Atmospheric Processing Module for Mars Propellant Production

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Outline

• Introduction
• Project Goals
• Design and Construction
• Testing
• Current Status
• NASA Plans for Mars ISRU
• Other NASA ISRU Projects at KSC
Introduction – Major Milestones in NASA’s History

- First American Satellite – 1958
- NASA Established – 1958
- First American to Orbit Earth – 1962
- First American Spacewalk – 1965
- First Astronauts to Orbit the Moon – 1968
- First Manned Lunar Landings – 1969 to 1972
- First American Space Station – 1973-1974
- First Robotic Landing on Mars – 1976
- Space Shuttle Flights – 1981-2011
- First Robotic Rovers on Mars – 2003
- First Spacecraft to Leave the Solar System – 2013
- First Mars Sample Return – 2026?
- First Humans on Mars – 2030’s?
Introduction to ISRU

• What is ISRU? – In Situ Resource Utilization
  – “Living off the land”
  – Use Space Resources to reduce cost and risk for NASA missions
  – Already used with Solar Panels for power
• Chemistry and engineering enable even more resources to be used
• Key space resources:
  – Lunar regolith and polar water ice/volatiles
  – Asteroid regolith, metals, and volatiles
  – Martian atmosphere and water ice/hydrates
Martian Resources

• Atmosphere of Mars
  – 96% CO₂
  – 2% Ar, 1.9% N₂
  – <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
Utilizing Martian Water and CO$_2$/Advantages of ISRU

- **ISPP: In Situ Propellant Production**
  - Electrolysis: $4 \text{H}_2\text{O} \rightarrow 4 \text{H}_2 + 2 \text{O}_2$
  - Sabatier Reaction: $\text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$ (Ni or Ru catalyst, 300-600°C)
  - Net Reaction: $\text{CO}_2 + 2 \text{H}_2\text{O} \rightarrow \text{CH}_4 + 2 \text{O}_2 = \text{Rocket Propellant!} \quad I_s = 369 \text{ s}$

- **Human Mars Mission Outline (DRA 5.0)**
  - Launch Surface Hab/Lander and Mars Ascent Vehicle in Year 1
  - MAV lands on Mars after 9 months
  - MAV produces ascent fuel for 11 months
  - Launch Transfer Vehicle and Crew (6) in Year 2
  - Crew lands on Mars after 6-9 months
  - Crew explores Mars for 1.5 years
  - Crew launches MAV to return to Transfer Vehicle
  - Crew returns to Earth in 6 months
  - Total Crew time away from Earth is ~2.5 years

- **ISPP saves >25 metric tons of mass**
- Also provides breathing oxygen for life support
- Eliminates two heavy lift launches!
MARCO POLO Project

• **ISPP: In Situ Propellant Production**
  – Demonstrate production of Mars Sample Return propellant
  – Reduce risk for human Mars missions

• **MARCO POLO - Mars Atmosphere and Regolith Collector/Processor for Lander Operations**

• **The Mars Atmospheric Processing Module (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$_2$
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

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

C&DH/PDU Module: (JSC)
- Central executive S/W
- Power distribution

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

Water Cleanup Module: (KSC)
- Cleans water prior to electrolysis
- Provides clean water storage

Life Detection Drill: (ARC-Honeybee)
- Replaces excavator mockup
- Takes core samples
- Provides some feed to Soil Dryer

1KW Fuel Cell and consumable storage (JSC & GRC)
- Using metal hydride for H2 storage due to available
- 1KW No Flow Through FC (GRC)
- 10KW FC not shown (JSC)

3m x 3m octagon lander deck
APM Goals/Requirements

- Collect and purify 88 g CO₂/hr (>99%)
  - From simulated Martian atmosphere
  - 10 mbar; 95% CO₂, 3% N₂, 2% Ar
- Supply 88 g CO₂/hr at 50 psia to the Sabatier reactor
- Convert CO₂ to 32 g CH₄/hr and 71 g H₂O/hr
- Operate autonomously for up to 14 hr/day
- Minimize mass and power
- Fit within specified area and volume
  - 9,000 cm² hexagon
  - 44 inches tall (112 cm, same as Water Processing Module)
- Support MARCO POLO production goals of 444 g CH₄/day and 1.77 kg O₂/day (50% of O₂) for a total of 2.22 kg propellant/day
- Sufficient for a Mars Sample Return Mission
Methane Dryer (Future)
Sabatier Reactor
Electro-chemical Methane Separator
Mixed Mars Gas Input
Chiller
CO₂ ballast tanks not shown
Vacuum Pump
Mixed Gas Input
[Replaced by Recycle Pump and Membrane Module]
Atmospheric Processing Operations

