Stellar Solutions 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 isn't 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's 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 isn't 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 working to close the gap in in-space manufacturing, significantly reducing the need for Earth-based production and the need for rockets and the fuel needed to send them to space.

Mission Overview

Brief Overview

Stellar Solutions' mission is to demonstrate the feasibility of manufacturing metal components in space using SkyForge. The objective is to take a powderized metal, melt it, and mold it into a usable shape - all while in orbit. The plan is to launch the payload with the BCT X-Sat Venus Class Bus, and once it is in a stable orbit, begin melting the metal on the sunny side of Earth and cool it during eclipse time. This passive thermal cycle reduces the need for complex cooling systems. To complete the objective, Stellar Solutions is using a well-established method that has been proven to work on Earth - injection molding. Injection molding has been used for a long time, so it is known to work. The payload will heat the metal, which is stored in a syringe-type device, with induction heating coils. As the metal melts into a liquid or semi-liquid form, it will be injected into a mold by the syringe using a screw-type pump (auger). The mold will be in the shape of a rod since they can be used in truss structures, which are commonly found on spacecraft. The payload will also have the capacity to eject the solidified rod into a storage compartment. This mission, if successful, can lead to more efficient manufacturing in space while also being a source of supply for assembly in space.

Top-Level Mission Requirements

Table 1 shows the mission requirements decided upon by Stellar Solutions for Mission Skyforge. Each requirement shows the conditions that need to be fulfilled for the mission to be successfully completed. The requirements come from the Request for Proposal (RFP) and mission objectives. The first requirement comes from the RFP, which states that the mission shall use the BCT X-Sat Venus Class Bus. Under this requirement, the specifics about the power system, the volume limit, and the mass limit are shown in Table 1. The following three top-level requirements deal with the mission objectives. They explain that the payload shall have the ability to transport the material within itself, shall be able to heat and cool the materials and itself, and shall mold the aluminum into a rod.

Table 1. *Mission Requirements*

Mission	**Smelt asteroid regolith and shape it into a support structure.**	
Req Num	**Requirement**	**Justification**
R 1	The mission shall use BCT X-Sat Venus Class Bus.	Requirement stated in RFP.
R 1.1	The payload shall use a maximum of 444 W if using the dual solar array.	Specifics were given in the RFP.
R 1.2	The payload shall have a volume up to	Specifics were given in the RFP.

	17.0” x 16.4” x 27.0.”	
R 1.3	The payload shall have a mass of no more than 70 kg.	The Venus bus can carry a payload of up to 70 kg.
R 2	The payload shall transport material within itself.	Material needs to be moved throughout the payload.
R 3	The payload shall have the ability to heat materials and cool them.	Heat generation and removal are necessary for the material to melt and for thermal regulation.
R 3.1	The payload shall be able to heat aluminum to at least 600℃.	Necessary to melt aluminum.
R 3.2	The payload shall maintain bus heating and cooling systems.	Prevents critical electrical and mechanical satellite components from being damaged.
R 4	The payload shall mold material into a rod for another satellite.	Molten material needs to be molded into a usable form.
R 4.1	The payload will have a mold of a rod with dimensions of 0.75 cm diameter and 8 cm length for structural components.	Some form of structure must be present to constrain the molten material’s desired shape.

System Decomposition

Figure 1 shows the system decomposition for all the subsystems within the spacecraft and the payload. The spacecraft comes with propulsion, GNC, power, communication, structures, C&DH, and thermal subsystems. From there, the mission relies specifically on the thermal, structural, and power subsystems. This is due to the mission’s main objective being melting. The payload must also have a form of C&DH to carry out commands such as “open valve” or “turn on induction heating coils.” The ground subsystem and launch vehicle are considered separately from the other subsystems due to not needing any assistance or information from the others. Each subsystem also shows which member of Stellar Solutions will be working as the lead for that part of the project.

