Paths to Industrial Scale Lunar In-Situ Resource Utilization (ISRU)

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Astrion

Economic outlook of ISRU

In 2021, PWC Lunar Market Assessment confirmed the potential of ISRU investments through the 2030s for the Moon. It contains projections but acknowledge high undertainty and variability

In 2018, ULA made an announcement of a market price for O2 in cis-lunar space

These are possibilities but this is mostly a technology-driven enterprise with government and growing private interest.

Business environment and viability outlook

Characteristics of the recent demand figures for commodities

- O_2 as a commodity has often been benchmarked by NASA's target of 10 t / year as a production as an oxidizer for propulsion systems to enable return of spacecraft to cis-lunar space or even to Earth.
- O_2 is sought by expected owner/operators of large landers such as Blue and Space X. The publicly available numbers vary.
- Metals (Fe, Al, and Si) production targets are driven by technology milestones that NASA inserts in SBIR/STTR proposal calls.
- Private firms create also their own targets based on other potential markets perceived in cis-lunar space.

Business environment and viability outlook

Risks and competition

- Partnerships for lunar access
  - Those who have partnered aim to gather fundamental data on small sample processing
- Partnerships for surface power
  - No such partnerships have been announced

- International competition among developed nations and geopolitics play a role
- Cheaper transportation from Earth competes with production and transportation from the Moon
- Reusing spacecraft in cis-lunar space may compete with surface ventures economically

First operational scenarios – high priorities ISRU applications

- **O2 production only** (10 t O2 per year) (verify its origin – one MAV refueling). Rationale: Enable two-way transportation between Earth and Moon to assure return of samples, hardware, resupply parts and new equipment for production businesses.
- **Safe repeat landings and launch at same location**
  - Use of regolith at large scale in multiple applications (from woven glass fibers to molten bricks and regolith/composites)
- **Power generation and reliable nav/com**
- **Radiation shelters** (survival need and semi-controlled environment for com hub, maintenance, perhaps product depots

The challenge in these early scenarios is to keep their design robust and resilient by limiting the scope of their functionality.

- This is an early generation and we should not try to send multi-tools that try to do too much on one machine. Design for a critical function very well and robust and equip it with what it needs for nav, awareness and health diagnostics.

If something goes really wrong, send the replacement units. We are not going to achieve self-sufficiency on the first generation or the second.

First operational scenarios – high priorities ISRU applications

What do those companies need?

1. **Location, location, location**
    1. Resource location and reserve estimates
    2. Location of the spaceport that they will supply for X years and the power/com infrastructure they will rely on.
    3. Environment of the location (terrain, illumination periods, thermal extremes and durations, etc…
2. **Power**: Once you have power in place and you can grow that power and a safe zone to come and go from, you can start producing something. The synergy between the acquisition of regolith for O2 production and that of building pads and shelters is important.

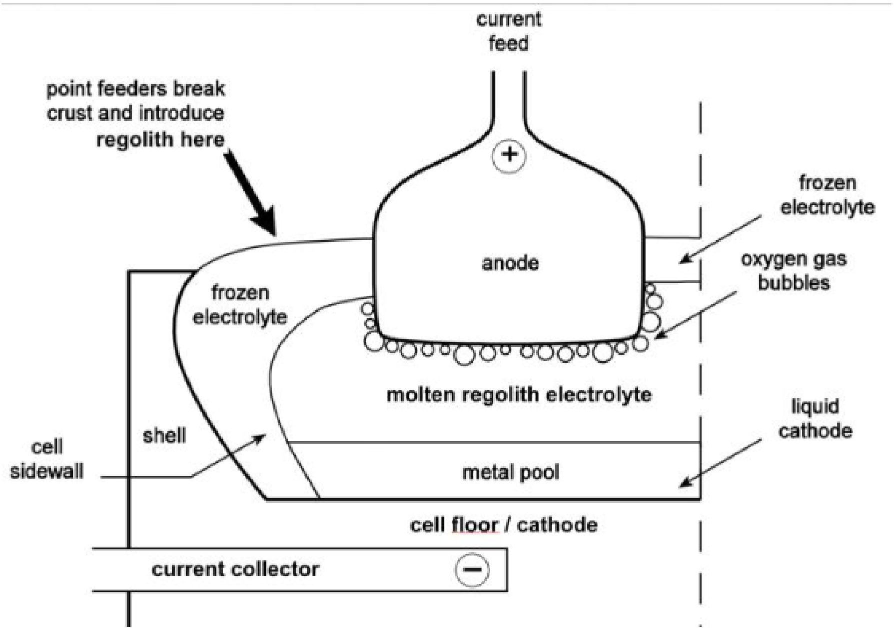
Advanced extraction technologies

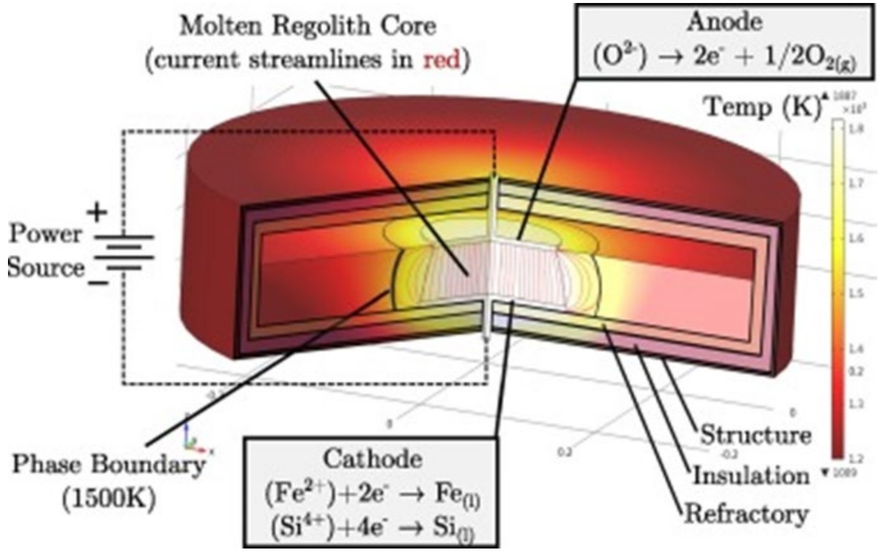
Major advances have been made in O2 extraction technologies for regolith

- Molten Regolith Electrolysis (MRE)
- Carbothermal Reduction of Regolith
- Hydrogen reduction of regolith
- Molten salt electrolysis of regolith

Many other technologies are of interest to researchers. These represent the major investments over the last few 3 decades.

Molten Regolith Electrolysis (MRE)





Based on D. Sadoway's patented molten Oxide Electrolysis, the MRE reactor design enables electrolysis of regolith into metal and oxygen without the need for fluxing agent, and without catalyst or consumable materials.

$$Regolith \rightarrow Metal + O_2$$

Produces oxygen and a ferrosilicon alloy, with other inclusions, that can be further processed.

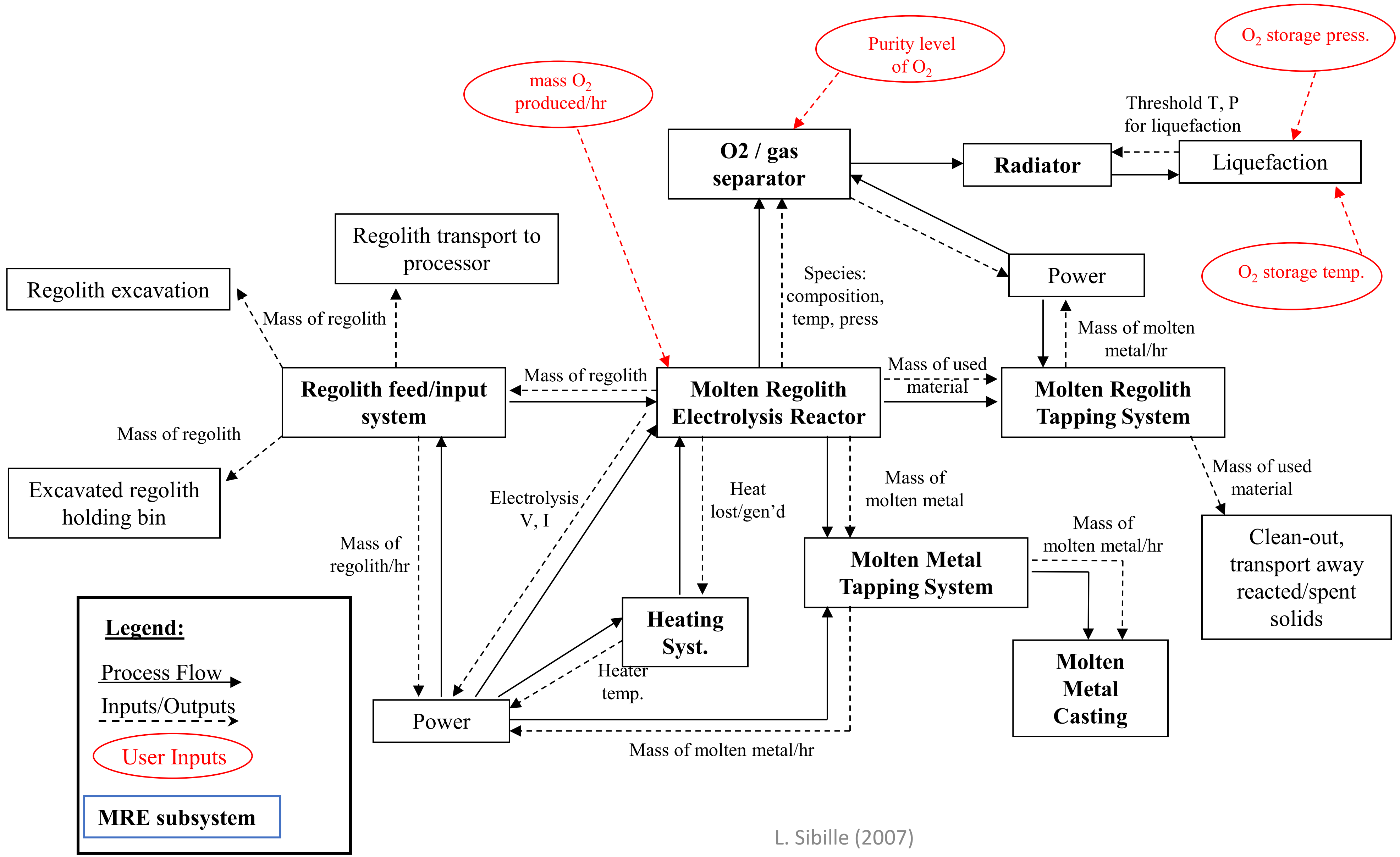
Operating temperature for MRE is set at (or above) 1600°C to keep regolith and metal products (ferrous alloys) in molten state. Temperature can be raised to increase yield.
Recent aluminum production reactors in development (MAGMA project - primary reactor feed aluminum electrowinning reactor).
Molten state of metal products allows the use of refining and post-processing techniques used in conventional extractive metallurgy.

