COSMIC

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COSMIC Capstone Challenge: Final Briefing

Stellar Solutions, Pennsylvania State University: Project Outbrief
Project: Skyforge

Students: Conal Richards, Brenden Quinonez, Avi Dokuparthi, Dan Bahamon, Cole Rinehimer, Mike Macdonald
Advisor: Professor Sara Lego
Mentor: Gregory Richardson

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Executive Summary

Stellar Solutions: Project Skyforge

- Current missions and plans show promise for extracting materials from a regolith. There are few projects and methods defined for turning the extracted material into useful products.
- Skyforge aims to aid in further development of interspace manufacturing by utilizing a payload that turns regolith into a rod structure.
- Rod structures, when incorporated into a structure will eliminate the need to supply Earth materials for structures in orbit.
- While the technology for the mission exists, it has never been used in a way Skyforge plans to. With current technology Skyforge could be launched in the near future.

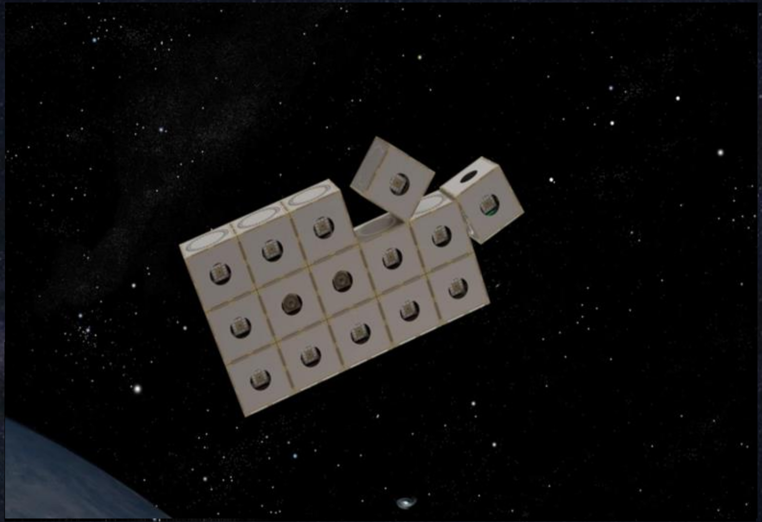

Image Credit: Hive Satellites Redefine Disaggregation | the Aerospace Corporation. *Aerospace Corporation*. https://aerospace.org/article/hive-satellites-redefine-disaggregation. [3]

Melt Material → Inject Material → Cool Material

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Team

Stellar Solutions: Project Skyforge

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2.4 Systems Engineering Milestones

- The total calendar time since project introduction has been 32 weeks
- Initial mission concept formulated by week 5. Skyforge set as the mission name.
- Self appointed and project milestones culminate into the preliminary design.

Engineering Milestone Timeline			
Milestone	Week	Date	Result
Project Introduction	0	28-Aug-24	Team introduction to C3 Cosmic ISAM design competition
Program Manager Selection	2	13-Sep-24	Conal Richards elected program manager.
Operations and Capability Decision	5	7-Oct-24	Defined operations to include ISAM capability for regolith material processing, per RFP.
System Requirement Definition	11	12-Nov-24	Defined system requrements for top-level mission design and subsystems. CONOPS outlined.
Trade Study Completion	16	15-Dec-24	Concept design trade study performed. Ideal concept chosen as an electromagnetic induction with injection molding.
Concept Design Finalization	27	4-Mar-25	Concept completed with general product design and mission scoping. Subsystem trade studies performed.
Preliminary Design Review Path	32	10-Apr-25	Concept refined and mission objectives verified. CAD modeling finalized.