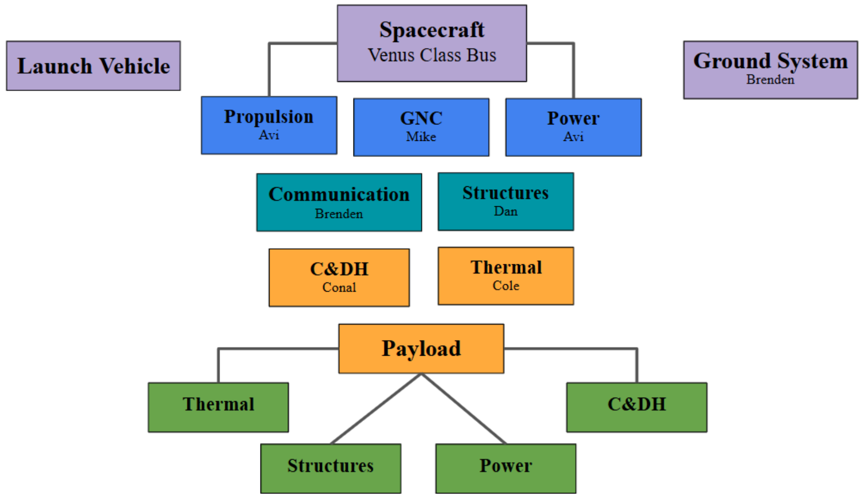

Figure 1. *Subsystem Decomposition Tree Diagram*

Macro-Level Mission Architecture

Figure 2 shows the macro-level mission architecture for the payload. This is the diagram that shows the entire lifetime of the project from launch to deorbit. Thus, it includes both the launch vehicle and the payload. As for all payloads, SkyForge also has a lifetime. The commencement of operations happens once the payload is in Low Earth Orbit (LEO). This is done by using the rideshare program by SpaceX. The payload will be part of a rideshare program with other payloads on the Falcon 9 rocket, which will drop off the payload on its orbit, which the team had chosen. This orbit was chosen due to inclination and orbit restrictions that will be detailed in the orbital analysis subsystem. The Falcon 9 rocket will be launched from Cape Canaveral, Florida. Once the Venus Class bus, with the payload inside, has been dropped into orbit, it will begin its mission. This will be to take in powderized aluminum into the syringe. Once the powderized aluminum is inside the syringe, the payload will melt the metal and mold it into a rod. These rods will then be transferred out to be used elsewhere. This process will continue until the end of the payload's lifetime. The proof-of-concept model focuses on the period for Skyforge to produce four rods, although the complete lifetime is expected to be until material decomposition due to thermal stress and cycling renders the material unusable within a specified safety margin.

The Venus Class bus and the payload within will be monitored and tracked by a ground station. The ground station was chosen based on which station would provide the most optimal telemetry and communication for the spacecraft. This location was chosen to be the Wallops Island, VA, Near Earth Network (NEN) satellite communications and telemetry facility. The specifications of why this ground station was chosen over others will be shown in the ground and communications subsystems.

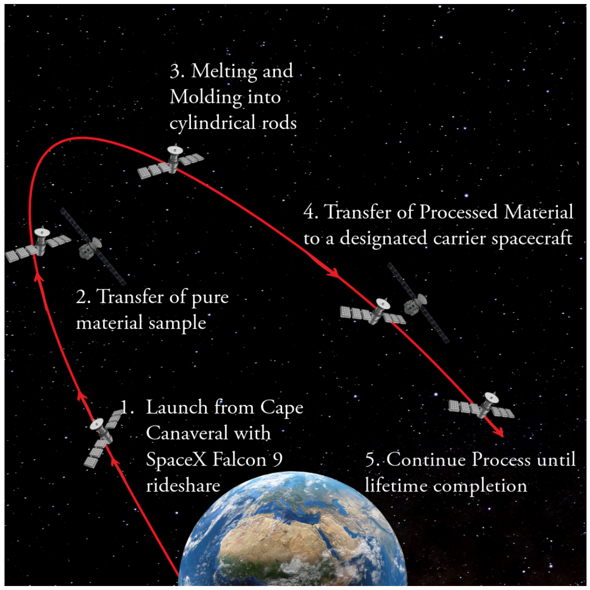

Figure 2. *Macro-Level Mission Architecture*

Payload Design

Micro-level mission architecture

The Concept of Operations for Skyforge changed considerably from the original idea, which used preloaded chambers of aluminum powder sourced from a regolith. The chambers were housed in a storage area and were subsequently loaded onto a conveyor and pulley-like system. The pulley system then lowered the filled chambers into an induction heating coil until the powderized aluminum was melted. The chamber was then emptied utilizing a piston-driven syringe that removed the molten material and injected the material into a mold to cool. The emptied chamber was initially considered for disposal due to the complications involved with creating a return system for used chambers to a storage area. Figure 3 provides a general outline for the sequence of events involved in the original design.

