DARPA LunA-10 TA-1
LSIC Spring Meeting, Initial SCR Summary

April 25, 2024

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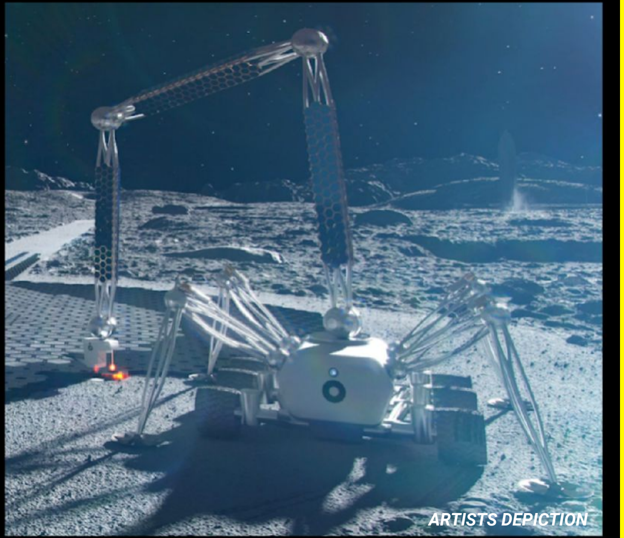
ICON's Olympus system is a multi-purpose construction system primarily using local Lunar resources as building materials to further the efforts of NASA as well as commercial organizations to establish a sustained Lunar presence.

ARTISTS DEPICTION

Our goal is to build infrastructure off-planet… …starting with the moon.

Lunar demonstration to close lab testing

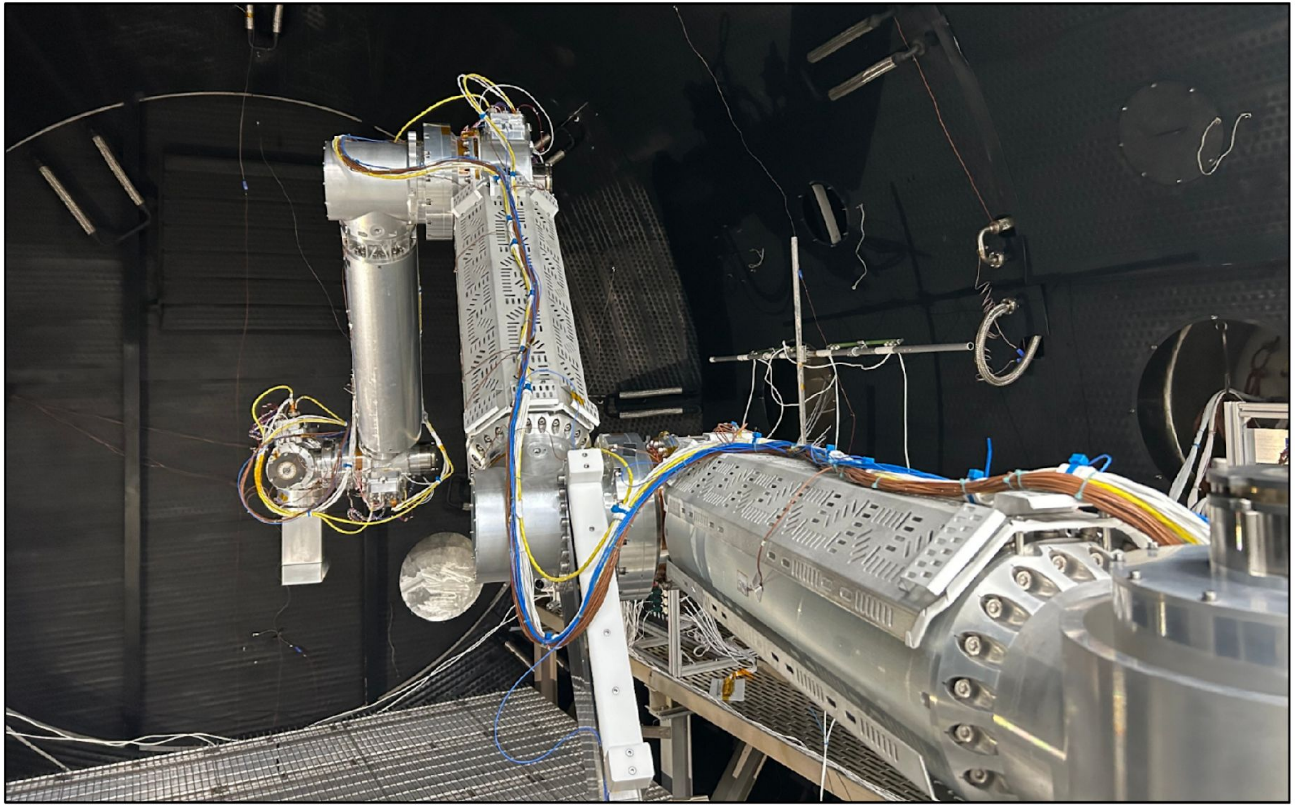
Going “off lander” for extended build volumes



Commercially scalable hab-capable system

2024 2025 2026 2027 2028 2029 2030 2031 2032

ICON's Laser VMX Lunar Construction System



ICON's Laser VMX robotic prototypes are capable of autonomously 3d printing with lunar regolith.