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3.1 Innovative Concepts

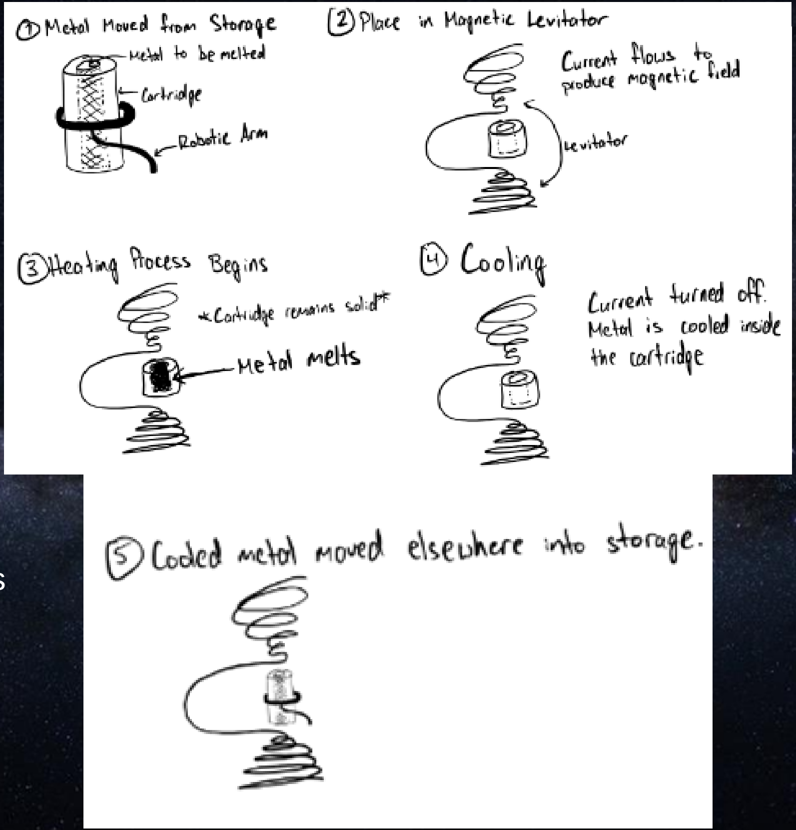
Concept 1: Levitation Heating

Concept Description:

- Using induction coils to induce a magnetic field which will levitate and melt material.
- The material will be in a mold which remains solid while the contents melt.
- A robotic arm would transport the cartridge within the payload.

Lessons Learned:

- The introduction of an arm creates more points of failure. This is especially so for thermal and mechanical components of the arm.
- Levitation increases risk of failure because the molten metal is difficult to contain once the magnetic levitator is turned off.



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3.1 Innovative Concepts

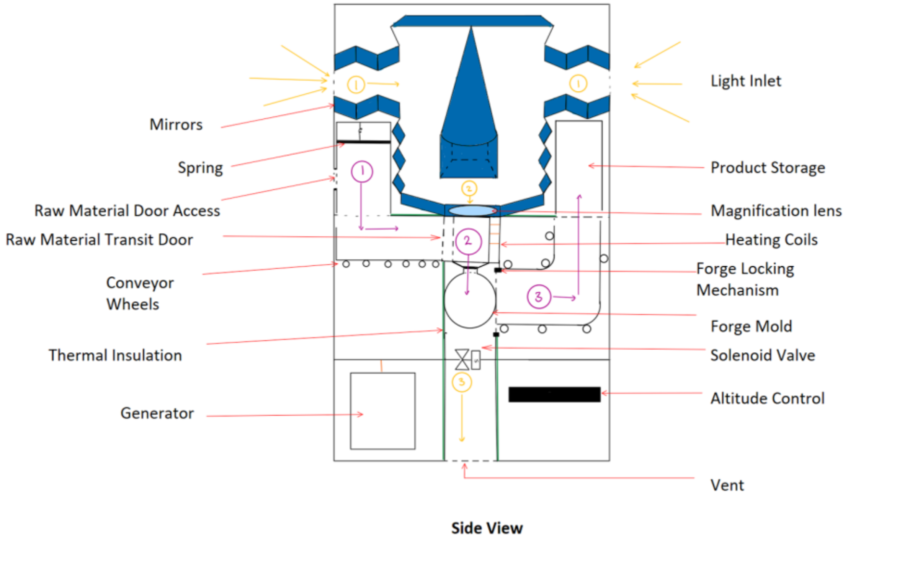
Concept 2: Solar Centrifuge

Concept Description:

- Material heated via concentrated solar thermal ray optic arrangement in conjunction with electric heating coils.
- Material moved with a pulley and spring system.
- Artificial gravity imposed through centrifugal force.

Lessons Learned:

- Complex designs correlate to more points of failure.
- The introduction of a rotating shell creates issues transferring material.



