National Aeronautics and Space Administration

An ISRU Propellant Production System to Fully Fuel a Mars Ascent Vehicle

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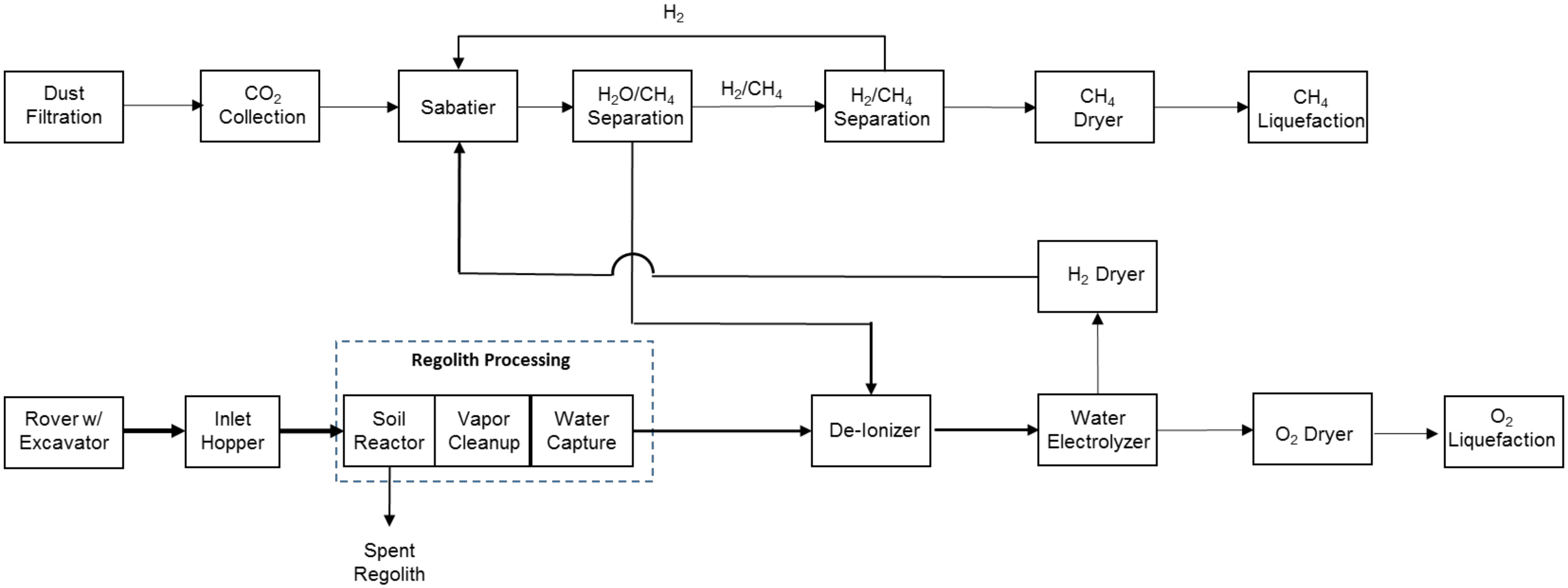
Motivation

- **ISRU of Mars resources was baselined in 2009 Design Reference Architecture (DRA) 5.0, but only for Oxygen production using atmospheric CO_2**
  - The Methane (LCH_4) needed for ascent propulsion of the Mars Ascent Vehicle (MAV) would need to be brought from Earth
- **HOWEVER: Extracting water from the Martian Regolith enables the production of both Oxygen and Methane from Mars resources**
  - Water resources could also be used for other applications including: Life support, radiation shielding, plant growth, etc
  - Water extraction was not baselined in DRA5.0 due to perceived difficulties and complexity in processing regolith
- **The NASA Evolvable Mars Campaign (EMC) requested studies to look at the quantitative benefits and trades of using Mars water ISRU**
  - Phase 1: Examined architecture scenarios for regolith water retrieval. Completed October 2015
  - Phase 2: Deep dive of one architecture concept to look at end-to-end system size, mass, power of a LCH_4/LO_2 ISRU production system

Approach

- **Evolvable Mars Campaign**
  - Pre-deployed Mars ascent vehicle (MAV)
  - 4 crew members
  - Propellants: Oxygen & Methane
- **Generate a system model to roll up mass & power of a full ISRU system and enable parametric trade studies.**
  - Leverage models from previous studies and technology development programs
  - Anchor with mass/power/performance from existing hardware
  - Whenever possible used reference-able (published) numbers for traceability.
  - Modular approach to allow subsystem trades and parametric studies



Top level production requirements

- **Propellant mass needs taken from most recently published MAV study:**
  - Polsgrove, T. et al. (2015), AIAA2015-4416
- **MAV engines operate at mixture ratios (oxygen:methane) between 3:1 and 3.5:1, whereas the Sabatier reactor produces at a 4:1 ratio. Therefore:**
  - **Methane production is the driving requirement**
  - **Excess Oxygen will be produced**
- **Production rate based on a mission timeline of 480 days (16 months)**
  - ISRU system arrives one launch opportunity ahead of humans
  - MAV must be fully fueled before human departure from earth

		Total mass needed	Rate at 480days continuous operation
Requirement:	**CH_4**	6978 kg	0.61 kg/hr
Reactants needed to meet requirement:	**H_2O**	15701 kg (785,050 kg 2% soil)	1.36 kg/hr (68.2 kg/hr soil@2%)
	CO_2	19190 kg	1.67 kg/hr
Results in:	**O_2**	27912 kg total (22728 kg propellant, 5184 kg leftover)	2.43 kg/hr

26 month launch opportunity
– 9 month transit time
– 1 month margin

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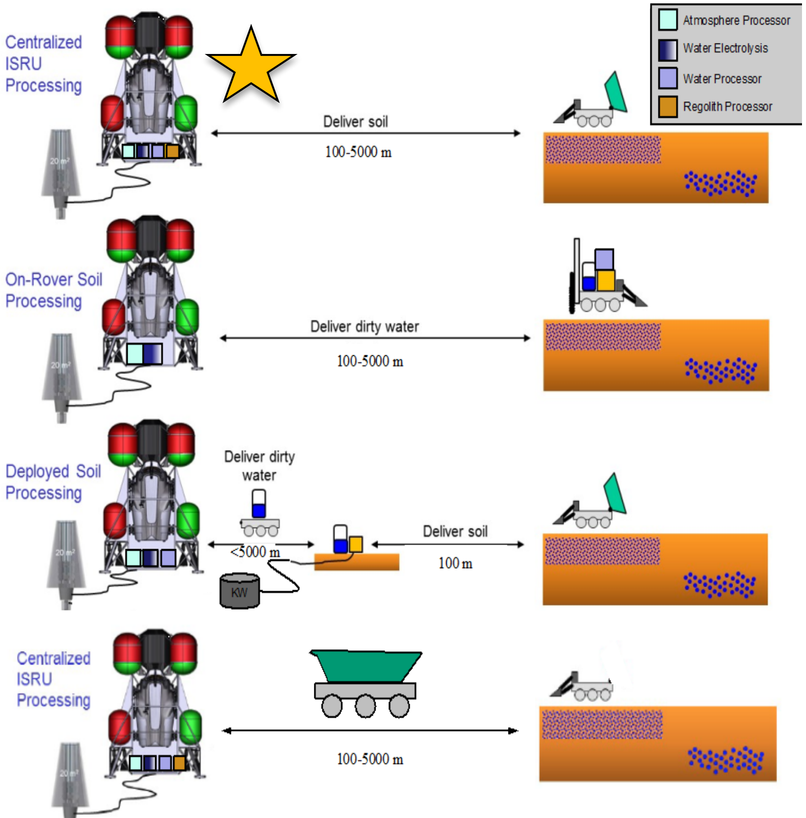
16 months

Assumptions

- **<u>Production Rate driver:</u>** *6978 kg of Methane needed + 0.5% margin*
  - Methane is the driver since excess oxygen will be produced using Sabatier process
- **<u>Time of ISRU production</u>:** *480 day operation, 24hr/day*
- **<u>Soil Water resource (baseline)</u>:** *Water from surface regolith = hydrates*
  - Ubiquitous (location independent)
  - Available in surface material (subsurface excavation not required)
  - Lower resource yield is more of a worse case for water extraction system
- **<u>Processing</u>:** *Regolith is transported* and delivered to a centralized processing plant that is co-located with the Lander/MAV



- **<u>Liquefaction</u>:** *Takes place in the MAV tanks*. ISRU system only includes mass/power for crycoolers needed to liquefy. MAV responsible for tanks and zero boil-off systems
- **<u>Power Source:</u>** Not part of ISRU system. Assumes a fission reactor will be needed for human presence, ISRU will use reactor when humans are not present. (TBD- as power needs are identified)
- **<u>Radiators</u>:** Not part of ISRU system. ISRU will be packed on lander.

