METAL PROCESSING.

IN SPACE. FOR SPACE.

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World's First Demonstration of Continuous Metal Casting in Microgravity for ISAM and SM&L

2023 Space Resources Roundtable

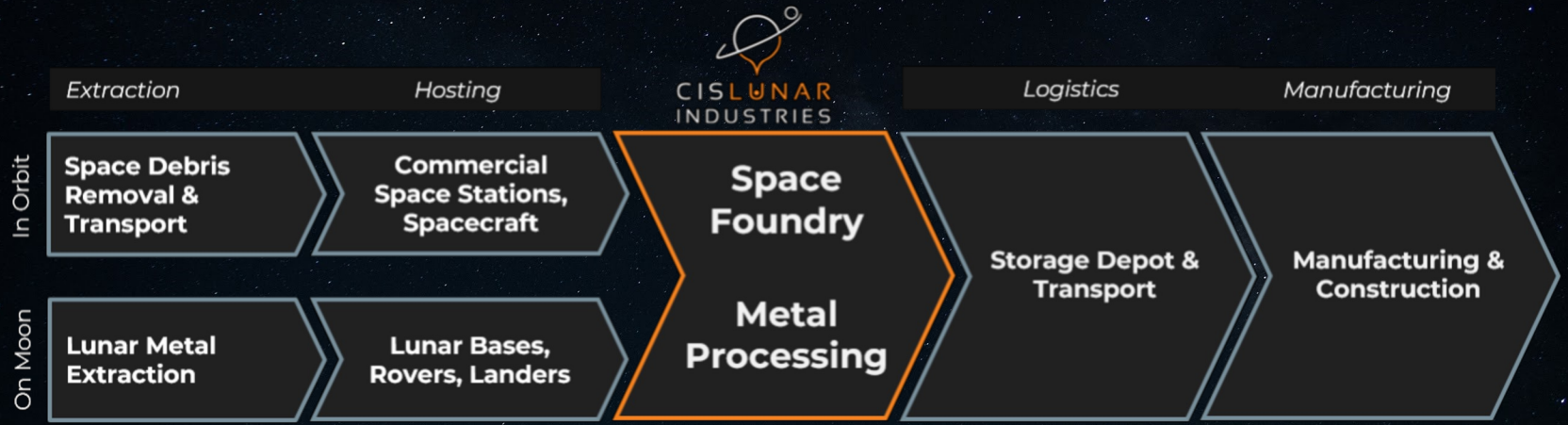
June 8, 2023

Joe Pawelski
CTO

Needs of Any New Industrial Economy

Orbital, Lunar, and Planetary In-Situ Resource Utilization

- Metal materials processing
- Propellant production
- End-of-life disposal
- Power infrastructure



MSF (Modular Space Foundry)

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Key Characteristics

- In-space metal foundry
- Electromagnetic induction processing of most conductive materials
  - Heats
  - Manipulates
  - Can be contactless

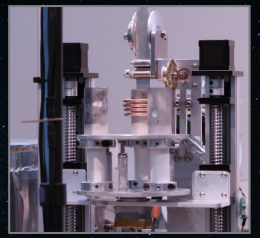
Inputs: RSO (Resident Space Object)

- Significant waste aluminum already in space
- Upper stages (Agena, Zenit, etc) and on ISS payloads
- Preferred melting geometry of Space Debris Analog Al-6061 feedstock (post cutting),
  - **Strips** (>0.060 x 0.75), **not Chips**

Outputs: MSF (Primary)

- (1.0") 25mm bar, size for ingots and metal propellant

2021



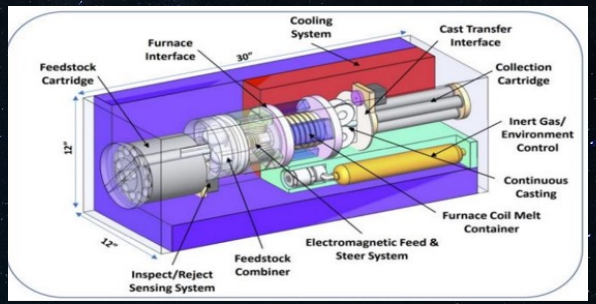
2022

Metal foundry and continuous casting hardware for in-space operation

2022

Nov 2022 – Zero-G flight continuous casting & EM steering

2024 and later



System Design

Experimental Setup

Parabolic Flight Objectives

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Alpha Parabolic Flight Objectives:

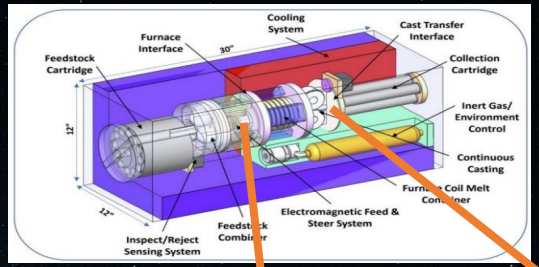
Validation of Steer and Cast subsystem design effectiveness and robustness for microgravity and hyper-gravity (2g) environments

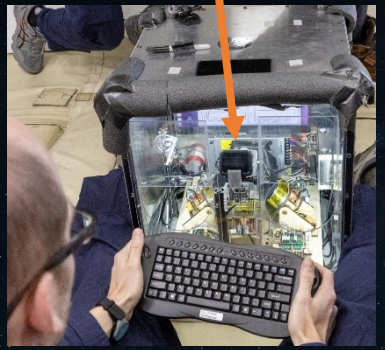
Steer Payload:

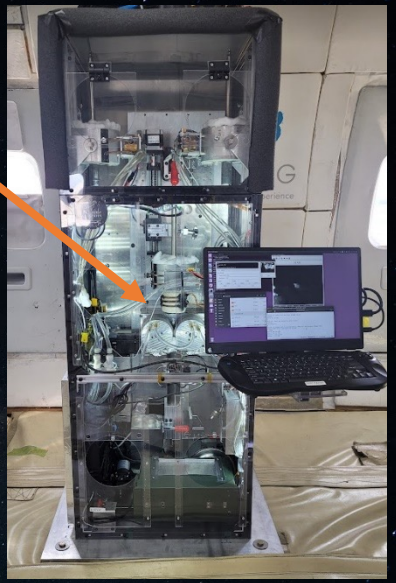
- Manipulate individual and multiple pieces of metal of various geometry

Cast Payload:

- Melt > 300 g samples of aluminum
- Continuously Cast > 5mm length rod







Alpha Parabolic Flight Results
(Subsystem Verification)

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Alpha Parabolic Flight Objectives:

