LSIC: Excavation & Construction Workgroup

September 25, 2020

CONFIDENTIAL

1.2 billion humans do not have adequate housing. **This is a crisis.**

Short Housing History:

It’s been sticks and bricks for hundreds of years, but everything is about to change.

1200s

Middle Ages
Early standardization of carpentry and architecture techniques.

1880s

Industrial Revolution
Climate control and industrial production of building materials.

1950s

Power Revolution
Power tools enable homes to be built faster.

The Future

3D Printing
Advancements in robotics, software, and materials create *10x improvements* in speed, quality, resiliency and sustainability

Advanced construction technologies that **advance** humanity.

Overview:

ICON is a construction technologies company.

Using 3D printing robotics, software and advanced materials, ICON is shifting the paradigm of homebuilding.

Robotics

Gantry-based platforms designed to precisely control the deposition of concrete over a large print area. Integrated advanced sensors ensure print accuracy and monitor the construction robotics throughout an entire print job.

Software

Industrial control software and an intuitive mobile-based user interface designed to make it easy to seamlessly select, design, and print structures. Control the Vulcan print system from anywhere in the world.

Materials

Proprietary 'Lavacrete' is designed to be deposited with no slump in a variety of climates and weather conditions. Our materials are engineered with characteristics that ensure strong bonding between layers plus a high compressive strength.

Robotics:

The Vulcan II automated concrete construction system

The 3800 lb gantry-style printer completes on-site, 3D printed homes and custom-designed structures up to 2,000 sq. ft. with the capability of printing multiple homes simultaneously. A Vulcan II is seen here printing three homes at once on a single concrete foundation.

Robotics:

The Vulcan II

Technical Specifications:

Nominal power:
16 kw

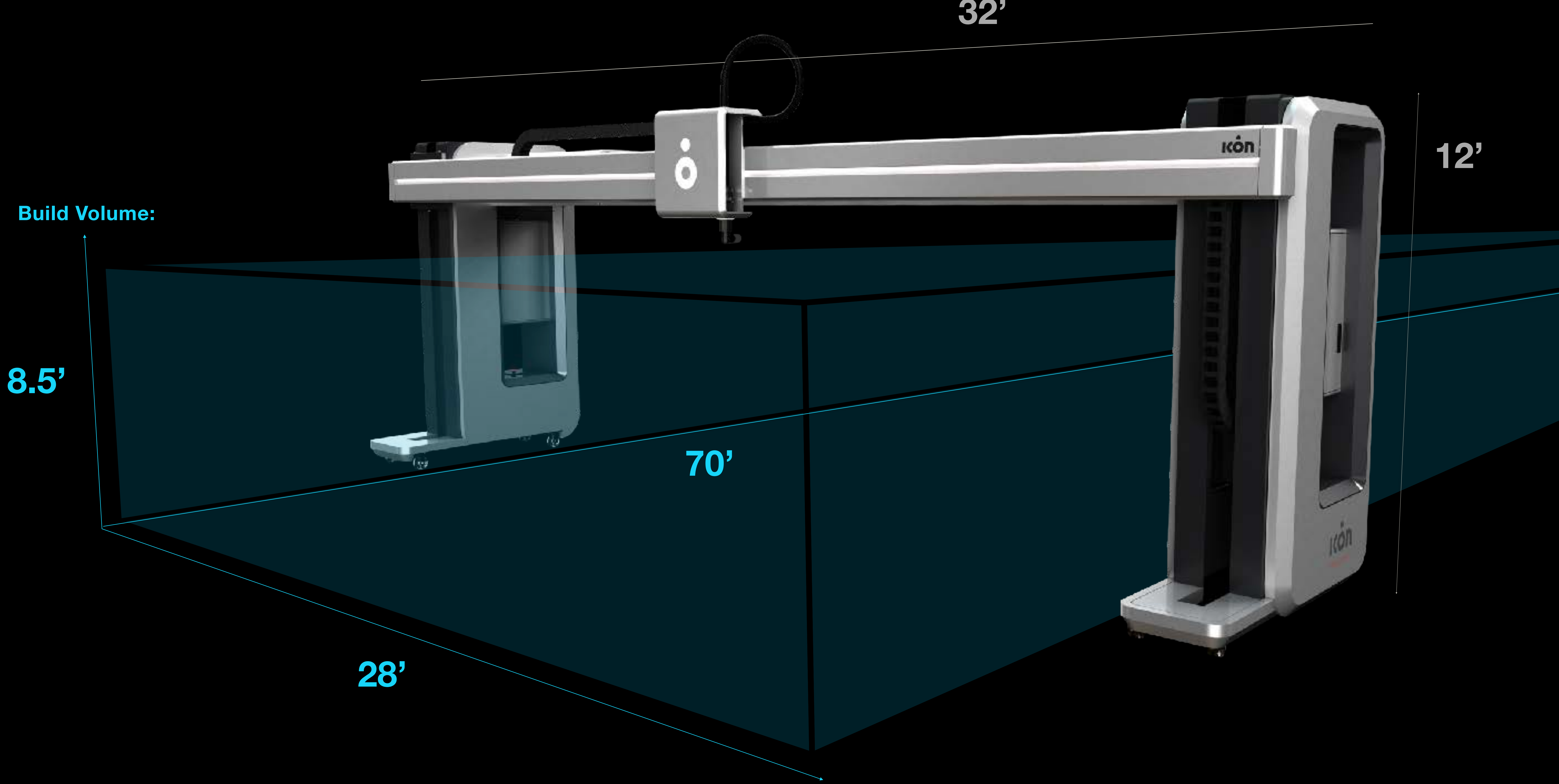
Voltage input:
230/240v
split-phase

Water usage:
2 gpm

Print Speed:
5-7”/sec

Weight:
3800 lbs.

Work Area:
1900 sq. ft.



Software:

Construction Operating System

In-house designed and developed software technology powers the Vulcan printing systems to be safe, reliable and secure. Mission Control provides full reachback capabilities for field operations from thousands of miles away.

(ICON's mobile interface for remote management.)

Software:

Handheld Operation

The Magma operator uses the mixing interface for prep, active batch mixing, and clean out assistance.

The Vulcan operator uses the print interface to initiate print jobs and control the machine while print operations are active.

Materials:

Layers of Material Science

Proprietary cementious-based material developed in ICON's laboratory is a unique blend that boasts a comprehensive strength of 6,000 PSI and is fine-tuned to deliver a tight thermal envelope across a variety of environmental conditions.

With a dedicated Materials Lab, our team of PhD scientists continue to push boundaries for terrestrial printing as well as off-world construction.

ICON Lavacrete 2.0	**6,000 PSI**
Concrete Slab	**4,000 PSI**
Cinder Block (CMU)	**1,500 PSI**
Lumber	**1,000 PSI**

Resiliency

A powerful building material with lasting durability

Lavacrete is one of the few materials that can flow like a liquid allowing it to be poured, extruded, or cast into an infinite amount of shapes for structures that are incredibly strong. With specific additives, Lavacrete's properties can be tailored to a specific environment or engineering requirement. Better yet, concrete base material is globally available, resilient, and one of the cheapest building materials on Earth.

Why 3D-print a home?

Average Print Speeds

Print speeds are based on averages for individual prints. Multi-home printing (printing several homes in-line at once) greatly accelerates printing times overall.

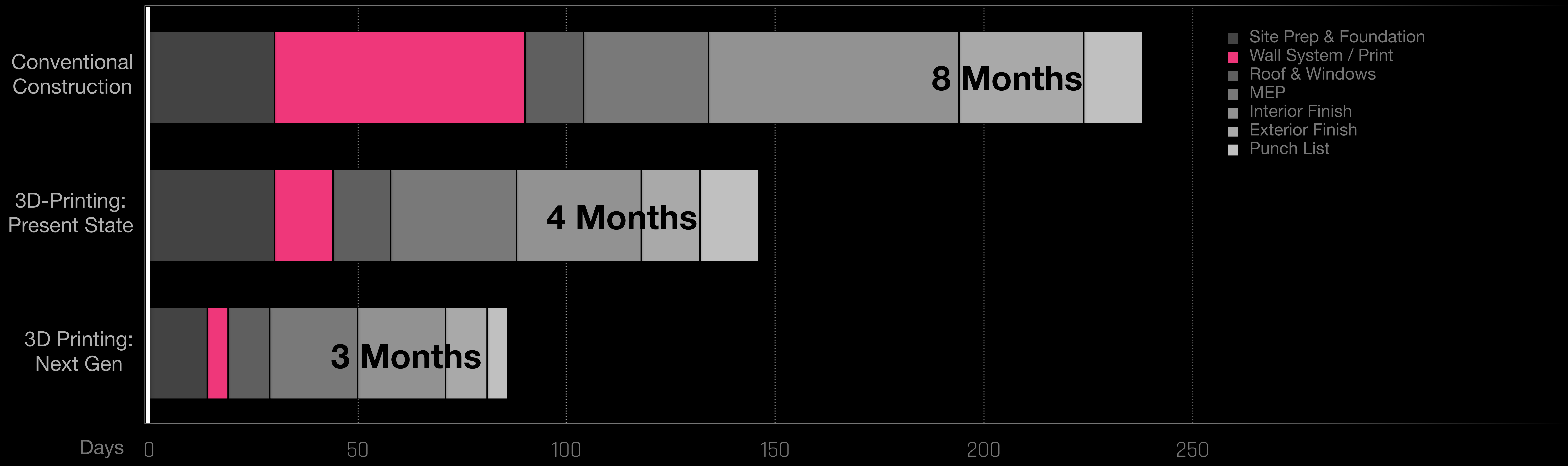
IN-LINE MULTI-HOME PRINTING
A more efficient way to produce large volumes of housing quickly via a single print job. Shown 3 homes being printed at once.

Print time:	**24 hours** per home	**50 hours** per home	**100-120 hours** per home
Home size:	**500 sq. ft.**	**1000 sq. ft.**	**2000 sq. ft.**

Why 3D-print a home?

Fastest construction system in the world.

The simplification of a home's shell via 3D printing reduces the overall construction time frame to at least half of the time needed in traditional construction. As our technology and architecture continue to evolve, construction time is reduced in addition to producing less waste.



Why 3D-print a home?

Benefits of 3D printing in homebuilding

SPEED

CUSTOMIZABLE

HIGH-PERFORMANCE

LOW COST

INDUSTRIAL SCALE

ZERO WASTE

Printed Projects

The Chicon House - Austin, Texas

The First Permitted, 3D Printed House in the U.S.

ICON first gained public attention in 2018 with its first 3D-printed structure, a small home in Austin, Texas. The wall system of this 350 sq. ft. structure was created in 48 hours using the first-generation Vulcan printer prototype.

Date: March 2018
Speed: 48 hours print time
Size: 350 sq. ft.
Layout: 2 Bdr / 1 Bath / Kitchen

Community First Village - Austin, Texas

Welcome Center

This 500 sq. ft. welcome center featuring two offices, kitchen and bath stands at the forefront of Community First! Village serving those who have experienced chronic homelessness in central Texas.

Date: May 2019
Speed: 24 hours print time
Size: 500 sq. ft.
Layout: 1 Bdr / Office / Kitchen / Living

Community First Village - Austin, Texas

Printing 3 Homes at a Time

Printed three homes at a time by a Vulcan II printer, these six homes are currently occupied as part of the Community First Village in Austin, Texas.

Date: March 2020
Speed: 24 hours print time per home
Size: 400 sq. ft. per home
Layout: 1 Bdr / Office / Kitchen / Living

New Story - Tabasco, Mexico

World’s First 3D-Printed Community

In partnership with housing nonprofit, New Story, the world’s first 3D-Printed Community uses the 500 sq. ft. homes for impoverished families. 3D-Printed two at a time, this community has rapidly grown and survived a major 7.1 earthquake with no visible damage.

Date: May 2019
Speed: 24 hours print time per home
Size: 500 sq. ft. per home (community of homes)
Layout: 2 Bdr / 1 Bath / Kitchen / Living

The United States Marine Corps:

Military Grade Equipment

In partnership with U.S.M.C. and the Defense Innovation Unit, ICON printed a large vehicle hide structure at Camp Pendleton without a foundation. The rugged and remote location with the Marines was not a problem for ICON’s equipment & team.