Direct production of O2 requires only gas purification.

Challenges: Containment materials fail in corrosive environment of molten metals, regolith and high temperature oxygen. Repeat tapping of molten material to vacuum.

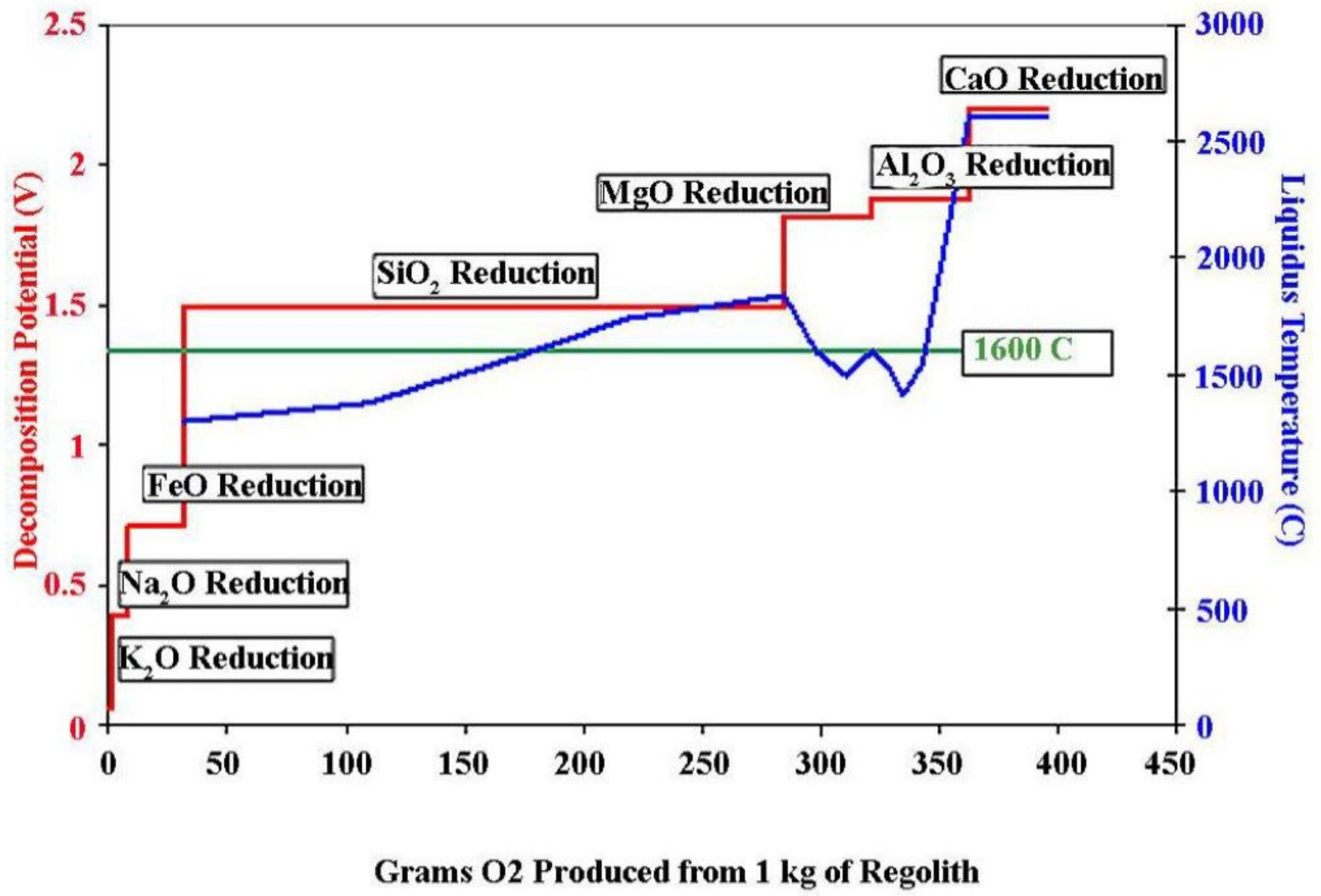
Development status: Integrated system tested in vacuum chamber at relevant scale. Sustained Joule heating and O2 production confirmed. Tapping system tested in ambient lab.

Molten Regolith Electrolysis
Information Flow (Inputs/Outputs)



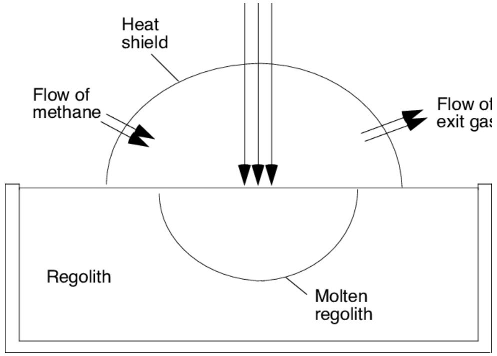
L. Sibille (2007)

Molten Regolith Electrolysis
Reduction yields and operating temperature



Poizeau/Sibille (2009)

Carbothermic Reduction (aka. Carbothermal reduction)



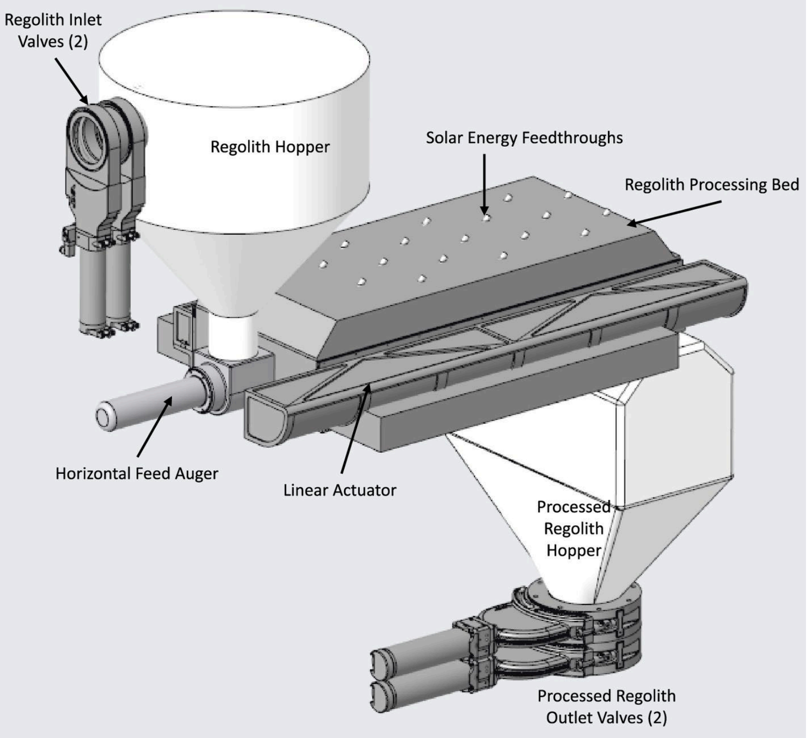
Pioneered by Gustafson & Rice (Orbitec, now Sierra Space), the carbothermal reduction reactor design enables multi-step production of gaseous O2 by first reducing regolith oxides molten locally under a flow of methane and electrolysis of the water produced.

