Mars ISRU for Production of Mission Critical Consumables – Options, Recent Studies, and Current State of the Art

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In 1978, a ground breaking paper titled, "Feasibility of Rocket Propellant Production on Mars" by Ash, Dowler, and Varsi discussed how ascent propellants could be manufactured on the Mars surface from carbon dioxide collected from the atmosphere to reduce launch mass. Since then, the concept of making mission critical consumables such as propellants, fuel cell reactants, and life support consumables from local resources, commonly known as In-Situ Resource Utilization (ISRU), for robotic and human missions to Mars has been studied many times. In the late 1990's, NASA initiated a series of Mars Human Design Reference Missions (DRMs), the first of which was released in 1997. These studies primarily focused on evaluating the impact of making propellants on Mars for crew ascent to Mars orbit, but creating large caches of life support consumables (water & oxygen) as a backup for regenerative life support systems for long-duration surface stays (>500 days) was also considered in Mars DRM 3.0. Until science data from the Mars Odyssey orbiter and subsequent robotic missions revealed that water may be widely accessable across the surface of Mars, prior Mars ISRU studies were limited to processing Mars atmospheric resources (carbon dioxide, nitrogen, argon, oxygen, and water vapor). In December 2007, NASA completed the Mars Human Design Reference Architecture (DRA) 5.0 study which considered water on Mars as a potential resource for the first time in a human mission architecture. While knowledge of both water resources on Mars and the hardware required to excavate and extract the water were very preliminary, the study concluded that a significant reduction in mass and significant enhancements to the mission architecture were possible if Mars water resources were utilized. Two subsequent Mars ISRU studies aimed at reexamining ISRU technologies, processing options, and advancements in the state-of-the-art since 2007 and to better understand the volume and packaging associated with Mars ISRU systems further substantiated the preliminary results from the Mars DRA 5.0 study. This paper will provide an overview of Mars ISRU consumable production options, the analyses, results, and conclusions from the Mars DRA 5.0 (2007), Mars Collaborative (2013), and Mars ISRU Payload for the Supersonic Retro Propulsion (2014) mission studies, and the current state-of-the-art of Mars ISRU technologies and systems. The paper will also briefly discuss the mission architectural implications associated with Mars resource and ISRU processing options.

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– Options, Recent Studies, and Current State of the Art

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Mars ISRU Mission Studies

Past Mars Studies with ISRU (DRM 1 to 4)

- Only considered atmospheric resources were available (CO_2, N_2, Ar)
- Evaluated two propellant production options
  - Make Oxygen (O_2) only and bring fuel from Earth
  - Make O_2 and methane (CH_4) with hydrogen (H_2) brought from Earth
- Produced various amounts of life support consumables as backup
  - Ex. DRM 3: 4500 kg of O_2; 3900 kg of N_2 ; 23,200 kg of water (H_2O)
- ISRU considered only after performing non-ISRU scenario
  - No change in Mars entry or rendezvous orbit compared to non-ISRU scenario
  - Influence of ISRU consumable availability or technologies not considered on other systems
- Decisions made on basis of mass/power comparisons. Did not evaluate volume required for ISRU hardware or hydrogen delivered from Earth

Recent Mars Studies with ISRU

- Considered both atmospheric (CO_2, N_2, Ar) and soil (H_2O) resources based on increasing knowledge from Mars Odyssey and subsequent missions

1. Mars Design Reference Architecture (DRA) 5.0 – 2007
   - First study to consider water as a resource; understanding of water on Mars and ISRU hardware for soil excavation and processing was very preliminary
2. Mars Collaborative Study (HEOMD, STMD, SMD) – 2013
   - Increased understanding of water on Mars and ISRU hardware needed for soil processing based on lunar ISRU development and ISRU analog field test experience
3. Mars ISRU Payload for Supersonic Retro Propulsion (SRP) Mission – 2014
   - First study to examine volume/packaging of ISRU production options

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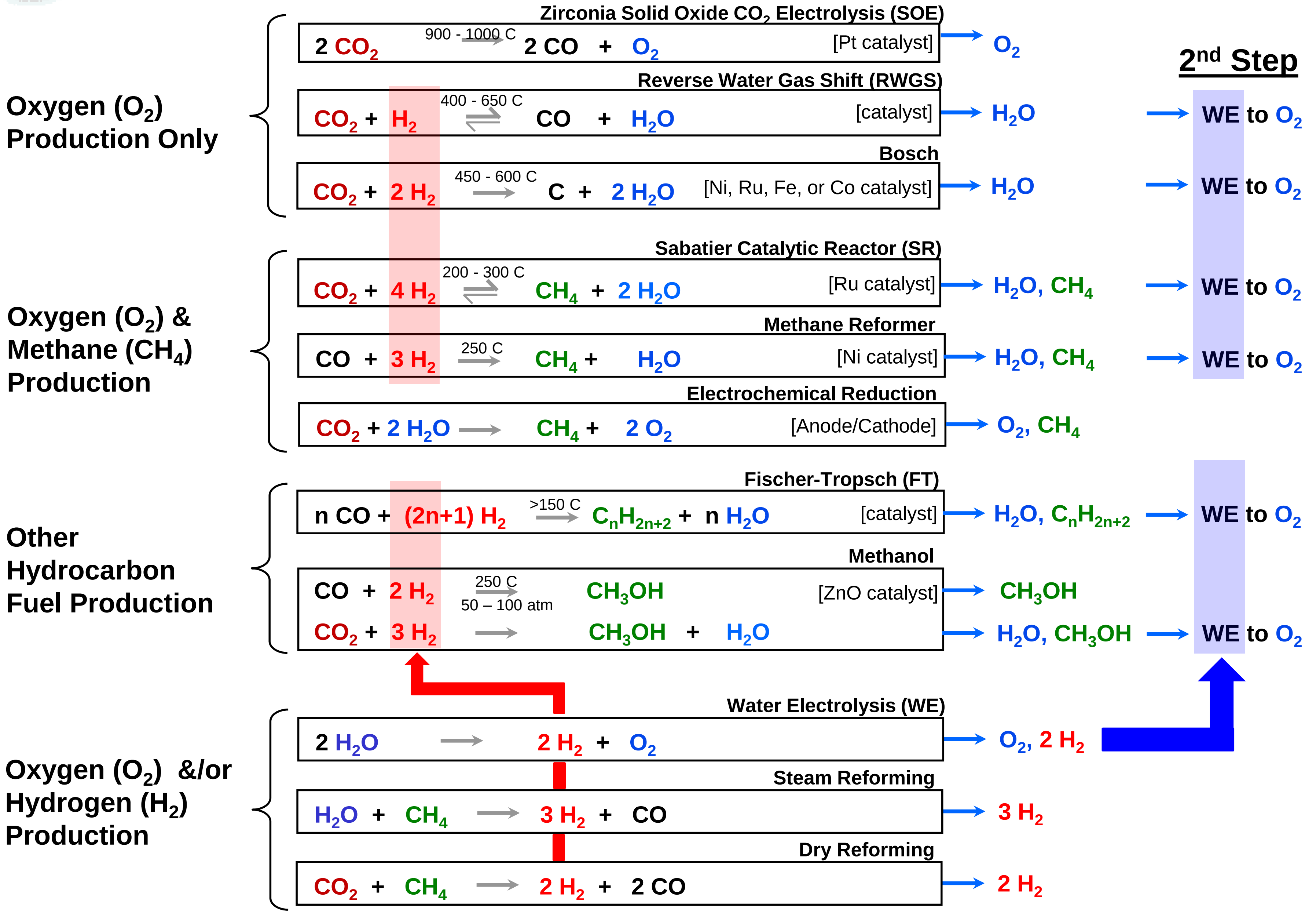
The Chemistry of Mars ISRU



2nd Step

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)

$2\,CO_2 \xrightarrow{900-1000\ C} 2\,CO + O_2$ [Pt catalyst] → O_2

Reverse Water Gas Shift (RWGS)

$CO_2 + H_2 \overset{400-650\ C}{\rightleftharpoons} CO + H_2O$ [catalyst] → H_2O → WE to O_2

Bosch

$CO_2 + 2\,H_2 \xrightarrow{450-600\ C} C + 2\,H_2O$ [Ni, Ru, Fe, or Co catalyst] → H_2O → WE to O_2

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)

$CO_2 + 4\,H_2 \overset{200-300\ C}{\rightleftharpoons} CH_4 + 2\,H_2O$ [Ru catalyst] → H_2O, CH_4 → WE to O_2

Methane Reformer

$CO + 3\,H_2 \xrightarrow{250\ C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4 → WE to O_2

Electrochemical Reduction

$CO_2 + 2\,H_2O \rightarrow CH_4 + 2\,O_2$ [Anode/Cathode] → O_2, CH_4

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)