Results from Laser VMX Structural Testing

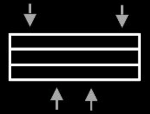
Testing and analysis show that the prints can survive the thermal conditions of the south pole and withstand the forces generated during launch and landing of an HLS class lunar lander. NASA corroborated our findings and selected Laser VMX as the primary process for its additive construction needs.

Compression
24 C: 348 MPa
57 C: 334 MPa
-184 C: 339 MPa
Thermal cycled: 252 MPa

Tension
24 C: 8.69 MPa

CTE
-184 C to 57 C:
-3.15×10^{-6}

Plasma Torch
Degradation: discoloration only



4-Point Bend
24C: 68.9 MPa

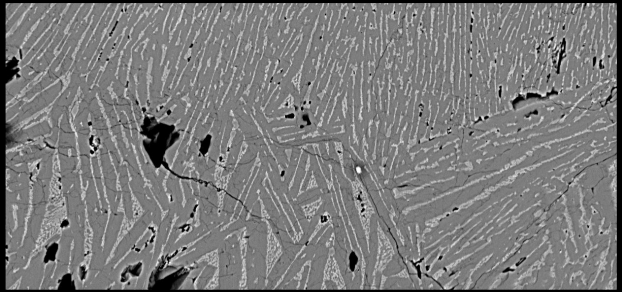


Figure: SEM imagines of Laser VMX grain structure

Figure: Cross section of printed Laser VMX sample

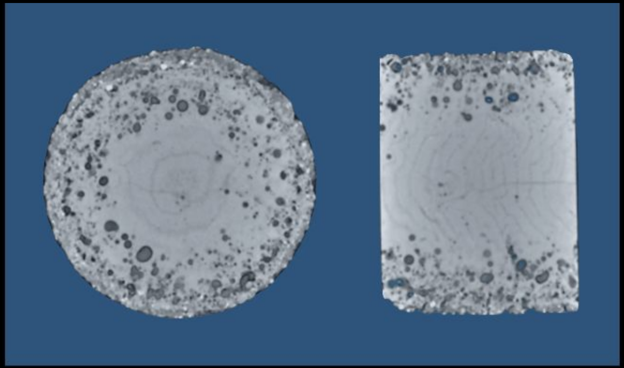


Figure: CT Images from Post-test ablation testing

Figure: Plasma Torch Testing (3MW/m2)

ICON’s Company Centered Lunar Framework

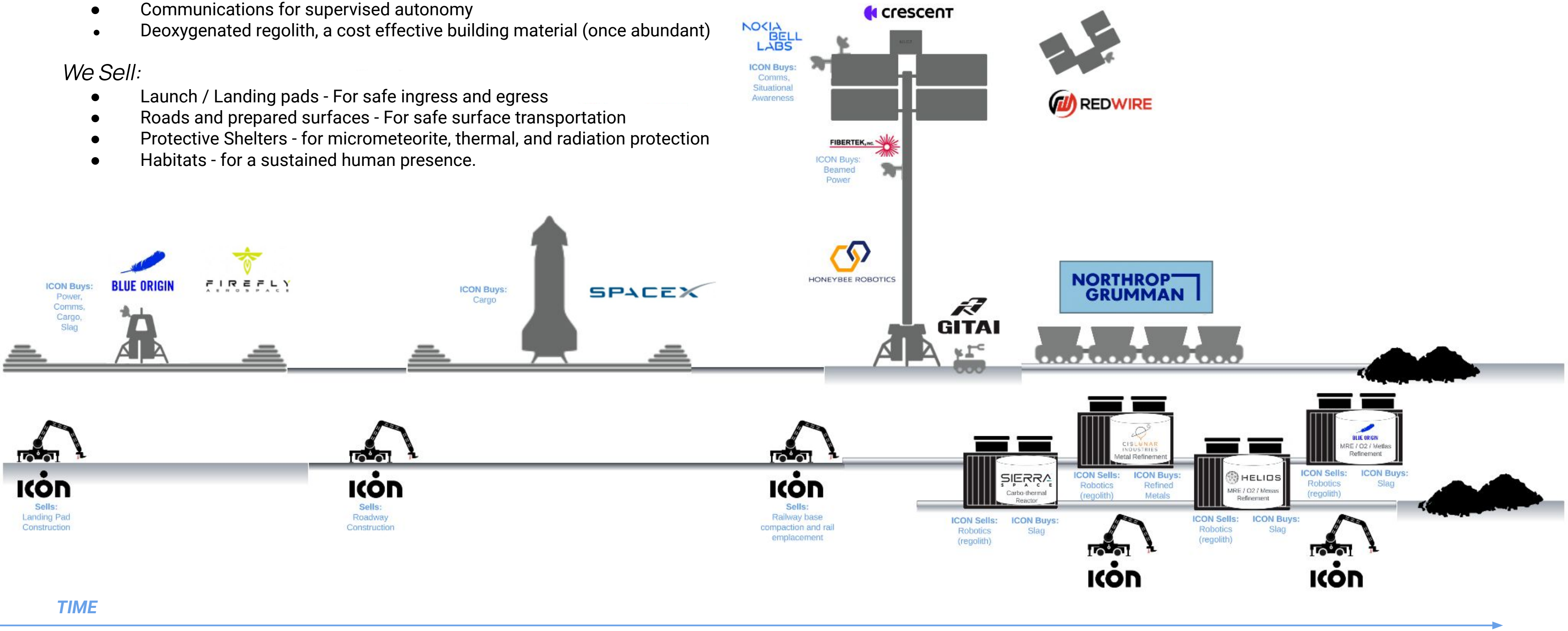
We Buy:

- Transit for our robots to the lunar surface
- Energy for our robots and processes
- Communications for supervised autonomy
- Deoxygenated regolith, a cost effective building material (once abundant)

We Sell:

- Launch / Landing pads - For safe ingress and egress
- Roads and prepared surfaces - For safe surface transportation
- Protective Shelters - for micrometeorite, thermal, and radiation protection
- Habitats - for a sustained human presence.

Note: Primary Connections, Buys and Sells shown in blue.



Notional ICON VMX-Enabled Landing Pad for Starship - Loads / Design

Assumed Pad Material Properties: Replicate sintered regolith using a low CTE ceramic material

- Compressive Strength = 345.0 MPa
- Tensile Strength = 17.3 MPa
- Modulus of Elasticity = 68.9 GPa
- Density = 2.6 g/cm³ (2,600 kg/m3)
- Poisson's Ratio = 0.25
- Coefficient of Thermal Expansion = 4.0x10-7 1/C

Applied Loading:

Dead Loads (D):
- Self-weight (Lunar Gravity)

Live Loads (L):
- Rocket plume pressure
- Landing leg bearing
- Off-nominal pad-edge landing analyzed

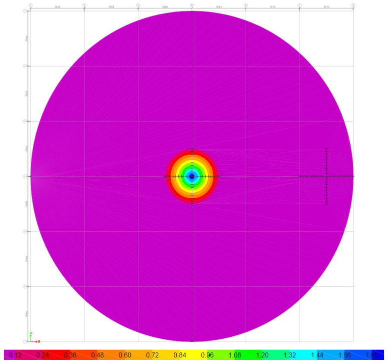


Figure: Loading Information – Plume Pressure

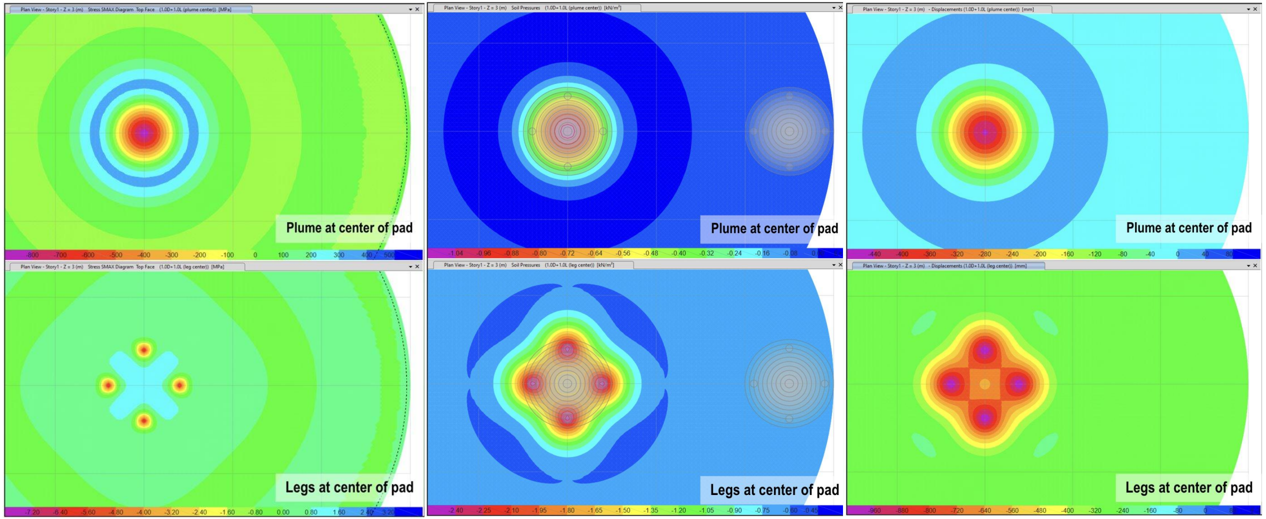


Figure: Model Example Results – Pad Stresses, Soil Bearing Stress, Vertical Deflection