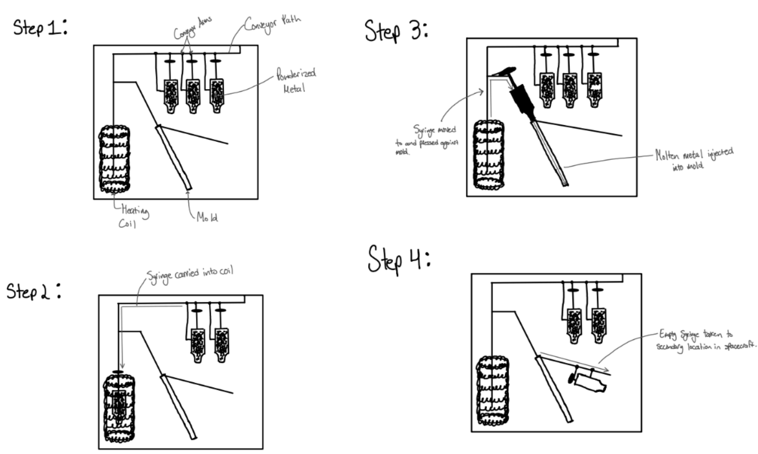

Figure 3. *Original Injection Molding Concept*

This original design had complications in its design that needed to be refined. The most significant change from the original to the new design is the switch from several smaller syringes that are transported throughout the process, to a larger, stationary syringe mechanism that is centrally located in the payload. This allows for several improvements, including the elimination of a potentially complicated transport system, more simplified thermal control and modeling, and the potential to reuse parts and materials. Another major change was from the original piston-driven syringe to that of an auger-like, screw-driven design that delivers molten material to cooling chambers. This affirms the benefits of reusability, saves space, and allows for more precise fluid injections. The changes in payload structure are illustrated in figure 4 as a sequence of events diagram, and in figure 5 as an isometric view of the generated CAD model.

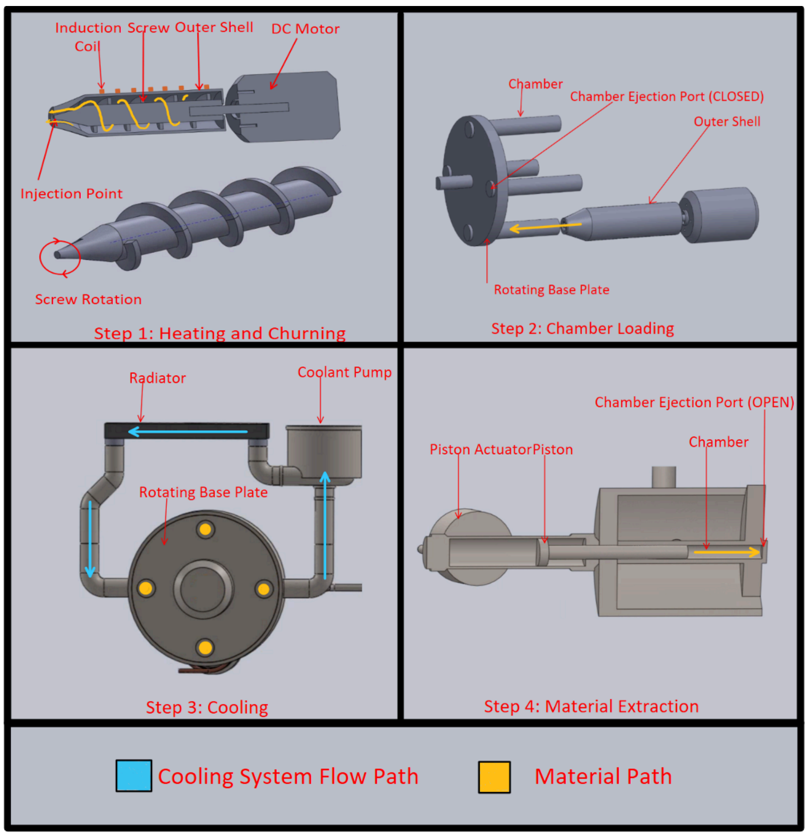

Figure 4. *Micro System Architecture Pathway*

Skyforge's updated design utilizes electromagnetic induction via a coiled device as its primary heat source. This is applied to heat the powdered aluminum that is provided via a transfer from another satellite. For the proof of concept and initial staging, a sample of aluminum powder is supplied in the shell of a screw-type pump (auger). The induction coils are wrapped around the exterior shell of the screw to provide a heat transfer method. The induction coil generates a strong magnetic field that induces electrical currents (eddy currents) onto the material inside the shell. The electrical resistance then causes the material to heat to the point of melting. Simultaneously, the rotating motion of the screw is performed by utilizing a DC motor. As the screw turns, an induced flow causes molten material to fill the chamber.