3.1 Innovative Concepts

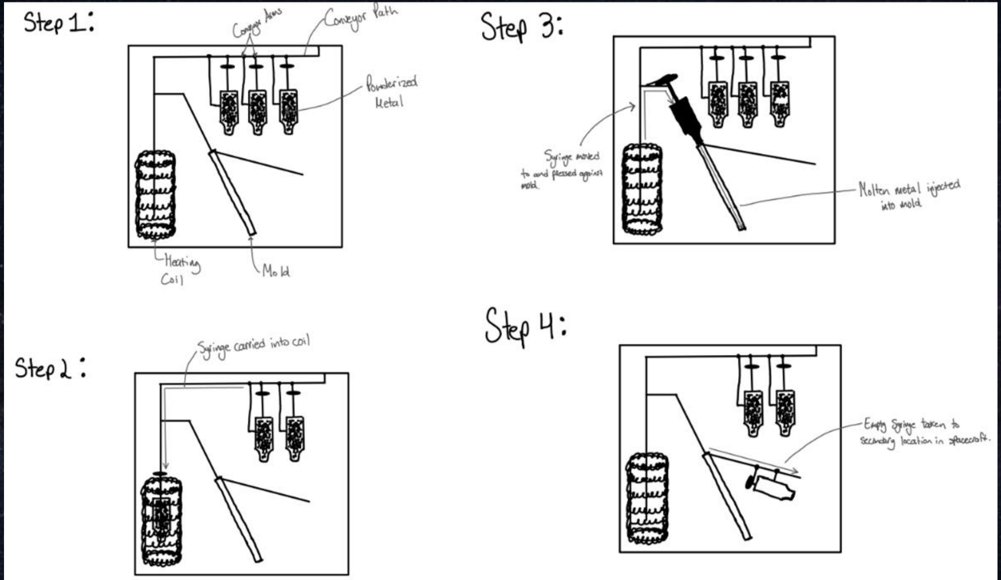
Concept 3: Injection Molding

Concept Description:

- Heated via an electric heating coil
- Chamber with preloaded regolith powder carried to coil via a conveyor/pulley system and heated.
- Syringe extracts molten material injects into mold to cool.

Lessons Learned:

- The use of one syringe and mold creates a possibility for slag accumulation.
- Reusability is vital to prove scalability.



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3.1 Innovative Concepts

Concept: Trade Study

Trade Study:

- A trade study was conducted to determine the most appropriate design.
- Injection molding was chosen due to its applicability in microgravity and simplistic design.

Criteria	Weight (%)	Injection	EM Levitation	Solar Centrifuge
Cost	10	9	5	5
Reliability	15	6	8	6
Thermal Management	20	6	8	7
Power Consumption	20	7	4	6
Scalability	5	8	8	10
Complexity	15	8	7	6
Design Uncertainty	10	7	5	6
Technology Maturity	5	7	9	8
Totals	100	705	650	640

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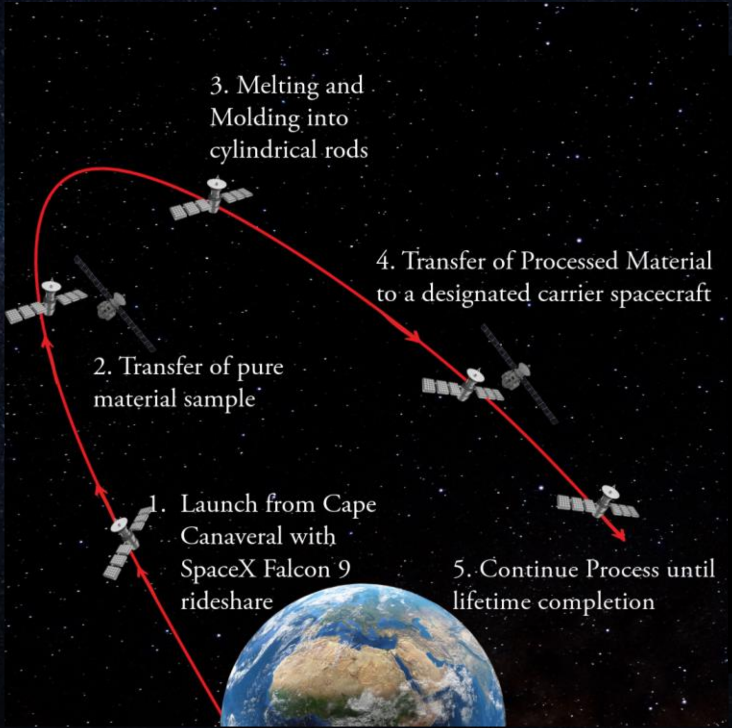
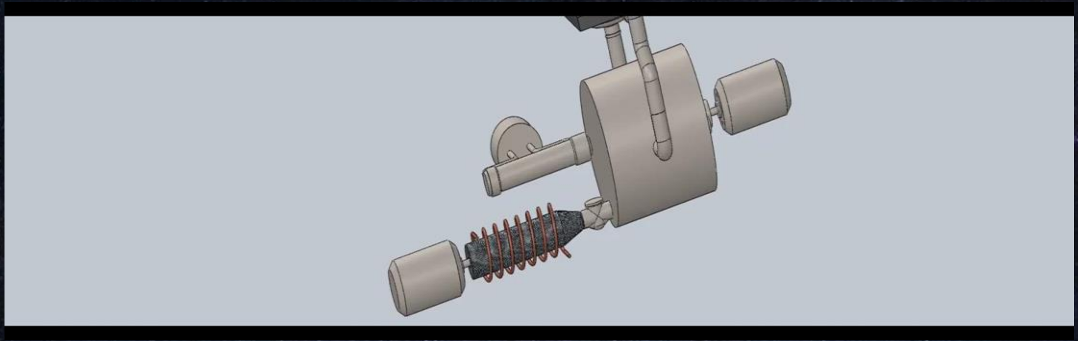
2.2 Storyboard of Complete Operation

