National Aeronautics and Space Administration

Mars Water Mining for Future Human Exploration

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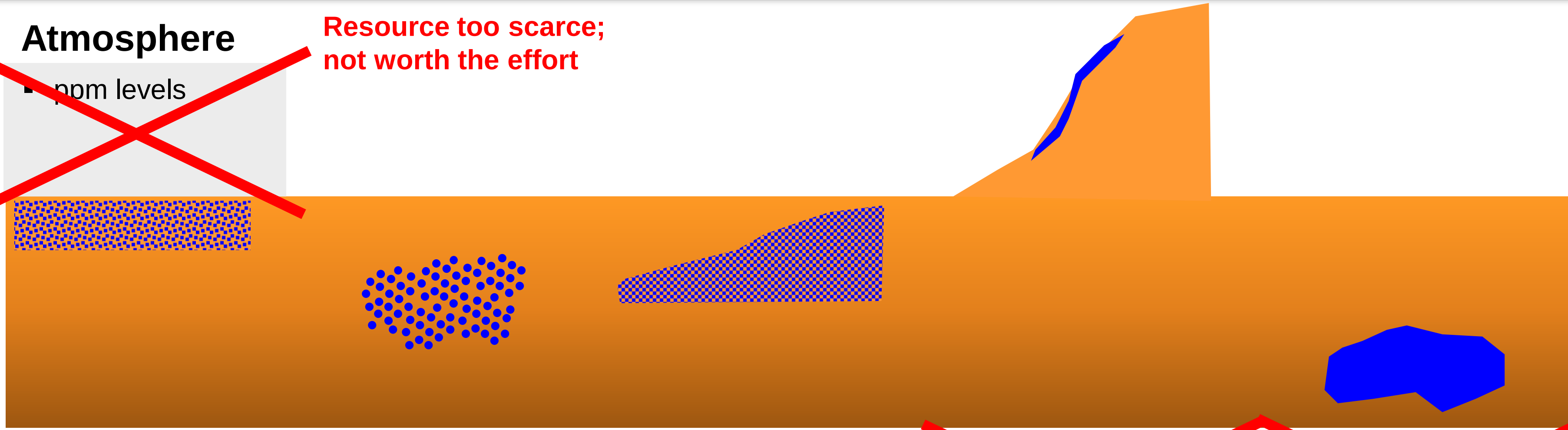
Water on Mars
(Simplified)

Atmosphere

- ppm levels

Resource too scarce; not worth the effort



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)

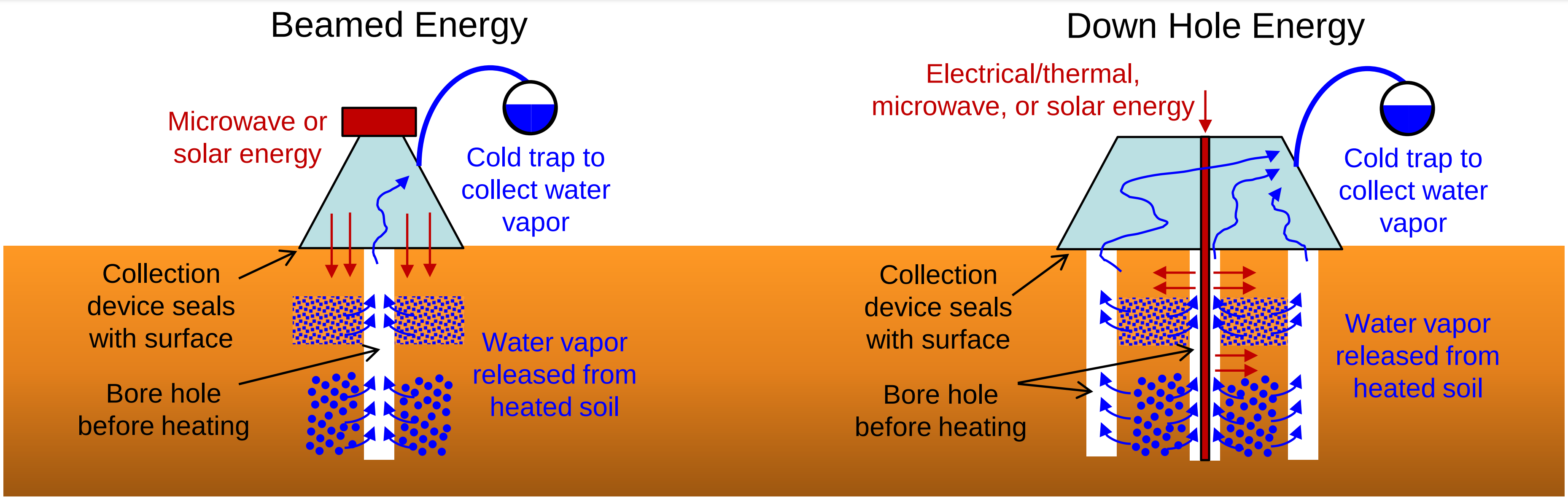
- Briny water has been theorized as cause of RSLs.
- Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range
- **RSL sites and possibly the active gullies are Special Regions.**

