Atmospheric Processing Module for Mars Propellant Production

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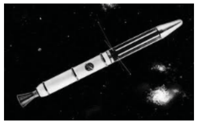
Outline

- 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

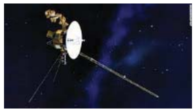
- First Manned Lunar Landings – 1969 to 1972

- 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?

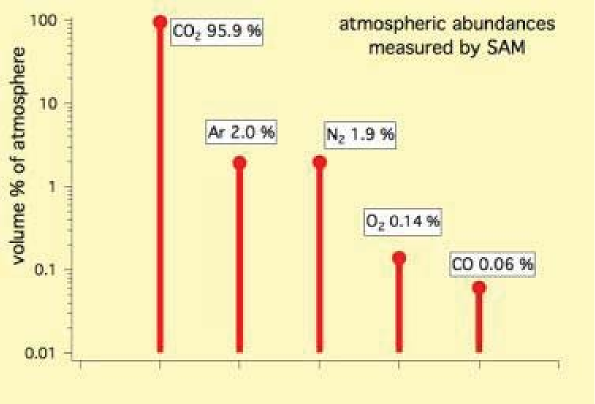
- First Humans on Mars – 2030's?

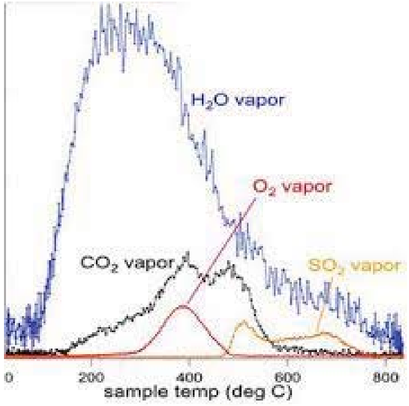
Introduction to ISRU

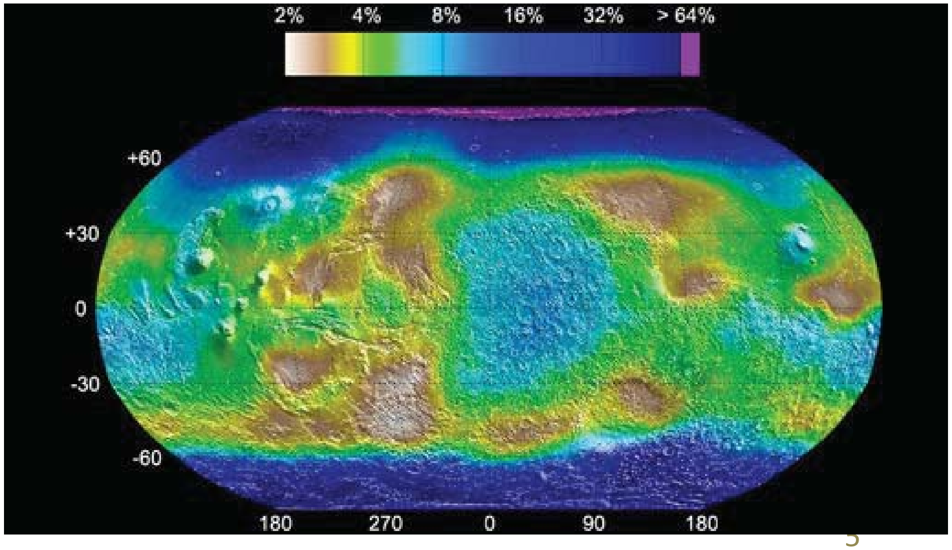
- **What is ISRU? – I**n **S**itu **R**esource **U**tilization
  - **"Living off the land"**
  - **Use Space Resources to reduce cost and risk for NASA missions**
  - **Already used with Solar Panels for power**
- **Chemistry and engineering enable even more resources to be used**
- **Key space resources:**
  - **Lunar regolith and polar water ice/volatiles**
  - **Asteroid regolith, metals, and volatiles**
  - **Martian atmosphere and water ice/hydrates**

Martian Resources

- Atmosphere of Mars
  - 96% 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

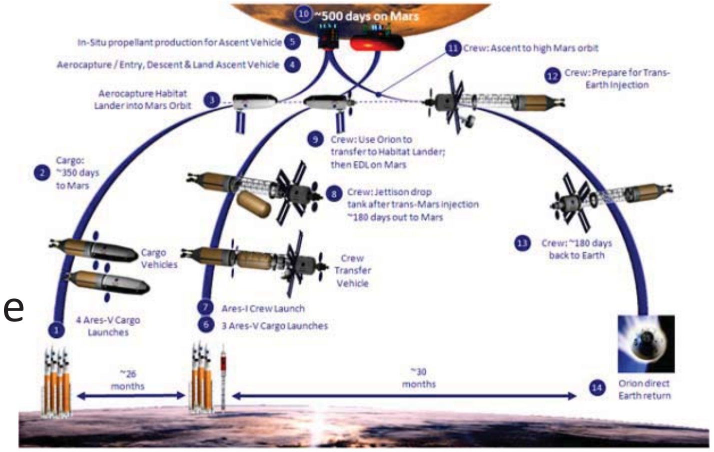






Utilizing Martian Water and CO_2/Advantages of ISRU

- **ISPP: In Situ Propellant Production**
  - Electrolysis: $4\ H_2O \rightarrow 4\ H_2 + 2\ O_2$
  - Sabatier Reaction: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$ (Ni or Ru catalyst, 300-600°C)
  - Net Reaction: $CO_2 + 2\ H_2O \rightarrow CH_4 + 2\ O_2$ = 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!**

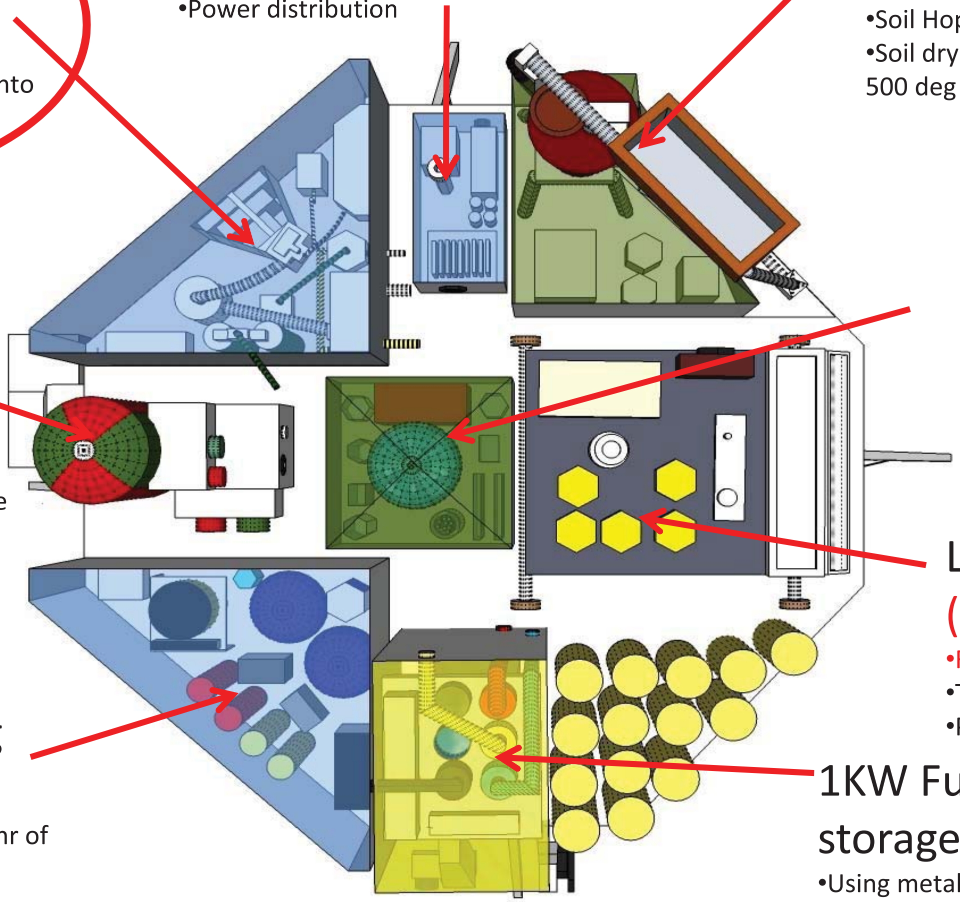
MARCO POLO Project

- **ISPP: In Situ Propellant Production**
  - Demonstrate production of Mars Sample Return propellant
  - Reduce risk for human Mars missions
- **MARCO POLO - M**ars **A**tmosphere and **R**egolith **CO**llector/**P**r**O**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

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 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

Water Processing Module: (JSC)

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

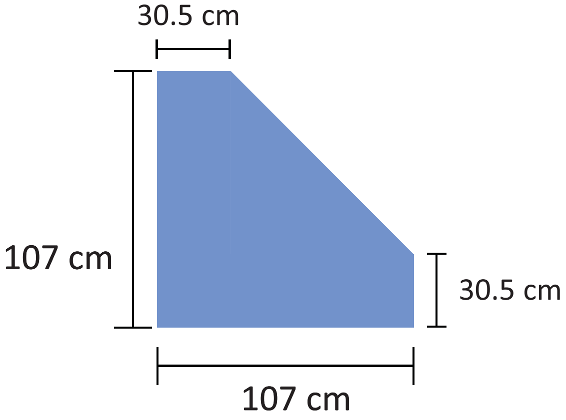
1KW Fuel Cell and consumable storage (JSC & GRC)