- Validation of design for microgravity
- Verification of software, controls, and data collection systems
- Verification of quad coil induction coil hardware operation
- Verification of EMI, power, and power-level flight requirements achieved
- Verification of mechanical subsystems

Top Level Outcome:

- ✓ *Payloads passed all FAA requirements: structural, power, and EMI*
- ✓ *Hardware, software, and sensors worked for.the duration of the flight and in repeatable with ground testing.*
- ✓ *No unknown-unknowns uncovered; Steer and Cast systems operated without unusual results.*

Alpha Parabolic Flight Results
(Subsystem Performance)

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Steer Payload:

- ✓ Steer a metal sphere controllably in 3D space
- ✓ Spin a metal sphere controllably in 3D space
- ✓ Gather a plurality of metal spheres in 3D space
- ✓ Steer a plurality of metal spheres in 3D space
- ✓ Gather a plurality of non-uniform metal debris in 3D space
- ✓ Steer a plurality of non-uniform metal debris in 3D space

Cast Payload:

- ✓ Melt > 300 grams of aluminum < 10 minutes, hold in hyper gravity
- ✓ ***Cast > 5mm length of 25mm diameter rod 25mm diameter***
- ✓ Known-unknown learned for zero-g continuous cast starting.
- ✓ Reset between parabolas
- ✓ Reset during parabolas from a freeze event

Alpha Parabolic Flight Lessons:

- *The startup sequence was too slow, leaving a small portion of the microgravity window for actual casting in zero-g.*
- *Hyper-gravity encouraged leaks that took a long time to tear down and setup.*
- *The 3 min duration between parabola sets was insufficient for reset from freeze event requiring reset work during parabolas*
- *Microgravity is a difficult environment to do anything but minimal tasks (engage button, toggle, etc.)*
- *Hyper-gravity is possible to work in, but slow. View is best limited to forward/sides to avoid motion sickness.*

Results: Steer Experiment

Alpha Parabolic Flight:
Steer Payload Description

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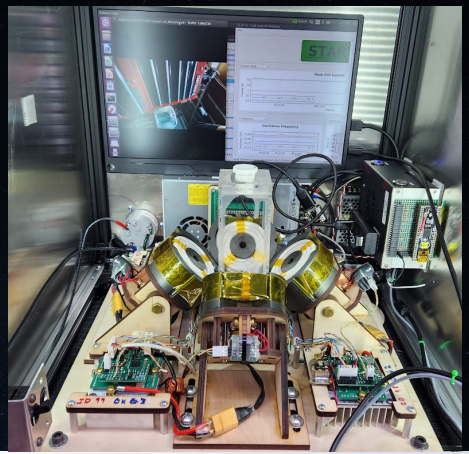
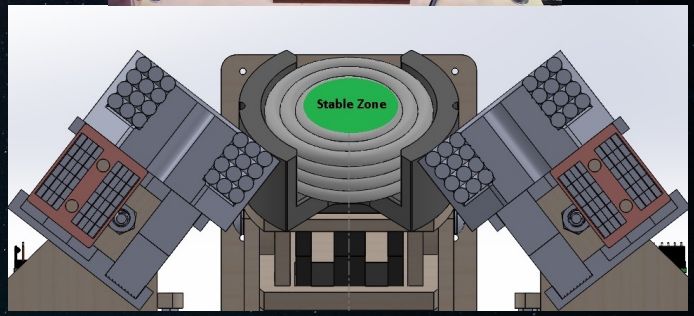
Steer Payload:

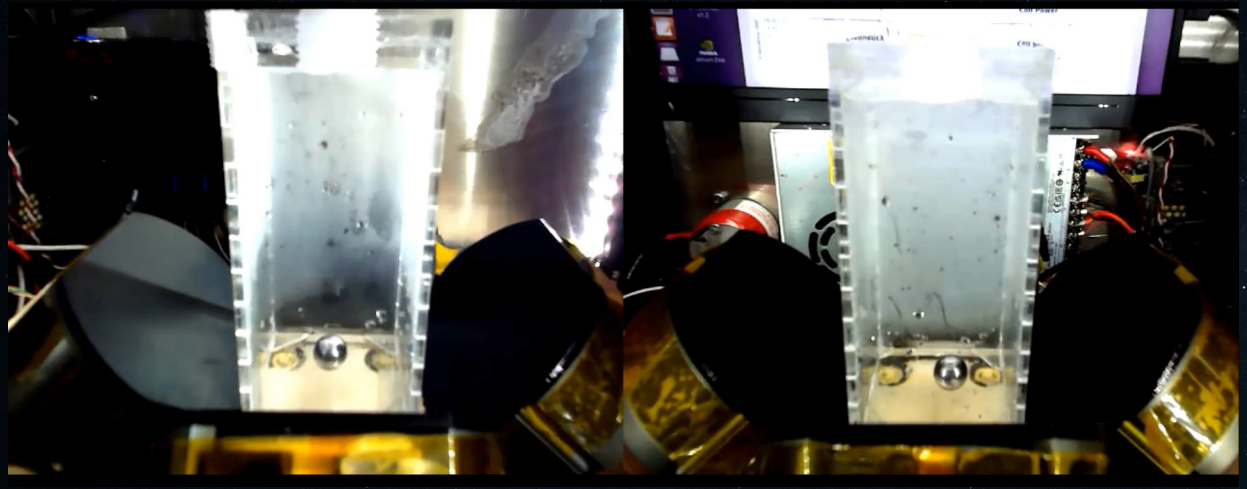
- An array of 4 "coils" generate RF magnetic fields which induce eddy currents and resulting magnetic forces in aluminum spheres and simulated debris.
- Coil array creates a null in magnetic field at the geometric center of the coils - results in stable positioning of objects at null.
- Electronic phase control of coil currents to make a "rotating" magnetic field result in rotation of the objects.
- Dual cameras with orthogonal views to capture object dynamics.
- Coil currents are pre-sequenced, open loop positioning only (no visual feedback).
- Low power system (<300W) - optimized for force generation rather than heating of objects.
- Test objects contained in acrylic container.





Alpha Parabolic Flight Results Steer Payload
(Steer + Spin)

- Single metal sphere steer and spin captured at 2 second intervals from flight video.
- Aluminum sphere in circular path ~1cm above the floor of sample box.
- Magnetic fields sequenced to provide stable region in the center of the coils for 4 seconds followed with 100mS of rotation field resulting in stabilized positioning and rotation.
- Sequence was repeated for 30 second duration to overlap the zero-g duration.
- Comparison to terrestrial experiment using water to simulate neutral buoyancy.
- Data helps to refine steer controls and model to control objects in 3d space.