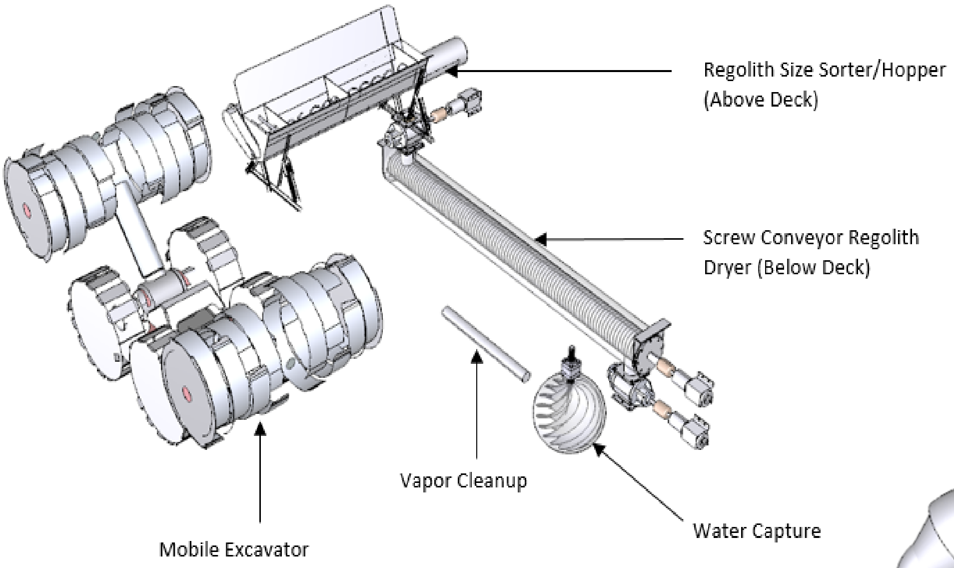
Subsystem Selection for this study

	Subsystem	Components	Heritage
Excavation	Excavation	RASSOR 2.0 excavator – Bucket drum rover	KSC prototype hardware, laboratory tests in regolith simulants
Regolith Processing	Regolith Processing	Auger Conveyor Dryer – heated auger with gas loop for continuous regolith processing	JSC design concept – numerical sizing model, conceptual CAD
		Vapor cleanup – Membrane separator	COTS
		Water collection – Cold trap	JSC design concept- numerical sizing model
Propellant Production	CO_2 Acquisition	Cryofreezer	COTS –flight heritage KSC cold head conceptual design numerical sizing
	Sabatier	Microchannel Sabatier	Solicited: Battelle PNNL
		Regenerative Gas dryer, desiccant	JSC development hardware
		CH_4/H_2 separator	Solicited: Hamilton Sunstrand
	Electrolysis	PEM electrolysis stack, Cathode feed	Giner Inc.
		Deionizer	COTS
		Inlet pump, mircorpump	COTS
		Regenerative Gas dryer, desiccant	JSC development hardware
	Liquefaction	Cryocooler	COTS

- **Use existing hardware with highest flight readiness**
  - Mass, power, performance
- **NASA development efforts; in-house and solicited**
- **Relevant COTS hardware**

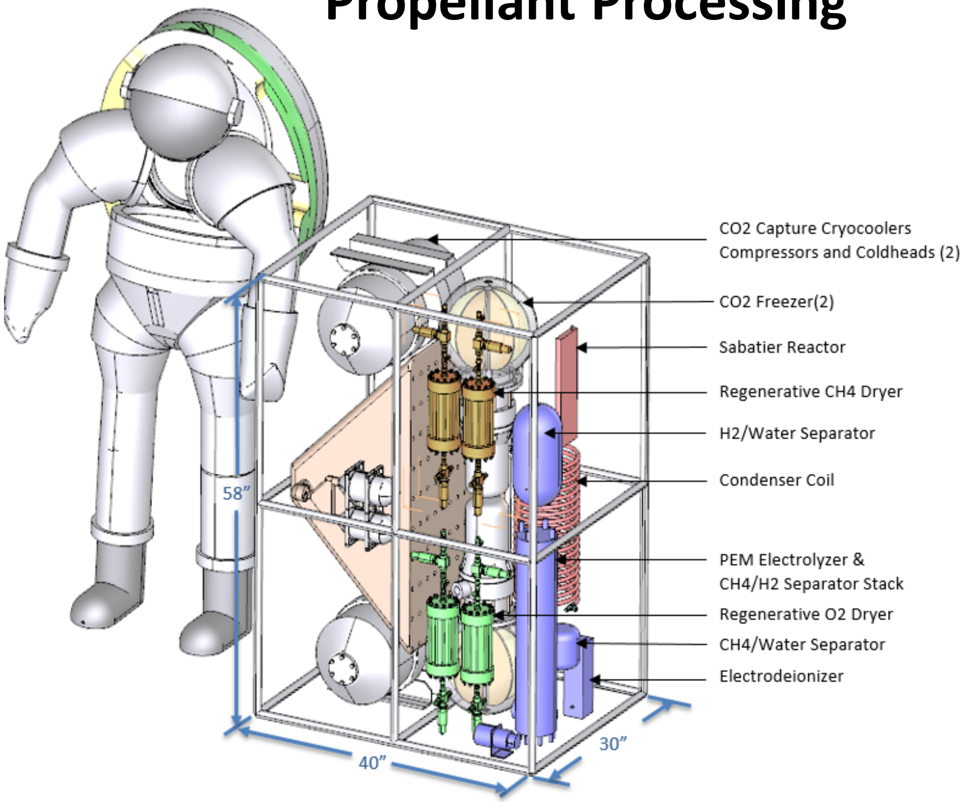
- **These are just a baseline to anchor model, technology trades TBD**

Notional Packaging: Subsystems



Excavation and Regolith Processing

Propellant Processing



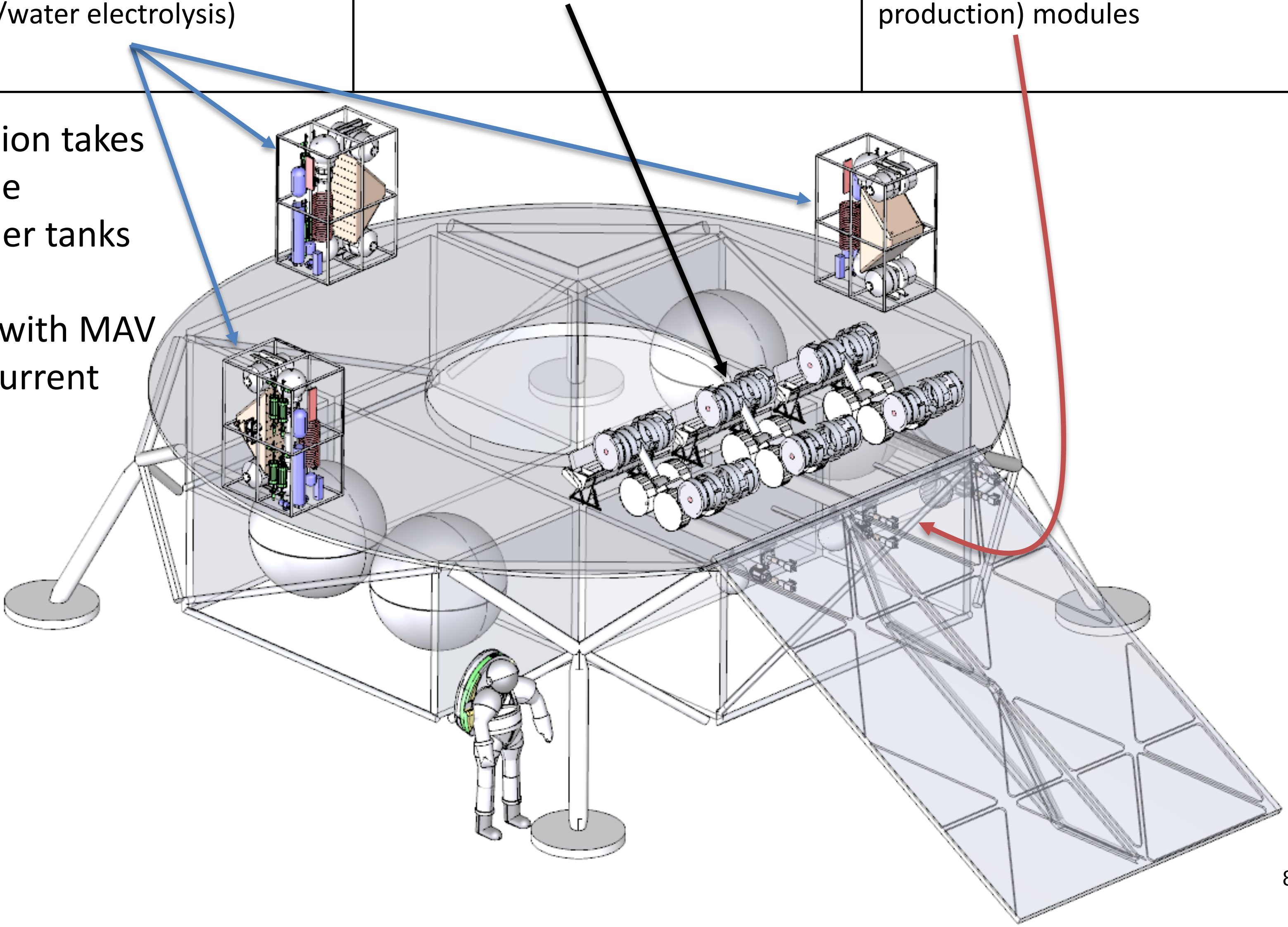
Notional Packaging: Full ISRU System

Approach: Production requirement met by 3 independent ISRU systems including:

3 Propellant production (atmosphere processing/water electrolysis) modules	3 mobile RASSOR excavators	3 regolith processing (water production) modules

*Liquefaction takes place in the MAV/Lander tanks

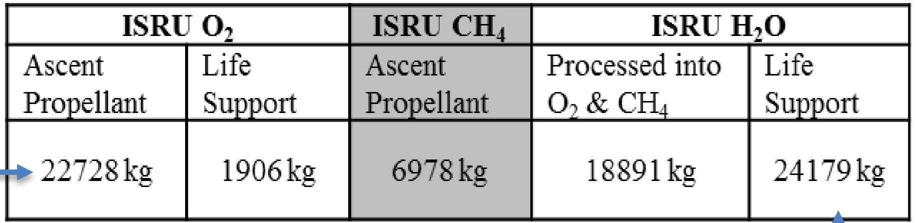
*Working with MAV team for current packaging



Case Study Variables

Methane & Oxygen ISRU *(soil water + atmosphere processing)*	**vs**	**Oxygen Only ISRU** *(atmospheric processing)*
Ascent Propellant Production	**vs**	**Ascent Propellants + Life support Consumables**
Low Yield Regolith *(Ubiquitous)*	**vs**	**High Yield Surface Regolith** *(Localized)*

- **Oxygen Only ISRU:**
  - As called out in DRA 5.0
  - Using Solid Oxide Electrolysis
  - Full system model
- **Life Support Consumables**
  - Defined in study below
  - Most conservative case, assumes highly 'water rich' scenario
    - Open loop ECLSS
    - Mars water use for everything from drinking water to Laundry.



ISRU O_2		**ISRU CH_4**	**ISRU H_2O**	
Ascent Propellant	Life Support	Ascent Propellant	Processed into O_2 & CH_4	Life Support
22728 kg	1906 kg	6978 kg	18891 kg	24179 kg

Stephen J. Hoffman, Alida Andrews, B. Kent Joosten, Kevin Watts, "A Water-Rich Mars Surface Mission Scenario", to be published IEEE-2422, *IEEE Aerospace Conference*, Big Sky, MO, March 4-11, 2017

M-WIP - Definition of Reference Reserve Cases

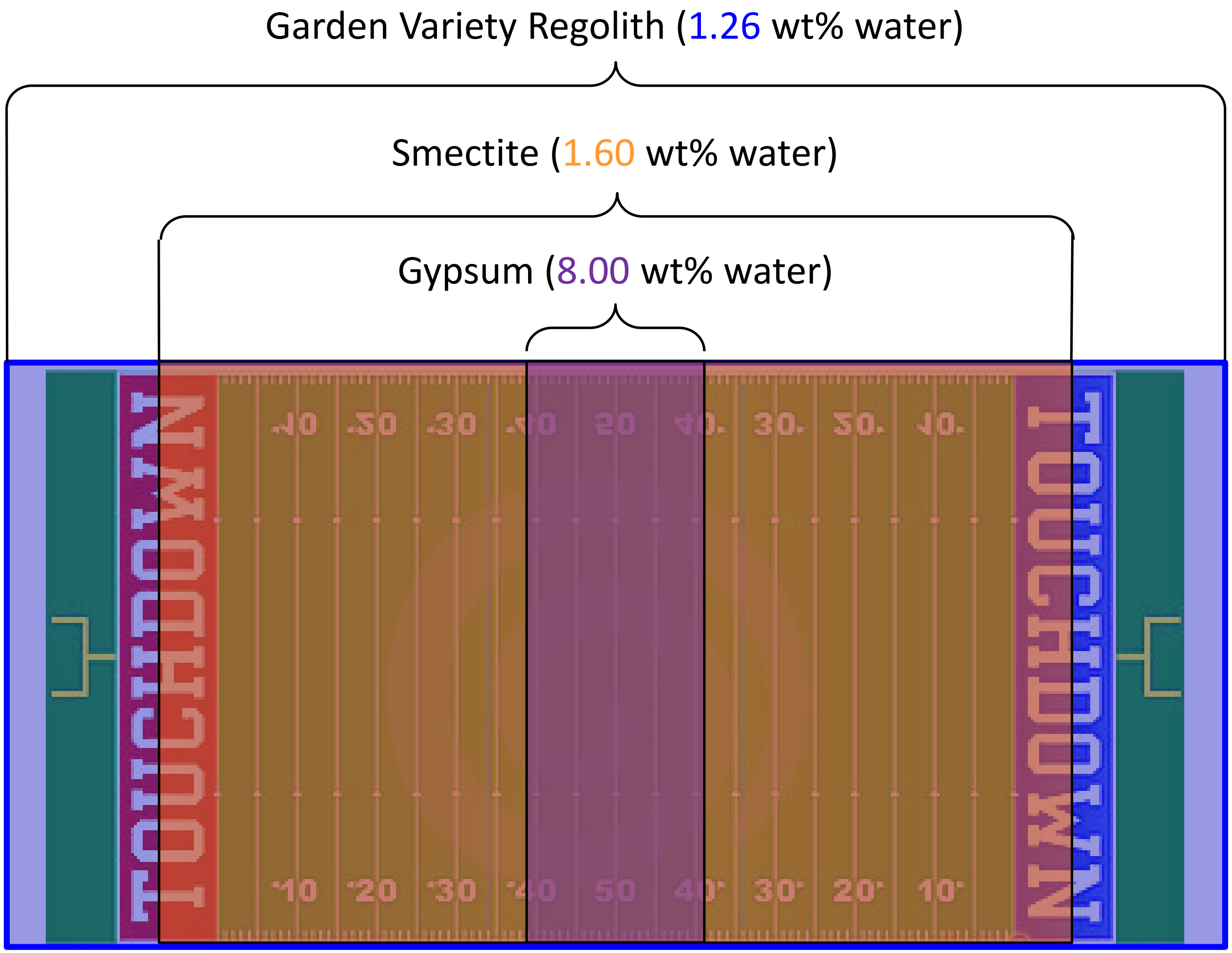
	Deposit Type			
Essential Attribute	A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	3 m	0 m	0 m	0 m
geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburdern	sand	NA	NA	NA
Concentration and state of water-bearing phase within the 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% akaganeite[5]	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

1. ~20 wt% water, 100-150°C
2. ~4 wt% water, 300°C
3. ~1 wt% water, >500°C
4. ~20 wt% water, 90°C
5. ~12 wt% water, 250°C
6. ~6 wt% water, 150°C

The M-WIP (Mars Water ISRU Planning) study was lead by SMD/Mars Program office and involved academy and industry members to identify impacts of Mars resources and their location, and the data still needed to best define them.

- The MWIP team report is posted: http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

Human Mission Mars Soil Excavation for Water


Garden Variety Regolith (1.26 wt% water)

Smectite (1.60 wt% water)