- 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

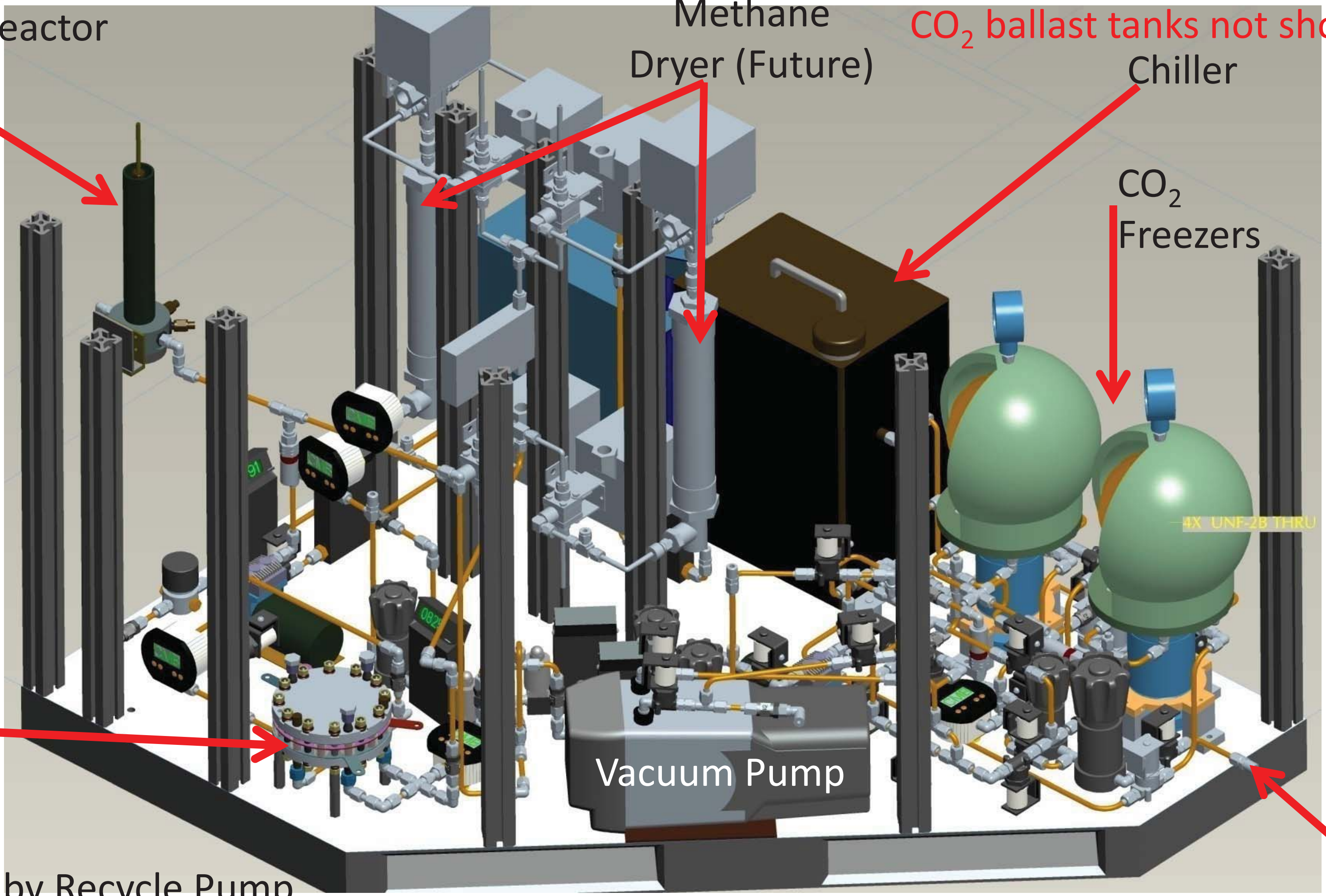
APM Goals/Requirements

- **Collect and purify 88 g CO_2/hr (>99%)**
  - From simulated Martian atmosphere
  - 10 mbar; 95% CO_2, 3% N_2, 2% Ar
- **Supply 88 g CO_2/hr at 50 psia to the Sabatier reactor**
- **Convert CO_2 to 32 g CH_4/hr and 71 g H_2O/hr**
- **Operate autonomously for up to 14 hr/day**
- **Minimize mass and power**
- **Fit within specified area and volume**
  - 9,000 cm^2 hexagon
  - 44 inches tall (112 cm, same as Water Processing Module)



- **Support MARCO POLO production goals of 444 g CH_4/day and 1.77 kg O_2/day (50% of O_2) for a total of 2.22 kg propellant/day**
- **Sufficient for a Mars Sample Return Mission**

Atmospheric Processing Module



Sabatier Reactor

Methane Dryer (Future)

CO_2 ballast tanks not shown

Chiller

CO_2 Freezers

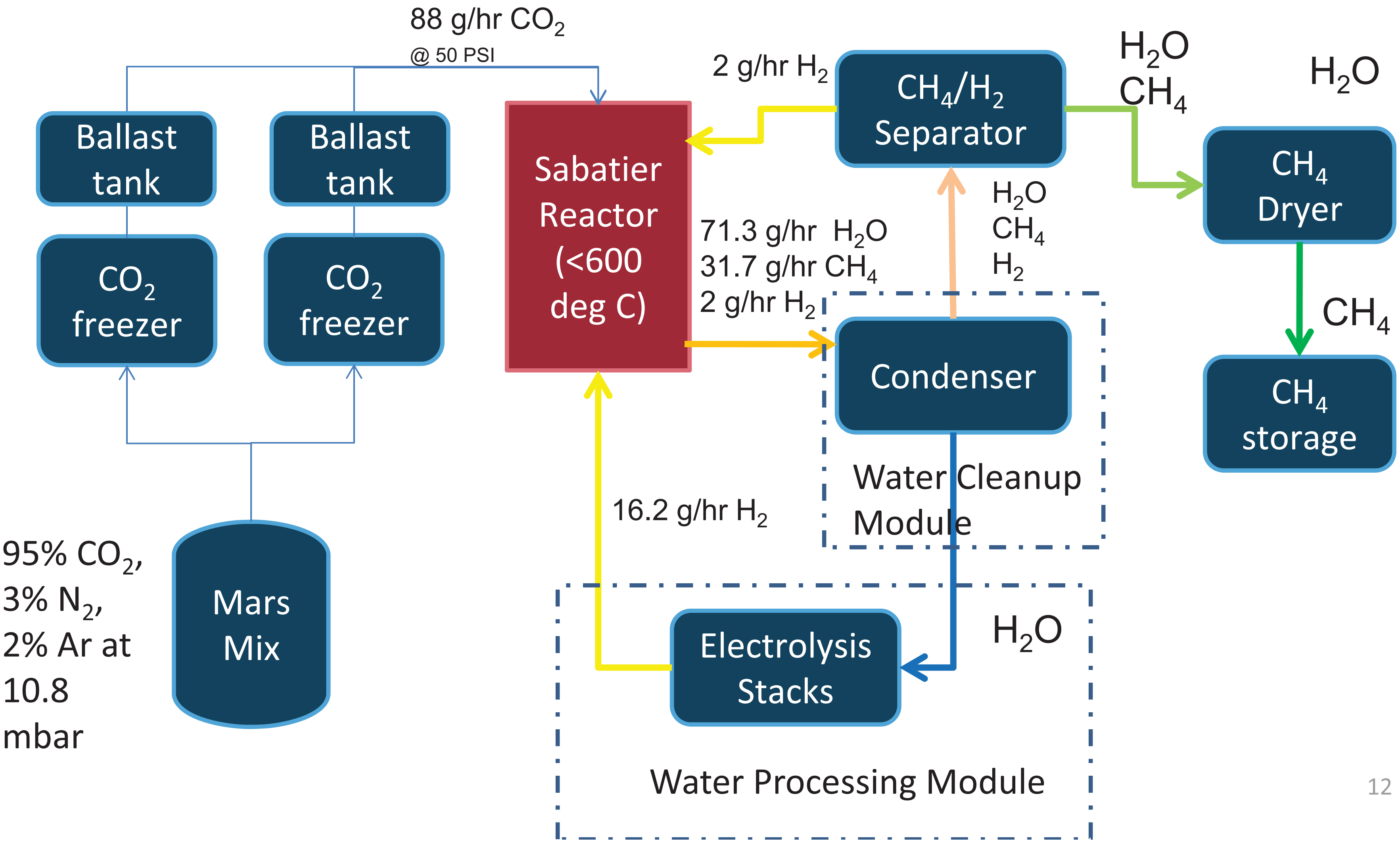
Vacuum Pump

Electro-chemical Methane Separator

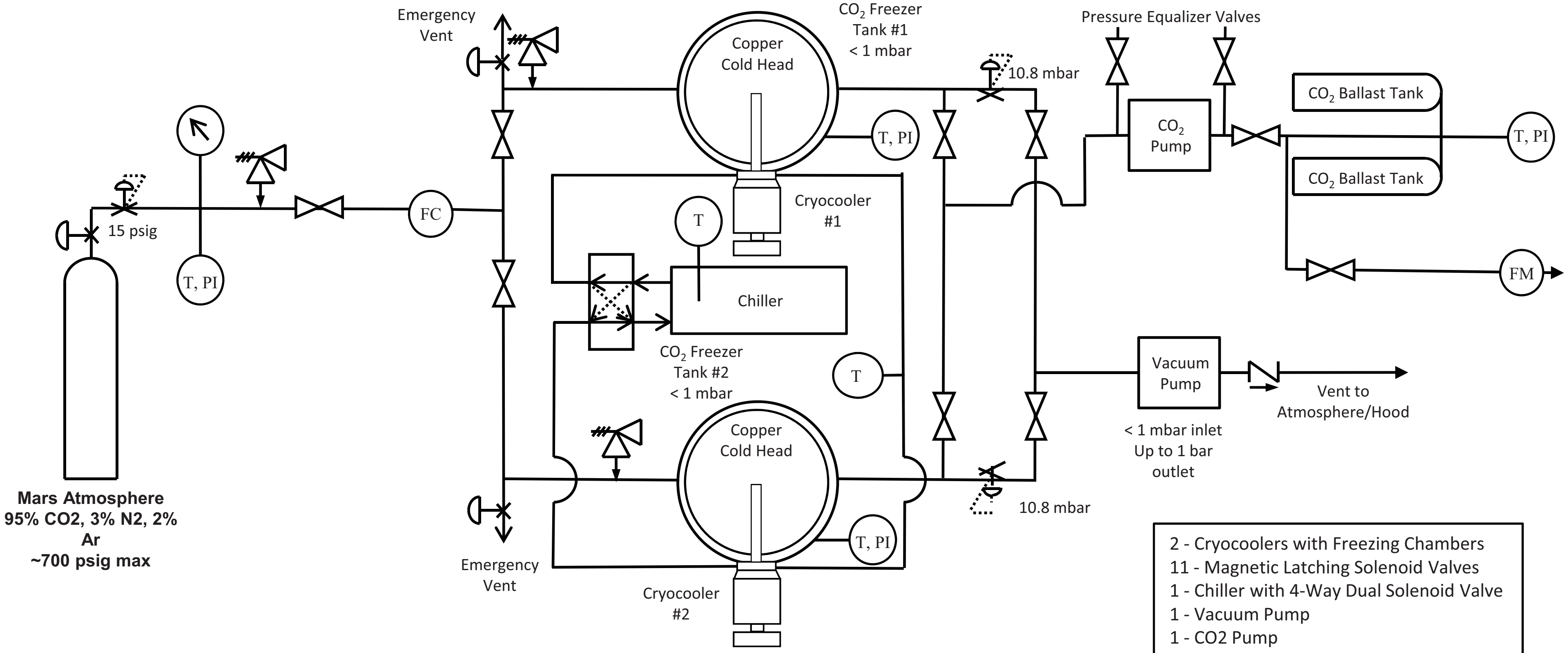
[Replaced by Recycle Pump and Membrane Module]

