EXPLORE MOON to MARS

A Lunar Water ISRU System Study for Human-Scale Propellant Production

PTMSS/SRR

June 10, 2021

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Objective

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- NASA's Artemis plan outlines a sustainable presence at the lunar surface in the 2028 timeframe and indicates the desire to develop ISRU technology to support this
- NASA's Human Exploration Mission Directorate (HEOMD) is developing mission scenarios and timelines
  - In order to infuse ISRU into these missions, estimates are needed for ISRU systems in term of Mass, Power, and Concept of Operations
- Two resources are available for Lunar ISRU for propellant production
  - Water from the polar regions
  - Oxygen bound in the regolith minerals
- NASA's Space Technology Mission Directorate (STMD) has developed a lead-follower approach where water-ice is the lead path and O_2 from regolith is the follower
- Detailed report of many of the finding are available in AIAA-2020-4042

The Goal of this study was to

- Perform a case study of an end-to-end ISRU ice water system; choosing baseline architecture and technology selections to determine:
  - Mass and Power estimates
  - Sensitivity to key variables associated with architecture and water deposit characteristics
- Compare the estimates for a water-ice system to those of an O_2 from regolith system

Ground Rules and Assumptions

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- Production requirement is based on propellant production, H_2 and O_2 with a mixture ratio of 6
  - The Oxygen requirement is stated, but hydrogen is the driving requirement, excess oxygen will be generated
- Power systems are NOT included in mass.
  - The power needs are stated, but a power solution is not included in this study.
  - Mass does not include the power plant nor any associated power transmission or conversion systems
- Packing is not addressed
  - System volume is not offered here, though much of this information is available as it relates to mass. Packaging of hardware on landers or other platforms is addressed. Therefore structural supports their masses are not included, though margin is held for this.
- Communication and command/control systems are not explicitly addressed
  - Mobility subsystems include estimates for mass & power load
- Margins held at subsystem level
- System level thermal management systems are not included
  - Subsystems/components may include radiators, insulation, and/or allocations survival heat

Mixture ratio (O/F)	6
Total production time	225 days
Commissioning time	48 hr
Mass Margins	20% growth 15% structure
Power Margins	20% growth
Extraction Efficiency	75%
Maximum battery discharge	80%
Regolith density	1.3 g/cc
PSR Min/Max/Sink Temperatures	50K, 120K, 85K
Ridge Min/Max/Sink Temperatures	100K, 300K, 152K
Radiative sky temperature	4K
PSR Traverse multiplier for hazard avoidance	1.5 x
Excavator Recharge time	5 hr
Tanker Recharge time	10 hr
Battery Energy density	140 Whr/kg