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

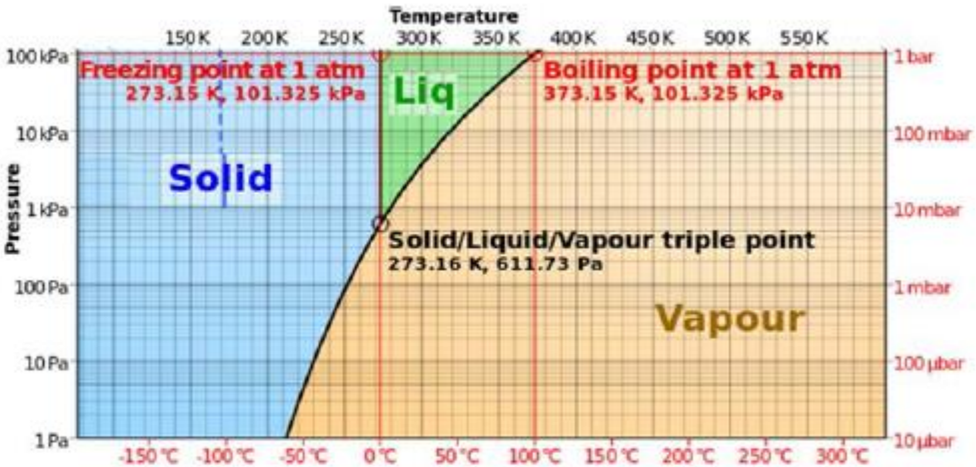
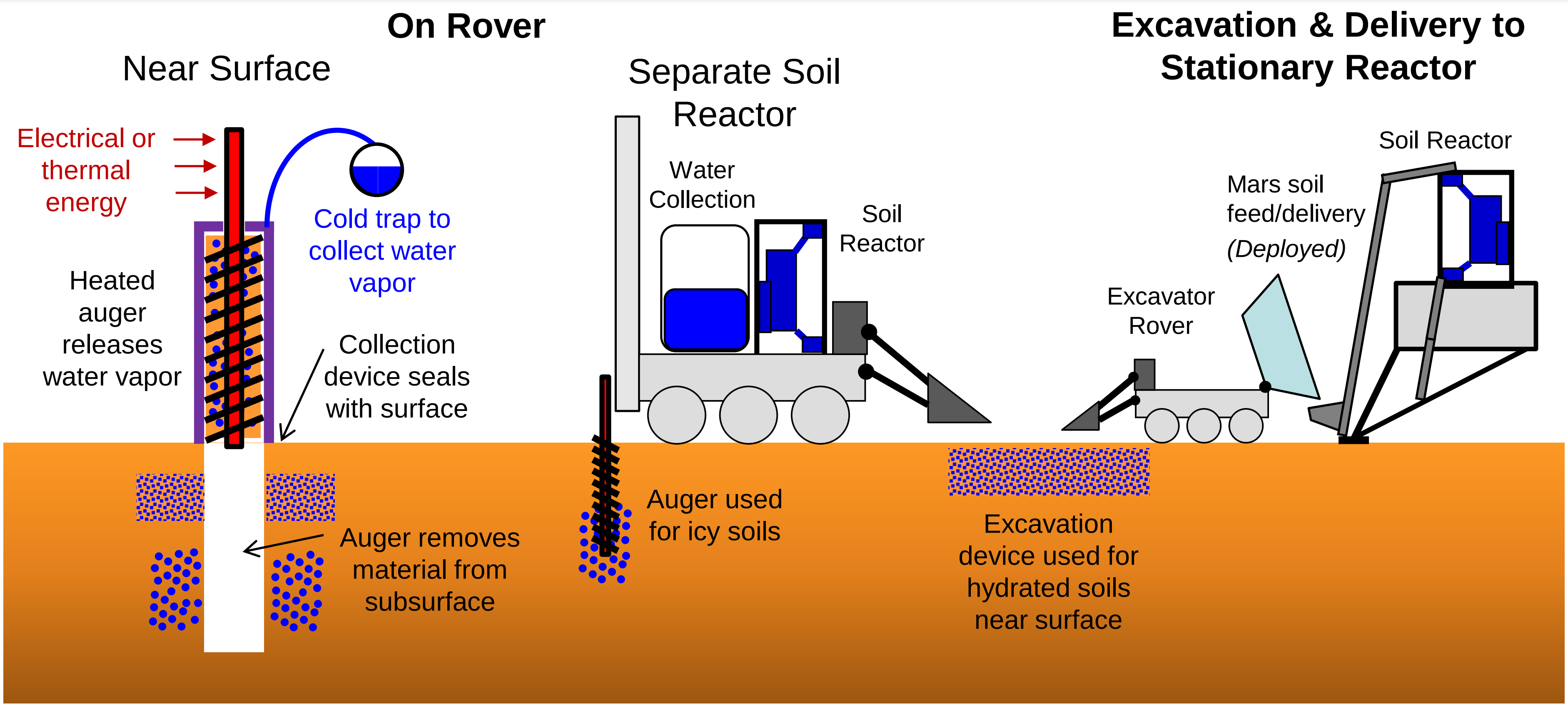


Figure 1. Phase diagram of water near the triple point.