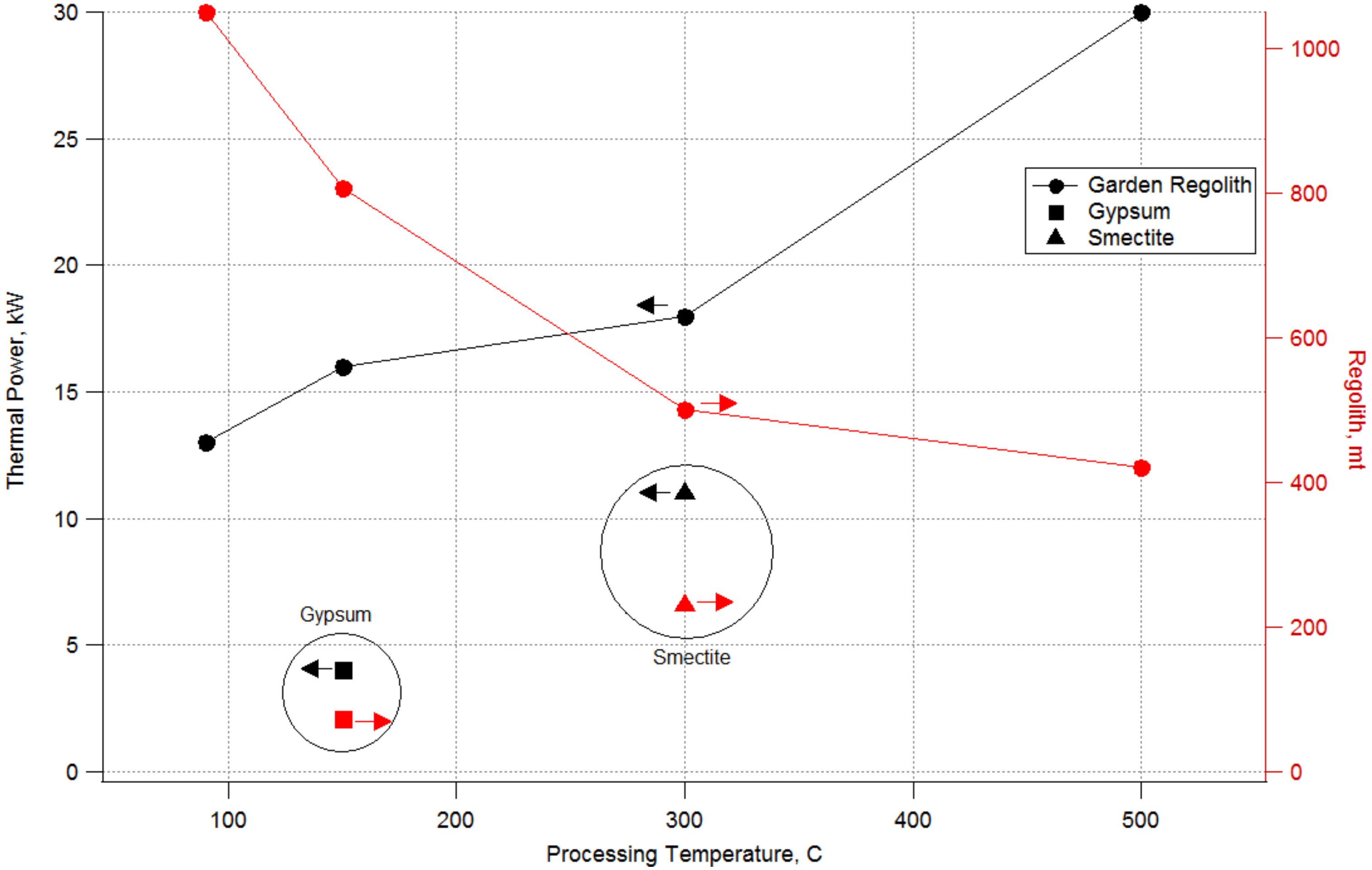
Gypsum (8.00 wt% water)

Surface area required per mobile excavator with the following assumptions:

- 3 mobile excavators used
- Each excavator provides 40% of required water
- Excavation depth = ~5cm (2.0 in)

Trade: higher yield regolith

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



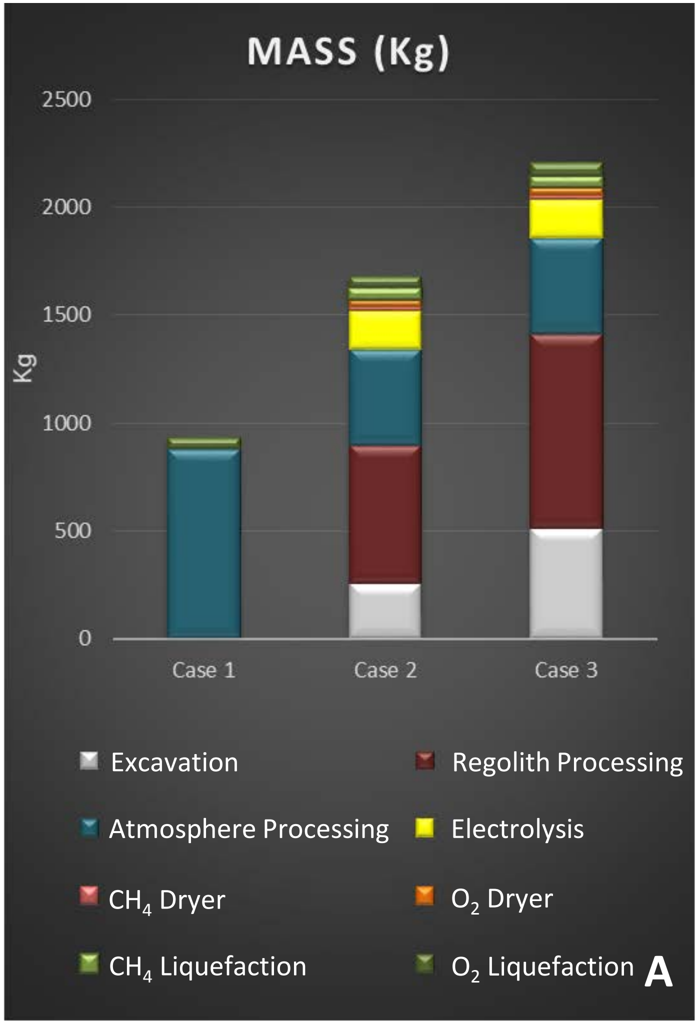
Case Study Definitions

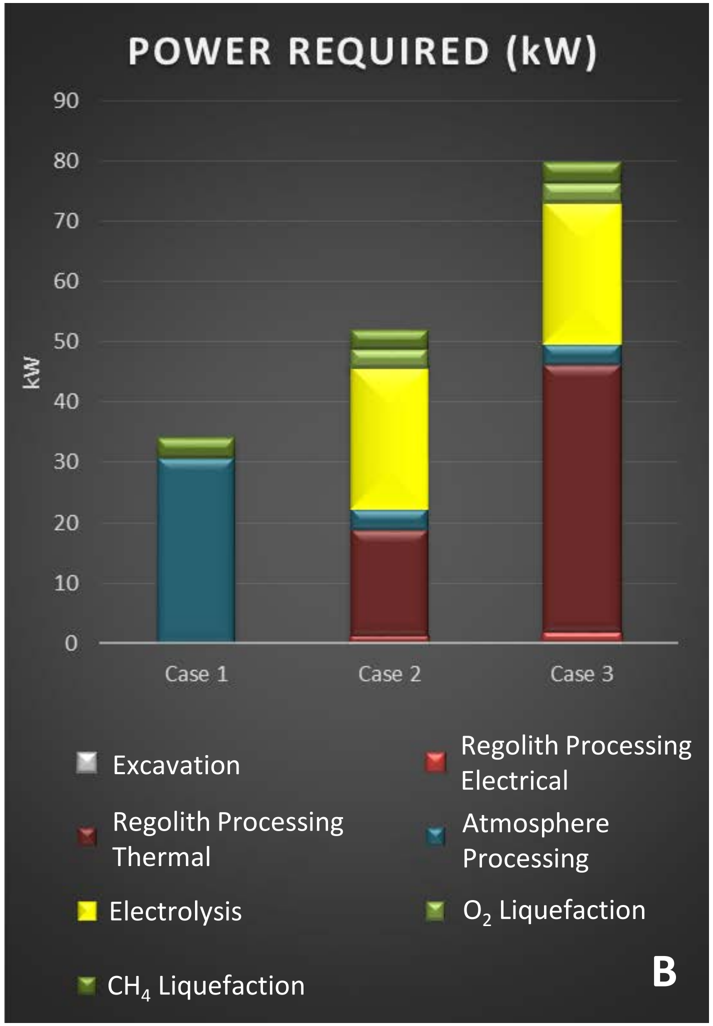
Case	Title	Description
0	No ISRU	Represented by the total propellant mass needed for ascent propulsion, this is meant to be a comparison of the landed mass needed for Mars Ascent. With no ISRU the total methane and oxygen for propulsion must be landed.
1	Oxygen-Only ISRU, propulsion	Oxygen for ascent propulsion is produced using atmospheric CO_2. All methane is transported from earth.
2	Methane ISRU, propulsion, Case D regolith	Methane and oxygen for ascent propulsion are both produced using both water from regolith and atmospheric CO_2. The regolith is assumed to be Case D, “Typical” regolith a represented by Gale Crater with ~1.3% water content.
3	Methane ISRU, w/life support, Case D regolith	Same as Case 2 but with additional water and oxygen requirements for life support
4	Methane ISRU, propulsion, Case B regolith	Same as Case 2 except using Case B regolith with ~8% water content
5	Methane ISRU, w/life support, Case B regolith	Same as Case 3 using Case B regolith with ~8% water content

Deposit Type			
A. Ice	**B. Poly-hydrated Sulfate**	**C. Clay**	**D. Typical Regolith (Gale)**
	8.6% @ 150°C	2.7% @ 300°C	1.3% @ 300°C

Results: Consumable production

Case 1	Case 2	Case 3
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water





Case 2 vs 3

- Only impacts excavators and regolith processor subsystems
- Size of regolith processors
- Number of excavators