$$MO_x + x\,CH_4 \rightarrow M + x\,CO + 2x\,H_2 \quad (1)$$

$$x\,CO + 3x\,H_2 \rightarrow xCH_4 + x\,H_2O \quad (2)$$

$$x\,H_2O \rightarrow x\,H_2 + 0.5x\,O_2 \quad (3)$$

$$MO_x \rightarrow M + 0.5xO_2$$



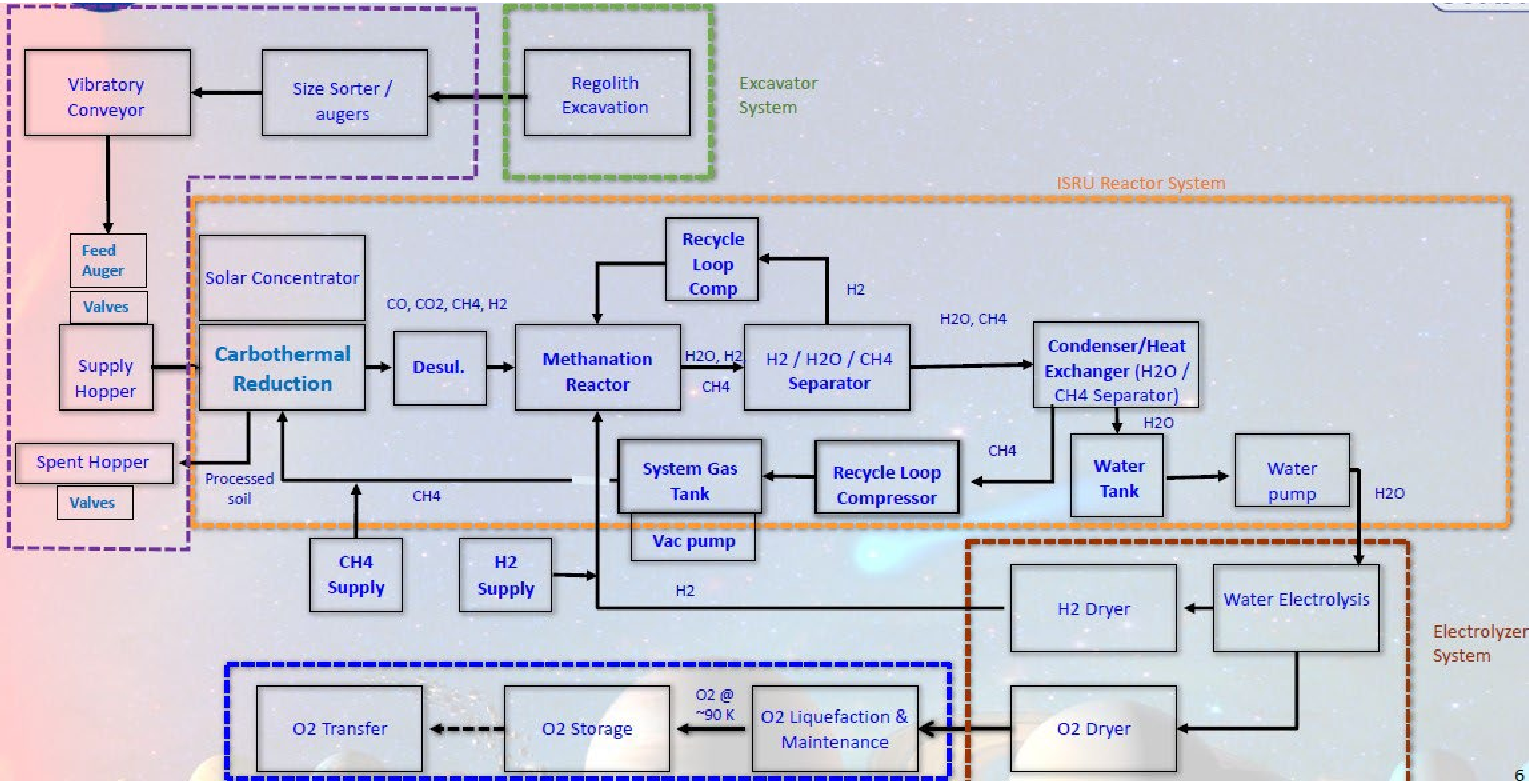
Produces oxygen and a ferrosilicon alloy, with other inclusions, expelled as as a solid.

Operating temperature is typically set at 1600°C to keep regolith in molten state and favor reduction of most oxides.

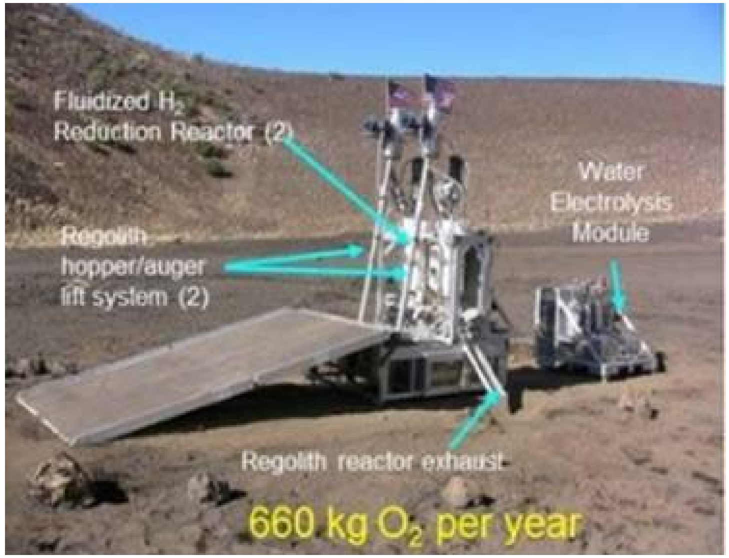
Challenges: Sensitivity to sulphur and high processing temperatures leading to loss of reagents, recovery of methane, multi-step processes (2 steps for O2 production), recovery of metals from oxide-metal solid, large number of subsystems (2 reactors, 2 reagents)

Development status: Reduction chamber with regolith handling tested in vacuum chamber. Reduction product confirmed. Single melt. Integrated system tested in lab environment.

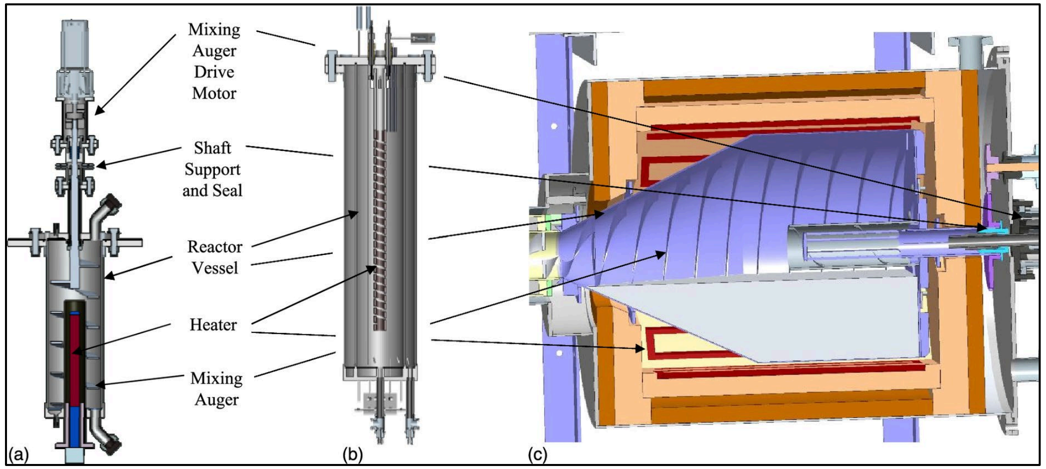
Carbothermal reduction (Process diagram)



Hydrogen Reduction of regolith



NASA – Lockheed Field Tests - 2010



Evolution in scale (Sanders, 2012)

The H2 reduction of regolith has been investigated since the Apollo era and has continued development in many labs. The reactor design enables direct reduction of ilmenite in mare regolith by hot H2 (~ 700-850 C) followed by electrolysis of water formed. Metal recovery (mixed in regolith oxides) is minimal so O2 is main product.

$$FeTiO_3 + H_2 \rightarrow TiO_2 + H_2O + Fe$$
$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

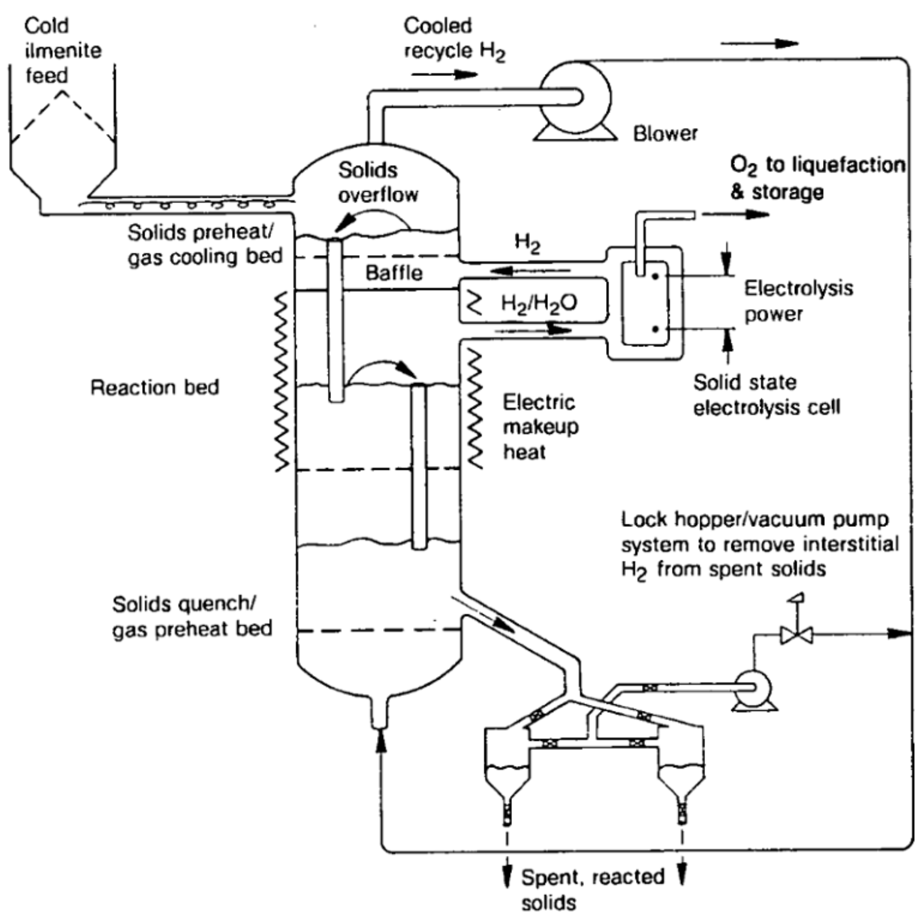
Produces oxygen and solid iron in oxide matrix enriched in TiO2 that can be further processed for Ti (No post-processing steps in development)