Mixed Mars Gas Input

Atmospheric Processing Operations

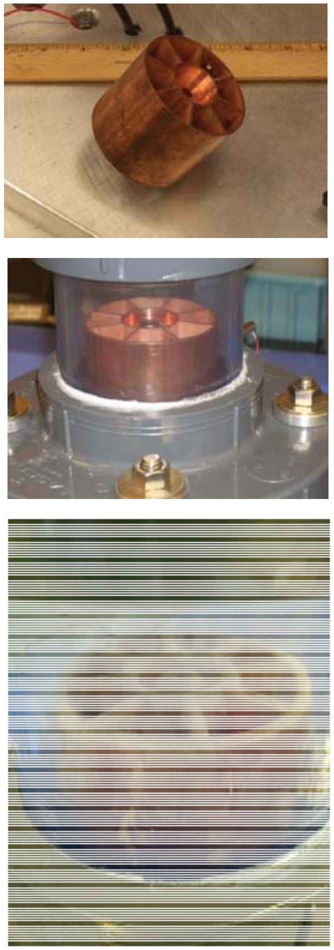


CO_2 Freezer – Final Design

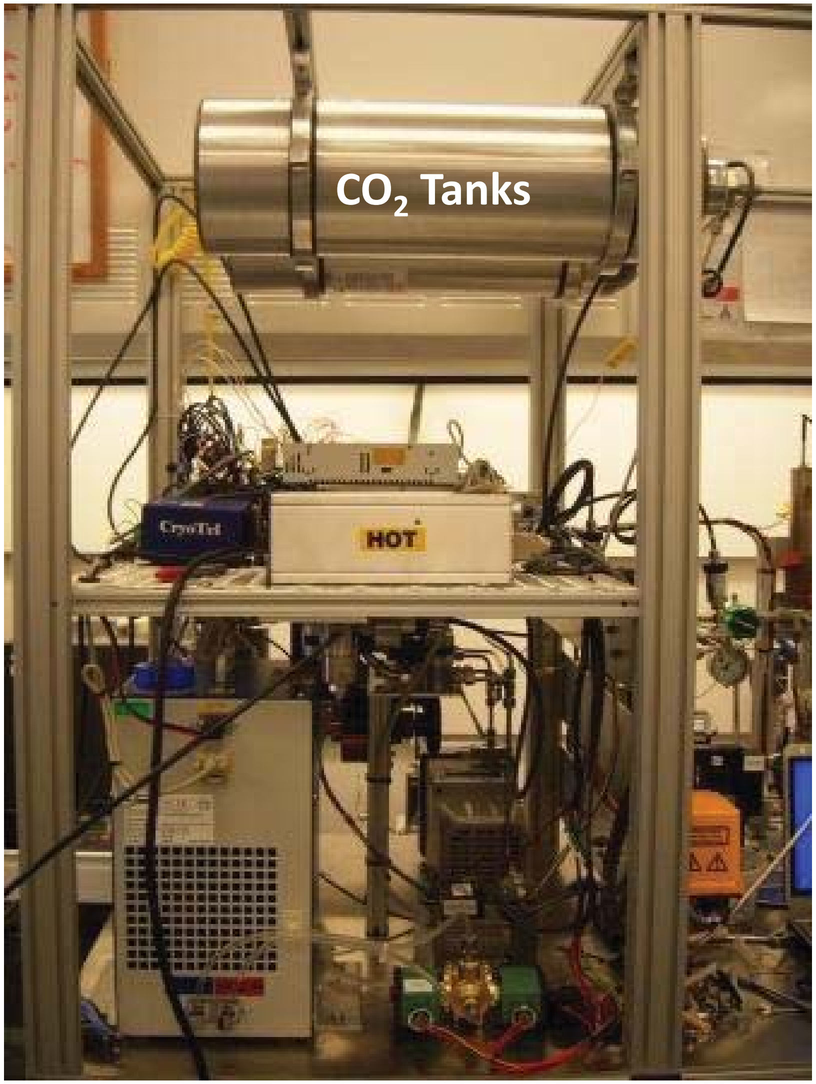


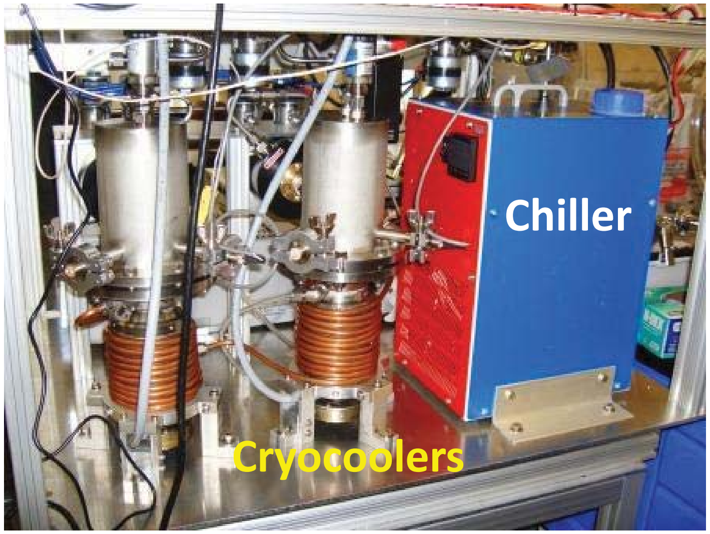
2 - Cryocoolers with Freezing Chambers
11 - Magnetic Latching Solenoid Valves
1 - Chiller with 4-Way Dual Solenoid Valve
1 - Vacuum Pump
1 - CO2 Pump
2 - CO2 Ballast Tanks
2 - Vacuum Back Pressure Regulators
3 - Pressure Relief Valves
1 - Flow Controller
1 - Flow Meter
3 - Thermocouples and 2 RTDs
3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