Lunar Water ISRU Architecture

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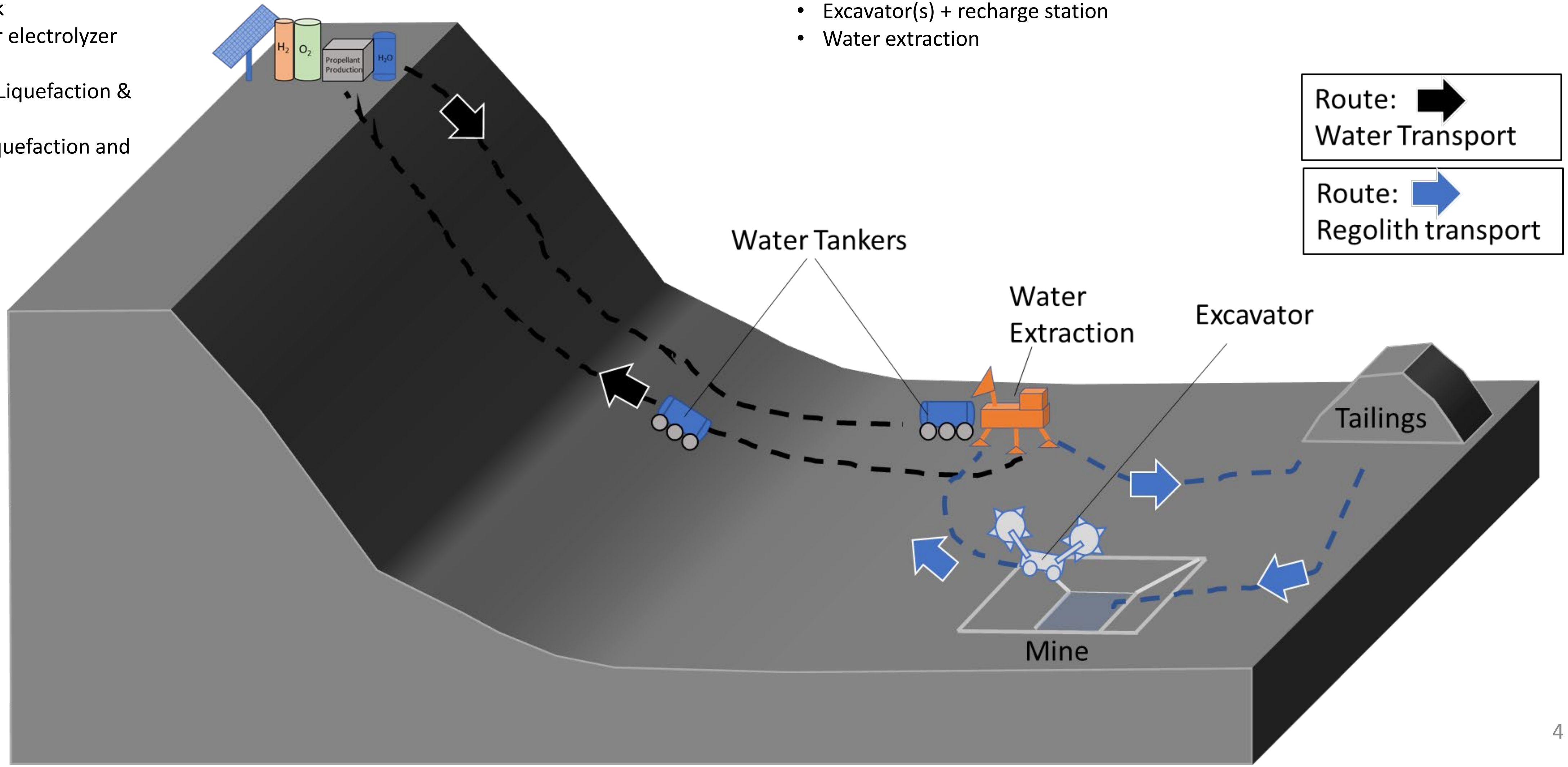
High Illumination Site ("Ridge") Propellant Production Site

- Water tank
- PEM water electrolyzer
- Gas dryers
- Hydrogen Liquefaction & Storage
- Oxygen Liquefaction and Storage