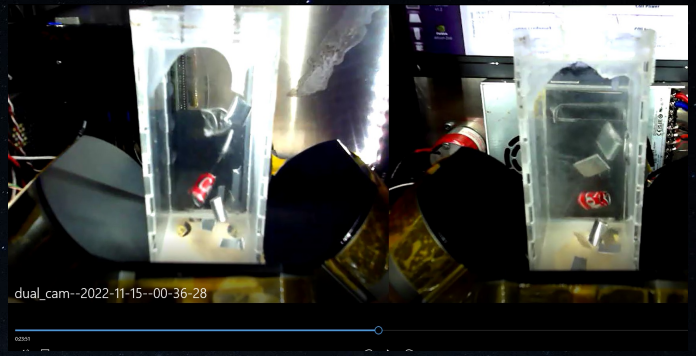


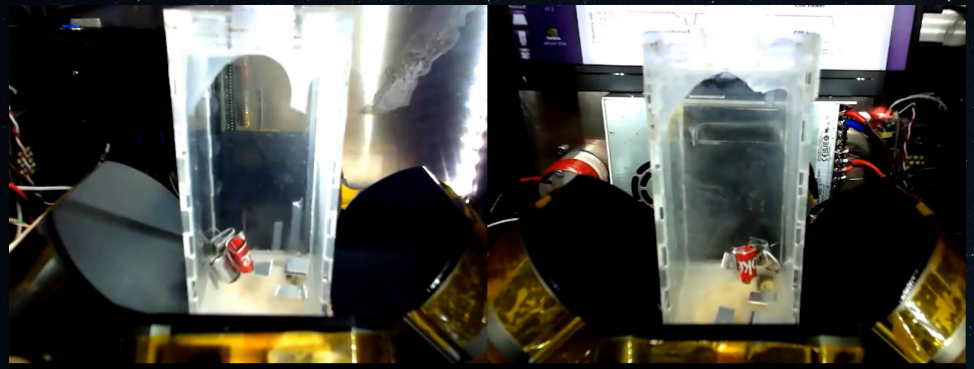
Alpha Parabolic Flight Results Steer Payload
(Gather + Steer Spheres)

- Frames show multiple objects randomly dispersed
- Can be gathered and guided together to the low-field region at the center of the quad coil array.

Alpha Parabolic Flight Results Steer Payload
(Gather + Steer Debris)

- Several small pieces of aluminum can material were put into the test container. Most of the object motion is due to the aircraft, but the objects still tend towards the low-field zone.
- Due to the thin profile of the materials, there was a tendency for material to orient itself "parallel" to the lines of magnetic force which weakens the induced current and resulting force. Spinning an object may help reduce this tendency.





Alpha Parabolic Flight Results:
Steer Payload Data Captured

Telemetry is recorded from drive units including:

- Supply Voltage
- Power consumed by each coil
- Operating Frequency
- Amplitude and Phase of currents

Parabola S1 – Single Sphere	Holding Current Set	Spin Current Set
1	80	80
2	80	80
3	60	60
4	40	40
5	80	80

Parabola S2 – 5 Spheres	Holding Current Set	Spin Current Set
1	80	80
2	80	80
3	80	80
4	80	--
5	80	80

Parabola S3 – Debris	Holding Current Set	Spin Current Set
1	80	80
2	80	80
3	80	80
4	80	80
5	80	80

Parabola S4 – Single Sphere	Holding Current Set	Spin Current Set
1	80	--
2	80	--
3	60	--
4	80	80
5	80	--

Parabola S5 – Single Sphere	Holding Current Set	Spin Current Set
1	100	--
2	100	--
3	80	80
4	80	80
5	--	--

Steer Payload Lessons Learned & Future Work

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Lessons Learned:

- The zero-g plane has significant acceleration "noise" which introduces perturbations to our systems.
- Capturing the motion noise with accelerometers and visual indicators would be beneficial to understand how the magnetic steering system performed in response to the noise.
- Higher field gradients will be required to overcome the acceleration noise and maintain useful control authority.

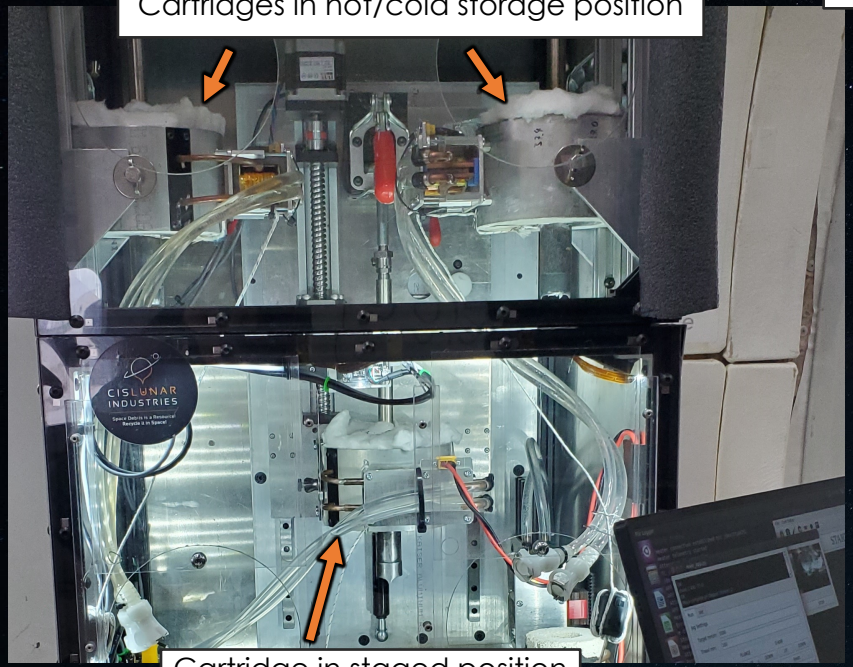
Future Work:

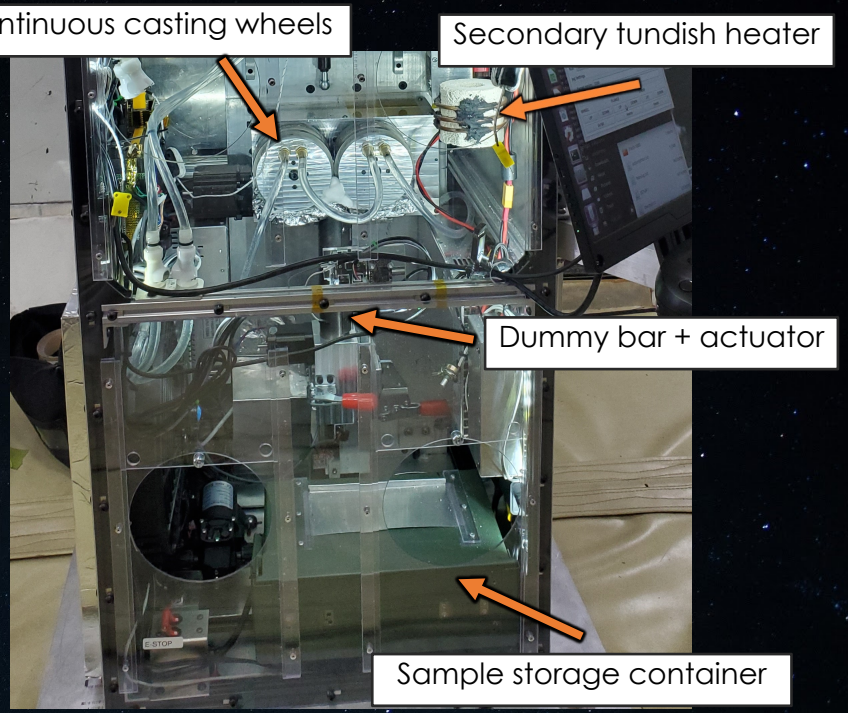
- Develop control concepts for multi-resonant coil arrays – namely, independent amplitude control which allows variable positioning the stable low-field zone.
- Visual position tracking of object to provide closed loop position control.
- Improve coil design for increased magnetic field gradients leading to greater forces and control authority to overcome aircraft dynamics.
- Add accelerometer to help analyze response to perturbations.

Results: Cast Experiment

Alpha Parabolic Flight

Cast Payload Description





Alpha Parabolic Flight Results

Cast Payload (Cast Rod)

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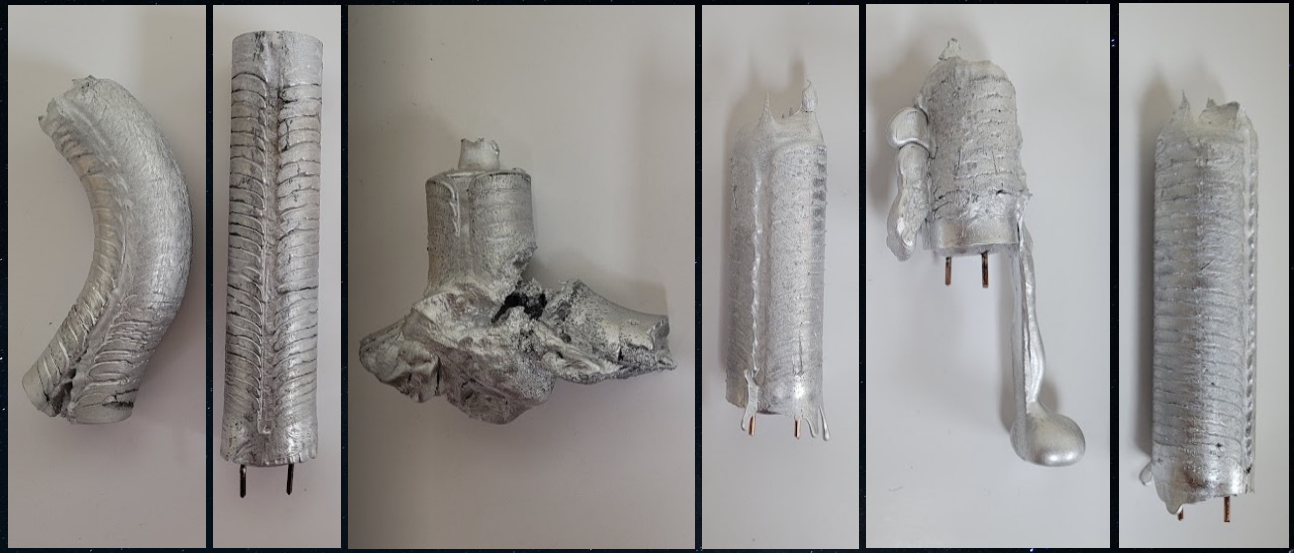
Cast Variables

Starting Conditions were based upon lab results. Comparison of sample 1 cast variables to others cast in the lab are provided in the table.

Sample	wet alum temp C	Dummy bar speed	Wheel speed	Accel m/s
1	675	220	220	200
2	675	220	220	200
Lab #51A	675	220	220	200
Lab #51	675	220	220	200
Lab #61	655	169	219	200
Lab #62	645	169	219	200
Lab #63	650	169	219	200

Comparison of parabolic sample to lab samples.