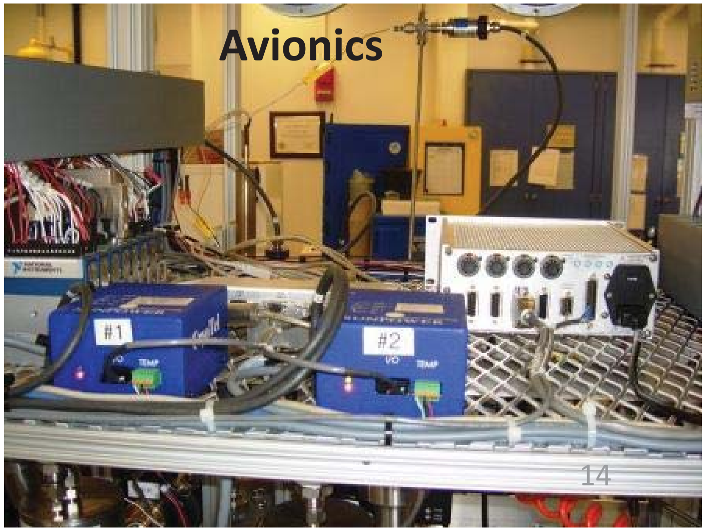
CO_2 Freezer



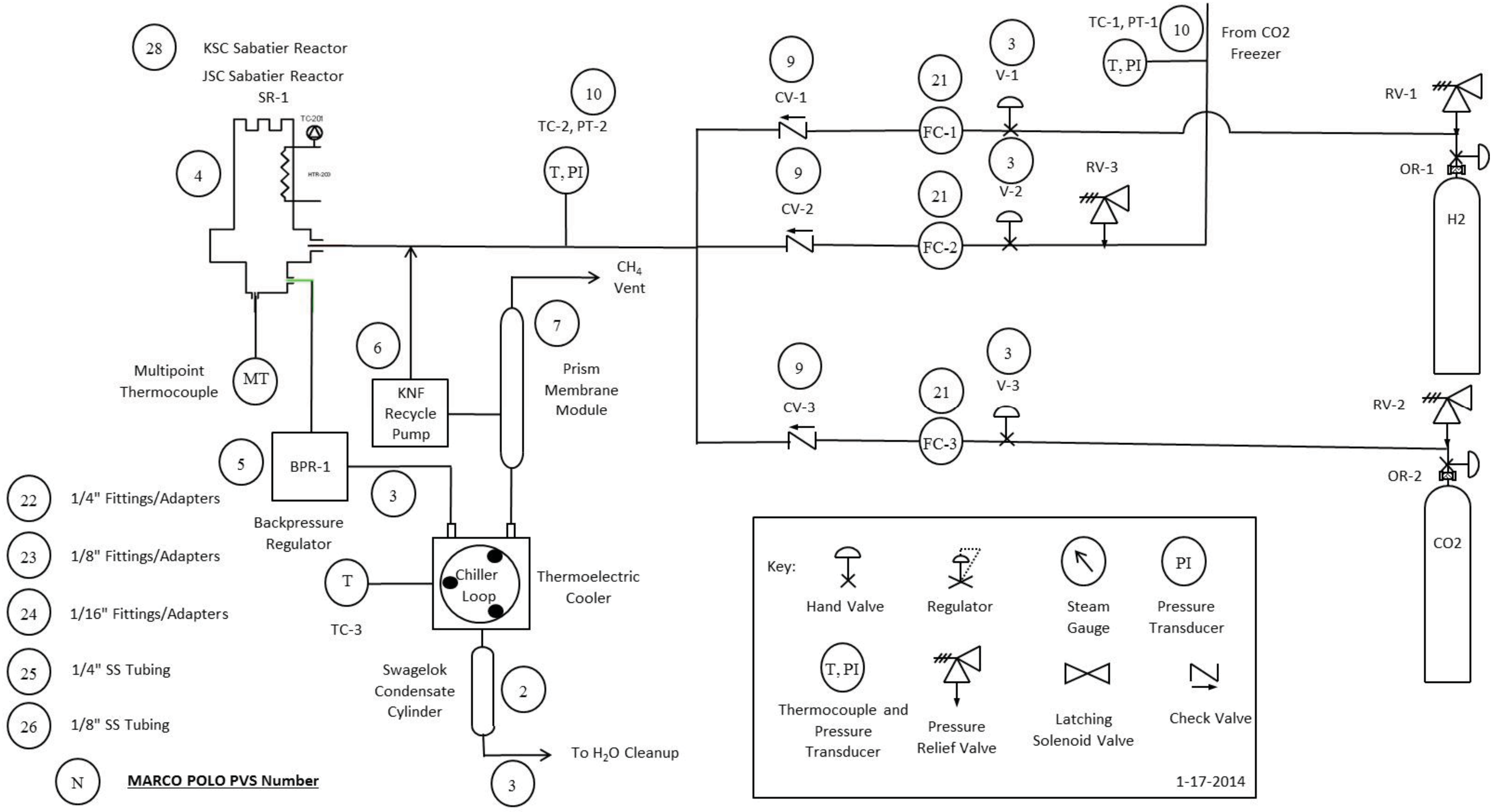
Copper Cold Head



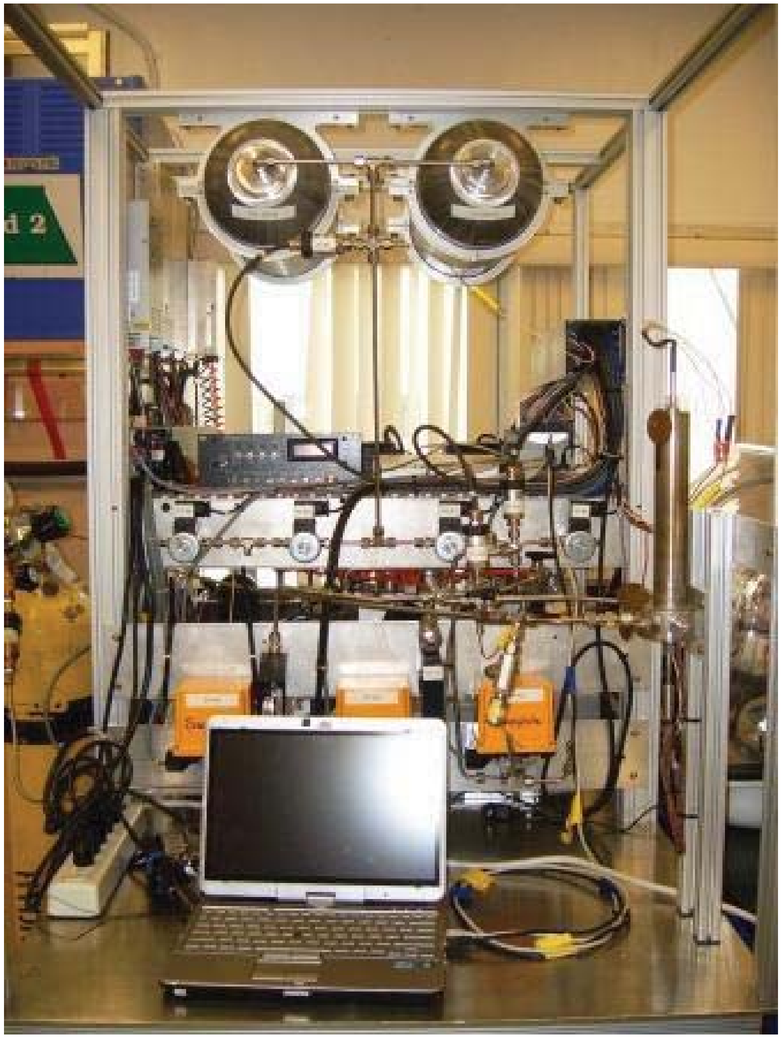




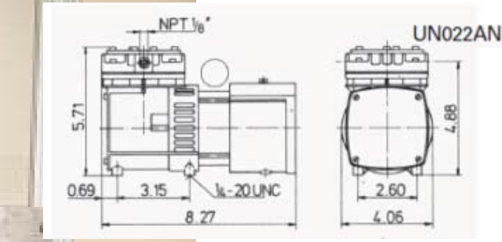
Sabatier Subsystem Design



Sabatier Subsystem



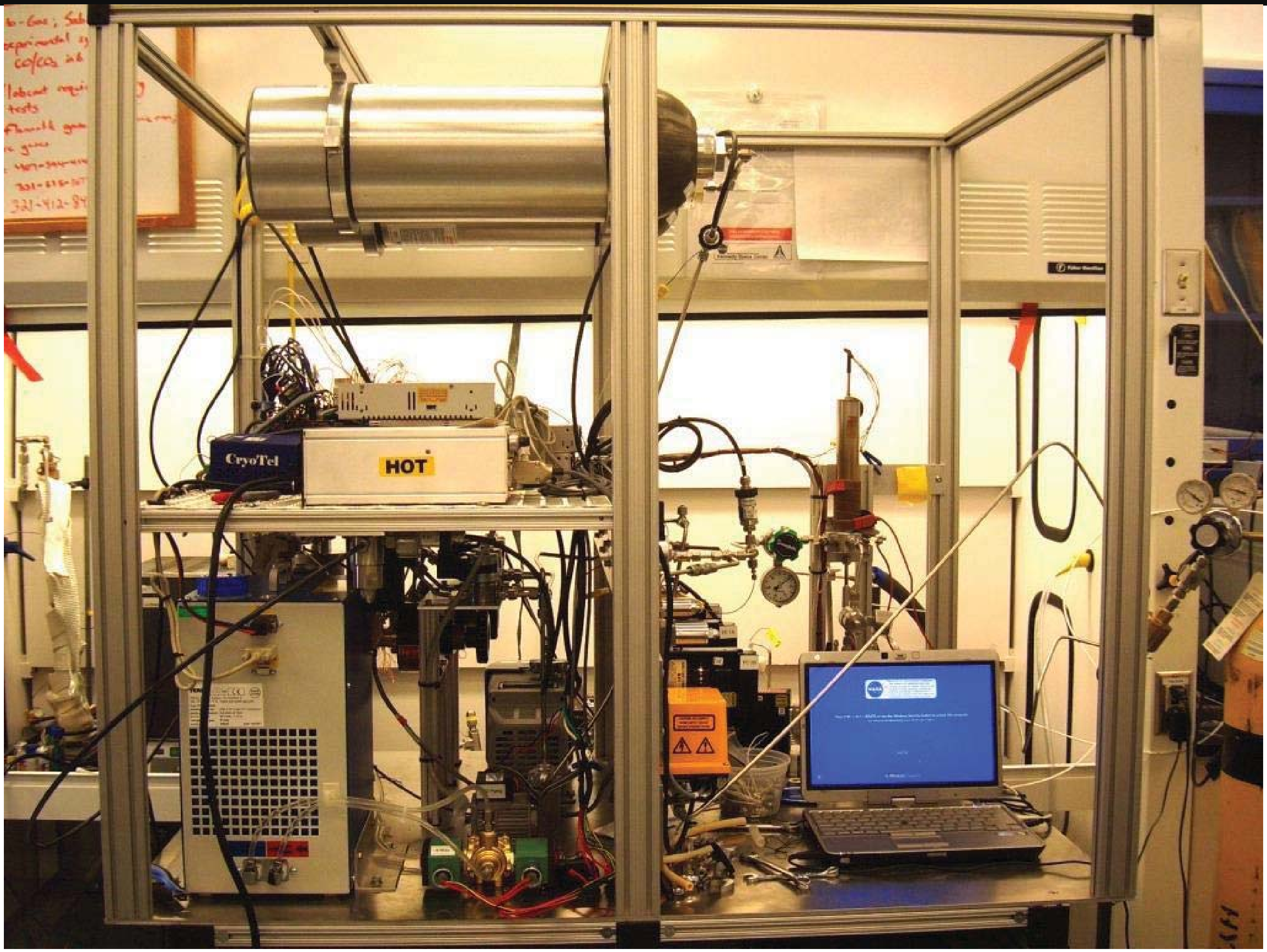
JSC Sabatier Reactor



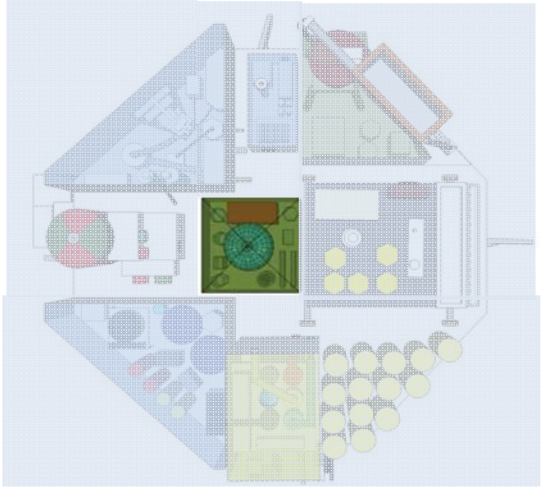
Recycle Pump

Membrane Module (Cut-Away View)

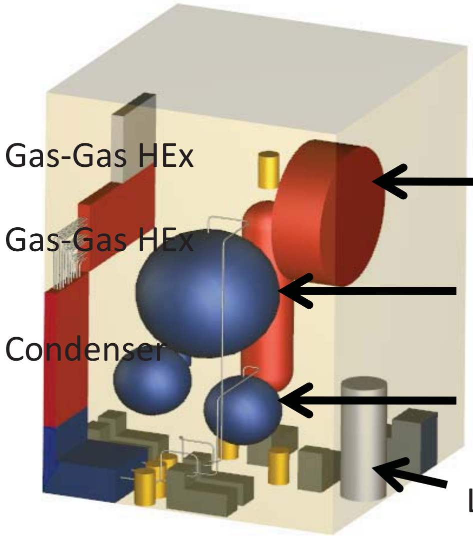
Atmospheric Processing Module

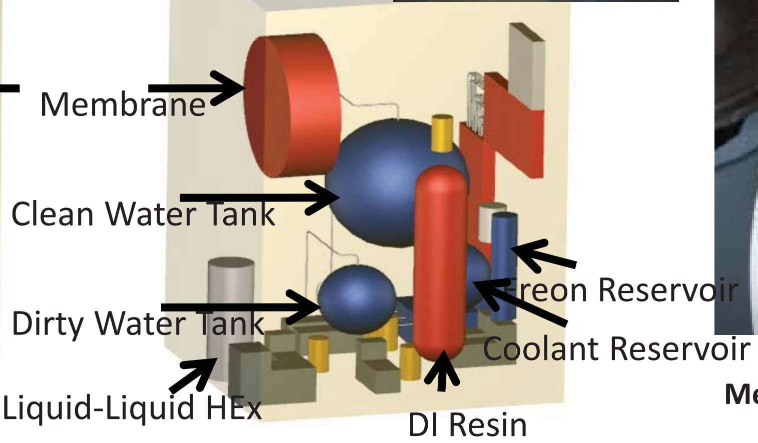


Water Cleanup Module (KSC)



- 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





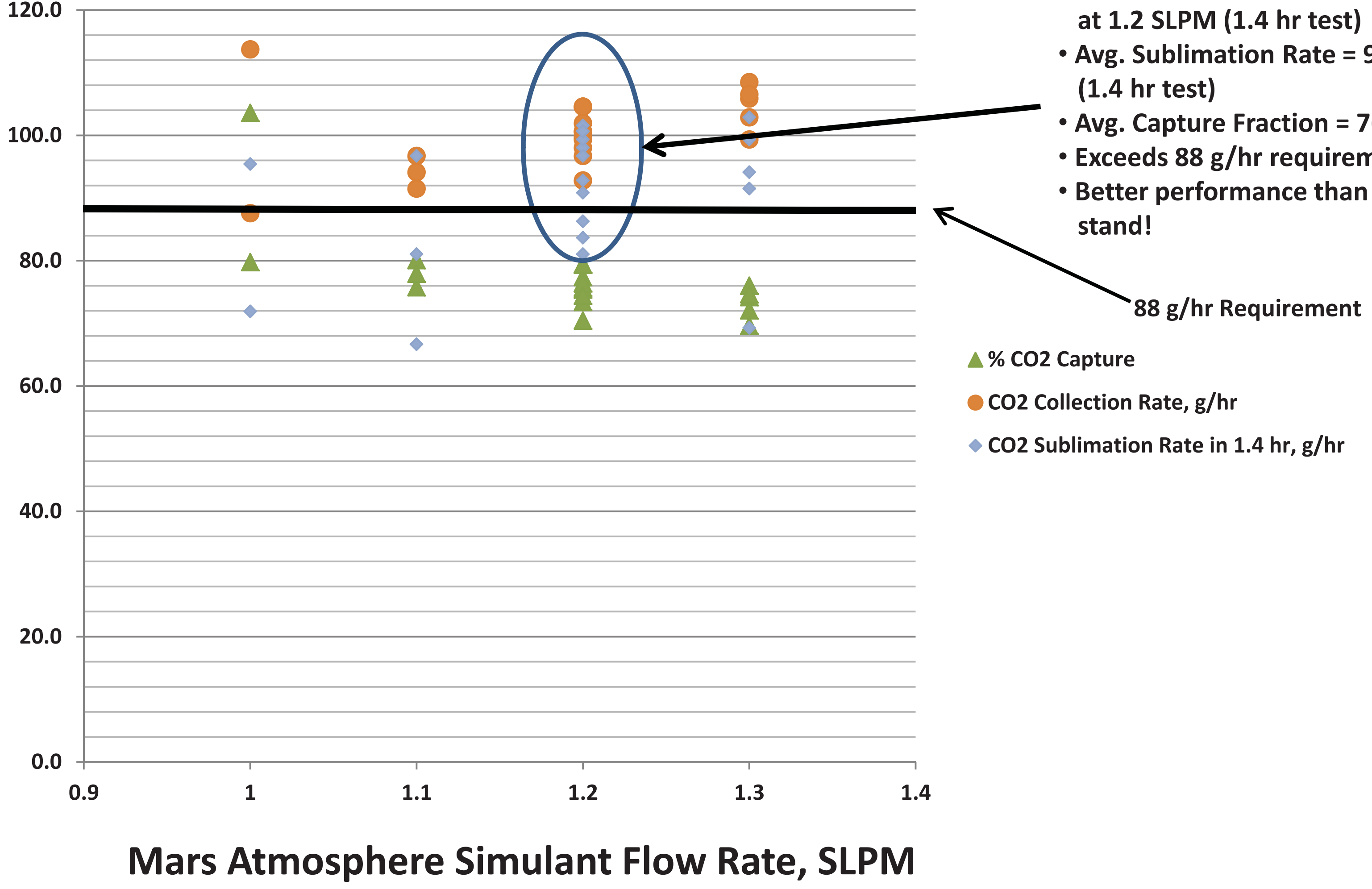
Membrane separator not included in the final version

Lander and Soil Processing Module (KSC)

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

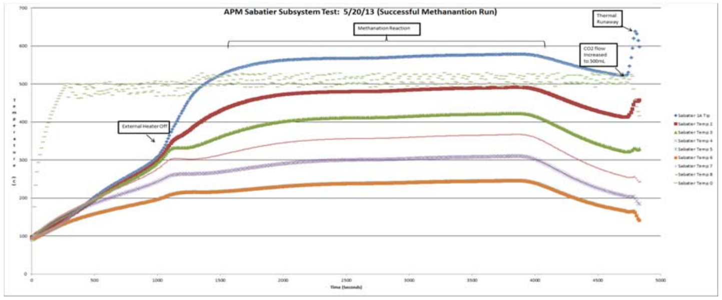
RASSOR (Regolith Advanced Surface Systems Operations Robot) will feed the hopper