Ballast tank

CO₂ freezer

Ballast tank

CO₂ freezer

Sabatier Reactor (<600 deg C)

88 g/hr CO₂ @ 50 PSI

2 g/hr H₂

2 g/hr CH₄

16.2 g/hr H₂

71.3 g/hr H₂O

31.7 g/hr CH₄

10.8 mbar

95% CO₂, 3% N₂, 2% Ar at Mars Mix

Electrolysis Stacks

Water Cleanup Module

CH₄/H₂ Separator

Condenser

CH₄ Dryer

CH₄ storage

88 g/hr CO₂ @ 50 PSI

H₂O

CH₄
CO₂ Freezer – Final Design

Mars Atmosphere
95% CO₂, 3% N₂, 2% Ar
~700 psig max

CO₂ Freezer Tank #1
< 1 mbar

CO₂ Freezer Tank #2
< 1 mbar

Cryocoolers with Freezing Chambers
2

Magnetic Latching Solenoid Valves
11

Chiller with 4-Way Dual Solenoid Valve
1

Vacuum Pump
1

CO₂ Pump
1

CO₂ Ballast Tanks
2

Vacuum Back Pressure Regulators
2

Pressure Relief Valves
3

Flow Controller
1

Flow Meter
1

Thermocouples and 2 RTDs
3

Pressure Transducers, etc.
3
CO₂ Freezer

Copper Cold Head

CO₂ Tanks

Chiller

Cryocoolers

Avionics
Sabatier Subsystem

JSC Sabatier Reactor
Recycle Pump
Membrane Module (Cut-Away View)
Atmospheric Processing Module
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

Membrane separator not 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.
CO₂ Freezer Testing

- Avg. Capture Rate = 100.3 g/hr at 1.2 SLPM (1.4 hr test)
- Avg. Sublimation Rate = 93.8 g/hr (1.4 hr test)
- Avg. Capture Fraction = 76%
- Exceeds 88 g/hr requirement
- Better performance than test stand!

88 g/hr Requirement

Mars Atmosphere Simulant Flow Rate, SLPM
JSC Sabatier Testing

- JSC Testing was successful (>99% conversion at 4.5:1 $\text{H}_2$/CO$_2$ ratio)
- First three KSC tests overheated
  - >600°C
- One test did not overheat (top) at 250 sccm CO$_2$ vs. 747 sccm desired (1000 sccm $\text{H}_2$)
  - Duplicate run did overheat (middle)
- Twelve tests at various flow rates overheated
- Two tests with simulated recycle gases ($\text{N}_2$/H$_2$/CO$_2$ = 6.0/3.35/0.75 SLPM) was slower to overheat, but still did so (bottom)
- Built a redesigned Sabatier reactor
Current Status

- CO₂ Freezer Subsystem essentially complete
  - Fully automated and fluid system functional
  - Need to test replacement CO₂ pump to reach 100 psi for overnight storage capability
- Sabatier Subsystem
  - Fluid system automated and functional
  - New reactor being installed
    - Based on proprietary design by Pioneer Astronautics
  - Testing needed to verify operation
- Plan integrated MARCO POLO testing in Swamp Works “Big Bin” regolith bin
  - Date TBD
- Testing will support Mars ISRU design studies
- Long Term Goal is to continue to refine the ISRU technologies for potential 2021 robotic Mars mission using a SpaceX ‘Red Dragon’ capsule as part of an Ames-led science effort
Mars 2020 Mission Science Definition Team Report (July 1, 2013):

- “The highest priority HEOMD payload is the demonstration of CO₂ capture and dust size characterization for atmospheric ISRU” p. 63
- “Collect atmospheric carbon dioxide. Analyze dust (size, shape, number) during CO₂ collection. Produce small quantities of oxygen and analyze its purity (option).” p. 61
- “Reduces risk for human missions and possible Mars sample return” p. 61
• Mars 2020 Mission Announcement of Opportunity (Sept. 24, 2013):
  • “A successful precursor mission is both prudent and required before incorporating ISRU into a mission-critical role for either crewed or robotic exploration missions. NASA’s Mars 2020 mission presents an ideal opportunity to validate critical ISRU technologies in an extraterrestrial environment.”