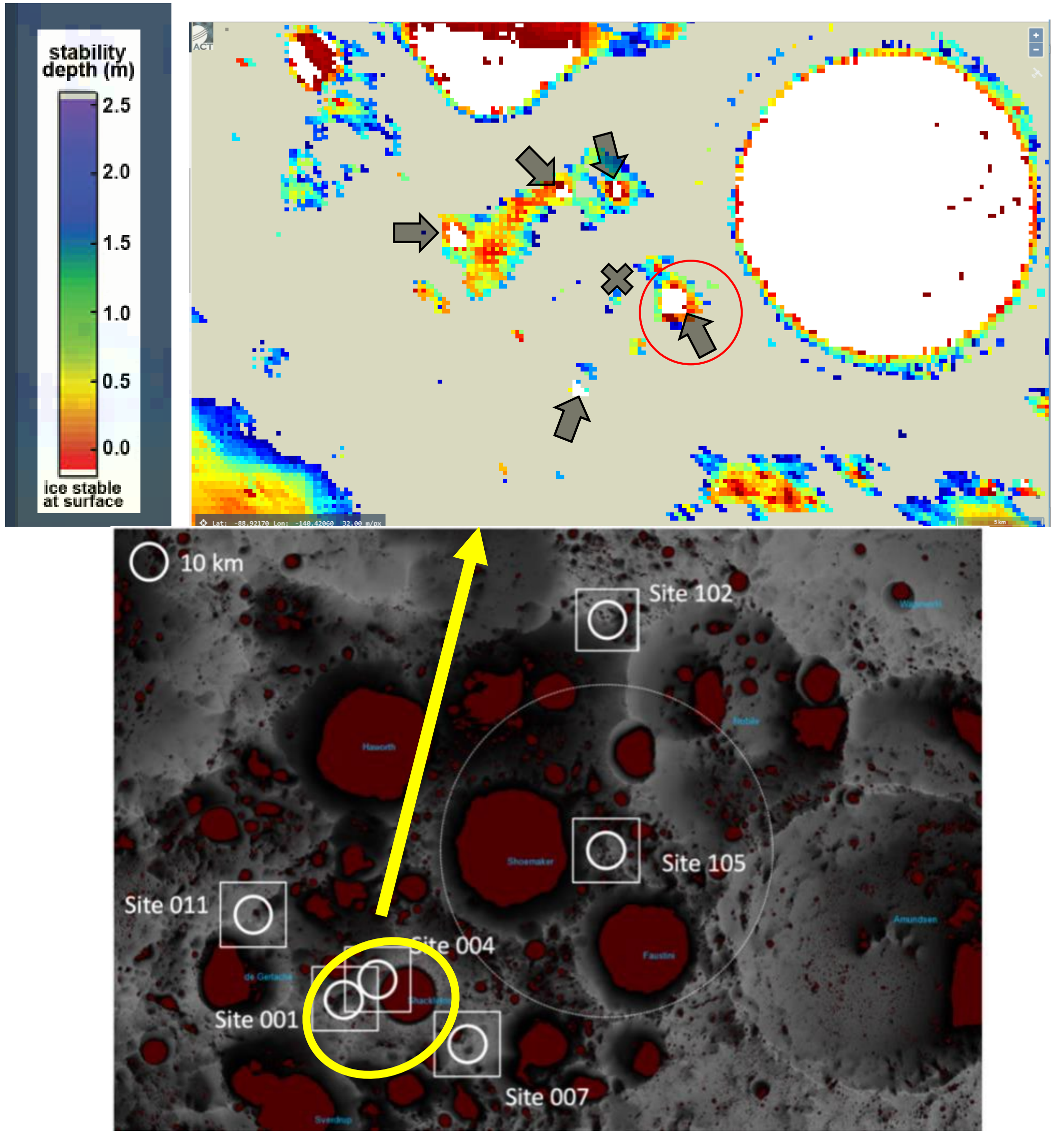
Permanently Shadowed Region (PSR) Mine site

- Excavator(s) + recharge station
- Water extraction



Notional site selection

- A baseline site was selected for ISRU operations to facilitate environmental assumptions for the model including temperatures and travel distances
- A water-ice deposit for ISRU has not been located and much is still unknown extent and distribution of lunar water ice. The notional site was selected based on:
  - Notional Human Landing Sites: regions of high illumination
  - Water stability and temperature maps using LROC Quickmap software
  - Slope and traverse distance to HLS sites
- Only near surface (<1m) water ice stability was considered; so mid to large permanently shadowed regions (PSRs) craters.
  - Water ice deposits of sufficient extent may exist outside these craters but were not speculated for this study