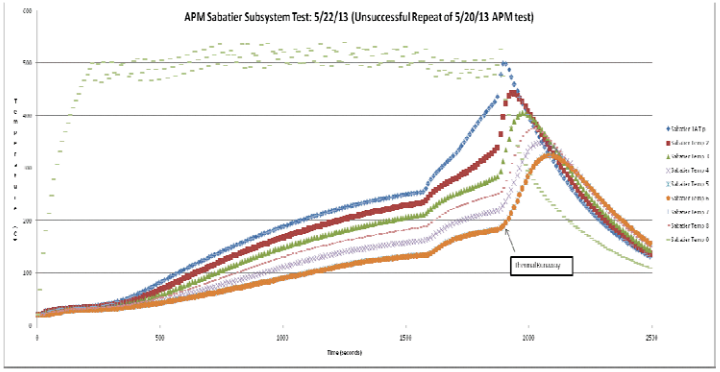
CO_2 Freezer Testing

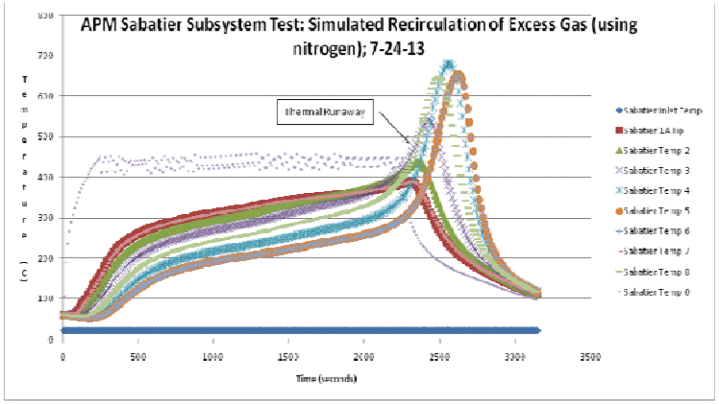


- **Avg. Capture Rate = 100.3 g/hr at 1.2 SLPM (1.4 hr test)**
- **Avg. Sublimation Rate = 93.8 g/hr (1.4 hr test)**
- **Avg. Capture Fraction = 76%**
- **Exceeds 88 g/hr requirement**
- **Better performance than test stand!**

JSC Sabatier Testing


APM Sabatier Subsystem Test: 5/20/13 (Successful Methanantion Run)


APM Sabatier Subsystem Test: 5/22/13 (Unsuccessful Repeat of 5/20/13 APM test)


APM Sabatier Subsystem Test: Simulated Recirculation of Excess Gas (using nitrogen); 7-24-13

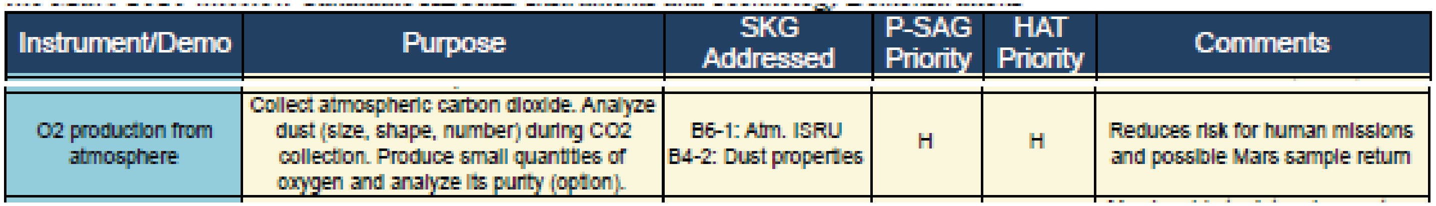
- JSC Testing was successful (>99% conversion at 4.5:1 H_2/CO_2 ratio)
- First three KSC tests overheated
  - >600°C
- One test did not overheat (top) at 250 sccm CO_2 vs. 747 sccm desired (1000 sccm H_2)
  - Duplicate run did overheat (middle)
- Twelve tests at various flow rates overheated
- Two tests with simulated recycle gases ($N_2/H_2/CO_2$ = 6.0/3.35/0.75 SLPM) was slower to overheat, but still did so (bottom)
- <u>Built a redesigned Sabatier reactor</u>

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 CO_2 capture and dust size characterization for atmospheric ISRU” p. 63**
- **“Collect atmospheric carbon dioxide. Analyze dust (size, shape, number) during CO_2 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**



Instrument/Demo	Purpose	SKG Addressed	P-SAG Priority	HAT Priority	Comments
O2 production from atmosphere	Collect atmospheric carbon dioxide. Analyze dust (size, shape, number) during CO2 collection. Produce small quantities of oxygen and analyze its purity (option).	B6-1: Atm. ISRU B4-2: Dust properties	H	H	Reduces risk for human missions and possible Mars sample return

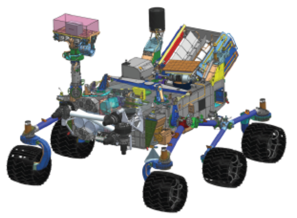


Figure 9-4. 2020 rover External Configuration concept with a potential MSL-heritage MMRTG power source.

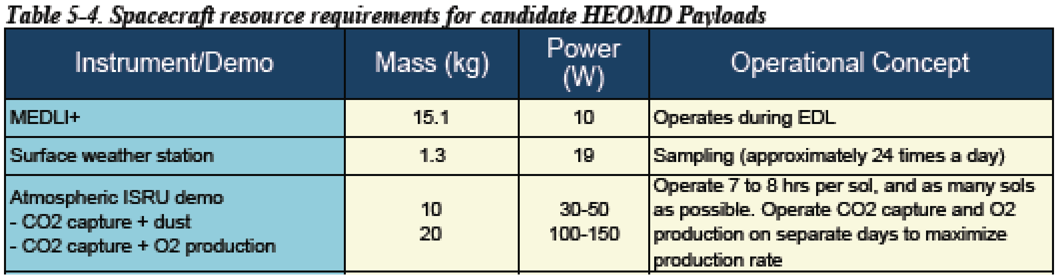


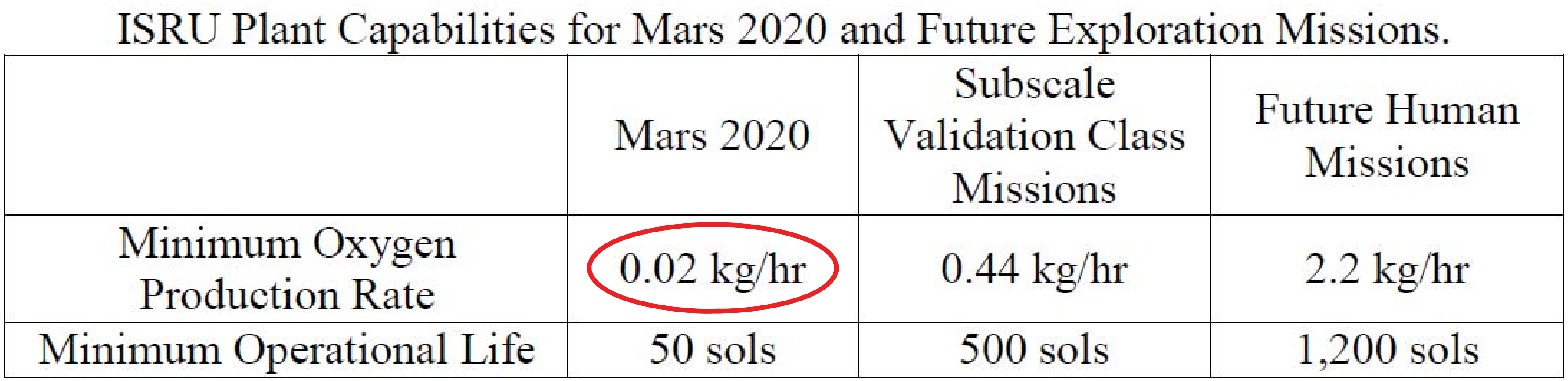
Table 5-4. Spacecraft resource requirements for candidate HEOMD Payloads

Instrument/Demo	Mass (kg)	Power (W)	Operational Concept
MEDLI+	15.1	10	Operates during EDL
Surface weather station	1.3	19	Sampling (approximately 24 times a day)
Atmospheric ISRU demo - CO2 capture + dust - CO2 capture + O2 production	 10 20	 30-50 100-150	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

p. 82

NASA Plans for Mars ISRU

- **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.”**



ISRU Plant Capabilities for Mars 2020 and Future Exploration Missions.

	Mars 2020	Subscale Validation Class Missions	Future Human Missions
Minimum Oxygen Production Rate	0.02 kg/hr	0.44 kg/hr	2.2 kg/hr
Minimum Operational Life	50 sols	500 sols	1,200 sols

- **Proposal selection in June 2014**

Other KSC ISRU Projects: RESOLVE

Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

RESOLVE **is an internationally developed payload (NASA and CSA) that that can perform two important missions for Science and Human Exploration of the Moon**

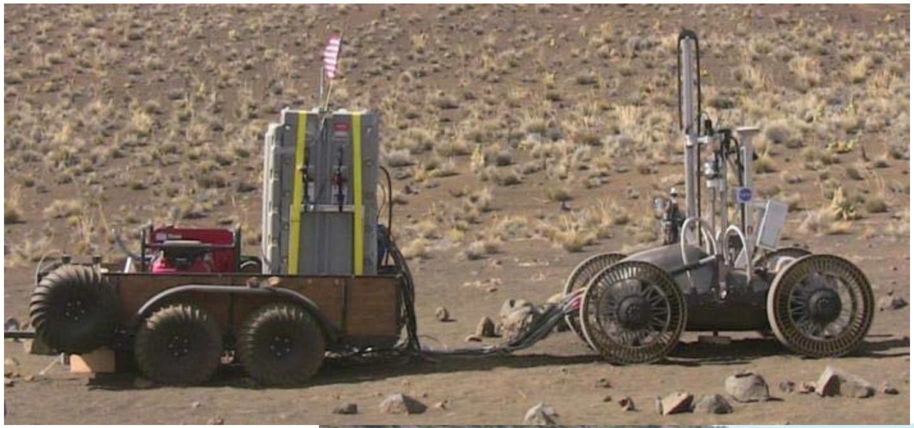
Prospecting Mission: (Polar site)

- ✓ **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: H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2
    - 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 H_2 through regolith to extract oxygen in the form of water**
  - **Capture, quantify, and display the water generated**

RESOLVE Analog Field Tests

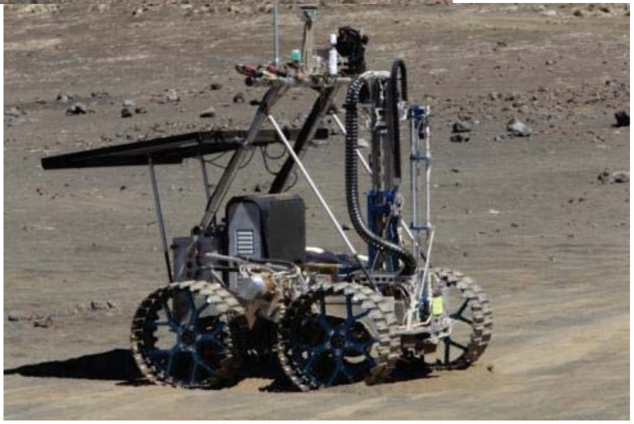


Nov. 2008

- **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

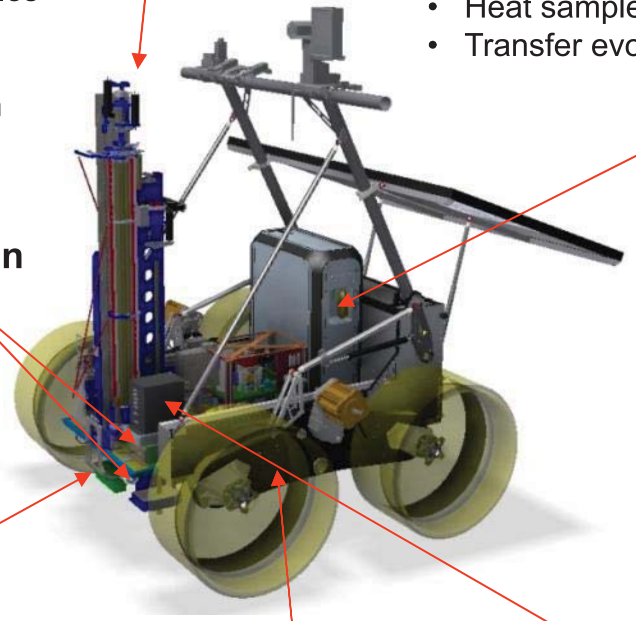


July 2012

- **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/H_2O 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)