Operating temperature for MRE is set at (or above) 1600°C to keep regolith and metal products (ferrous alloys) in molten state.

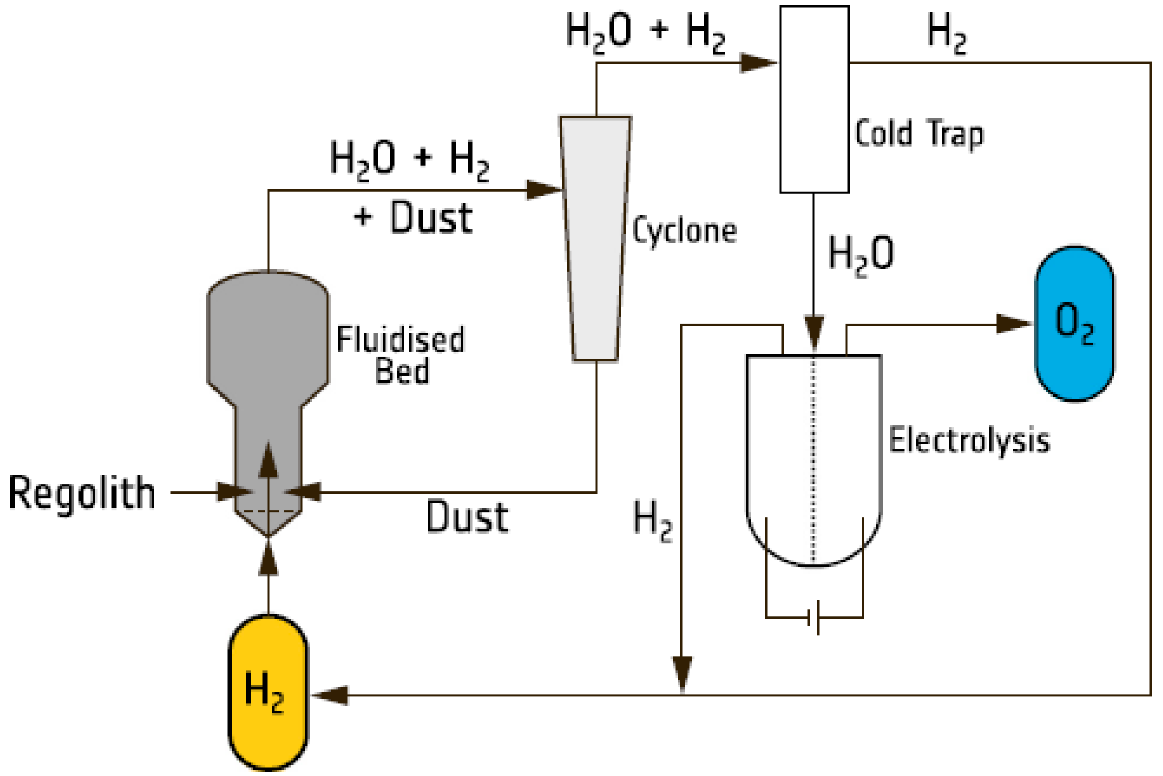
Challenge: Low yield, requires ilmenite concentrations, H2 embrittlement of containment materials , dust clogging in fluidized system, oxygen

Development status: Full scale PILOT field tests in ambient conditions (NASA/Lockheed, Hawaii, 2010). Multiple loading and removal operations. Recent development for European payload (ALCHEMIST). No integrated vacuum tests yet.

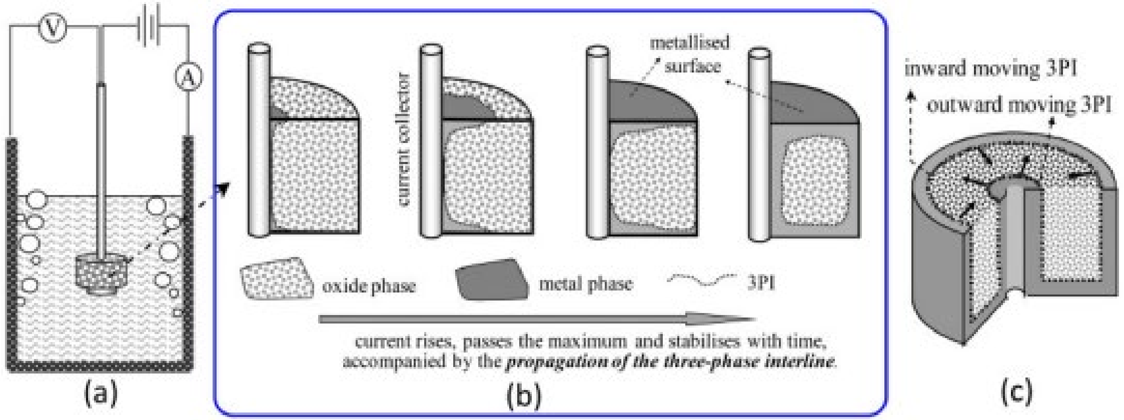
Hydrogen Reduction of regolith – Process

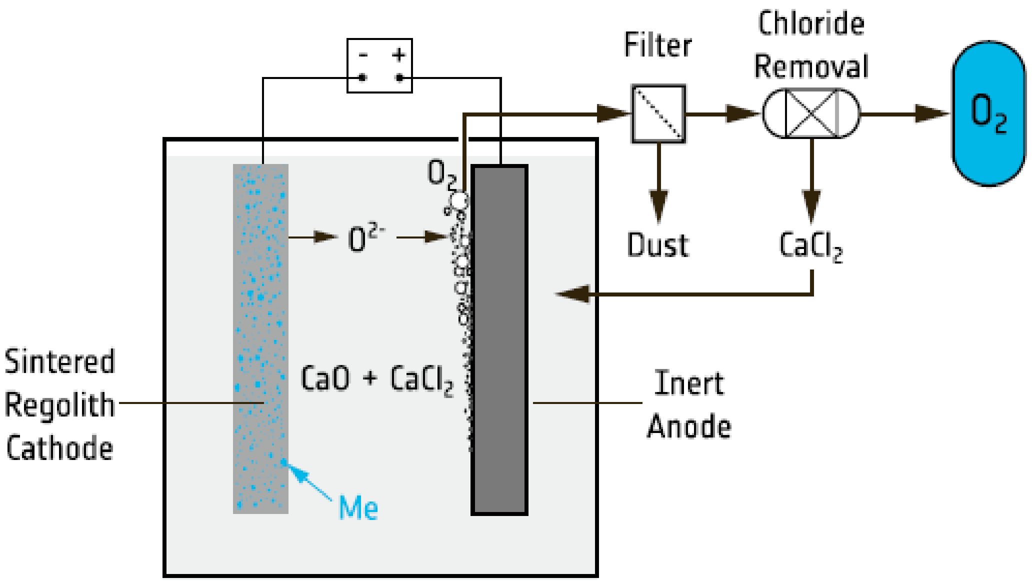


NOTE: Cyclones and possibly other gas-solids separators are also required but not shown.



Molten Salt Electrolysis of Regolith (Metalysis – FFC)





The FFC Cambridge process patented by Fray, Farthing and Chen and evolved as Metalysis is based on the deoxidation of metal oxides formed into a cathode caused by electrolytic transport of oxygen to an anode through a chloride salt electrolyte. The process aims to purify high value metals and can be applied to regolith processing.

At the regolith cathode, the process of deoxidation occurs:

$$M_xO_y + 2y\,e^- = xM + yO^{2-}$$

CaO participates in the process from the electrolyte and can enhance the reaction by calciothermy (reduction of other oxides by Ca)
Many intermediate phases form inside the cathode.