$n\,CO + (2n+1)\,H_2 \xrightarrow{>150\ C} C_nH_{2n+2} + n\,H_2O$ [catalyst] → H_2O, C_nH_{2n+2} → WE to O_2

Methanol

$CO + 2\,H_2 \xrightarrow[50-100\ atm]{250\ C} CH_3OH$ [ZnO catalyst] → CH_3OH

$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$ → H_2O, CH_3OH → WE to O_2

Oxygen (O_2) &/or Hydrogen (H_2) Production

Water Electrolysis (WE)

$2\,H_2O \rightarrow 2\,H_2 + O_2$ → O_2, $2\,H_2$

Steam Reforming

$H_2O + CH_4 \rightarrow 3\,H_2 + CO$ → $3\,H_2$

Dry Reforming

$CO_2 + CH_4 \rightarrow 2\,H_2 + 2\,CO$ → $2\,H_2$

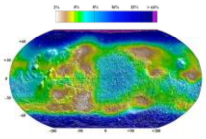
Mars Design Reference Architecture (DRA) 5.0

Mars ISRU Depends on Resource of Interest

Atmospheric Resource Processing

- **Strengths**
  - Atmospheric resources are globally obtainable (no landing site limitations)
  - Production of O_2 only from carbon dioxide (CO_2) makes >75% of ascent propellant mass
  - Significant research and testing performed on several methods of atmospheric collection, separation, and processing into oxygen and fuel; including life support development
- **Weaknesses**
  - Production of methane requires delivery of hydrogen (H_2) from Earth which is volume inefficient or water from the Mars soil (below)
  - Mars optimized ISRU processing may not use baseline ECLSS technologies

Mars Soil Water Resource Processing (ties to Lunar Ice & Regolith)



- **Strengths**
  - Surface material characteristics studied from Mars robotic landers and rovers
  - Water (in the form of hydrated minerals) identified globally near the surface
  - Lunar regolith excavation and thermal processing techniques can be utilized for Mars
  - Low concentrations of water in surface hydrated mineral soil (3%) still provides tremendous mass benefits with minimal planetary protection issues
- **Weaknesses**
  - Risk associated with the complexity of the required surface infrastructure must be evaluated. Significant autonomous operations required.
  - Local/site dependency on water resource concentration and form
  - Concerns from planetary protection and search for life with subsurface material processing

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Mars Resource & ISRU Process Options

- **Four Options for Mars ISRU Ascent Propellant Production:**
  1. Make oxygen (O_2) from Mars atmosphere carbon dioxide (CO_2); Bring fuel from Earth
  2. Make O_2 and fuel/CH_4 from Mars atmosphere CO_2 and hydrogen (H_2) from Earth
  3. Make O_2 and fuel/CH_4 from Mars atmosphere CO_2 and water (H_2O) from Mars soil
  4. Make O_2 and H_2 from H_2O in Mars soil

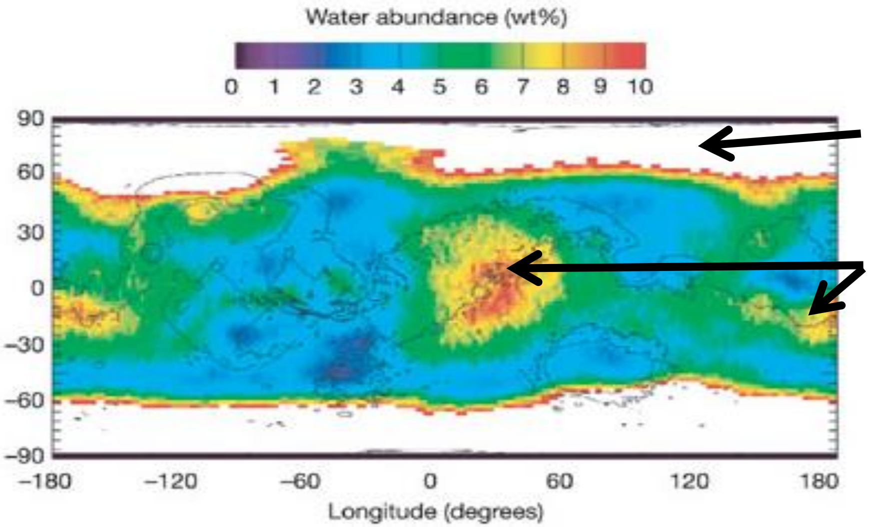
	ISRU Resource Processing Options	**ISRU Products**	**Mars Resource(s)**	**Earth Supplied**		**Process Subsystems/Options**									
						CO_2 Collection & Conditioning	Solid Oxide CO_2 Electrolysis	Reverse Water Gas Shift (RWGS)	Sabatier	Bosch	Liquid Water Electrolysis	Solid Oxide H_2O Electrolysis	Ionic Liquid Electrolysis	Soil Processing	Soil Excavation & Delivery
Enabling	Atmosphere Processing	O_2	CO_2	CH_4 (~6600 kg)	1	X	X								
					2	X		X			X				
						X				X	X				
						X							X		
		O_2, CH_4, H_2O		H_2* (~2000 kg)		X	X		X			X			
						X		X	X		X				
						X							X		
Enabling or Enhancing	Soil Processing	O_2, CH_4, H_2O	H_2O	CH_4 **(~6600 kg)							X			X	X
	Atmosphere & Soil Processing	O_2, CH_4, H_2O	CO_2 & H_2O		3	X			X		X			X	X
						X			X			X		X	X

