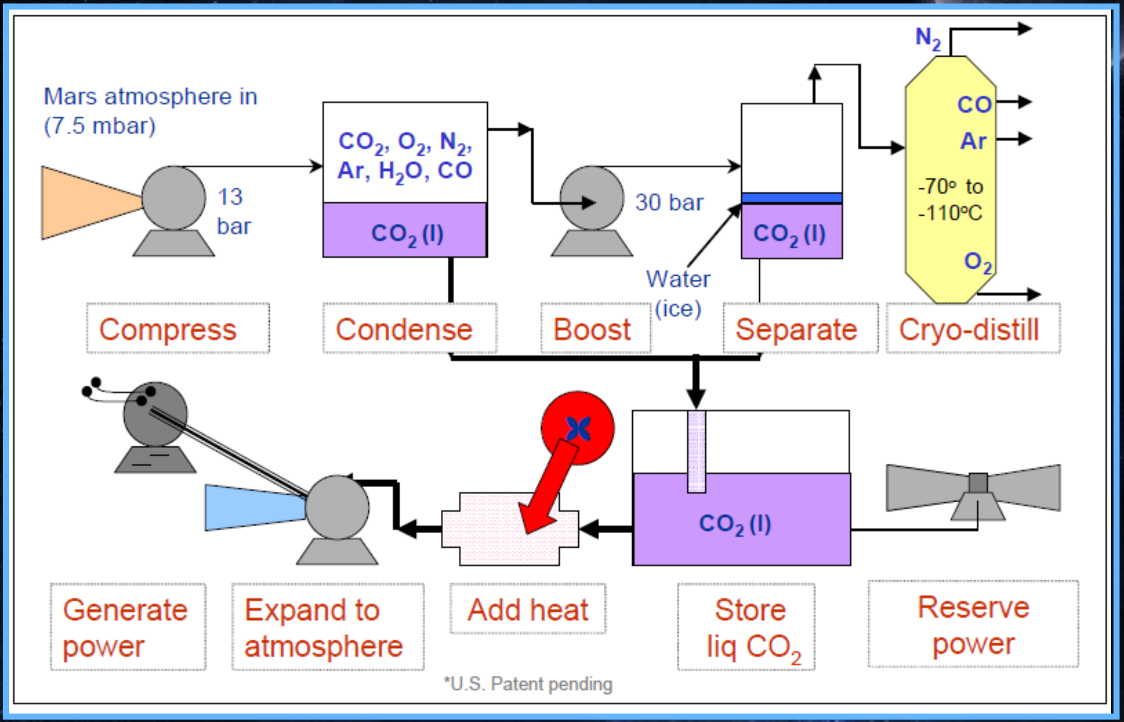
Pioneer MACDOF
(LN$_2$ Chilling)

KSC "Ferris Wheel"
Cold Head Testing



Lockheed Cryocooler Freezer
0.9 Watt-h/g CO$_2$

Direct Compression/Liquefaction



Mars Atmosphere Resource
Recovery System (MARRS)
– NIAC Study

TRL 1-2

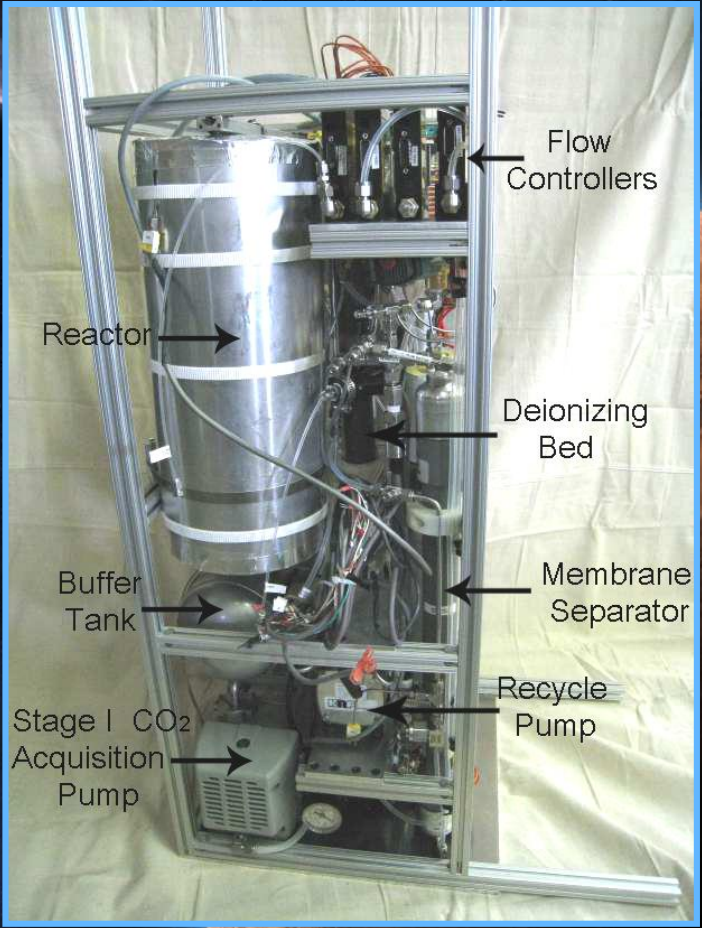
- CO_2 Liquefaction and Collection of Other Gases
- Compress very large volumes of the atmosphere to the high pressures required to liquefy CO_2
- Geared toward larger scale operations: settlements
- Requires very high power source - nuclear reactor
- Not appropriate for Mars Sample Return or early human exploration

England, Christopher, and J. Dana Hrubes. "Recovering the Atmospheric Resources of Mars: Updating the MARRS Study." AIP Conference Proceedings. Ed. Mohamed S. El-Genk. Vol. 813. No. 1. AIP, 2006.

Direct Compression & Processing

- ISRU processes (SOE, RWGS, Sabatier) tolerate lower purity CO_2
- Pioneer Astronautics tested combined RWGS-Sabatier process with $CO_2/N_2/Ar$ for 5-continuous days without degradation of catalyst
  - 1 kg/day of 3.5 O_2 to 1 CH_4
  - Power = 893 W (678 W optimized)
- N_2 and Ar not separated, but removed during condensation or cryodistillation of products
- Gas separation downstream from CO_2 reduction process may be easier and still provide useful buffer gases
- Two-stage COTS mechanical compression required 242 W (plus chiller), and may require more power than freezing, but was claimed to be less complex
- Mass comparison needs to be done

TRL 4



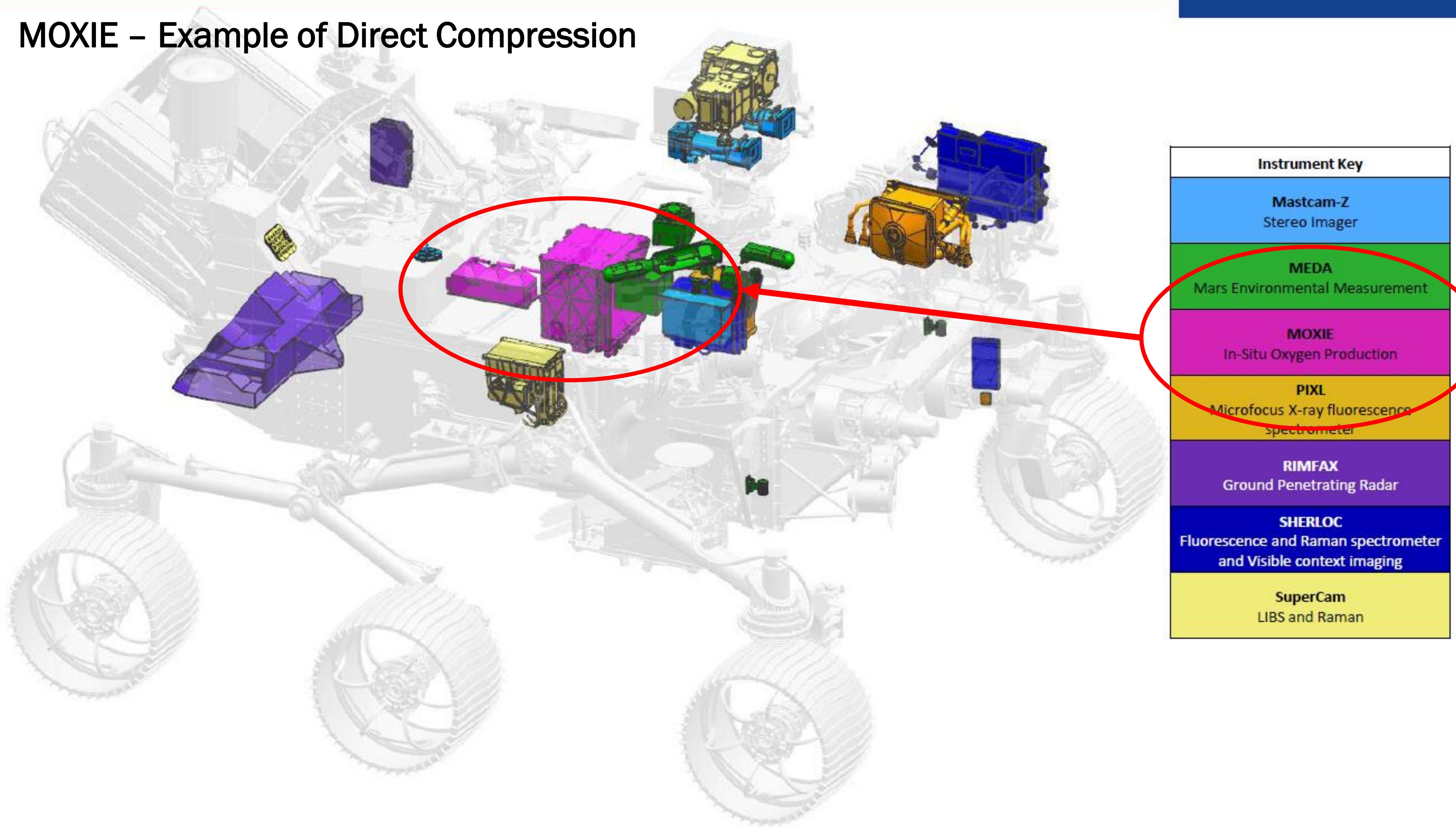
Pioneer IMISPPS

46 cm x 41 cm x 94 cm; 115 kg (54 kg optimized)

Zubrin, Robert M., Anthony C. Muscatello, and Mark Berggren. "Integrated Mars In Situ Propellant Production System." *Journal of Aerospace Engineering* 26.1 (2012): 43-56 & Bruinsma et al. NASA SBIR Contract NNK06OM03C