The material is transferred from the screw to the injection site through a series of four chambers in a revolving carousel-like structure. Once the chamber is filled with molten material, a switch will actuate to shut a valve and cut the supply of molten liquid to the injection site. The base plate that is fixed to each of the chambers is rotated to allow a new chamber to be filled. Once proper alignment of the chamber and syringe is identified, the cutoff valve is opened, and flow resumes into another chamber.

Each chamber that is filled with molten material is cooled via a crossflow heat exchanger that is separate from the screw and chamber assembly. Each chamber will be sealed and cooled with a refrigerated, closed system with the only purpose of cooling the injected material. Once a material is cooled and solidified, A door is opened in the injection plate and a force is applied onto the mold with a piston to free the solidified material. This forces the cooled material into an ejection chamber. The chamber is then considered empty and available to be supplied with molten material via the syringe again. This process is provided visually in figure 5 and is intended to be performed continuously until the event of an emergency or until the end of life for the payload.

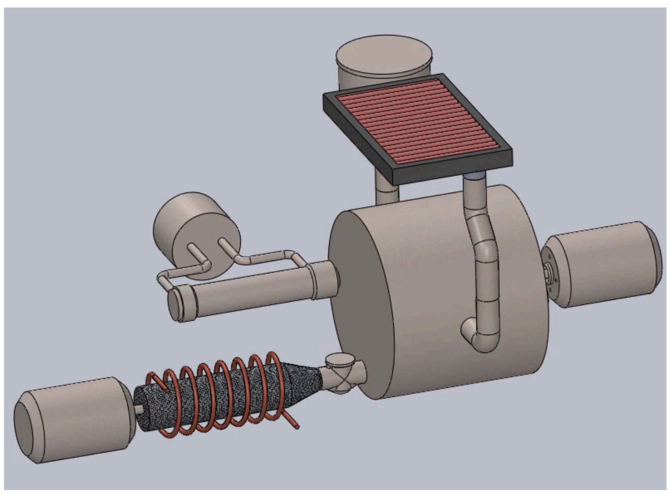

Figure 5. *Payload Isometric View*

Structure

Table 2 shows a trade study for the selection of the syringe exterior material. Material choice for this component is critical, as it houses the payload's most significant thermal process. Specifically, the melting point needs to be significantly greater than that of aluminum, as well as having a low coefficient of thermal expansion to avoid loss of functionality due to deformation. It also needs to have low thermal conductivity because the heat must be trapped in the syringe when the payload is in phases of lower heating (away from the sun). These are the most important factors, which is why they are heavily weighted. Mass is weighted low because, like most of the payload, this is a small component, therefore the difference in total mass is not overly significant regardless of the material. Cost is also weighted low; this is because the syringe is the payload's most critical component, and therefore cost comes secondhand to quality. Also, as previously mentioned, these are small components, so a large amount of material isn't used. Tensile strength is moderately weighted because although these components don't face significant mechanical stress during operation, they need to withstand any launch forces or vibrations. Manufacturability is also moderately weighted, as certain materials can be more difficult to manufacture with; such difficulties can affect mission timelines and potentially create component quality issues. The 3 materials chosen for comparison are Carbon-Phenolic Composites, Ti-6AI-4V Titanium Alloy, and Silicon Carbide.

Table 2. *Syringe Exterior Material Trade Study*

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**

As indicated by table 2, Carbon-Phenolic Composite is the best choice when accounting for all categories. This material particularly excelled in the thermal properties, having an exceptionally low conductivity and coefficient of thermal expansion of 0.5 - 2.0 W/m•K and 1 - 5 μm/m•K respectively. It also doesn't have a melting point; rather, it experiences sublimation at about 3500 ℃.

Table 3. *Payload Mass Budget*

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**

Table 3 displays the payload's mass budget. With a total estimated mass of 9.82 kg, the payload comes in significantly below the maximum allowed mass for this mission in the RFP. The reason for the low mass is the decision to fabricate a small part for the proof of concept, as the power needed for heating significantly increases with the mass of material being smelted. The low mass allows for the potential to increase the scale of the payload in the future, as well as launching in conjunction with other small payloads or experiments, saving launch costs and time.

Propulsion

The propulsion subsystem for Stellar Solutions' mission, SkyForge, is not needed. This is because the mission is about smelting a metal and molding it into a usable shape, so there is no need for the payload to switch orbit or move around in space. As the mission does not need the payload to meet other satellites or debris, the orbit that it is placed on is where it will stay. All that needs to be done is to take the launch vehicle up into space, where it will be dropped off in the orbit that the team chooses. The payload will then spend the rest of its lifetime in this orbit.