At the anode, O_2 is formed:

$2\,O^{2-} = O_2 + 4\,e^-$ in the case of an inert anode (SnO_2)
$C + 2O^{2-} = CO_2 + 4e^-$ in the case of a carbon anode
$C + O^{2-} = CO + 2e^-$

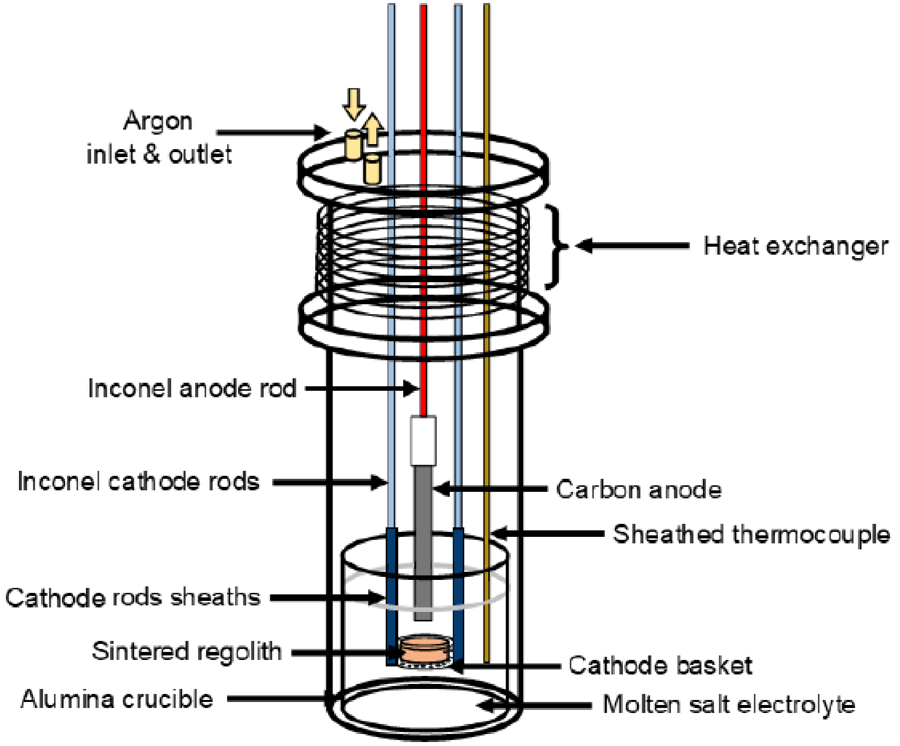
Produces oxygen and chloride and a complex partially reduced alloy, with oxide inclusions as a solid.

Operating temperature for FFC Cambridge can vary from 680 – 950 C with various electrolytes and varying current efficiencies from 20 to 85%.

Molten Salt Electrolysis of Regolith (Metalysis – FFC)

Challenges: limited kinetics at current TRL (45-60% O2 removal in 24h*) and multiple steps involved (forming regolith, recycling electrolyte, washing, solid metal with oxide as product)

Development status: Tests in ambient conditions with < 100 g of mare basalt simulants. Investigations in electrochemical process on-going. Integration of material preparation and post-electrolysis removal and handling not reported.



FFC Cell for regolith deoxidation (Meurisse, 2022)

Metalysis Process diagram (Metalysis, 2023)

Notional efficiencies for O2 extraction

- These efficiencies are for O2 only. They represent the yield from the total available O2 in the regolith.
- Metal yields are only being determined for the most advanced technologies and published quantitative data is not available.

Process	Temperature (ºC)	Bulk Yield (wt.%)	Reactants	Fluid Products
Hydrogen Reduction (Ilmenite)[12, 13]	800-1100	1-2	Iron oxides (ilmenite), H_2	H_2O
Carbothermal Reduction [14]	500-1800	9-20	Regolith, CH_4, H_2	H_2O, CH_4
Molten (magma) electrolysis [15]	1300-1600	30-35	Regolith	O_2
Molten salt electrolysis (FFC-Cambridge process)[16, 10]	825-950	40-45	Regolith, molten salt ($CaCl_2$)	O_2
Ionic Liquid (IL) electrolysis [11]	< 200	44	Regolith, IL	H_2O
Fluorination[9]	< 700	32	Regolith, F_2	O_2, F_2, other fluorides
Vacuum pyrolysis[16]	900-2500	6-23	Regolith	O_2

Bulk O2 yield from different extraction technologies (Ferreres 2021)

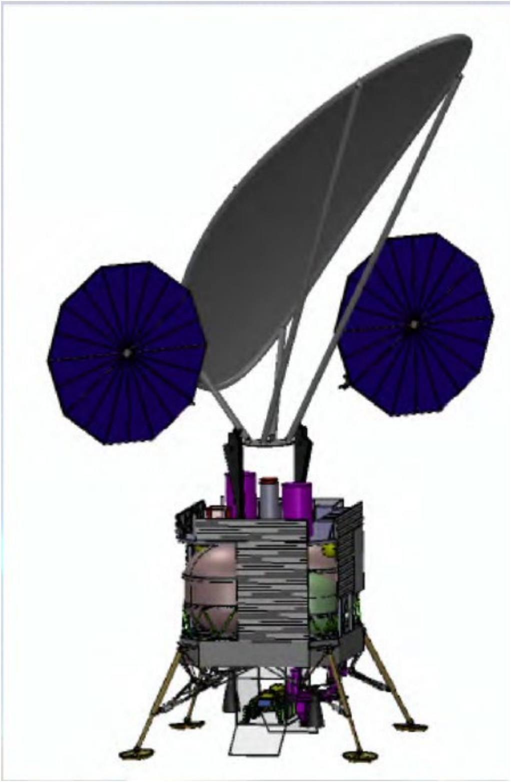
Early O_2 production scenario from regolith

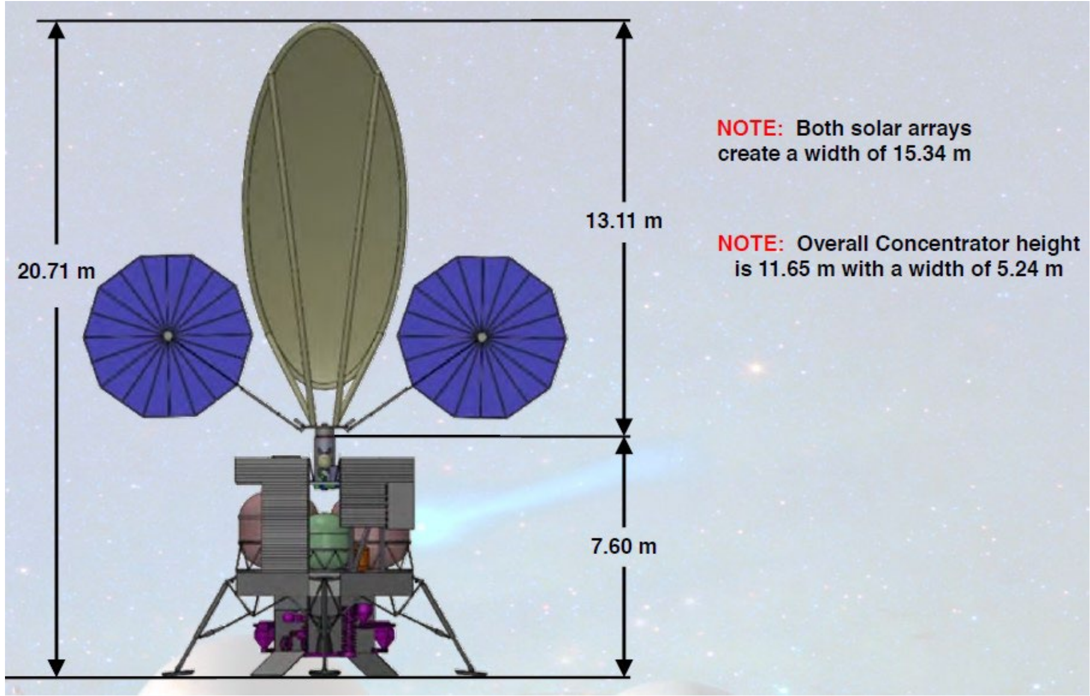
Production goal at 10 t O_2 per year (NASA notional target).

- 2020: Linne et al. develop a full concept study for a lunar ISRU pilot plant to meet the goal using a notional cargo lander with a 15-t payload capacity.
- Study developed a notional integrated system to fit on the lander:
  - Appropriate component sizing and packaging by CAD
  - Support systems for operations (solar electrical and solar thermal power, thermal management, avionics, cabling)
  - Mission assumes self-sufficiency (no other pre-deployed surface assts)
    - Onboard power fulfill needs
    - Excavator rovers on board
    - Regolith delivery and feed
    - Extraction method selected as Carbothermal Reduction
  - Site location: Polar region near Malapert crater with >210 days of illumination
- **RESULT: System would achieve 7 t O2 during 7.4 months of continuous sunlight with 15 t payload capacity**