Notional site selection

Paths to HLS sites

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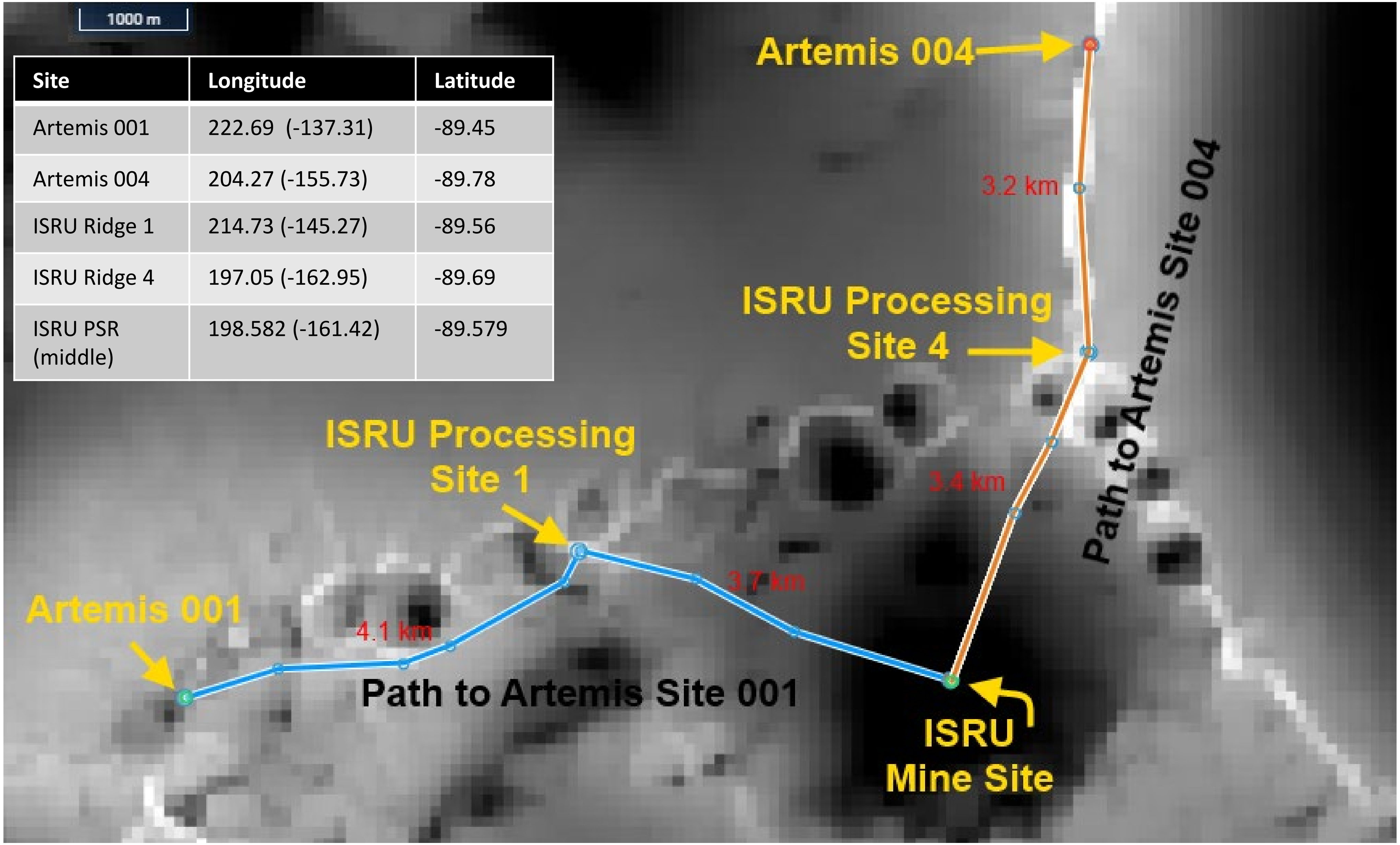
Site	Longitude	Latitude
Artemis 001	222.69 (-137.31)	-89.45
Artemis 004	204.27 (-155.73)	-89.78
ISRU Ridge 1	214.73 (-145.27)	-89.56
ISRU Ridge 4	197.05 (-162.95)	-89.69
ISRU PSR (middle)	198.582 (-161.42)	-89.579