Date: July 2020
Speed: 36 hours print time
Size: 4 arches at 26’ length x 13’ width x 15’ height
Crew: 8 Marines trained

The United States Marine Corps:

Print & Place Construction

Date:	July 2020
Speed:	36 hours print time
Size:	4 arches at 26’ length x 13’ width x 15’ height
Crew:	8 Marines trained

Upcoming Projects: Residential

17th Street Project

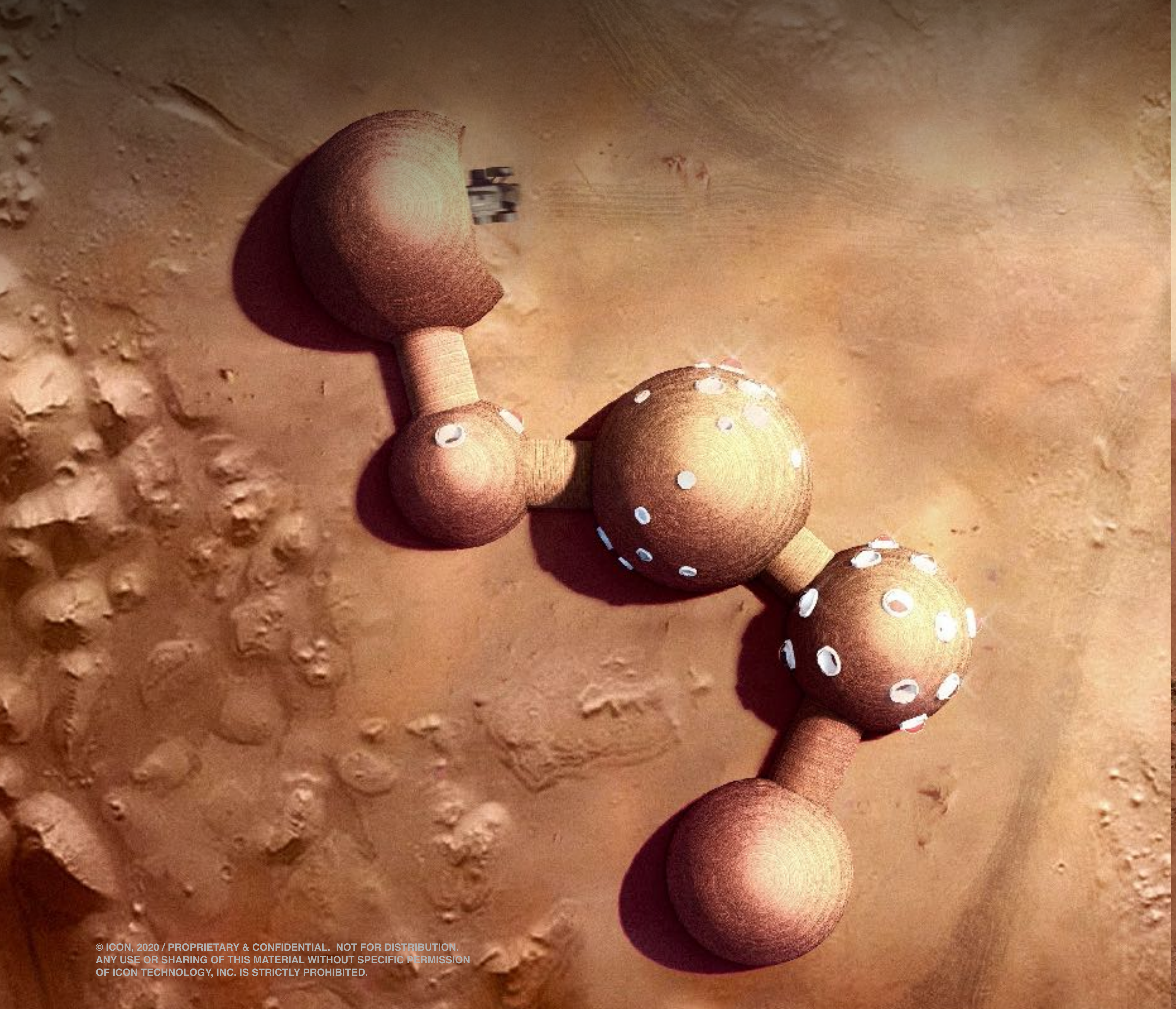
Vulcan 3D-Printers will deliver a series of homes ranging in size from 900 sq. ft. to 2,000 sq. ft. and be the first homes sold in the U.S. at market rate.

> “All civilizations become either space-faring *or* extinct.”
>
> **- Carl Sagan**

NASA

Mars 3D-Printed Habitat Centennial Challenge

In 2018, ICON's first introduction to NASA was via the Mars 3D-Printed Habitat Centennial Challenge.



On the Moon... to stay.

Building a single habitat on the Moon will be the most technically difficult construction projection the history of humanity.

Our First Home on Another World.

What we build on other worlds must not only be the pinnacle of scientific and engineering achievement, but also must be worthy of humanity's hopes and dreams in space.

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ISRU Additive Construction

Rockets are not ***efficient*** movers of building materials.

Even with commercial space flight dramatically dropping the launch costs to all-time historic lows, flying pre-built structures doesn't make financial sense. Even flying building materials from Earth to the Moon is costs prohibitive.

$ 0.11 per Kg

Costs of dry ICON Lavacrete on Earth

$ 10,000 per home

Dry concrete costs to print an avg. 1200 sq ft home.

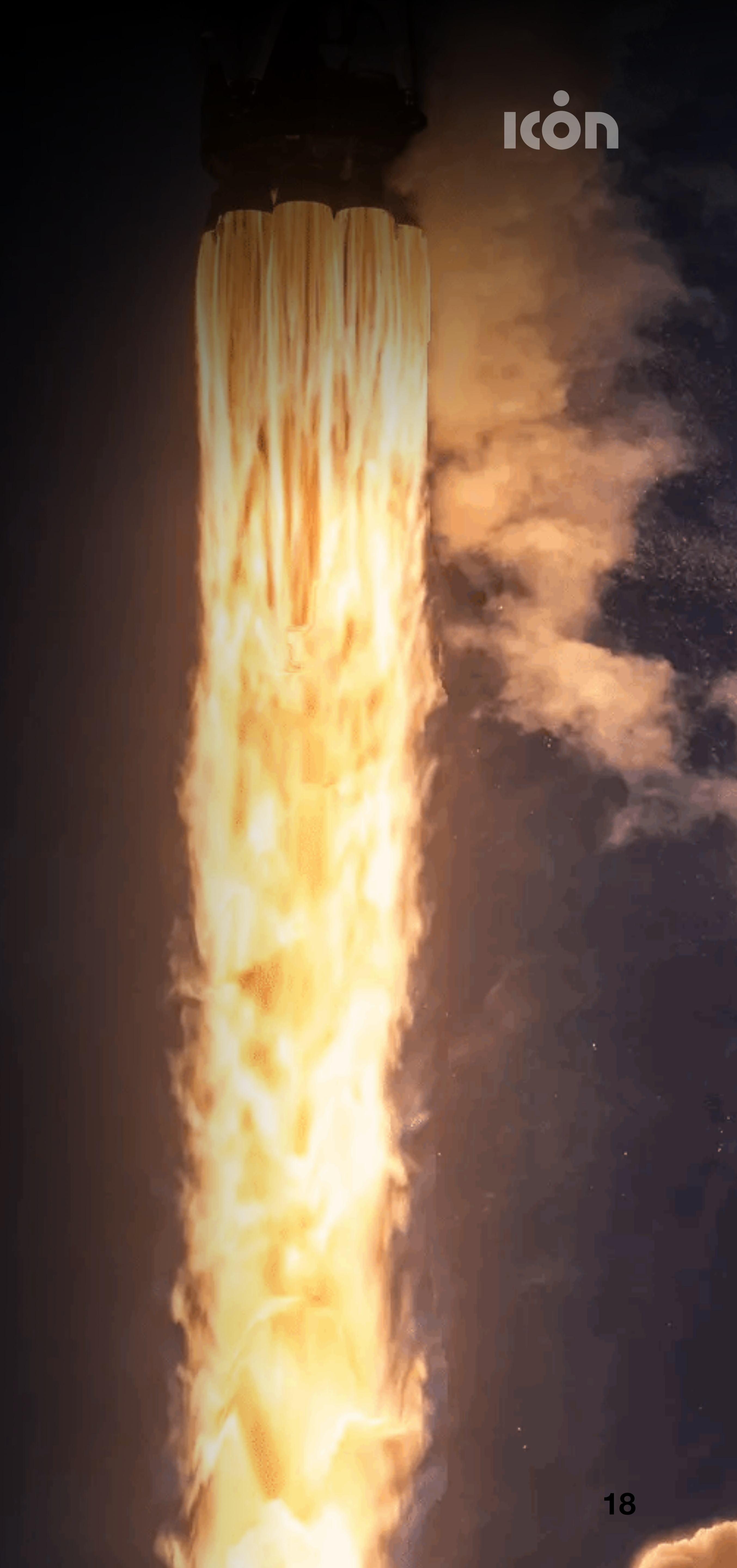
$ 15,000 per Kg

Cost per Kg of Lavacete to Lunar Surface

$ 1,400,000 per home

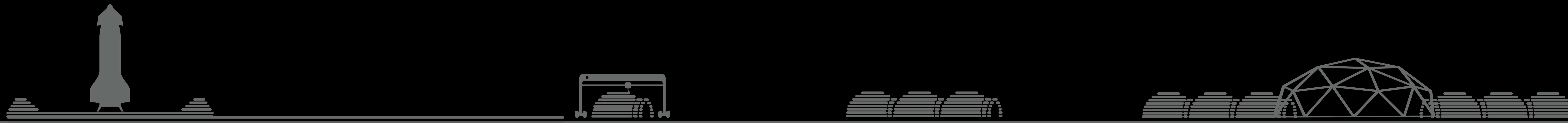
Dry concrete costs to print a 350 sq. ft. structure like the Chicon House on the Moon.

Source: The Space Review



Phased construction / Masterplanning

An Additive Construction system on the lunar surface builds in phases starting critical infrastructure. Subsequent phases build from this initial infrastructure as a foundation of a permanent settlement.



Phase 1

Initial construction focus is on creating critical infrastructure such as landing pads, roadways, blast walls, etc.

Phase 2

With established infrastructure in place, construction begins on the initial base habitats.

Phase 3

The lunar base according to master plan is built out to support the determined population size for the first permanent settlement off of Earth. Current NASA thinking is more on the scale of an outpost, rather than a city.

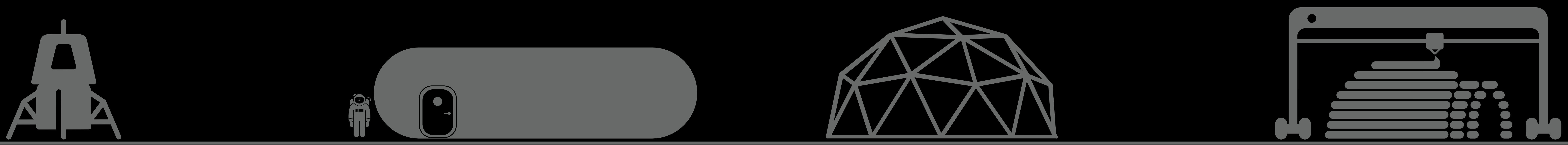
Strategic Expansion

Building towards the complete master plan for the Lunar bases, additional structures are constructed as the growing needs change over time.

One construction system using ISRU:

Costs make it prohibitive to fly entire structures or even just building materials for construction to destinations in the cosmos. It is much more economically feasible to fly a piece of construction equipment to a destination that can build multiple types of structures from local available resources.

Habitat Construction Methods



Landed Prefabricated Habitats

- High TRL
- Quick to deploy
- Systems tested and verified on Earth
- Massively expensive to transport to off-world locations
- No flexibility
- Size constrained
- Limited tradition shielding
- Limited impactor protection
- Limited insulation value

Inflatable Habitats

- Higher TRL
- Medium Deployment Speed
- Some additional assembly & systems required
- Massively expensive to transport to off-world locations
- No flexibility
- Limited tradition shielding
- Limited impactor protection
- Limited insulation value

Multiple Specialized Systems

- Very expensive and lengthy development process
- Multiple fail points
- In Situ Resource Utilization
- Complex Operations

3D Printing / Additive Construction

- Highest In Situ Resource Utilization
- One system, many possibilities
- Simplified Operations
- Highest inherent insulation, protection, and shielding properties
- Most cost effective way to deliver multiple components of lunar infrastructure

3D Printing with regolith likely has the highest inherent safety.

Thermal Insulation

Radiation Shielding

Micrometeorite / Projectile Protection

ICON Off-World Construction System Objectives

Develop an autonomous construction system capable of delivering landing pads, roads, habitats, and other forms of construction on the lunar surface by 2025 using a 3D printing / additive construction paradigm with a strong bias towards in-situ resources. The system must be extensible and designed with an eye toward multiple deposition subsystem usage and eventual Martian operations.

Lunar ISRU Additive Construction System

Product Objectives

Develop an autonomous construction system capable of delivering landing pads, roads, habitats, and other forms of construction on the lunar surface by 2025 using a 3D printing / additive construction paradigm with a strong bias towards in-situ resources.