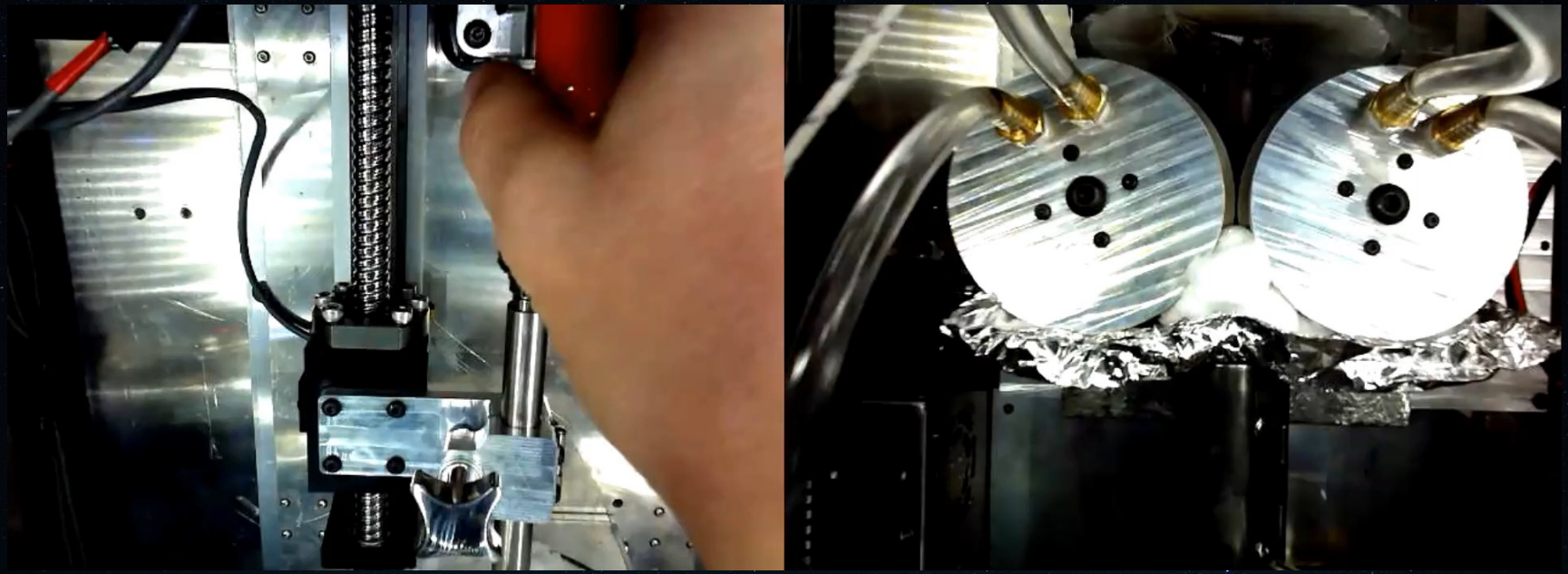


#51 | #51 A | Sample 1 (Parabolic) | #61 | #62 | #66

Alpha Parabolic Flight Results

Cast Payload (Cast Rod)

Sample 1



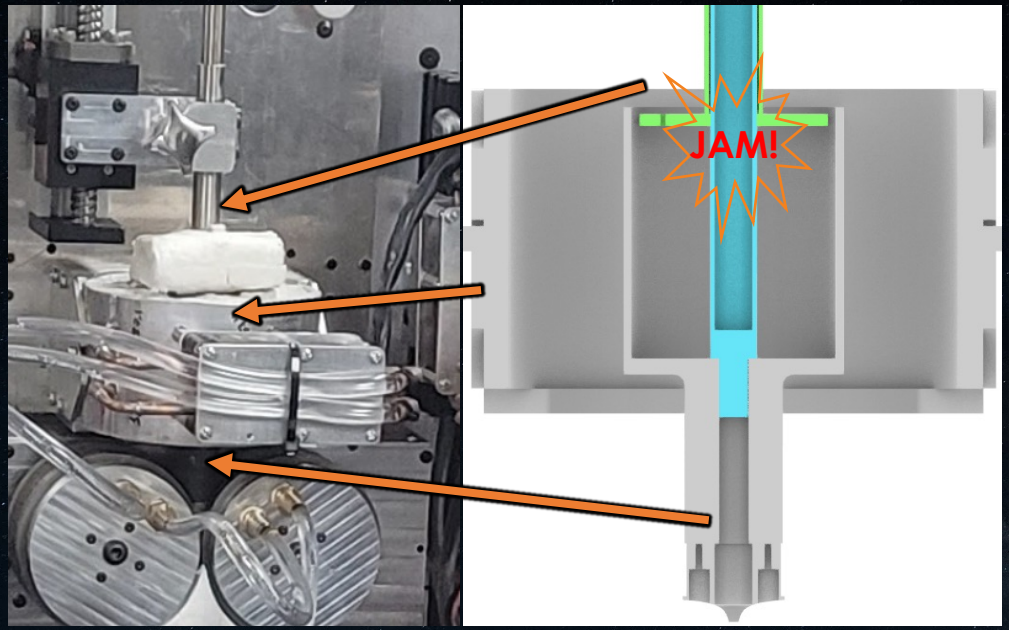
Alpha Parabolic Flight Results

Cast Payload (Cast Rod)

Sample 2

Alpha Parabolic Flight Results

Cast Payload (Cast Rod)



Plug = blue

Plunger = green

Sample 2

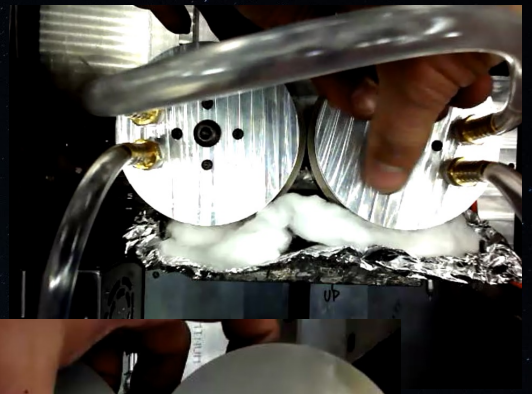
The second sample was affected by a plug jam in the plug/plunger interface.
As a result, only a small amount of material was injected into the casting region.

Alpha Parabolic Flight Results

Cast Payload (Reset Cast)

Cast Payload:

- Cast was designed for rapid disassembly in the event that a break-out occurred so any shape of frozen aluminum can be removed easily during the cast refinement process.
- The break-out on the first sample was a good test of a quick reset of the system after a break-out event.
- The process was the worst case, involving removal of the casting wheels.
- This took longer than expected causing us to skip the 3rd cartridge.
- Several updates to the cast system were made to further expedite resets - but did not make it on the flight due to time constraints.

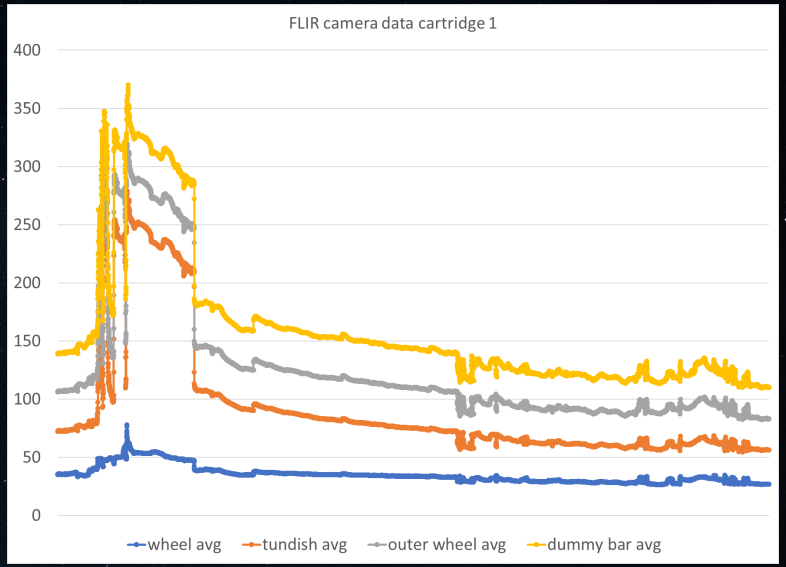


Alpha Parabolic Flight Results

Cast Payload (DATA)