Power

- Thermal heat could be provided by recuperation

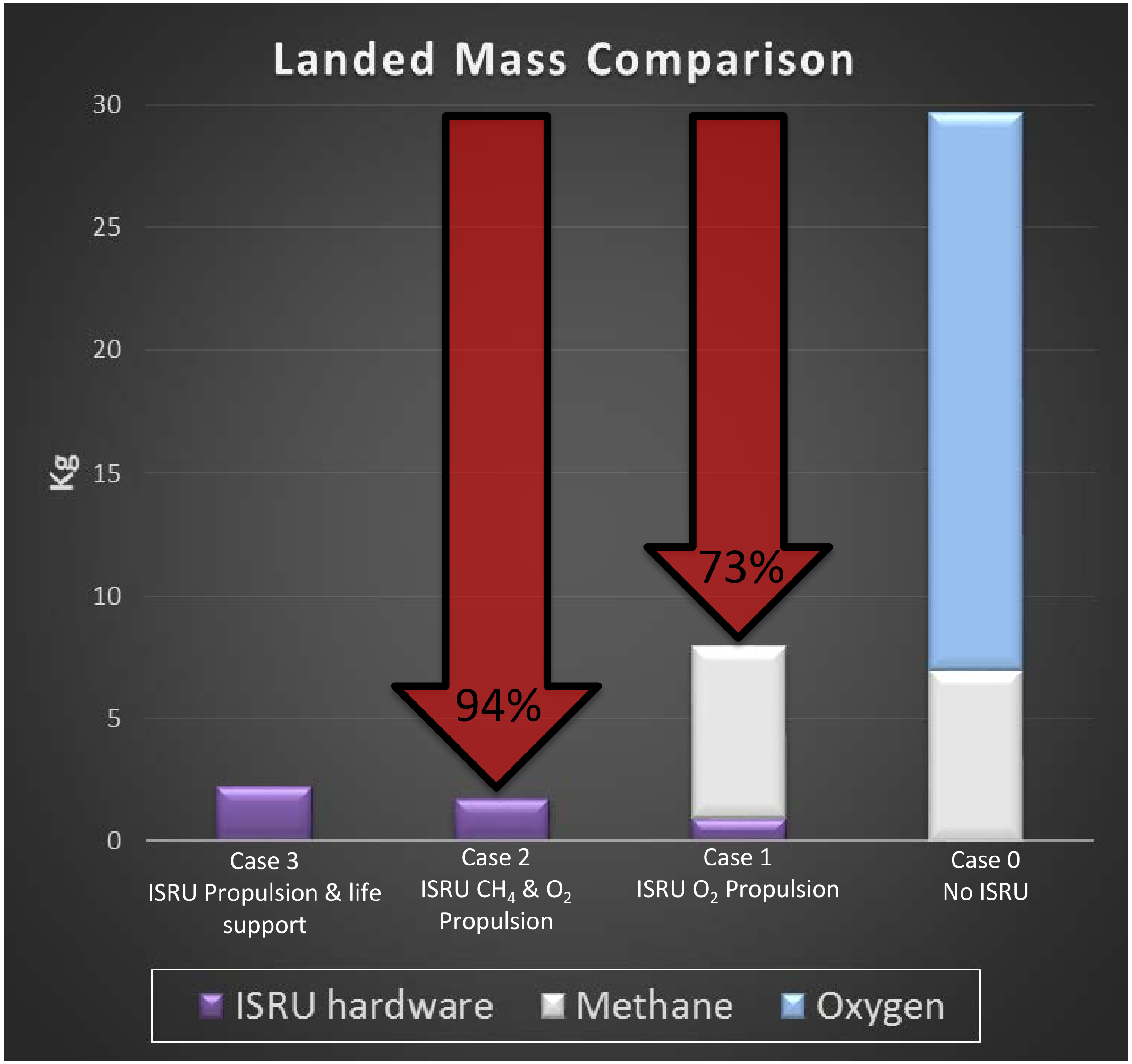
Mass Results

	ISRU system Landed Mass Comparison (ISRU Hardware + Propellant from Earth)		
	The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.		
	ISRU Hardware Mass, mT	Total Mass, mT	Production Ratio: Propellant produced per kg of total mass
Case 3 ISRU propellants, & life support	2.2	2.2	13.5
Case 2 ISRU propellants, baseline regolith	1.7	1.7	17.7
Case 1 ISRU O_2 propellant	0.93	8.0 (1mt hardware + 7mt Methane)	2.9
Case 0 No ISRU	0	29.7 (23mt Oxygen + 7mt Methane)	na

- **The addition of methane production increases mass 1 mT over the oxygen-only case suing the lowest yield regolith**
- **Total mass considers ascent propellant mass transported from earth. However producing that propellant in-situ will save additional mass:**
  - Propellant required to deliver hardware and ascent propellants from LEO
  - EDL systems to land the ascent propellant
  - Storage and conditioning systems for propellant during transit and surface operations
- **Propellant production Ratio = Mass Propellant Produced / Hardware mass**
  - Full ISRU offers a 6x improvement over oxygen-only ISRU using the lowest yield regolith

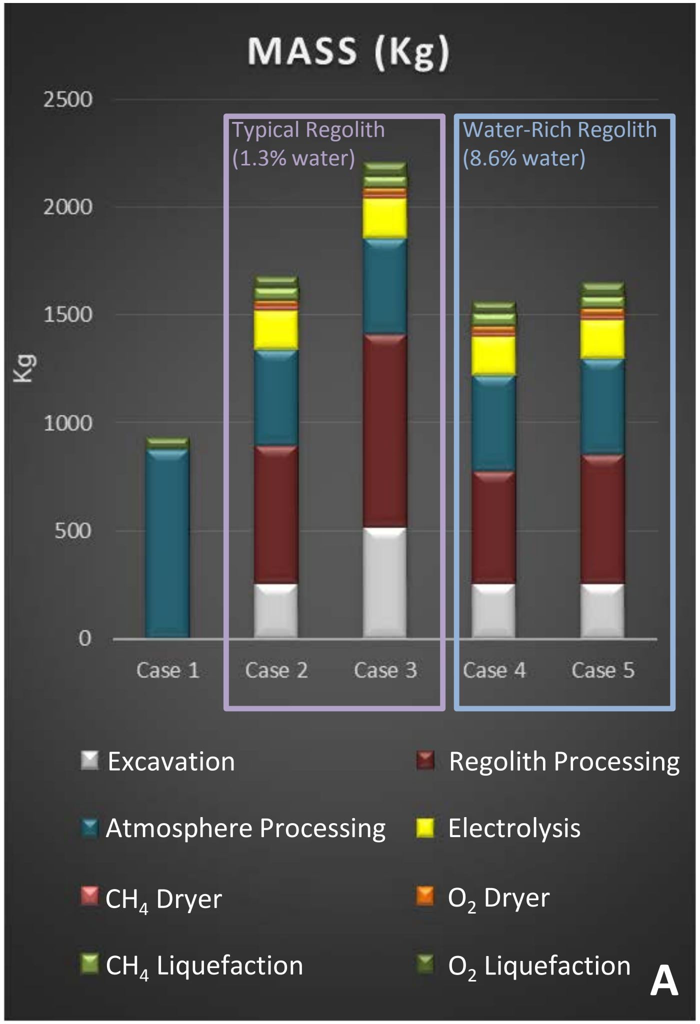
Overall Mass comparison

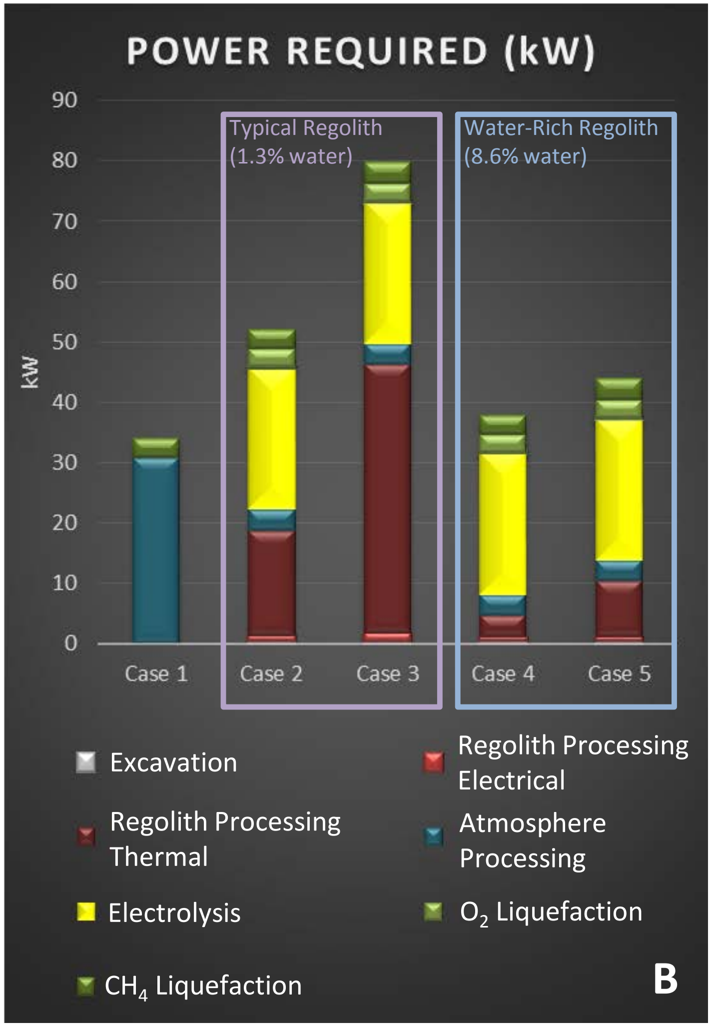
- **Mass reductions are compared to total ascent propellants only**
- **Mass savings in LEO is about 10kg per ever 1 kg of propellant produced**
  - LEO Mass savings on the order of 300 mT with full ISRU system
  - Reduces cost and eliminates several heavy lift launch vehicles