Macro-Mission Architecture



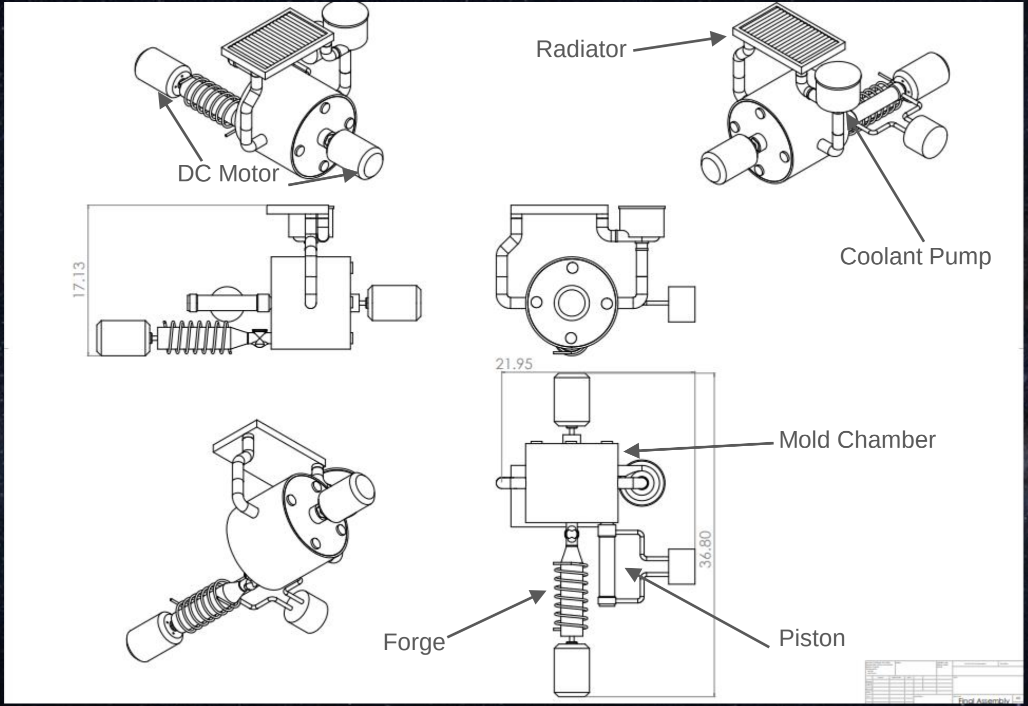
2.1 Animation of Key Operating Sequence

- **1: Heating and Churning**
  - The induction coil generates a strong magnetic field
  - The electrical resistance then causes the material to heat to the point of melting.
  - The rotating motion of the screw is performed by utilizing a DC motor.
- **2: Chamber Loading**
  - As the screw turns, the axial flow causes molten material to fill the chamber.
- **3: Cooling**
  - Mold is cooled to a solid state through a fluid cooling system.
- **4: Extraction**
  - A door is opened in the injection plate and a piston forces the solidified product into an ejection chamber.



Subsystem Traits & Analysis

3-View Component Breakdown



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Subsystem Traits & Analysis

Mass, Power and Component Analysis

Payload Mass Budget	
Component/System	**Mass (kg)**
Heat/Injection Mechanism	0.735
Mold Chamber Mechanism	1.406
Coolant Fluid System	2.871
Omnistore MS-600 Coolant	1.33
Piston Mechanism	0.532
Powderized Aluminum	0.0432
Radiator	1.443
20% Margin	1.461
Total	**9.8212**

- Most component masses calculated using Solidworks mass properties
- Coolant mass estimated using density and volume of fluid flow regions.
- Given a 20% margin of error.

Power Budget	
Payload Power	
Component	**Power Used (W)**
Heating	115.0
Mechanical Components	29.4
Sensors	5.4
Cooling	20.0
20% Margin	34.0
Spacecraft Power	
Component	**Power Used (W)**
Attitude Control	15.0
Comms	5.0
Propulsion	0.0
Thermal	15.0
20% Margin	7.0
Available Power	198.2

- Calculated by using real-world examples (especially for the mechanical components and sensors).
- Power needed for heating was calculated using an induction heating power requirement calculator.
- Given a 20% margin of error, which is industry standard.