Power

The main power requirements come from the RFP and the project's needs. Since the payload will need to generate a lot of heat, a lot of power will be consumed for the mission's upkeep. Thus, it is necessary to include the different sources of power consumption, which includes the power used by the X-Sat Venus Class bus. The goal of Stellar Solutions is to make this mission as power efficient as possible, which means cutting down on power usage whenever possible without intruding on the main operations of the payload. The power does not have a minimum requirement; however, if the power usage is efficient, there is no need to use extra power. Having no lower limit is good, but there is an upper limit: the battery space and a maximum stored energy of 10.2 Ah.

The power required to run all the systems and mechanical components on board and run the heating and cooling aspects of the thermal requirements is what the power subsystem entails. The different aspects of the payload that were considered under the calculation of how much power will be used by the payload and bus are the mechanical components, the thermal components, and the communications and sensors. Propulsion and attitude control would normally be included in power consideration, but in this mission, the need for propulsion and attitude control is not there. Thus, there will be no need to allocate power to these subsystems. The batteries on board the X-Sat Venus Class bus will be recharged while the payload is in the sun, as the solar arrays will have the most exposure to solar rays at that time. The components will be running throughout the entirety of the orbit, although they will be running at lower power consumption during the eclipse since the heating will occur mostly while on the sunny side of the orbit.

All the power calculations were done using existing components that could be used. For example, for the mechanical components, the servo and stepper motors that are normally used in projects like this were considered. This is the case for sensors and cooling/thermal systems as well. Equations 1 and 2, voltage and power equations, respectively, show the equations that were used to calculate the power needed for the mechanical components.

$$V = I * R \tag{1}$$

For this equation, V is voltage, I is current, and R is the resistance of the components. Using the current that runs through the components and their equivalent resistance, the voltage needed to run the components can be found. Then, using equation 2, the power needed to operate them is calculated.

$$P = V * I \tag{2}$$

This equation calculated the power needed to run the component. Using voltage and current, the power, or P in the equation, can be found.

Table 4 presents the power that each component will need to run smoothly. A margin of error was included in the case that extra power is needed in any component. The available power that the components of the payload and spacecraft can siphon from is 444W, which is enough, according to the calculations made by Stellar Solutions. The margin that was used was 20%, which is an industry standard. This allows for any miscalculations or components that were overlooked.

Table 4. *Power Budget*

Power Budget		
Payload Power		
Component	**% Power**	**Power Used (W)**
Heating	25.90990991	115.04
Mechanical Components	6.621621622	29.4
Sensors	1.216216216	5.4
Cooling	4.504504505	20
20% Margin	7.65045045	33.968
Spacecraft Power		
Component	**% Power**	**Power Used (W)**
Attitude Control	3.378378378	15
Comms	1.126126126	5
Propulsion	0	0
Thermal	3.378378378	15
20% Margin	1.576576577	7
Available Power	44.63783784	198.192

The payload has components that relate to heating, cooling, mechanical, and sensors. The heating component describes the amount of power that will be needed to run the heating coils at a high enough temperature to melt the aluminum. This was calculated using an online website that calculates information about how much power induction heating coils take to melt certain materials. [2] The website considers the initial and final temperature, the diameter and length of the rod, and the material to calculate how much power is required to melt the aluminum. The website also calculates the volume, specific weight, specific heat capacity, specific cold resistance, temperature coefficient, melting point, etc. To ensure a margin of error, the dimensions of the syringe that were used on the website were larger than the dimensions of the project's syringe. This allows for an estimate that is more than what the thermal component needs. The heating component ended up using around 115 W of power and 26% of the available power. The mechanical components are the motors and pistons that will be used in the design of the payload to move parts and elements. These parts used around 29.4 W and 6.6% of the available power. Next up are the sensors, mainly the thermocouples and pressure sensors that are needed to make sure everything is running smoothly with no problems. The sensors used around 5.4 W of power, meaning it used up around 1.2% of the available power. For cooling, power is needed to run fans that will cool the payload while it completes its mission. The cooling fans will use up around 20 W of power, or about 4.5% of the available power. The 20% margin for all the components for the payload adds up to around 34 W of power, or 7.7% of the available power.

