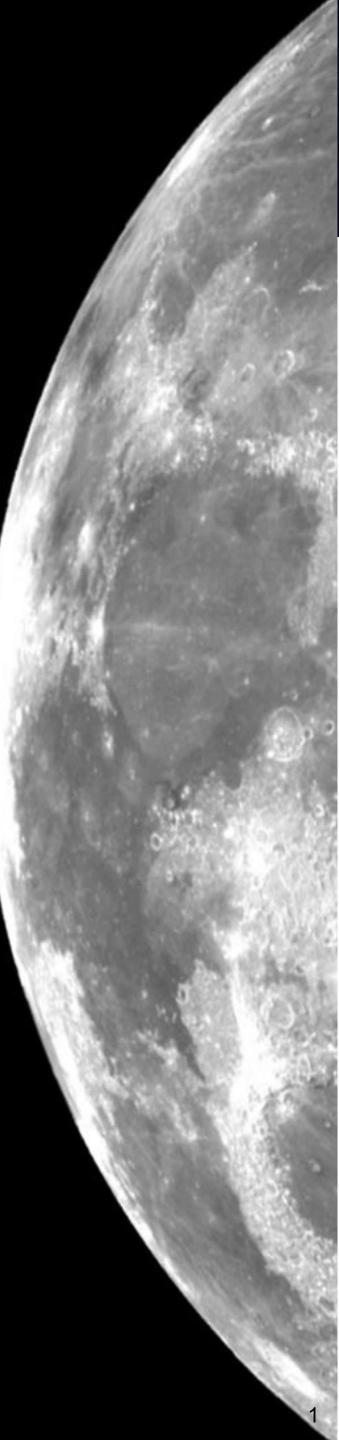


Vertical Regolith Transport System for Lunar & Mars ISRU Applications

Dr. Aaron Olson, NASA KSC / UB-G
Dr. James Mantovani, NASA KSC / UB-E
Dr. Beverly Kemmerer, NASA KSC / UB-E
Jonathan Gleeson, KSC-LASSO

KSC Swamp Works
NASA Kennedy Space Center, FL 32899

Presented at the 2022 Space Resources Roundtable, Golden, CO, June 7-10, 2022

Acknowledgements

Thanks to:

- NASA GCD ISRU FLEET Project: Diane Linne, PI and Erica Montbach, PM
- NASA Flight Opportunities Program
- NASA KSC Exploration Research & Technology Programs Directorate, and the KSC Engineering Directorate

Outline

- Motivation and ISRU Conveying Needs/Requirements
- Helical Vertical Conveying Options
- Vertical Lunar Regolith Conveyor (VLRC) Prototypes
- Suborbital Lunar Gravity Flight

Background

Previous Work

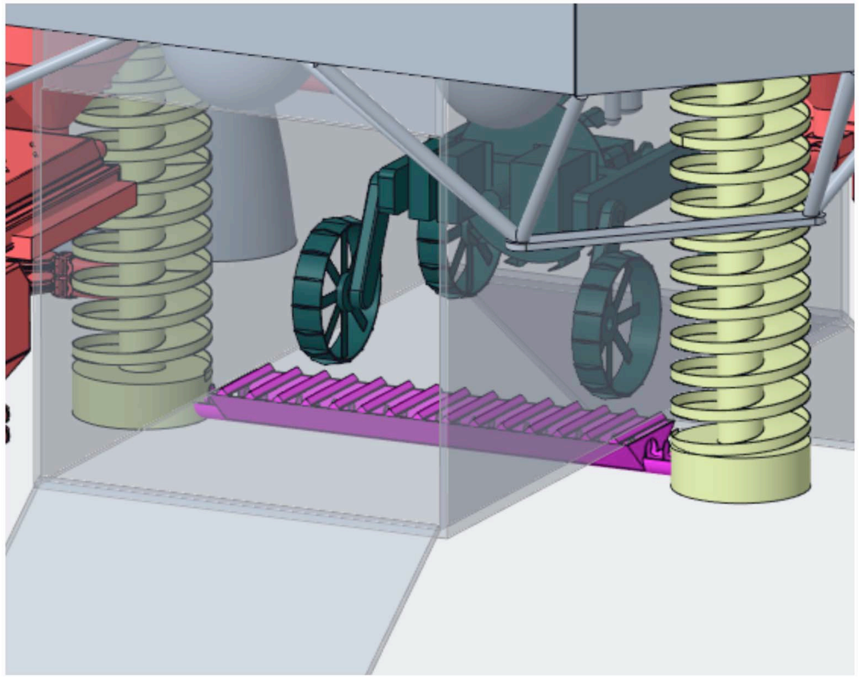
- This work builds on previous efforts that were internally funded at NASA KSC from 2008 - 2011 to develop a Vibratory Regolith Conveyor that demonstrated a stick-slip method of conveying granular material up a smooth stainless-steel inclined surface. This led to a tech demo of a spiral conveyor that also used stick-slip method.

Current Work and Status

- NASA KSC first started supporting a Regolith Transport task under the ISRU FLEET project in August 2021 to develop a vibratory lunar regolith conveyor (VLRC).
- The VLRC was proposed to GCD and the NASA Flight Opportunities Program in 2021 to fly on a Blue Origin Lunar Gravity suborbital flight opportunity and was selected to fly as early as Jan 2023.
- Multiple VLRCs are being developed to operate under vacuum and lunar gravity conditions in a custom-built vacuum chamber for a double locker on the Blue Origin New Shepard rocket.
- An analytical model of a VLRC is under development to model the vertical transport of regolith along a spiral ramp as well as up a linear ramp.
- We have obtained external test data from testing a commercial Spiral Conveyor using BP-1 crushed basalt.

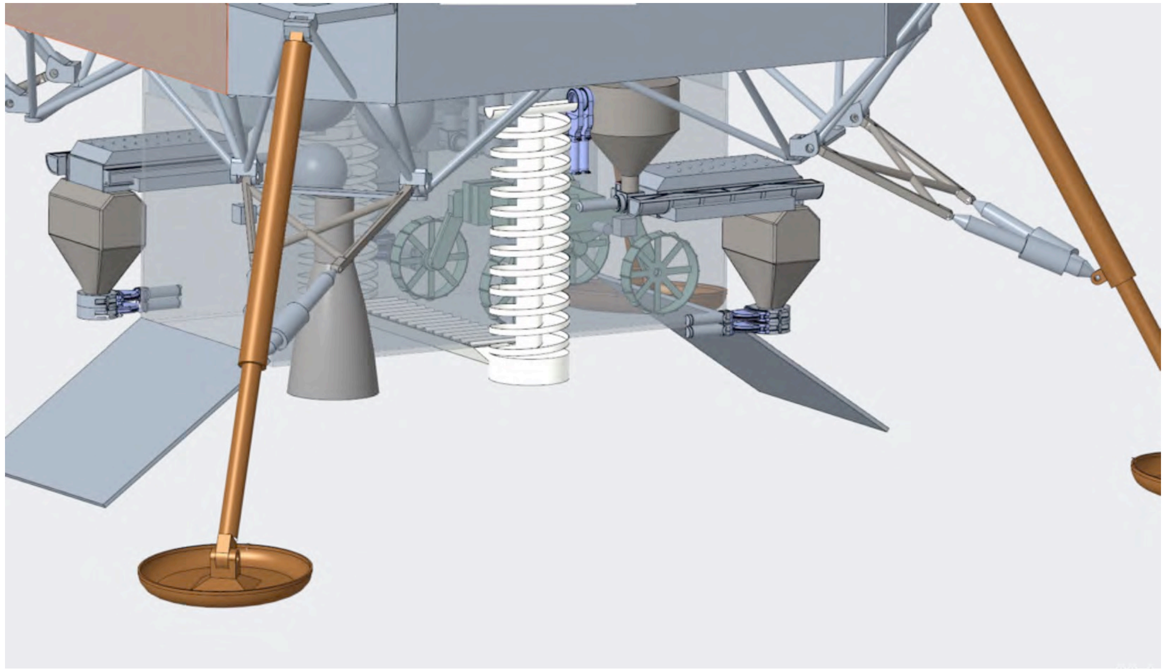
Possible ISRU Applications of Vertical Conveying

- Estimated Regolith Convey Rate: 2 kg/min (2019 ISRU COMPASS Study)