Early O_2 production scenario from regolith: Carbothermal Pilot Plant

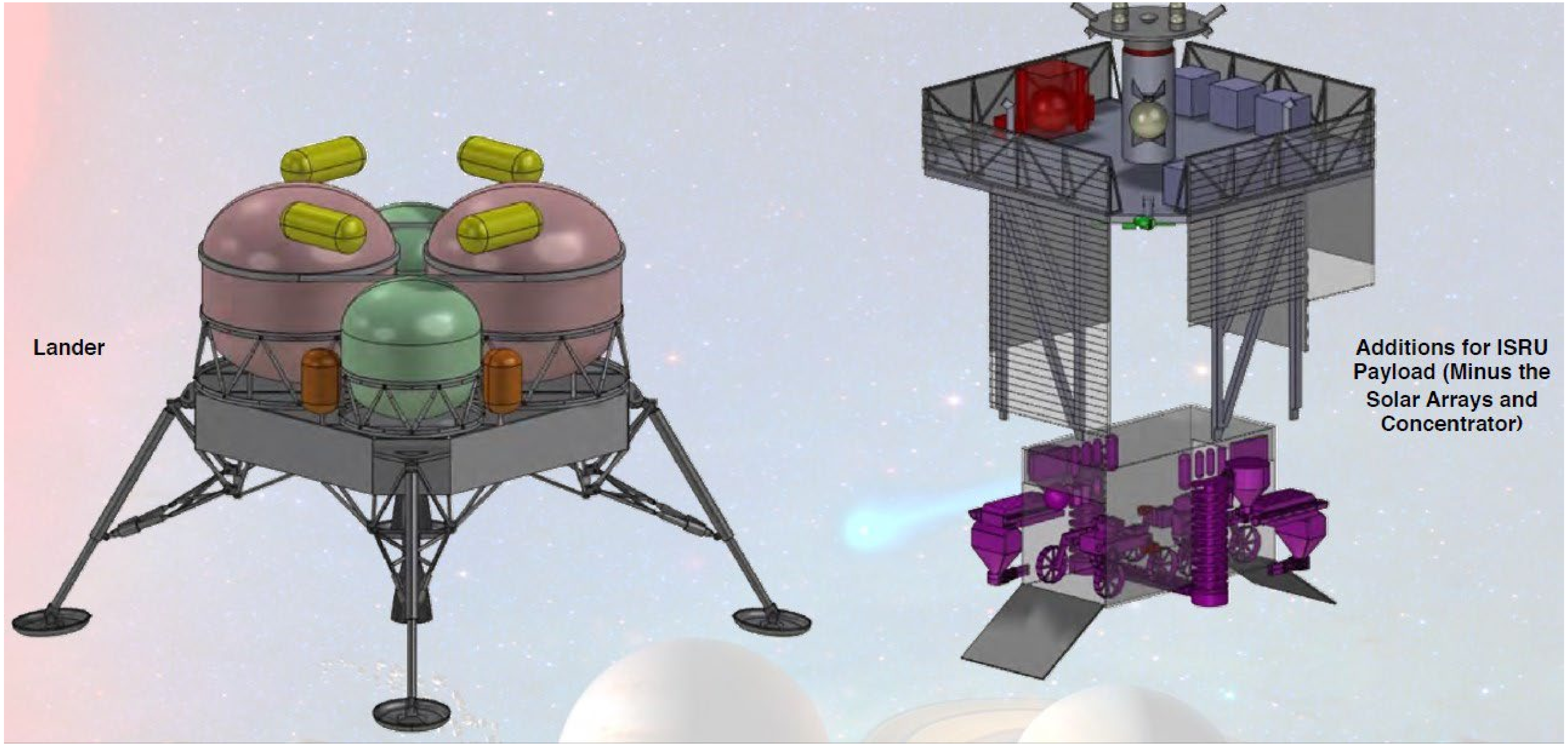
Full lander configuration for carbothermal pilot plant (Linne, 2021)





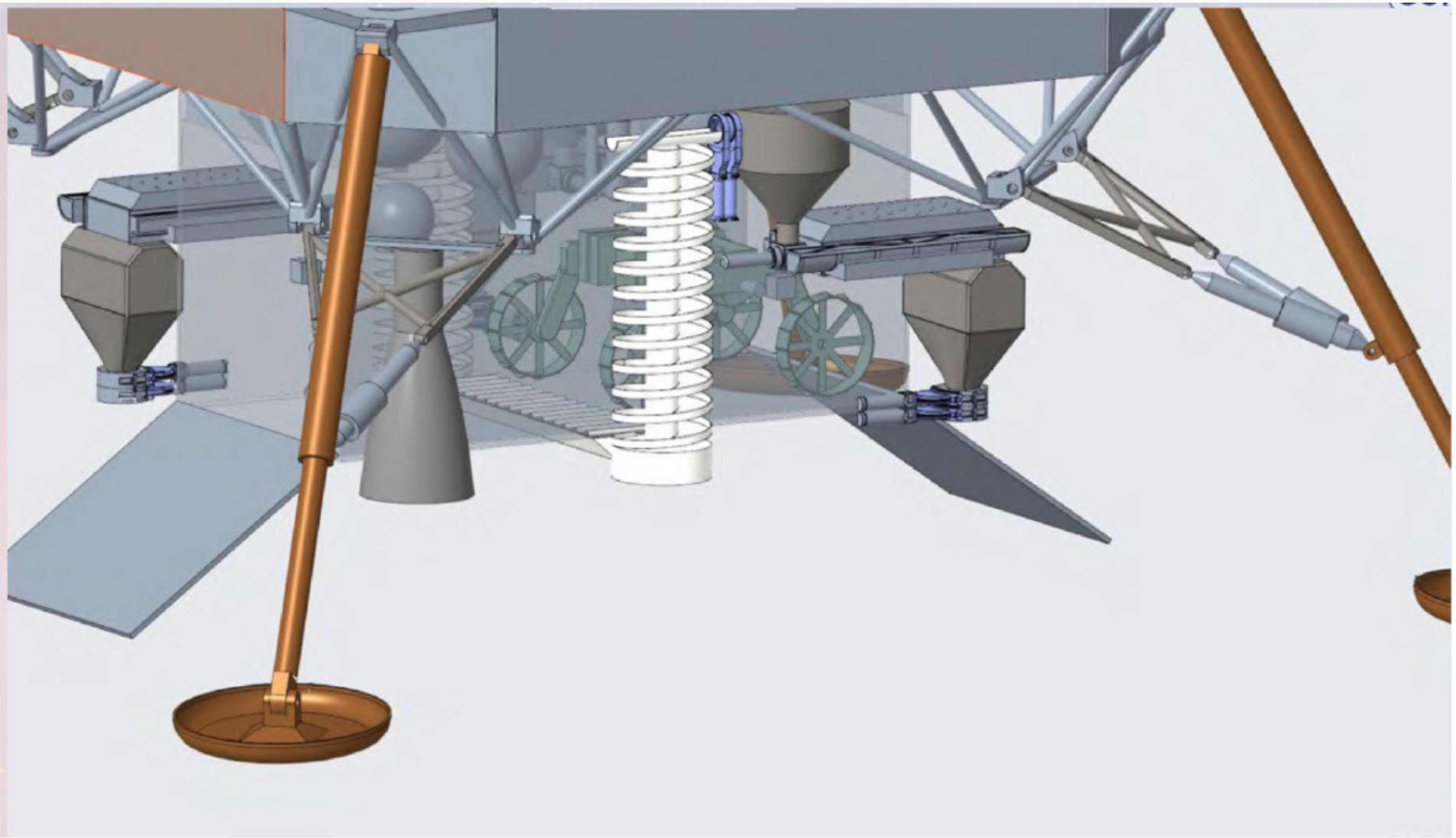
Early O_2 production scenario from regolith: Carbothermal Pilot Plant

Full lander configuration for carbothermal pilot plant (Linne, 2021)



Early O_2 production scenario from regolith: Carbothermal Pilot Plant

Under lander configuration for carbothermal pilot plant (Linne, 2021)



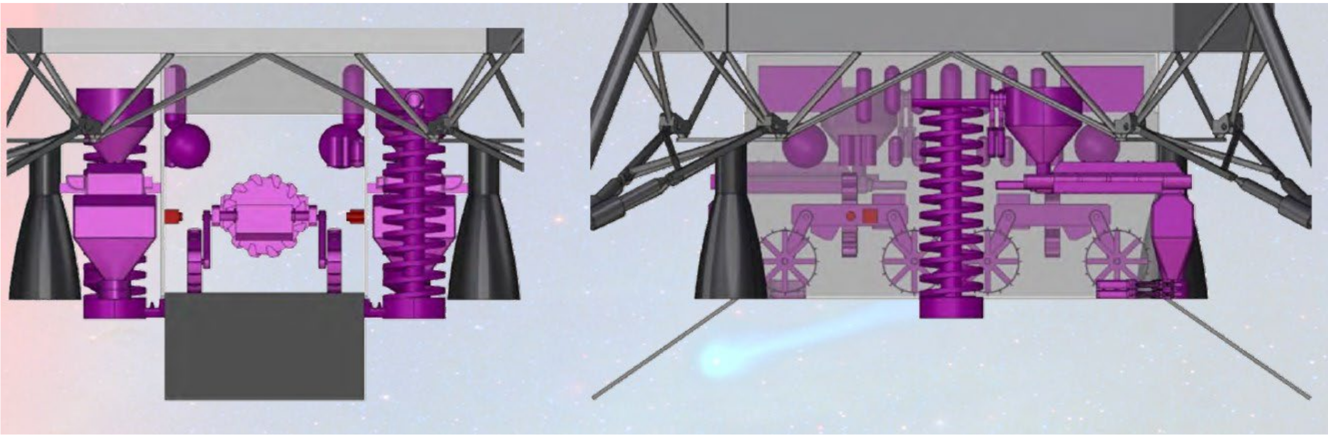
Early O_2 production scenario from regolith: Carbothermal Pilot Plant

Carbothermal Pilot plant mass estimates (Linne, 2021)