For the spacecraft power, the components relate to attitude control, comms, propulsion, and thermal. The first component that power is needed for in the spacecraft is the attitude control. The attitude control is to make sure the solar arrays are facing the sun, and they use 15 W of power, or about 3.4% of the available power. Next up are the comms, which take up 5 W of power combined, or about 1.1% of the available power. Propulsion, as said above, is not needed for the mission. So, for the propulsion component, there is no power usage at all, meaning extra power is available for other components of the mission. The last component of the spacecraft is the thermal parts that need power so that the spacecraft can stay at a reasonable temperature. This will be about 15 W of power and will use around 3.4% of the available power. The 20% margin for all the bus components adds up to about 7 W of power or 1.6% of the available power.

After calculating how much power everything uses, along with including the 20% margin of error, we found that there is still about 44.6% of the available power left, which can be used in heating and cooling for the payload because that is crucial to the mission. Otherwise, it can be used to scale the mission up or add another mission in the bus alongside this mission.

Thermal

The thermal subsystem requirements primarily deal with controlling where the heat goes. For example, the payload must be insulated so the heat doesn't escape and cause problems. The payload will also use a fluid coolant loop and a crossflow heat exchanger to cool the material. The assumption is that no heat will be lost in the plumbing system, and it can be assumed to be a stationary heat sink at the radiator to remove heat and a stationary heat source inside the crossflow heat exchanger. A crossflow heat exchanger was chosen using a trade study as shown in table 5.

Table 5. *Heat Exchanger Trade Study*

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

The coolant Globaltherm Omnistore MS-600 was also chosen using a trade study as shown in table 6.

Table 6. *Coolant Trade Study*

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 Potencical	40%	5	7	8
Common Use	15%	10	10	6
Totals	100%	4.8	6.4	8.6

The thermal subsystem will be based on melting pure aluminum powder with a melting point of about 600℃. Assuming we must heat the aluminum to 700℃ to make sure everything is melted; it will take approximately 2.8*108 J to melt. This also assumes the melting must happen within half of the orbital period while in the sun. This was found using size measurements determined by the team and the equation:

$$Q = KA(T - T\ sun\ ) * t\ sun\ /d \qquad (3)$$

where A is the surface area, Tmelt is the melting point of aluminum, Tsun is the temperature of space while in the sun, tsun is the time in the sun, and d is the diameter of the cylinder. This number can be further reduced by heating the aluminum over multiple orbits rather than all at once. For cooling the mold, Solidworks was used to determine how long it would take to bring the temperature of the part from 700℃ to 400℃ immersed in a coolant. This process will primarily take place during an eclipse since it is colder on the dark side of the orbit, making the process more efficient. It was estimated to take about 4 orbits to cool the material slowly. The cooling system also includes a small pump that will move the coolant to the radiators, this pump will be approximately 20W and move approximately 300 Gallons per hour. It was also discovered that a ceramic-based material would be the best insulator for the forge portion to minimize heat loss. This was found simply by looking at different materials' R values and choosing a material that has a high value while still considering the structural needs of the payload.

Communication

The communications architecture is based largely on the orbit, ground station and power capabilities of the launch vehicle and payload. Since the desired orbit specified is near circular/elliptical, this provides optimal opportunities as far as ground station locations as well as the elimination of the need for ground system relays, however the transmission delay should be a consideration for the communications systems. The main constraints and considerations for this system's architecture are broken accordingly to fit the payload and designated ground system capabilities. These constraints and considerations include: Coverage, Connectivity, Operating Bands, along with size, mass, power, and thermal budgets.

The ground station points towards two viable options for the selection of a facility: Wallops Island VA facility, White Sands NM facility. Each facility was considered due to their geographic locations, carrier antenna size, and connectivity to established ground station networks. A link budget analysis of the communications subsystems associated with each ground station is performed for both uplink and downlink capabilities to determine the optimal communications facility. The link budget data for both sites in question are summarized in table 7.

Table 7. *Link Budget Comparison*

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

The values for the link budget analysis data points are based on the listed values for the Wallops Island 4.7-meter ground station and the White Sands ground station as part of the NASA Near Earth Network (NEN) [3], [4]. This calculation was performed using the listed S-band frequency along with the BPSK R=½, Viterbi modulation, as listed in NASA's Near-Earth Network User's Guide [4]. The propagation path length used in this calculation was based on the defined orbit, with a semi-major axial radius of 6874.14 km to determine the path length, assuming that the ground stations are at sea-level altitude.