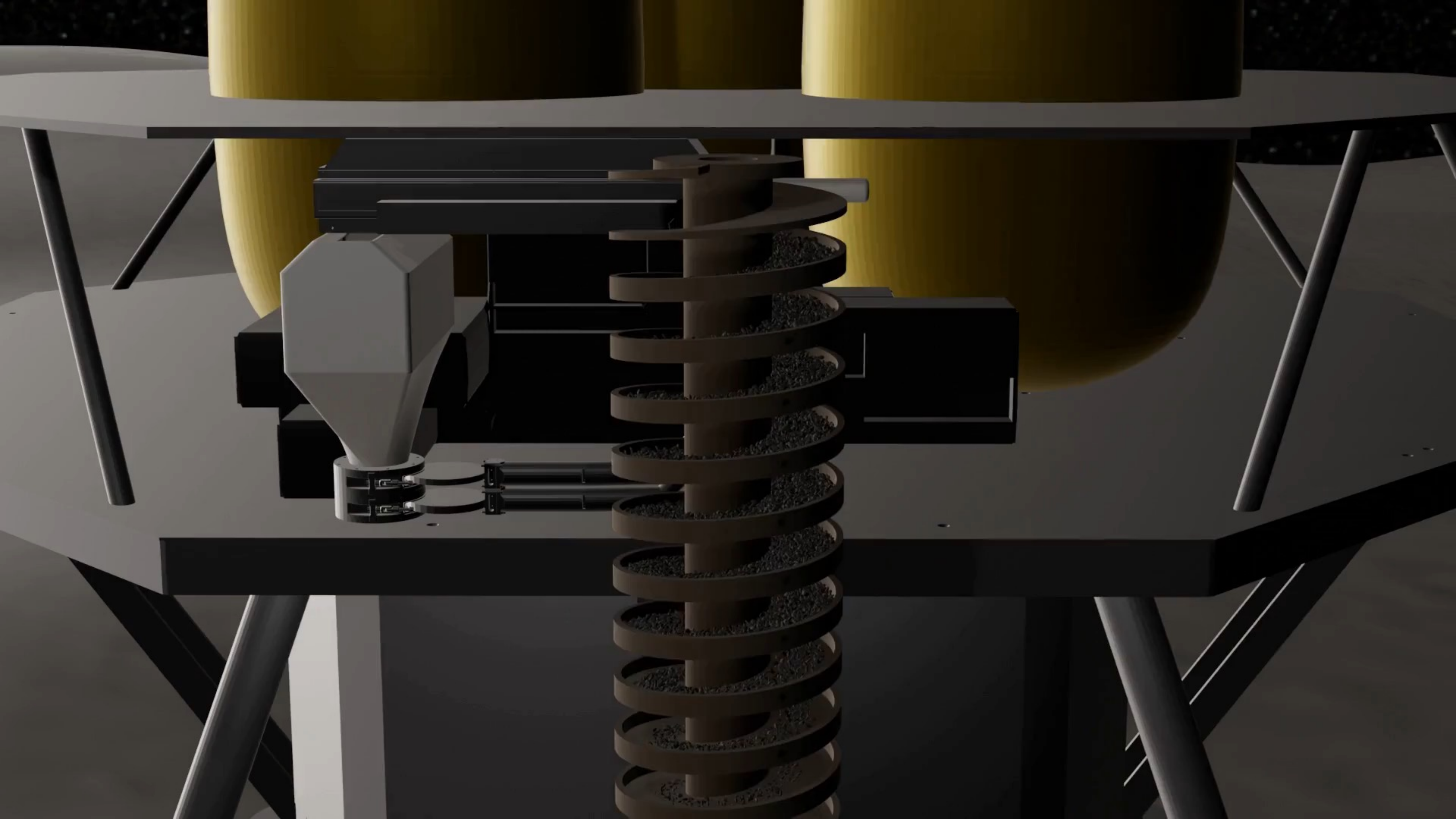
Concept for transporting regolith to ISRU systems on a lander deck. From "Lunar Production System for Extracting Oxygen from Regolith," D. L. Linne, et al., J. Aerosp. Eng., 2021, 34(4): 04021043.

https://doi.org/10.1061/(ASCE)AS.1943-5525.0001269



*Concept for transporting regolith to ISRU systems on a lander deck. From "Oxygen Production System for Refueling Human Landing System Elements," D. L. Linne, et al., presented at the **2019 SRR / PTMSS Symposium**.*

https://ntrs.nasa.gov/api/citations/20190029197/downloads/20190029197.pdf



Typical Commercial Helical Conveyor

- Vibrating systems selected to reduce wear due to regolith – rotating component interaction
- Commercial helical conveyors (spiral elevators)
  - Twist and lift motion with spring base
  - Material is thrown or hops along helical path
- Lunar Simulant Testing
  - KSC provided BP-1 for testing using a commercial helical conveyor (Vibra-Screw, Inc., Totowa, NJ)
  - Dust tolerant

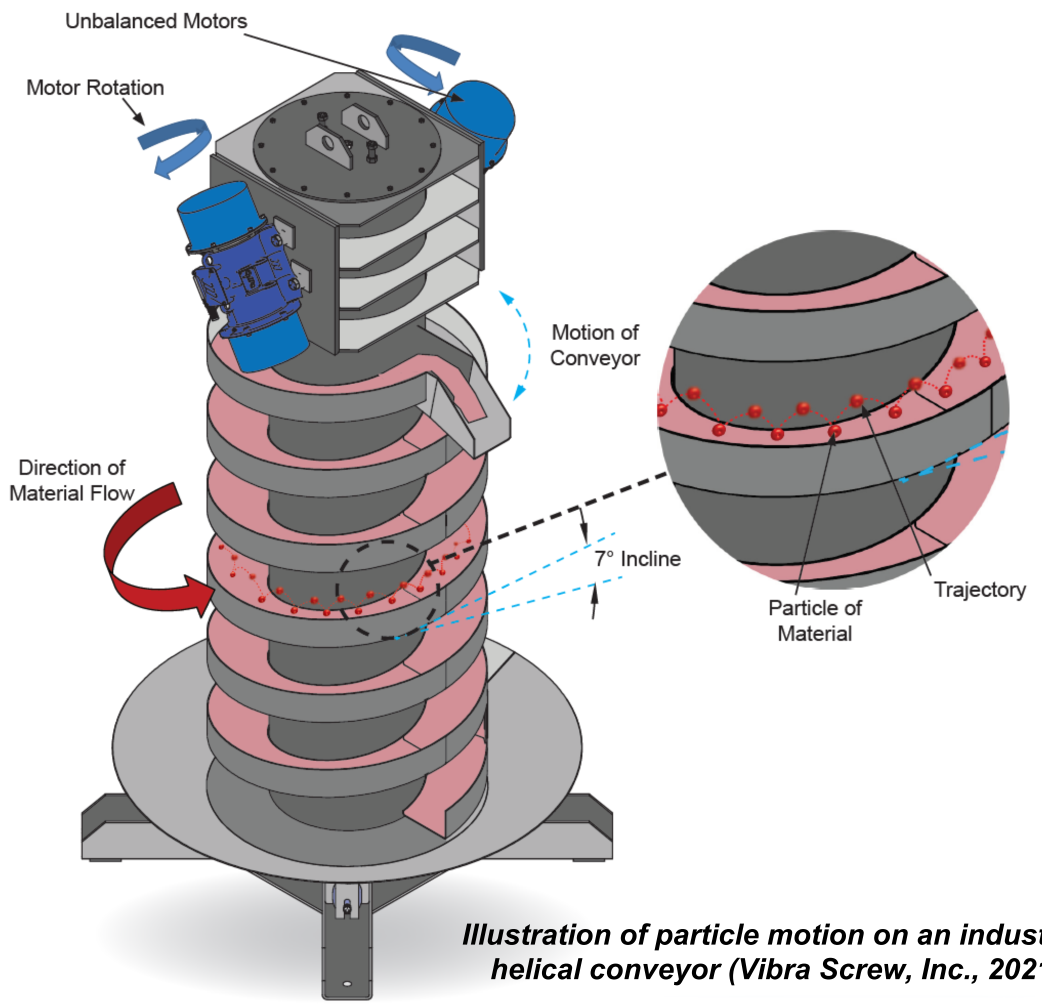
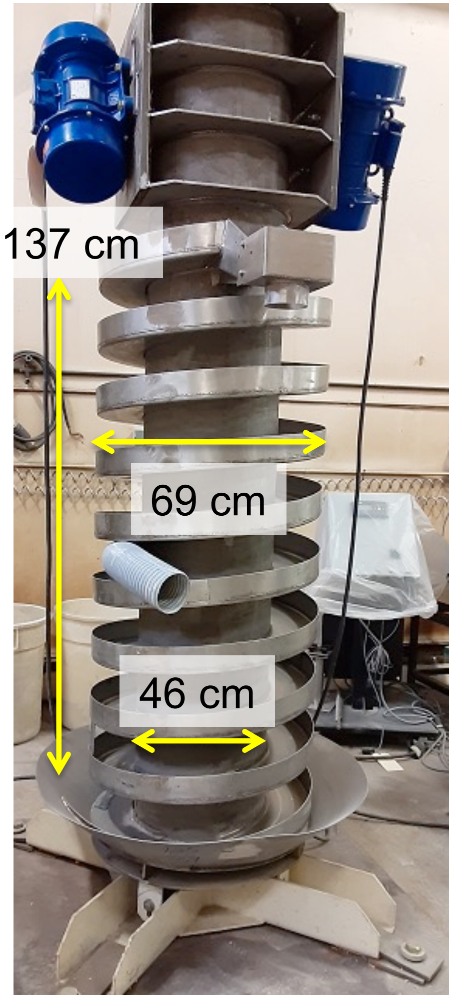