01

Interface with launch / landing vehicles

(Initial conversations underway)

02

Long distance communication, monitoring and control

(Concept work started)

03

Deploy & move on the lunar surface

(Early conceptual stage)

04

Survive & Operate in the Lunar Environment

(Concept work started)

05

Produce multiple structure types with ISRU

(In rapid prototyping)

Lunar ISRU Additive Construction System

The Lunar Environment

The Lunar Environment:

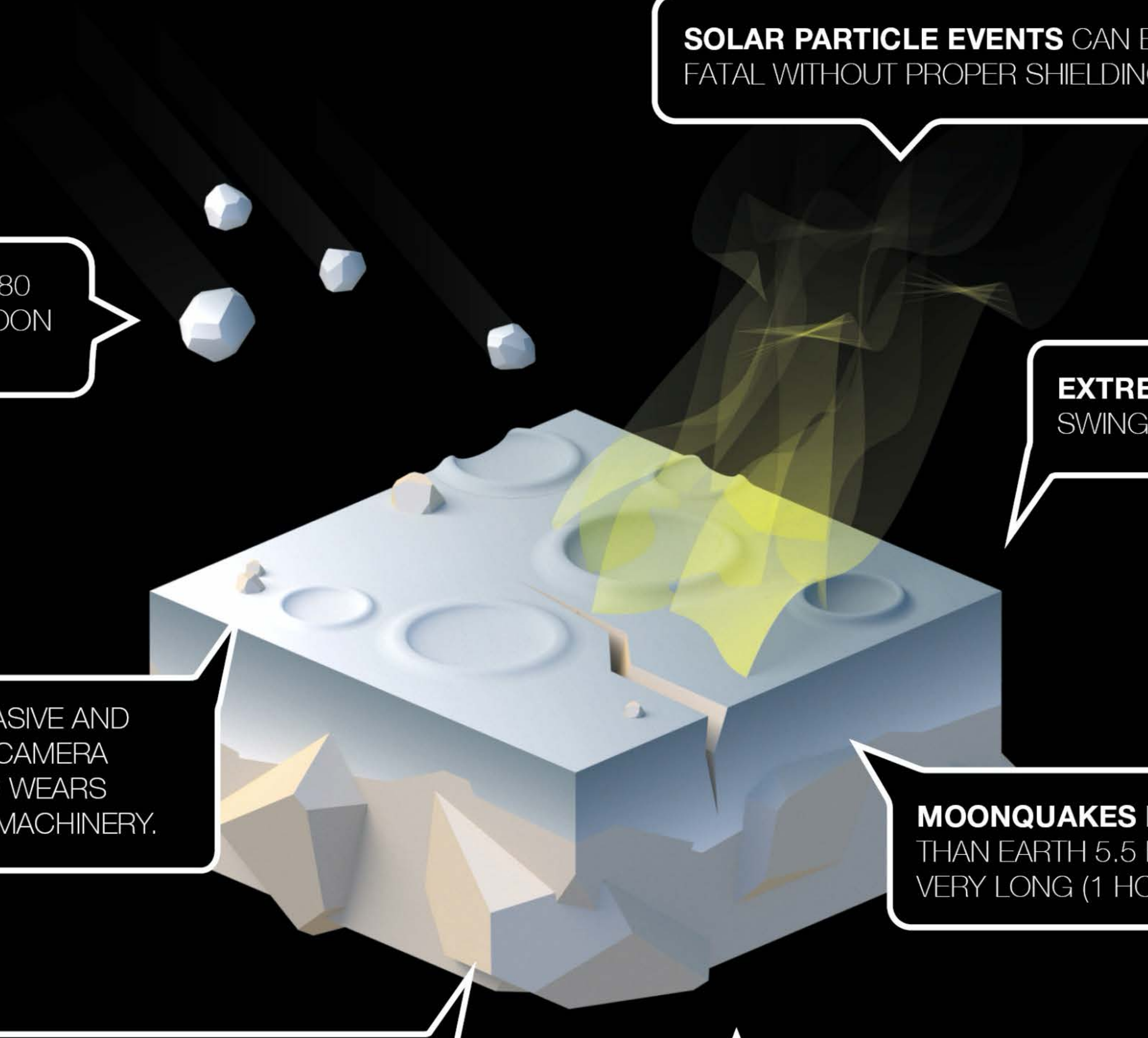
Moon to Earth Comparisons

	Moon	Earth	Ratio
MASS (1024 KG)	0.07346	5.9724	0.0123
VOLUME (1010 KM3)	2.1968	108.321	0.0203
EQUATORIAL RADIUS (KM)	1738.1	6378.1	0.2725
POLAR RADIUS (KM)	1736.0	6356.8	0.2731
VOLUMETRIC MEAN RADIUS (KM)	1737.4	6371.0	0.2727
ELLIPTICITY (FLATTENING)	0.0012	0.00335	0.36
MEAN DENSITY (KG/M3)	3344	5514	0.606
SURFACE GRAVITY (M/S2)	1.62	9.80	0.165
SURFACE ACCELERATION (M/S2)	1.62	9.78	0.166
ESCAPE VELOCITY (KM/S)	2.38	11.2	0.213
GM (X 106 KM3/S2)	0.00490	0.39860	0.0123
BOND ALBEDO 0.11	0.11	0.306	0.360
GEOMETRIC ALBEDO	0.12	0.434	0.28
V-BAND MAGNITUDE V(1,0)	-0.08	-3.99	-
SOLAR IRRADIANCE (W/M2)	1361.0	1361.0	1.000
BLACK-BODY TEMPERATURE (K)	270.4	254.0	1.065
TOPOGRAPHIC RANGE (KM)	13	20	0.650
MOMENT OF INERTIA (I/MR2)	0.394	0.3308	1.191
J2 (X 10-6)	202.7	1082.63	0.187

Moon Fact Sheet
Dr. David R. Williams, dave.williams@nasa.gov NSSDCA, Mail Code 690.1
NASA Goddard Space Flight Center, Greenbelt, MD 20771

The Lunar Environment:

Lunar Hazards



SOLAR PARTICLE EVENTS CAN BE FATAL WITHOUT PROPER SHIELDING.

METEORITES ABOUT 180 METEORITES HIT THE MOON EVERY YEAR.

EXTREME TEMPERATURE SWINGS

LUNAR DUST IS HIGHLY ABRASIVE AND HIGHLY STATIC, IT CLINGS TO CAMERA LENSES, HELMET VISORS AND WEARS THROUGH SPACE SUITS AND MACHINERY.

MOONQUAKES LESS ENERGETIC THAN EARTH 5.5 RICHTER BUT LAST VERY LONG (1 HOUR).

THE MOON'S MAGNETIC FIELD IS 1% OF EARTH'S ALLOWING THE LUNAR SURFACE TO BE REACHED BY **100X THE RADIATION** COMPARED TO THE EARTH'S SURFACE

CLOSE TO ZERO ATMOSPHERIC PRESSURE

Lunar ISRU Additive Construction System

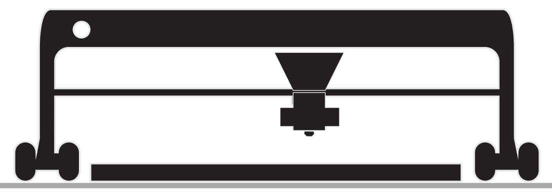
High-Level System Architecture Research & Development

Lunar ISRU Additive Construction System

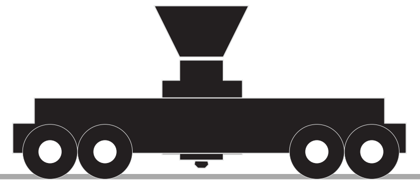
Analysis of Alternative System Architectures

Analysis of Deposition Mobility Platforms

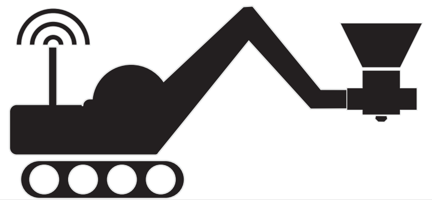
Gantry



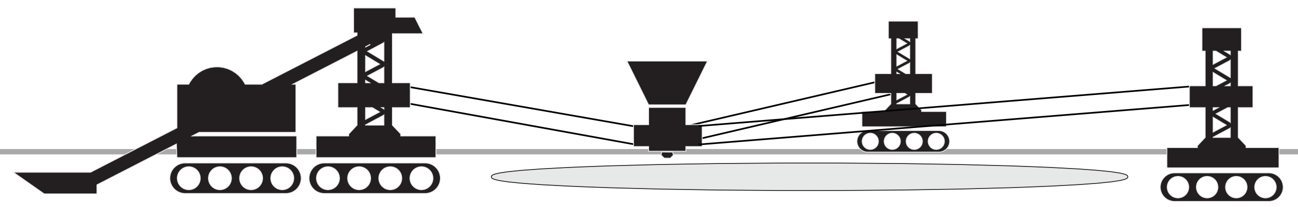
Rover



Robotic Arm



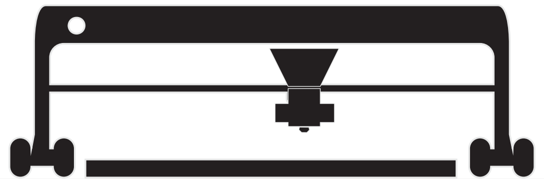
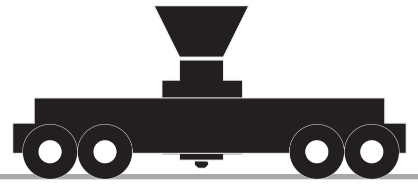
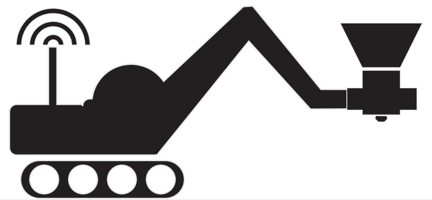
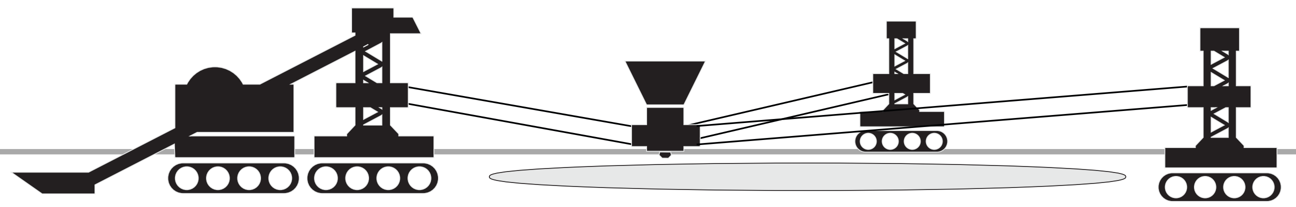
“Flying Delta”