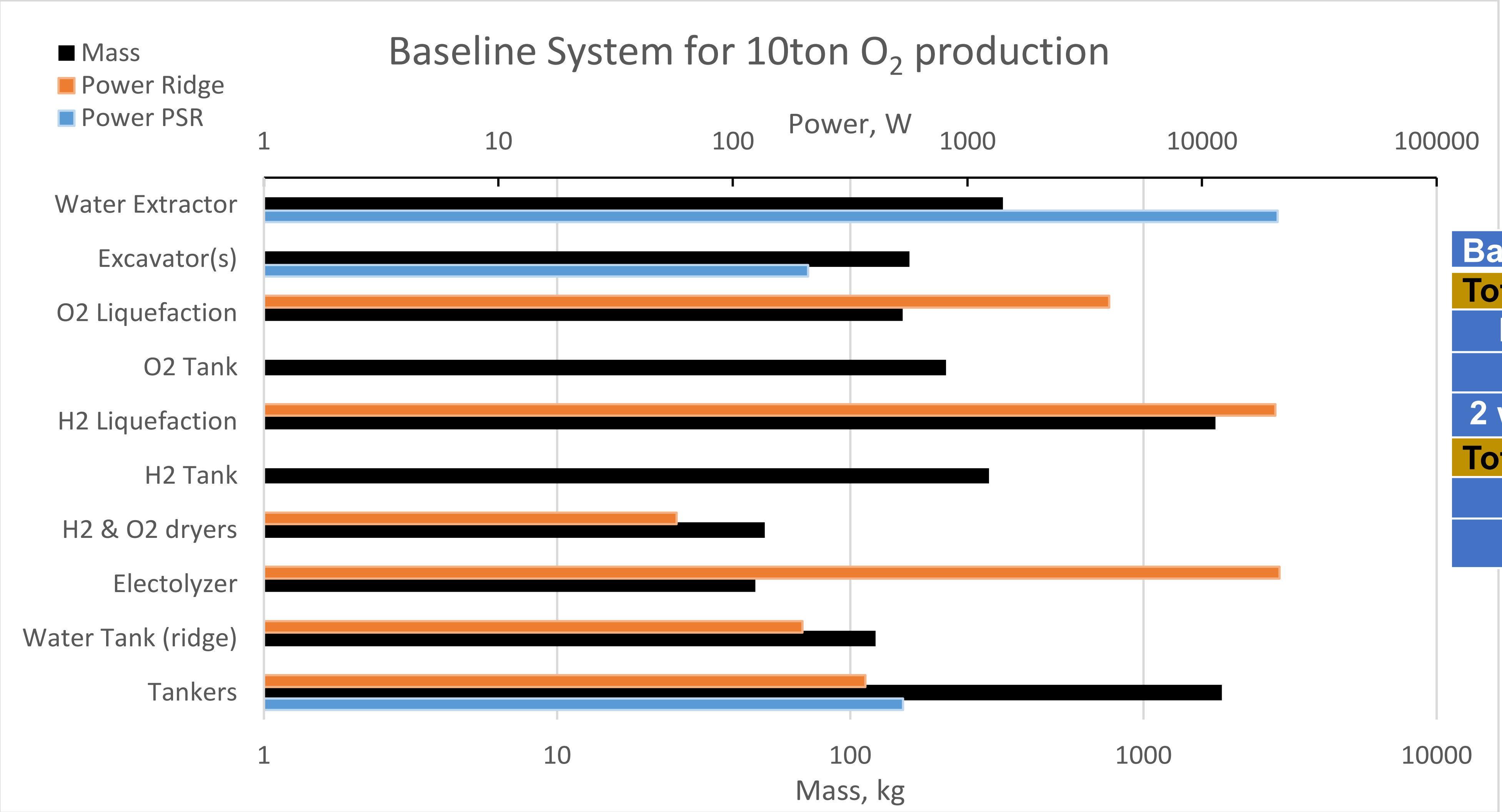
Revision: 225 day assumption

- The operational timeline assumption of 225 days was based on maximum illumination on the notional ridge area, as a starting point
  - The analysis shown in the following slides contain this assumption, even though this does not align with the site shown on the previous graphic.

- Further analysis of the region show that this illumination is only available at a few specific coordinates, which
  1. Limits flexibility of ISRU ridge site positioning
  2. Potentially requires co-location of ISRU propellant processing plant with other surface assets
  3. Extends traverse distances if current mine site is held

- Revisions to this architecture are being explored including
  - Adding Dormancy to operations
  - Exploring power sources options
  - Continued analysis/evolution of prospective ISRU sites

Baseline Case
Subsystem contributions



Baseline case: Results	
Total Mass	**4.9 tons**
Ridge System	2.6 tons
Mine system	0.49 ton
2 water Tankers	1.8 ton
Total power	**68 kW**
Ridge Power	46 kW
Mine Power	22 kW

Sensitivity Study

Parameter	Baseline		Reason
Production time	225 day	Decreasing time results in Increase Mass/ Power	System has to be sized for higher throughput
Production quantity	10 mT O_2	Increasing quantity for same production time Increases Mass and Power	System has to be sized for higher throughput