Cast Payload:

- Plots of thermal couple and IR on wheels (deg C)

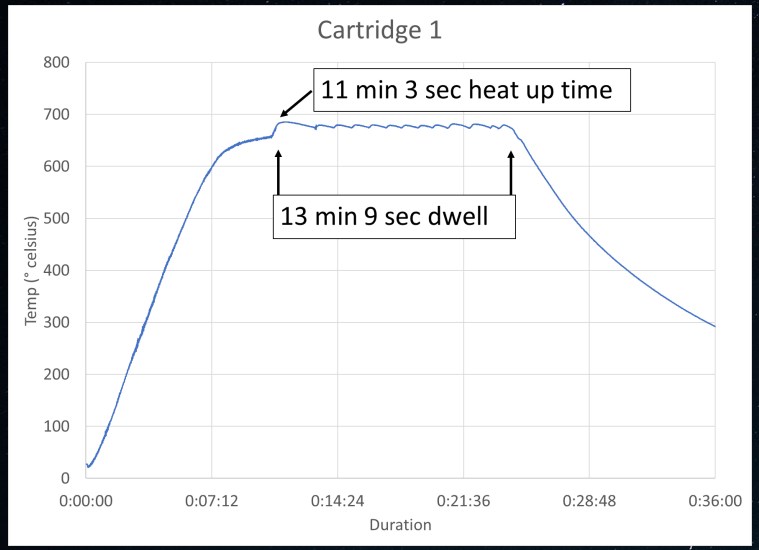


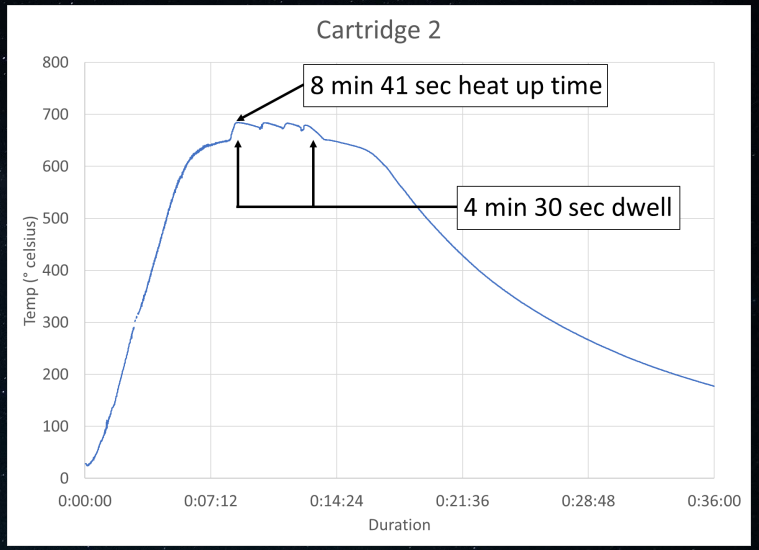
Alpha Parabolic Flight Results

Cast Payload (DATA)

Cast Payload:

- Plots of melting aluminum samples in the cartridges





Alpha Parabolic Flight Results

Cast Payload (Solutions)

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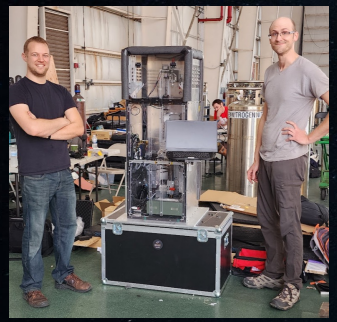
Alpha Parabolic Flight Objectives:

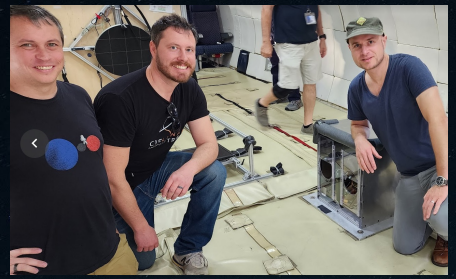
- The startup sequence took too much time in micro gravity, and we missed a large part of the microgravity window.
- Hyper-gravity increased the pressure of the melt above the still cooling and fragile sample causing it to be destroyed.
- The increased pressure during hyper-gravity encouraged leaks that took a long time to reset.
- The time during microgravity is useless for manual work, hyper gravity is very slow to do anything meaningful.
- System thermocouples might not fully represent system temps.
- Time goes by very quickly up there

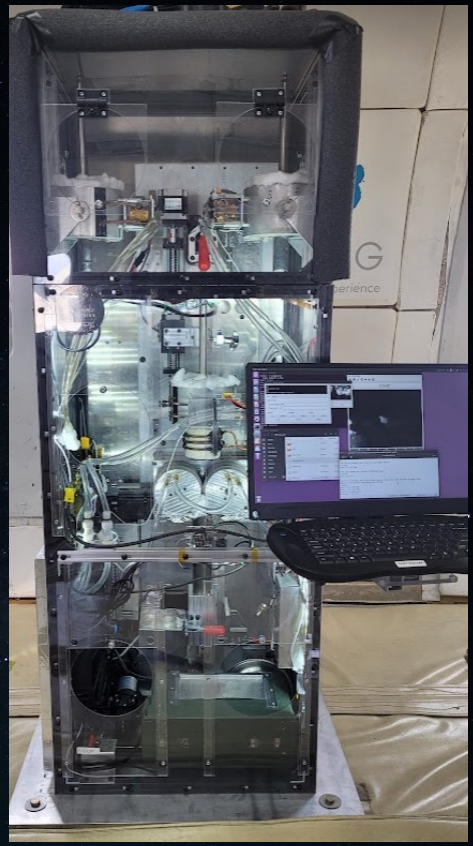
Beta Parabolic Flight Solutions:

- Increase initial plunger rate and/or add a spring or inert gas to pressurize liquid, replace plunger with squeeze induction coils, use Steer subsystem for metal delivery
- Increase cast rate and/or reduce sample size, add cooling (argon stream) to ensure solidification of cast rod prior to 2g.
- Utilize graphite seals and ceramics to overcome expansion and erosion issues
- Motorize/automate all routine movements, reduce failure modes and severity, automate the majority of tasks required for reset
- Add thermal couples (supports 8), provide redundancy for TC vs IR imaging (IR target with TC)
- Practice casting sessions that mimic flight conditions

Parabolic Equipment Photos







Parabolic Flight Photos

Appendix

Alpha Parabolic Flight Results
Cast Payload (Cast Rod)

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Sample 1

- Continuous casting system produced a partial rod in microgravity
- The microgravity portion of the rod was evidently fractured and displaced by the increase pressure that occurred during hyper-gravity.
- Break-out required extra intervention
- to reset for the next test.