<table>
<thead>
<tr>
<th>ISRU Plant Capabilities for Mars 2020 and Future Exploration Missions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars 2020</td>
</tr>
<tr>
<td>Minimum Oxygen Production Rate</td>
</tr>
<tr>
<td>Minimum Operational Life</td>
</tr>
</tbody>
</table>

• Proposal selection in June 2014
RESOLVE is an internationally developed payload (NASA and CSA) that can perform two important missions for Science and Human Exploration of the Moon

Prospecting Mission: (Polar site)
✓ Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials
  – Map the surface distribution of hydrogen rich materials
  – Determine the mineral/chemical properties of polar regolith
  – Measure bulk properties & extract core sample from selected sites
    ▪ To a depth of 1m with minimal loss of volatiles
  – Heat multiple samples from each core to drive off volatiles for analysis
    ▪ From <100K to 423 K (150 C)
    ▪ From 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
  – Determine the constituents and quantities of the volatiles extracted
    ▪ Quantify important volatiles: H₂, He, CO, CO₂, CH₄, H₂O, N₂, NH₃, H₂S, SO₂
    ▪ Survive limited exposure to HF, HCl, and Hg

ISRU Processing Demonstration Mission: (Equatorial and/or Polar Site)
✓ Demonstrate the Hydrogen Reduction process to extract oxygen from lunar regolith
  – Heat sample to reaction temperature
    ▪ From 423 K (150 C) to 1173 K (900 C)
  – Flow H₂ through regolith to extract oxygen in the form of water
  – Capture, quantify, and display the water generated
RESOLVE Analog Field Tests

Nov. 2008
- RESOLVE Gen II on Scarab Rover
- Power, avionics, and ground support equipment on separate trailer

FEB. 2010
- RESOLVE Gen II+ on CSA Juno Rover
- Power, avionics, and ground support equipment on separate Juno

July 2012
- RESOLVE Gen IIIA on CSA Artemis Jr. Rover
- Everything on single rover platform
RESOLVE Gen III

Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment

Sample Acquisition System
Auger Drill Subsystem
- Collect and transfer subsurface material down to 1 m below surface
- Maintain sample stratigraphy and volatiles (below 150 K)
- Meter samples for processing
- Auger material to surface for evaluation
- Measure geotechnical properties of regolith during drilling

Surface Mineral/Volatile Evaluation
Near Infrared Volatile Spectrometer Subsystem (NIRVSS) - ARC
- Measure surface bound OH/H₂O while traversing (at min. of 0.5% by mass)
- Detect form of water (ice/hydration) in auger tailings
- Detect water vapor in evolved gases
- Image surface and drill tailings

Resource Localization
Neutron Spectrometer Subsystem (NSS) - ARC
- Locate hydrogen and hydrogen bearing volatiles down to 1 meter below the surface while traversing (at min. of 0.5% by mass)

Volatile Content/Oxygen Extraction
Oxygen & Volatile Extraction Node (OVEN) - JSC
- Accept samples from Sample Acquisition System
- Heat samples from <150 K to 423K for volatile extraction
- Heat samples to 1173 K for oxygen extraction
- Transfer evolved gases to LAVA volatile analyzer

Volatile Content Evaluation
Lunar Advanced Volatile Analysis (LAVA) - KSC
- Accept evolved gas from OVEN; provide hydrogen for oxygen extraction
- Perform analysis in under 2 minutes
- Measure water content in evolved gas
- Characterize volatiles of interest (below 70 amu)
- Measure D/H and O¹⁶/¹⁸ isotopes
- Capture & image water evolved