The assumptions made in this calculation were of the pointing losses, the sampling rate, and the implementation line loss. The pointing losses were made as conservative estimates of the error being at 1 and .05 degrees for the payload and ground station respectively. The implementation line loss is based on typical values observed in other missions, as -1.2 dB. The sampling rate is selected based on the data type and estimated sampling based on the type of data needed. This is combined with the amplitude of information needed to produce a bit rate for downlink data transfer.

The information types include Thermal heating, Thermal at the cooling chamber, thermal temperatures at the heat exchanger, altitude, velocity, and attitude calculations during normal operations (including maximum expected during docking and transfer of material. Due to the lack of necessity for audio or visual representations of data, this bit rate remains relatively low at around 100 kBps.

The selection of antenna type for the communications system was performed by taking the ground station into account. Due to the high antenna gain during uplink operations along with a high frequency from the ground facility, there are limitations on the type of antenna to be used. Due to the high gain of nearly 40 dB along with an EIRP of 59 dB, the optimal configuration for the antenna type is the parabolic reflector.

The remaining assumptions and calculations are based on minimizing the transmitter power and antenna size. Based on the maximum size of the payload and maximum power capacity, the transformer antenna was chosen to be 0.07 m with a power of 5mW. The total values for each station link budget suggest an adequate margin for either station, as they are above the threshold of 3dB-5dB to ensure an adequate margin for error.

Command & Data Handling

In the case of Skyforge, developing a command and data handling system poses many unique challenges. Despite these difficulties, the architecture of the mission also offers opportunities to simplify the C&DH subsystem and ease demands. Throughout the majority of the mission, sparse interaction with the payload is acceptable, as the only required data are periodic temperature readouts and standard telemetry. However, during the heating process, more consistent communication and data handling will be required as critical mission checkpoints are reached. In addition to these raw computational challenges, the design will also have to be rugged in the event that parts of the system fail from heat damage or more traditional software bugs.

First, it was essential to select an optimal C&DH architecture. This architecture would have to meet demands throughout the mission and continue operation in the event of failure. A trade study is shown in Table 8, which demonstrates which aspects of the system were most important and which computer architecture was most appropriate for the mission. Higher scores (1-3 scale) under each category denote greater preference. Because this mission already requires testing of new technologies, a highly robust architecture was necessary to allow continued operation in the event of component failure. With the particular risk of damage from internal heating, risk became the most heavily weighted category. Reliability was further highlighted with the categories of complexity and maintenance. Regardless of mission scale, thermal systems demand energy efficiency, making power use an essential category. Additional considerations were included, such as computer system cost and allowance for reconfiguration as the design evolves.

Table 8. *Trade Study for Computer Architecture Design*

Criteria	Weight	Central	Ring	Federated Bus
Risk	0.25	2	1	3
Maintenance	0.15	3	2	2
Power	0.2	3	3	1
Weight	0.05	2	3	1
Cost	0.1	3	3	1
Complexity	0.15	2	3	1
Reconfiguration	0.1	3	1	3
Totals	1	2.55	2.15	1.85

Centralized architecture was an attractive choice from the beginning, offering a basic, rugged computer system. The trade study supported this assumption strongly. Additional needs, such as high reliability and flexibility, were also met with a central architecture. A simple data flow minimizes risk for any sensors feeding the central processor.

For near-Earth missions, typical data rates for uplink fall around 1-2 kbps with rates up to 1 Mbps for memory reload. Downlink is notably more demanding, especially for mission-critical steps on Skyforge. Data rates for this are likely to range up to 5 Mbps for engineering information with some margin for sensor and experiment data [3]. To accommodate these requirements, the Raspberry Pi 4 has been selected [5].

Raspberry Pi computers are appealing for their adaptability and easy of use. Additionally, the Pi 4 has been tested on orbit and flight proven by the European Space Agency. For several years, the agency has hosted the "Astro Pi Challenge," in which radiation-hardened computers were flown to the International Space Station to execute commands written by students [6]. Knowing the Raspberry Pi will be easy to use even in harsh environments makes it an obvious choice.

Host Spacecraft Integration and Mission Analysis

Host Spacecraft Integration

The host spacecraft's power and communication systems offer many advantages towards integration to the Venus X-Class Bus. However, some important challenges must be addressed, as some specifications of the host spacecraft are unknown. Power is exactly known, and Skyforge will fly with the dual solar array configuration of the Venus bus. This provides 444 W of power during "daytime" operations, which constitute a majority of the payload's orbit.

Regarding structural integration, many characteristics of the Venus bus are unknown, including what interfaces are available for attaching payloads. Despite this, the small size of Skyforge allows for mounting almost anywhere inside the volume provided in the RFP. This streamlines the process of attachment and allows for other payloads to be included on the same mission. Attachment points on the payload can be applied to any components which do not experience large thermal gradients, such as pumps or the main carousel.