Mars 2020 Payload Family Picture

MOXIE – Example of Direct Compression



Instrument Key
Mastcam-Z Stereo Imager
MEDA Mars Environmental Measurement
MOXIE In-Situ Oxygen Production
PIXL Microfocus X-ray fluorescence spectrometer
RIMFAX Ground Penetrating Radar
SHERLOC Fluorescence and Raman spectrometer and Visible context imaging
SuperCam LIBS and Raman

http://mepag.nasa.gov/meeting/2016-03/21_MEPAG_160303_FINAL%20v2.pdf

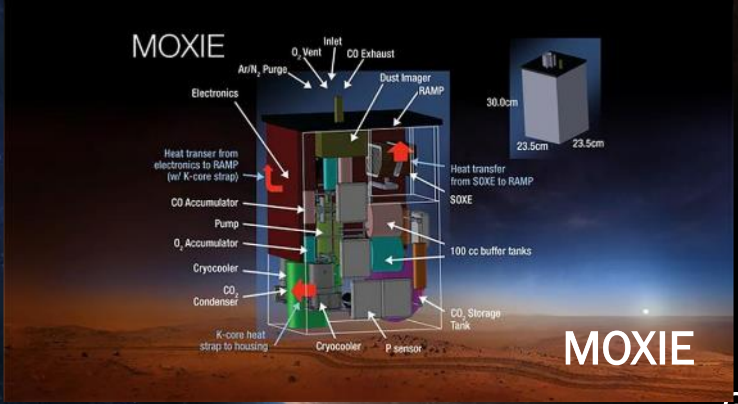
Direct Compression/Processing – MOXIE

- MOXIE is the Mars OXygen In situ resource utilization Experiment on the Mars 2020 Rover
- Led by Dr. Michael Hecht, MIT/Haystack Obs.
- Electrolyzes CO_2 to oxygen (~10 g/h) and carbon monoxide
- Initially specified a small cryocooler
- Switched to a small scroll pump from Air Squared (Broomfield, CO)
- N_2 and Ar are not separated from feed, but vented with CO
- Compressor Requirements:
  - A mass flow rate of at least 100 grams per hour
  - An outlet pressure of at least 760 Torr, with 7 Torr inlet pressure
  - A compressor and motor not exceeding 175 mm in length
  - Full compatibility with the working fluid: 95% CO2, 3% N2, and 2% Ar
  - A total mass of compressor, motor, and controller not exceeding 1.8 kg
  - The ability to function in the Martian environment
  - Further improvements in size, weight, and efficiency throughout development

"MOXIE Single-Stage Scroll Pump Design" for Mars 2020

https://airsquared.com/news/scroll-compressor-jpl-mars-2020/

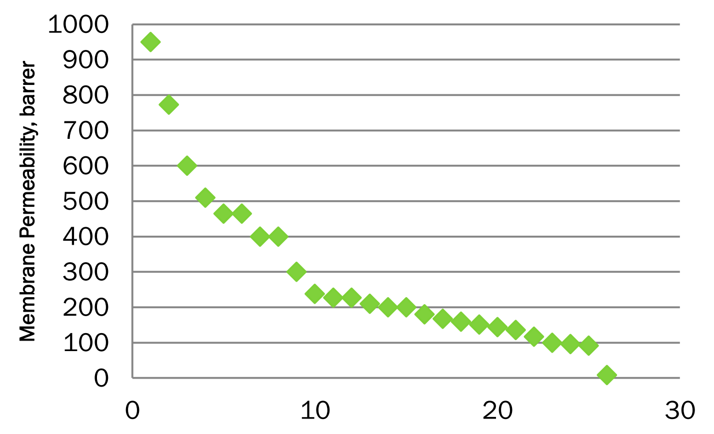
TRL 6 after development



Hoffman, Jeffrey A., Donald Rapp, and Michael Hecht. "The Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 Rover." *AIAA SPACE 2015 Conference and Exposition*. 2015.

CO_2 Capture with Membranes

- Evaluated 28 other membrane materials
  - Top 10 identified
- Mainly polymeric-based: poly-acetate, polyimides, polyamides, poly-sulfone, polycarbonates, and polyethylene, plus zeolite membranes
- Selectivity and permeability are inversely related
- Pressurization is required (1-10 atm)
- Polyacetylene and polydimethylsiloxane have the highest permeability
- Trades are needed for selectivity vs permeability and power to compress the CO_2 for separation
- Synthesis required in some cases



Distribution of membrane permeability. Note: For clarity, the top two ranked materials are not included in this graph (1 barrer = 7.5×10^{-14} (cm^3(STP)-cm)/(cm^2-s-Pa)).

TRL 2-3

Chemical Processes - Membrane Separations

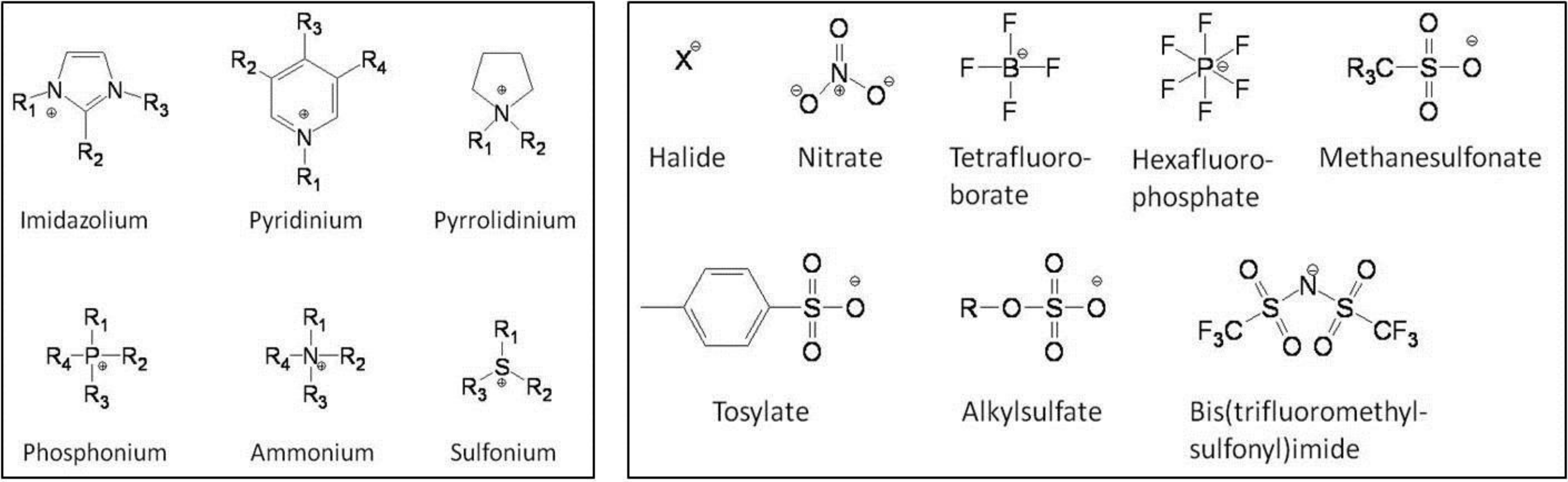
- Air Products Prism modules have been tested by LMA, Pioneer Astronautics and KSC
  - KSC results are good with minor H2 losses (0.26% average)

		Calculated	Measured	Calculated	Measured	Calculated	Measured
	Stream	H2 (slpm)	H2 (slpm)	CO2 (slpm)	CO2 (slpm)	CO (slpm)	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

TRL 4

KSC RWGS Membrane Results

Ionic Liquids for CO$_2$ Adsorption/Electrolysis



Cations

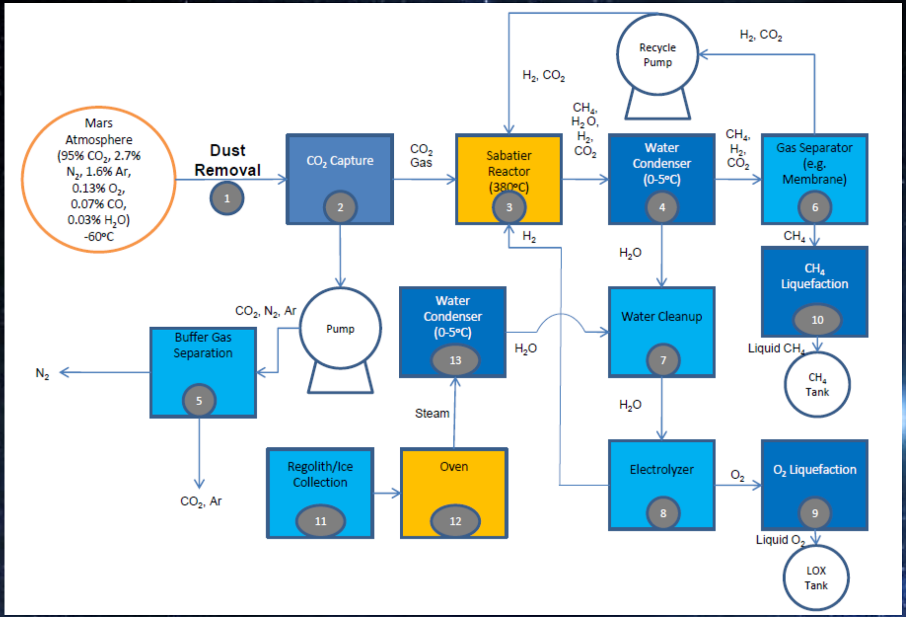
Anions

Typical cations and anions for ILs

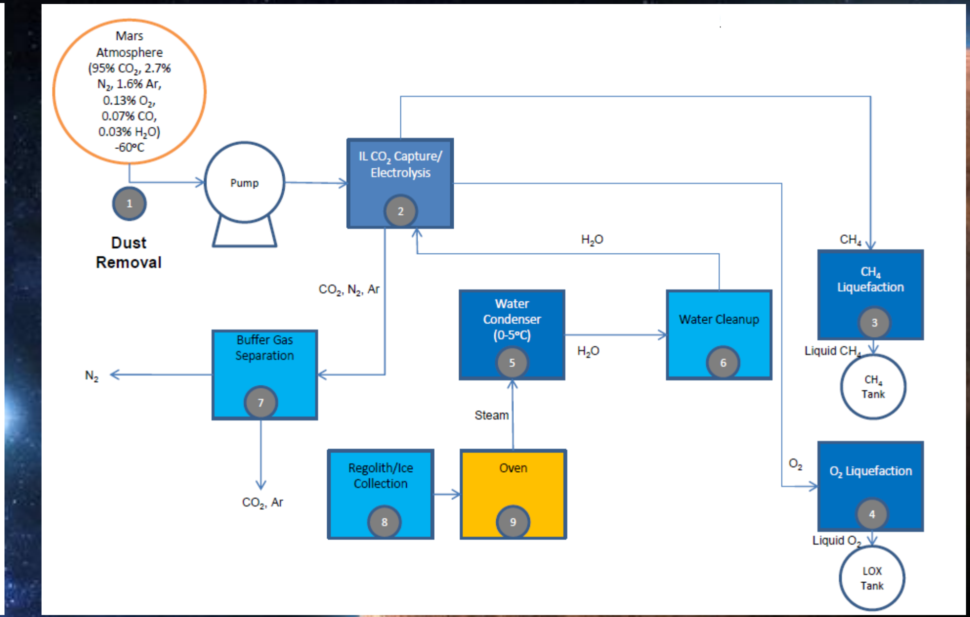
Ionic Liquids are organic, ionic compounds that are liquid at or near room temperatures