Water Extraction via Excavation & Processing Reactor

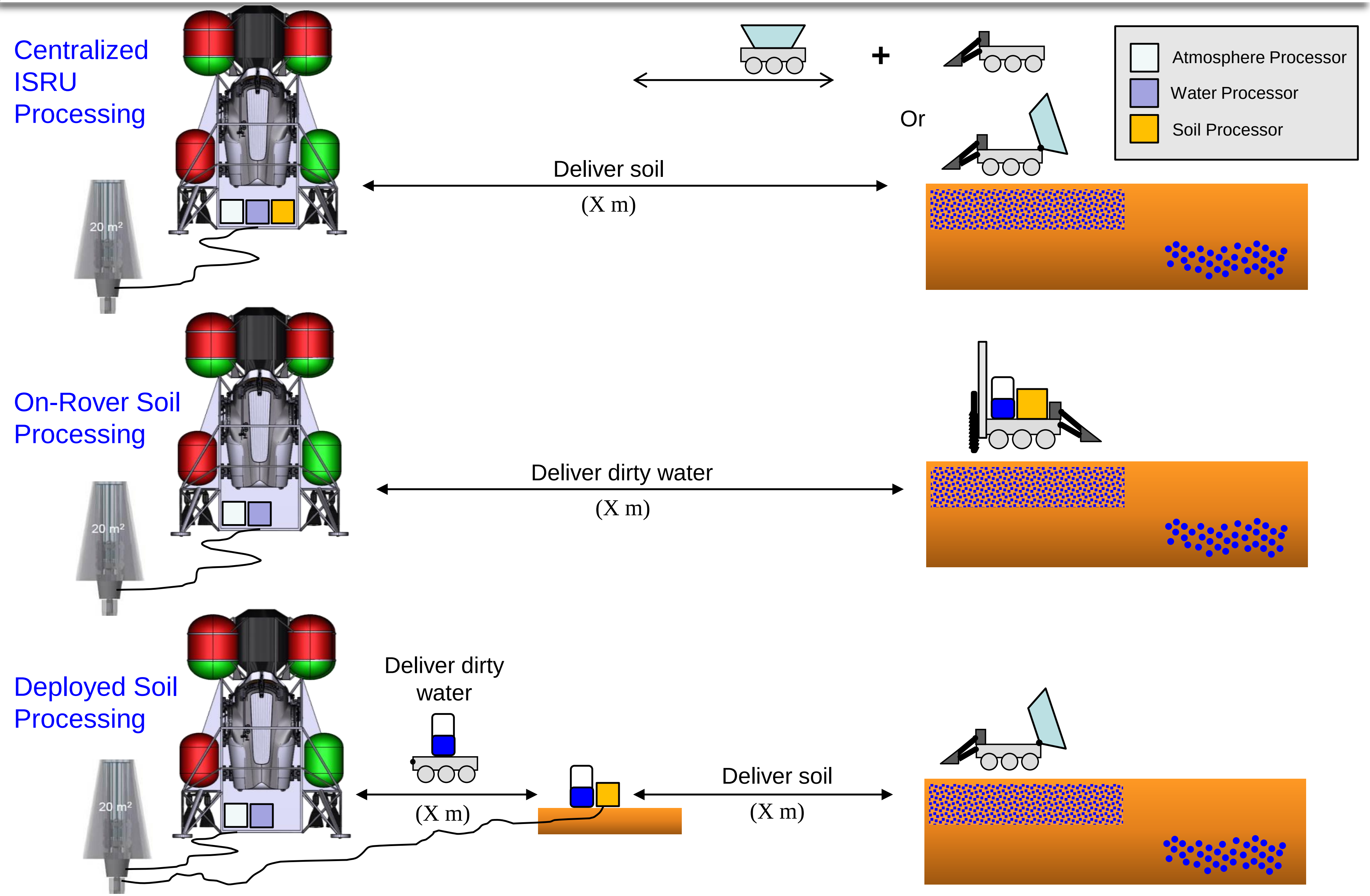


- Soil is removed from subsurface
- Soil is heated via thermal to remove water vapor; can be higher temperature than *in situ* heating

- 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 *in situ* heating

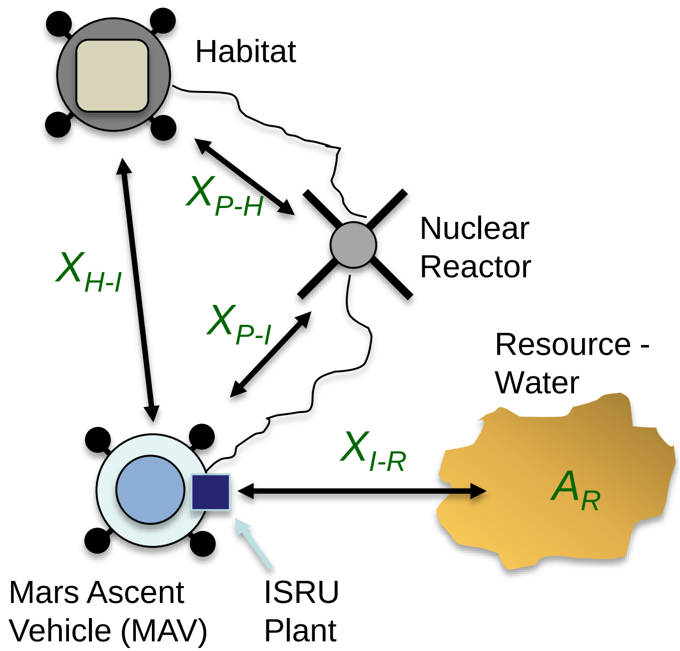
- Water vapor is condensed and stored
- Soil is dumped back onto surface after processing