1, 2, & 3 Were Evaluated in Mars DRA 5.0

*H_2 for water and methane production

**Assumes methane fuel vs hydrogen fuel for propulsion

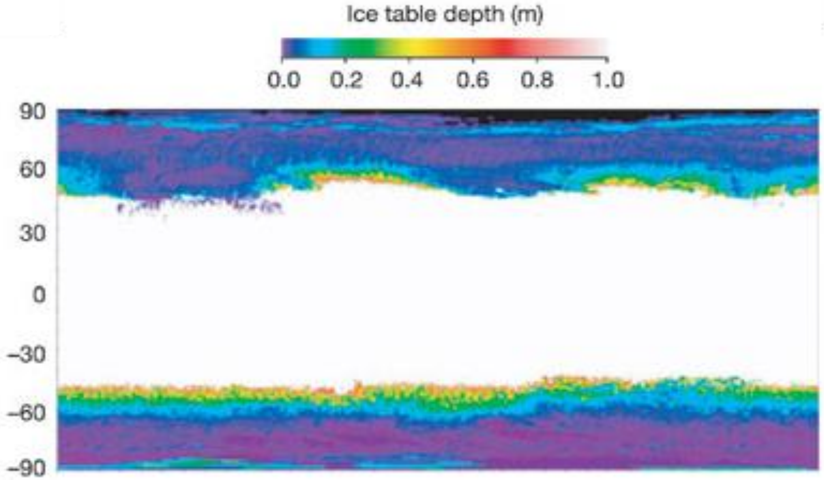
Mars Water Form & Distribution

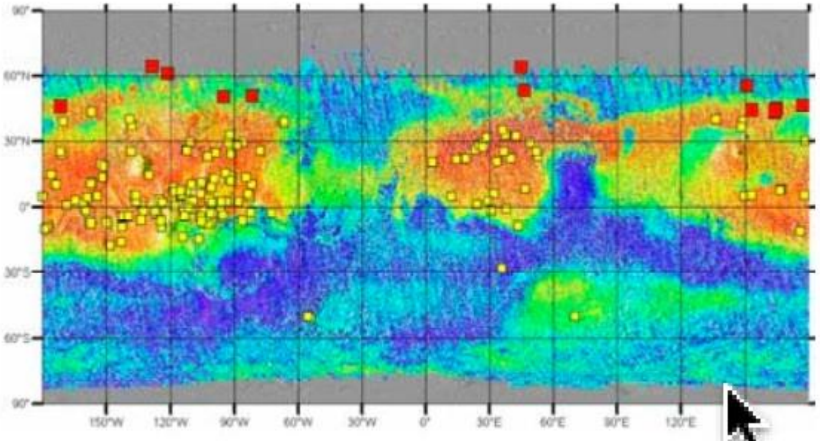


Mid- and high-latitude shallow ice

Thought to be dominated by hydrated minerals

Mid-Latitude Ice-Rich Mantles

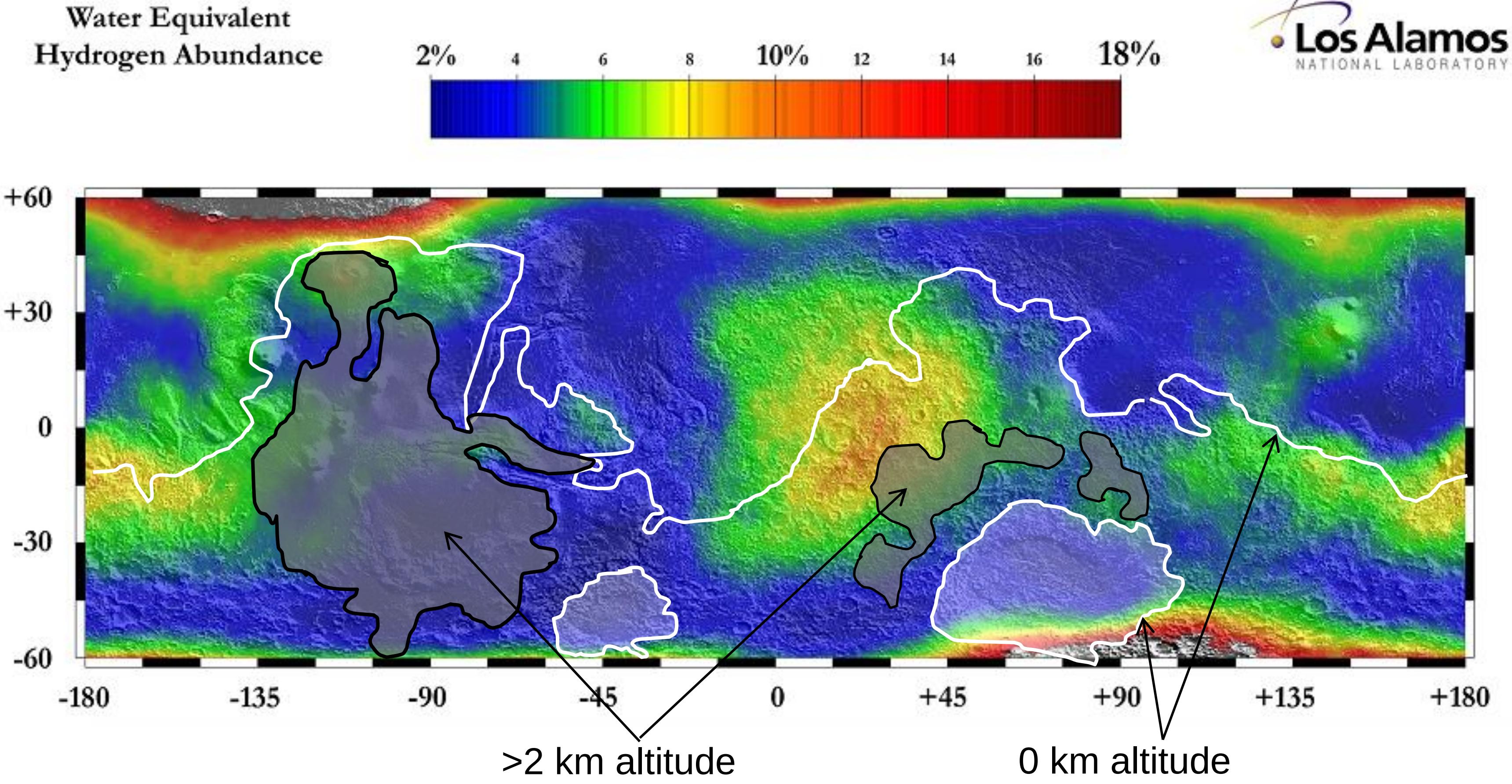




New Craters Confirm Shallow, Nearly Pure Ice

- Newly formed craters exposing water ice (red) are a subset of all new craters (yellow). Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)

Water Abundance and Mars Altitude



Water resources between 5-8% near the surface is highly possible for ISRU

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Mars Design Reference Architecture (DRA) 5.0

- **Evaluate Atmosphere Processing Only**
  - Re-evaluate past technologies and system concepts and perform internal trade to determine best approach for following three ISRU applications:
    - Propellant production only
    - EVA and Life support backup only
    - ➢ Combined propellant and EVA/life support backup
  - Evaluate H_2 delivery vs fuel delivery from Earth on Lander volume and mass. Use habitat lander as basis of 'goodness'
- **Evaluate Feasibility and Size of Mars Soil/Water Processing System**
  - Make O_2 and CH_4 with Mars water and atmospheric CO_2
  - Define Mars soil and water properties at possible exploration sites of interest
    - Coordinate with Science community
    - ISRU study assumed 3-8% global concentration and only top few centimeters was excavated/processed due to Planetary Protection concerns
- **Evaluate ISRU on Mars Architecture above simple impact on ascent vehicle and surface systems**
  - Evaluate both circular and highly elliptical orbit impact of ISRU-fuel ascent vehicle on Architecture
- **ISRU Production Requirements**

	Amount needed per 550 days - crew 6				
ISRU to Close Crew & EVA Consumables	O_2	Water	N_2/Ar	Earth H_2	Comment
- Mars Atm. Processing only	1906		133	399	- Closes water thru making water and shortfall of H_2 closure brought from Earth
- Mars Soil Processing only		2146 3586	133 133	160	- Closes water and shortfall of H_2 closure brought from Earth - Closes water and H_2 shortfall thru in-situ water only
- Mars Atm. & Soil Processing	1281	2146	133		- Closes water and covers O_2 equivalent to H_2 closure shortfall

ISRU for All Consumables	O_2	Water	N_2/Ar	Earth H_2	Earth CH_4
O_2 Only for Propulsion w/ Earth CH_4	24891		133	399	6567
O_2/CH_4 Propellant for Propulsion w/ Earth H_2O	24891		133	2069	
O_2/CH_4 Propellant for Propulsion w/ Mars H_2O	24266	16788	133		

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Soil Excavation & Processing Assumptions & Ground Rules

- **Soil**
  - Water content in Mars soil 3% by weight; 1000 kg/m^3; homogeneous distribution (no dry layer at top)
    - Also examined impact of 8% water by weight and 2000 kg/m^3
  - 6% sulfur in soil by weight

- **Soil Excavation**
  - Excavation hauler vehicles; level ground
    - 8 hr case: assume each excavator can provide the needed 4 batches; continuous operation over the 8 hrs; recharge at night
    - 24 hr case: assume each excavator can provide the needed 6 batches; operate for 12 hrs and recharge for 12 hrs each day
  - Distance traveled: 500 m from site to plant (loaded); 500 m from plant to dump site (loaded); 500 m from dump site to excavation site (unloaded)
  - Speed: 0.5 m/s during hauling
  - Depth per cut: 4 cm; Total depth: 8 cm
  - Dump time to inlet hopper = 5 min.; Time to fill dump from outlet hopper = 5 min.
  - Excavation concept assumed: Front-end loader
  - Hauler concept assumed: Dump bin

- **Soil Processing**
  - Water extraction system includes: hopper, auger, extraction reactor (fluidized bed, H_2 reduction reactor model), gas clean-up (packed bed, desulfurization model), and water condenser
  - Processing energy provided by separate electrical power system
  - Soil processing batch time: 2 hrs
  - Inlet and outlet hoper sized to hold 2 days worth of Mars soil for processing for ECLSS cases and 1 day for propellant production
  - Heat up power is estimated using basalt model for lunar ISRU
  - Processing temperature – heat from soil from input 300K (27C) to processing 600K (327C)

Mars Human Exploration DRA 5.0
ISRU vs Non-ISRU Ascent Results

- **Lowest Power/Volume**: Process atmospheric CO_2 into O_2; Bring methane (CH_4) from Earth
- **Lowest Mass**: Process atmospheric CO_2 with Soil processing for H_2O into O_2 and CH_4
- Study Results
  - Atmosphere processing into O_2 baselined: **Lowest Risk**
  - Continue evaluation of water on Mars and soil processing to reduce risk

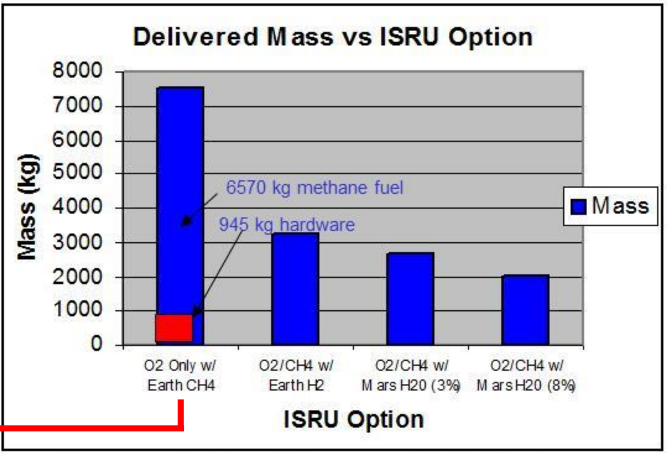
DAV Mass (no ISRU)		
Ascent Stg 2	18,540	kg
Ascent Stg 1	27,902	kg
Minimal Habitat†	5687	kg
Descent stage*	27,300	kg
Total	79,428	kg