Notional ICON VMX-Enabled Landing Pad for Starship - Dust / Analysis

Rocket landings propel regolith, gravel, and rocks at high velocities—potentially damaging or even destroying spacecraft, scientific instruments, and other critical lunar infrastructure. Given the absence of atmospheric drag and reduced gravity, lunar ejecta will travel great distances with minimal energy loss, creating an atmosphere of pollution that could enshroud the Moon and inhibit future travel.

For this study, a nominal plume-surface interaction was used for loading. Landing accuracy drives the design rather than apron size to mitigate for dust.

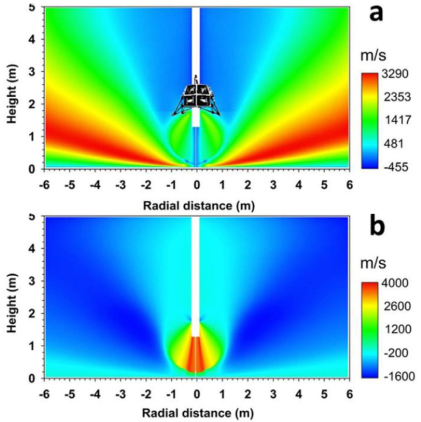


Figure A: Plume gas horizontal velocity profile at h = 1.5 m.
Figure B: Plume gas vertical velocity profile at h = 1.5 m.
(Mishra et al., 2022)

Distance from centroid of vehicle (m)	Percent of plume pressure	Plume Pressure (kPa)
0	100%	1700
1	90%	1530
2	80%	1360
3	70%	1190
4	60%	1020
5	50%	850
6	40%	680
7	30%	510
8	20%	340
9	10%	170
10	0%	0

Figure: Plume-surface interaction assumptions

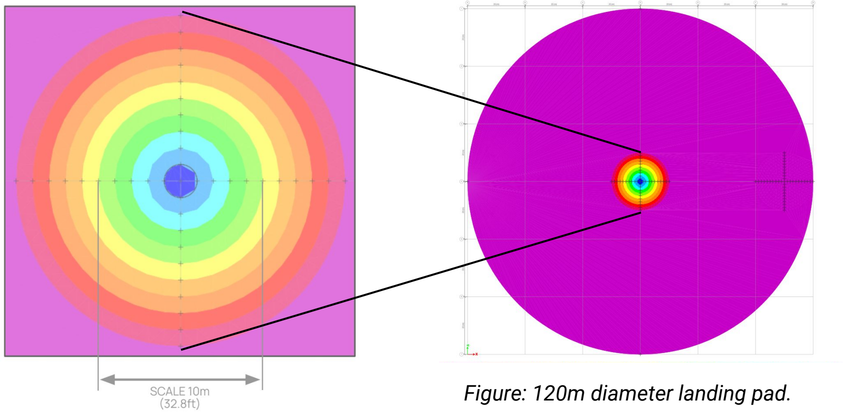


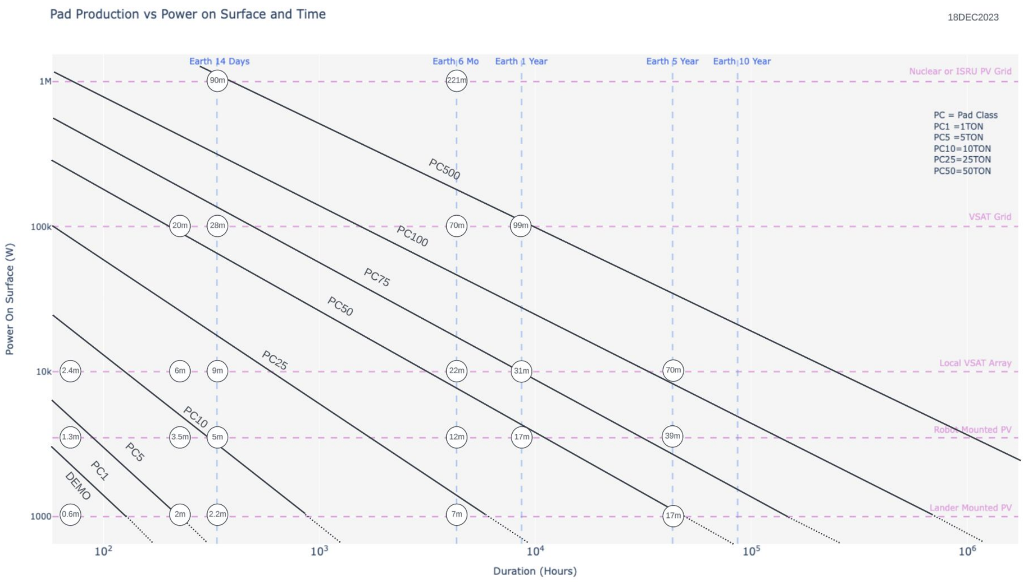
Figure: 120m diameter landing pad.