Water Extraction from Soil Architectures

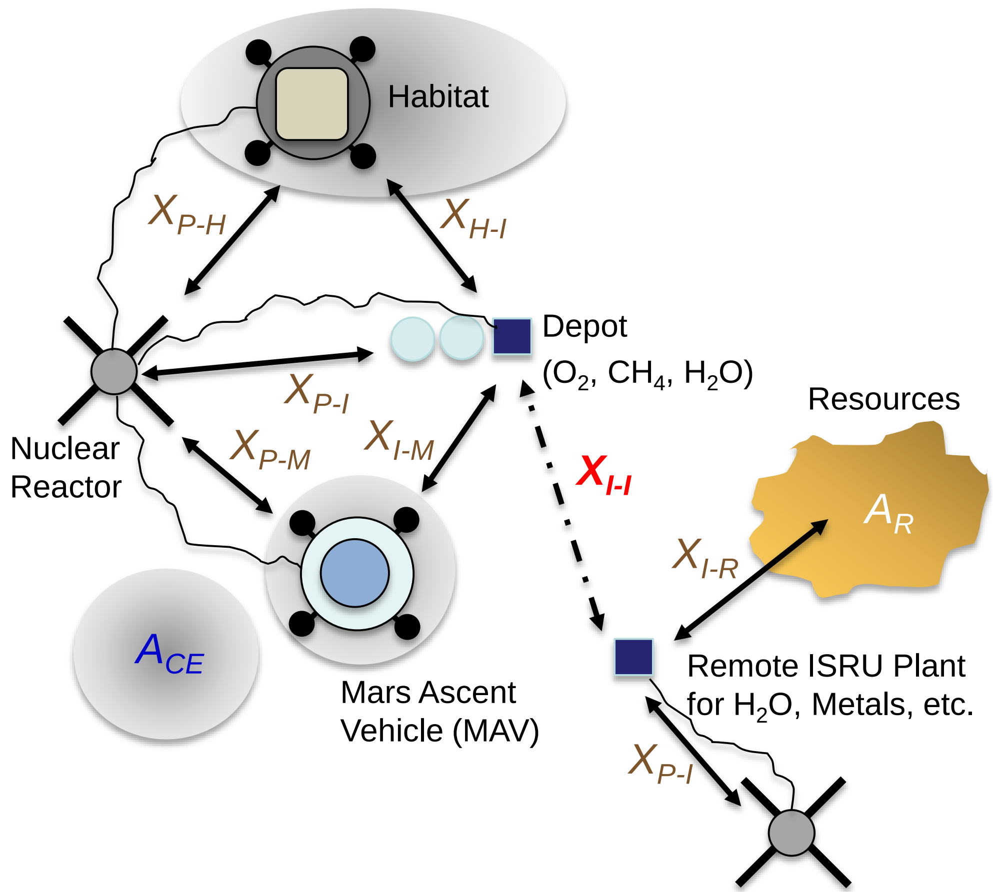


Mars Surface Infrastructure and ISRU

Emplacement Phase



Consolidation or Utilization Phase



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*

A_R = *Area of Resource*

X_{I-M} = *distance between ISRU Plant and MAV*

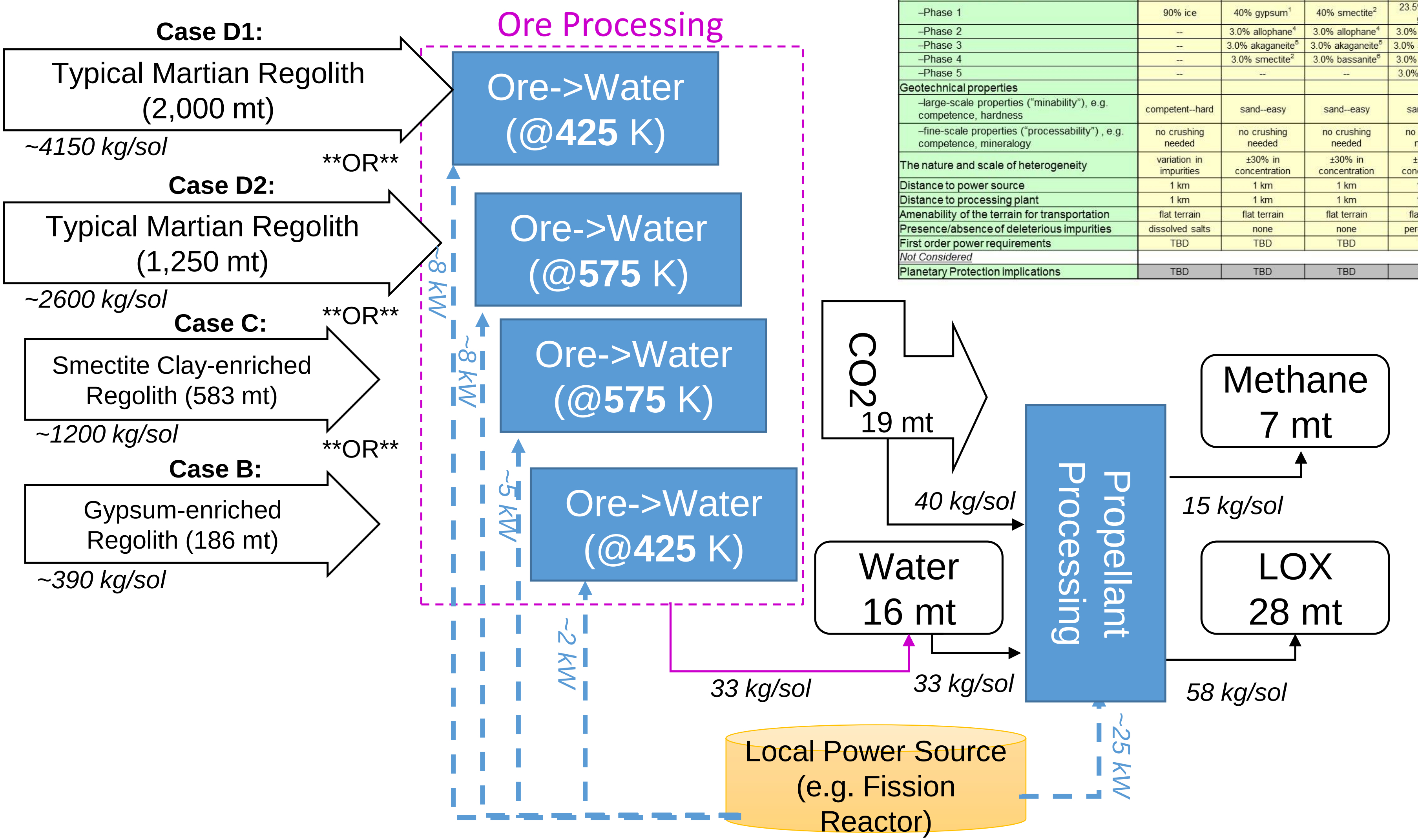
X_{I-I} = *distance between ISRU Plants*