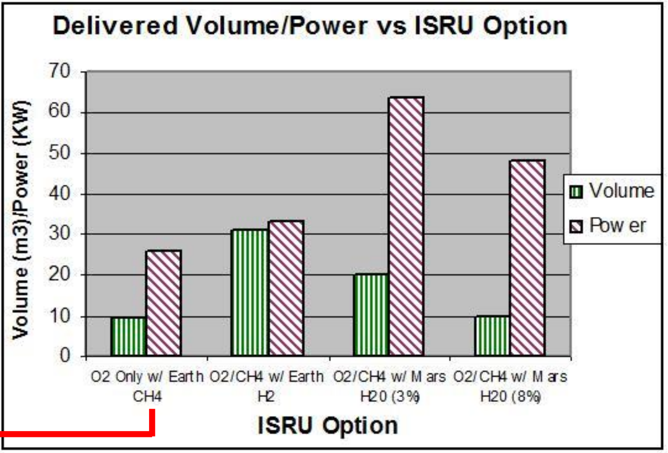
*** Wet mass; does not include EDL System**

† Packaging not currently considered

DAV Mass (w/O2 ISRU)		
Ascent Stg 2	9,330	kg (CH4)
Ascent Stg 1	12,156	kg (CH4)
ISRU and Power†	11280	kg
Descent stage*	21,297	kg
Total	54,062	kg

>25 MT savings (>30%)





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Mars Collaborative Study

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Mars Collaborative Study - 2013

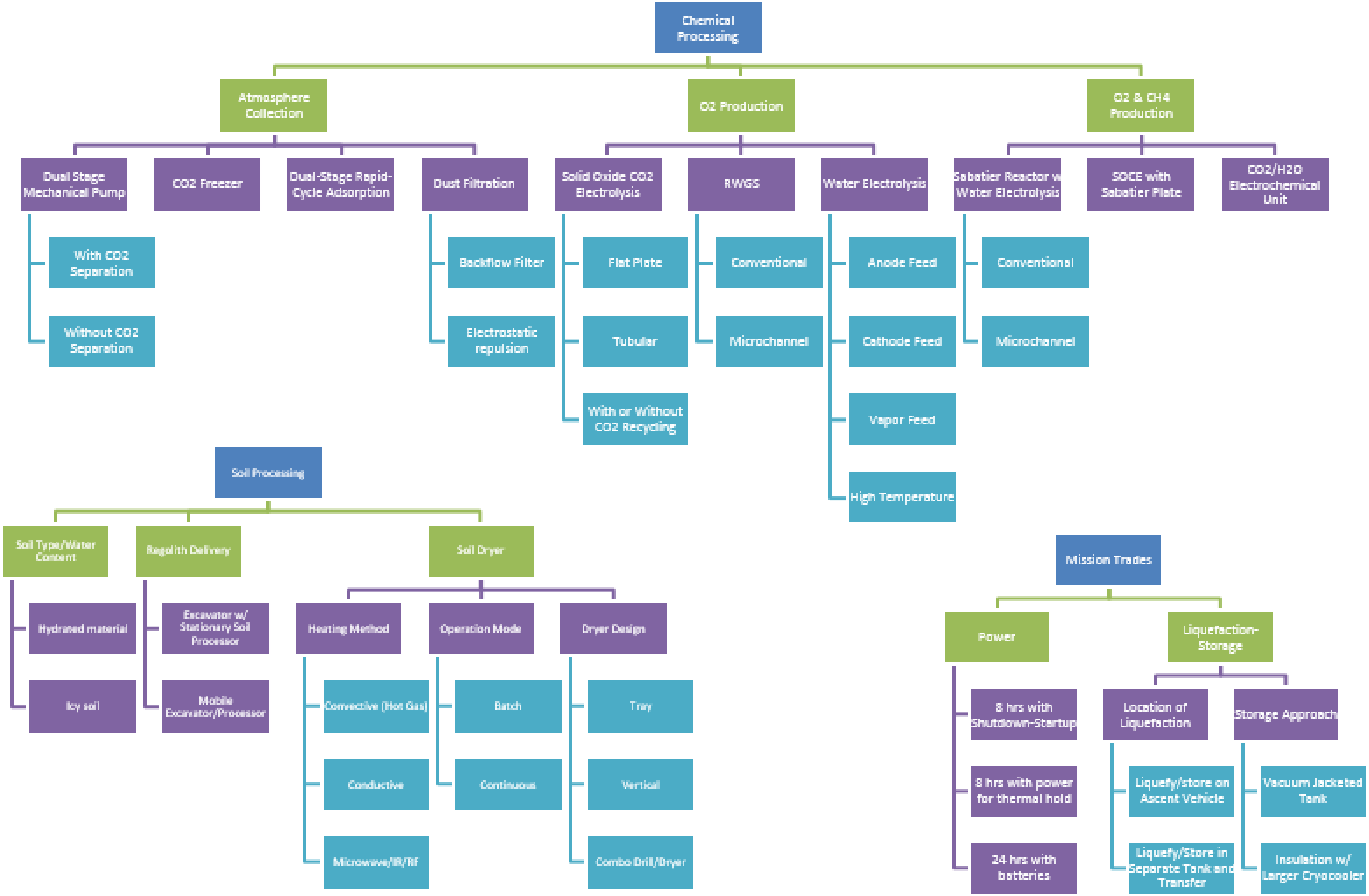
Purpose

- **Evaluate Mars ISRU technology and system options for propellant production on Mars for a sample return mission**
  - Oxygen from Mars atmosphere (carbon dioxide)
  - Oxygen and Fuel from Mars atmospheric carbon dioxide and water in soil
- **Examine impact on scale to human mission needs on technology and system selection**
  - Determine acceptable scale for risk reduction of human mission
  - Examine whether technologies can be scaled down to Mars 2020 precursor
- **Examine state-of-the-art (SOA) of Mars ISRU technologies and potential development cost/risk**
  - Look for synergism with fuel cell power, life support, and propulsion technology development and system applications
  - Look ahead to potential advancements in 5 to 10 years in SOA

Approach

- **Decouple ISRU plant trade from mission by focusing on production rates**
- **Begin evaluation at major subsystem level**
- **Start with realistic schematics with components and sensor locations identified for major subsystems**
  - Oxygen (O_2) Production from Atmosphere Resources
  - Oxygen/Methane (O_2/CH_4) Production from Atmosphere/Soil Resources
- ➢ **Subsystem down-selection decisions effected by complete system performance**
  - Need Power and Cryogenic Fluid System support to understand ‘system’ implications
  - Need to ensure decisions on interface temp/pressure is consistent at system level

Mars ISRU Trade Tree



- Chemical Processing
  - Atmosphere Collection
    - Dual Stage Mechanical Pump
      - With CO2 Separation
      - Without CO2 Separation
    - CO2 Freezer
    - Dual-Stage Rapid-Cycle Adsorption
    - Dust Filtration
      - Backflow Filter
      - Electrostatic repulsion
  - O2 Production
    - Solid Oxide CO2 Electrolysis
      - Flat Plate
      - Tubular
      - With or Without CO2 Recycling
    - RWGS
      - Conventional
      - Microchannel
    - Water Electrolysis
      - Anode Feed
      - Cathode Feed
      - Vapor Feed
      - High Temperature
  - O2 & CH4 Production
    - Sabatier Reactor w Water Electrolysis
      - Conventional
      - Microchannel
    - SOCE with Sabatier Plate
    - CO2/H2O Electrochemical Unit

- Soil Processing
  - Soil Type/Water Content
    - Hydrated material
    - Icy soil
  - Regolith Delivery
    - Excavator w/ Stationary Soil Processor
    - Mobile Excavator/Processor
  - Soil Dryer
    - Heating Method
      - Convective (Hot Gas)
      - Conductive
      - Microwave/IR/RF
    - Operation Mode
      - Batch
      - Continuous
    - Dryer Design
      - Tray
      - Vertical
      - Combo Drill/Dryer

- Mission Trades
  - Power
    - 8 hrs with Shutdown-Startup
    - 8 hrs with power for thermal hold
    - 24 hrs with batteries
  - Liquefaction-Storage
    - Location of Liquefaction
      - Liquefy/store on Ascent Vehicle
      - Liquefy/Store in Separate Tank and Transfer
    - Storage Approach
      - Vacuum Jacketed Tank
      - Insulation w/ Larger Cryocooler