Boom Tower

Lunar ISRU Additive Construction System

Analysis of Deposition Mobility Platforms

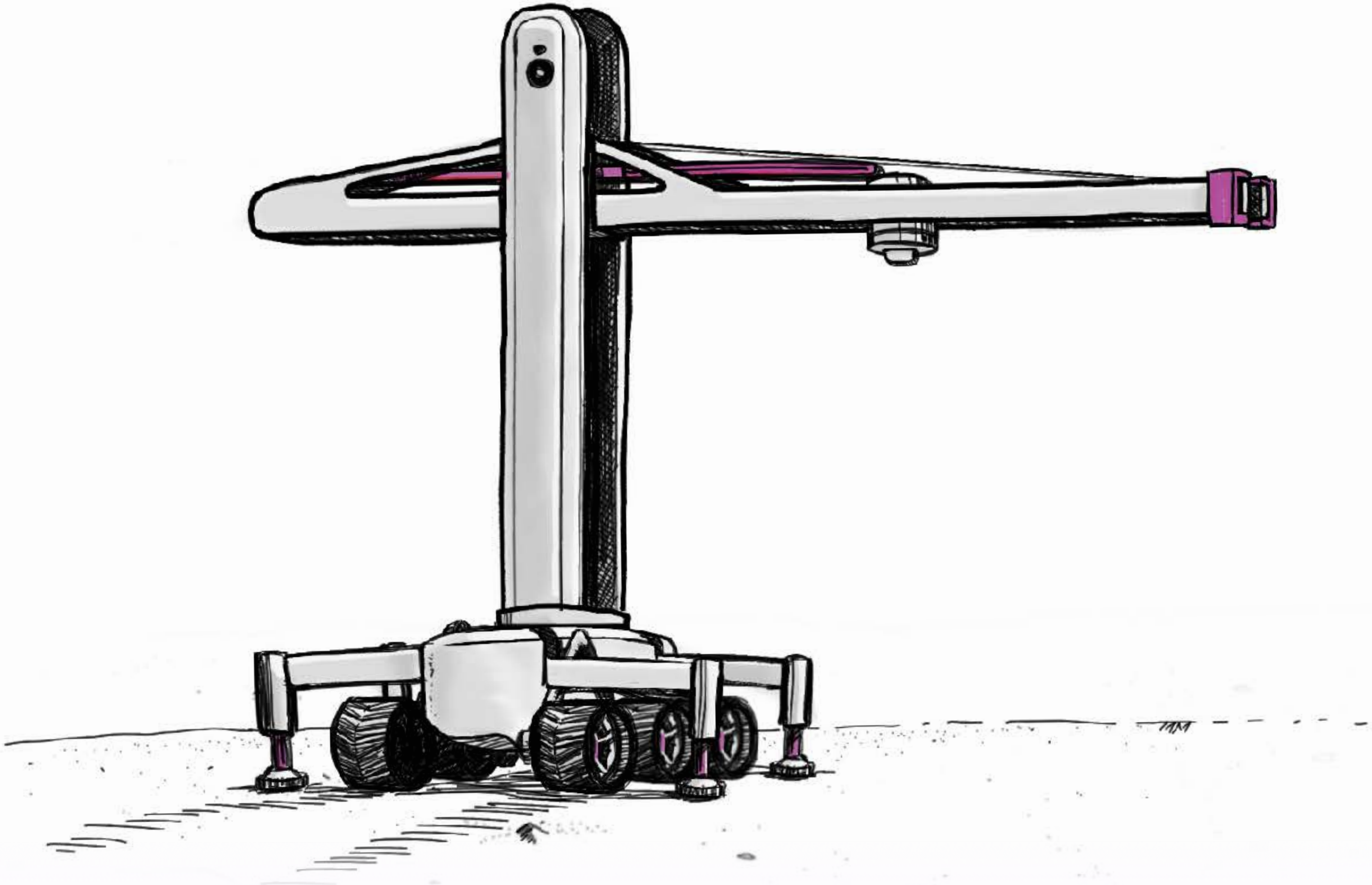
Gantry		• Can print planer or vertical structures • Very stable platform • Good mass / print volume ratio • Minimal contact with lunar dust	• Well-understood control systems • Potentially converted into a boom arm
Rover		• Height limited - Best for planer structures • Stability dependent on terrain • Limited size means limited build volume • Constant contact with lunar dust	• Well-understood control systems • Possible good choice for sub-scale demonstrations
Robotic Arm		• Can print planer or vertical structures • Unstable platform at full extension • Reach limits the build volume • Complex joints to seal against dust	• Understood control systems • Potentially interesting applications for a robotic arm used with other systems
“Flying Delta”		• Can print planer or vertical structures • Stable platform with many failure points • Best for very large structures • Cable systems wear fast in lunar dust	• New control systems needed • Potentially the best option for very large planar structures like rocket landing pads
Boom Tower		• Can print planer or vertical structures • Stable platform • Excellent mass / print volume ratio • Minimal contact with lunar dust	• Understood control systems • Largest build volume for both planer or vertical structures outside of a flying delta printer

Comparison of Deposition Mobility Platforms

Architecture	Mass	Power	Complexity	Dust Risk	Versatility	Total
Gantry	*High (2)*	*Medium (3)*	*Medium (3)*	*Low (4)*	*High (4)*	16
Flying Delta	*High (1)*	*High (4)*	*High (1)*	*Low (5)*	*Medium (3)*	14
Rover	*Low (5)*	*Low (5)*	*Low (5)*	*High (1)*	*Low (1)*	17
Robotic Arm	*Medium (3)*	*Medium (3)*	*High (1)*	*High (2)*	*Medium (3)*	12
Boom Tower	*Medium (3)*	*Medium (3)*	*Low (4)*	*Low (4)*	*High (5)*	19

Lunar ISRU Additive Construction System

The Boom Tower



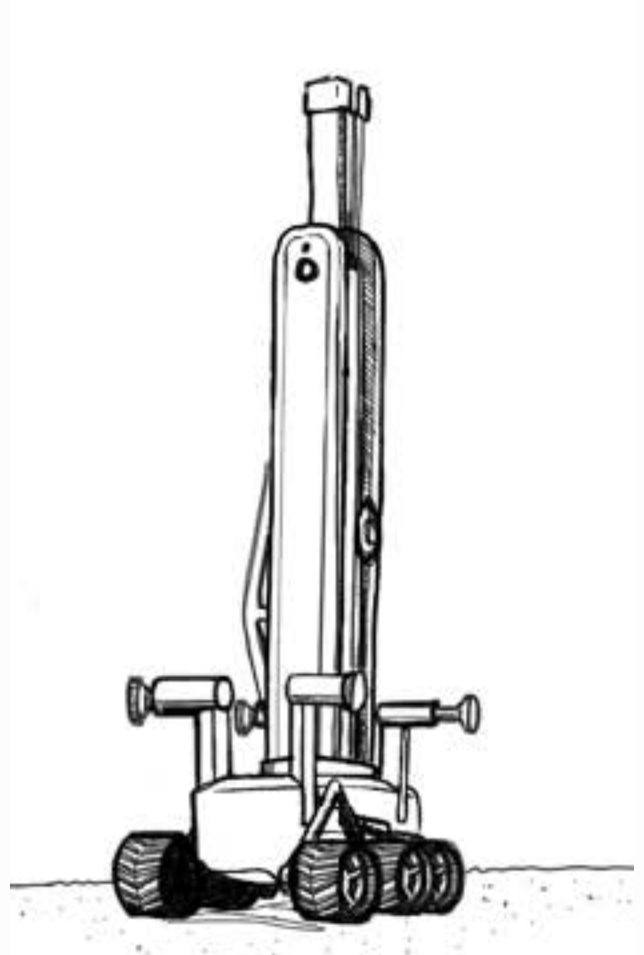
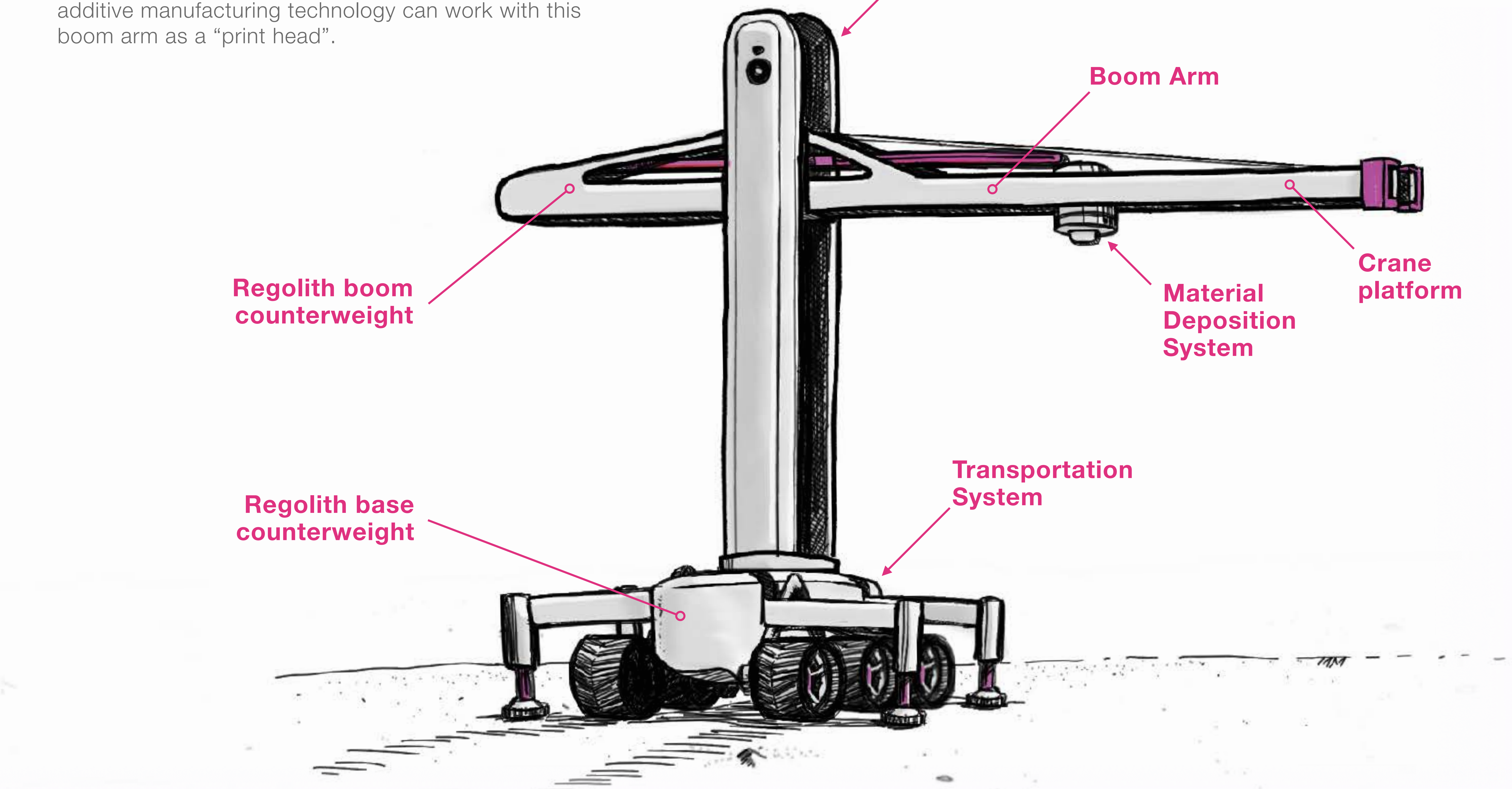


Fig. 2 - Flight/Landing Config

Lunar ISRU Additive Construction System

The Boom Tower

Similar to a self-erecting tower crane in function, this boom tower design provides a a very large build volume in a space and mass optimized platform. Any continuous additive manufacturing technology can work with this boom arm as a “print head”.



Tower (Z-prime)

Boom Arm

Regolith boom counterweight

Material Deposition System

Crane platform

Regolith base counterweight

Transportation System

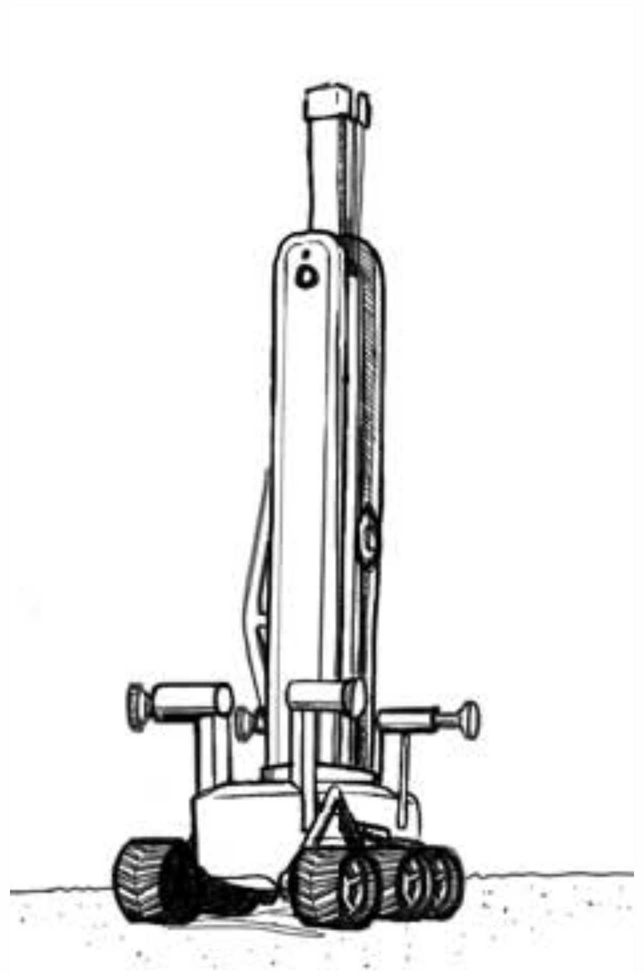


Fig. 2 - Flight/Landing Config

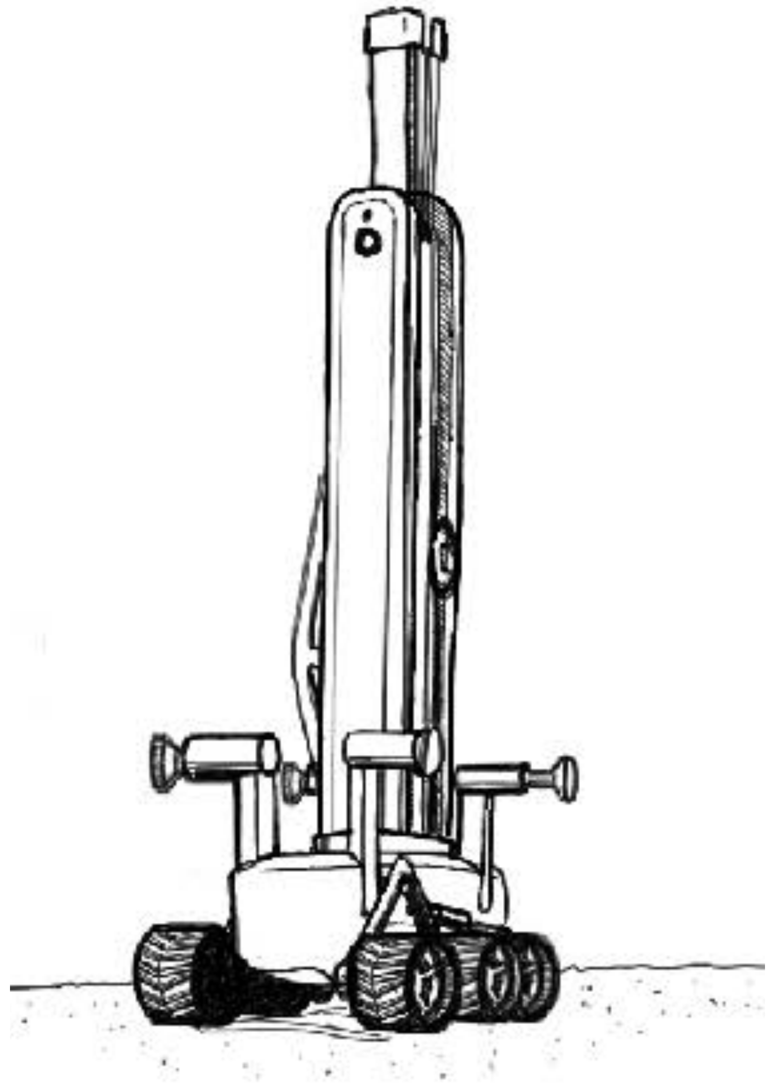
Fig. 3 - Self-Propelled, Self-Erecting Tower Crane found in smaller scale construction applications on Earth