A_{CE} = *Area of Civil Engineering*

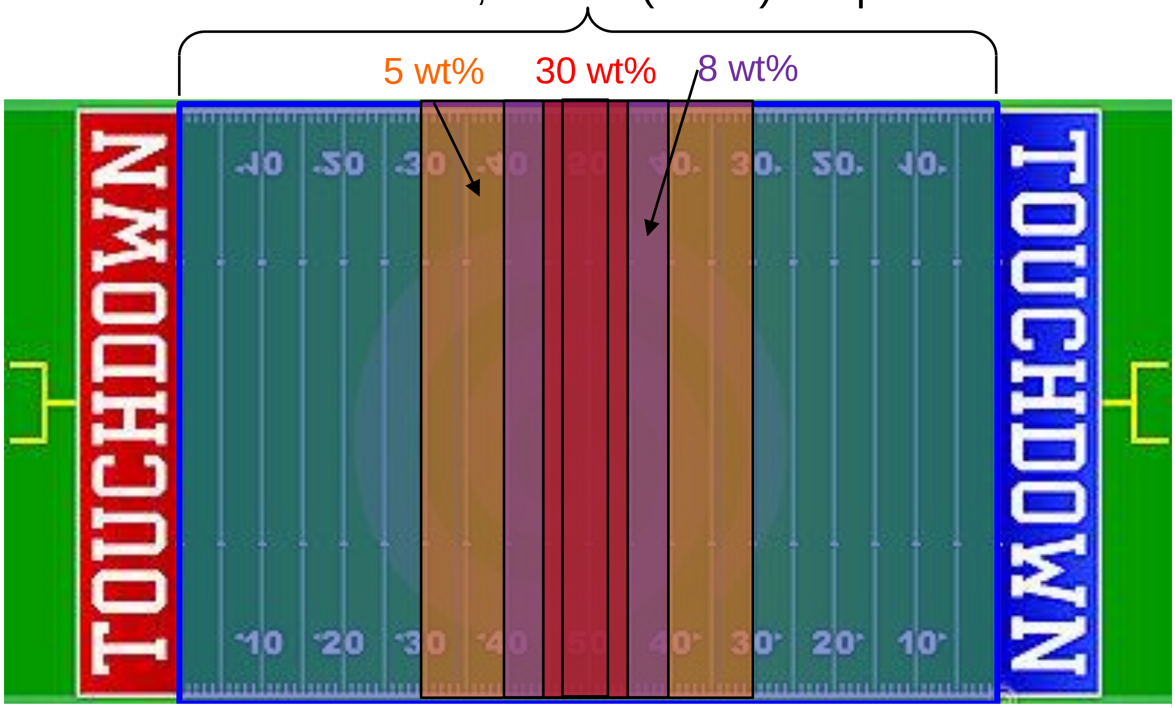
End-to-End Soil Processing

Water ISRU Planning (M-WIP), April 2016

Essential Attribute	Deposit Type: A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	variable (1-10m)	0 m	0 m	0 m
Deposit geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburden	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum[1]	40% smectite[2]	23.5% basaltic glass[3]
–Phase 2	--	3.0% allophane[4]	3.0% allophane[4]	3.0% allophane[4]
–Phase 3	--	3.0% akaganeite[5]	3.0% akaganeite[5]	3.0% akaganeite[5]
–Phase 4	--	3.0% smectite[2]	3.0% bassanite[6]	3.0% bassanite[6]
–Phase 5	--	--	--	3.0% smectite[2]
Geotechnical properties				
–large-scale properties ("minability"), e.g. competence, hardness	competent--hard	sand--easy	sand--easy	sand--easy
–fine-scale properties ("processability") , e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration
Distance to power source	1 km	1 km	1 km	100 m
Distance to processing plant	1 km	1 km	1 km	100 m
Amenability of the terrain for transportation	flat terrain	flat terrain	flat terrain	flat terrain
Presence/absence of deleterious impurities	dissolved salts	none	none	perchlorate?
First order power requirements	TBD	TBD	TBD	TBD
Not Considered				
Planetary Protection implications	TBD	TBD	TBD	TBD



Human Mission Mars Soil Excavation for Water



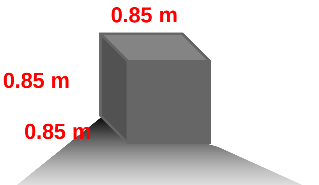
H_2O	1.238 kg/hr	Soil	1500 kg/m3
	480 days	Ice	940 kg/m3