2013 Studies

FY13 Mars Collaborative Study Planning

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Mars Collaborative ISRU Study Results (1)

ISRU Process	0.15 kg/hr		0.35 kg/hr		0.75 kg/hr	
	kg	W	kg	W	kg	W
Solid Oxide CO_2 Electrolysis	55	1444	126	3295	264	6976
Reverse Water Gas Shift w/Water Electrolysis	57	1328	101	3084	189	6770
Solid Oxide CO_2/H_2O Electrolysis w/Sabatier & Mars Soil	56	1631	90	3788	128	8110
Sabatier w/Water Electrolysis & Mars Soil	64	1744	95	3793	149	7775

Note:

1. Mass of rover for soil excavation is not shown since it uses the sample fetch rover once the samples have been collected
2. Liquefaction mass and power not included since they will be similar for all options with the same production rate

ISRU Subystem/System Attributes	CO_2 Freezer	Rapid Cycle Adsorption Pump	SOE	RWGS/WE	Sabatier/WE	SOE w Sabatier	Sabatier/WE; Soil Processing	SOE w Sabatier; Soil Processing
Complexity	G	M	G	P	G	G	P	P
Number of active components	6	15	8	20	11	10	21	20
Rapid Startup/Shutdown	M	G	P	G	G	P	G	P
Commonality with Life Support	M	G	P	M	G	M	G	M
Commonality with Fuel Cell Power			G	M	M			

Rankings are relative: G=Good, P = Poor, M = Medium

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Mars Collaborative ISRU Study Results (2)

- **Mars Atmosphere CO_2 Collection**
  - Microchannel Rapid-Cycle CO_2 Collection technology preferred over CO_2 Freezer
  - CO_2 Freezer more likely scalable down to Mars 2020 mission
- **O_2 Production from Mars Atmosphere**
  - Both Solid Oxide CO_2 Electrolysis (SOCE) and Microchannel Reverse Water Gas Shift with Water Electrolysis (RWGS/WE) have comparable mass and power
  - SOCE is slightly lighter and simpler but may be more risky. Less synergistic with life support but more synergistic with solid oxide fuel cell; Best packaging for Mars 2020 ISRU demonstration
  - All microchannel design (CO_2 collection, RWGS reactor, water vapor separation) may be best for packaging and scalability to human mission; Also not as effected by day/night operation cycle from solar power.
- **O_2 and CH_4 Production from Mars Atmosphere and Soil**
  - Both Solid Oxide CO_2 Electrolysis (SOCE) with Sabatier and Microchannel Sabatier with Water Electrolysis have comparable mass and power
  - Mars soil excavator or processor appears to be able to fit on sample cache rover; power system will need to be supplemented
  - Similar pros/cons for SOCE vs microchannel as O_2 Production only
  - Ionic liquid concept shows tremendous promise but is still too low in TRL to select
- **Key Findings on ISRU Concept Discriminators**
  - When considering only mass and power of the ISRU system concept, atmosphere only vs atmosphere/soil are comparable to each other
  - Advanced technologies such as microchannel reactors, heat exchangers, water/gas separators, and carbon dioxide adsorption pumps provide significant mass/volume improvement over conventional technologies as production rates increase
  - Oxygen only production from the Mars atmosphere is less synergistic with life support systems than oxygen/fuel production since these ISRU processes produce carbon monoxide

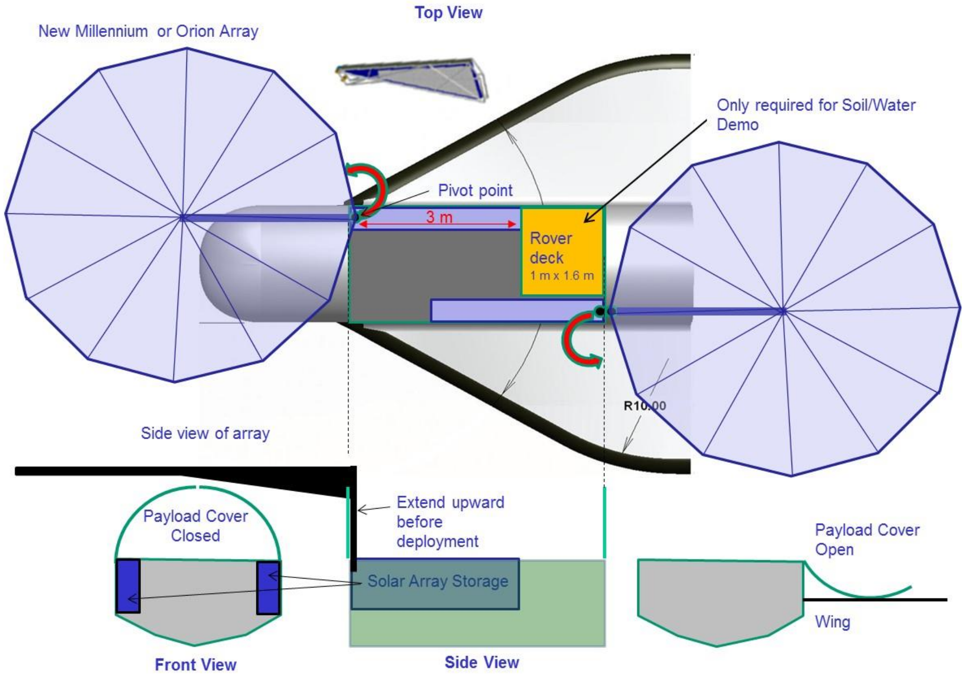
Mars ISRU Demo Payload for Supersonic Retro Propulsion (SRP) Mission

Mars ISRU Demo Payload for Supersonic Retro Propulsion (SRP) Mission

- **Assumptions for ISRU payload definition:**
  - Mass of (TBR) 2MT maximum
  - Deck height for payload ~ 1 meter height above surface; horizontal landing
  - CG roughly centered (soft requirement)
  - Cylindrical payload volume: 2 m dia. X 4 m long

- **ISRU payload study purpose:**
  a. Determine highest production rate/scale possible within payload mass/volume limits
     - Define maximum amount of power to ISRU payload – use solar arrays
     - Define/utilize remaining payload for ISRU and storage.
  b. Provide 3-D packaging concept for atmosphere processing and soil processing demonstrations
  c. Determine payload applicability to human scale mission

- **ISRU Demo Payload Options:**
  - Atmosphere processing for oxygen (O_2) production alone with O_2 storage
  - Soil processing for water (H_2O) with O_2 storage
  - Combined Atmosphere/Soil Processing for O_2 and Methane (CH_4) production and storage



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Mars ISRU SRP Payload Study Analysis Overview

- **ISRU Demo mass, power, and volume are first order estimates**
  - All items required for successful operation included in payload. No sharing of SRP subsystems/hardware
  - Technologies & processes were selected to bound the wide scope of possible process configurations.
  - No day/night operation (startup/shutdown impacts) or power impacts analyzed. Just assumed constant production rate for 8 hours per Mars day (sol).
  - Components requiring heat rejection were identified for start of thermal management/packaging
  - Packaging based on subsystem connectivity
  - **Center of Gravity (c.g) management not considered in ISRU demo packaging at this time.**

- **Notional landing location/latitude and time of year selected that was not based on an actual mission concept (not available)**
  - 15 deg. north latitude selected. Considered reasonable location for landing (low MOLA)
  - Landing at Ls 180 maximizes solar power generation capability at landing location; assume landing 50 days prior for 100 day mission

- **Power/packaging evaluation performed for notional landing location**
  - Packaging of 5.5 to 6 m diameter array possible based on notional payload bay and use of ATK UtraFlex solar array design parameters
  - Equates to rough estimate of 6.5 to 7.5 KWe power generation possible
    - Assumed 6.5 KWe for 8 hours per sol as reasonably conservative estimate

