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: $\text{CO}_2 + 2 \text{H}_2\text{O} \rightarrow \text{CH}_4 + 2 \text{O}_2$ = Rocket Propellant! $I_{sp} = 369$ 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 CO₂ Freezer Subsystem
  – Sabatier (Methanation) Subsystem

• Collect, purify, and pressurize CO₂

• Convert CO₂ into methane (CH₄) and water with H₂

• Other modules mine regolith, extract water from regolith, purify the water, electrolyze it to H₂ and O₂, send the H₂ to the Sabatier Subsystem, and liquefy/store the CH₄ and O₂
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)

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

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)

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
• 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
Atmospheric Processing Module

- Sabatier Reactor
- Methane Dryer (Future)
- Electro-chemical Methane Separator
- Methane Separator
- CO₂ ballast tanks not shown
- Chiller
- CO₂ Freezers
- Vacuum Pump
- Mixed Mars Gas Input

[Replaced by Recycle Pump and Membrane Module]
Atmospheric Processing Operations

- Mars Mix
  - 95% CO₂
  - 3% N₂
  - 2% Ar at 10.8 mbar
- Ballast tank
- Ballast tank
- CO₂ freezer
- CO₂ freezer
- CO₂ freezer

88 g/hr CO₂ @ 50 PSI

2 g/hr H₂

Electrolysis Stacks
16.2 g/hr H₂

Sabatier Reactor (<600 deg C)

Condenser

CH₄/H₂ Separator

H₂O
CH₄

Water Cleanup Module

Water Processing Module

CH₄ Storage

CH₄ Dryer

H₂O
CH₄
CO₂ Freezer – Final Design

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

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.
CO\textsubscript{2} Freezer

- Copper Cold Head
- CO\textsubscript{2} 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 H₂ and O₂
- 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
CO$_2$ 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
JSC Sabatier Testing

- JSC Testing was successful (>99% conversion at 4.5:1 H₂/CO₂ ratio)
- First three KSC tests overheated
  - >600°C
- One test did not overheat (top) at 250 sccm CO₂ vs. 747 sccm desired (1000 sccm H₂)
  - Duplicate run did overheat (middle)
- Twelve tests at various flow rates overheated
- Two tests with simulated recycle gases (N₂/H₂/CO₂ = 6.0/3.35/0.75 SLPM) was slower to overheat, but still did so (bottom)
- Built a redesigned Sabatier reactor
Current Status

• CO$_2$ Freezer Subsystem essentially complete
  – Fully automated and fluid system functional
  – Need to test replacement CO$_2$ 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
NASA Plans for Mars ISRU

- 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

<table>
<thead>
<tr>
<th>Instrument/Demo</th>
<th>Purpose</th>
<th>SKG Addressed</th>
<th>P-SAG Priority</th>
<th>HAT Priority</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ production from atmosphere</td>
<td>Collect atmospheric carbon dioxide. Analyze dust (size, shape, number) during CO₂ collection. Produce small quantities of oxygen and analyze its purity (option).</td>
<td>B6-1: Atm. ISRU</td>
<td>H</td>
<td>H</td>
<td>Reduces risk for human missions and possible Mars sample return</td>
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<tr>
<td>MEDL+</td>
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<td>Surface weather station</td>
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<tr>
<td>Atmospheric ISRU demo - CO₂ capture + dust</td>
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<td></td>
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<tr>
<td>- CO₂ capture + O₂ production</td>
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Table 5-4. Spacecraft resource requirements for candidate HEOMD Payloads

- MEDL+ Mass (kg): 15.1, Power (W): 10, Operating Concept: Operates during EDL
- Surface weather station Mass (kg): 1.3, Power (W): 19, Operating Concept: Sampling (approximately 24 times a day)
- Atmospheric ISRU demo Mass (kg): 10, Power (W): 30-50, Operating Concept: Operate 7 to 8 hrs per sol, and as many sols as possible. Operate CO₂ capture and O₂ production on separate days to maximize production rate

“...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.”

ISRU Plant Capabilities for Mars 2020 and Future Exploration Missions.

<table>
<thead>
<tr>
<th></th>
<th>Mars 2020</th>
<th>Subscale Validation Class Missions</th>
<th>Future Human Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Oxygen Production Rate</td>
<td><strong>0.02 kg/hr</strong></td>
<td>0.44 kg/hr</td>
<td>2.2 kg/hr</td>
</tr>
<tr>
<td>Minimum Operational Life</td>
<td>50 sols</td>
<td>500 sols</td>
<td>1,200 sols</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 (1)
Complete RESOLVE Mission Traverse on Mauna Kea

- 9 of 12 ‘hot spots’ found
- >1 km total traverse
- ~500 m between auger/cores
### 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

### LEND Results

**LEND Data (circa Fall 2009)**

**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

100-m radius landing ellipse

2 kilometers

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

Photo 1. Shuttle Volume F trash.

Photo 2. Shuttle trash, not Volume F trash, contained in a large ziplock plastic film bag.

Photo 5. A food ‘football’ from the Shuttle Volume F trash.

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 (CO₂, CH₄, H₂O, 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.
TtSG General System Analysis

• 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))

1917 kg

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

Input H₂O
H₂O
(from water supply)
H₂O
(water to brine)

H₂O
(required to balance H₂ deficit)

Water Electrolysis

O₂
(Free + Oxidative)

H₂O

Generic Process

O₂

CO₂
1440 kg

H₂

H₂O

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
TtSG General Systems Analysis

Solid (Wet) Waste

Water

Preparation

Oxygen

Heat

Incineration

Flue Gas (e.g., CO₂, H₂O)

Ash

Quench/Condensation

De-NOx

CO₂

Sabatier Reactor

CH₄

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
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 $>C_4$)
  - 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

\[ O_2 \text{ ER} = 0; \text{Pyrolysis} \quad \text{Liquids and Char} \]
\[ O_2 \text{ ER} \sim 0.1-0.3; \text{Gasification} \quad \text{Syn gas; CO, CO}_2, \text{ H}_2, \text{ CH}_4, \ldots \]
\[ O_2 \text{ ER} \sim 1; \text{Incineration} \quad \text{CO}_2, \text{ H}_2\text{O}, \ldots \]

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