Water wt%	Soil wt%	Water kg	Soil kg	Total kg	Extraction 80%	Ave Density kg/m3	Tot Vol m3	FB Depth cm	FB Field yds
3	97	14261.76	461130.2	475392.0	594240.0	1483.20	400.65	9.58	100.00
5	95	14261.76	270973.4	285235.2	356544.0	1472.00	242.22	5.79	60.46
8	92	14261.76	164010.2	178272.0	222840.0	1455.20	153.13	3.66	38.22
30	70	14261.76	33277.4	47539.2	59424.0	1332.00	44.61	1.07	11.14
70	30	14261.76	6112.2	20373.9	25467.4	1108.00	22.99	0.55	5.74

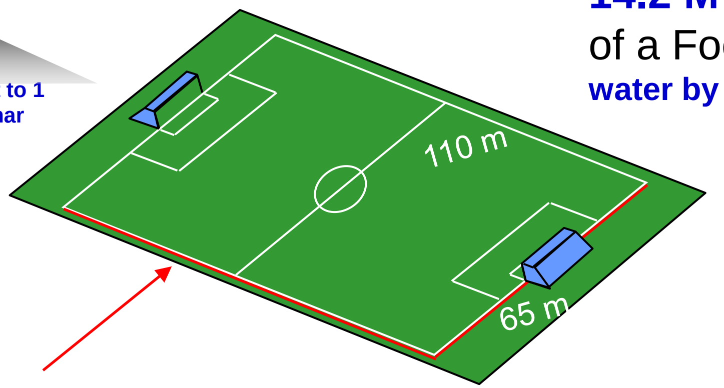
ISRU Examples and Analogies

- Excavation rates required for lunar 10 MT O_2/yr production range based on extraction efficiency of process selected and location
  - H_2 reduction at poles (~1% efficiency): 150 kg/hr
  - CH_4 reduction (~14% efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr
- Excavation rates required for 14.2 MT H_2O/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

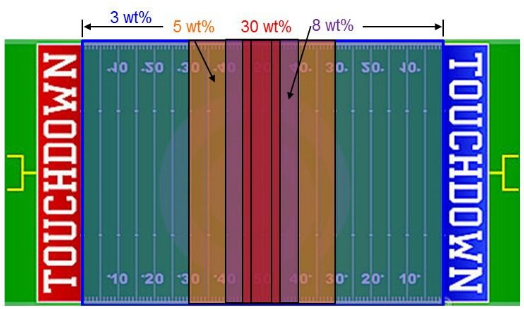


Volume equivalent to 1 Metric Ton of lunar regolith



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)**

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)**



H_2O 1.238 kg/hr, 480 days; Soil 1500 kg/m3; Ice 940 kg/m3

Water wt%	Soil wt%	Water kg	Soil kg	Total kg	Extraction 80%	Ave Density kg/m3	Tot Vol m3	FB Depth cm	FB Field yds
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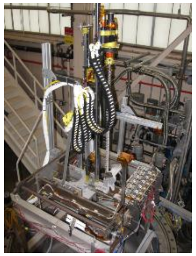
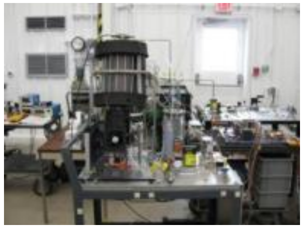
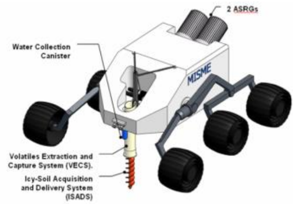
Past/Recent Mars ISRU Technology Development





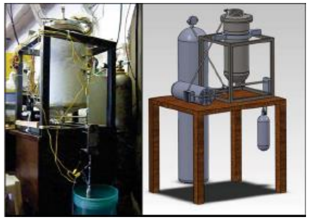
- Sample drills and augers (JPL, ARC, SBIRs)
- Scoops and buckets (GRC, KSC, JPL, Univ., SBIRs)
- Auger and pneumatic transfer (KSC, GRC, SBIRs)






- H_2 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)

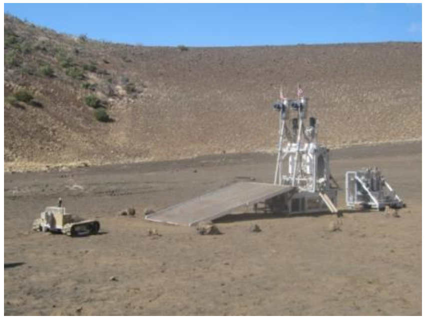


- Combustion, Pyrolysis, Oxidation/Steam Reforming (GRC, KSC, SBIRs)

Past/Recent Mars ISRU System Development

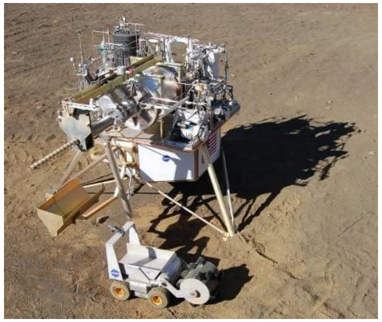
Lunar/Mars Soil Processing

- 1[st] Gen H_2 Reduction from Regolith Systems (NASA, LMA)



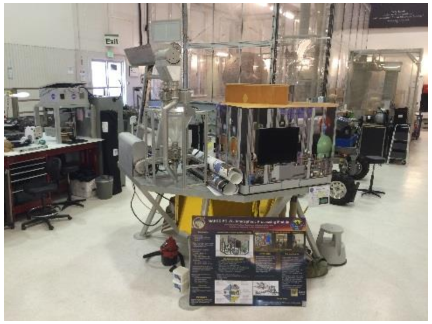
ROxygen H_2 Reduction
Water Electrolysis
Cratos Excavator