Potential Benefits for ISRU

Current Mars Bipropellant Production Process Diagram

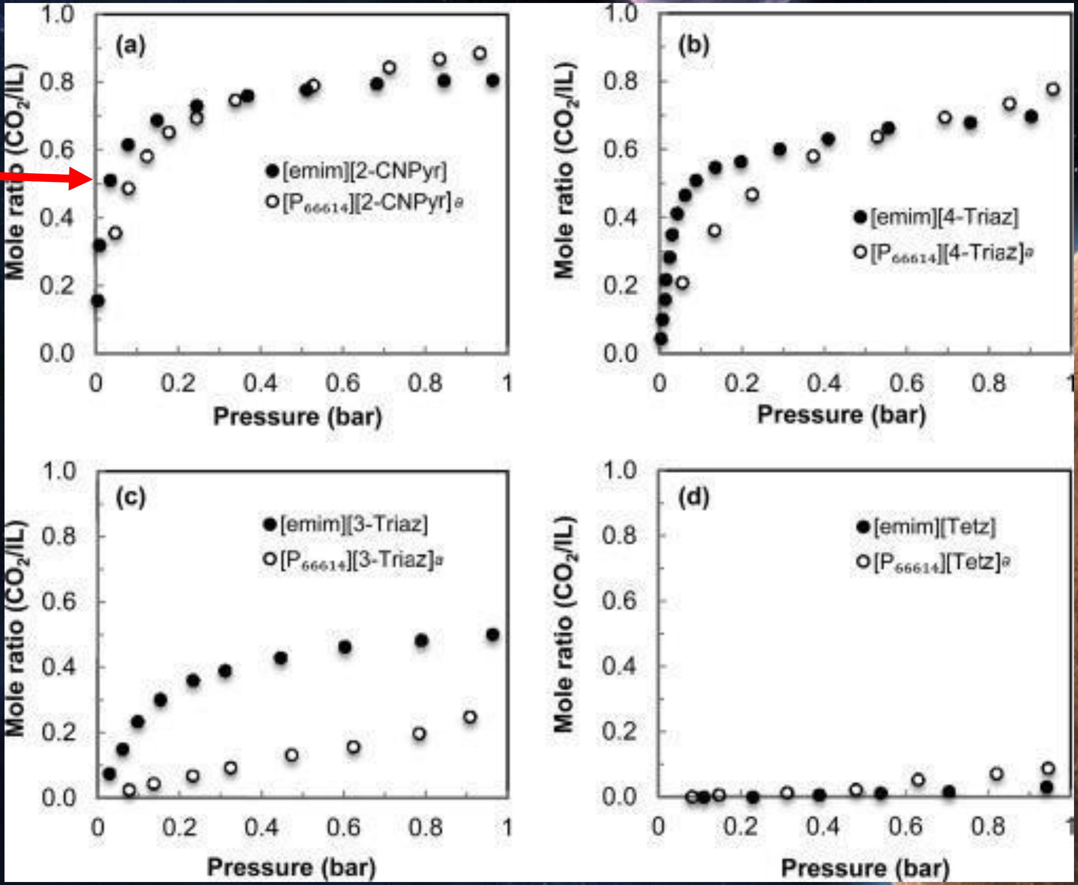


Mars Bipropellant Production Process Diagram with IL Electrolysis



- Advantages of IL capture/electrolysis:
  - No high temperature processing of CO_2
  - One less pump and no cryocoolers
  - Four fewer major process steps
  - Estimated ~50% less mass and ~25% less power

CO_2 Uptake at Low Partial Vacuum ~50% Mole Fraction at ~10 mbar



"CO_2 absorption capacity in (a) [emim][2-CNPyr], (b) [emim][4-Triaz], (c) [emim][3-Triaz], and (d) [emim][Tetz] at 22 °C. The CO_2 solubility in $[P_{66614}]^+$ counterparts from ref 10 are also shown for comparison." (Brennecke, 2014)

Summary of KSC Results (Underlined ILs = Candidates)

Ionic Liquid	CO$_2$ Capacity, wt.% (R.T., 1 atm, dry)	Electro-chemical Window, V	Conduc-tivity with CO$_2$ (mS/cm, 40°C)	Compatible with Cu	Other Issues	Tested Solubility of Water, v/v%	Methane Production Rate
[BMIM][TFSI]	0.46	2.1		No			
[BMIM][PF$_6$]	0.50	2.4		Yes	Precipitate, Cu darkened		0
[BMIM][BF$_4$]	0.55	1.8		Yes			Small
[HMIM][B(CN)$_4$]	0.70	0.6		No			
[EMIM][BF$_4$]	2.6	1.6		No			
AZ-1	9.0	4.4	0.67	No		5	
AZ-2	9.6	2.4		Yes	IL darkened		0
AZ-3	15.6		1.2	Slow color change	Precipitate	5	Possible CH$_4$ and CO (TiO$_2$ only)

Ionic Liquids for CO_2 - Summary

TRL 2

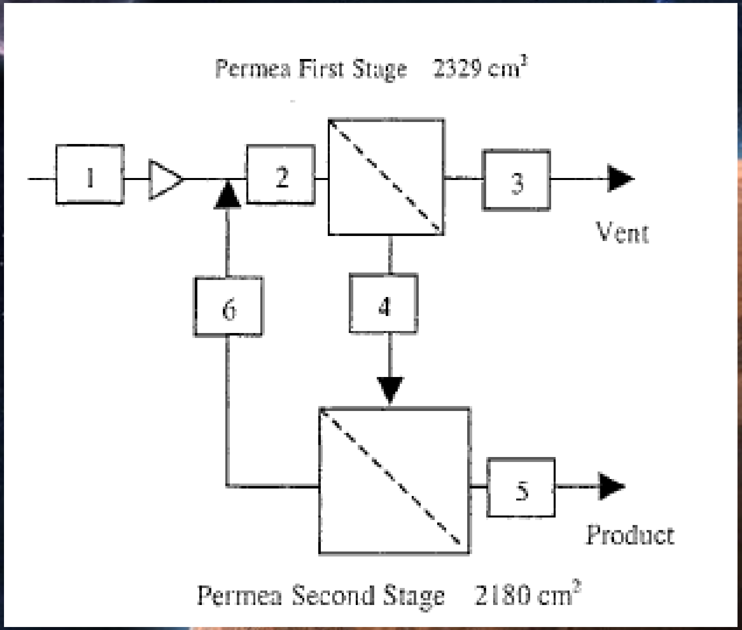
- In general, the benefits of ILs are:
  - Low volatility
  - Wide range of regeneration temperatures
  - Less energy to regenerate
  - Potentially lower corrosion
  - High temperature stability
  - Ability to tune performance

- Some major challenges for ILs that still need to be addressed:
  - Limited commercial availability
  - Limited understanding of the reaction mechanisms and kinetics

- Some major challenges for IL membranes that still need to be addressed:
  - Improvements in membrane fabrication (in general)
  - Improvements in large scale membrane fabrication
  - Improvements in producing defect free coating for the membranes

Buffer Gas Separation

- COTS Membrane Modules Are Adequate
- Parrish (KSC, 2002) studied 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.
- Predicted 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)

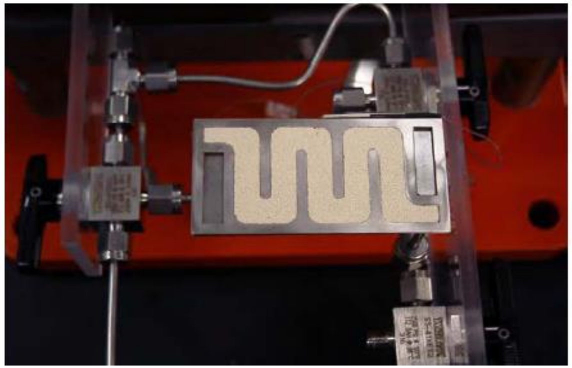
TRL 3-4

Parrish, C., “Membrane Separation Processes at Low Temperatures,” AIAA Paper 2002-0461, 40th Aerospace Science Meeting & Exhibit Proceedings, 14-17 January 2002, Reno, Nevada.

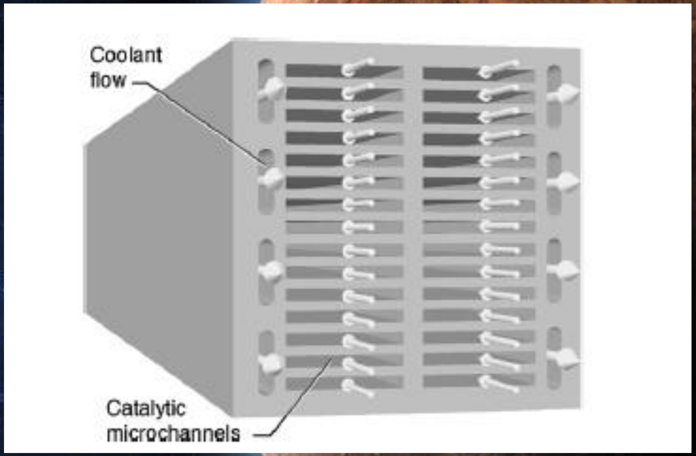
Microchannel Technologies

- 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 CO_2 Absorber



PNNL illustration of a section of microchannel reactor.