Description Case 2 ISRU CD-2018-162	QTY	Unit Mass (kg)	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
O2 Production			519.7	17%	86.9	606.6
ISRU Reactor System			193.0	19%	37.6	230.6
Methanation Reactor and Separator	2	10.7	21.4	20%	4.3	25.7
Desulfurization Subsystem	4	10.0	40.0	20%	8.0	48.0
Carbothermal Reduction Chamber	2	45.3	90.6	20%	18.1	108.7
Recycle Loop Compressors	2	0.4	0.8	20%	0.2	1.0
Condenser Heat Exchanger	2	4.3	8.6	20%	1.7	10.3
Hydrogen Tank	2	2.1	4.2	8%	0.3	4.5
Methane Tank	2	2.1	4.2	8%	0.3	4.5
Condenser/Electrolyzer Water Tank	2	7.1	14.2	20%	2.8	17.0
System Gas Tank, with Compressor	2	4.5	9.0	20%	1.8	10.8
Materials Processing and Handling			224.6	13%	28.9	253.5
Supply Hopper	2	9.5	19.0	20%	3.8	22.8
Spent Hopper w/ Valve	2	22.0	44.0	20%	8.8	52.8
Feed Auger w/ Valve	2	22.8	45.6	20%	9.1	54.7
Size Sorter Dump Trough w/ 2 Augers	1	36.0	36.0	20%	7.2	43.2
Vibratory Conveyor	2	40.0	80.0	0%	0.0	80.0
Electrolyzer			102.1	20%	20.4	122.5
Pump	2	1.5	3.0	20%	0.6	3.6
Electrolyzer Subsystem	2	38.9	77.8	20%	15.6	93.4
Dryer Subsystem	2	0.9	1.8	20%	0.4	2.2
Valves and Lines	2	9.7	19.4	20%	3.9	23.3

Early O_2 production scenario from regolith: Carbothermal Pilot Plant

Excavator mass estimates (Linne, 2021)



Description Case 2 ISRU CD-2018-162	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Excavator System			**212**	**21%**	**44**	**256**
Excavator			**200.0**	**20%**	**40.0**	**240.0**
Excavation and Processing			**200.0**	**20%**	**40.0**	**240.0**
Mobile Excavator with transverse bucket wheel	2	100.0	200.0	20%	40.0	240.0
Electrical Power Subsystem			**12.0**	**30%**	**3.6**	**15.6**
Power Management & Distribution			**12.0**	**30%**	**3.6**	**15.6**
DC to AC rover recharge	2	4.5	9.0	30%	2.7	11.7
Rover recharge coupling	2	1.5	3.0	30%	0.9	3.9

Early O_2 production scenarios from regolith

- The 2020 Carbothermal mission study showed the extent of hardware and complexity of a self-sufficient pilot plant for ~ 7 t O_2 for 7.4 months of continuous ops. The electrical power required would be 15 kWe with an additional 32 kWth from a concentrator
- Current estimates for a MRE system of similar capacity yield similar range of payload mass (~ 610 kg) for a production range of 8-10 t O2 during the same 7.4 months of continuous sunlight. In addition, the MRE system would yield molten metal alloy ingots.
- Extension to other O2 producing system will require more data from developers (non-published or published) at the right scale.
  - Given their levels of complexity (number of subsystems and steps) similar to carbothermal, the results may be similar or greater for payload mass.
  - However, the major differences in kinetics and yields will greatly decrease the production rate per year for an equivalent payload mass.

Early O_2 production scenarios from regolith

Beneficiation systems are not included in these calculations.

- The quantitative benefits have not been determined for many extraction techniques
- The benefits are not known for MRE and carbothermal that both access a wide range of oxides in the non-beneficiated regolith.
  - So far, MRE has performed well in processing highlands and mare materials with similar yields and efficiencies. Site mineralogy is an important data for reactor parameter control and modeling during operations (digital twin).
  - Carbothermal may benefit from enriched iron content and data on minor chemical compounds such as S, and other volatiles may be very important for process performance and adjustment (operating T, mass flow, etc..)
- Site specificity and knowledge will be very important for other technologies and beneficiation for feedstock enrichment is likely to be needed.
  - H2 reduction requires high ilmenite concentrations to be effective and volatile content is important for gas processing
  - FFC – Metalysis will benefit from beneficiation for cathode fabrication and expected performance

Production scenarios – First targets for raw commodities

- Production levels may require more than one reactor for several reasons:
  - Design constraints
    - Transportation and offloading limits (lander capacity, payload arrangements, fairing dimensions, offloading equipment capability)
    - Low kinetics and multiple parallel operations of subsystems (e.g., cathode manufacturing and removal)
    - Thermal management
    - Power availability (current capacity, power interface standards)
  - Redundancy and operational safety
    - Production level assurance require uninterrupted production during power availability periods (power allocation is always a constraint, whether it is driven by power sharing or generation and storage limits)
    - 3 reactor concept has been studied to target 2/3 of the production rate at any given time at a minimum. Reactors also would be sized to handle the demand production with capability margins (e.g. a 3t/y reactor would be capable of 5t/y)
    - Regolith delivery points can also choke and may be multiplied for redundancy with transport lanes that can connect to any reactor
    - The same applies to product refinement systems, and customer delivery points, power source connections depending on how much risk is accepted or mitigated.

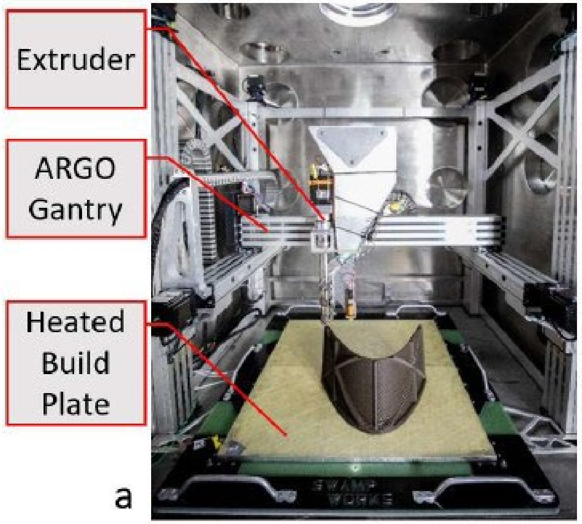
In-situ construction through ISRU scenarios – High priority in early phase of infrastructure

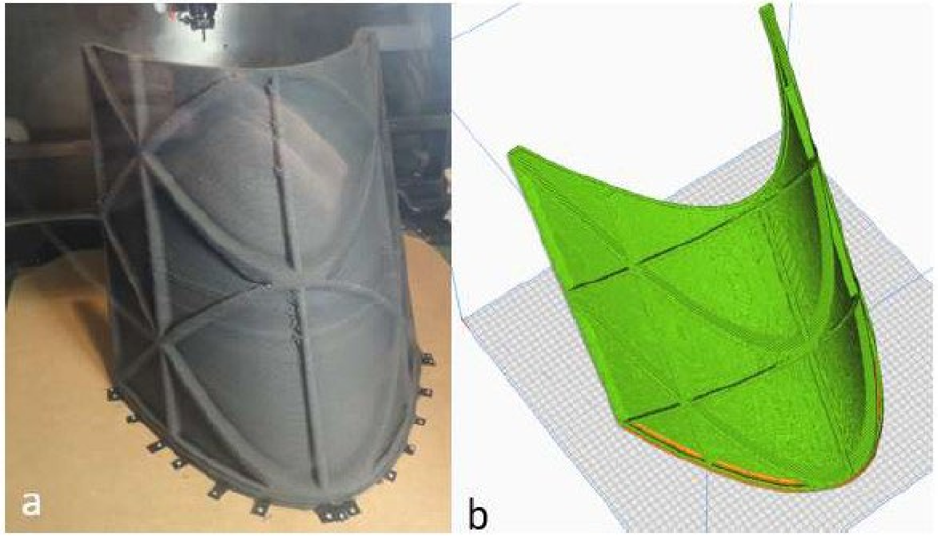
- Landing / Launch pads and port infrastructure
  - No time to cover the reasons for the need to protect from engine plume impacts
  - Notional pad needs (50 m diameter possibly for large landers)
  - Numerous techniques in development (some in advanced testing at relevant scale)
    - Astroport – Molten regolith brick formation and deposition
    - Mason/Redwire – Microwave sintering on surface
    - Space Factory – 3D printing of regolith/polymer blend
  - Verification and validation tasks will likely become critical as the pad could be discussed as a source of liability between pad constructor and lander operators.
  - Associated ISRU/"Lunarwork":
    - Berm building and terrain shaping
    - Trenching
    - Off-pad road building for moving small one-way landers
  - <u>Site selection and mineralogy sensitivity</u>
    - Requires co-development of site surveying, site grading, and high precision positioning, navigation for completion
    - Mineralogy and volatile content will impact many transformation processes

In-situ construction through ISRU scenarios – High priority in early phase of infrastructure

Unpressurized shelters

- Express need and criticality
- Enable process demo without path criticality thus paving the way for in-situ growth and maturation of several ISRU systems
  - Regolith excavation and delivery
  - Regolith processing
  - 3D design based on in-situ measurements
  - 3D printing
  - May be coupled with foundation work if needed for seismic isolation





Sub-scale regolith/polymer shelter model fabrication in vacuum (Gelino, 2024)

In-situ construction through ISRU scenarios – Unpressurized shelters

Rendering of regolith/polymer shelter fabrication LINA on lunar polar surface (Space Factory, 2024)

Section II
challenges for early phases and growth of Lunar ISRU

From technology feasibility to operational readiness in ISRU

First contact and performance degradation through limited operations:

- Mars and Lunar rovers:
  - Traverse challenges – wheel damage, immobilization (Mars, Lunokhod)
- Apollo suits and drills
  - Dust invasion of glove joints
  - Drill abrasion and seizing

Rendering of surface operations (Sanders, 2018)

From technology feasibility to operational readiness in ISRU

- Systems interfaces: critical paths and risk posture
  - Umbilicals
  - power connectors
  - avionics, sensors,
  - rover wheel actuators, arms are exposed interfaces

RASSOR / IPEx precusor in action (Schuler, NASA KSC Swampworks 2023)

From technology feasibility to operational readiness in ISRU

- Transition from roving for science to mining

  Excavators like IPEx are designed for 40 cm/s hauling speed with 70-90 kg of regolith

  Recharging capability on the order of 500 W in 70 minutes

  IPEx (ISRU Pilot Excavator) has completed a full mission run of 5 days in ambient. Drum tests have been completed in lunar G/vacuum.