Notional ICON VMX-Enabled Landing Pad for Starship - Scaling Model

The whitespace chart to the right reflects the Laser VMX landing pad production vs. time for pad classes, with 1cm average thickness.

Smaller pads can be produced in relatively short timescales, less than 1 year with a single landing and robot.

When going for larger pads, like what would be required for a reusable Lunar starship, robotic parallelism are likely to be required to bring production to reasonable time-scales. (Multiple robots per pad, road, etc).



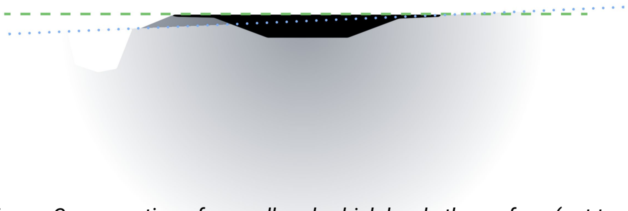


Figure: Cross section of a small pad, which levels the surface (not to scale).

Figure: An larger pad's nominal shape scales, needing much more material throughput and energy.

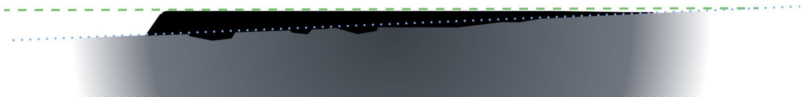


Figure: A possible solution for faster landing pad production is to locate areas of large rock, and product only the pad-surface required to make the rock flat, and suitable for landing.

Notional ICON VMX-Enabled Landing Pad for Starship – Economics

ICON

The first full scale construction robot on the surface is ideally capable of completing at least 4 CLPS Class landing pads, with connecting roads for ingress and egress.

The cost structure will consist of landing, launch, and occupancy fees for the duration the pad is in use. As the lunar economy grows, so will the number and, likely, size of rockets on the lunar surface. As demand increases, so will the value of the landing pads and other horizontal infrastructure.

An initial construction-scale system is assumed to make one or two small landing pads near a region of interest, and should be able to recover the investment as the rate of launches and landings increases.

When scaling up, the robot reliability and throughput will go up, without a substantial increase in launch costs, resulting an outlook for profitable pad, road, and eventually habitat construction into the late 2030s.

The "Notional Reusable Starship Pad" is particularly large due to the incredibly large loads seen during landing, so additional considerations and designs are required to fully assess the financial viability.

ICON Olympus Construction System 1			
2027-2030 Era	500-1000kg class		
Item	**Cost**		**unit**
Engineering / Management	$	24,000,000	usd
Flight Hardware	$	15,000,000	usd
Launch / Landing Services	$	200,000,000	usd
Operation	$	1,000,000	usd
	$	**240,000,000**	**usd**
Robots Operational On Surface		1	
Pads created per robot		2	
Pads created		2	
Pad lifetime		20	yr
Launch-Landings / Year / Pad (Avg)		12	
Launch-Landings / Lifetime (per Pad)		240	
Launch-Landings / Lifetime		480	
Cost / Landing	$	500,000	usd
Revenue over n years	$	240,000,000	usd
Profit	$	-	usd

ICON Olympus Construction System Critical Mass			
2030 - 2035 Era	1000-2000kg class		
Item	**Cost**		**unit**
Engineering / Management	$	24,000,000	usd
Flight Hardware	$	60,000,000	usd
Launch / Landing Services	$	800,000,000	usd
Operation	$	4,000,000	usd
	$	**888,000,000**	**usd**
Robots Operational On Surface		4	
Pads created per robot		10	
Pads created		40	
Pad lifetime		20	yr
Launch-Landings / Year / Pad (Avg)		12	
Launch-Landings / Lifetime (per Pad)		240	
Launch-Landings / Lifetime		9600	
Cost / Landing	$	250,000	usd
Revenue over n years	$	2,400,000,000	usd
Profit	$	1,512,000,000	usd

Off-board Heat Rejection System - Problem Summary and Potential Solutions

High-Power lunar operations will rely on an ability to remove thermal energy from the system

Terrestrial applications can reject heat via conduction fed convection processes [fig: A].