Operation Control
Flight Avionics - KSC
- Space-rated microprocessor
- Control subsystems and manage data

Surface Mobility
- Traverse wide range of lunar surface/material conditions
- Tele-operation and autonomous traverse modes
- Carry RESOLVE payload; provide power, comm., and thermal management

RESOLVE Mission Requirements
- Nom. Mission Life = 5+ Cores; 14 Days
- Mass = 170 kg rover/80 kg payload
- Ave. Power; 200-300 W
RESOLVE Gen IIIA Field Development Unit (FDU)
Assembly & Integration (2)
Complete RESOLVE Mission Traverse on Mauna Kea

- 9 of 12 ‘hot spots’ found
- >1 km total traverse
- ~500 m between auger/cores
RESOLVE Mission Options – Potential South Pole Landing Sites

### Site Analysis

<table>
<thead>
<tr>
<th>Site</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow “Frost Line”</td>
<td>&lt;0.1 m</td>
<td>&lt;0.2 m</td>
<td>&lt;0.1 m</td>
</tr>
<tr>
<td>Slopes</td>
<td>&lt;10</td>
<td>&lt;15</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Neutron Depletion</td>
<td>4.5 cps</td>
<td>4.7 cps</td>
<td>4.9 cps</td>
</tr>
<tr>
<td>Temporary Sun*</td>
<td>4 days</td>
<td>2-4 days</td>
<td>5-7 d</td>
</tr>
<tr>
<td>Comm Line of Sight*</td>
<td>8 days</td>
<td>17 days</td>
<td>17 days</td>
</tr>
</tbody>
</table>

* may not coincide

### Predicted Volatile Stability

**Solar Power Potential**
RESOLVE Mission Options – Notional Traverse

- Major waypoint
- Discovery: traverse re-plan
- Excavation site
- Pre-planned traverse path
- Executed path

2 kilometers

100-m radius landing ellipse

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction
Other KSC ISRU Projects: Trash to Gas

- Logistics, Reduction and Repurposing (LRR) Project Overview
- TtSG overview and processes
Human Spaceflight Produces Trash!

Long term effects include:
- Pollution
- Wasteful spending
- Planetary protection
- Bad press

To maximize our resources, reduce trash volume, and minimize polluting in space habitats and long duration missions we need to re-evaluate the trash produced and do something innovative and sustainable with it.

Presently the trash is brought back home to earth or burned during Earth atmospheric re-entry.

Human spaceflight trash includes:
- Food packaging (adhered/uneaten)
- Clothing
- Human waste products
- Paper products
- Etc.
Utilizing Spaceflight Trash!

Utilize technology to produce useful products from the trash.

Activated Carbon • Salt • Wax

Water • Fuel Depots • Aluminum • In-Situ Manufacturing

Plant Life Support • Recycling Depot • Fertilizer • Basis of Chemical Production

Reduce Trash Volume • Rocket Fuel

Breathing • Fuel Cells • Reduce Logistics Delivered from Earth

Maximizing our resources to reduce trash and pollution.
TtSG Overview

- Strayer et al. AIAA-2011-5126; Characterization of Volume F trash from four recent STS missions: weights, categorization, water content
TtSG Overview

- LOX Methane engines
- Resistojets
  - Electrothermal propulsion for station keeping, reboost and orbit maintenance
  - Detailed systems were designed for past space stations (Freedom)
  - Can use multiple fuels (CO$_2$, CH$_4$, H$_2$O, etc...) in same thruster
TtSG Overview

Why TtSG?
- Reduce volume of trash - Current human spaceflight missions either carry trash during the entire round-trip mission or discard trash inside a logistic module which is de-orbited into Earth’s atmosphere for destruction.
- Cleans waste
- Produce something useful from a waste product

KSC-01PP-0726: Workers in the Space Station Processing Facility are removing contents from the Multi-Purpose Logistics Module (MPLM) Leonardo to begin removing the contents after STS-102. The MPLM brought back nearly a ton of trash and excess equipment from the Space Station.
**Assumptions**
- Crew of 4 for 360 days
- Waste types: Human Waste, packaging, food, MAGs, tape, clothing, towels, washcloths, paper
- Total waste: 1900 kg wet waste, 4200 kg from crew metabolism (CO\(_2\), H\(_2\)O)