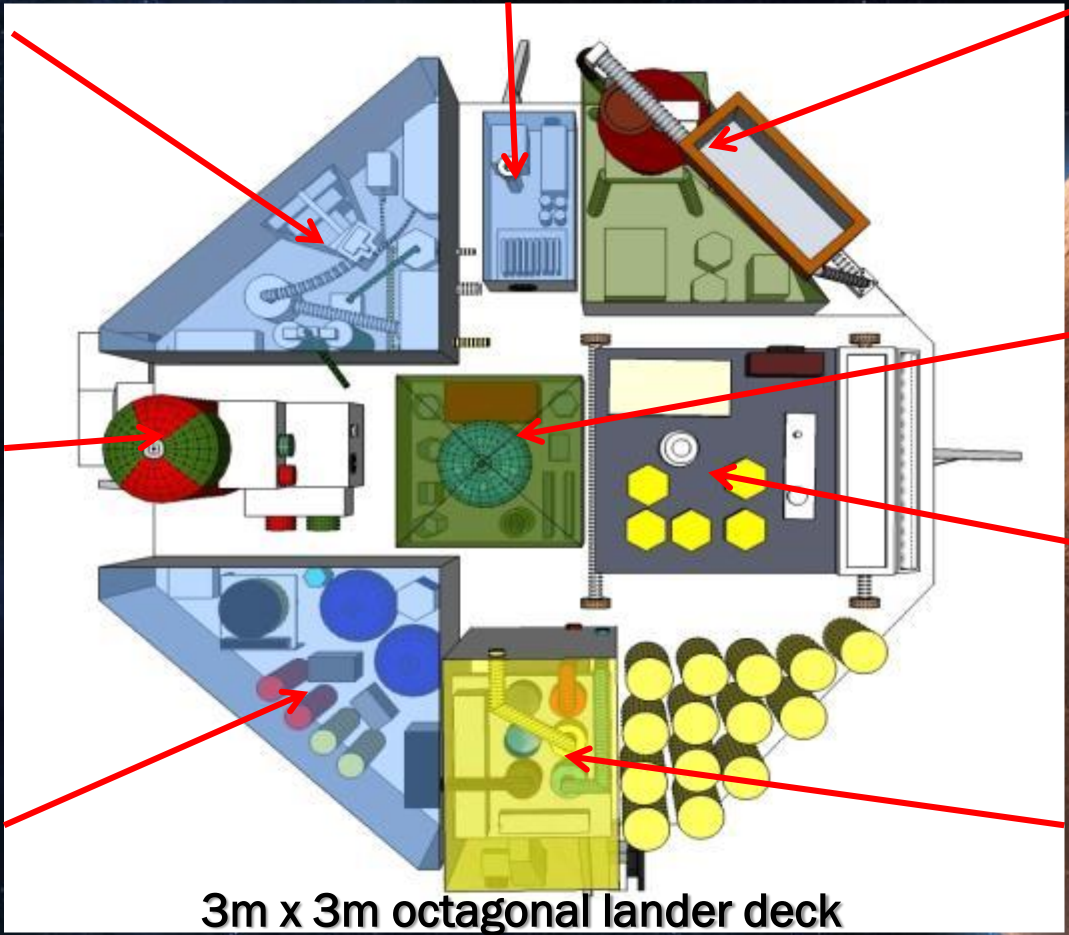
MARCO POLO/ Mars ISRU Pathfinder

- ISPP: In Situ Propellant Production
  - Demonstrate production of Mars Sample Return propellant
  - Reduce risk for human Mars missions
- **MARCO POLO** - **Ma**rs **A**tmosphere and **R**egolith **CO**llector/**PrO**cessor for **L**ander **O**perations
- The **M**ars **A**tmospheric **P**rocessing **M**odule (**APM**)
  - Mars CO_2 Freezer Subsystem
  - Sabatier (Methanation) Subsystem
- Collect, purify, and pressurize CO_2
- Convert CO_2 into methane (CH_4) and water with H_2
- Other modules mine regolith, extract water from regolith, purify the water, electrolyze it to H_2 and O_2, send the H_2 to the Sabatier Subsystem, and liquefy/store the CH_4 and O_2
- Test in a Mars analog (field demo)

What is MARCO POLO?

- First generation integrated Mars soil and atmospheric processing system with mission relevant direct current power
  - 10 KW Fuel Cell for 14 hrs of daytime operations
  - 1KW Fuel Cell for 10 hrs of night time operations
- Demonstrates closed loop power production via the combination of a fuel cell and electrolyzer.
  - The water we make and electrolyze during the day provides the consumables for the 1KW Fuel Cell that night
- Planned for remote and autonomous operations

Lander Design Concept



C&DH/PDU Module: (JSC)

- Central executive S/W
- Power distribution

Atmo Processing Module:

- CO2 capture from Mixed Mars atmosphere (KSC)
- Sabatier converts H2 and CO2 into Methane and water (KSC/JSC)

Liquefaction Module: (TBD)

- Common bulkhead tank for Methane and Oxygen liquid storage

Water Processing Module: (JSC)

- Currently can process 520g/hr of water (max 694 g/hr)

Soil Processing Module: (JSC)

- Soil Hopper handles 30kg (KSC)
- Soil dryer uses CO2 sweep gas and 500 deg C to extract water

Water Cleanup Module: (KSC)

- Cleans water prior to electrolysis
- Provides clean water storage

Excavator: (KSC)

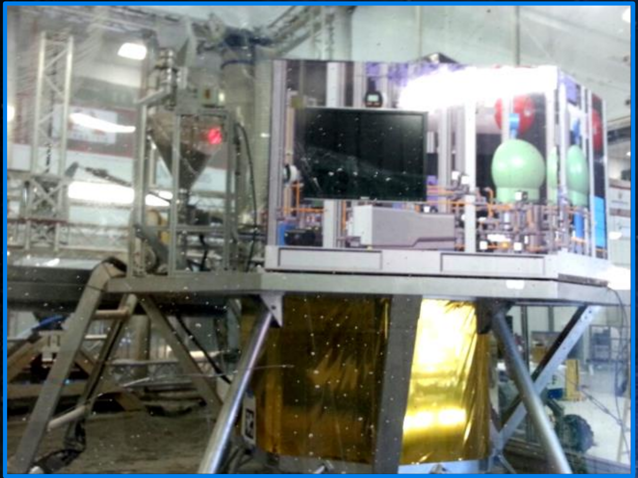
- RASSOR 2.0 Rover
- Provides feed to Soil Dryer

1KW Fuel Cell and consumable storage (JSC & GRC)

- Uses metal hydride for H2 storage due to availability
- 1KW No Flow Through FC (GRC)
- 10KW FC not shown (JSC)

3m x 3m octagonal lander deck

Existing Hardware



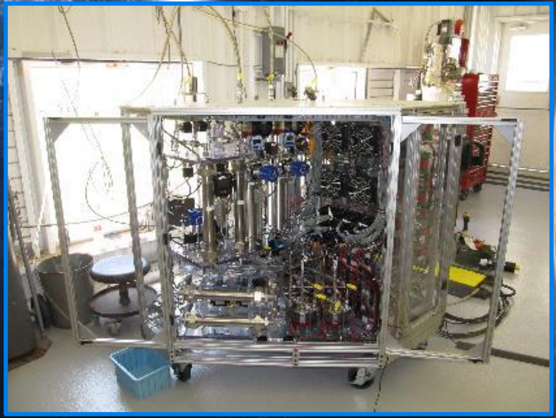
KSC: Mockup Lander w/Hopper, Mock Oven, and APM Simulator in Regolith Bin

KSC: RASSOR 2.0 Excavator Rover

KSC: Common Bulkhead Cryotank

JSC: Soil Processing Module

KSC/JSC: Water Cleanup Module

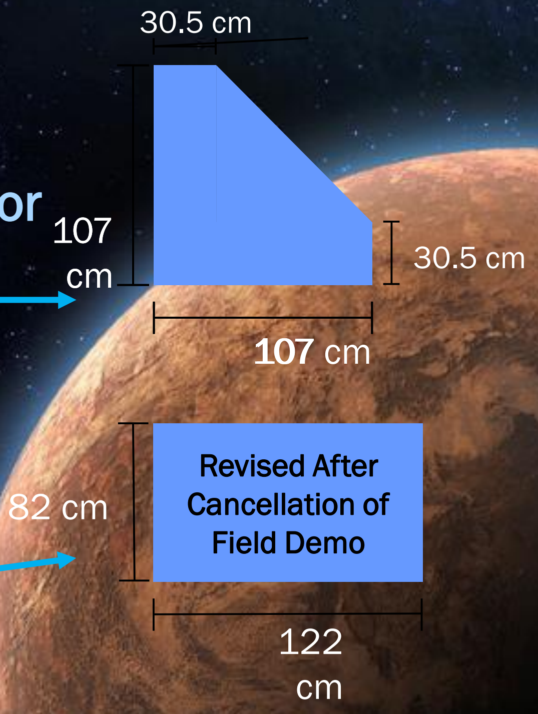


JSC: Water Processing Module (Electrolyzer)