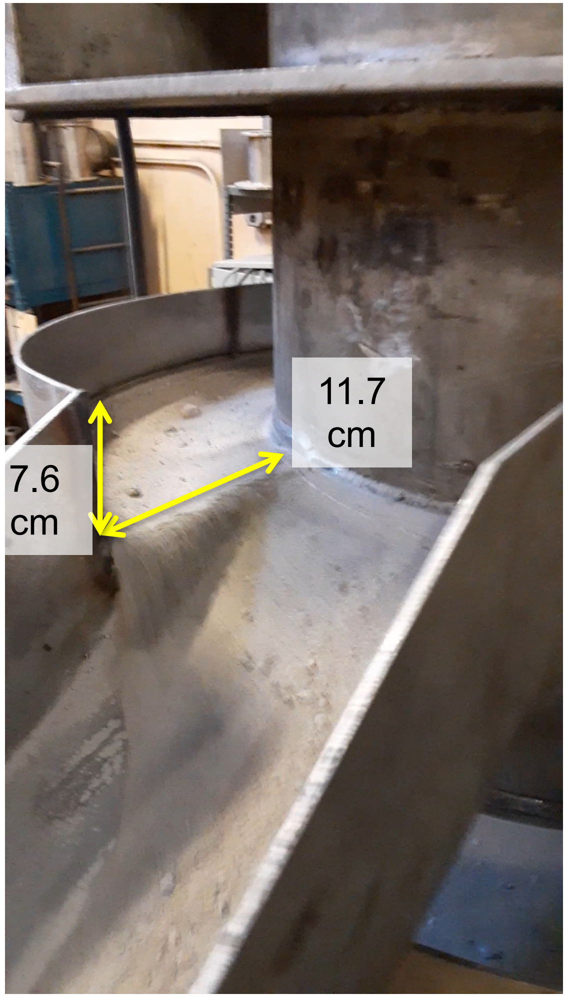
Illustration of particle motion on an industrial helical conveyor (Vibra Screw, Inc., 2021)

Commercial Helical Conveying of Lunar Simulant

- Commercial System (Vibra Screw, Inc.)
  - 45 cm inner diameter, 11.7 cm path width
  - Path slope: 4.8° to 7.3°(outer to inner radius)
  - ~240 kg system mass
  - Drive: Two unbalanced 60 Hz 15.6 kN eccentric force motors offset at ±60 deg from horizontal
- Simulant: BP-1 (full size distribution up to 2 cm rocks)
- System tested for material convey speed as a function of eccentric loading and frequency



WF 1500/680 – U16X Model Helical Conveyor (Vibra Screw, Inc., 2021)



BP-1 conveyed at 133 g/s on an industrial helical conveyor (Vibra Screw, Inc., 2021)

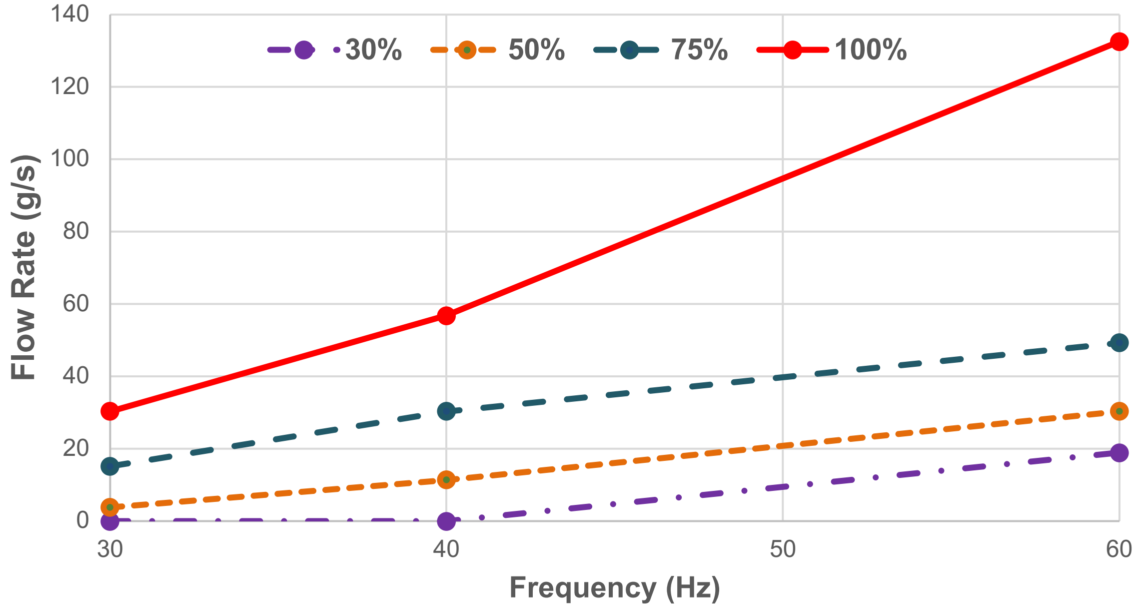
Commercial Helical Conveying of Lunar Simulant

Test Conditions and Results

- Flow rate increases with increased eccentric loading and drive frequency

Parameter	Value
Flow Rate	7.9 kg/min (120 kg/min max)
Avg. Particle Speed	15.2 cm/s
Avg. Particle Depth	0.4 cm
Frequency	60 Hz
Amplitude/Stroke	0.46 cm
Power	3.7 kW

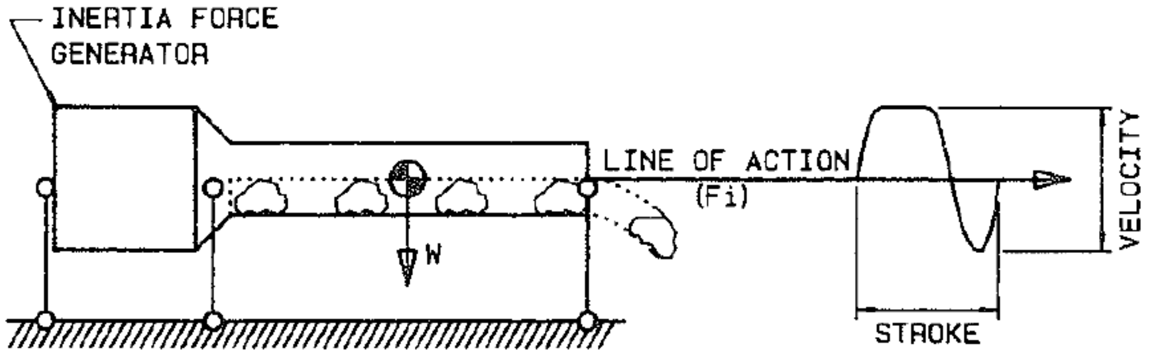
- Efficiencies:
  - Test Results - Power: 28 J/g, Mass: 1818 kg/(kg/s)
  - Max – Power: 1.9 J/g, Mass: 120 kg/(kg/s)