**Production**
- 800 – 1500 kg of methane/year
  - Carbon is limiting reagent, so if CO\(_2\) is used you have to find a hydrogen source
  - Enough for 1 lunar ascent vehicle
- ~800 kg of oxygen
- ~900 kg of water
- ~1100 kg of CO\(_2\)
TtSG General Systems Analysis

Solid Waste
4 Crew/360 Days
1917 KG (Wet)
(1145 KG (Dry))

Water Recovery System
(100% Condensate Recovery
85% Urine Recovery)

Water Electrolysis

Crew Metabolism
(1202 kg O₂ Required
3600 kg H₂O Required
1123 kg of water derived from food)

Sent to Propulsion
CH₄
1476 kg
O₂
2291 kg

Generic Process

H₂O (from water supply)

H₂O (water to brine)

Input H₂O

H₂O (required to balance H₂ deficit)

O₂

H₂O

O₂ (Free + Oxidative)

H₂

CO₂

1440 kg

CH₄
TtSG General Systems Analysis

Solid (Wet) Waste → Preparation → Incineration → Quench/Condensation → De-NOx → Sabatier Reactor → CH₄

- Water
- Heat
- Flue Gas (e.g., CO₂, H₂O)
- Oxygen
- Ash
- Water
- CO₂
- Hydrogen
- Water
TtSG Processes

- KSC, GRC, ARC have hardware that they are testing
- All processes have a 3-4 TRL
  - Pyrolysis
    - Decomposition of waste materials with heat in the absence of oxygen
  - Gasification
    - Decomposition of waste materials with heat in the presence of oxygen and/or steam
  - Incineration
    - Decomposition of waste materials with combustion
  - Steam Reforming
    - Decomposition of waste materials with heat in the presence of steam
  - Catalytic Decomposition- Low Temperature Decomposition of waste materials in the presence of a catalyst
    - Wet air oxidation
    - Photocatalytic oxidation
  - Ozone Oxidation
    - Decomposition of waste materials with heat in the presence of ozone

Ozone Oxidation System (ARC)
KSC Processes

• **Pyrolysis:**
  – On-going effort at ARC as part of SBIR program
  – Thermal decomposition of waste material under inert environment or vacuum
  – Main products are a mixture of hydrocarbons (typically >C\text{4})
  – KSC will characterize this process as part of the Gasification effort; ARC has existing hardware from SBIR program

• **Gasification:**
  – Previous effort at KSC (CDDF 2009)
  – Thermal decomposition of waste material in the presence of oxygen
  – Main products: syn gas with mixture of carbon oxides, hydrogen, methane, hydrocarbons
  – Previous experience resulted in significant amount of wax material

• **Incineration:**
  – Combustion of waste material under the presence of oxygen
  – Main combustion products: mixture of carbon oxides and water
  – Trace products: other trace elements within waste
  – ARC has existing hardware from SBIR program

\[
\begin{align*}
O_2 \text{ ER} &= 0; \text{ Pyrolysis} & \text{Liquids and Char} \\
O_2 \text{ ER} &\sim 0.1-0.3; \text{ Gasification} & \text{Syn gas; CO, CO}_2, H_2, CH_4, \ldots \\
O_2 \text{ ER} &\sim 1; \text{ Incineration} & \text{CO}_2, H_2O, \ldots
\end{align*}
\]

ER: Equivalence ratio equals 1 for stoichiometric oxygen
TtSG Schedule

- **FY12:**
  - Testing existing prototypes
  - Efficiency analysis
  - Waste characterization analysis

- **FY13:**
  - Mixed trash testing
  - Down-selection to two processes for breadboard design

- **FY14:**
  - Complete breadboard design testing
  - Upgrade analysis

- **FY15:**
  - Build upgraded prototype
  - Provide mission architecture recommendations

- **FY17:**
  - ISS flight project design complete

Thermal oxidation reactor at KSC
Future MARCO POLO Historic Marker?
Follow us on Facebook:
https://www.facebook.com/NASA.ISRU

Any Questions?
Ultimate Destination - Mars