Subsystem Traits & Analysis

Thermal Analysis

- Heats the metal to 700C while managing excess heat via a cross flow heat exchanger.
- Uses Globaltherm Omnistore MS-600 as a coolant to bring the molded material to 400C

Criteria	Weights	Cross Flow	Counter Flow	Cocurrent Flow
Rate of Heat Remova	60%	10	8	7
Easy of setup	10%	9	5	5
Cost	15%	8	8	8
Size	15%	9	6	5
Totals	100%	9.45	7.4	6.65

Criteria	Weights	Water	Ethlylene Glycol	Globaltherm® Omnistore MS-600
Volititly/Corrosion	5%	10	10	10
High Boiling Point	40%	2	4	10
High Heat Transfer Potentical	40%	5	7	8
Common Use	15%	10	10	6
Totals	100%	4.8	6.4	8.6

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Subsystem Traits & Analysis

Structural Analysis

Bill of Materials
DC Motor (2)
Screw Motor Shaft
Mold Motor Shaft
Conveyor Screw
Conveyor Shell
Revolving Mold Chambers
Coolant Tank
Coolant Piping
Coolant Pump
Radiator
Piston
Piston Pump
Piston Piping
Powderized Aluminum
Induction Coil

Criteria	Weight (%)	Carbon Phenolic Composite	Ti-6Al-4V Titanium Alloy	Silicon Carbide (CMC)
Mass	5	8	6	4
Melting Point	20	10	7	8
Thermal Conductivity	25	9	6	8
Coefficient of Thermal Expansion	25	10	8	9
Cost	5	5	6	4
Manufacturability	10	3	7	4
Tensile Strength	10	5	9	6
Totals	**100**	**8.2**	**7.1**	**7.25**

- Carbon-Phenolic Composite chosen for syringe shell material.

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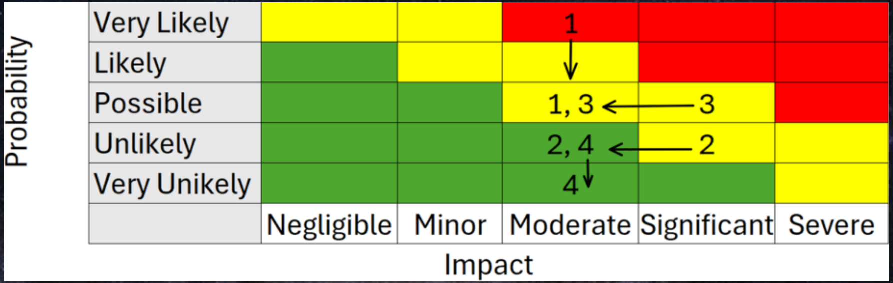
1.5 Risks

Risk Identification, Mitigation, and Solutions	
Risk	Mitigation
1. Slag Generation	∘Syringe will be in constant motion ∘Proposed scraping mechanism in chamber & syringe ∘Syringe heating times are maximized
2. Molten Material Leakage	∘Seals installed at boundaries ∘Electrical power removed from system. Coolant removes decay heat ∘Chambers are individually isolated if leakage source is known ∘Leakage feeds into cooling system, which is designed to remove heat
3. Mold Lodged in Chamber	∘Four separate chambers provide redundancy ∘System isolated and investigated at a convenient time ∘Stuck chamber isolated and operation continues.
4. Loss of Power	∘Continuous circulation of molten material minimizes slag accul ulation ∘Minimize power to cooling systems. Maximize circulation in syringe ∘Installation of backup battery system

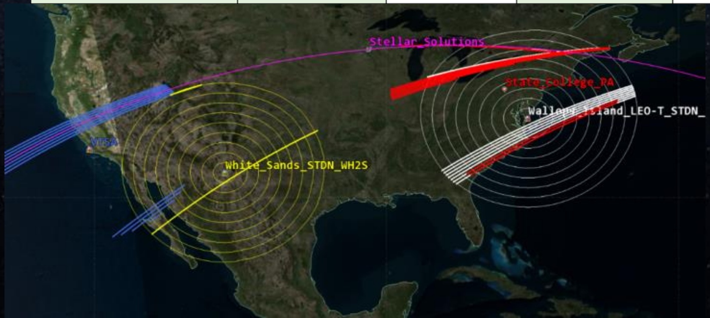


2.3 Data Handling and Comms

Communications Architecture

- Optics necessary to provide non-continuous visual confirmation of satellite integrity as well as verification of electrical orbit signaling.
- Two ground stations in the Near Earth Network and one ground station with a dedicated network were chosen for analysis.
- The total line of sight data was modeled using the STK software.
- The facility at Wallops Island, VA was chosen due to its total line of sight availability, eligible link margin, and its proven capabilities with other speacraft in the NEN.