PILOT H_2 Reduction
Water Electrolysis
Bucketdrum Excavator



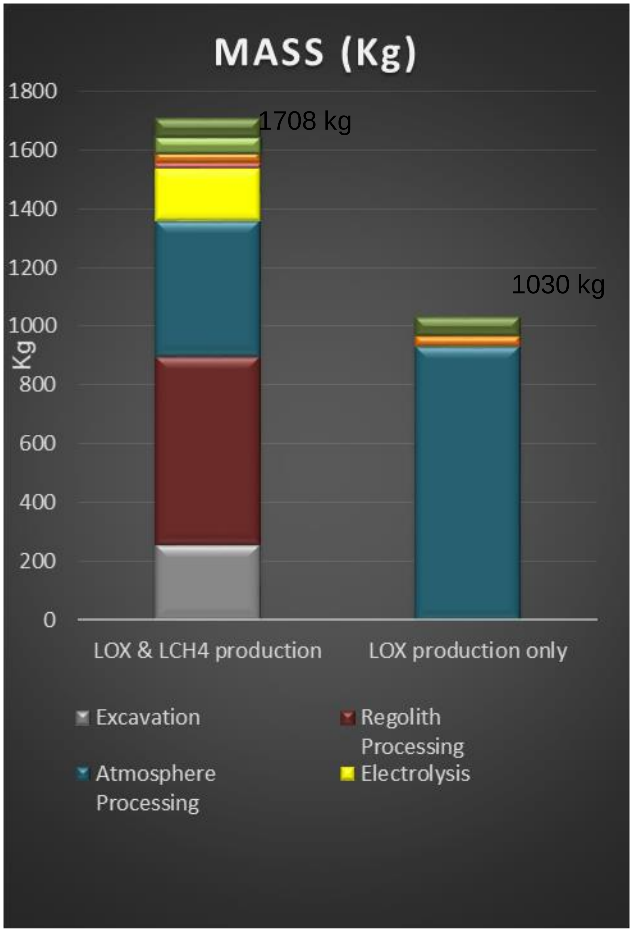
- 2[nd] Gen MARCO POLO soil processing system (JSC, KSC)

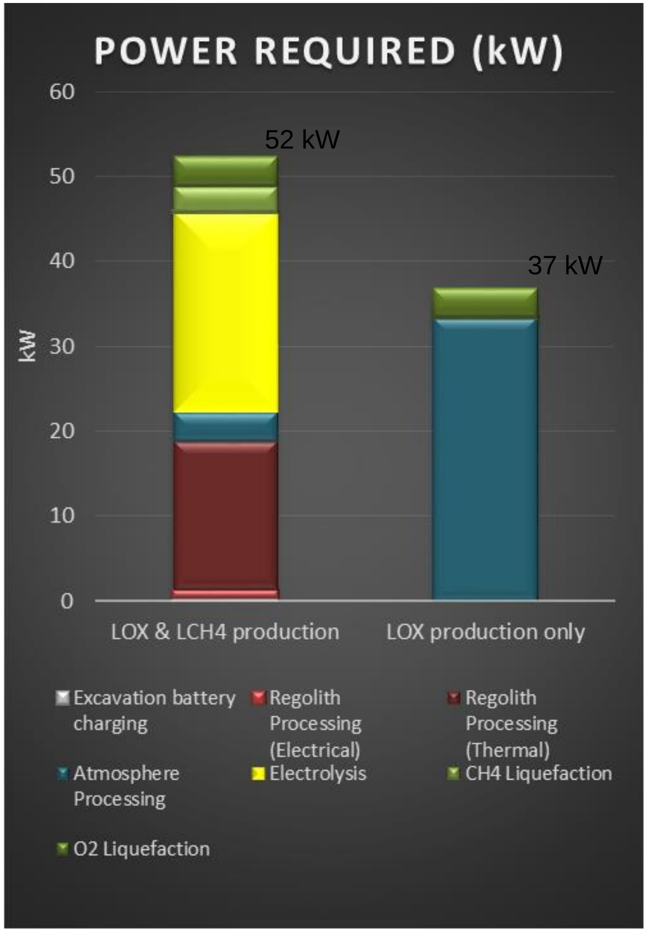
Soil Processing Module
10kg per batch; 5 kg/hr
0.15 kg/hr H_2O
(3% water by mass)