Depth to ice (overburden)	20 cm	Increasing depth delays the start of production: Stepwise increase to mass and power depending on excavator duty cycles	Number of excavators is variable based on timelines, if another excavator is required, stepwise increase in mass/power
Time between water transport	10 days	Increase time results in increase mass, minimal power impact	Longer time between trips requires a larger water tank. Power is in the recharge draw, which does not change much
Bulk Regolith water concentration	5wt%	Decreasing concentration increases mass and power, non-linear.	System has to be sized for higher throughput. When systems hit scalability limit, must add modules resulting in non-linearity

Comparison to O2 from Regolith
O2 system

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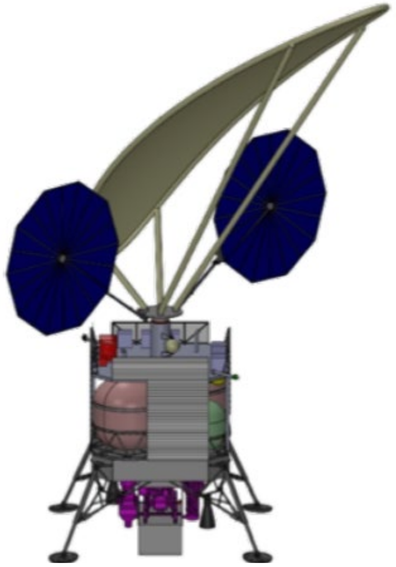
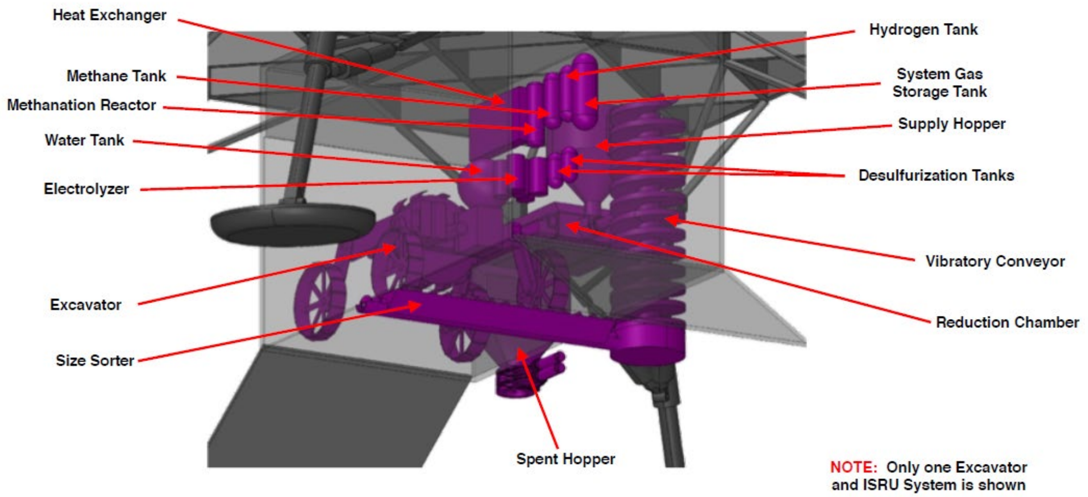
- Oxygen from regolith system from Ref. 2 with production rate of 10 mT of oxygen
- Target oxygen from the silicate minerals in the surface regolith using a Carbothermal reaction process
  - Reduction of oxides with a carbonaceous source (Methane) at temperatures in the range of 1650 -1800°C (regolith melting temperature)
  - Methane is recycled.
- Resource is ubiquitous and in readily accessible surface material.
- System assumed to be in region of high illumination and leverages direct solar heating
  - Solar concentrator for regolith melting
  - Solar array for electrical power
- This study included lander packaging