Considerations	Weight	Goal	Ground Stations		
			Wallops Island	White Sands	Dedicated
Cost Efficiency	10%	Max	3	3	1
Normalized Value			1	1	0
Availiablity Time	20%	Max	2	2	3
Normalized Value			0	0	1
Mean Coverage Time (sec)	30%	Max	217.82	169.50	201.29
Normalized Value			1	0	0.66
Number of Access Points	25%		16	2	11
Normalized Value			1	0	0.64
Level of Certainty	15%	Max	3	3	2
Normalized Value			1	1	0
Total Value	100%		0.8	0.25	0.56

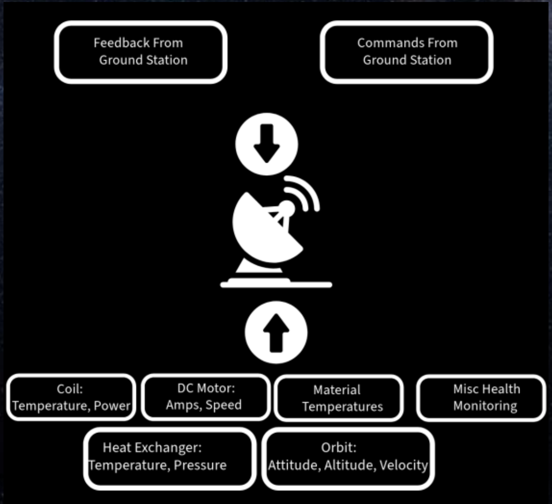


Project: Skyforge

2.3 Data Handling and Comms

Calculations & Data Specifications

- Due to the lack of necessity for audio or video systems on the payload, the expected bit rate is relatively low
- Communications equipment was considered for two ground stations in the Near Earth Network: The Wallops Island, VA facility and the White Sands, NM facility. Both ground station facilities provide an adequate link margin for communications operations.



Calculated Link Budget Summary		
Ground Station	Wallops Island, VA	White Sands, NM
Payload Antenna Size [m]	0.05	0.05
Carrier Antenna Size [m]	4.70	18.00
Data Rate (kBps)	93.00	93.00
Frequency [GHz]	2.12	2.12
EIRP [dB]	59.14	80.40
Link Margin (Uplink) [dB]	30.17	47.45
Link Margin (Downlink)[dB]	10.46	22.02

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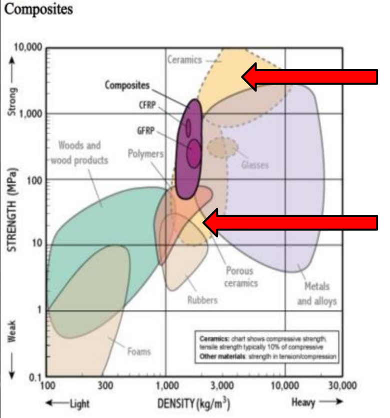
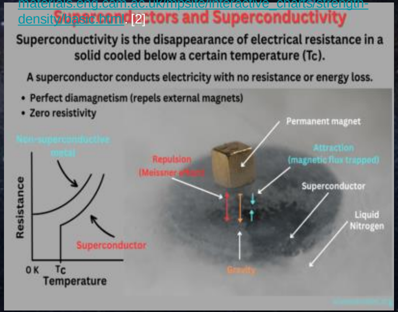
3.2 Technology Gap Assessment

Technology Gap Assessment		
Technology	**Reasoning**	**Impact**
High Efficiency Coils	∘Skyforge utilizes electrical induction heating coils. Currently, there are many lossed in electrical energy to heat the coils.	∘Lower energy consumption per Watt energy. ∘Allows for the possiblity of larger scale production.
Optimized Ceramic Composites	∘Ceramics were considered as a heat transfer medium due to its potential for thermal insulation ∘Ceramics were considered due to electrical resistance, minimizing static buildup on the spacecraft.	∘Allows for a compilation of thermal insulation, electrical resistance and high strength per unit density.
Optimized Space Welding Techniques	∘Rod sizes are relatively small ∘Smaller rod sizes need greater precision and care when incorporating as structural material	∘Ensures capability for use as structural material, when welded into a structure ∘Eliminates a need for larger scale operations



Strength - Density. *Cam.ac.uk*. University of Cambridge, UKhttp://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/strength-density/[illegible].[2]



Helmenstine, A. Superconductors and Superconductivity. *Science Notes and Projects*. https://sciencenotes.org/superconductors-and-superconductivity/.[3]

Project: Skyforge

3.3 Biggest Challenges Encountered

- Most of the challenges faced were brought up at an early stage, during either team meetings or during concept design.
- Most challenges were overcome with concise design strategies.
- Some challenges had to be overcome with reasonable assumptions.