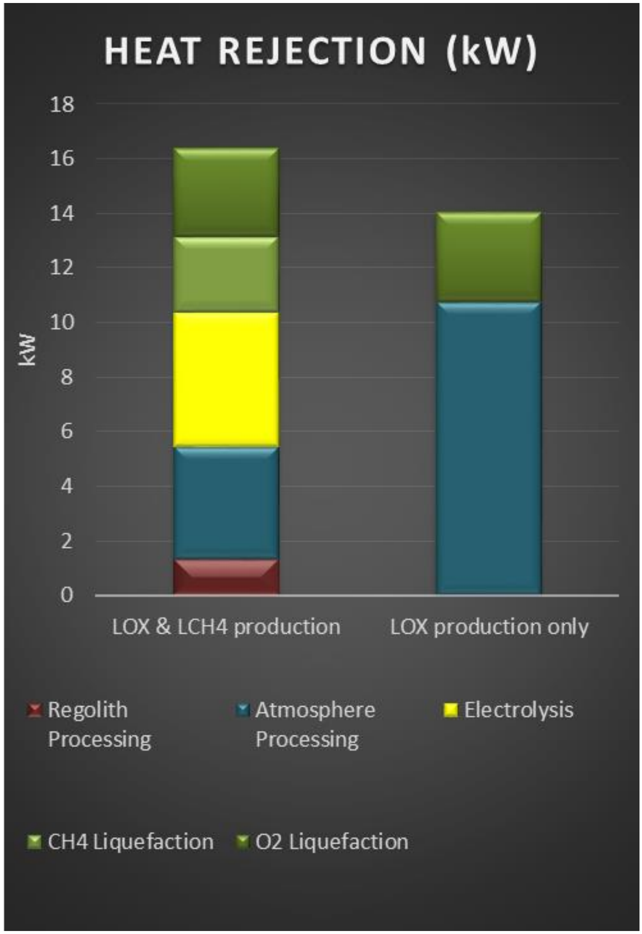


Total ISRU system (3 modules)

- Assumptions: 3 independent ISRU systems each producing 40% of the needed products, 15% mass added for structure, 20% margin added to power and mass.
- O_2-only system assumes a cryofreezer for CO2 extraction and Solid Oxide Electrolysis for conversion







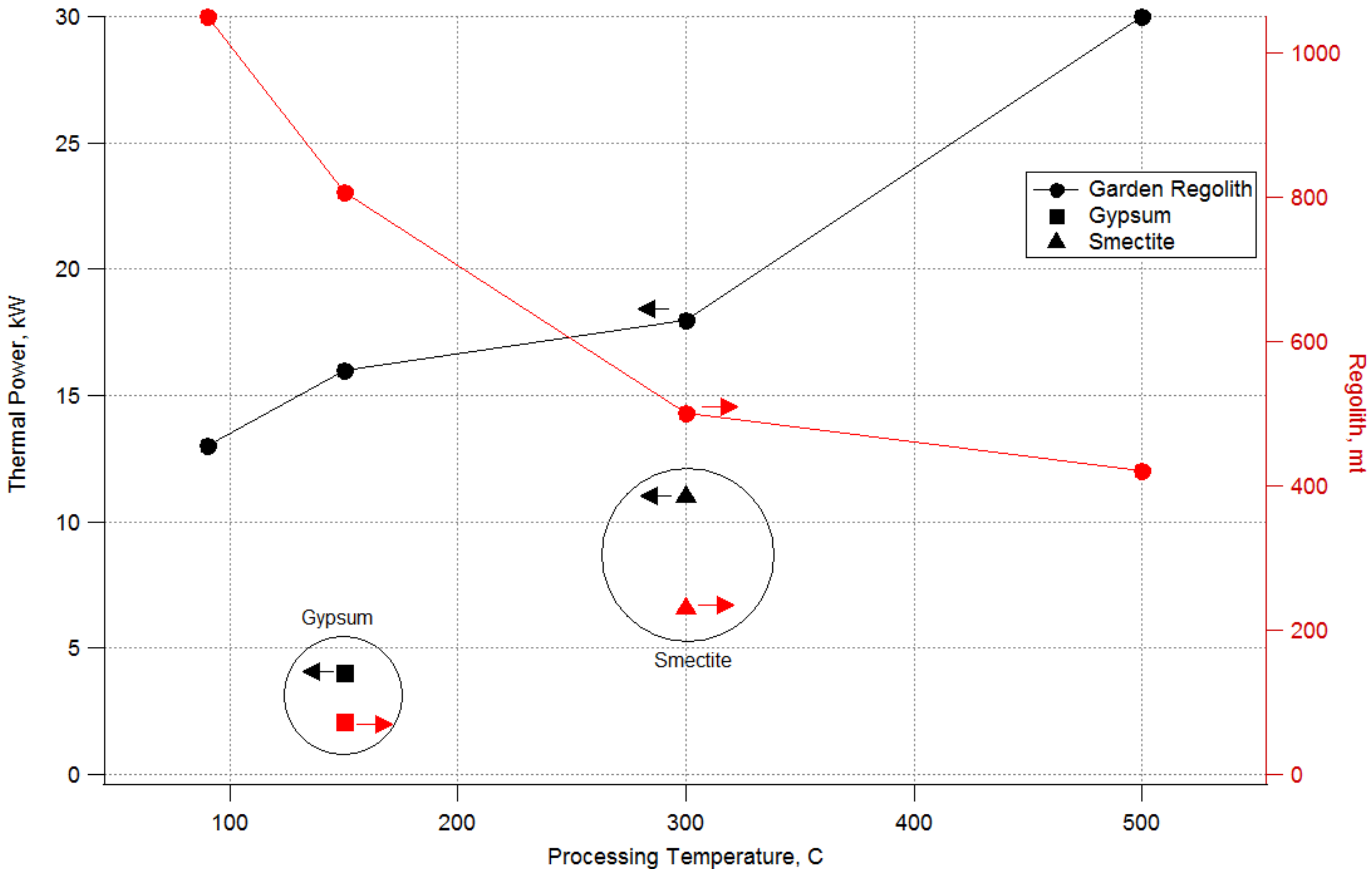
66% higher mass

42% higher power

17% more waste heat

Trade: higher yield regolith (1 of 2)

- The real benefit of targeting higher yield regolith is the power saving
  - Less regolith to heat
  - Heating at a lower temperature



Trade: higher yield regolith (2 of 2)

- 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 150C.
  – 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