Lunar ISRU Additive Construction System

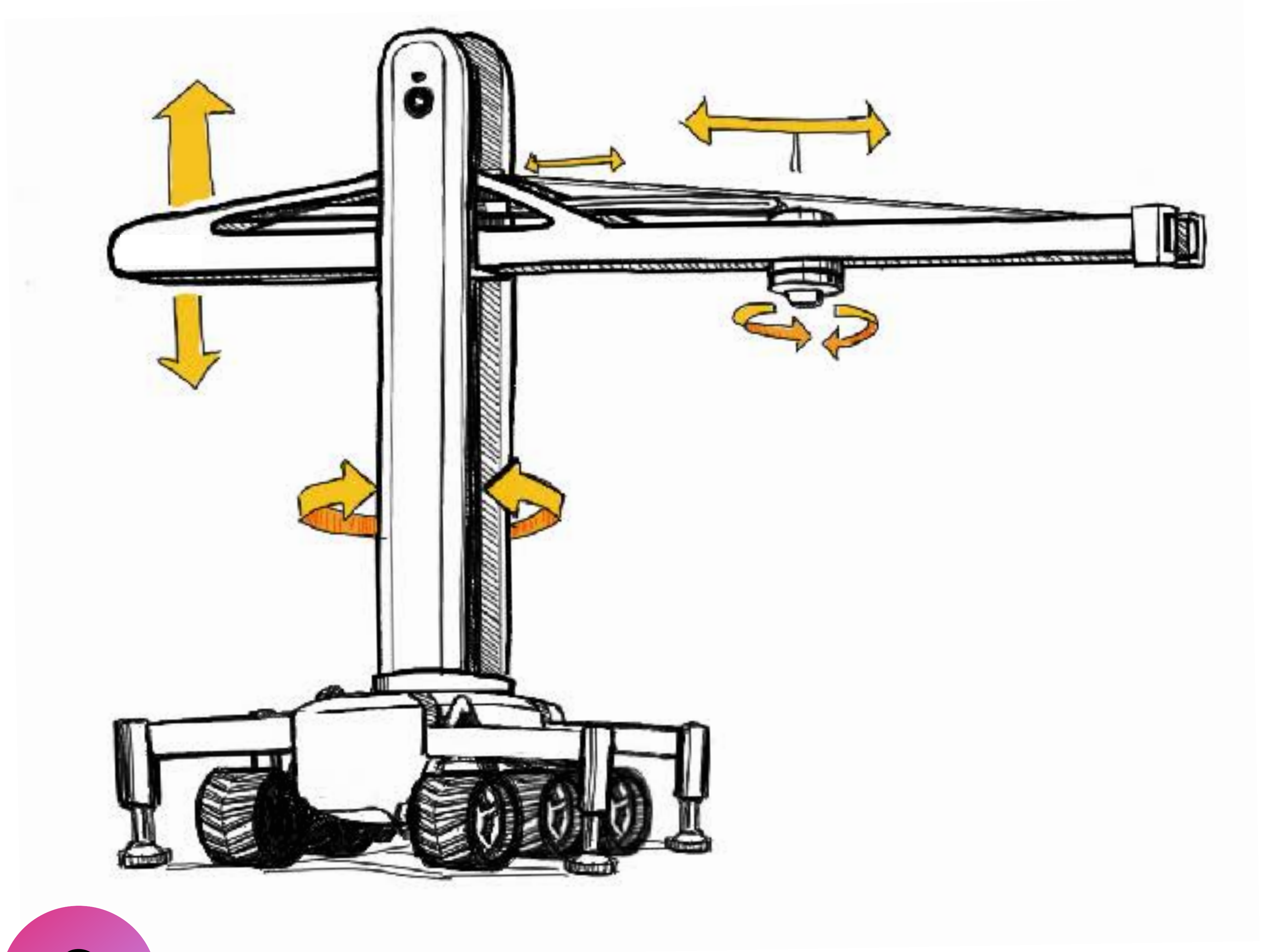
The Boom Tower architecture

The Boom Tower format mixes elements of various tower cranes on Earth (flat top, luffing, hammerhead, mobile, and self-erecting tower cranes) to create a flight optimized, large format printer that can easily handle planer as well as volumetric structures.