RESOLVE Mission Requirements

- Nom. Mission Life = 5+ Cores; 14 Days
- Mass = 170 kg rover/80 kg payload
- Ave. Power; 200-300 W

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 $O^{16/18}$ isotopes
- Capture & image water evolved

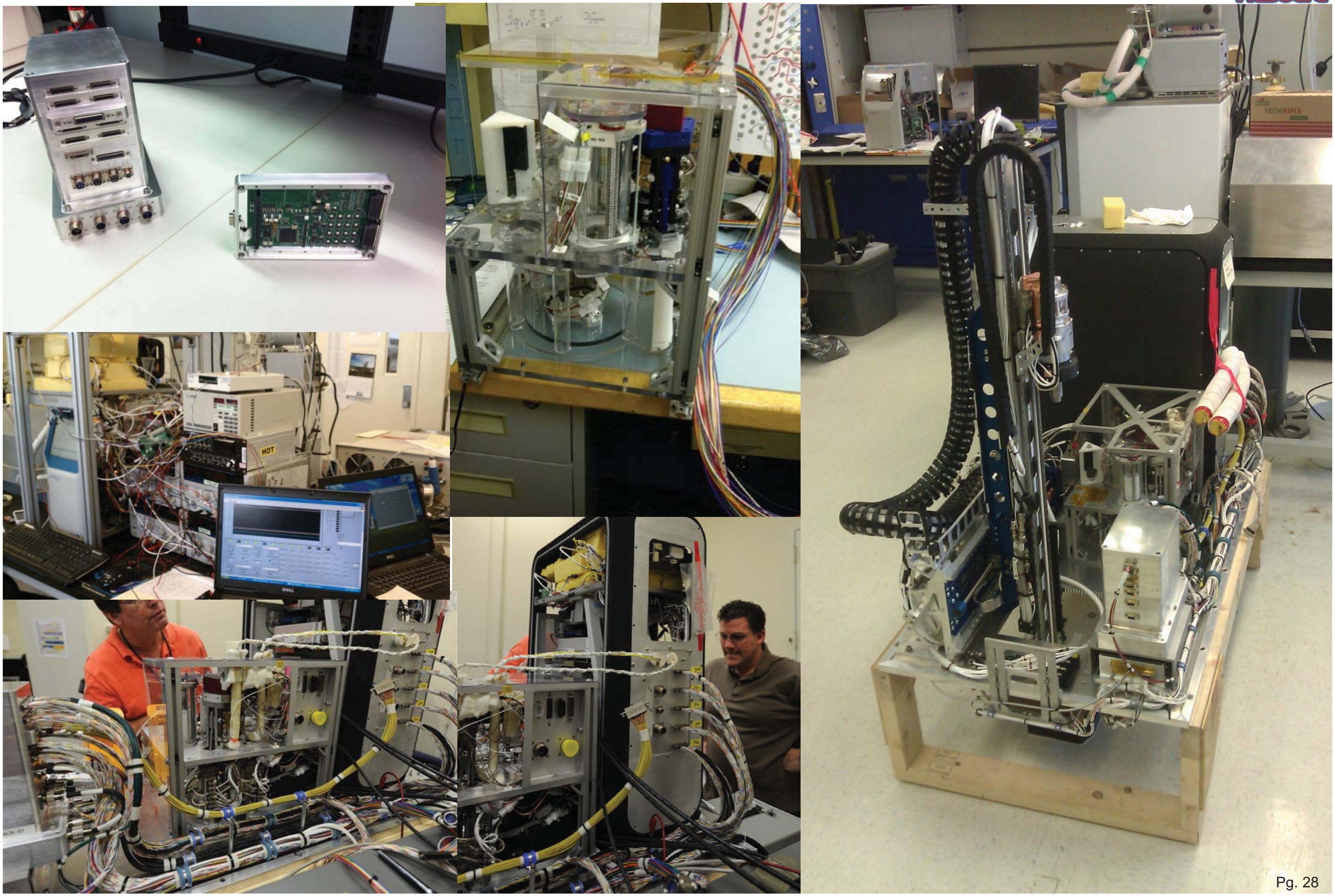
Operation Control **Flight Avionics - KSC**

- Space-rated microprocessor
- Control subsystems and manage data

Surface Mobility

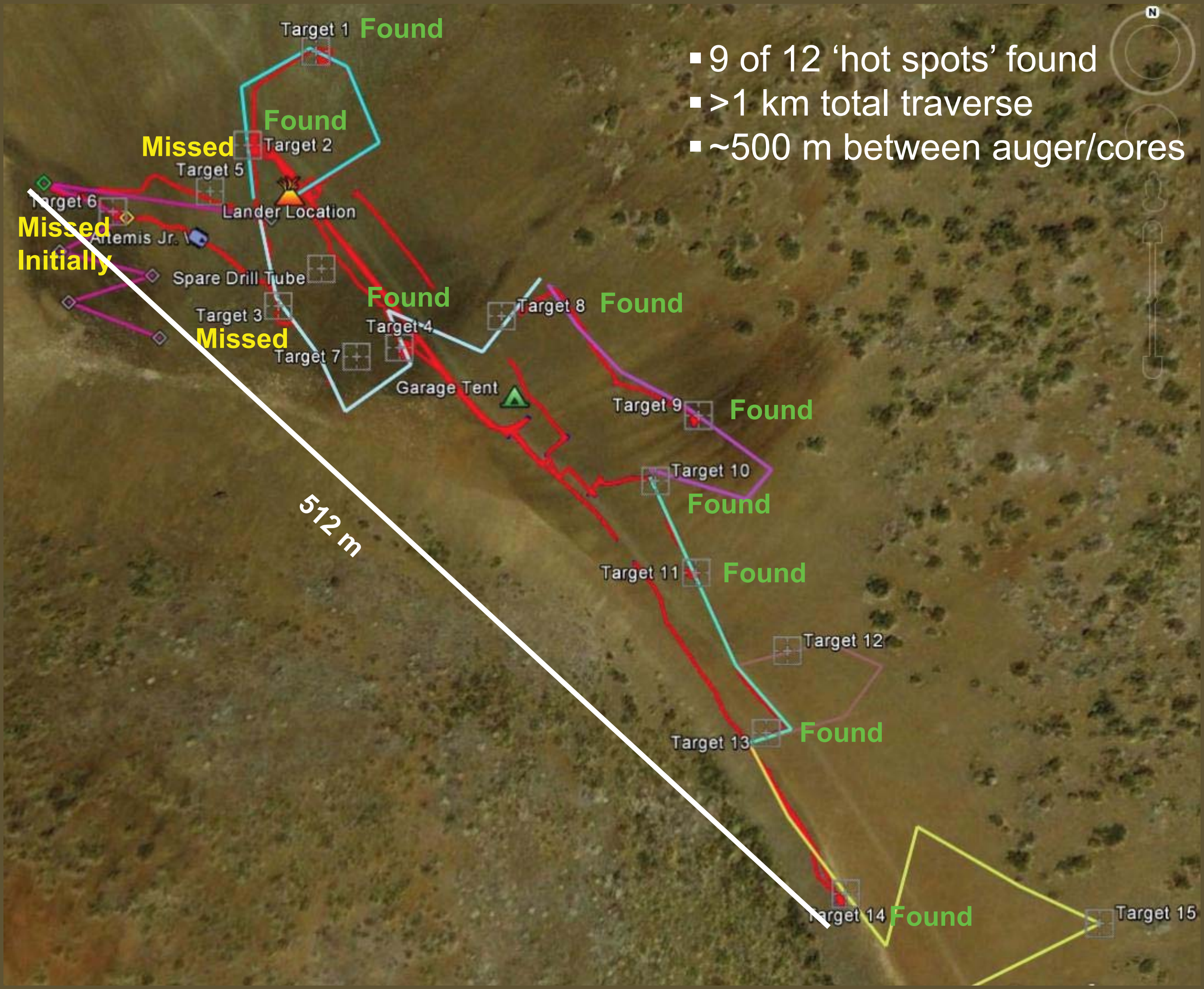
- Traverse wide range of lunar surface/material conditions
- Tele-operation and autonomous traverse modes
- Carry RESOLVE payload; provide power, comm., and thermal management

RESOLVE Gen IIIA Field Development Unit (FDU) Assembly & Integration (1)



RESOLVE Gen IIIA Field Development Unit (FDU) Assembly & Integration (2)

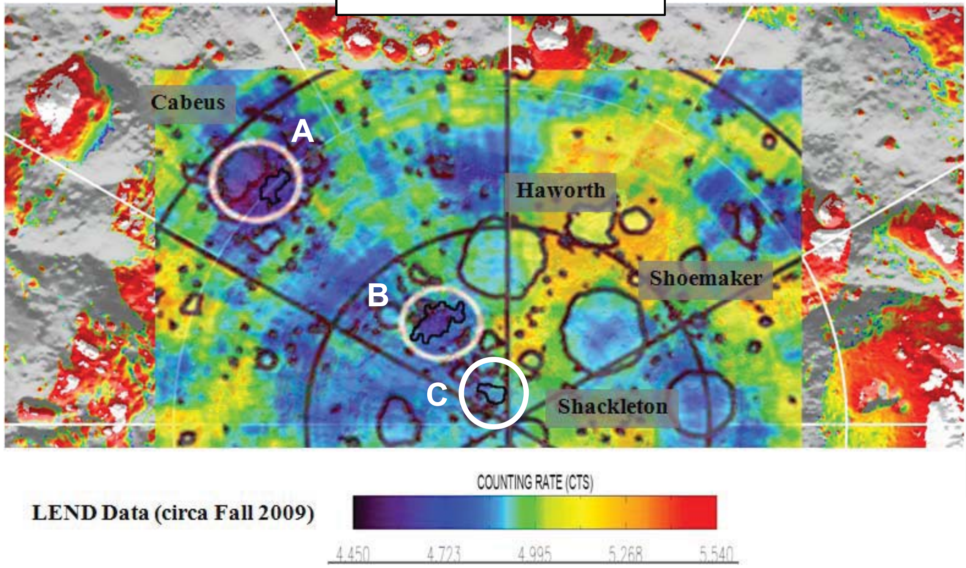
Complete RESOLVE Mission Traverse on Mauna Kea



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

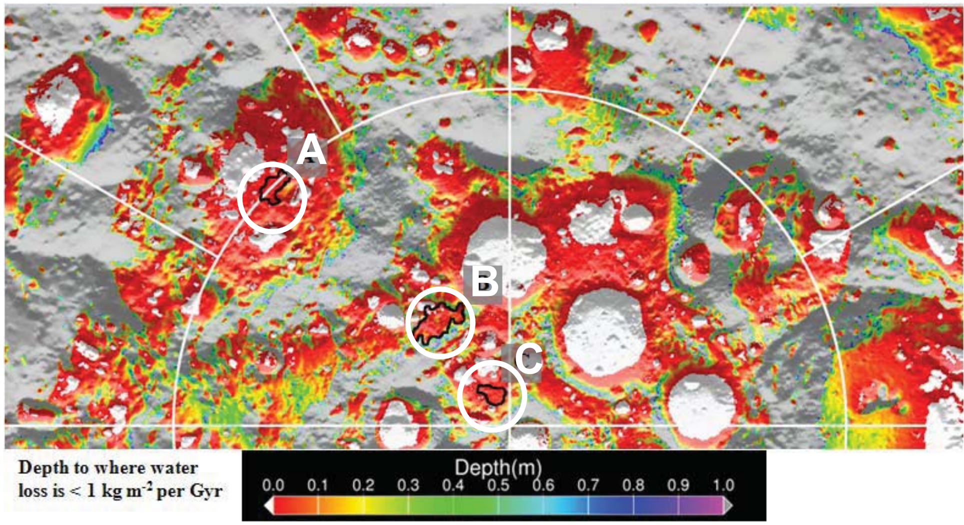
RESOLVE Mission Options – Potential South Pole Landing Sites