Cis-Lunar and other spacecraft rely solely on radiators.

Future Lunar missions may not be able to rely on radiative cooling alone, dumping heat into a thermal mass allows that heat to be used when needed either during lunar night or for power generation [fig: D].

Using lunar regolith as a storage medium, whether to dump waste heat or to store thermal energy, is not a new concept

Using regolith in the following ways:

- Loose
- Compacted
- Sintered
- Loose material contained in a vessel (made of melted and solidified regolith or other materials)

Some have even considered water or other media as storage media, either brought from Earth or extracted locally

Can we use ICON VMX material as a thermal mass/battery and take advantage of its relatively high thermal conductivity [b] and heat capacity and insulate the mass using loose regolith (with it's very low net thermal conductivity [Fig: C])

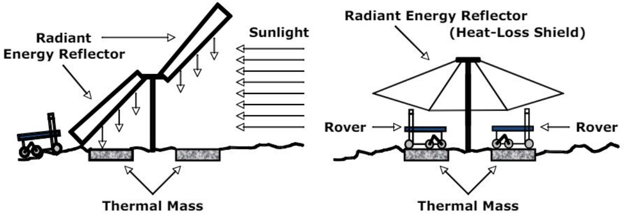


Image: Balasubramaniam, R., Gokoglu, S.A., Sacksteder, K.R., "An Extension of Analysis of Solar-Heated Thermal Wadis to Support Extended-Duration Lunar Exploration", 48th Aerospace Sciences Meeting, Orlando, FL, January 4-7, 2010.

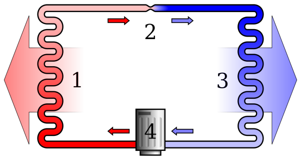


Figure: A

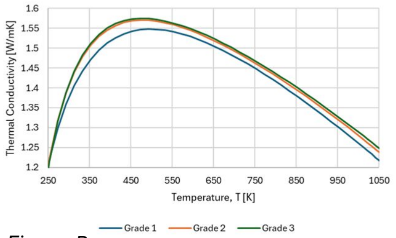


Figure: B

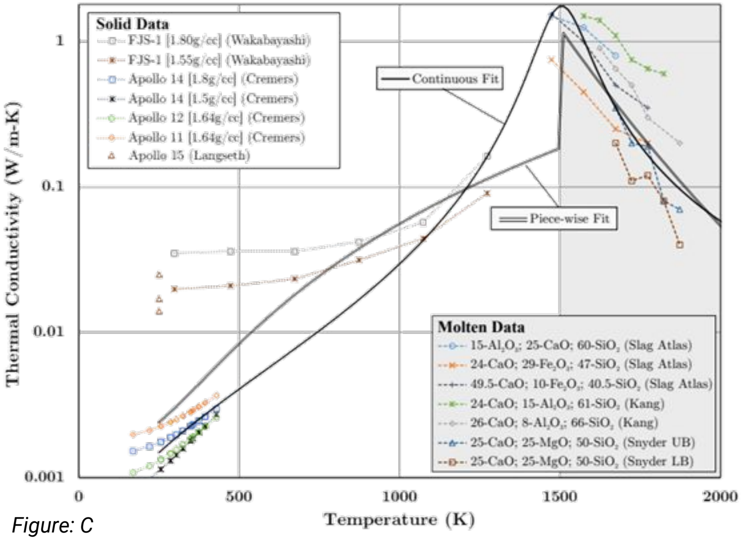


Figure: C

Off-board Heat Rejection System - Design Examination

Three (3) thermal models were created

[a] Thermal mass in regolith flush with surface with "blanket" covering exposed surface.
[b] Mass buried in regolith 0.2 m, below surface.
[c] (not shown) as [a] but with a layer of graphene strips (tendrils) between layers of VMX,
[d] as [b] but with graphene tendrils

Assumptions:

All model versions use a VMX thermal mass: 1 m x 0.5 m x 0.2 m, initial temperature 240 K (~235 kg)

Regolith region into which VMX mass is set: 2 m x 2 m x 0.5 m, initial temperature 240 K

Regolith surface initial temperature 50 K

Graphene thermal strap is used to connect mass to a point on the regolith surface at which a thermal "connector" is envisioned

Two scenarios analyzed: case 1 with connector held to 800 K, and case 2 with 1 kWt applied to SC interface connector