  Ready for TRL 6.

What is lunar ISRU industrial scale? Transition from readiness to resiliency

- Evolution of scale (10t, 50t, 100t O2 per year, metal demand: casting a few wheels to building a new shelter from aluminum or regolith/composites.
- The scale will be dwarfed for a long time by anything the mining sector does on Earth except for small tonnage metal recycling
- Industrial Lunar Mining and ISRU may have unique characteristics:
  - Small units with highly redundant interface points
  - Intermittent production periods
  - Dormancy and restarts with technology replacements (Phase-in concept)
  - In-situ production capability of given commodity may progress in steps (positive or negative) because of demand variability, technological progress, and power and com growth and availability.

Longevity & life cycles: Direct lunar application of terrestrial mining knowledge

The mining sector experience points to major impact factors to longevity and life cycle of equipment under terrestrial conditions:

- Excavators and mineral processing equipment

Abrasive Material	Impact on Excavator Components	Range of Wear Rates for Comparable Steels	Range of Wear Rates for Comparable Aluminum Alloys
Quartz/Silica	Rapid wear on bucket teeth, hydraulic seals, and undercarriage parts due to high hardness	0.8 - 1.2 mm/year	1.5 - 2.8 mm/year (Al6082, A356)
Granite/Basalt	Significant impact and micro-chipping on cutting edges and thrust components	0.5 - 0.9 mm/year	1.2 - 2.5 mm/year (Al7075, Al6082)
Sandy, Grit-Rich Tailings	Persistent abrasive action on tracks, conveyor chains, and bucket edges	0.6 - 1.0 mm/year	1.3 - 2.6 mm/year (A356, LM25)
Abraded Slurry	Erosive wear through hardened deposits that act like a grinding medium on surfaces	0.7 - 1.3 mm/year	1.4 - 2.9 mm/year (Al7075, A356)

  - Local variations in mineralogy, adhesion of fines, vacuum and charge effects, thermal cycling of working metals will challenge regolith mining and transport equipment in unexpected ways

- Extractive equipment
  - Vast experience in extractive metallurgy guides the way (materials, assay methods, command & control)
  - We don’t know yet what will get us in lunar ops – mineralogy of the feed, impurities accumulation, local thermal sinks, gas separation in low G, molten flow management.
  - Applicability of terrestrial methods may be hampered by scale-down limitations for lunar equipment and require innovative breakthroughs (flow control in low G, vacuum/process interface)

Industrial lunar ISRU: How much do we need to borrow from terrestrial mining approach?

- The images of industrial scale activity on the Moon depict a multitude of machines and infrastructure elements all working together. A lot is missing from those pictures:
  - Breakdowns and forced maintenance
  - Machines being repaired on site or towed away
  - Interrupted production or commodity route blockage by malfunctioning hardware
  - Deployment of shielding or additional power on site
  - Incidents and their responses: protection of other equipment, isolation and shielding, activation of redundant systems, etc…
- ISRU site planning and management infrastructure
- Dedicated support assets versus complex multi-purpose machines, redundancy and maintainability through modular designs

Industrial lunar ISRU: Adapting to unique conditions using terrestrial mining approaches

Lunar ISRU will face challenges from usage timeline and operational density

- Usage timeline: Duration and frequency of use/dormancy
  - Some systems cannot go dormant for long (trapped molten material freeze) leading to competing risk scenarios (draw more from shared power or accept long repair/recovery).
  - Regolith left in augers, in stopped hoppers may become dense over time (vibration, thermal cycling) or molten material solidifies in trapped areas. Linked to resiliency and longevity
- Operational density: number of functions in a system executed during a time period.
  - Example: excavators may work hard for 3 hours and go dormant for 8 hours.
  - How many systems are interfacing through exchange of physical commodities at a given time?
  - Impacts power and communication demand and affect reliability and longevity of working systems
- The site location and layout will play critical roles (mine planning):
  - Frequency and duration of solar illumination impact solar energy harvesting and thermal management
  - Traverse distances and terrain impact efficiency of repair and maintenance cadences

Industrial lunar ISRU: Does everything have to be done outside?

An evolutionary path for Lunar ISRU may be to delay exposing complex operations and technologies to the environment

- Terrestrial mining uses the approach along the chain of operations:
  - Mineral processing (milling, some beneficiation, chemical separation, assaying) and extractive processing (furnaces, ladles, tundish, pours, shaping) are done inside housing to protect from the environment (rain, lightning, winds, dust) and for operational security
- Low pressure, non-vacuum lunar processing enclosures would:
  - Protect from major environmental fluctuations and impacts (dynamic thermal gradients, illumination,
  - Allow the mitigation of impacting the surrounding lunar environment that is important for scientific research (exosphere, ground contamination) and other operations (heat dissipation from reactors create high IR values for sensors
  - Enable thermal management of processes in milder conditions
  - Enable easier access for maintenance and repairs
  - Create less constraints on product extraction from processing reactors.
  - Can be limited to a segment of the process (e.g., reagent recycling, pre-process sintering, removal of metal products)
  - May make operational security and IP protection more manageable

The value of such approach would have to be evaluated technically, operationally and economically to determine viability

Conclusions: Paths to resilient and reliable lunar ISRU

A clear purpose for lunar ISRU needs to emerge.

Purpose will drive demand for ISRU and regulatory and social/ethical frameworks will lead to resiliency

Technologically, the concept of ISRU can support a finite era of lunar occupation by humans using robotic activities.

Economically, during that era, several business cases will emerge as sustainable through both government – private contracts and private – private contracts.

Currently, no clear purpose is being articulated to invest in a permanent expansion of human presence and activities on the Moon with clear benefits for humanity.

In contrast, the purpose of sustaining humanity on Earth drives terrestrial ISRU through mineral and energy mining and its products are critical to that purpose.

Focus on hardware robustness and repurpose-able as early as possible

- Parallel generational evolution build reliable production capability as technology and operational knowledge evolves
- Phase-in of new technologies with ability to reuse modular elements

Section III: Critical path knowledge and capability demonstrations

Specific data would accelerate development of ISRU systems

From orbit to ground assessments

Orbital maps of Moon are extraordinarily valuable

- Allowed all the progress so far in ISRU concepts and feasibility assessments
- These products have resolutions on the order of 100s m/pixel
- The Apollo samples provide connectivity from regional scale to ground local

Terrestrial mining projects require a very stringent and exhaustive data collection with validation process to establish reserves for investment purposes

- We need to know what we will find, and what is the geological context of the regolith to be acquired. The level of confidence in that data is paramount
- The prospect analysis process used in petroleum exploration may be useful for water reserve but probably too overbearing for early ISRU on the Moon
- Targeted regions determined by orbital data need to be explored with low level multispectral surveys (International Lunar Resource Prospecting Campaign)
- The level of volatiles need to be understood at the local scale to enable multiple ISRU technologies to evolve in single site

Specific data would accelerate development of ISRU systems

The environment on the surface needs to be mapped in many dimensions and in sufficient detail

- Combined layered maps
  - topography – illumination - electrical maps and forecast (dynamics with Earth-Moon-Sun phases)
  - This will require a lot of surface knowledge to be accumulated over time
    - Start now: It affect communications and navigation now (recent landings are prime example)
- These products need to also add to our sporadic knowledge of the geotechnical properties of the regolith and its subsurface
- Expand knowledge through visual and sensor observations of the behavior of regolith under early subsystems capability demonstrations
  - Trenching, excavating, hopper and transports
  - Document triboelectric charging effects on hardware performance
  - Tie this to site mineralogy
  - Conduct relevant scale demonstrations even of partial extractive systems
- Operating within a site with precision will be an early need

Specific data will build confidence to fund development of ISRU systems

Types of knowledge will be key for investors to show clear interest in ISRU development/deployment

- A clear vision of a market in development with phase transitions that make sense
- The risk environment is very vague and opaque at this time. We do not know muc about how complex, hard-working systems will successfully deliver over time.
- The classification of resources with verifiable and secure data
- A system for verification and validation of commodity production and delivery per specification
- What positive exit points exist in ISRU business plans?
  - Is asset sale on the lunar surface a viable concept?
  - Is accumulated data valuable enough to other actors to recoup large investment?