Company Details

Founded in Luxembourg in 2017

Moved to US (Colorado) in 2019

First NASA Contract 2021

First Space Force Contract 2023

Employees: 12, full-time and part-time

Backgrounds in Heavy Industry, Systems Engineering, Hardware Development, Manufacturing, Finance, Operations, Business

Hardware: Multiple working prototypes of Modular Space Foundry, Modular Configurable Electric Power Converter (MCEPC), electromagnetic induction furnace, continuous casting subsystems

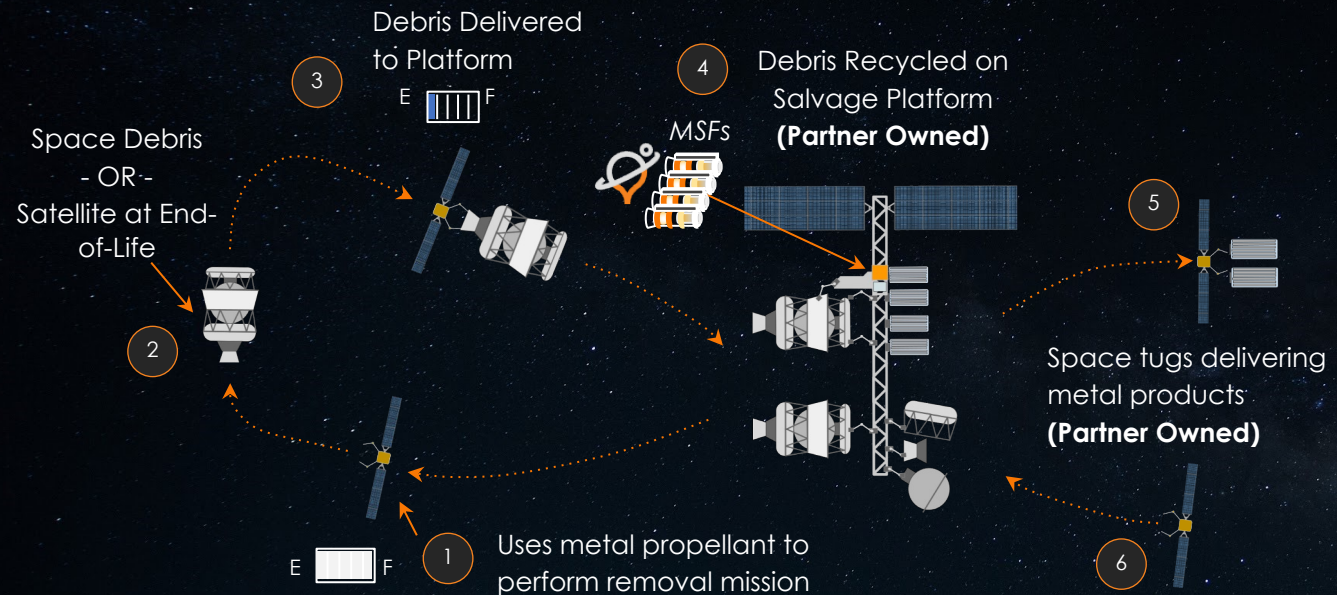
Funding: >$3.9M closed

$1.7M Space Force contract, $925K NASA contracts, $250K Colorado grant, $330K ISS NL grant, active commercial contract

$715K equity investment

Satellite Salvage & Recycling

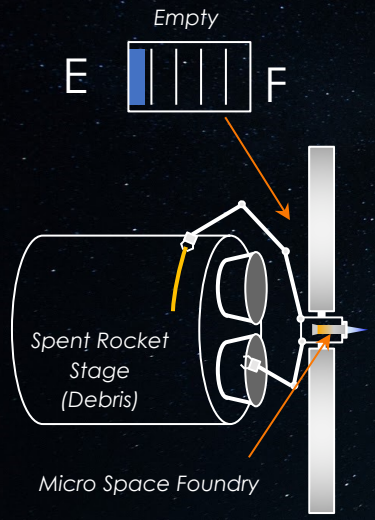
Recycle space debris and satellites at end-of-life at space stations to produce key materials for sale to the emerging In-space Servicing, Assembly, and Manufacturing (ISAM) industry



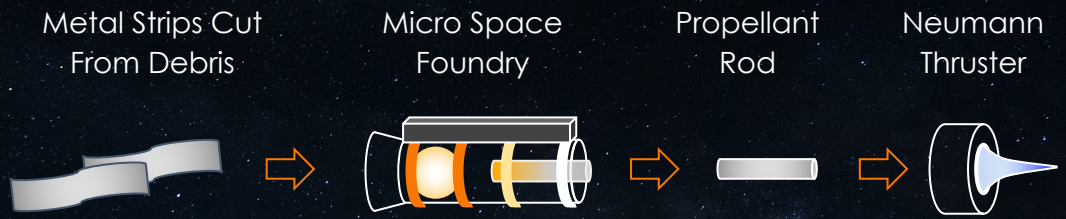
- **CisLunar is focused on metal processing**
- Partners provide space "real estate" and utilities
- Partners provide space "trucking"

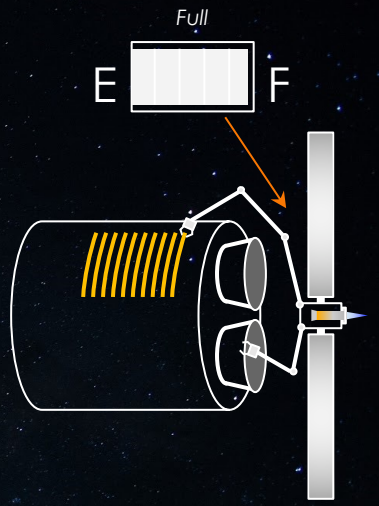
Debris to Delta-V

An onboard MSF transforms metal from captured debris into propellent allowing a customer spacecraft to **refuel itself** for the next mission