Team Challenges and Response		
Challenge	Reason	Response
Operation in Microgravity	∘Microgravity limits applications of some current models based on molten material flow.	∘Injection molding chosen to alleviate issue during material transfer. ∘Rotating motion of the auger introduces a desired flow path.
Payload Size Limitations	∘Payload size determines the complexity of the model. ∘Payload size determines the shape and size of molds.	∘Concept design was made with a compact design in mind ∘Small truss rods were selected due to their applicability to form larger structures when connected.
Rod Material Selection	∘Rod materials should be representative of nearby regolithic sources ∘Rod material should be able to melt at a temperature reasonable with a heating coil	∘Near Earth asteroids matrial composition researched ∘Aluminum selected due to lower melting point and abundance

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4.1 Paper

Stellar Solutions: Project Skyforge

- Information about the paper
  - Abstract (169 words)
  - Length (20 pages)
  - There were 14 sources referenced
  - Could be presented at the SmallSat Conference, August 23-26, 2026 Salt Lake City, UT. The SmallSat is most applicable to design and capabilities that are possible with current design structure.

Skyforge Preliminary Design:
The Melting of Material in LEO Through Injection Molding and Electromagnetic Induction

Dan Bahamon, Cole Rinehimer, Brenden Quinonez,
Conal Richards, Avimukta Dokuparthi, Mike Macdonald

Abstract

It is too expensive and time-consuming to launch new materials into space whenever a spacecraft needs servicing or repair. Stellar Solutions aims to combat this problem by creating a forge in space where new parts can be manufactured constantly. The mission goes as follows: prove that it is possible to melt aluminum into a truss structure while in low earth orbit. This idea has been tried on the ISS through a method called Electromagnetic Levitation, however there was a person on board who orchestrated the event and retrieved the part. Project Skyforge aims to complete the melting and molding of 4 rods with semi-autonomous operation. The melting process will involve the use of coils of wire to induce electromagnetic fields in the material being melted. The material will move through an auger into the molds. Once hardened, the part will be pushed out of the mold by a piston. This mission is created with the hope of eventually being upscaled and applied to other materials such as asteroid regolith.

Introduction

Right now, to build spacecraft and satellites up in space, most spacecraft parts are built on Earth and then sent up to use, which requires a lot of excess fuel and rockets. This approach is not sustainable in the long run, especially as space exploration and satellite deployment continue to grow. The challenge is to figure out how to manufacture these satellite and spacecraft components in space rather than on Earth. Stellar Solutions is tackling this problem by combining two existing technologies that are used on Earth - induction heating and injection molding - to produce the spacecraft components directly in orbit, removing the need to use more rockets and the fuel that is needed to send them to space. Stellar Solutions' effort to fill this capability gap is Mission SkyForge.

The induction heating system chosen by Stellar Solutions is not entirely new, as the European Space Agency (ESA) has already tested a similar system called the ElectroMagnetic Levitator (EML). The EML uses electromagnetic fields to heat and solidify metals in a high-vacuum environment. According to Guinart-Ramirez and her colleagues, the induction coil heating system has been proven to work in space [1]. However, until now, the technology has only been used to test feasibility and experiments, not in the manufacturing of actual parts.

Stellar Solutions' goal is to take this technology a step further by using it to create real, usable spacecraft components. The path that Stellar Solutions is taking to complete this goal is to use injection molding - something that has been used on Earth for a long time but has not been used in space. By combining induction coil heating and injection molding, Stellar Solutions is

1.6 Path to PDR

Venus X-Class Bus Integration

- **Power**
  - Establish connection to dual solar array
  - 444 W of steady state power during “daytime” operations
- **Structure**
  - Payload mounting made easy by small size
  - Attachment created by mounts on thermally stable components
  - Mounting may vary depending on Venus Bus interface
- **Communication**
  - Connection established with host spacecraft comms-systems
  - Specifications are unknown, though likely within common ranges for LEO spacecraft
  - 5 kBps is highest anticipated data rate for engineering and “health” data
  - Most communications are for health and analysis, therefore requiring a semi-autonomy

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1.6 Path to PDR

Future Work and Next Steps

- Implement backup battery for emergencies
- Research superconducting materials
- Develop components for slag removal
- Minimize imperfections in product
- Identify enhanced thermal insulators
- Trade study of ceramic insulators

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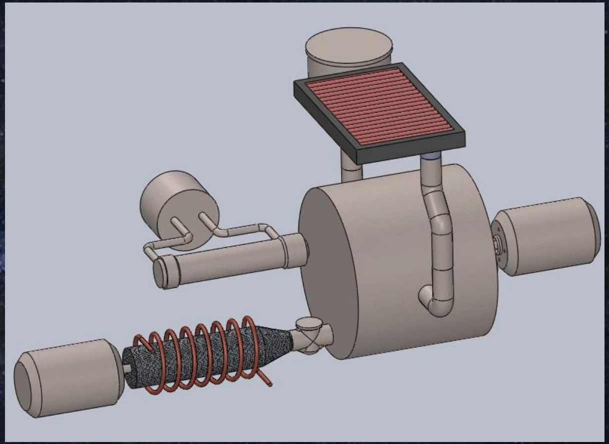
Summary