Trades: All

Case 1	Case 2 + 4	Case 3 + 5
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water



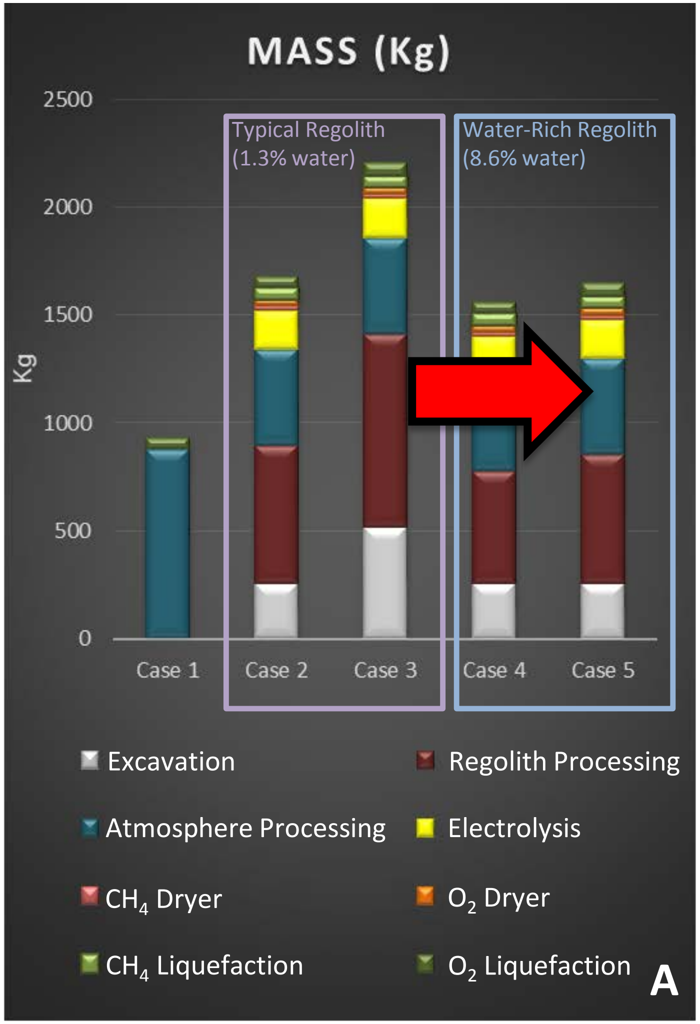


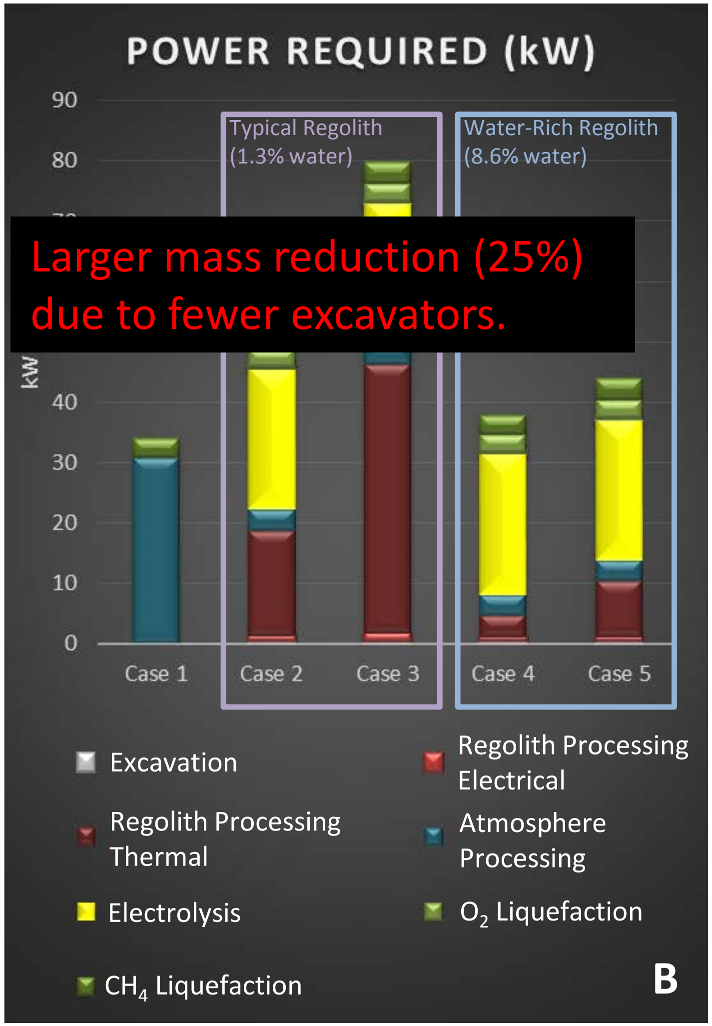
<u>Higher Yield regolith</u>

- The addition of life support consumables has only marginal impact on mass and power
- Due to decrease in processing temperature, power levels are comparable to Oxgyen-only case

Trades: All

Case 1	Case 2 + 4	Case 3 + 5
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water





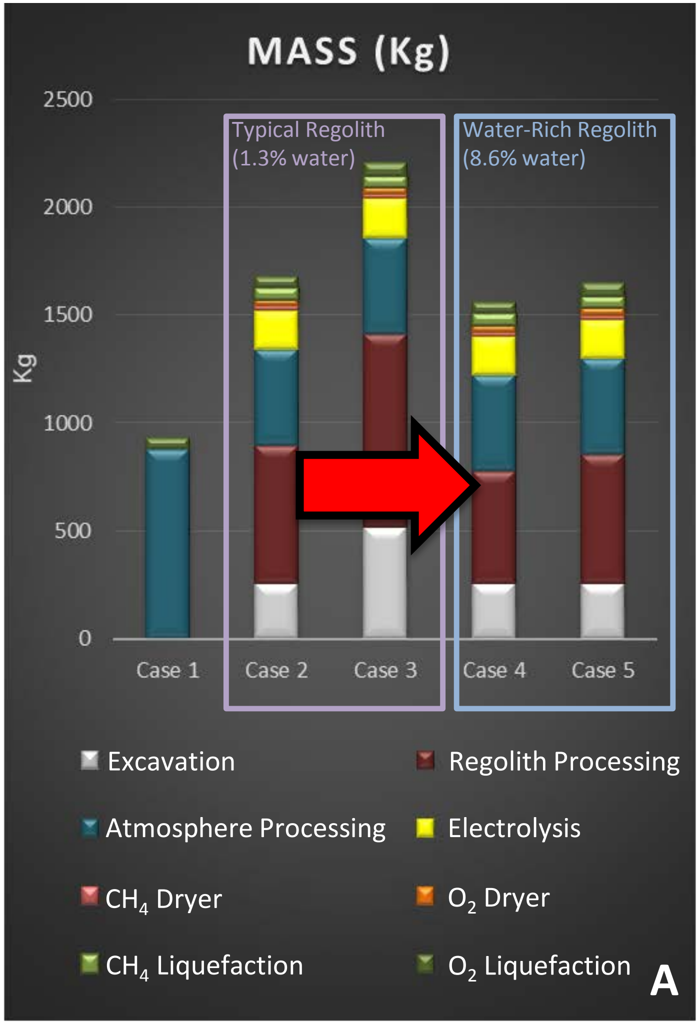
Larger mass reduction (25%) due to fewer excavators.