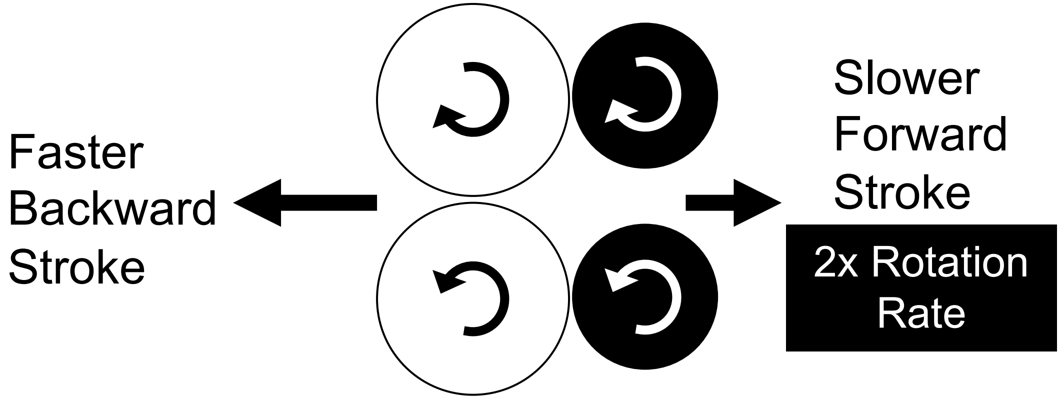
Flow Rate of KSC BP-1 vs. Frequency for Different Eccentric Loadings

Stick – Slip Method of Regolith Conveying

- Stick-slip conveyors
  - Quick return/deceleration or hard stop motion profiles created by linkage or rotating unbalances
  - Can operate at an incline
  - $\mu_s \geq a_{struct}/(g\cos(\theta)) + \tan(\theta)$ – no slip
  - No commercial helical versions identified
- Advantages of Stick-slip conveyors for NASA
  - Can produce higher transport efficiency
  - Lower wear compared to “throwing” conveyors
  - Dust tolerant



Example of Stick-Slip method for a horizontal conveyor with quick return velocity profile

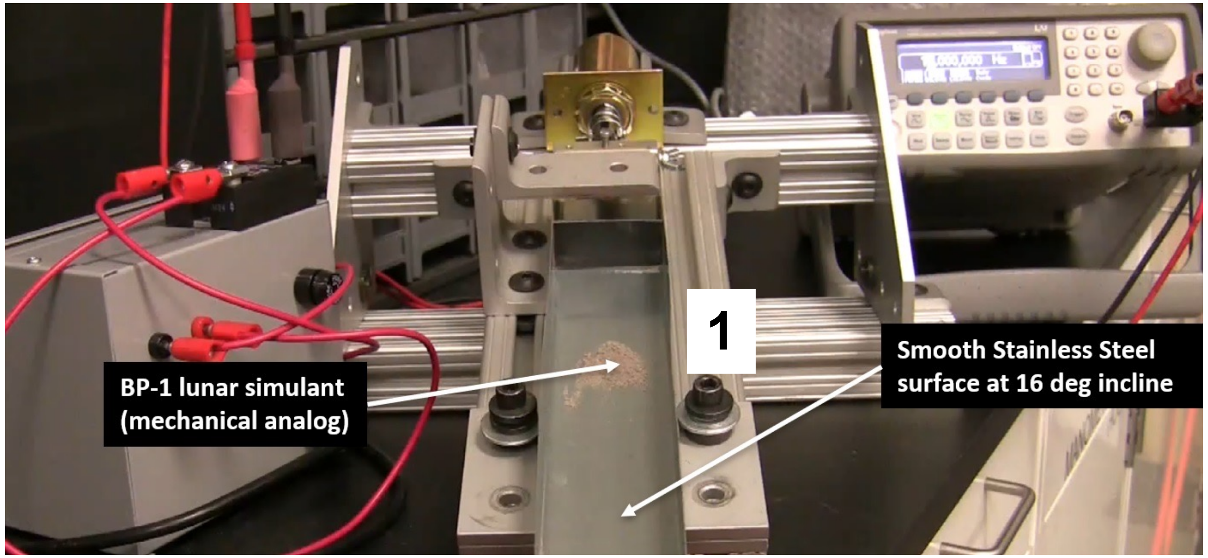


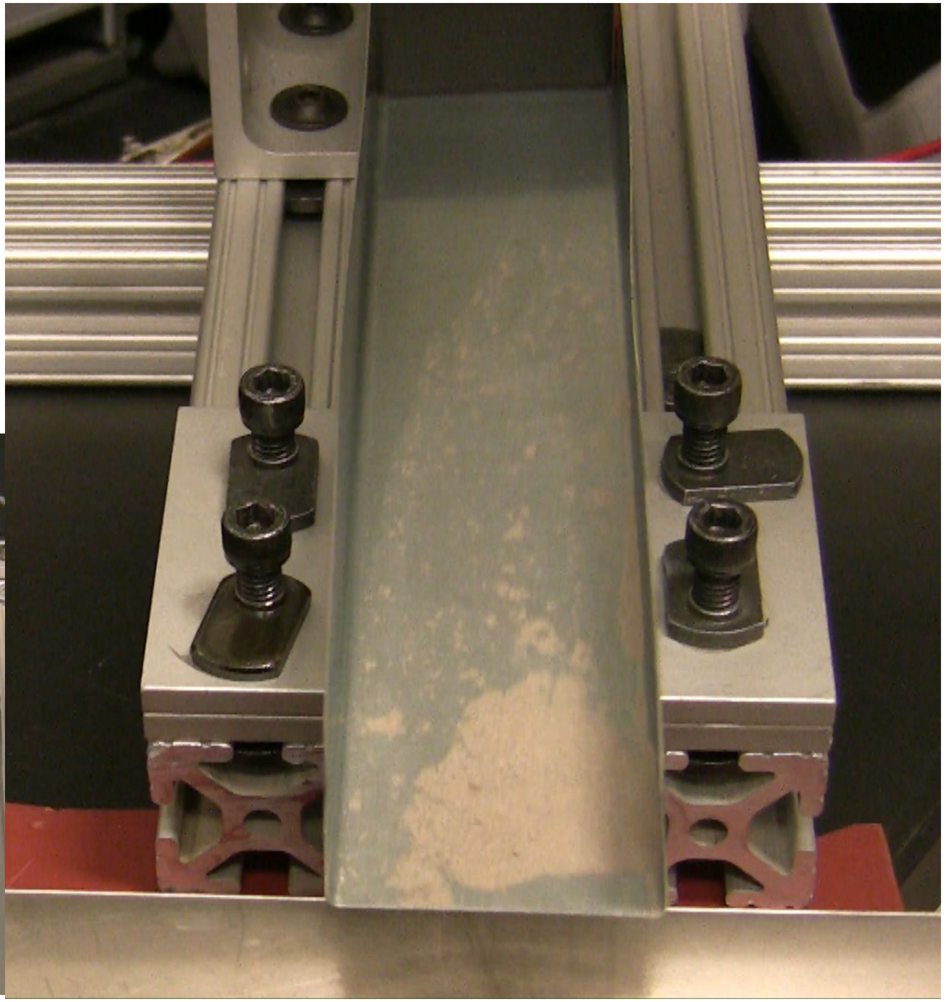
Rotating unbalanced stick-slip drive Concept

KSC Demo of Stick – Slip Inclined Conveyor

KSC Innovation Fund Project (internally funded project 2010-11)

- Structure
  - 5 cm wide tray with 16 deg slope above horizontal
- Drive: 56 N 24 VDC, 27 W solenoid and return spring at up to 12 Hz (<1 cm stroke)