1 **Flight configuration**



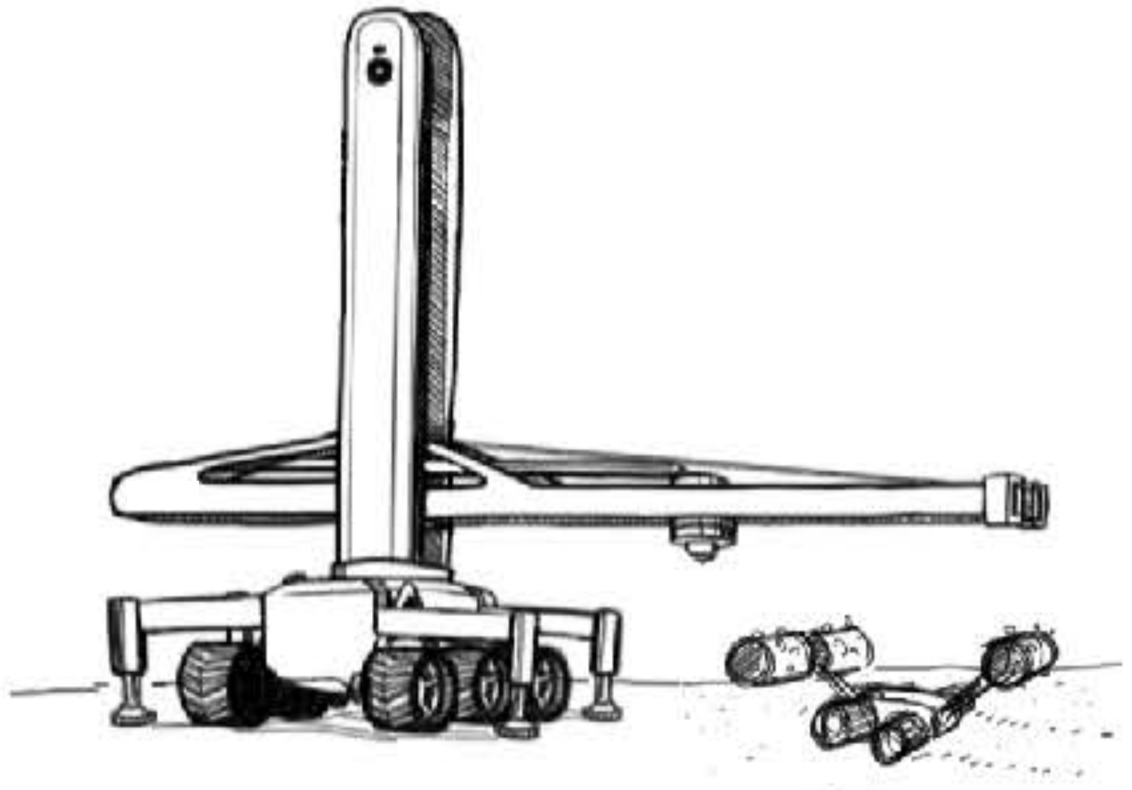
2 **Mobile configuration**

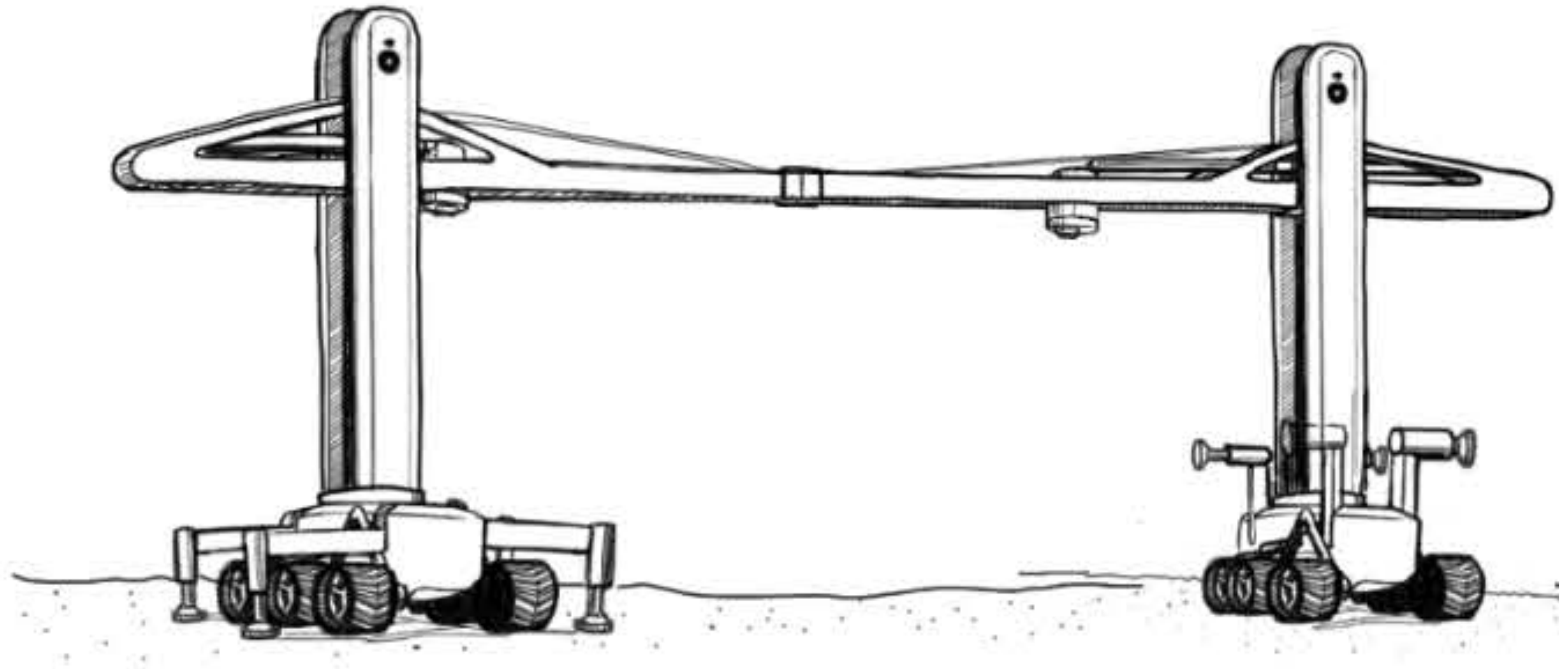


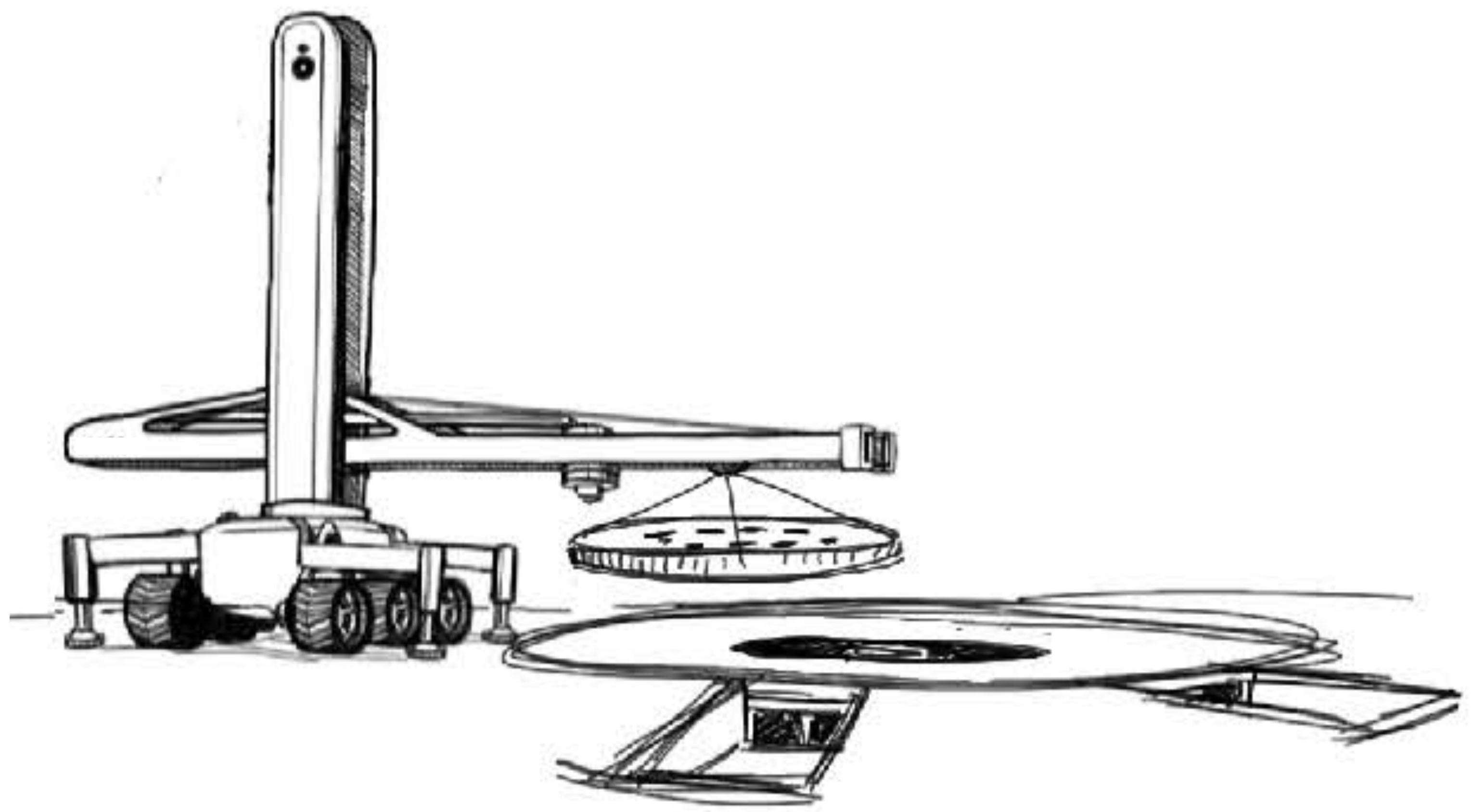
3 **Printing configuration**

Lunar ISRU Additive Construction System

Olympus Boom Tower configurations







Boom Tower

The Boom Tower concept is centered around the idea of the simplest mechatronics with the largest build volume possible on existing or future launch vehicles. A self folding Boom Tower compacts easily into a tall flight configuration for elongated payload fairings such as New Glenn or even SpaceX's existing Falcon family of rockets. This boom design could easily achieve very large build volumes in excess of 40'x60'.

Large Gantry / Rotary Gantry

Two Boom Towers will fit on a single Blue Moon lander (depending on payload mass), meaning a single launch could deliver two printers to the lunar surface. With twin printers on the surface, more options are possible, such as joining the twin printers together. This combination provides the option to use the printer assembly as either a radial gantry or a traditional, large format gantry for construction.

Print and Place Operations

Given the Boom Tower is based on construction crane architecture, it naturally lends itself to crane like operations during construction. This means structures can be printed in pieces then lifted into place by the printer itself. As a radial printer, the Boom Tower has multiple build sites that it can address.

Lunar ISRU Additive Construction System

Deposition Sub-System Research & Development

Lunar ISRU Additive Construction System

Material Deposition System conceptual approaches

1 Continuous extrusion of molten regolith.

2 Continuous Laser or Microwave sintering.

3 Molten regolith casting of construction materials.

4 Extrusion with a binder agent/ material.

Microwave Sintering Experiments

Microwave sintering experiments

Fig. 1 - Sintered sample from test run #19

Fig. 2 - Sintered samples from test run #19 fractured for inspection

Fig. 3 - IR camera of microwave heating process on refectory bricks which could be sintered to LHS-1 in experiments

Fig. 4 - ICON successfully demonstrated that changing microwave frequency moves the hot spot in the multimode cavity to heat and sinter new material. This IR imagery shows a LHS-1 sample heating in a graphite crucible from test run #15.

Microwave sintering experiments

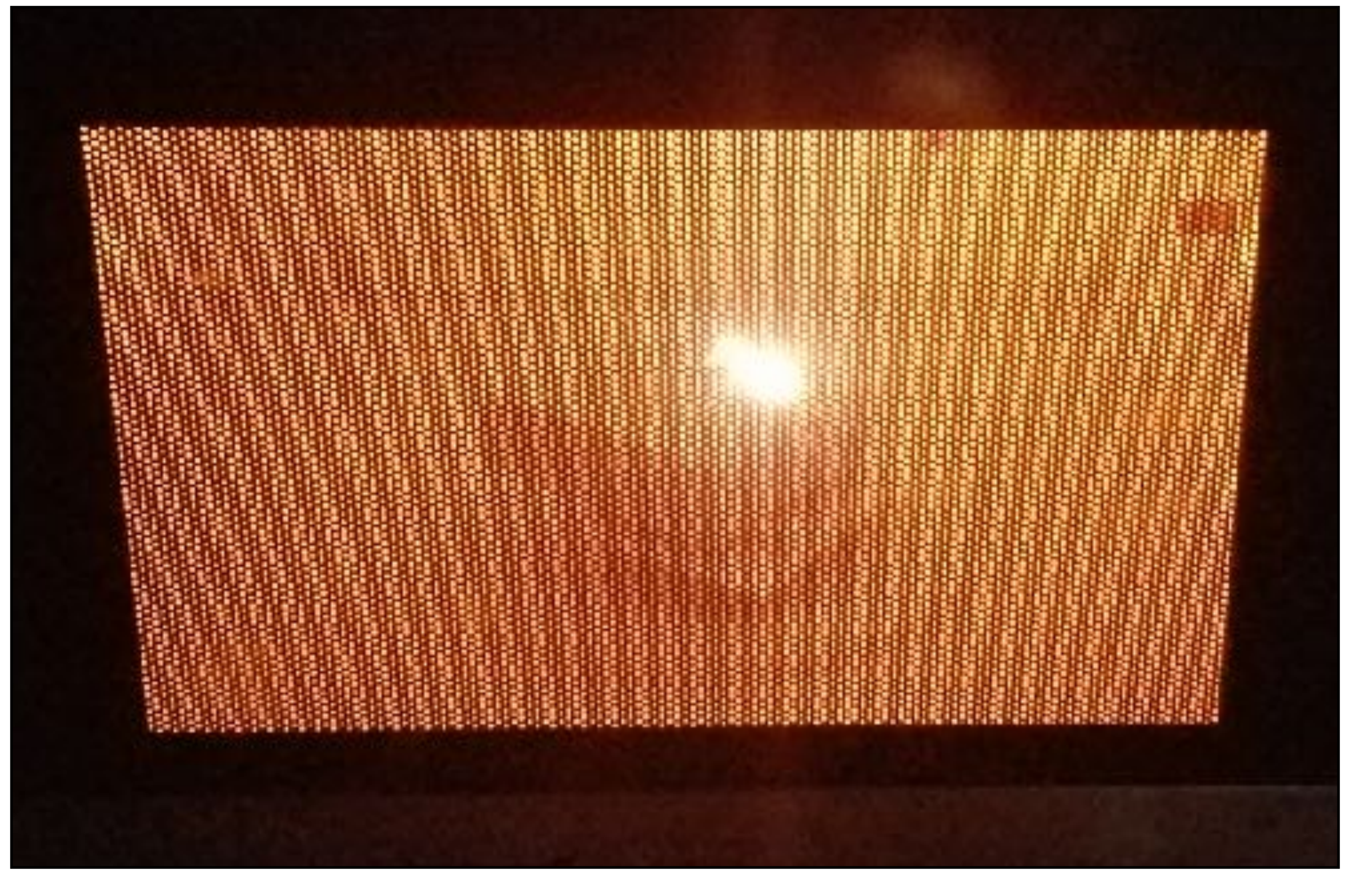


Fig. 1 - Test run #7, LHS-1 in a reusable graphite crucible. Graphite appears to reflect microwaves and handles high heat well.

Fig. 2 - Test run #7, LHS-1 heating in refractory brick crucible, Refractory bricks can be sintered to LHS-1 is the hotspot is hot enough.

Fig. 3 - LHS-1 sample test run #7

Fig. 4 - LHS-1 sample post heating from test run #15. The two areas of focused microwaves generated hot spots that sintered the regolith.

Fig. 5 - LHS-1 sample test run #15

Fig. 6 - LHS-1 sample broken open from test run #15. Voiding appears to be caused by off-gassing of regolith during the heating process.

Lunar ISRU Additive Construction System

Laser sintering experiments

Lunar ISRU Additive Construction System

Laser Sintering Experiments - material handling prototypes

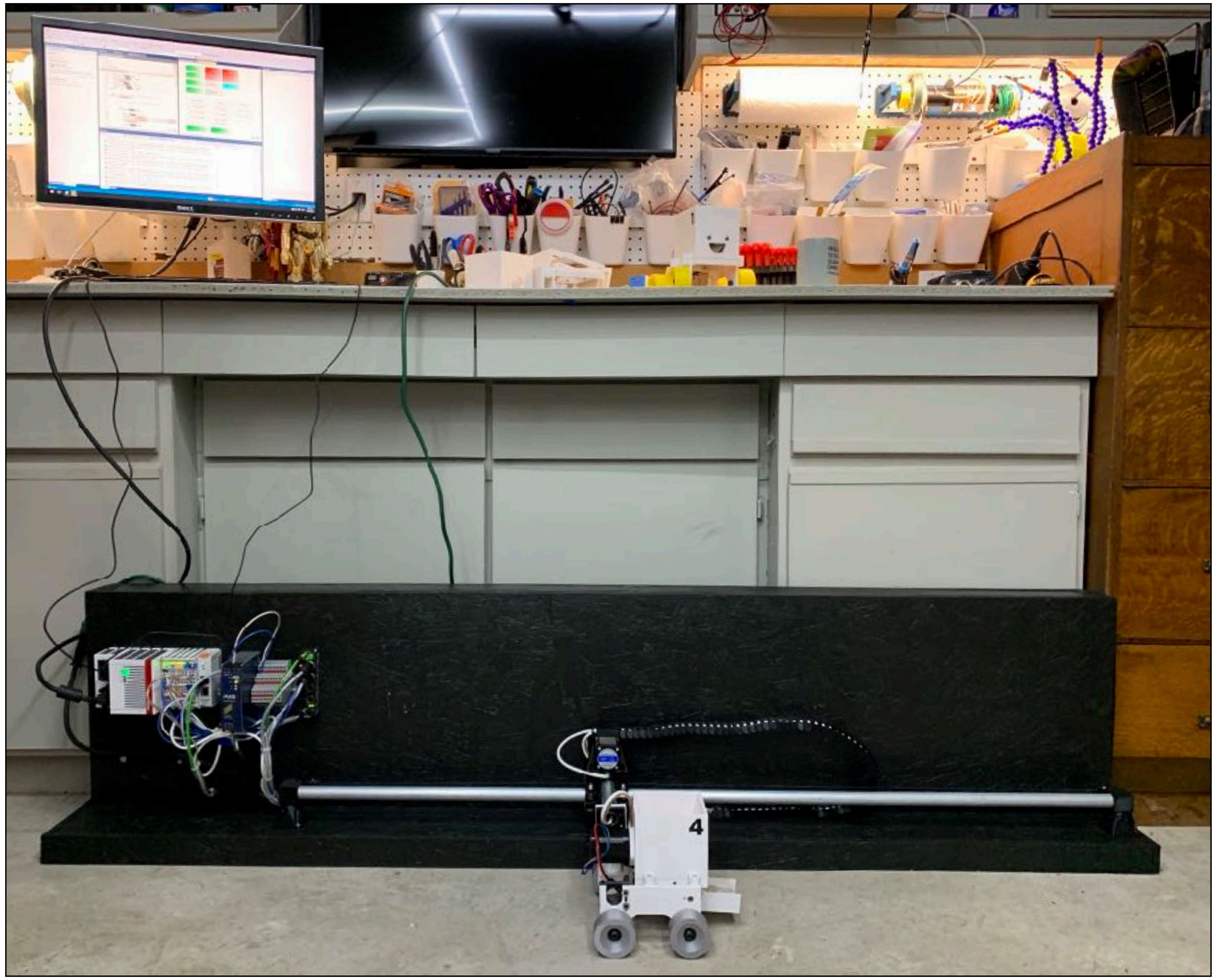


Fig. 1 - BB-04 mounted to a universal drive axis for upcoming sintering experiments with the laser sintering assembly