MSF is added as a subsystem to the customer spacecraft





1. Cut metal from captured debris

2. Feed metal into Micro Space Foundry

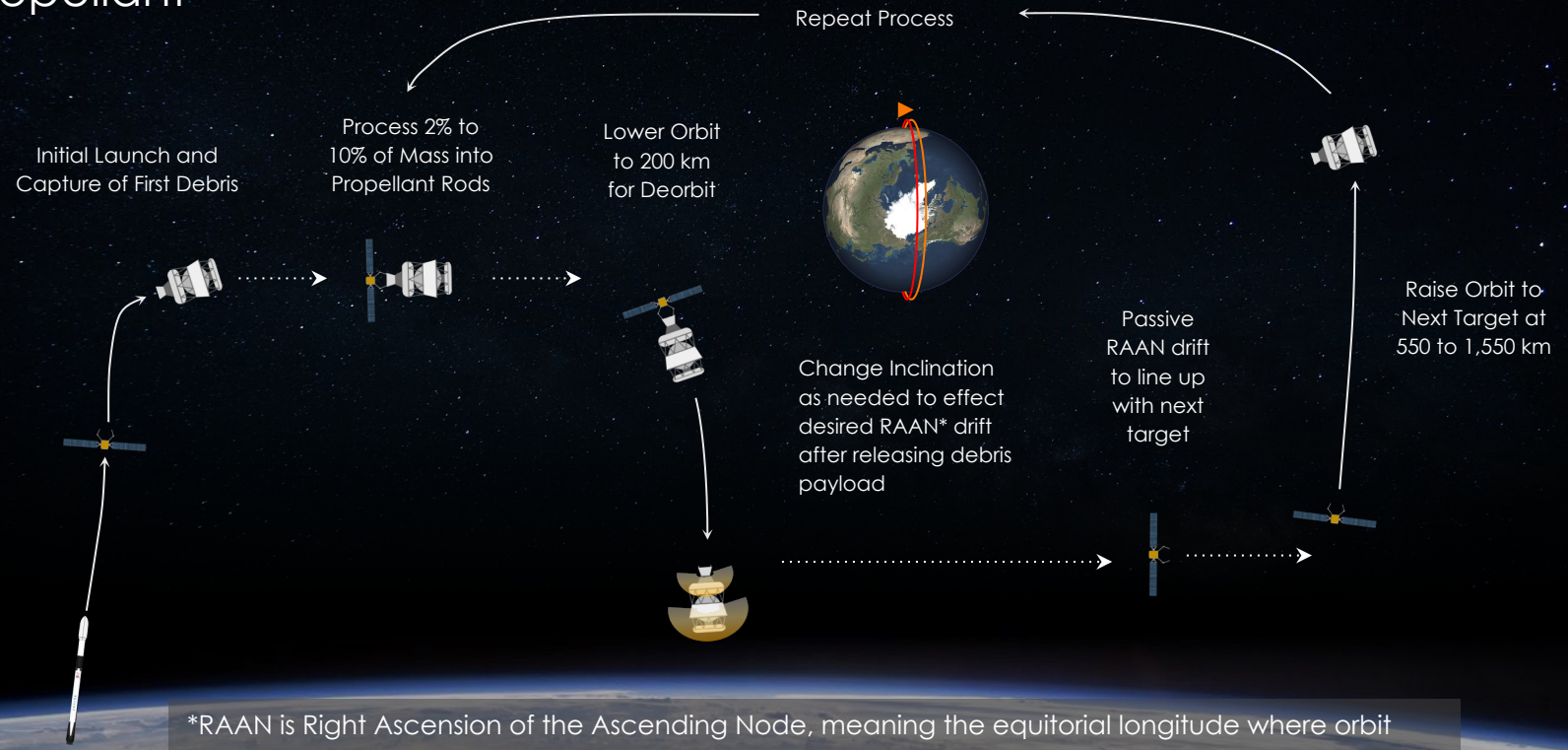
3. Melt and mix metal

4. Make propellant rods ready for use

- Propellant refilled
- Lifespan extended
- Cost Lowered

Debris to Delta-V Mission Profile:

MSF + Neumann Thruster for LEO active debris removal w/ recycled debris as propellant



*RAAN is Right Ascension of the Ascending Node, meaning the equitorial longitude where orbit changes are made

Enables Use of Space Debris as a Resource

$5B to **$12B** potential material value

Existing rocket upper stages in LEO & GEO

LEO (Low Earth Orbit):

- >1,300,000 kg
- >902 stages
- Assume $1k/kg to $5k/kg for basic materials, significant discount to launch from Earth

Near-GEO (Geosynchronous Earth Orbit):

- >484,000 kg
- >254 stages
- Assume $10k/kg to $15k/kg for basic materials, significant discount to launch from Earth

Mass and object count from ESA – Space Environment Statistics (https://sdup.esoc.esa.int/discosweb/statistics/)

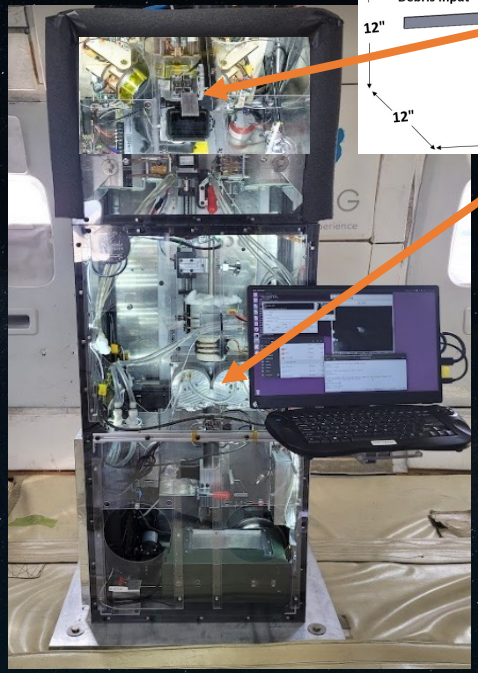
Beta Parabolic Flight Objectives

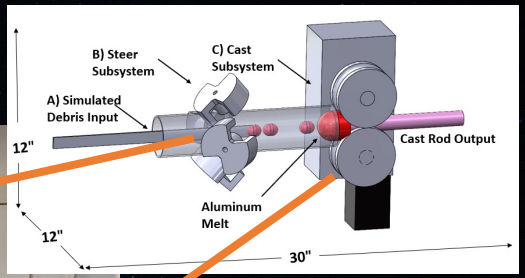
Beta Parabolic Flight Objectives: (Planned Spring 2023)

- Combine Steer and Cast subsystems into a single payload
- Demonstrate melting solid metal and steering droplets onto a collection target
    - Measure rate of metal deposition on target
- Cast numerous rods > 25mm length
    - Demonstrate using metal sample injector
    - Demonstrate using metal from combined steer subsystem

***Steer target and cast tundish swapped with feed through interface to connect and test steer and cast payloads.**

****Lower melting metals (Galinstan) used to reduce heating requirements.**





Beta Concept Composite Render