KSC: Atmospheric Processing Module

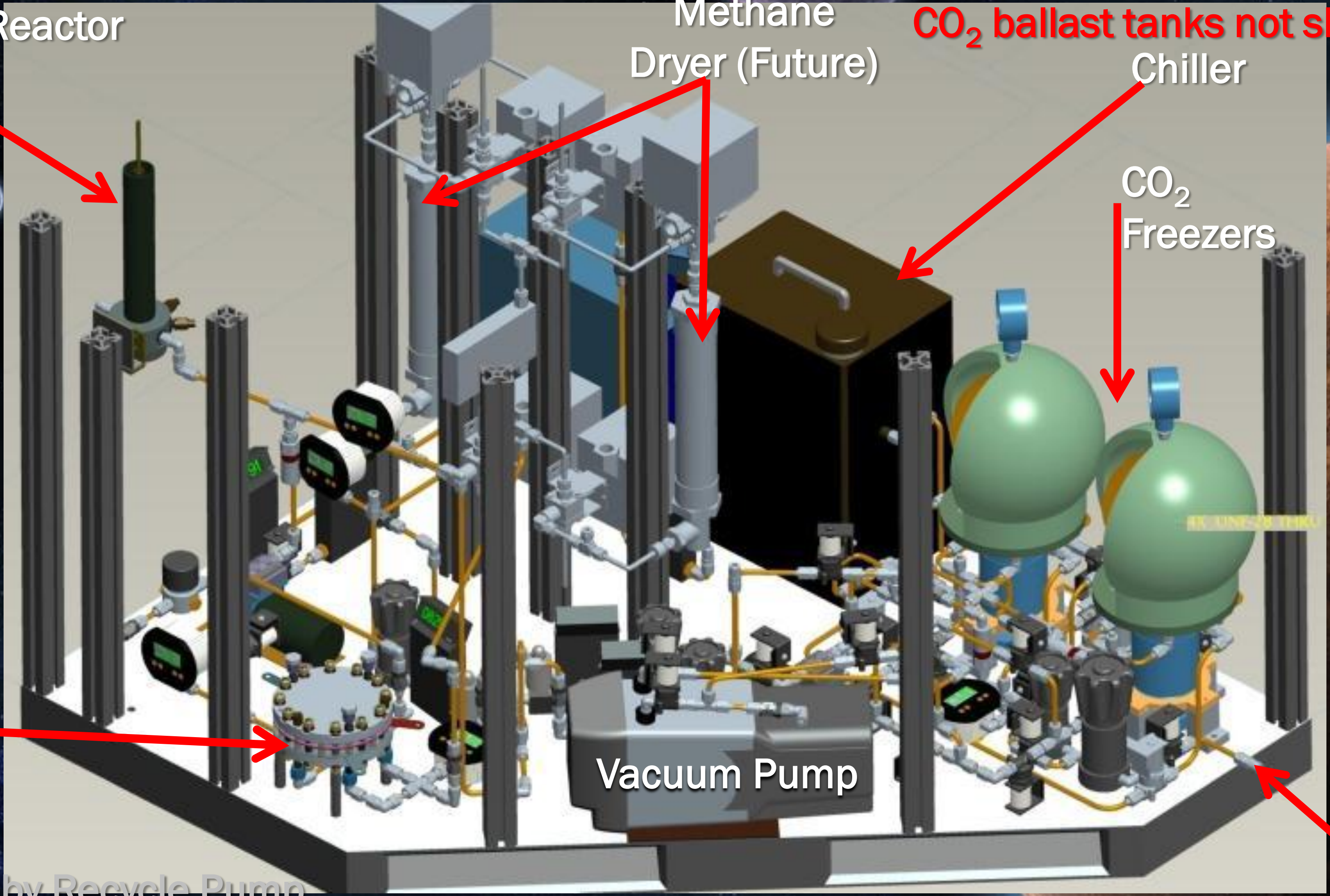
APM Goals/Requirements

- Collect and purify 88 g CO_2/h (>99%)
  - From simulated Martian atmosphere
  - 10 mbar; 95.4% CO_2, 3% N_2, 1.6% Ar
- Supply 88 g CO_2/h at 50 psia to the Sabatier reactor
- Convert CO_2 to 32 g CH_4/h and 72 g H_2O/h
- Operate autonomously for up to 14 h/day
- Minimize mass and power
- Fit within specified area and volume
  - 9,000 cm² pentagon
  - 10,000 cm² rectangle for easier lab operations
  - 44 inches tall (112 cm, same as Water Processing Module)
- Support MARCO POLO production goals of 0.032 kg CH_4/h and 0.128 kg O_2/day (50% of O_2) for a total of 2.22 kg propellant/14 h day
- Sufficient for a Mars Sample Return Mission
- ~13% of full-scale O_2 production goal for human Mars Missions (1 kg O_2/h/module x 3 modules = 3 kg O_2/h), i.e. 1/8th scale



Revised After Cancellation of Field Demo

Atmospheric Processing Module Design



Sabatier Reactor

Methane Dryer (Future)

CO_2 ballast tanks not shown

Chiller

CO_2 Freezers

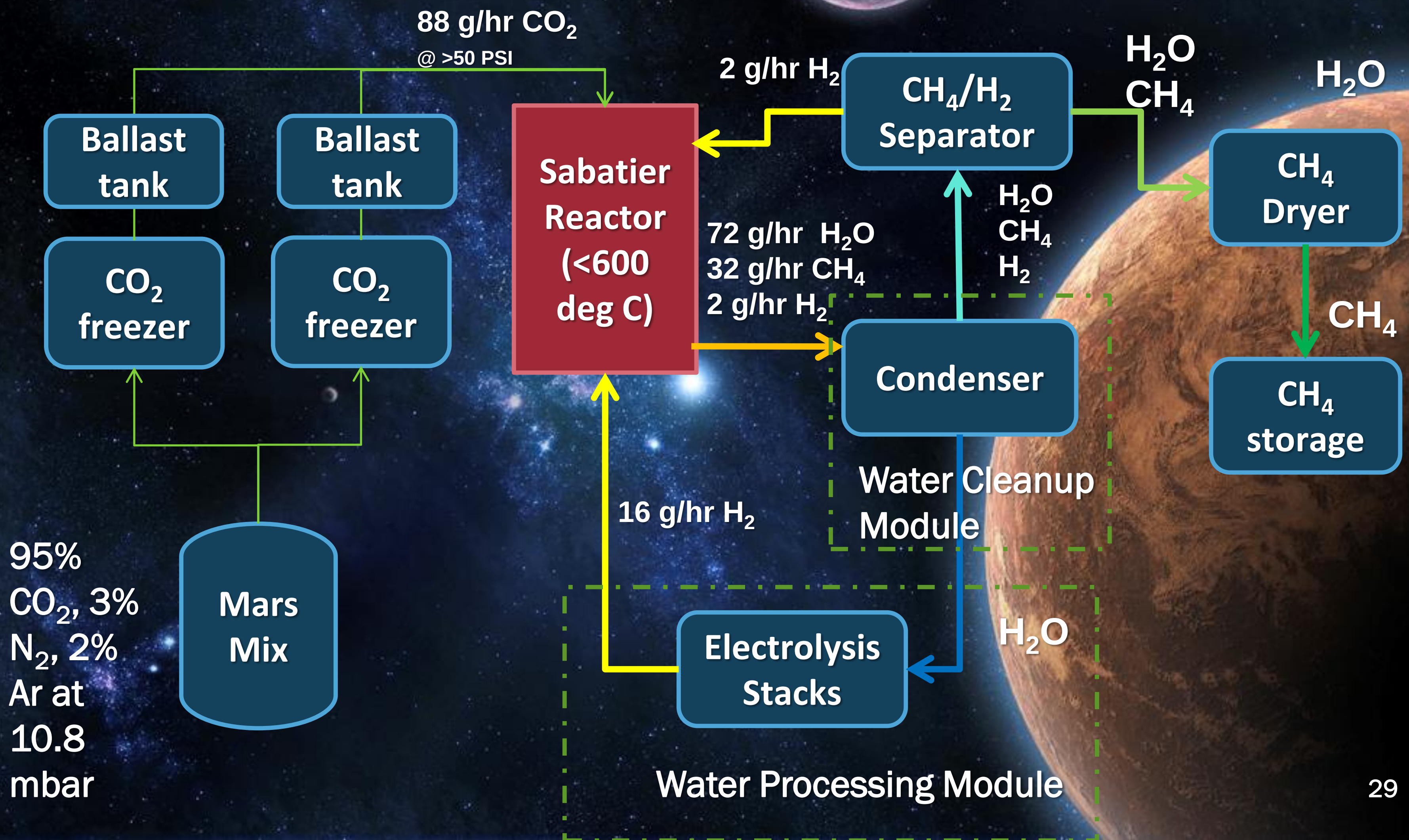
Electro-chemical Methane Separator

[Replaced by Recycle Pump and Membrane Module]

Vacuum Pump

Mixed Mars Gas Input

Atmospheric Processing Operations



88 g/hr CO_2

@ >50 PSI

Ballast tank

Ballast tank

CO_2 freezer

CO_2 freezer

Sabatier Reactor (<600 deg C)