Fig. 2 - BB-04 deposition experiments using Greenspar 90 material for calibration

Lunar ISRU Additive Construction System

Laser Sintering Experiments - material handling prototypes

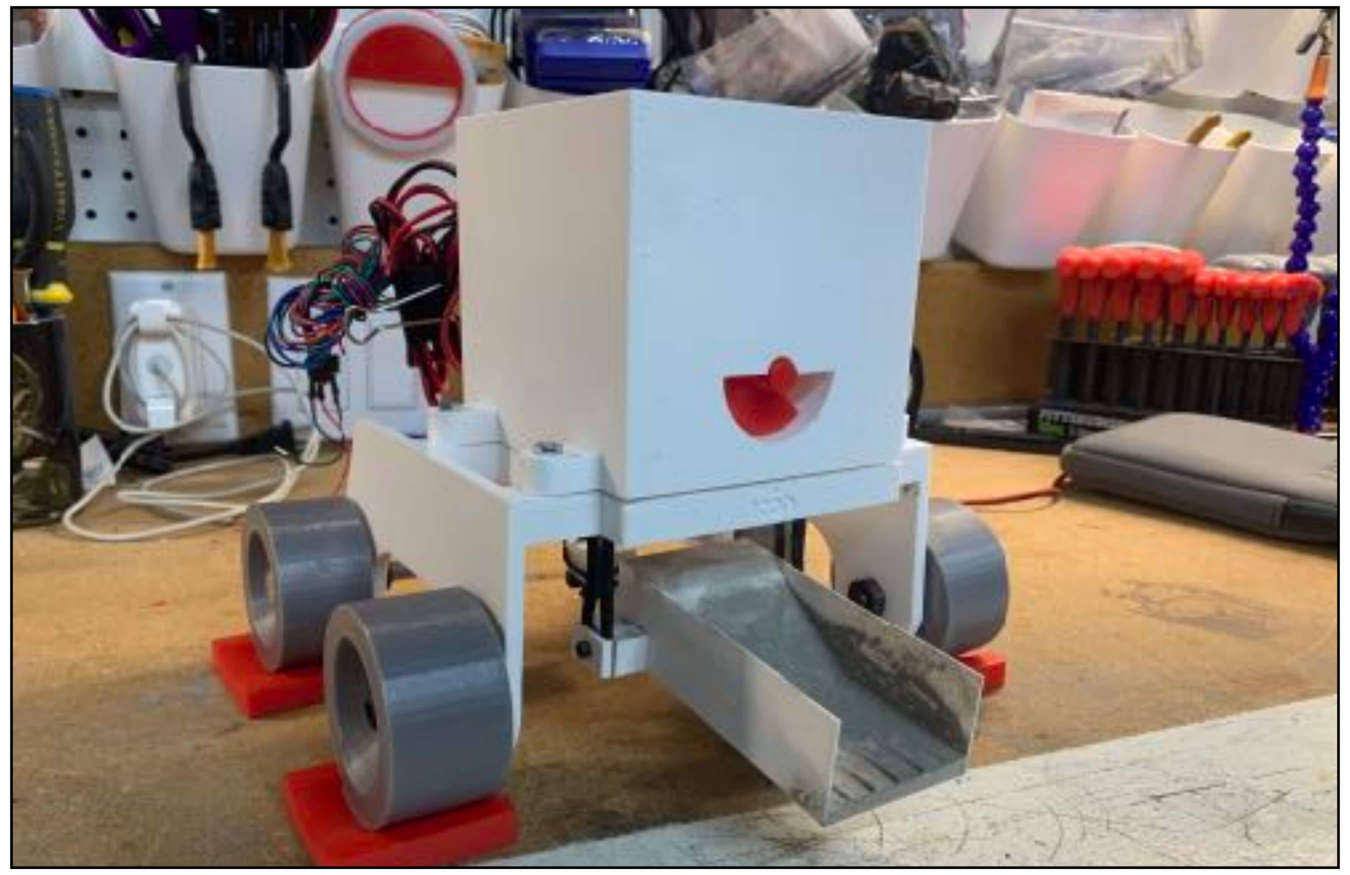


Fig. 1 - BB-03 with improved vibration plate & auger design

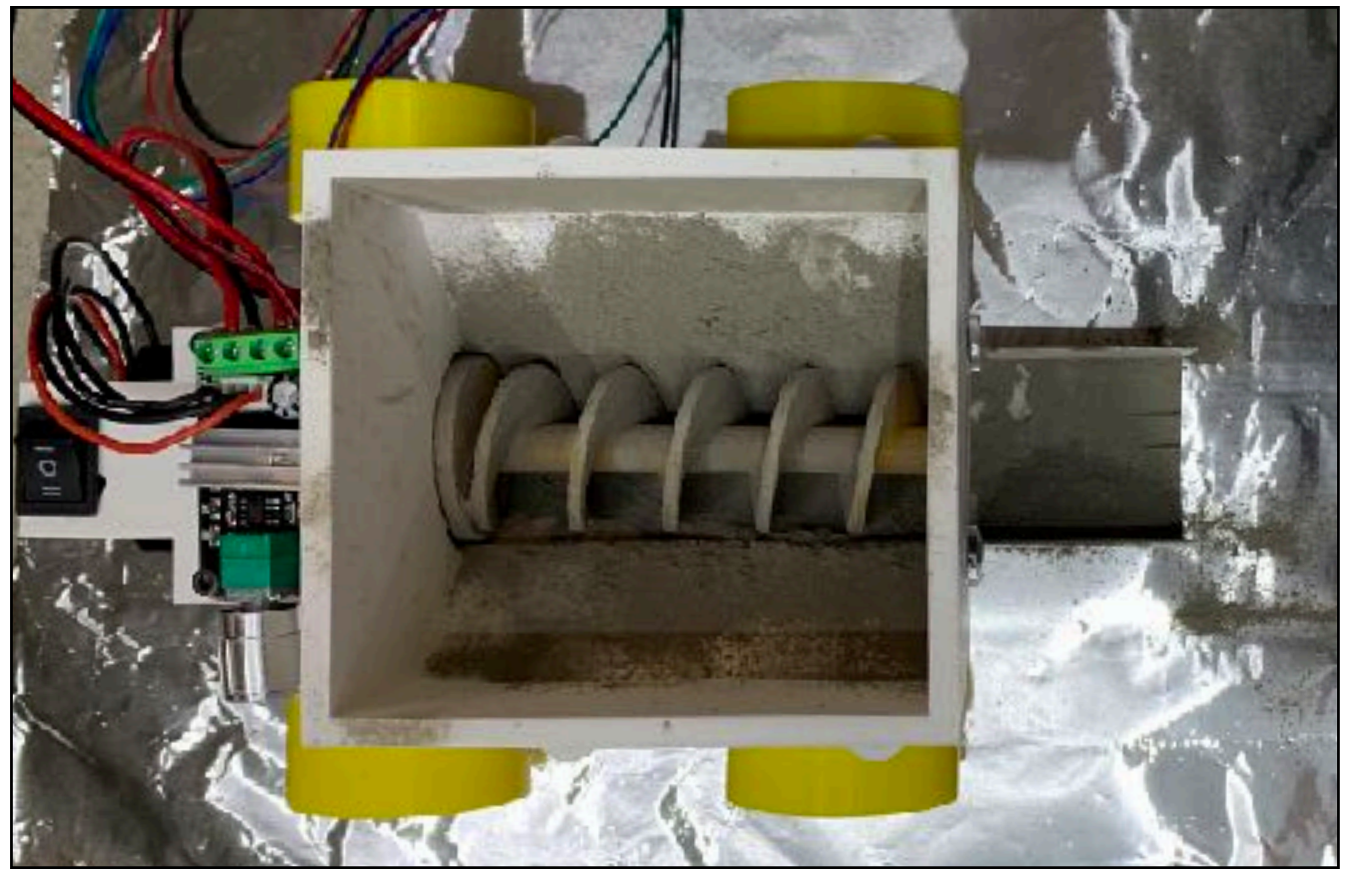


Fig. 2 - BB-01 Hopper & auger assembly

Fig. 3 - Bead line width and depth were repeatable across tests

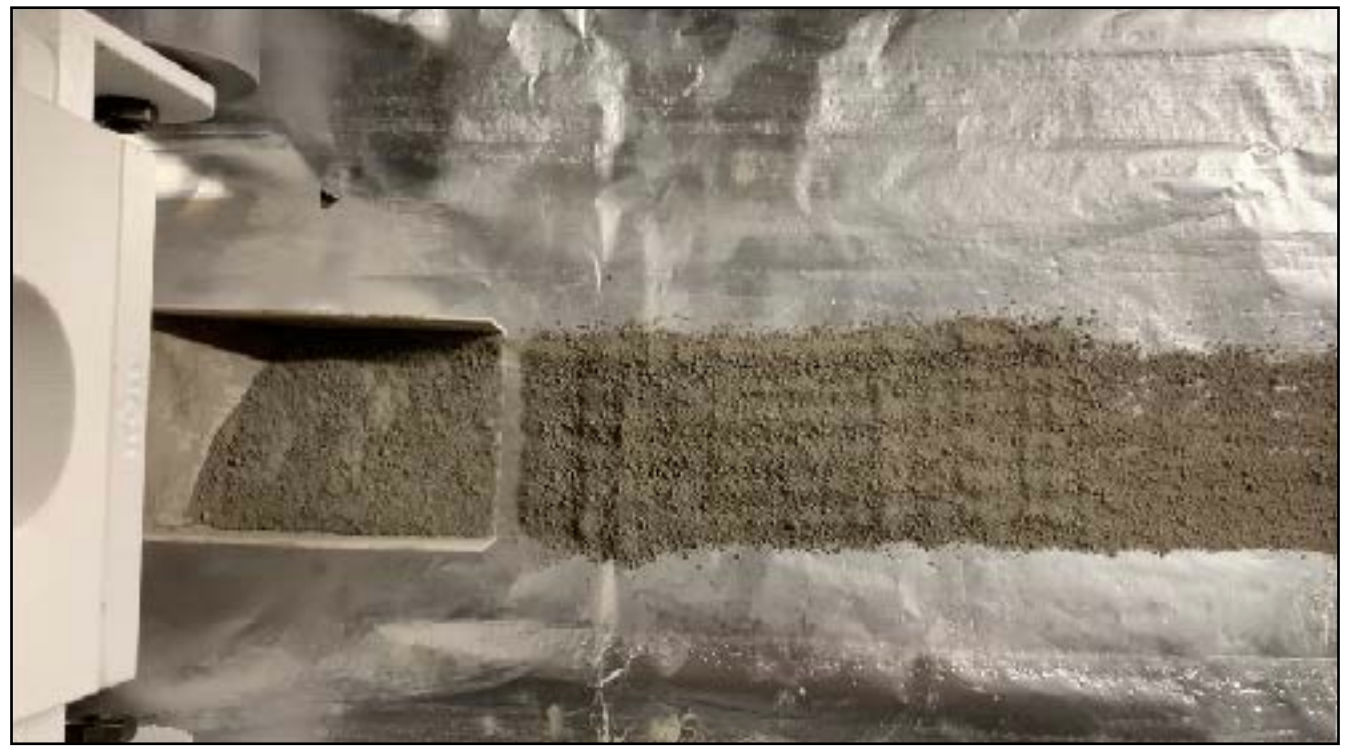


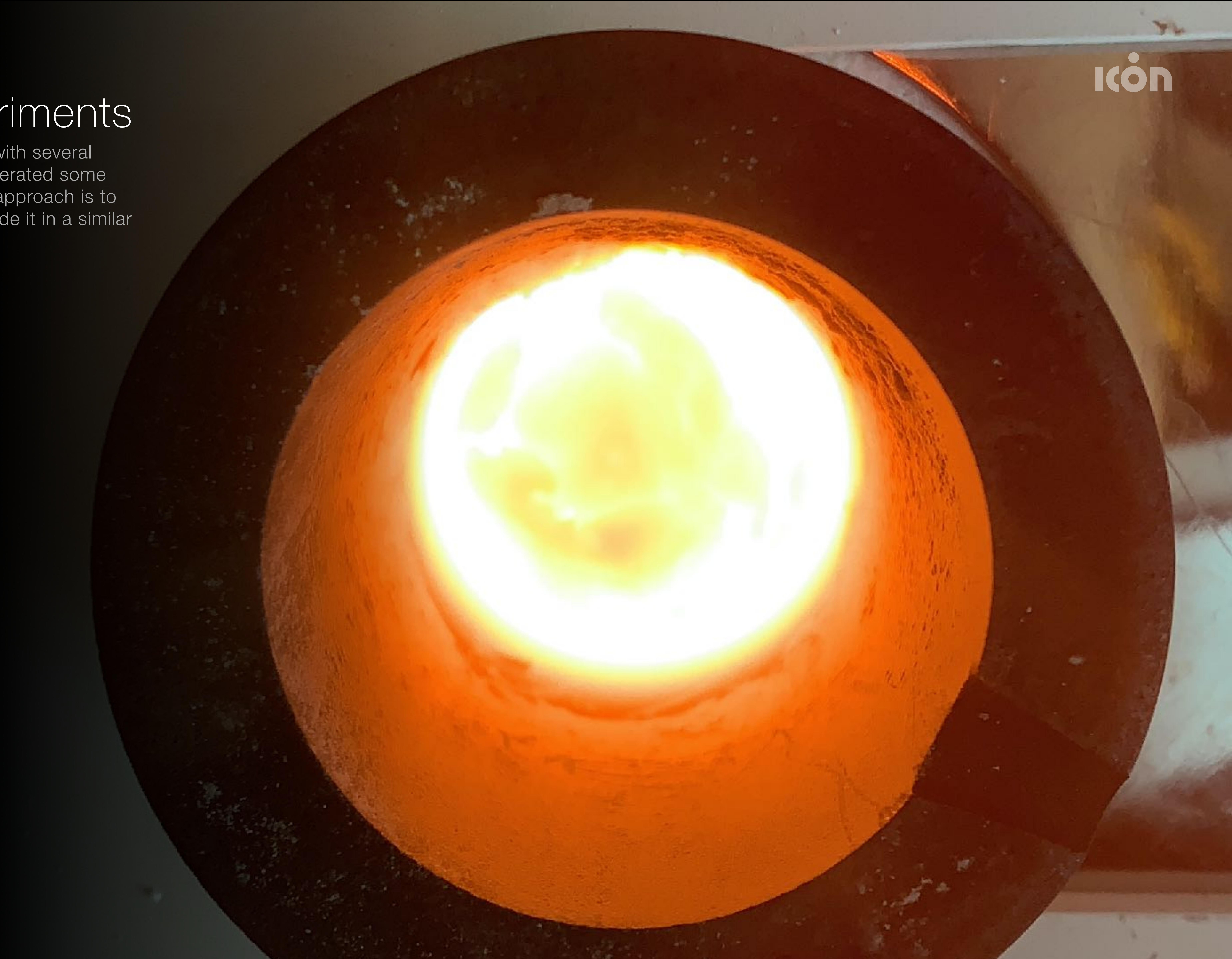
Fig. 4 - Guide vanes can leave "grooves" in powder at incorrect vibration frequencies and travel speeds

Fig. 5 - Vibration intensity + travel speed can create uniform powder beds for sintering. One without the other creates irregularities in powder bed depth.

Fig. 6 - Centripetal force from the vibration motor's axis being aligned with the vibration plate's center line allows regolith to be moved from left / right inside the vibration plate dependent on motor direction. Pulsing the vibration motor and/or reversing motor direction provide for "cleaning" of the vibration plate.

Molten simulant experiments

ICON’s experimentation and rapid prototyping with several different potential printing technologies has generated some very interesting material science. One of these approach is to heat lunar regolith into a molten state and extrude it in a similar Fashion as a desktop FDM plastic printer.



Lunar ISRU Additive Construction System

Molten simulant experiments

Fig. 1 - Sample 2A-006
First flowing sample of molten LHS-1 in the ICON labs.

Fig. 2 - Sample 2A-008

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Molten simulant experiments

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Molten simulant experiments

Moon Glass