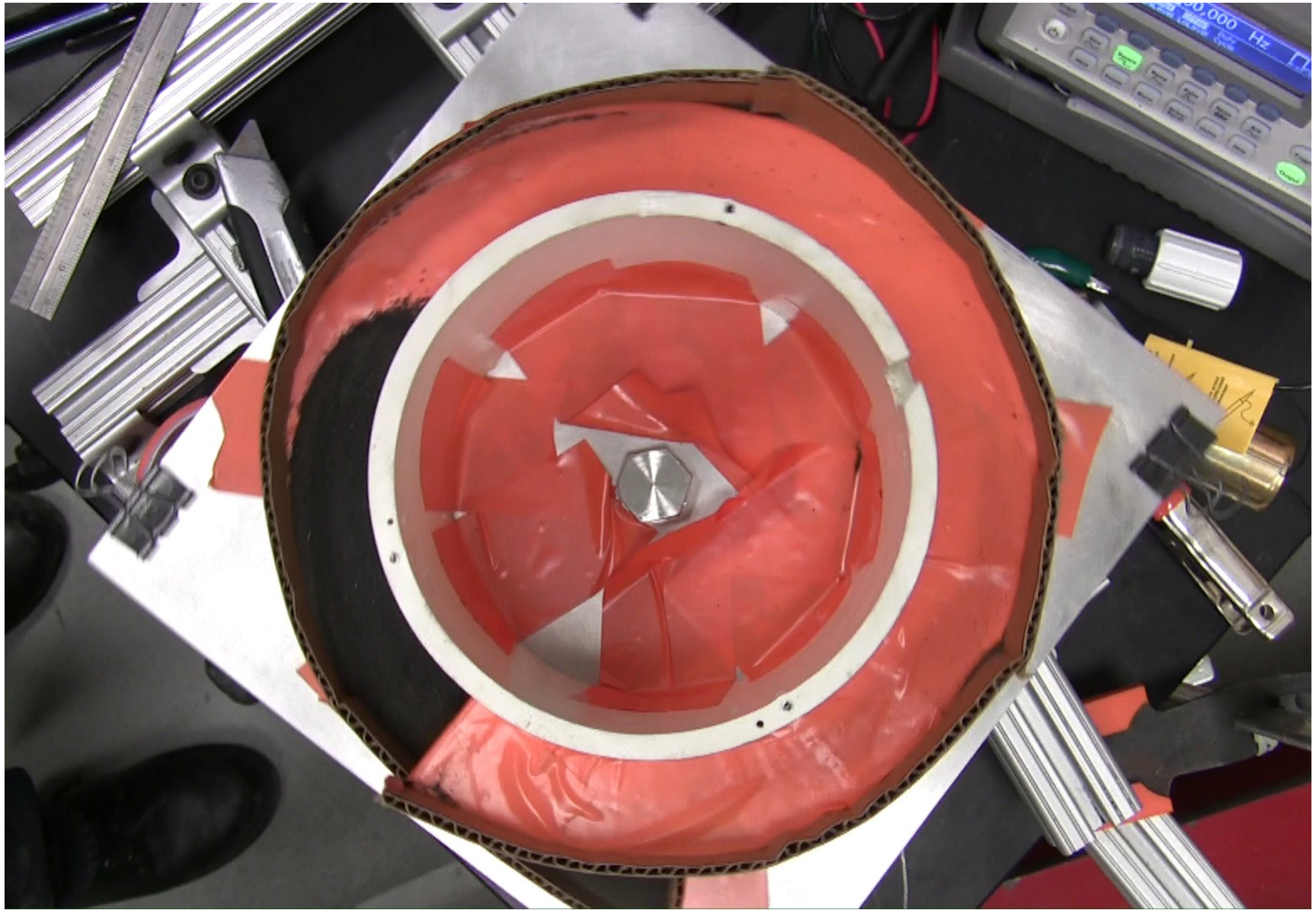
Linear Vibratory Regolith Conveyor demonstrated at NASA KSC in 2010 (Mantovani et al, 2011)

Vertical Lunar Regolith Conveyor Prototypes

Stick-Slip Loop

- 20 cm I.D., 5 cm path width
- 1.5 – 2.2 deg slope (O.D. to I.D.)
- Solenoid: 56 N 24 VDC
- 2.2 N/cm return spring

Parameter	Value
Flow Rate	0.26 kg/min (2.1 kg/min max)
Avg. Particle Speed	3 cm/s
Avg. Particle Depth	0.3 cm
Frequency	3 Hz
Amplitude/Stroke	2.5°
Power	27 W

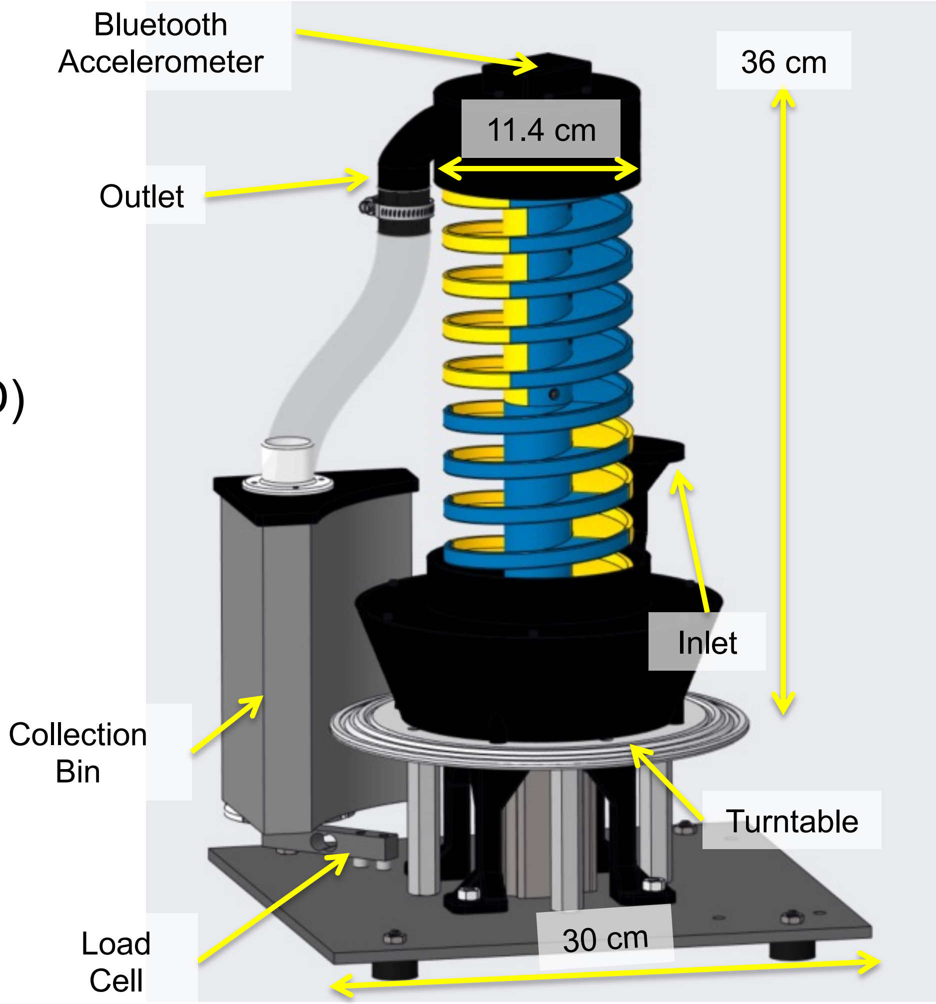


JSC-1A simulant conveying on single loop helical stick-slip conveyor (Mantovani et al, 2011)

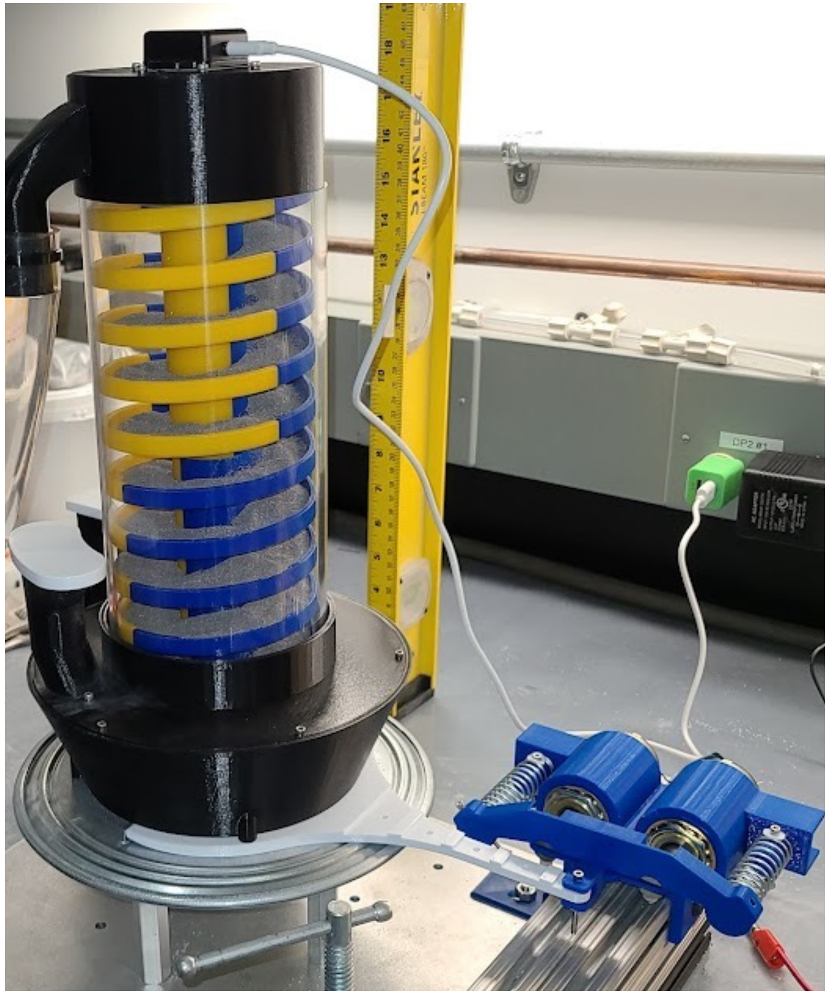
Vertical Lunar Regolith Conveyor Prototypes