2 g/hr H_2

CH_4/H_2 Separator

H_2O
CH_4

H_2O

CH_4 Dryer

CH_4

CH_4 storage

72 g/hr H_2O
32 g/hr CH_4
2 g/hr H_2

H_2O
CH_4
H_2

Condenser

Water Cleanup Module

16 g/hr H_2

95% CO_2, 3% N_2, 2% Ar at 10.8 mbar

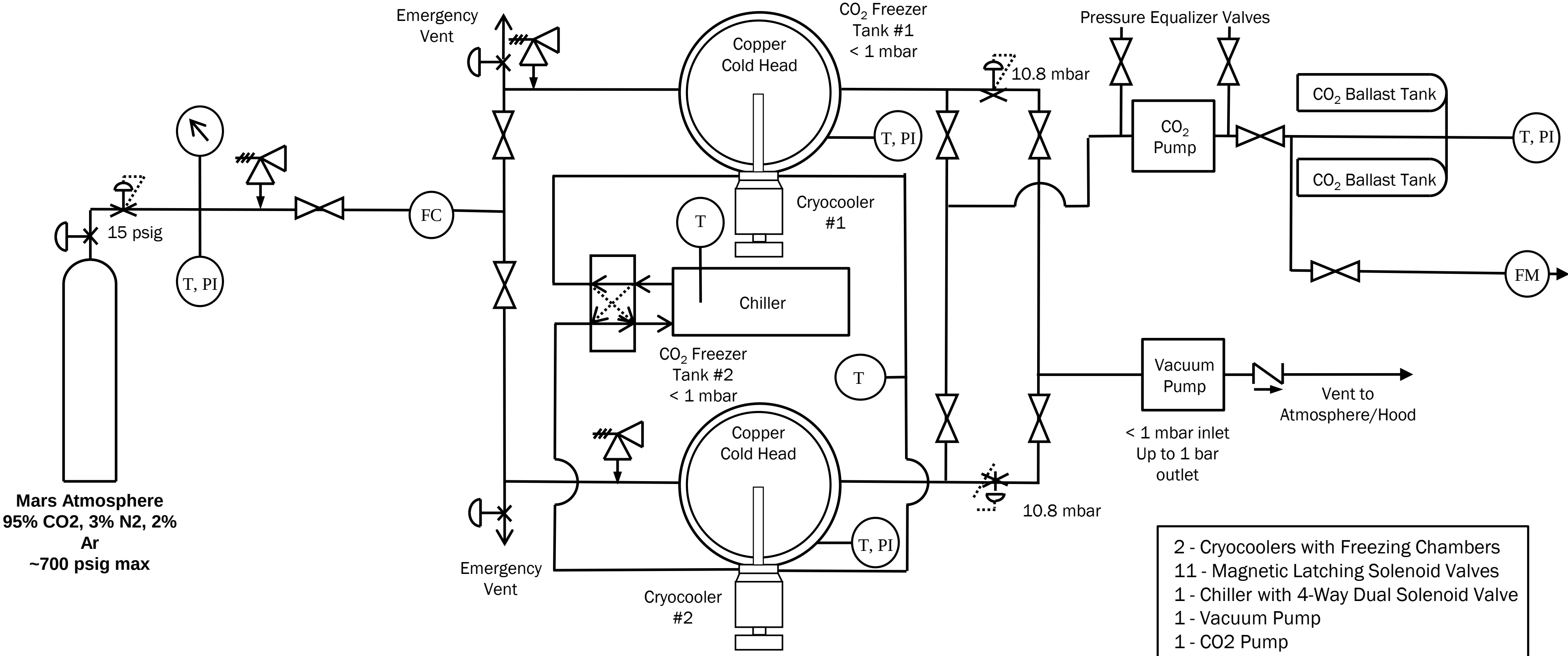
Mars Mix

Electrolysis Stacks

H_2O

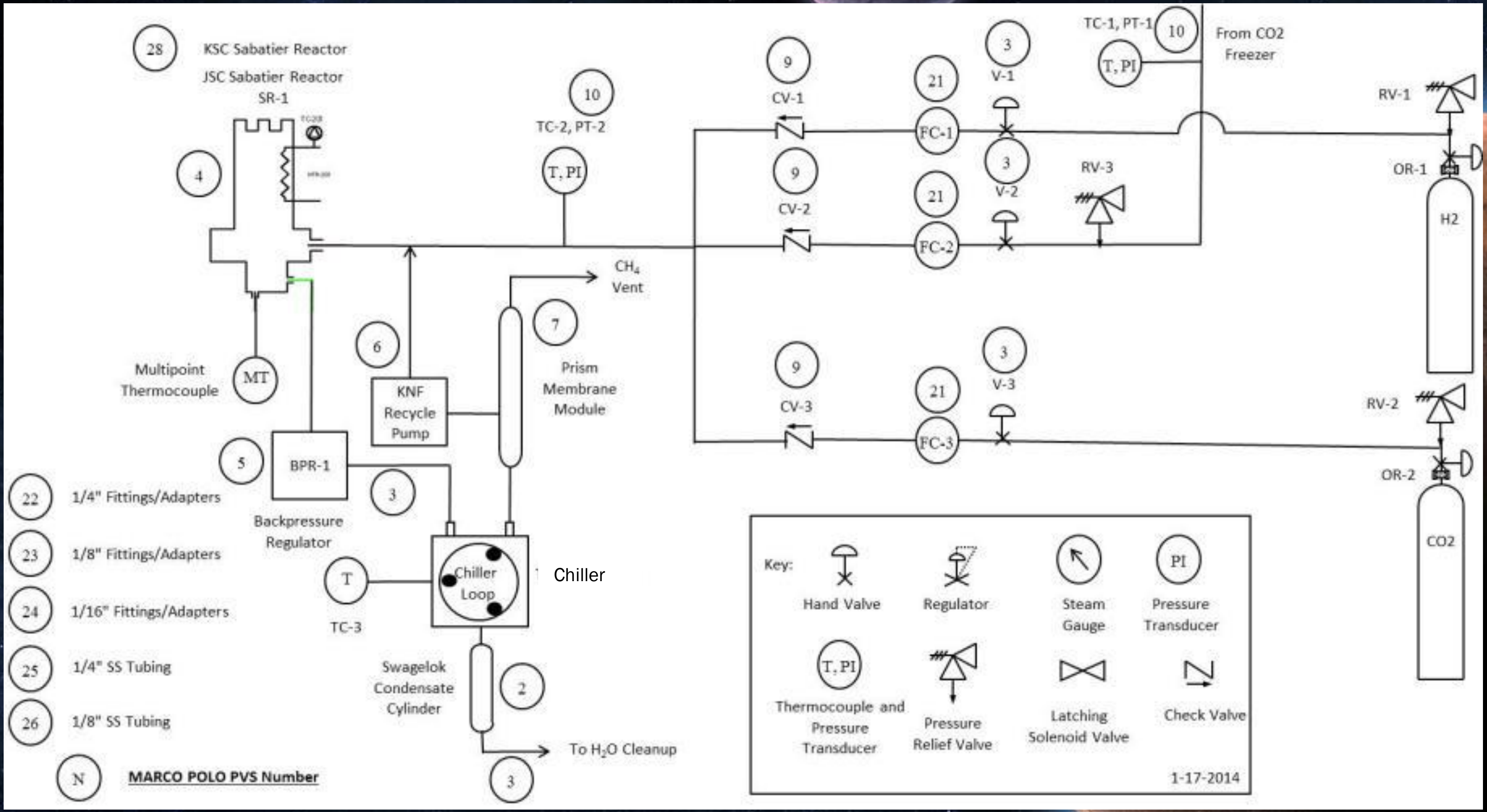
Water Processing Module

CO_2 Freezer – Final Design

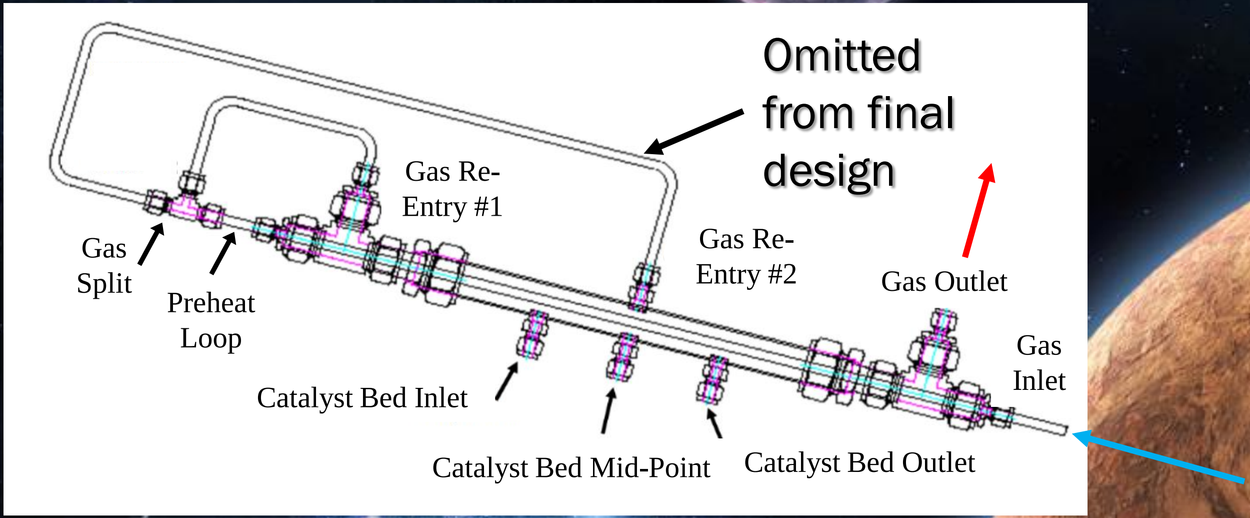


- 2 - Cryocoolers with Freezing Chambers
- 11 - Magnetic Latching Solenoid Valves
- 1 - Chiller with 4-Way Dual Solenoid Valve
- 1 - Vacuum Pump
- 1 - CO2 Pump
- 2 - CO2 Ballast Tanks
- 2 - Vacuum Back Pressure Regulators
- 3 - Pressure Relief Valves
- 1 - Flow Controller
- 1 - Flow Meter
- 3 - Thermocouples and 2 RTDs
- 3 - Pressure Transducers, etc.

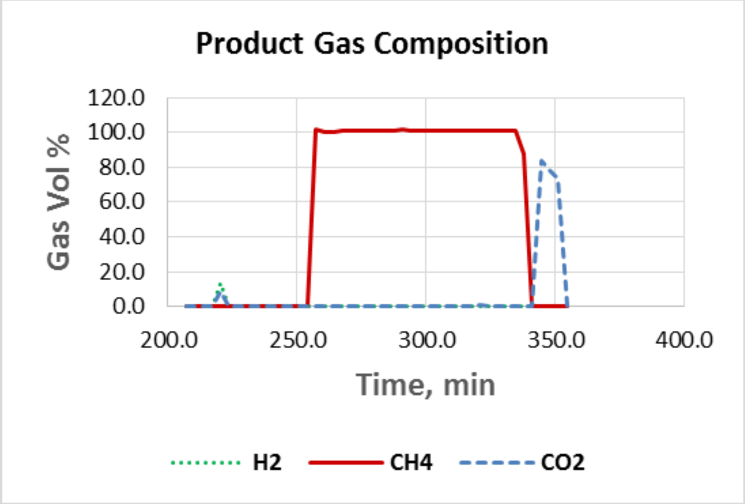
Sabatier Subsystem Design



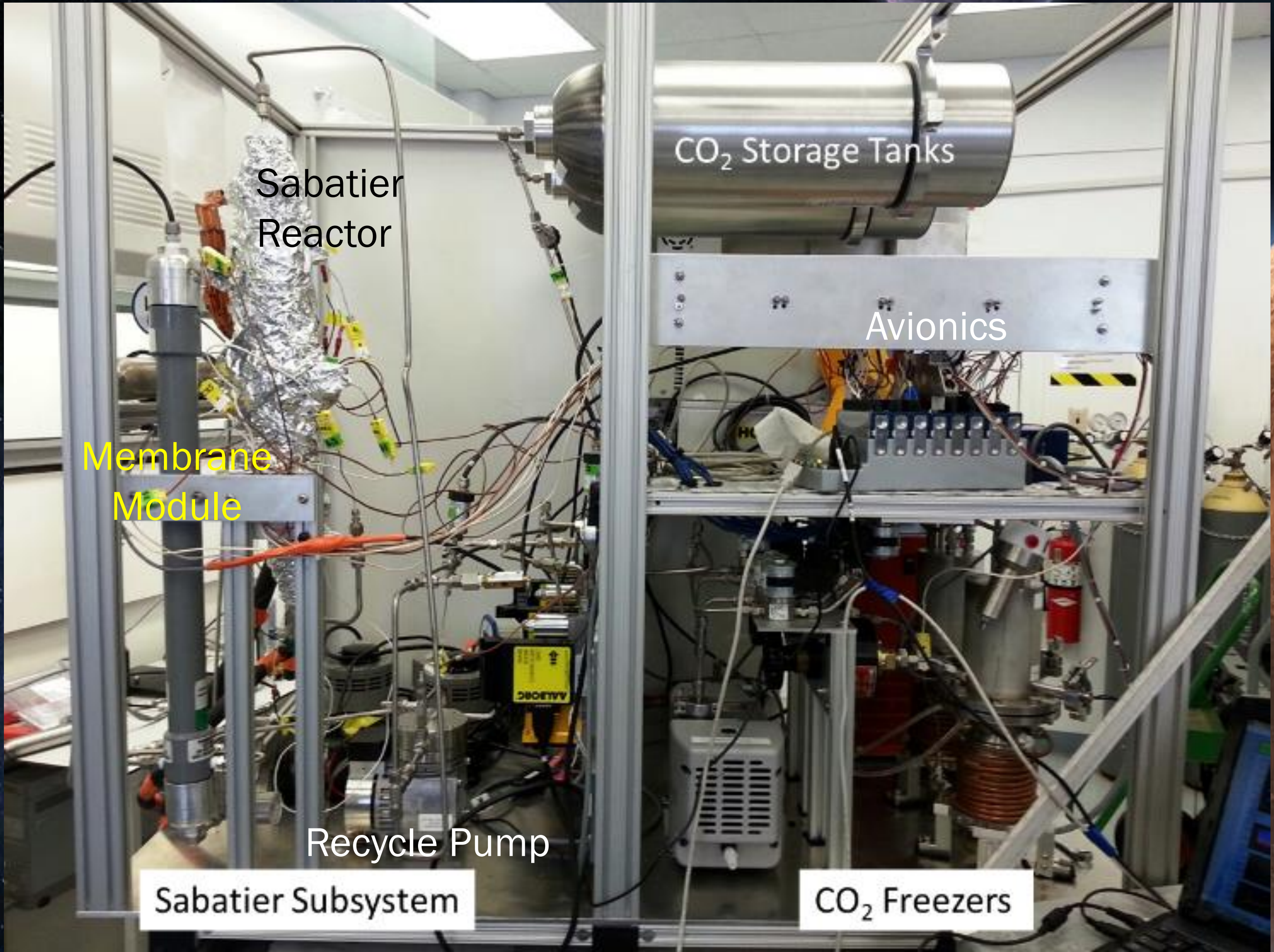
Design of KSC Sabatier Reactor



- 30 cm long stainless steel tube w/2.54 cm OD and 0.21 cm wall thickness
- Single-pass conversion = 90% @ 88 g CO_2/h + 3.5:1 H_2/CO_2
- Based on Pioneer Astronautics design for steam oxidation of trash to methane
- 1.5 h integrated test with CO_2 Freezers and recycling system showed 100% conversion to pure CH_4