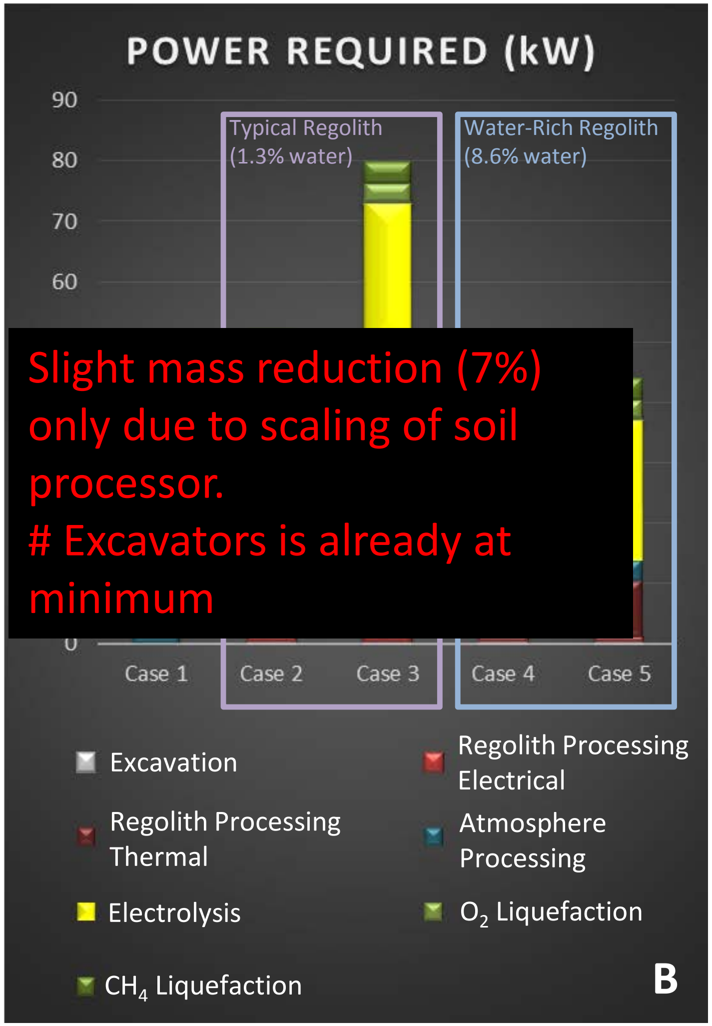
<u>Higher Yield regolith</u>

- The addition of life support consumables has only marginal impact on mass and power
- Due to decrease in processing temperature, power levels are comparable to Oxgyen-only case

Trades: All

Case 1	Case 2 + 4	Case 3 + 5
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water





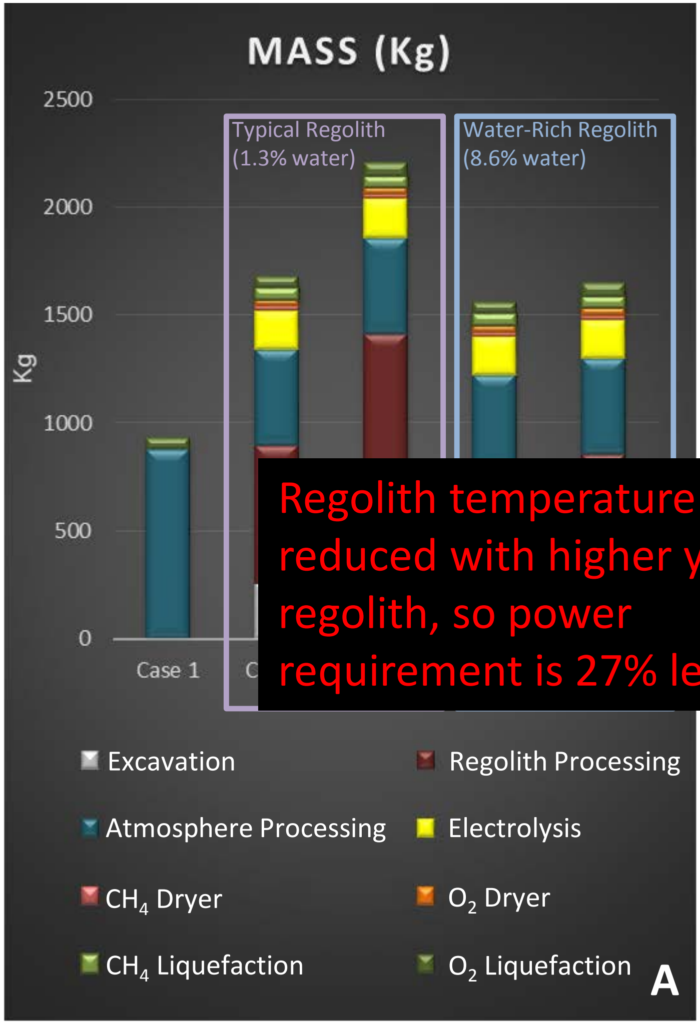
Slight mass reduction (7%) only due to scaling of soil processor.
Excavators is already at minimum

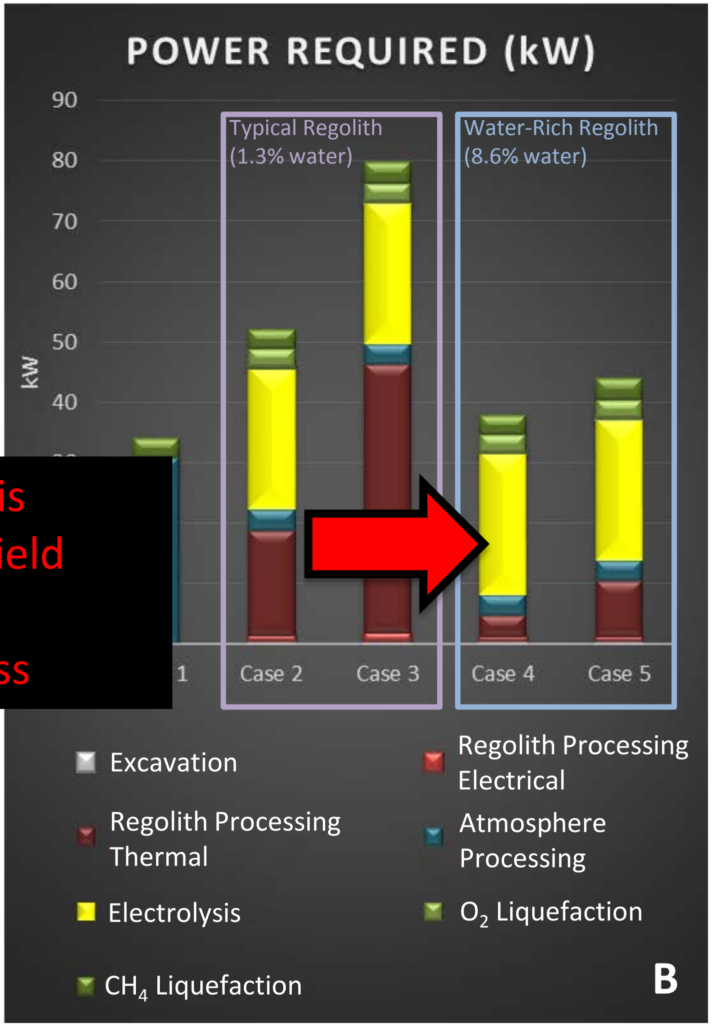
<u>Higher Yield regolith</u>

- The addition of life support consumables has only marginal impact on mass and power
- Due to decrease in processing temperature, power levels are comparable to Oxgyen-only case

Trades: All

Case 1	Case 2 + 4	Case 3 + 5
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water





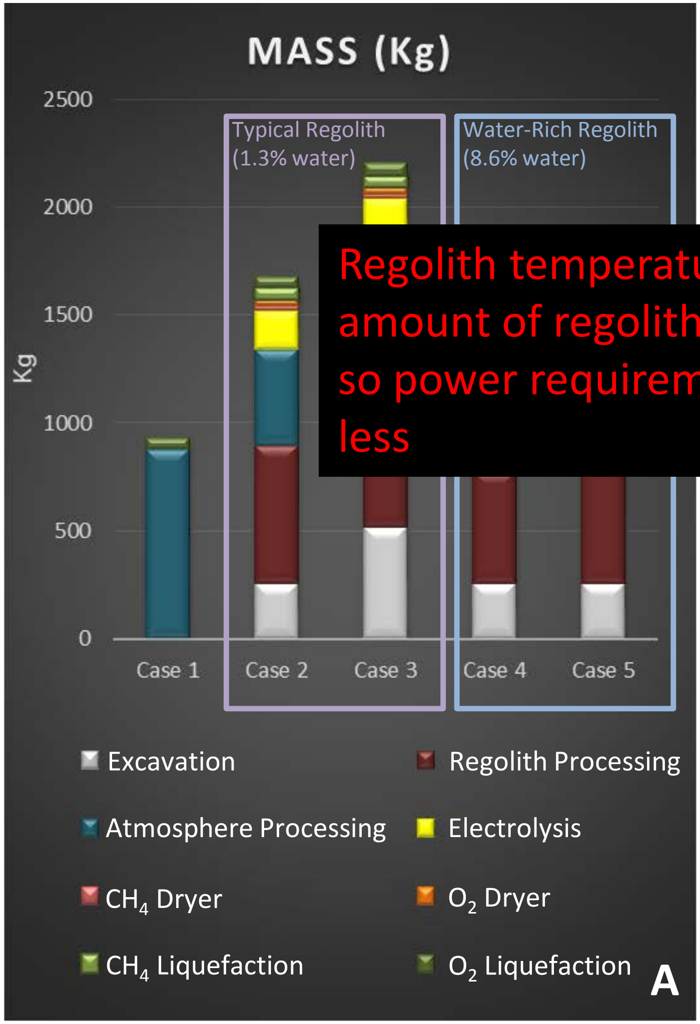
Regolith temperature is reduced with higher yield regolith, so power requirement is 27% less