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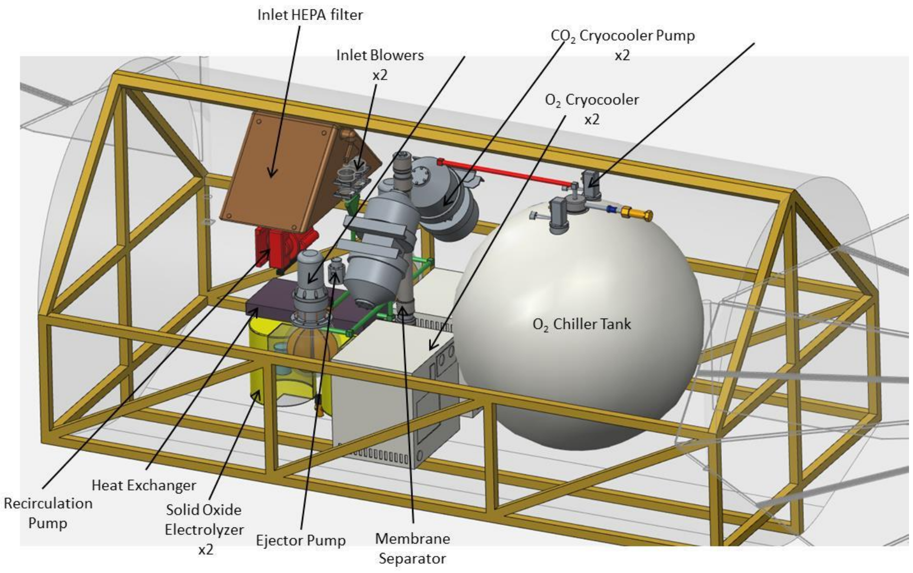
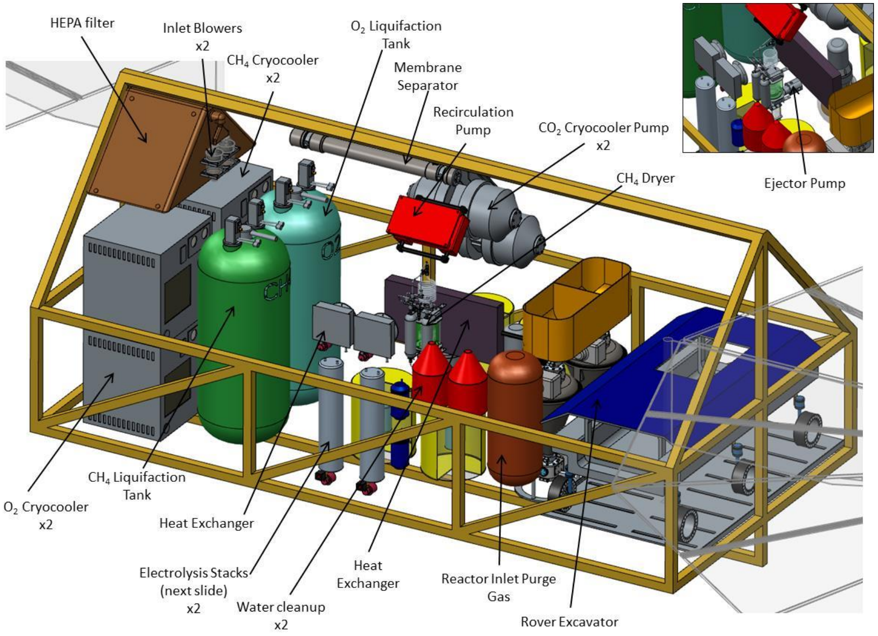
Mars ISRU Demo SRP Payload Study Options

- **Mars Atmosphere Processing (O_2 only)**
  - Electrostatic precipitator w/ regenerative HEPA filter
  - CO_2 collection (freezing)
  - CO_2 processing: Solid Oxide Electrolysis
  - CO/CO_2 separation and recycling to increase performance
  - O_2 liquefaction
  - O_2 storage (100 days)

- **Mars Atm/Soil Processing (O_2/CH_4)**
  - Electrostatic precipitator w/ regenerative. HEPA filter
  - CO_2 collection (freezing)
  - CO_2 processing: Sabatier Reactor
  - Rover/Excavation
  - Soil processing reactor (up to 450 C)
  - Water separation/cleanup module
  - Water electrolysis (Cathode Feed PEM)
  - O_2 & CH_4 product dryer
  - O_2 & CH_4 liquefaction & Storage (reduced)





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Mars ISRU Demo SRP Payload Study Results

Mars Atm ISRU Demo

O_2 Production rate: 0.45 kg/hr	Mass (kg)	Power (KW)
Filtration	1.23	0.00025
CO_2 Collection/Freezer	173	2.23
SOE Processor	5.6	3.7
SOE Recirculation system	34.6	0.187
O_2 Liquefaction and Storage	70	0.6
Secondary Structure (15%)	42.7	
Solar Arrays (2)	45	
Power conditioning/batteries*	TBD	TBD
Thermal Management/Radiators	TBD	TBD
Total	372.1	6.72

Mars Soil ISRU Demo

O_2 Production rate: 0.48 kg/hr	Mass (kg)	Power (KW)
Rover Excavator**	170	
Soil Processor & Water Cleanup	193	3.1
Water Electrolysis (2)	40	2.8
O_2 Dryer	4.1	0.064
O_2 Liquefaction and Storage	72	0.7
Secondary Structure (15%)	71.9	
Solar Arrays (2)	45	
Power conditioning/batteries*	TBD	TBD
Thermal Management/Radiators	TBD	TBD
Total	596.0	6.66

Combined Atm/Soil ISRU Demo

O_2 Production rate: 0.48 kg/hr;	Mass (kg)	Power (KW)
Filtration	1.3	0.00025
CO_2 Collection/Freezer	43	0.574
Sabatier Microchannel Reactor	1	0.082
Rover Excavator**	170	
Soil Processor & Water Separation	193	1.7
Water Capture/Temp Storage	3.7	0.5
Water Electrolysis (2)	40	2.8
O_2 and CH_4 Dryers	5	0.098
O_2 Liquefaction and Storage	72	0.7
CH_4 Liquefaction and Storage	58	0.42
Secondary Structure (15%)	88.1	
Solar Arrays (2)	45	
Power conditioning/batteries*	TBD	TBD
Thermal Management/Radiators	TBD	TBD
Total	720.1	6.9

CH_4: 0.12 kg/hr

Rover oversized for mission

ISRU Plant Only

	Atm	Soil	Combined
Mass (kg)	246.59	272.67	330.05
Power (KW)	6.12	5.96	5.75

Rover not included

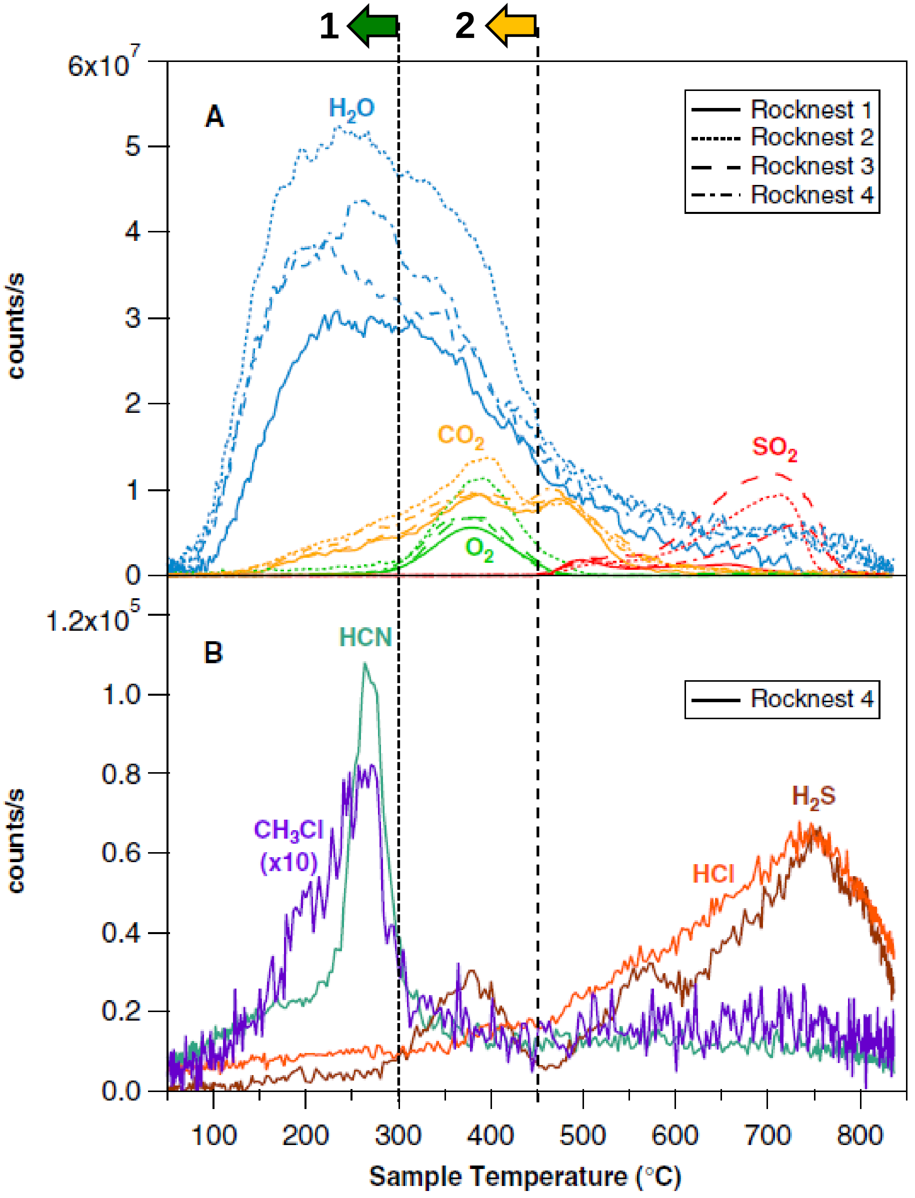
Human mission would include 3 units (each slightly scaled up)