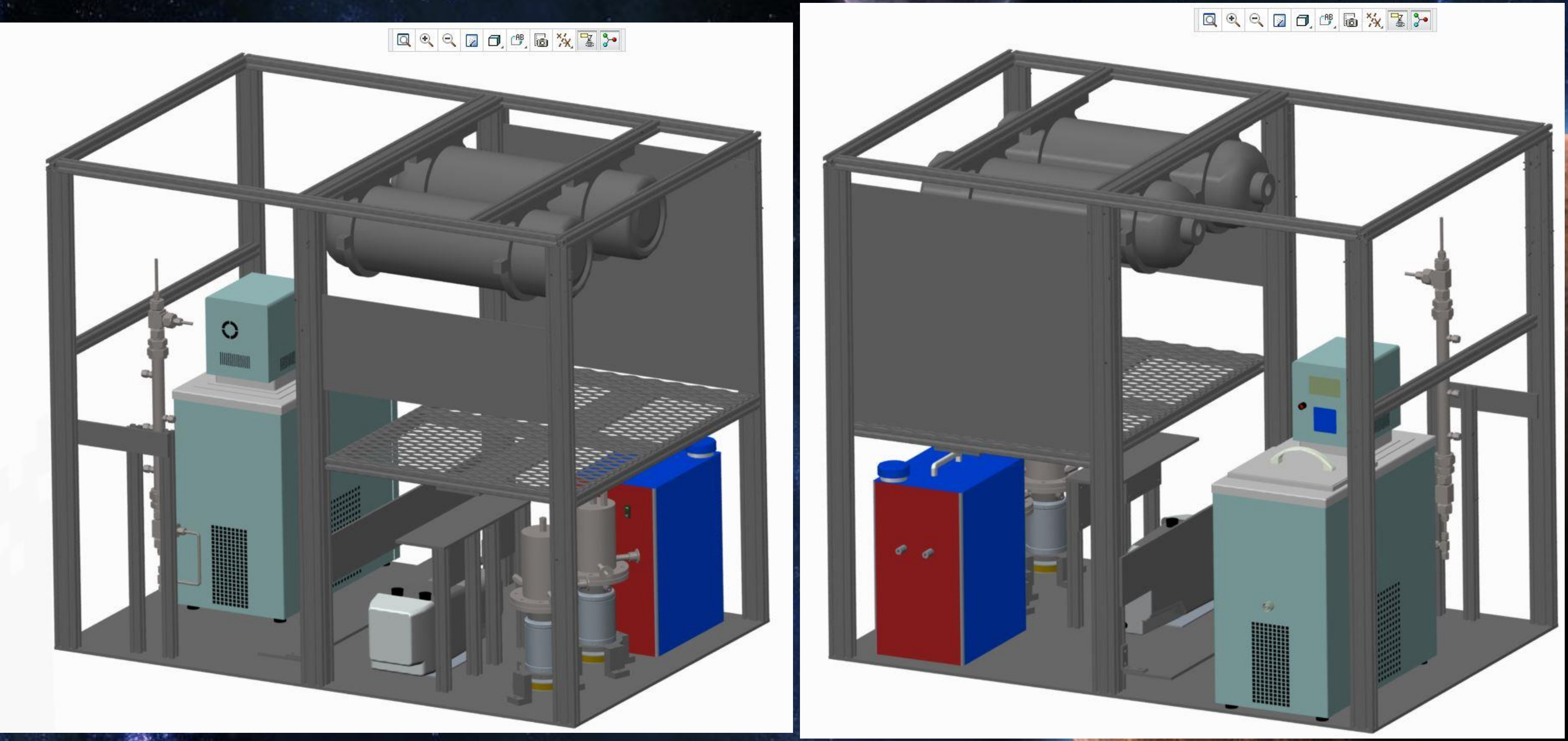
Atmospheric Processing Module



Copper Heat Exchanger

CO_2 Freezers and Chiller

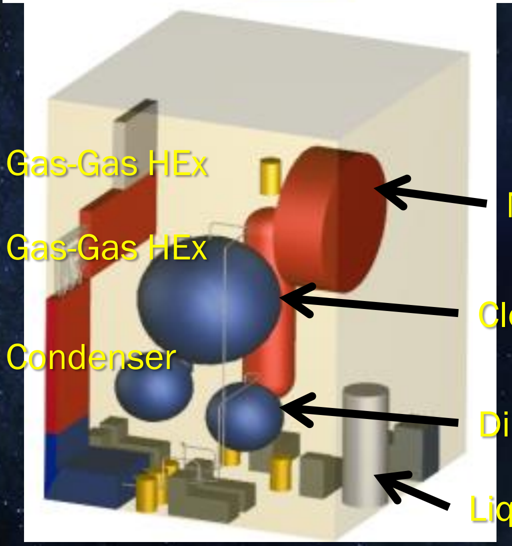
3D Model of the APM Major Components

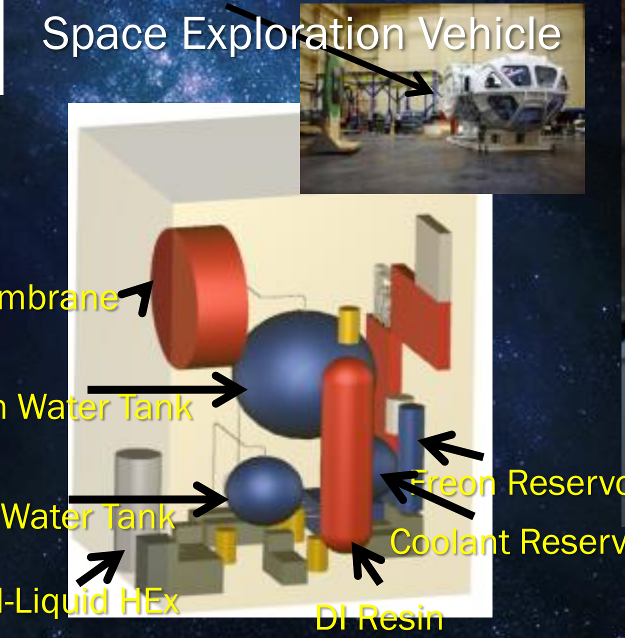


Major component mass = 154 kg

Water Cleanup Module (KSC)

- Tested with Water Processing Module at JSC
- Used to recycle fuel cell water from the MMSEV to H_2 and O_2
- MMSEV = Multi Mission Space Exploration Vehicle





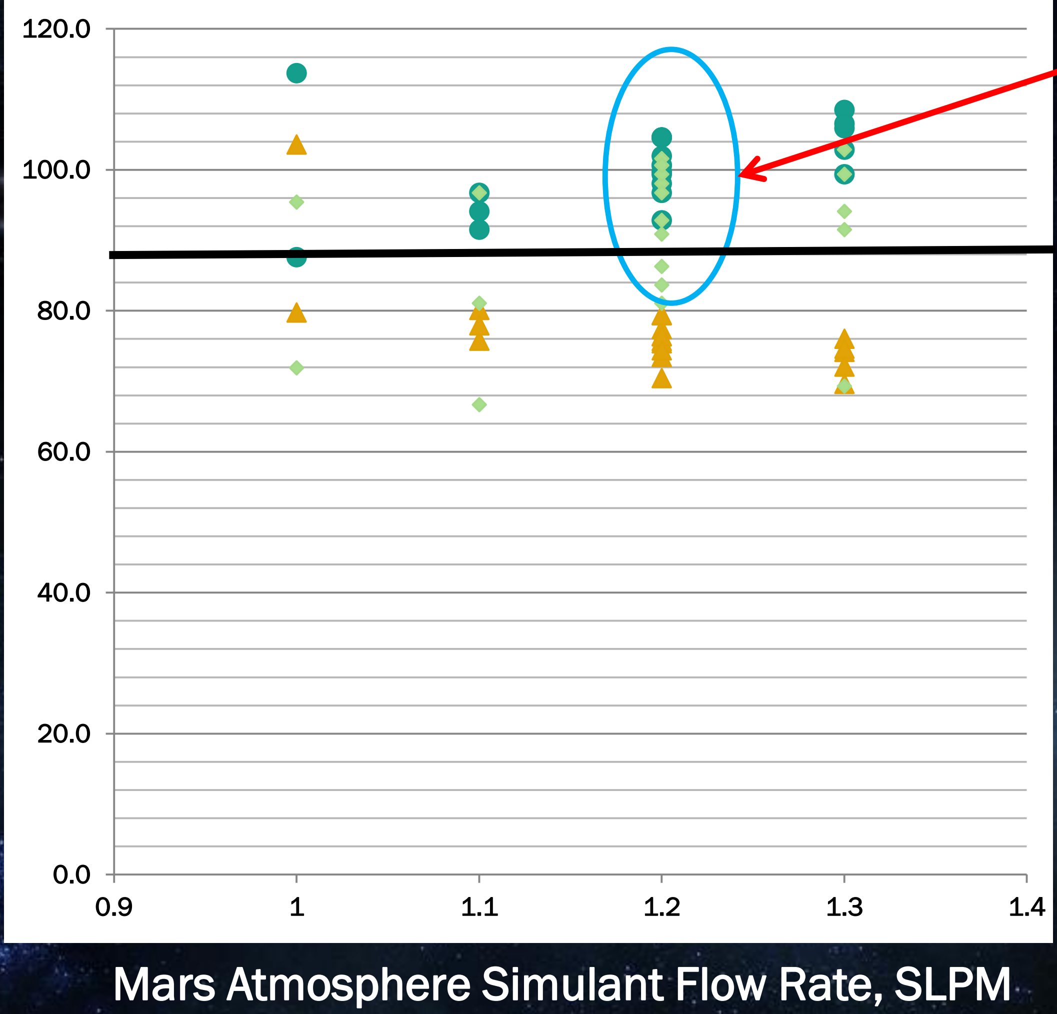
Ion exchange resin instead of membrane separator included in the final version

Lander and Soil Processing Module (KSC)

Van Townsend (KSC/ESC) with MARCO POLO lander and Soil Processing Module (under construction)

RASSOR (Regolith Advanced Surface Systems Operations Robot) will feed the hopper
(2 x 40 kg drums, 25 cm/s, 60% on duty time)