Compact VLRC Prototype

- Structure
  - 4 cm inner diameter
  - 3 cm path width
  - 4-12 deg slope (O.D. to I.D)
  - Ball bearing turntable
- Drive
  - Two 56 N 24 VDC, 27 W solenoids
  - 3 N/cm return spring
  - 2.54 cm solenoid stroke
  - 10 deg stroke
  - ~ 3 Hz limit



Compact Lab-Scale VLRC Prototype Model (Olson et al., 2022)



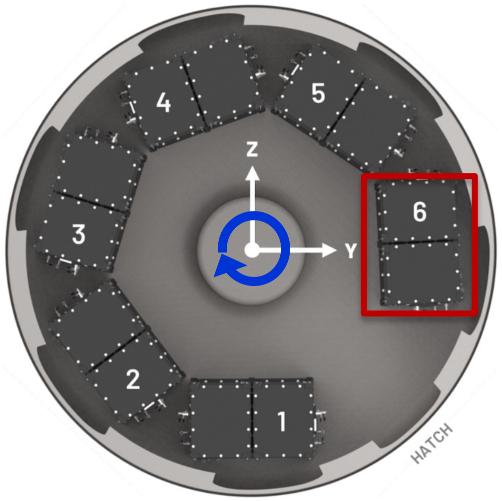
Lab-Scale VLRC Prototype Conveying BP-1 simulant (Olson et al., 2022)

Suborbital Lunar Gravity Testing

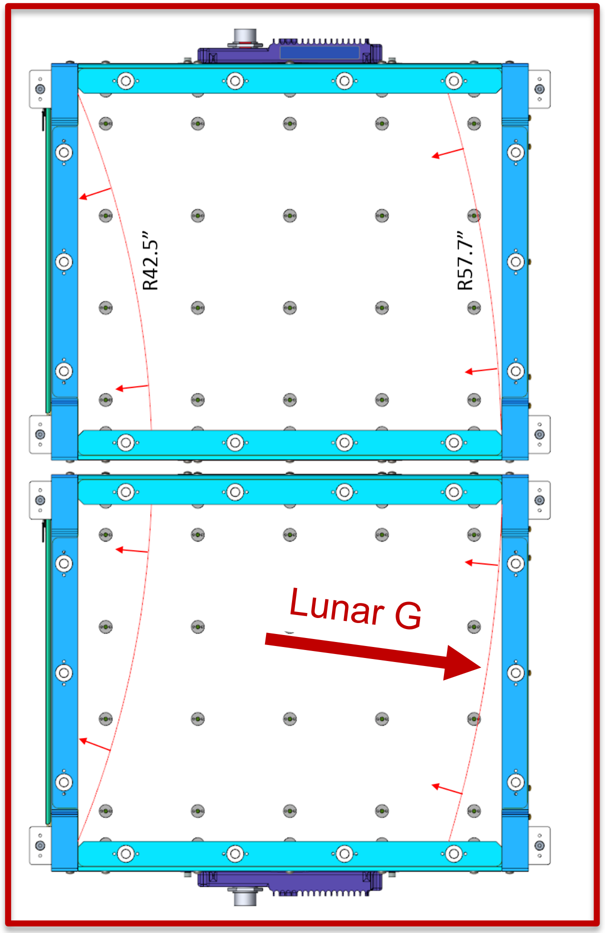
- Several VLRC Prototypes will be flown in simulated lunar gravity under vacuum on a New Shepard capsule (nominally in 2023)

11 RPM

Capsule simulating 1/6 gravity by spinning during freefall (Ref: Blue Origin Payload User's Guide)



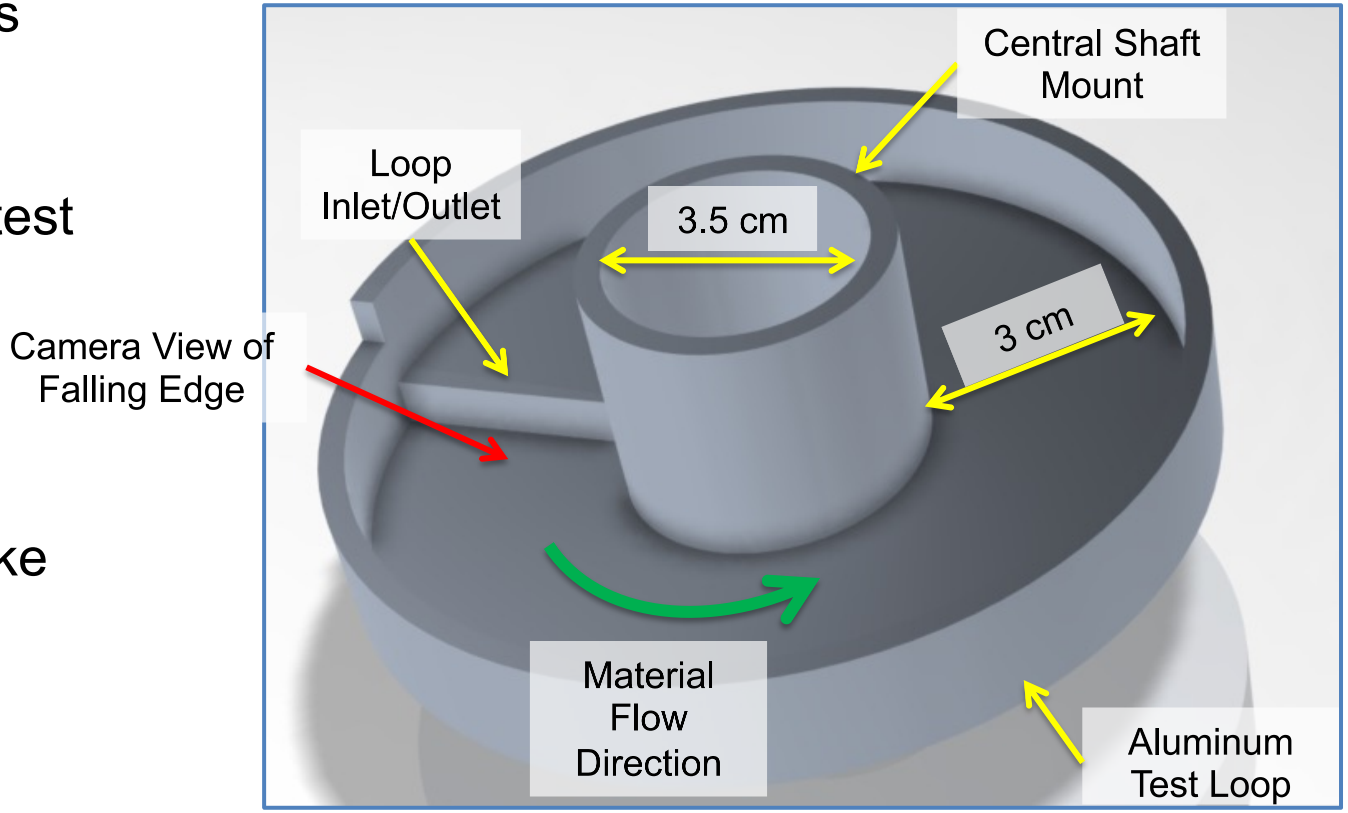
Payload locker arrangement inside capsule and the associated centripetal acceleration during the spin phase of flight