Linne, D.L., Schuler, J.M., Kleinhenz, J.E., Colozza, A., Fincannon, H.J., Suzuki, N.H., and Moore, L., Lunar Production System for Extracting Oxygen from Regolith. Journal of Aerospace Engineering. Submitted February 2020. PENDING.

Comparison to O2 from Regolith

Assumption differences

Mass

- The ISRU system, without the lander and bus was used for the comparison
- The O2 system included solar panels for power, this mass was subtracted since the water system does not include power
- The O2 system requires hydrogen from earth whereas the water system produces this. An approximation of the hydrogen mass and tank was added.

Power

- The water system power disregards thermal versus electrical power; assumes even thermal (heating) must come from electrical source
- The O2 system uses a solar concentrator to supply direct heating to the regolith for reaction.

Water Ice ISRU System		**O_2 from Regolith ISRU System**	
Total Mass	**4.9 mT**	**2.7 mT**	
Ridge System	2.6 mT	*ISRU system*	0.429 mT
Mine system	0.49 mT	*H_2 from earth*	2.3 mT
2 water Tankers	1.8 mT		
Total power	**68 kW**	**45 kW**	
Ridge Power	*46 kW*	*Electrical*	*11.8 kW_e*
Mine Power	*22 kW*	*Direct thermal*	*33.3 kW_t*

Comparison to O2 from Regolith

Results

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Water Ice	O_2 from Regolith
4.9 mT	2.7 mT *each successive mission will require 2 mT of hydrogen from earth, so mass favorably is lost at 2nd mission.
68 kW	45 kW
Resource is not yet characterized, exploration is required prior to operations to determine extent.	Resource is largely known from returned.
Highly reliant on location with accessibility challenges; likely requires higher traverse distances and some operations in an extreme environment (PSR).	The resource is very accessible and ubiquitous.
This case study requires operations at two locations.	Case study does full operations at one location.
Thermal energy for resource extraction is lower; water vaporization energy.	Thermal energy for resource extraction is high, requires melting of regolith
Use of non-electrical heat sources is challenging.	The system can use direct solar thermal heating to reduce electrical power.
Provides full propellant for vehicles. Water can also be used for other applications.	Only oxygen is provided.