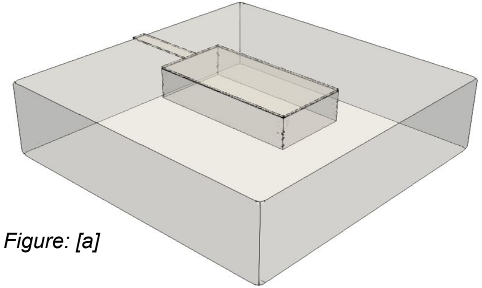


Figure: [a]

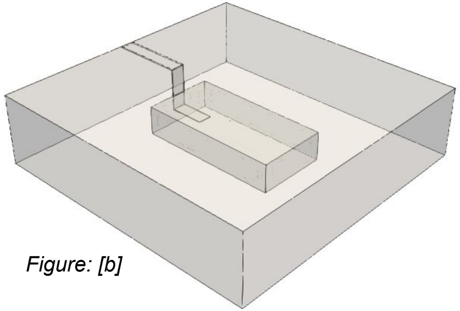


Figure: [b]

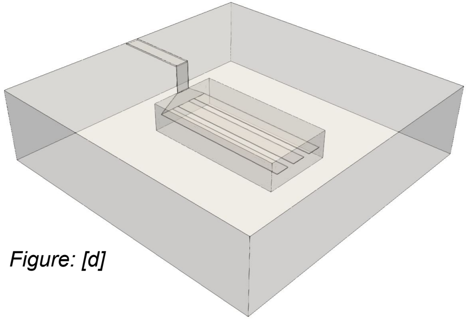
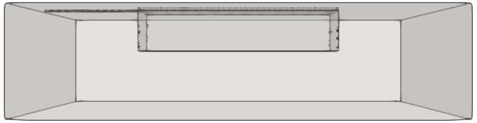
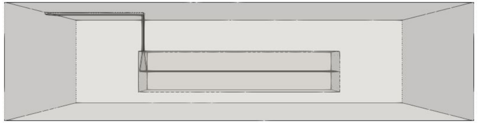


Figure: [d]





Off-board Heat Rejection System - Constant Temperature Results

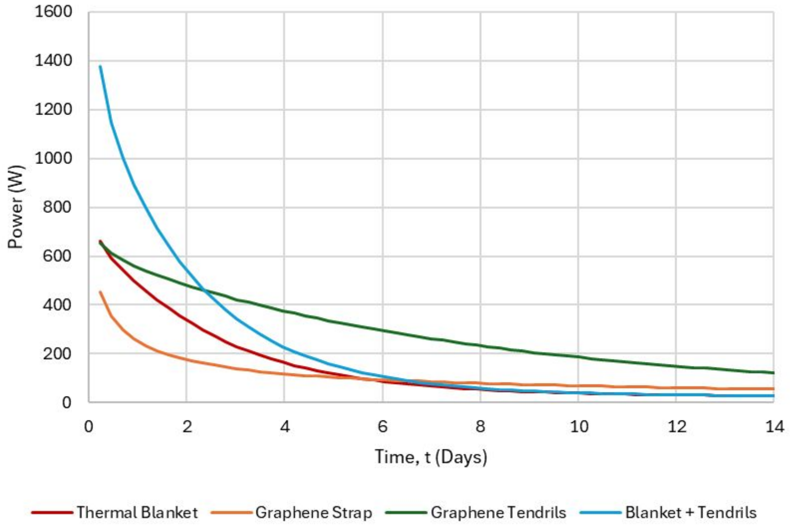
Selected results for configurations A->D run with constant temperature interface

Shown here are detailed results for the blanket on monolithic VMX Grade 1 and summary results for all configurations exposed to the 800 K interface BC

Evaluations for other VMX grades were done, results are very similar, with more detail will be provided in the SCR report

Temperature evolution of the mass over time is shown below with the VMX block becoming near isothermal at day 14

Graph to the right shows power flowing into the battery as a function of time for all configurations evaluated. Used as a heat sink case 1C offers the highest cooling flux initially while case 1D provides the most consistent sink



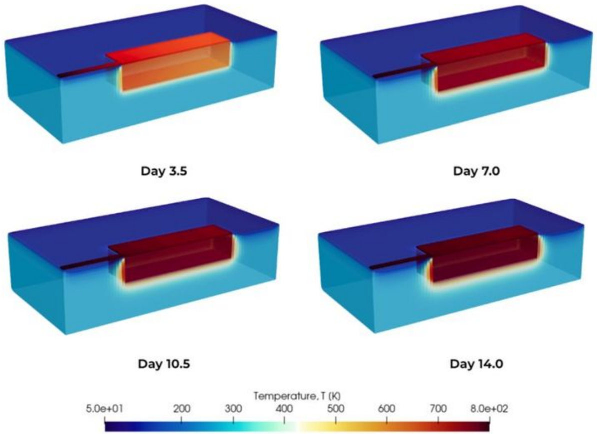


Figure: Example of a simulation-set run in CFD, 14 Earth days, 800 K Input

	CASE 1A: Thermal Blanket	CASE 1B: Graphene Strap	CASE 1C: Blanket + Tendrils	CASE 1D: Graphene Tendrils
Input Energy	48.0 kWh	38.0 kWh*	74.4 kWh	99.1 kWh
Ave. Temp	780 K	643 K*	788 K	691 K

