Mars Water Mining for Future Human Exploration

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Water on Mars
(Simplified)

### Atmosphere
- ppb levels

### Hydrated Soil
- Water of hydration in minerals
- <2 to ~13% by mass
- Primary at equator and lower latitudes
- At/near surface

### Permafrost
- Subsurface ice/permafrost within the top 5 meters in the mid latitudes
- Deeper ice/permafrost may exist at lower latitudes
- Concentration %?

### Icy Soils
- Shallow, nearly pure ice in newly formed craters in mid-upper latitudes. Fresh impacts expose ice excavated from 0.3-2.0 meters depth
- Dirty ice at polar locations: Estimated to be 90-100 wt% H_2O, mixed with dust from global dust storms

### Recurring Slope Lineae (RSL)
- Briny water has been theorized as cause of RSLs.
- Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range
- RSL sites and possibly the active gullies are Special Regions.

### Aquifers
- Suspected to be >1 km below surface
- Possible Special Region

- Not considered to be Special Regions
In Situ Water Extraction from Mars Soils

- Energy heats soil so that water converts to vapor (may transition thru liquid phase)
- Release of water helps further heat conduction into soil
- Water vapor follows ‘path of least resistance’ to bore hole
  - Vapor may also re-condense away from heat in colder soil
- Water vapor collected in cold trap in liquid/solid form
- Process may take hours

Figure 1. Phase diagram of water near the triple point.
Water Extraction via Excavation & Processing Reactor

- Soil is removed from subsurface
- Soil is heated via thermal to remove water vapor; can be higher temperature than \textit{in situ} heating

- Soil is removed from surface/subsurface and transferred to soil reactor
- Soil is heated via thermal, microwave, and/or gas convection to remove water vapor at higher temperatures and pressures than for \textit{in situ} heating

- Water vapor is condensed and stored
- Soil is dumped back onto surface after processing
Water Extraction from Soil Architectures

Centralized ISRU Processing

Deliver soil (X m)

Deliver dirty water (X m)

On-Rover Soil Processing

Deployed Soil Processing

Deliver dirty water (X m)

Deliver soil (X m)
Mars Surface Infrastructure and ISRU

**Emplacement Phase**

- Habitat
- Nuclear Reactor
- Resource - Water
- Mars Ascent Vehicle (MAV)
- ISRU Plant

**Consolidation or Utilization Phase**

- Habitat
- Depot (\(O_2\), \(CH_4\), \(H_2O\))
- Resources
- Remote ISRU Plant for \(H_2O\), Metals, etc.
- Mars Ascent Vehicle (MAV)

Distance Formulas:

- \(X_{H-I}\) = distance between Habitat and ISRU Plant
- \(X_{P-I}\) = distance between Power and ISRU Plant
- \(X_{P-H}\) = distance between Power and Habitat
- \(X_{I-R}\) = distance between ISRU Plant and Resource
- \(X_{I-M}\) = distance between ISRU Plant and MAV
- \(X_{I-I}\) = distance between ISRU Plants
- \(A_{CE}\) = Area of Civil Engineering
- \(A_R\) = Area of Resource
Water ISRU Planning (M-WIP), April 2016

End-to-End Soil Processing

**Case D1:**
Typical Martian Regolith (2,000 mt)
~4150 kg/sol

**Case D2:**
Typical Martian Regolith (1,250 mt)
~2600 kg/sol

**Case C:**
Smectite Clay-enriched Regolith (583 mt)
~1200 kg/sol

**Case B:**
Gypsum-enriched Regolith (186 mt)
~390 kg/sol

Ore Processing

Ore->Water (@425 K)

Ore->Water (@575 K)

Propellant Processing

Water 16 mt

Methane 7 mt

LOX 28 mt

Local Power Source (e.g. Fission Reactor)

~25 kW

~8 kW

~5 kW

~3 kW

~1 kW
Human Mission Mars Soil Excavation for Water

3 wt% water; 9.6 cm (3.8 in) deep

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<th>Water wt%</th>
<th>Soil wt%</th>
<th>Water kg</th>
<th>Soil kg</th>
<th>Total kg</th>
<th>Extraction 80%</th>
<th>Ave Density kg/m³</th>
<th>Tot Vol m³</th>
<th>FB Depth cm</th>
<th>FB Field yds</th>
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ISRU Examples and Analogies

- Excavation rates required for lunar 10 MT O₂/yr production range based on extraction efficiency of process selected and location
  - H₂ reduction at poles (~1% efficiency): 150 kg/hr
  - CH₄ reduction (~14% efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr

- Excavation rates required for 14.2 MT H₂O/mission production range based on water content
  - Hydrated soil (3%): 41 kg/hr
  - Icy soil (30%): 4 kg/hr

- Cratos & LMA rovers: 10 to 20 kg/bucket at field test in Hawaii

- Robotic excavation competitions:
  - 2009: 437 kg in 30 min.; remote operation
  - 2015: 118 kg in 20 min; autonomous operation

- Soil Processing
  - ROxygen: 5-10 kg/hr
  - PILOT: 4.5-6 kg/hr
  - Pioneer SBIR: 4 kg/hr
  - MISME: 0.2 kg/hr

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14.2 MT of Mars water per mission requires excavation of a Football field to a depth of 1.1 to 9.6 cm! (30% to 3% water by mass)

10 MT of lunar oxygen per year requires excavation of a Soccer field to a depth of 0.6 to 8 cm! (14% to 1% efficiencies)
Past/Recent Mars ISRU Technology Development

- Sample drills and augers (JPL, ARC, SBIRs)
- Scoops and buckets (GRC, KSC, JPL, Univ., SBIRs)
- Auger and pneumatic transfer (KSC, GRC, SBIRs)
- H₂ Reduction of regolith reactors (NASA, LMA)
- Microwave soil processing (MSFC, JPL, SBIR)
- Open and closed Mars soil processing reactors (JSC, GRC, SBIRs)
- Downhole soil processing (MSFC, SBIRs)
- Capture for lunar/Mars soil processing (NASA, SBIRs)
- Water cleanup for lunar/Mars soil processing (KSC, JSC, SBIRs)
- Combustion, Pyrolysis, Oxidation/Steam Reforming (GRC, KSC, SBIRs)
Past/Recent Mars ISRU System Development

**Lunar/Mars Soil Processing**

- **1st Gen H₂ Reduction from Regolith Systems (NASA, LMA)**
  - ROxygen H₂ Reduction
  - Water Electrolysis
  - Cratos Excavator

- **2nd Gen MARCO POLO soil processing system (JSC, KSC)**
  - PILOT H₂ Reduction
  - Water Electrolysis
  - Bucketdrum Excavator
  - Soil Processing Module
    - 10kg per batch; 5 kg/hr
    - 0.15 kg/hr H₂O
    - (3% water by mass)
Total ISRU system (3 modules)

- Assumptions: 3 independent ISRU systems each producing 40% of the needed products, 15% mass added for structure, 20% margin added to power and mass.
- O₂-only system assumes a cryofreezer for CO₂ extraction and Solid Oxide Electrolysis for conversion.

66% higher mass  
42% higher power  
17% more waste heat
The real benefit of targeting higher yield regolith is the power saving:
- Less regolith to heat
- Heating at a lower temperature
The MWIP team has identified Reference cases for soil-water resources. The best case is that of a Gypsum deposit which has 8 wt% water releasing at 150°C.

- The percentages on the graphs show the increase over the LOX-only case.
- Targeting water-Rich deposits offers marginal mass improvement, but significant power reduction.