LEND Results

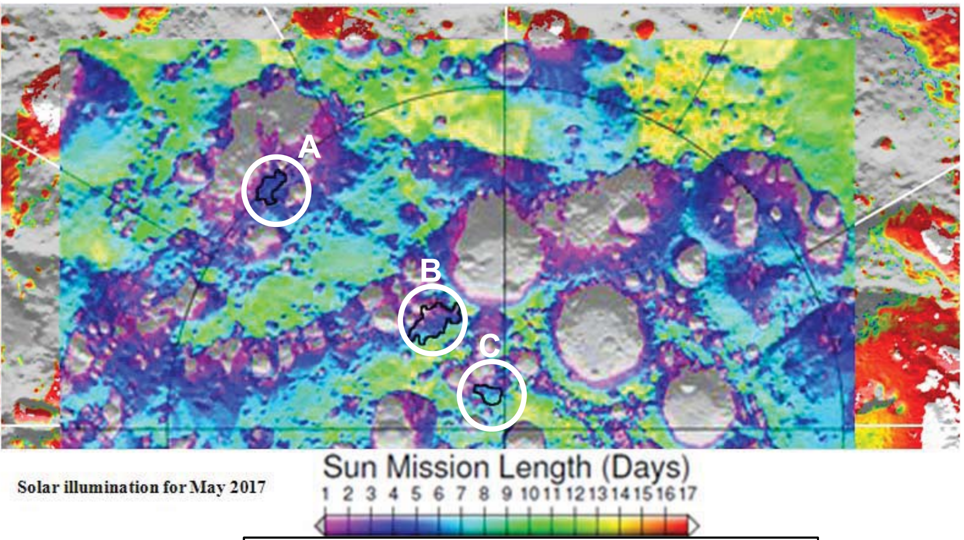


Site Analysis

Site:	A	B	C
Shallow "Frost Line"	<0.1 m	<0.2 m	<0.1 m
Slopes	<10	<15	<10
Neutron Depletion	4.5 cps	4.7 cps	4.9 cps
Temporary Sun*	4 days	2-4 days	5-7 d
Comm Line of Sight*	8 days	17 days	17 days
* may not coincide			

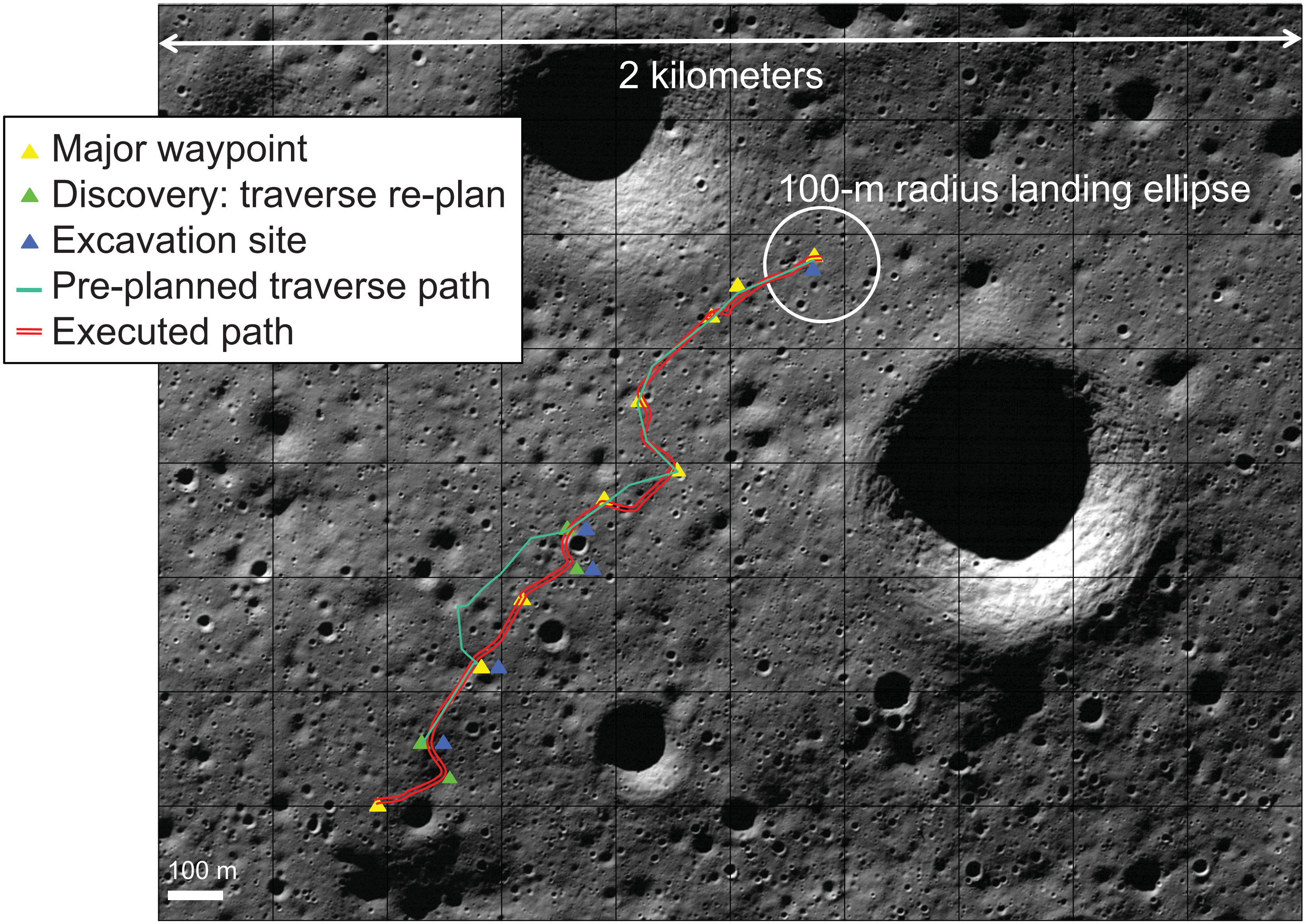


Predicted Volatile Stability



Solar Power Potential

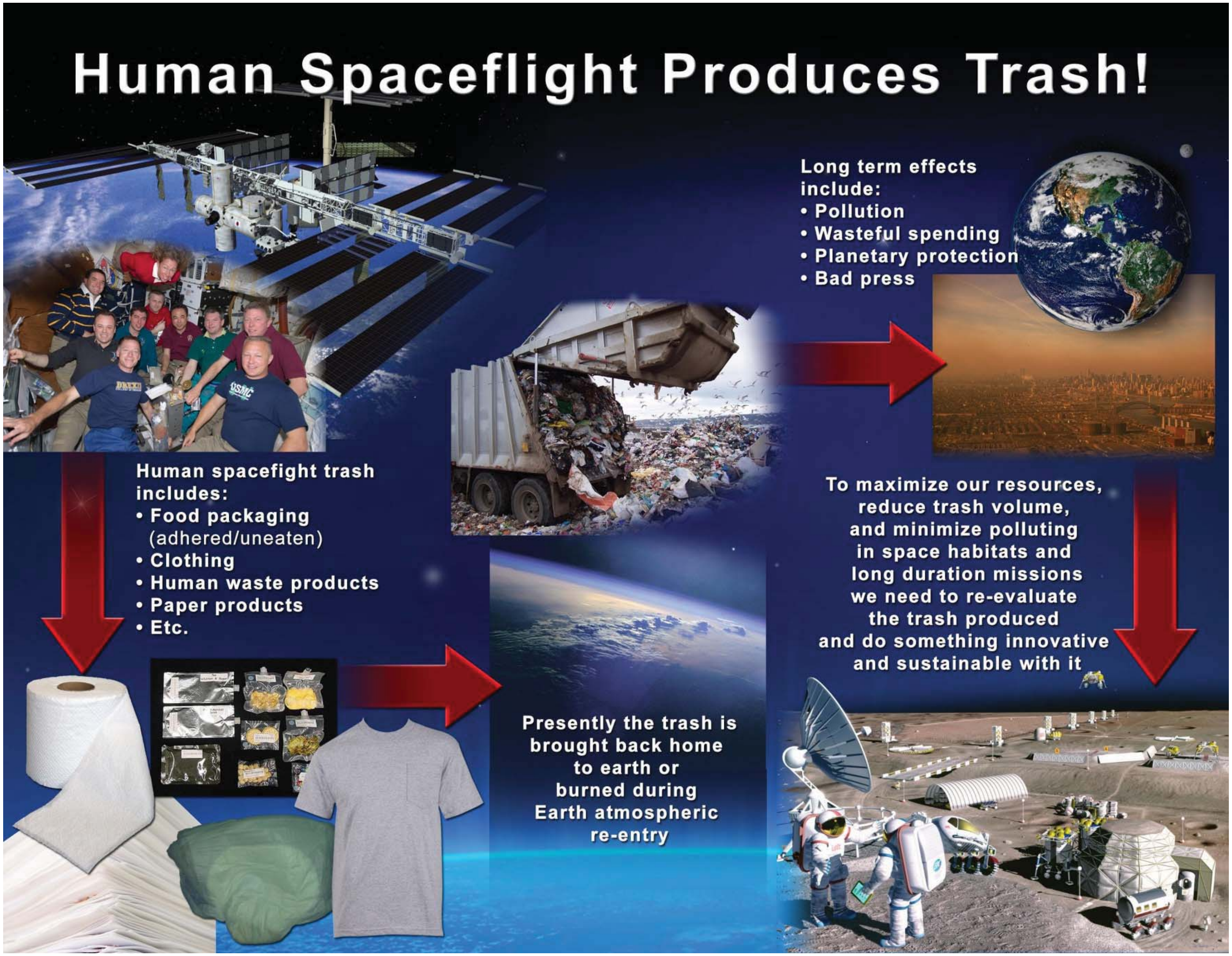
RESOLVE Mission Options – Notional Traverse



Other KSC ISRU Projects: Trash to Gas

- Logistics, Reduction and Repurposing (LRR) Project Overview
- TtSG overview and processes

TtSG Overview



Human Spaceflight Produces Trash!

Human spacefight trash includes:
- Food packaging (adhered/uneaten)
- Clothing
- Human waste products
- Paper products
- Etc.

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

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

TtSG Overview

Utilizing Spaceflight Trash!

Utilize technology to produce useful products from the trash

C

Activated Carbon • Salt • Wax

H_2O

Water • Fuel Depots • Aluminum • In-Situ Manufacturing

CO_2

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

CH_4

H_2

Reduce Trash Volume • Rocket Fuel

O_2

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.

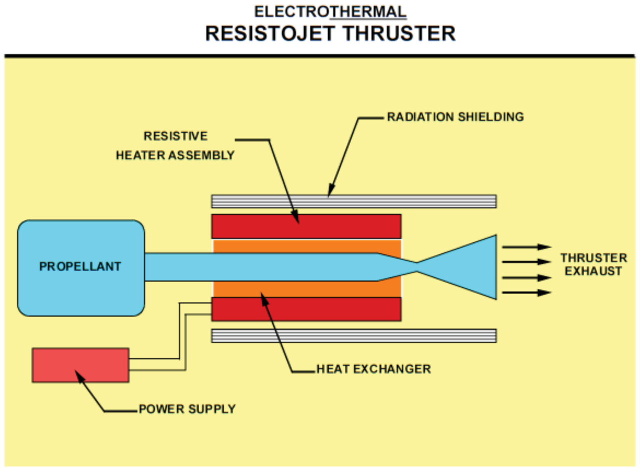
Photo 2. Shuttle trash, not Volume F trash, contained in a large ziplock plastic film bag.