Figure: Table and graph of input energy and average temperature.
** extreme non-uniform temperature*

Commercialization Model - Business Model

The first full scale construction robot on the surface is ideally capable of completing at least 4 CLPS Class landing pads, with connecting roads for ingress and egress.

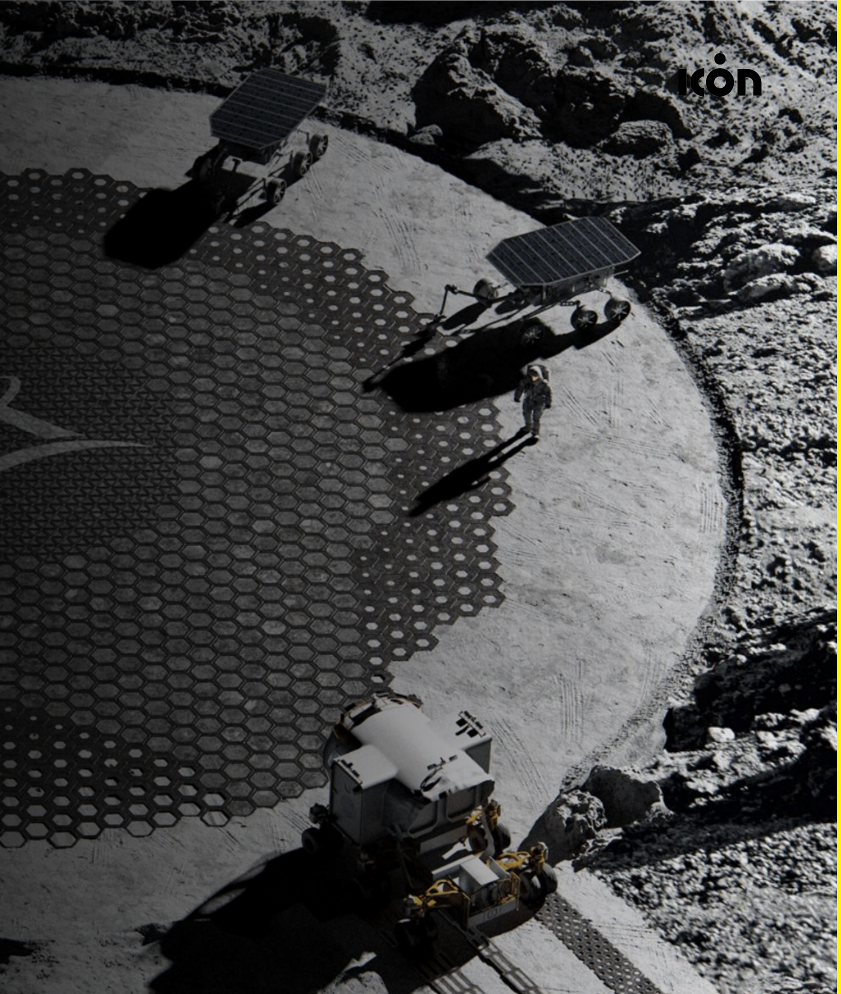
Since the launch / landing pad production cost can be amortized over a large volume of uses, the owner of a landing pad could foreseeably charge per use. It is worth emphasizing that the cost to spacefaring entities using the pad is negligible when compared to the program and launch costs to arrive, as well as mitigated risks and the ability to service areas that are highly adjacent to other lunar assets for commercial purposes.

The cost structure will consist of landing, launch, and occupancy fees for the duration the pad is in use. As the lunar economy grows, so will the number and, likely, size of rockets on the lunar surface. As demand increases, so will the value of the landing pads and other horizontal infrastructure.

Just as planes must use runways, rockets must use landing pads on the lunar surface to contain lunar ejecta. Operating landing pads, therefore, is analogous to ownership of other critical “gateway” infrastructure, such as airports, ports, and railways.

Foundational infrastructure is one of the greatest economic multipliers*.
An investment into this technology will multiply across the value chain and provide a strong return on investment for the creation of a sustainable lunar economy.

*Foster , Vivien, Maria Vagliasindi, and Nisan Gorgulu . “The Effectiveness of Infrastructure Investment as a Fiscal Stimulus: What We've Learned.” World Bank Blogs, February 2, 2022.



ARTISTS DEPICTION

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