CO_2 Freezer Testing



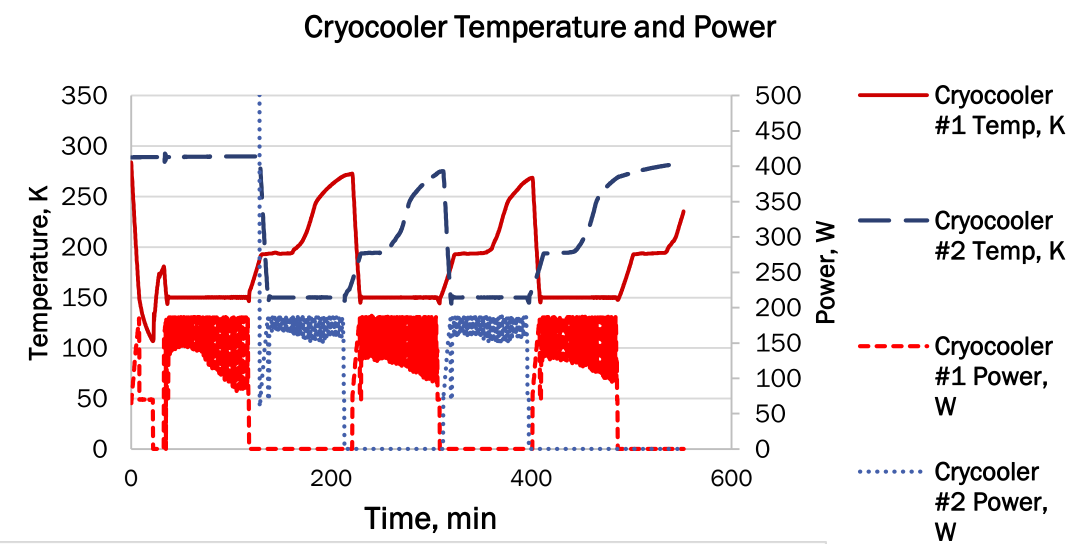
- Avg. Capture Rate = 99±3 g/hr at 1 .2 SLPM (1.4 hr test)
- Avg. Sublimation Rate = 95±8 g/hr (1 .4 hr test)
- Avg. Capture Fraction = 79±3%
- Exceeds 88 g/hr requirement
- Better performance than test stand!

Long-Duration Tests Were Successful

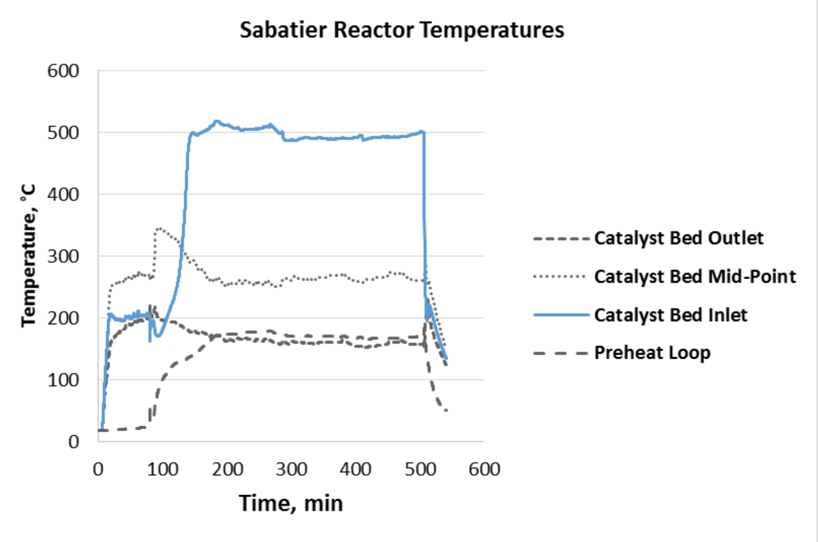
Run No.	***1***	***2***	***3***	***4***
Sabatier Run Duration	7.0 h	7.0 h	7.0 h	7.0 h
Gas Composition	CO_2	CO_2	Mars Gas	Mars Gas
Average CO_2 Freezing Rate (Goal = 88 g/h)	**102 g/h**	**100 g/h**	**102 g/h**	**99 g/h**
Average Fraction of CO_2 Frozen	**80%**	**70%**	**70%**	**73%**
Average Cryocooler Power	139 W	150 W	158 W	138 W
Average "Lift" Needed to Freeze CO_2	**0.19 W/g/h**	**0.21 W/g/h**	**0.22 W/g/h**	**0.20 W/g/h**
Average CO_2 Supply Rate to Freezers	128 g/h	142 g/h	146 g/h	135 g/h
Average CH_4 Production Rate	**32 g/h**	**32 g/h**	**32 g/h**	**32 g/h**
Average CH_4 Purity	**99.9%**	**99.9%**	**96.0%***	**99.9%**
Average H_2O Produced	**67 g/h**	**69 g/h**	**64 g/h**	**70 g/h**
Missing H_2O (vs. 72 g/h)	6.9%	4.2%	11.1%	2.8%

*Due to pressure losses during manual draining of Sabatier water condenser

Selected Results from Long-Duration Tests



CO_2 Freezer Cold Head Temperatures and Cryocooler Power Consumption during the Third Run of the 7-h Integrated Test Series



Sabatier Reactor Temperatures during the Second Run of the 7-Hour Integrated Test Series

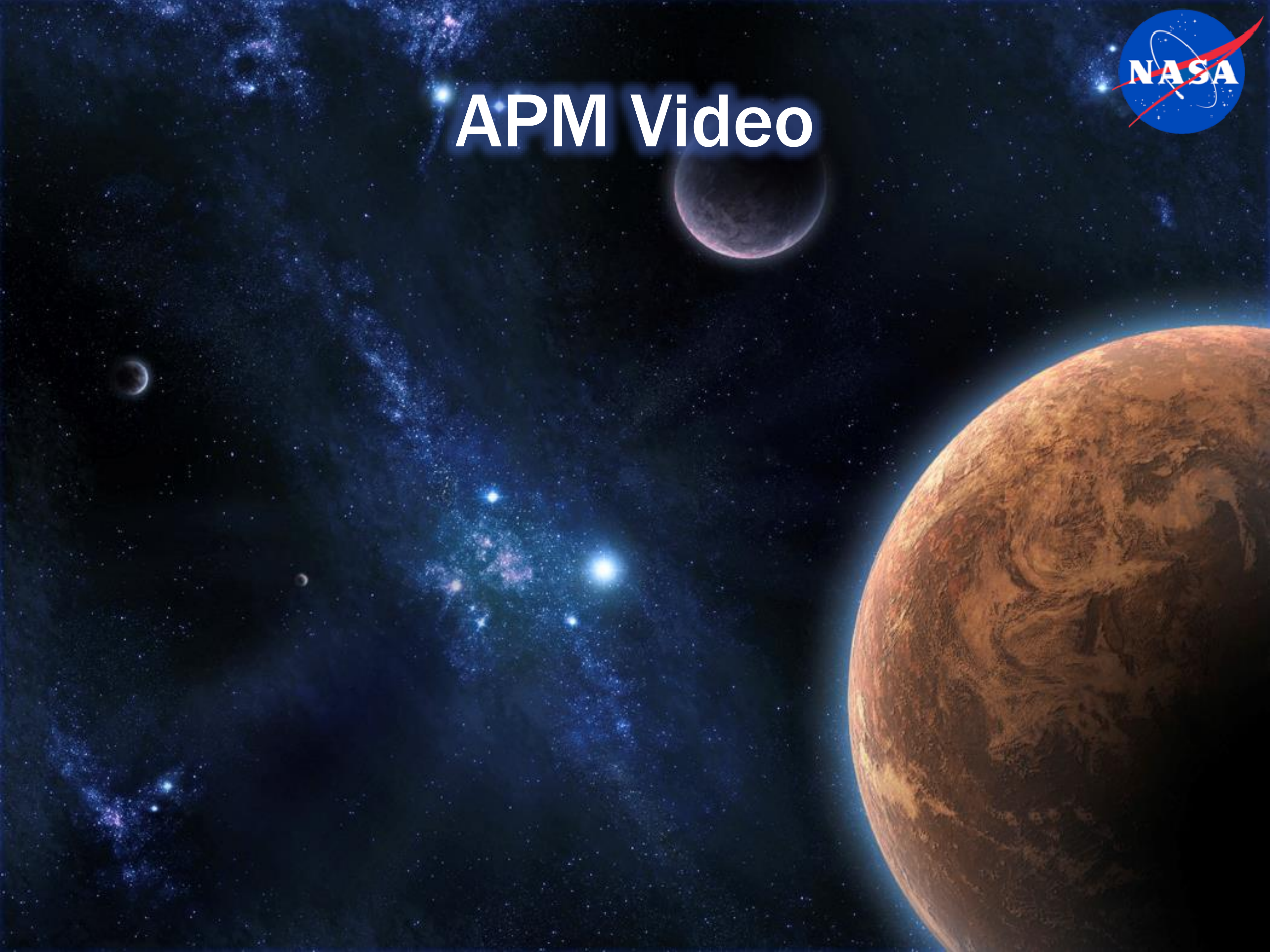
Conclusions from the Long-Duration Tests

- CO_2 Freezer Subsystem operates well
  - Exceeds 88 g/h freezing and supply rate
  - Freezes ~70% of incoming CO_2
  - Provides valuable data for power to freeze CO_2 at Mars pressure
    - Averages 0.22 W/g CO_2 frozen = only 108% of theoretical
  - Contributes to Human Mars Mission ISRU system designs, e.g. 680 W lift for 3.1 kg CO_2/h
- Sabatier Subsystem also operates well
  - New reactor is efficient
  - Recycling system (membrane module + recycle pump) works well (but recycle pump failed recently)
  - Pure CH_4 obtained at expected rate
  - ~6% of water is missing (<1% of loss is in CH_4)

Recent Work and Current Status

- Additional integrated tests performed
- Faster and slower production rates tested
  - 1.0-1.6 SLPM feed to CO_2 Freezers (87-71% frozen; 4800-5400 J/g)
  - Sabatier works at 0.3 to 1.2 SLPM CO_2 (0.75 SLPM nominal, 550°C max T)
  - Some CO observed in CH_4 after higher flow rates (catalyst damaged)
- Better LabVIEW automation implemented (sequences)
- Performed “virtual” integrated MARCO POLO tests with other systems at KSC in May and September – Hardware integration planned in FY17
- Ran Sabatier Subsystem w/Mars Gas Simulant – Good results. But Ar & N2 in CH4
- Now modeling CO_2 Freezers and Sabatier for scaling up to full-scale versions
- Long Term Goal is to continue to refine ISRU technologies for potential robotic Mars missions using Mars Pathfinder (2026/28)

APM Video



Video of Virtual Integrated Test

https://www.youtube.com/watch?v=cRLnAeL3wdU

Challenges

- Trade Studies based on small-scale tests and modeling followed by testing of full-scale components and subsystems up to TRL 6
- Funding (as usual)

Future Direction [Tony's Wish List – Same As 2 Weeks Ago]

- NASA has restarted its ISRU Project
- NASA should fully embrace ISRU
- Integrated human exploration of the inner solar system
- Moon, asteroids, Mars moons, Mars
- Commercial development of key technologies in partnership w/NASA to reduce costs
  - i.e. shared funding
  - Habitats, ISRU, spacecraft, launch vehicles, etc.
  - Asteroid mining
- Pick an architecture and stick with it for >>8 years