- **The Mission**
  – Stellar Solutions' Skyforge mission will demonstrate metal injection molding of structural components in the harsh space environment
- **Innovation**
  – Demonstration of injection molding in space
  – Payload operations under intense thermal gradients
- **Impact**
  – Proves viability of semi-autonomous industrial operations
  – Encourages future space construction and industrialization efforts
  – Lowers launch costs and simplifies spacecraft design
- **Lessons Learned**
  – Heat management requires high-grade coolants and careful design
  – Moving material in microgravity heavily influences production processes



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Questions

Stellar Solutions: Project Skyforge

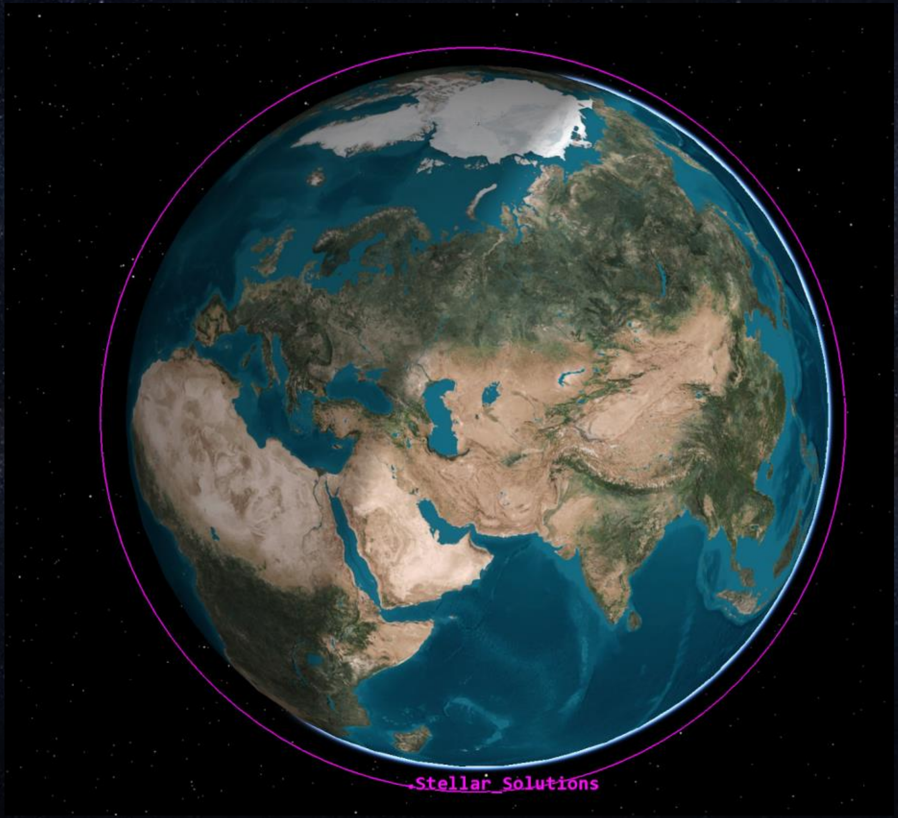
Questions?

Backup Slides

Backup

Orbital Analysis and Features

- **Orbit Characteristics:**
  - $a = 6878$ km
  - $e = 0.00$ (circular orbit)
  - $i = 45.1°$
  - $\Omega = 29.8°$
  - $\omega = 0.00°$
  - $T = 94.61$ min
- **Eclipse Times:**
  - 34 – 36 min



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Backup

Communications Calculations

- **Bit Rate calculation**
  - Data rates account for motor, thermal heating and cooling, and orbital maneuvering such as docking, if needed.
  - The margin for error in bit rate allows for substantially more measurements.
  - Bit error and ground station systems calculated using S-band frequency and modulation outlined in the Near Earth Network User's Guide.

- **Line of Sight Modeling**
  - Line of sight modeled in STK.
  - Ground stations set and total line of sight access points and time in line of sight used to assist in ground station determination.

	Thermal	DC motor Speed	Thermal Cooling	Heat Xchanger	Attitude	Altitude	Velocity
Amp	2000	9000	3000	500	100000	7000	1000
Eq.	0.05	0.5	0.01	0.05	0.000001	0.000001	0.0001
n	14.29	13.14	17.19	12.29	35.54	31.70	22.25
Sample Rate	5	10	5	5	100	100	100
Bit Rate (Bps)	71.44	131.36	85.97	61.44	3554.12	3170.47	2225.35
Sum (R) Bps	9300.14858						
Total with Error	93001.49						