*Mass and power available for batteries

**Rover not optimized for soil excavation or production rate

Water/Volatiles Released from Mars Soil

(SAM instrument: Rocknest sample)



Region 1: <300 C

- 40-50% of the water released
- Minimal release of HCl or H_2S

Region 2: <450 C

- >80% of the water released
- CO_2 and O_2 released from decomposition of perchlorates and oxidation of organic material
- Some release of HCl or H_2S, but before significant amounts are release at higher temperatures

Predicted Volatile Release Based on Lab Experiments

CO_2 released by

1. Absorbed atmosphere <200C
2. Oxidation of organic material >200 C
3. Thermal decomposition of carbonates >450 C

O_2 released by

1. Dehydroxylation of clays <350 C
2. Decomposition of non-metal and metal oxides >500 C

CH_3Cl and CH_2Cl_2 released by

1. Decomposition of $Mg(ClO_4)_2$ perchlorate >200C

Mars ISRU State of the Art

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Mars ISRU Propellant Production

Large Gap between Needs and Demonstrated

Needs

- **Propellant production for human mission ascent (Mars DRA 5.0)**
  - For O_2 only: 2.2 to 3.5 kg/hr O_2; 480 days or 300 days
  - For O_2/CH_4:
    - 0.55 to 0.88 kg/hr CH_4
    - 1.2 to 2.0 kg/hr H_2O; (41 to 66 kg/hr soil @ 3% H2O by mass)

- **Propellant production for Mars Sample Return**
  - 0.35 to 0.5 kg/hr O_2; 420 to 500 days (multiple studies)
  - 0.75 to 1.5 kg/hr O_2; 35 or 137 days (Mars Collaborative Study 4-2012)

- **Propellant production for Mars ISRU Demo**
  - 0.02 kg/hr O_2; 50 operations (Mars 2020 AO requirement)
  - 0.00004 kg/hr O_2; 10 operations (MIP demo on Mars 2001 Surveyor)

Demonstrated

- **Mars ISRU Testbeds (late '90s early '00s):**
  - LMA/JSC Sabatier/Water Electrolysis: 0.02 kg/hr O_2; 0.01 kg/hr CH_4
  - KSC RWGS/Water Electrolysis 0.087 kg/hr O_2
  - Pioneer Astronautics (SWE & RWGS): 0.02 kg/hr O_2; 0.01 kg/hr CH_4
    (IMISPPS): 0.031 kg/hr O_2, 0.0088 kg/hr CH_4

- **Atmosphere Processing: MARCO POLO** (Individual subsystems)
  - CO_2 Collection: 0.088 kg/hr CO_2
  - CO_2 Processing: 0.066 kg/hr of O_2; 0.033 kg/hr of CH_4; 0.071 kg/hr of H_2O
  - Water Processing: 0.52 kg/hr H_2O; 0.46 kg/hr O_2

- **Soil Processing:**
  - Lunar H_2 Reduction - ROxygen Reactor: 5 to 10 kg/hr soil:
  - Lunar H_2 Reduction - PILOT Reactor: 4.5 to 6 kg/hr soil:
  - Mars Soil Auger - MISME: 0.18 to 0.2 kg/hr soil
  - Mars Soil Reactor-Pioneer Ast. Hot CO_2 4 kg/hr soil per batch

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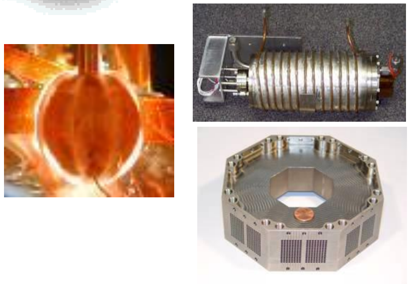
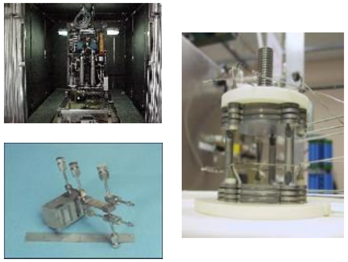
Past/Recent Mars ISRU Technology Development



CO_2 Collection & Separation

- Mars atmosphere adsorption pump (JPL, ARC, LMA, JSC)
- Microchannel adsorption pump (PNNL, SBIR)
- Mars atmosphere solidification pump (LMA, SBIR, NASA)

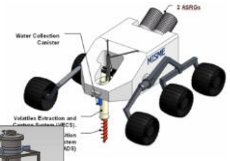


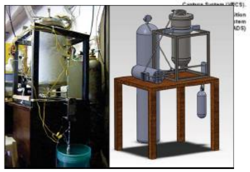
CO_2 Processing

- CO_2 electrolysis & low pressure dissociation (NASA, Univ. of Arizona, Old Dominion, Industry, SBIRs)
- Reverse Water Gas Shift (KSC, PNNL, SBIRs)
- Sabatier reactors (NASA, Industry, SBIRs)
- Methane reformer (JPL, SBIRs)
- Hydrocarbon fuel reactors - methanol, toluene, ethylene, etc. (SBIRs)
- Microchannel reactors/heat exchangers (PNNL, SBIRs)

Water Processing

- Water electrolysis/decomposition (NASA, Industry, SBIRs)
- Water cleanup for lunar soil processing (KSC, SBIRs)
- Water vapor/gas cleanup for lunar soil processing (NASA, SBIRs)





Soil Processing

- H_2 Reduction of regolith reactors (NASA, LMA)
- Lunar volatile extraction (NASA, Industry)
- Mars soil processing (JSC, SBIRs)

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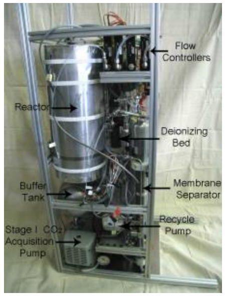
Past/Recent Mars ISRU System Development

Mars Atmosphere Processing

- 1st Gen Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing (NASA, Lockheed Martin)
- 1st Generation Reverse Water Gas Shift with and w/o Fuel production (NASA, Pioneer Astronautics)
- 2nd Gen MARCO POLO atmosphere processing (JSC, KSC)

Sabatier/Water Electrolysis w/ CO_2 Absorption (LMA & JSC) *[Tested under simulate Mars surface conditions]*

Combined Sabatier/ RWGS/Water Electrolysis (Pioneer Ast.)

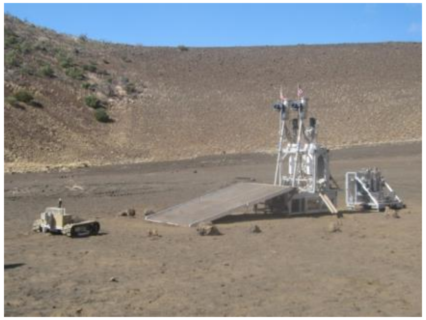


CO_2 Electrolysis (GRC) *[Tested under conference conditions]*

Reverse Water Gas Shift/ Water Electrolysis (KSC & Pioneer Astrobotics)

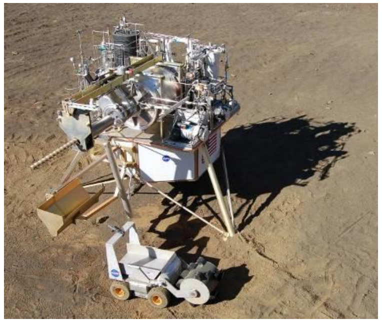
Lunar/Mars Soil Processing

- 1st Gen H_2 Reduction from Regolith Systems (NASA, LMA)
- 2nd Gen MARCO POLO soil processing system (JSC, KSC) – *design only*



ROxygen H_2 Reduction
Water Electrolysis
Cratos Excavator

PILOT H_2 Reduction
Water Electrolysis
Bucketdrum Excavator



MARCO POLO
- Soil dryer with regolith delivery and avionics
- Water cleanup and storage