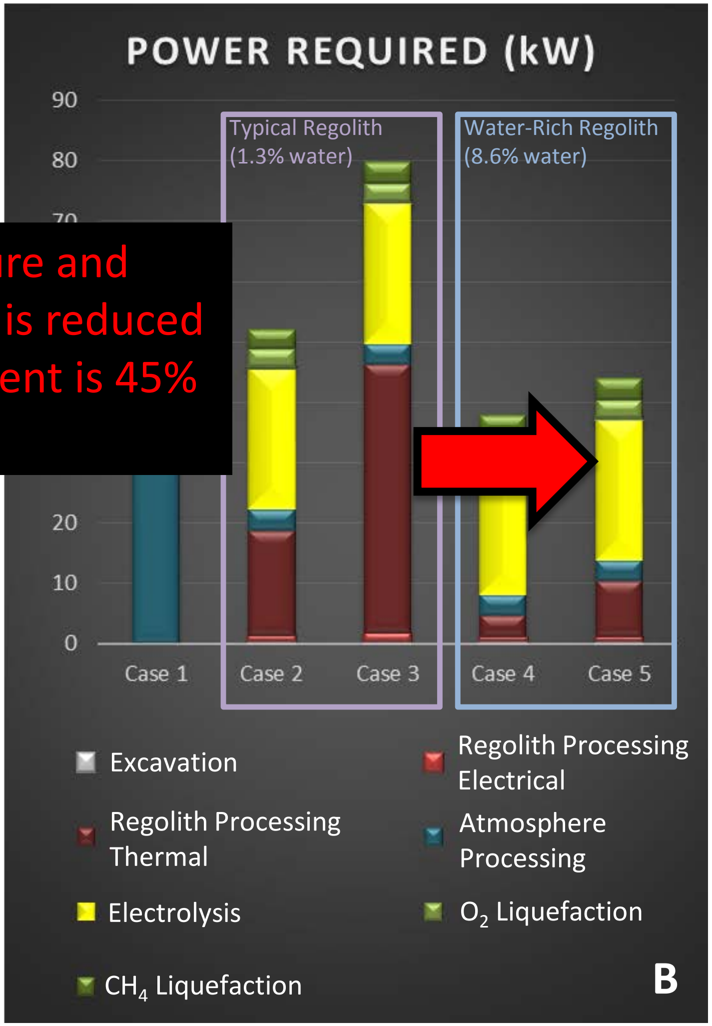
Higher Yield regolith

- The addition of life support consumables has only marginal impact on mass and power
- Due to decrease in processing temperature, power levels are comparable to Oxgyen-only case

Trades: All

Case 1	Case 2 + 4	Case 3 + 5
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water





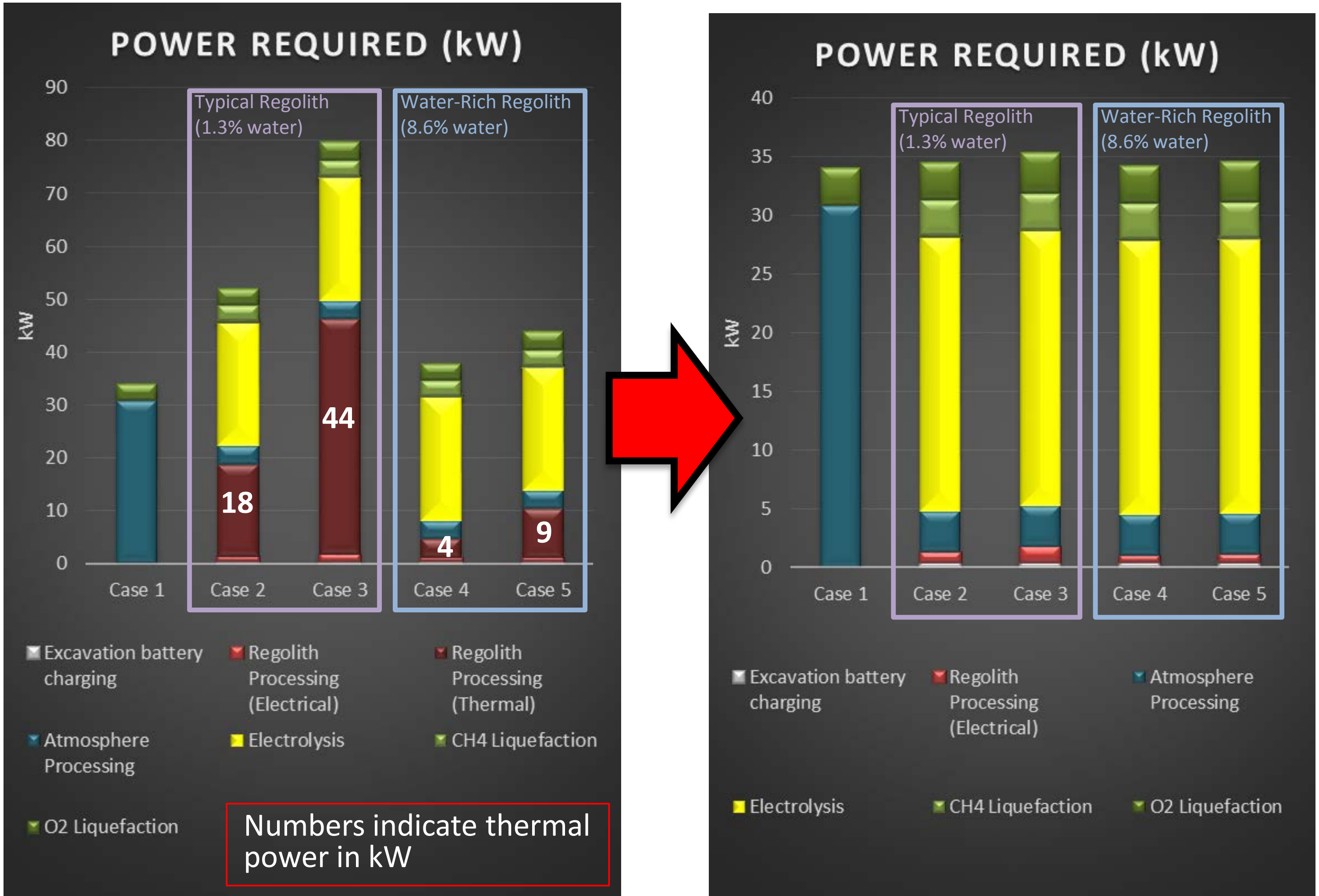
Regolith temperature and amount of regolith is reduced so power requirement is 45% less

<u>Higher Yield regolith</u>

- The addition of life support consumables has only marginal impact on mass and power
- Due to decrease in processing temperature, power levels are comparable to Oxgyen-only case

Power results

- **The EMC architecture estimated 40kW would be needed for crew habitation (surface activities). ISRU would use power source during unscrewed periods.**
  - All but Case 3 fall in this ball park. Case 3 approach was a ‘water rich’ scenario, so using the lowest yield regolith for this case is overly conservative



Numbers indicate thermal power in kW

- **Using heat recuperation for the regolith thermal heat significantly reduces electrical power requirements.**

Heat could be recuperated from fission reactor

Conclusions

- **Model for end-to-end Mars ISRU systems have been developed to look at power/mass/volume trades**
  - Oxygen only and Methane/Oxygen systems
  - Modular to permit other technologies and architectures
  - A “deep dive” study was preformed on one system to examine benefits from an EMC mission standpoint
- **A system to produce all 30 mT of Mars ascent propellant is estimated to weigh 1.7 mT using the lowest yield regolith.**
  - An oxygen-only system weighs 0.93 mT + 7 mT of methane = 8 mT
- **Using higher yield regolith has only marginal impact on mass, but reduces power requirements 52kW to 35kW, where an oxygen only system is 35kW.**
  - This power reduction is primarily thermal energy to heat the regolith, which could be recuperated from other sources.
- **The inclusion of life support consumables (worst case) from ISRU would only have a marginal impact provided that a higher yield regolith is used.**
  - This would require targeting a resource rich specific landing site

Oxygen only: Reduces Propellant mass 73%, could save 230 mT in LEO

Methane/Oxygen: Reduces Propellant mass 94%, could save 300 mT in LEO