Molten experiments with LHS-1 at the ICON labs has produced a lunar glass material that has been extruded. The intense green coloring earned the samples the nick name “pickle glass” early ton in the lab.

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Molten simulant experiments

Manufactured Geology

Molten experiments in the ICON labs have yielded some promising, initial results. Molten samples have an appearance somewhere between glazed ceramic pottery and metallic rock. Compression testing revealed these manufactured ceramics have ultra high strength exceeding 18,000 psi on average and so far have tested as high as 29,384 psi.

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Molten simulant experiments

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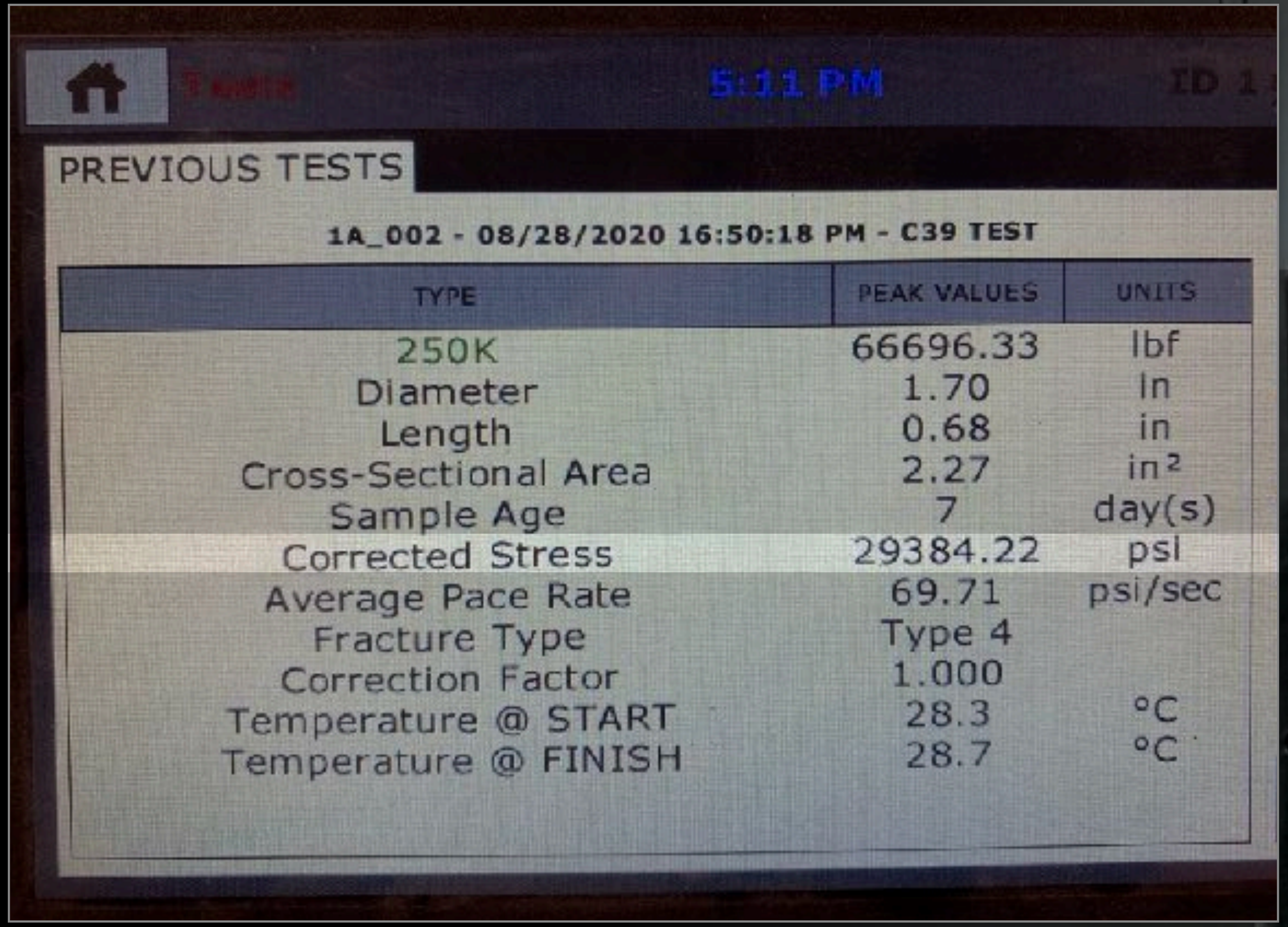
Molten simulant experiments



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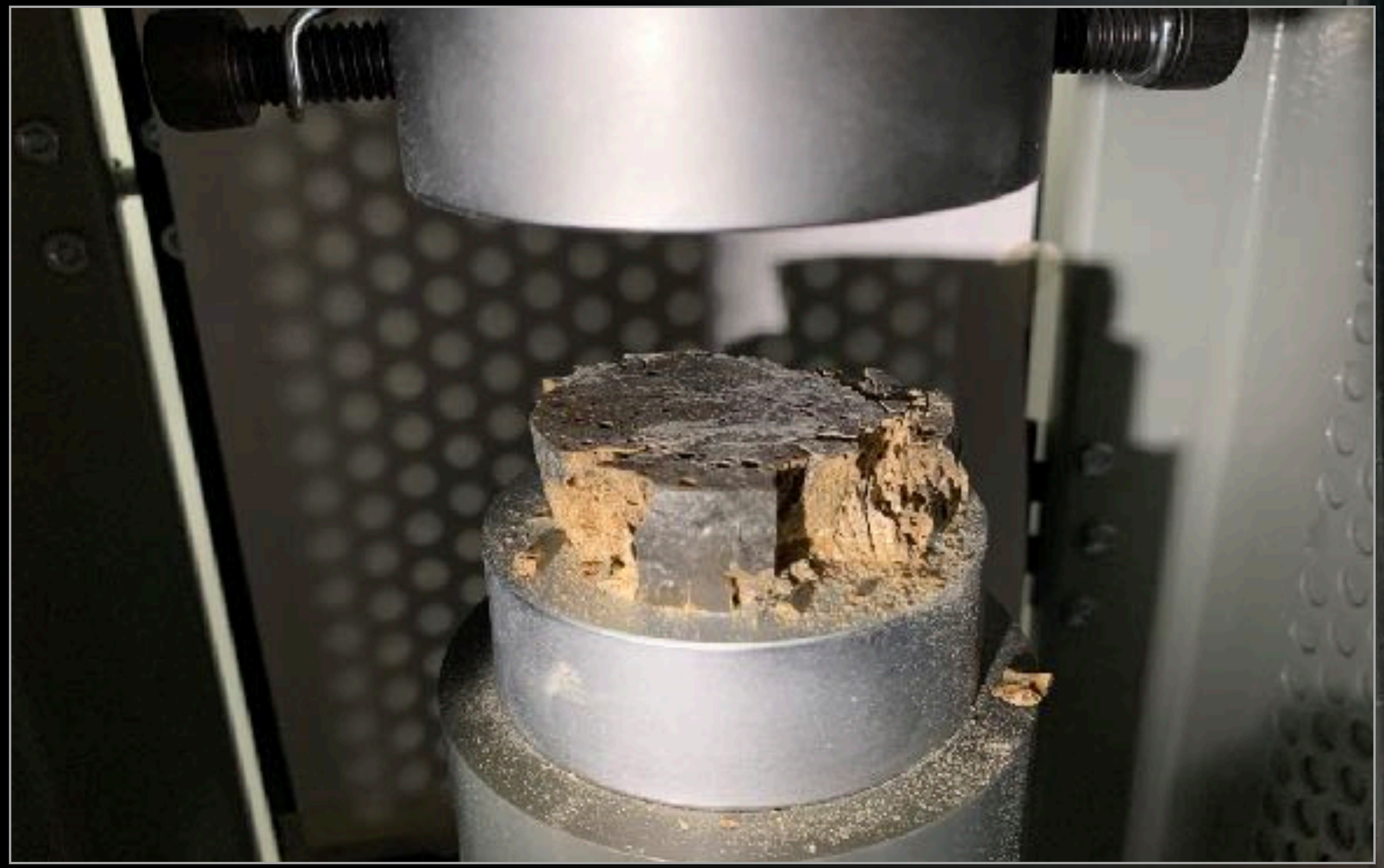
ID 1

PREVIOUS TESTS

1A_002 - 08/28/2020 16:50:18 PM - C39 TEST

TYPE	PEAK VALUES	UNITS
250K	66696.33	lbf
Diameter	1.70	in
Length	0.68	in
Cross-Sectional Area	2.27	in²
Sample Age	7	day(s)
Corrected Stress	29384.22	psi
Average Pace Rate	69.71	psi/sec
Fracture Type	Type 4	
Correction Factor	1.000	
Temperature @ START	28.3	°C
Temperature @ FINISH	28.7	°C



Lunar ISRU Additive Construction System

Molten simulant experiments

LHS-1 sample

29,384 psi

Lunar ISRU Additive Construction System

Comparison of Technology Approaches

Process	Accuracy	Speed	Versatility	Power	ISRU	Lunar Environment Sensitivity
Continuous Laser Sintering	*High*	*Low*	*Medium*	*Medium*	*High*	*Medium*
Continuous Microwave Sintering	*Low*	*Medium*	*Low*	*Medium*	*High*	*Medium*
Molten Process	*Medium*	*High*	*High*	*Medium*	*High*	*Low*
Extrudable Concrete / Admixture	*Medium*	*Medium*	*Low*	*Low*	*Very Low*	*Very High*

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