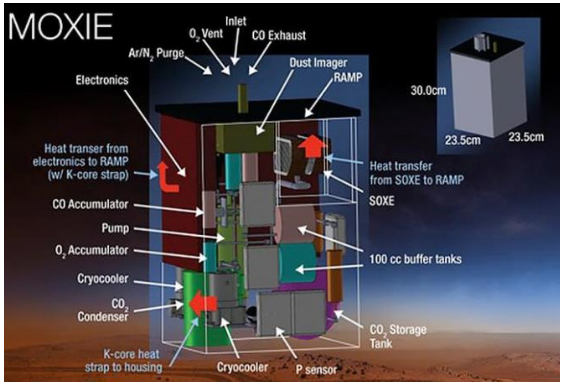
Current ISRU Activities

SBIR Technologies

- Mars dust filtration
- CO_2 collection and pressurization
- CO_2 electrolysis
- Microchannel Sabatier reactors

Mars 2020 ISRU Demo

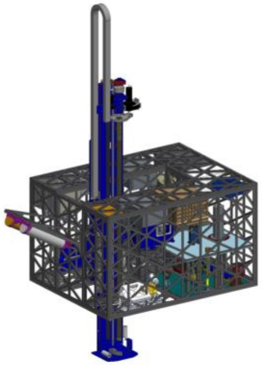
- Make 0.02 kg/hr O_2; <600 W-hrs; 50 sols of operation



Water/Volatile Characterization/Prospecting

- Resource Prospector Mission – RESOLVE payload

RESOLVE
- Measure H_2O . 0.5% wt. down to 1 m
- Measure: H_2, CO, NH_3, CH_4, H_2S
- Nom. Mission Life = 10+ Cores
- Mass = 100 kg
- Dimensions : 68.5 x 112 x 1200 cm
- Ave. Power; 200 W



Advanced Exploration Systems (AES)

- Trash to Supply Gas; Steam Reforming/O_2 Combustion
- Mars Architecture, Systems, & Technologies for Exploration & Resources (MASTER)
  - Demonstrate integration and operation of ISRU, Power, and Life Support systems around liquid oxygen and methane under different mission architectures
  - Proposed AES new start in FY15

Results/Conclusions

- **Using Mars atmosphere carbon dioxide (CO_2) alone is the lowest risk**
  - CO_2 is available everywhere on Mars and no ISRU hardware needs to be deployed
  - Multiple options exist to extract oxygen (O_2) from CO_2
  - Least amount of hardware and volume of all ISRU options
- **While lower in mass, carrying hydrogen (H_2) from Earth to make O_2/methane (CH_4) is volumetrically and technically difficult**
  - H_2 is <1/3 the mass but 3 times the volume compared to CH_4 brought from Earth
- **Using both Mars atm. CO_2 and water (H_2O) from the Mars soil is the lowest mass.**
  - Extra hardware for soil excavation and processing significantly less than mass of ascent fuel brought from Earth
  - Power needed for either approach is similar enough not to impact power system greatly
  - Mass benefit increases and power difference decreases with increase in water content in soil above 3% by mass.
- **Using both Mars atmosphere CO_2 and H_2O from the Mars soil provides the greatest architecture/mission benefits.**
  - 100% of O_2/fuel produced on Mars
    - Allows for Mars ascent, surface hoppers, and production of fuel cell reactants for surface mobility
  - Water can be used for life support, plant growth, and radiation shielding
  - Processes and technologies are similar to lunar water/O_2 extraction from regolith and NEA mining.
    - Proving Ground activities on lunar surface, NEAs, and Phobos will reduce risk

Backup

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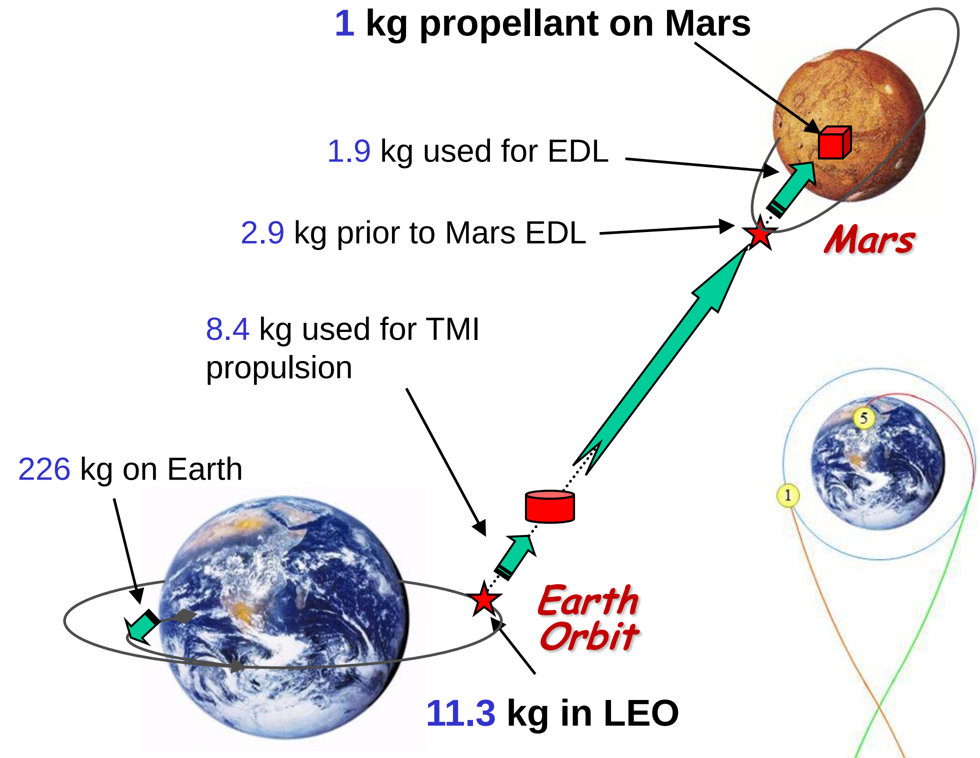
How Propellant Production Enables Future Moon & Mars Missions

Every 1 kg of propellant made on Mars saves 7.5 to 11.3 kg in LEO

- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO



1 kg propellant on Mars

1.9 kg used for EDL

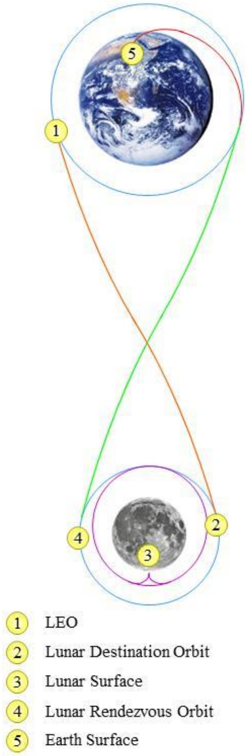
2.9 kg prior to Mars EDL

8.4 kg used for TMI propulsion

226 kg on Earth

11.3 kg in LEO

Estimates based on Aerocapture at Mars



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

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Why Methane Fuel?

- **Simplicity of ISRU Processing**
  - Single step process for methane.
    - Two or more steps for most other hydrocarbon fuels
  - High processes conversion:
    - >99% methane product from CO_2 in single pass (recycle H_2)
    - Other fuels (such as Fischer Tropsch) have wide band of hydrocarbons produced; must separate and recycle (increase complexity), or accept (decrease in engine performance)

- **Higher propulsion efficiency**
  - Pros: Higher Isp than most other hydrocarbons
    High ox/fuel (O/F) mixture ratio. (Max. benefit for O_2 only ISRU)
    Clean burning; no coking
  - Cons: Methane is lower density than other hydrocarbons
    High H-to-C ratio (Min. benefit for Earth provided H_2 ISRU options)

	NTO/MMH Press-fed	LO_2/Hydrazine Press-fed	LO_2/Methane Press-fed	LO_2/Propane Press-fed	LO_2/Methanol Press-fed	LO_2/Ethanol Press-fed	LO_2/Ethylene Press-fed	LO_2/Kerosine Press-fed	LO_2/LH_2 Press-fed	LO_2/LH_2 Pump-fed
Isp	328	365	362	357	335	340	364	352	441	454
MR	1.9	1.0	3.5	3.25	1.5	2	2.75	3.0	5.25	6.0
Fuel Density (kg/m^3)	880	1020	422	500-580	792	789	568	810	71	71
Fuel B.P (K)	360	387	111.7	230.9	337.8	351.5	169.5		20.3	20.3

Based on Chamber Pressure (Pc) = 500 psi; Area Ratio (AR)=150:1; Efficiency = 93%

- **Higher compatibility with liquid oxygen**
  - Same technology, insulation, cryocoolers, and tanks used for CH_4 as with LO_2
  - Thermal compatibility of lines and engine/thruster thermal management

Overall, choice of methane fuel is an overall balance of performance, storage, compatibility, and production

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