Suborbital Lunar Gravity Testing

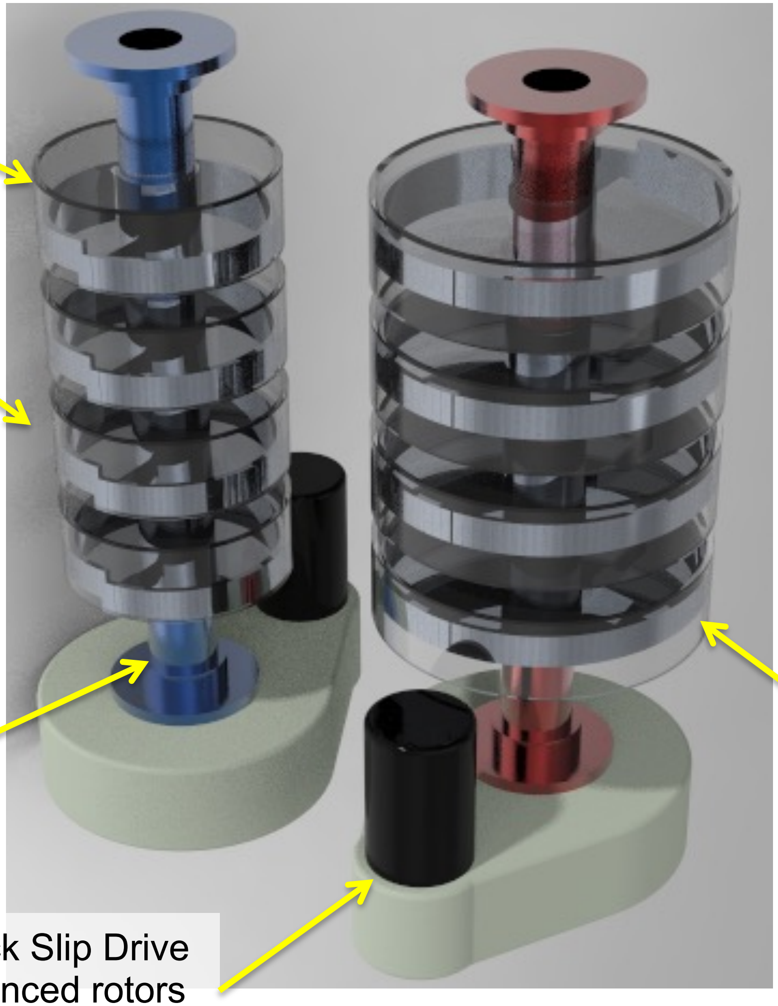
Suborbital Flight Experiment Objectives

- Use Lunar-G flight data to inform modeling and optimization of VLRC
- Use of VLRC continuous (360 deg) test loops
  - Range of pitch/slopes
  - Range of simulant types/sizes
  - Range of drive frequency & stroke
- Double locker experiment
  - 23 kg, 144 W limits
  - 2 minutes of simulated lunar gravity
- Internal vacuum chamber (rough pump)



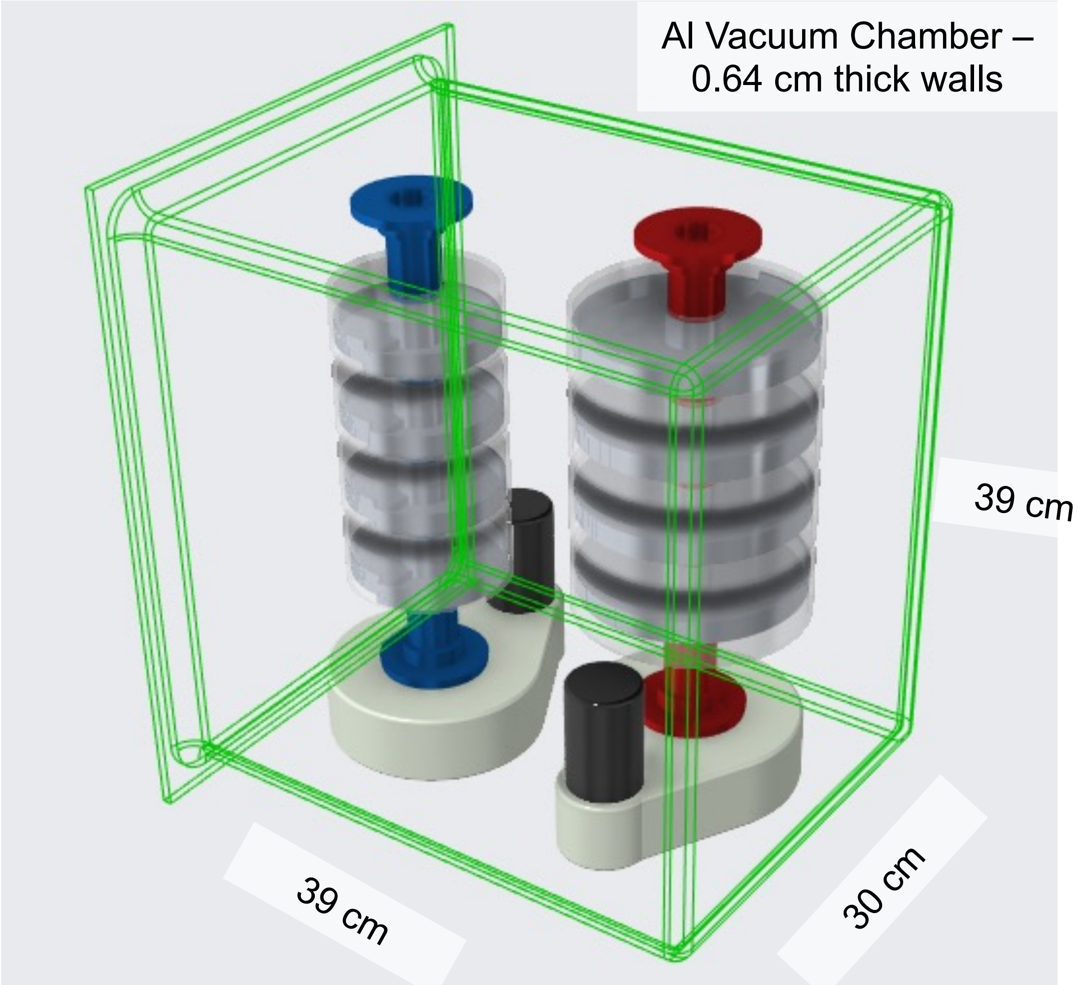
Example of Single-loop VLRC for Lunar-G Flight Testing