Backup

Summary

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- A Case study was performed for a lunar water ISRU system to examine mass, power, conops, and sensitivities in order to enable infusion into mission architectures. The system assumed:
  - ISRU operations at 2 sites: a PSR and an highly illuminated Ridge site
  - Water was transported between the two sites using 2 alternating water tanker vehicles
  - Subsystem technologies with available empirical performance data were chosen, but may not be the optimum solution
    - A surface excavator was selected, necessitating a pit-mine approach to reach water rich regolith
  - Assumptions were made regarding resource distribution; 5 wt% water (bulk over mined depth) and a 20 cm dry overburden
- The study did not include a surface power solution, but power needs are stated
  - Thermal and electrical energy requirements were not separated
- The baseline system to produce 10 mT of O_2 and 1.67 mT of H_2 in 225 days was 4.9 mT and 68 kW
  - Water concentration of 1 wt% is not considered a viable solution
  - Increasing depth of the overburden results in step changes in mass and power, one occurs at >1m that results in an untenable solution
  - Increasing the number of water transport trips results in lower mass, but increases risk and wear in an currently unquantifiable way
- Extracting Oxygen from the ubiquitous silicate minerals is a lower mass and power solution (~2.7 mT, 45 kW) for the same production requirements
  - However, each successive mission will require an additional 2 mT of H2 from earth, so mass favorably is lost at 2nd mission

Subsystem Technologies

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Subsystem technologies with empirical performance data were preferred, so the selections are not optimized and are not decisional

Subsystem	Technology	Description & Reference
Excavator	RASSOR	A dual bucket drum excavator.[11]
Regolith hopper	RASSOR hopper	Designed to match 1 RASSOR bucket wheel for laboratory use; 2 are used in model.
Water Extraction	Auger Dryer	An auger is used to convey regolith through a heated casing. Sizing model based on terrestrial models.[12]
Water Tank for water tankers	Sized: (Aluminum, 50% ullage)	Calculated based on water capacity.
Water Tanker: Mobility platform	Sized	Calculated assuming a payload ratio 1.5 where all battery mass and water tank are payload.
Fluid Transfer	DTAU + COTS water pump lookup table w/flow rate	The DTAU (Dust Tolerant Automated Umbilical) [14].
Water Tank for Electrolyzer	Sized	Calculated based on water capacity.
Water Cleanup	TBD	Not currently included in model.
Electrolysis	Liquid Cathode PEM + COTS water pump lookup w/flow rate	PEM based on performance from NASA SBIR
Gas Dryer	Regenerative desiccant	JSC in house development hardware
H_2 Liquefaction	Cryocoolers	Modeled off COTS, includes radiator mass estimate
O_2 Liquefaction	Cyrocoolers	Modeled off COTS, includes radiator mass estimate
H_2 and O_2 Storage (Tanks)	Sized: Aluminum thin wall (3mm)	Calculated based on capacity.

Baseline Case

- The baseline case for this study targeted the production of 10 mT of Oxygen for use as propellant in an O_2/H_2 system at mixture ratio 6
  - Estimate for the amount of propellant needed to support a human scale ascent vehicle or lander; approximation based on current and previous architecture estimates
  - At this mixture ratio, using water electrolysis, hydrogen is the limiting factor: excess oxygen will be produced.

Baseline Case Key Inputs	
Water concentration	5%
Production requirement	10 mT O_2
Actual production	13 mT O_2 1.7 mT H_2
Water required	15 mT water
Regolith required (75% extraction efficiency)	398 mT
Mine size at 30cm depth	32m x 32m
Time to water transport	10 days

Baseline case: Results	
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Sensitivity Study

Regolith bulk water concentration

Bulk water concentration is water content over the mine depth. Includes any heterogeneities

- Values chosen are consistent with possible interpretations of Neutron data

- The water extraction system drives results.
  - Water extractor subsystem reaches scalability limit, so multiple units are needed; increasing mass and power particularly at 1 wt%
  - At higher concentrations there is less impact since minimum number of units is reached
- 1wt% is unlikely to be a viable ISRU water-ice deposit (for these assumptions)