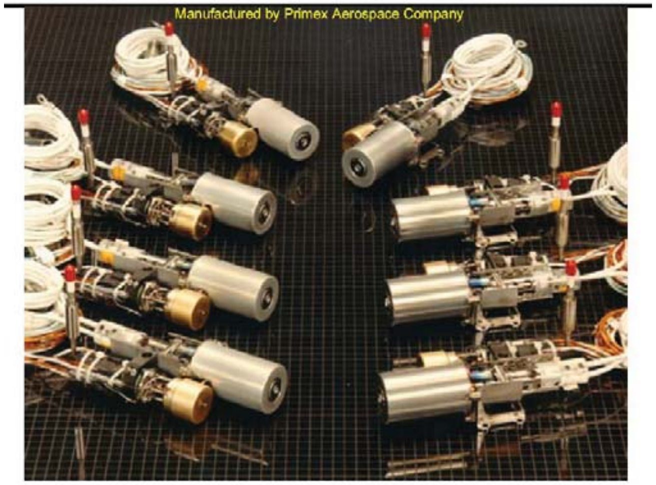
Photo 5. A food ‘football’ from the Shuttle Volume F trash.

Photo 6. A Maximum Adsorption Garment (MAG, EVA diaper) ‘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 mutliple fuels (CO_2, CH_4, H_2O, etc…) in same thruster





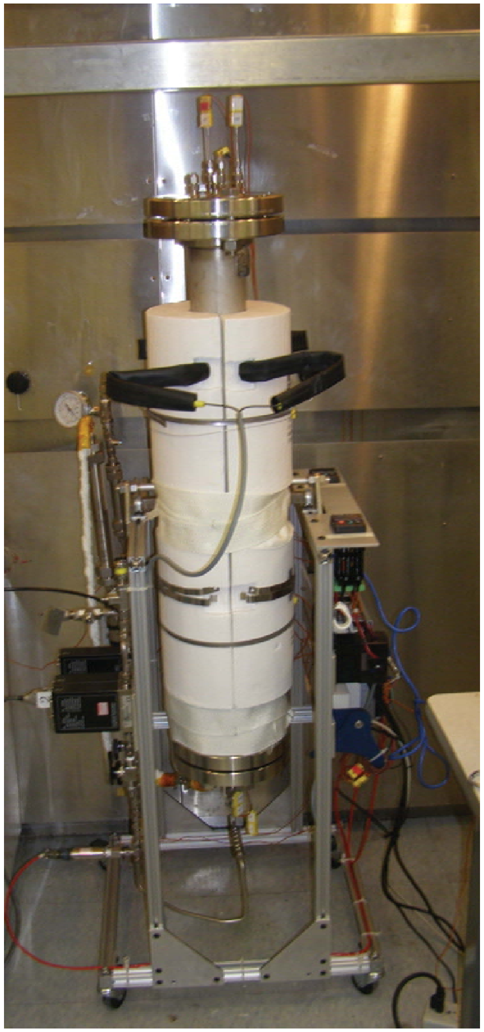
TtSG Overview

- 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

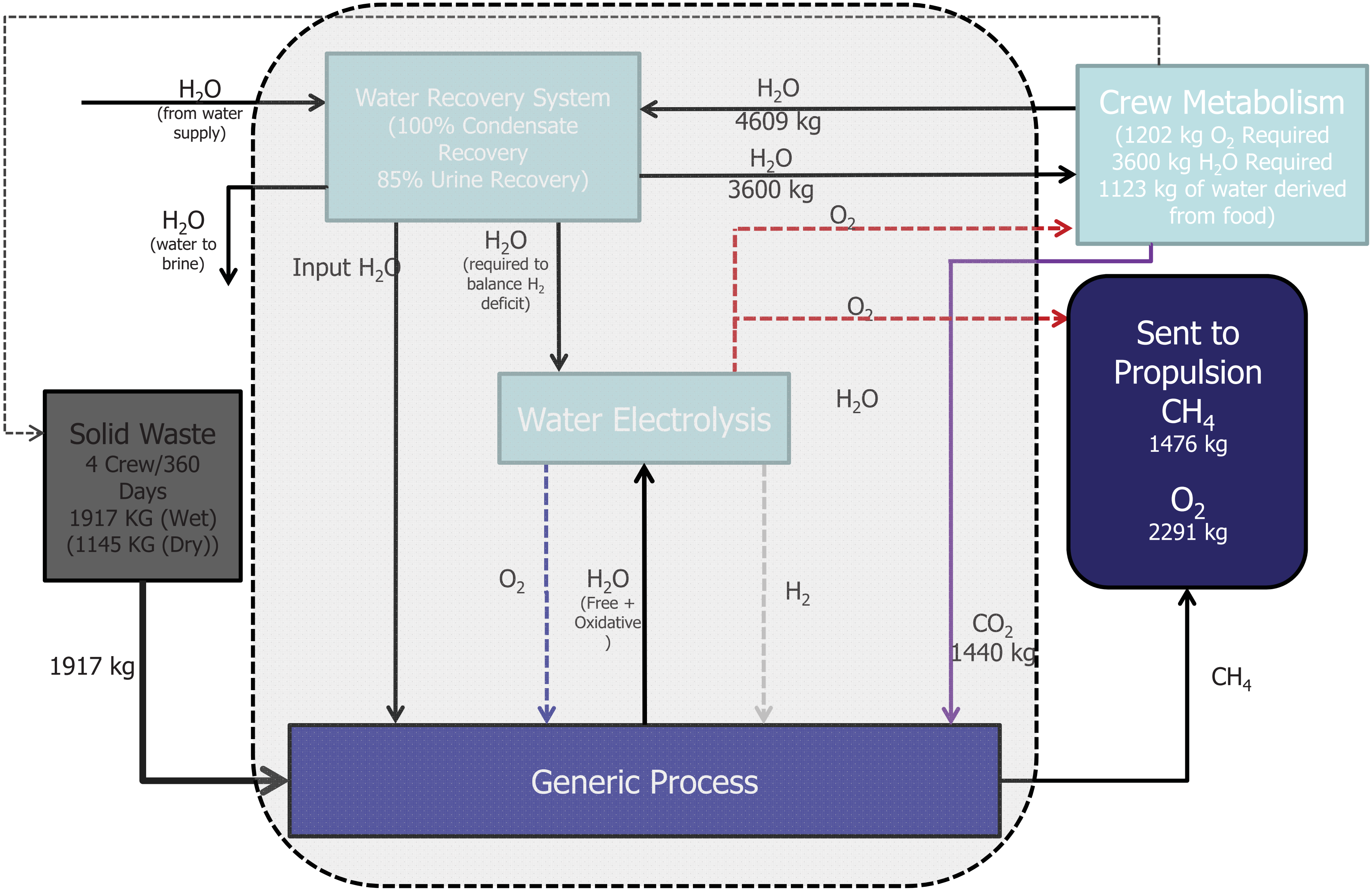
KSC-01PP-0726: Workers in the Space Station Processing Facility are removing contents from the Multi-Purpose Logistics Module (MPLM) Leonardo to begin removing the contents after STS-102. The MPLM brought back nearly a ton of trash and excess equipment from the Space Station.

TtSG General System Analysis

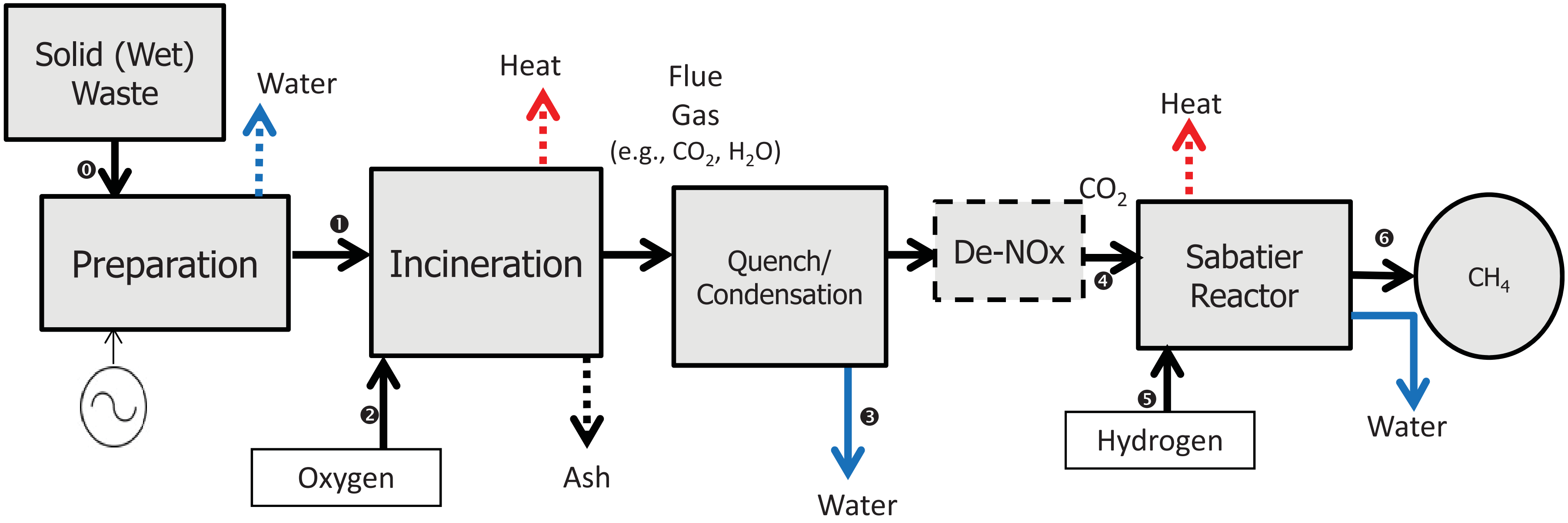
- Assumptions
  - Crew of 4 for 360 days
  - Waste types: Human Waste, packaging, food, MAGs, tape, clothing, towels, washcloths, paper
  - Total waste: 1900 kg wet waste, 4200 kg from crew metabolism (CO_2, H_2O)
- Production
  - 800 – 1500 kg of methane/year
    - Carbon is limiting reagent, so if 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

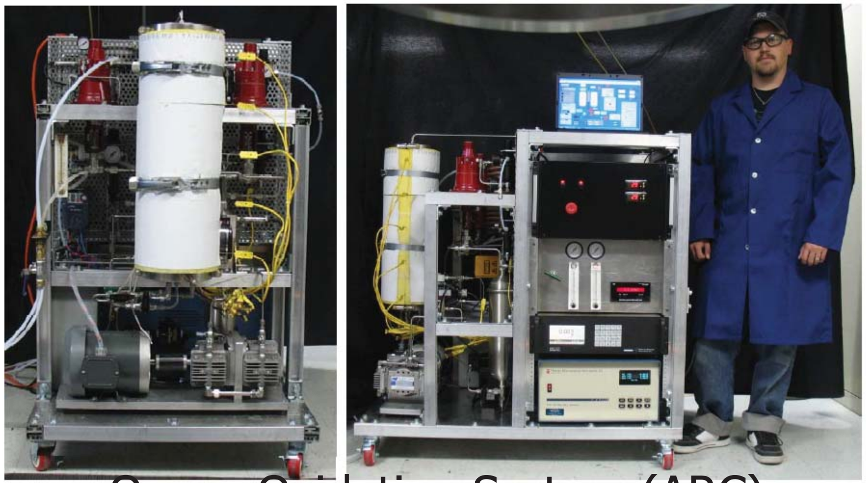


TtSG General Systems Analysis



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

- **Pyrolisis:**
  - 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 ER = 0; Pyrolysis → Liquids and Char

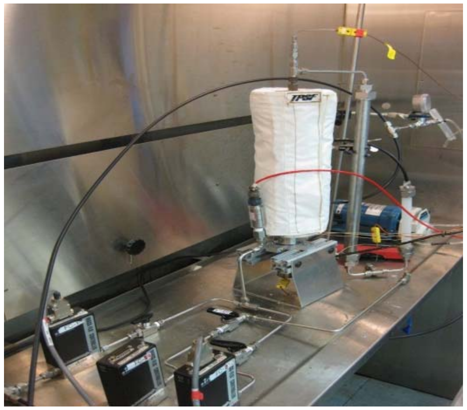
O_2 ER ~ 0.1-0.3; Gasification → Syn gas; CO, CO_2, H_2, CH_4, …

O_2 ER ~ 1; Incineration → CO_2, H_2O, …

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?

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Any Questions?

Ultimate Destination - Mars