Suborbital Lunar Gravity Testing



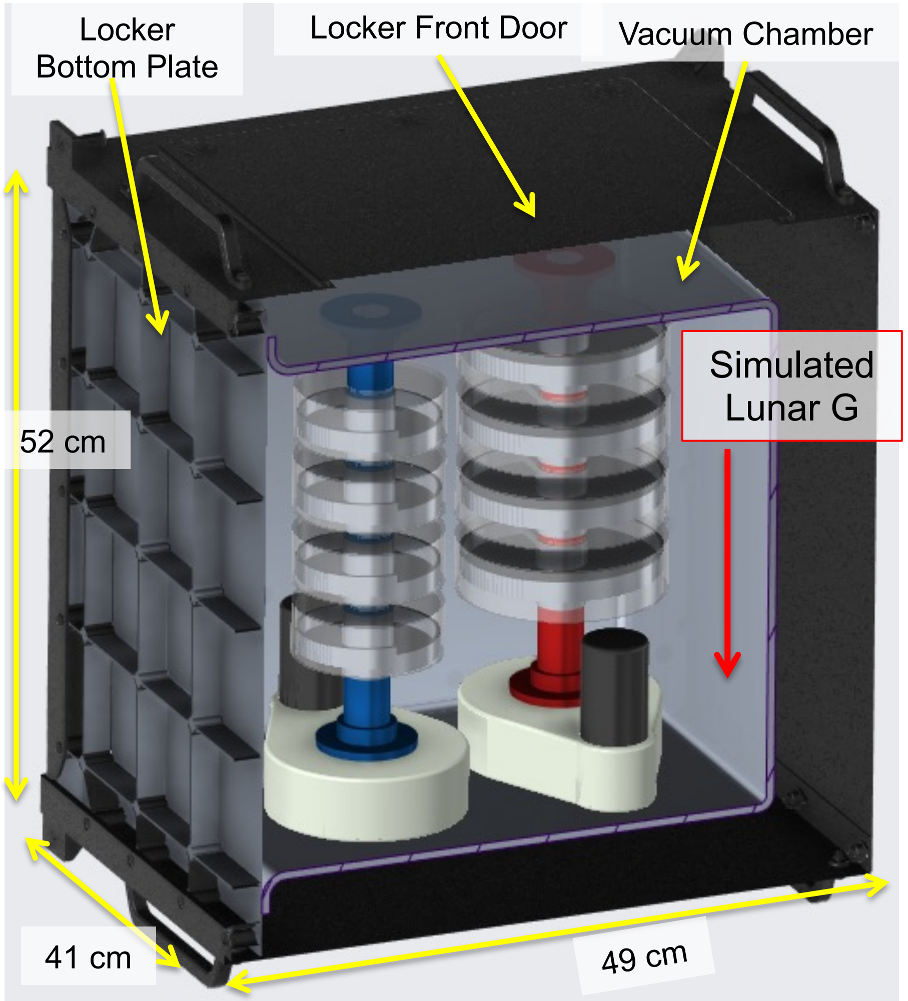
Camera & Lighting Locations TBD

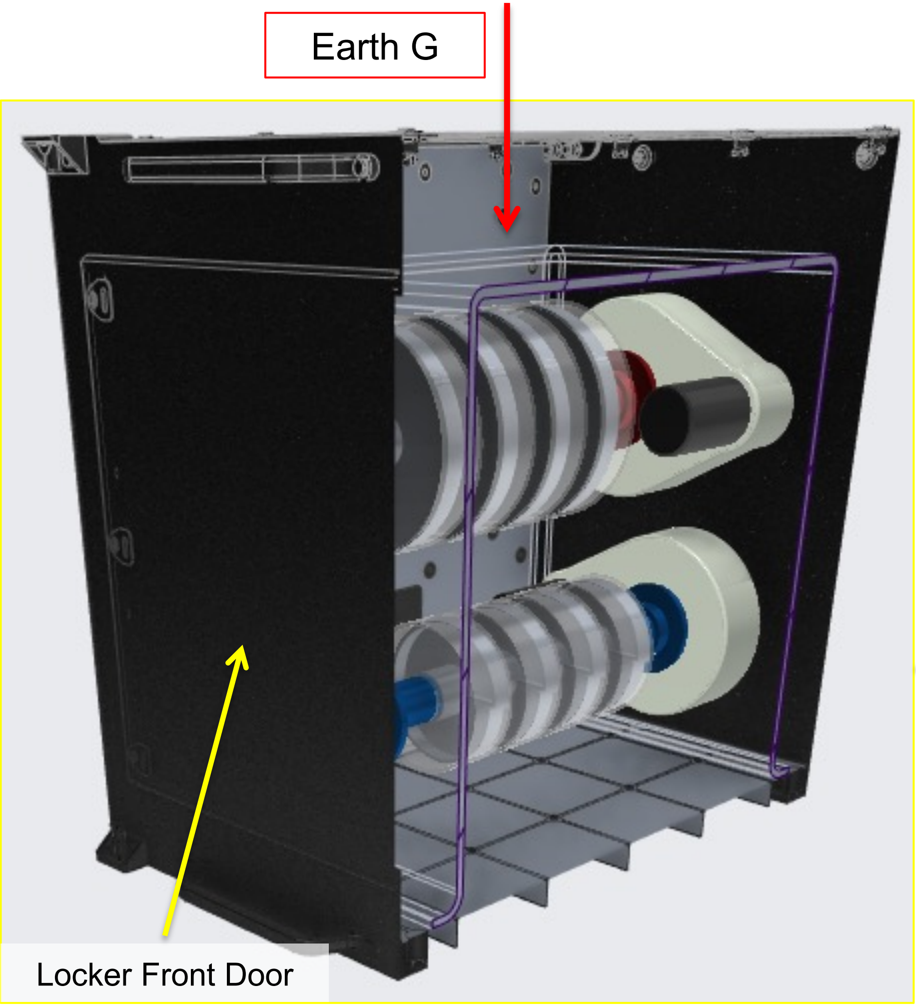
Vacuum Chamber to Stack Support Structure not shown



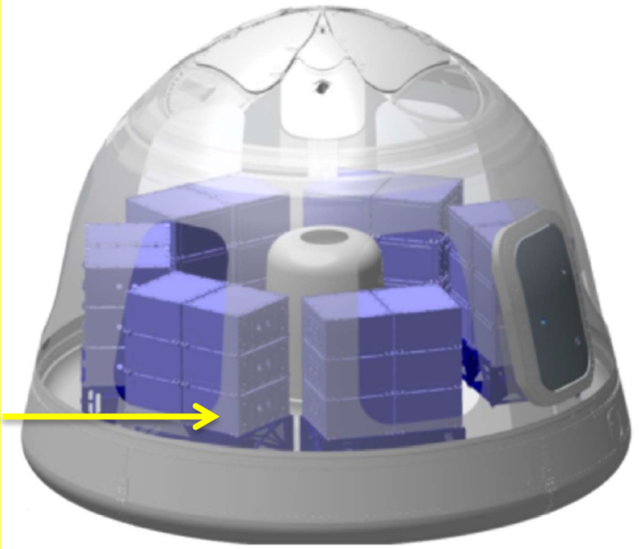
Two Stack VLRC Lunar Gravity Experiment Design Concept

Suborbital Lunar Gravity Testing



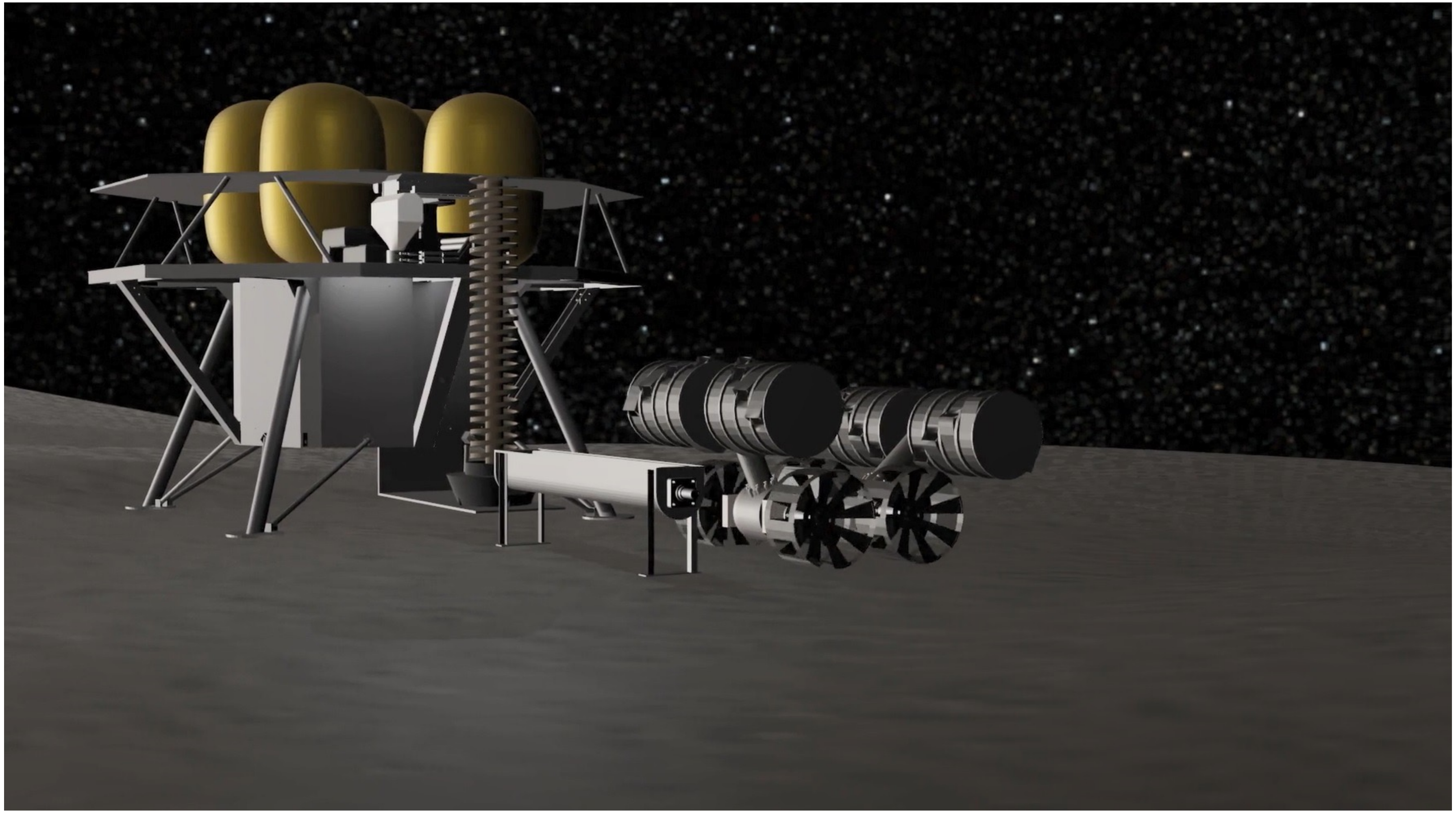


Two Stack VLRC Lunar Gravity Experiment Design Concept Inside of Double Payload Locker



Blue Origin New Shepherd Capsule with payload lockers visible.
(Ref: Blue Origin Payload User's Guide)

Questions



Animation of VLRC for an ISRU O2 Production Reactor Conops was developed by Joseliz Perez, NASA KSC Intern, 2022. Credit: NASA KSC