Based on common data rate values for small spacecraft, it is assumed that the Venus bus can transmit about 5 kBps of engineering data with some margin for scientific information [3]. This falls well within required data rates for Skyforge. Despite the unknowns in this area, if the Venus bus has a communication system similar to other spacecraft of its size, Skyforge will not need to carry additional antennae or transmitters.

Launch Vehicle

To launch Skyforge, Stellar Solutions will take advantage of the Smallsat Rideshare Program offered by SpaceX. These missions launch to a variety of orbits onboard a Falcon 9 rocket [7]. In the case of Skyforge, a launch to LEO with moderate inclination will be selected. Services like these guarantee ease of access to orbit and a variety of launch opportunities. The Falcon 9 also offers high reliability and low launch costs due to reusability.

Orbital Analysis

The orbit was chosen using the *Systems Tool Kit* (STK). We chose an orbit with the following characteristics: $a = 6878$ km, $e = 0$, $i = 45.1°$, $\Omega = 29.8°$, $\omega = 0°$, $T = 94.61$min. The eclipse time for the orbit is 35 minutes on average. This provides enough time for cooling the forge over 4 orbits while the heating will occur in view of the sun where it is hotter. The GNC system will be used as provided on the Venus class bus with no modifications. The payload has few moving parts, all of which are small. The aluminum will be traveling slowly through the forge at a speed around 8 cm/hr which will not produce a large torque. The center of mass will remain approximately constant within the payload as well due to the light weight of aluminum. The attitude control system will only be used to ensure that the dual solar array is facing the sun.

Ground Subsystem

The ground subsystem was analysed with two key points in mind: The availability of antenna services and command data processing. The mission objectives for the ground subsystem aim to address the key points while ensuring that the overall mission requirements are met.

The determination of viable ground stations was performed by researching possible data networks and dedicated mission antennae to support the mission. The satellite networks that were considered for this analysis consisted of NASA's Near-Earth Network (NEN) and the Air Force Satellite Control Network (AFSCN). The ground locations dictated by each of the networks reflect the proposed location. The determination of a ground system also included the consideration of a dedicated system that is based near the location local to the design team in State College, PA to analyze the potential benefits from a convenient location and user access availability.

Each facility was considered for utilization for a ground station based on the best options for telemetry and tracking data. The study of an adequate ground station was determined by modeling the orbit for the payload using AGI's STK modeling system. The line-of-sight access radius was set to match the ground station based on horizon viewing angle, lighting, the nadir angle, and atmospheric attenuation. Figure 7 provides a 2-dimensional view of the spacecraft in relation to each ground station. The swept lines represent total line of sight paths for the duration of one week.

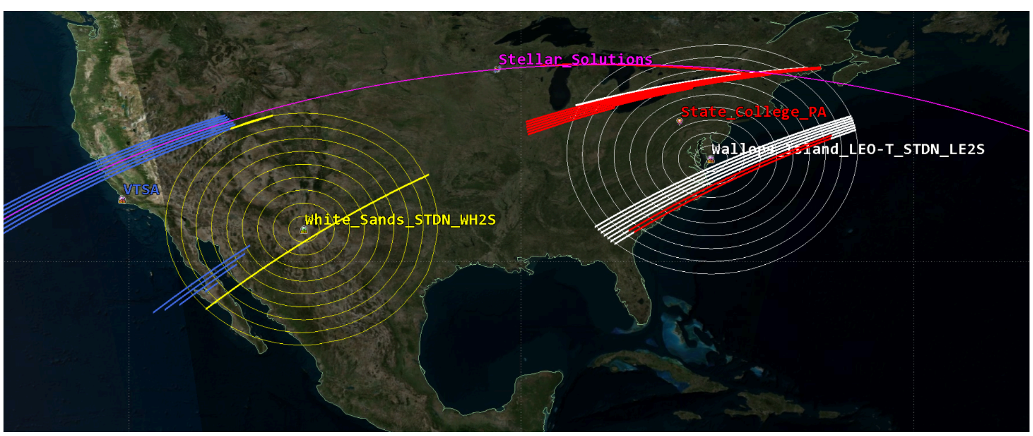

Figure 6. *Line of Sight for Payload (One Week)*

One problem encountered with the ground station analysis was the lack of information regarding communications and telemetry monitoring equipment data from the AFSCN due to confidentiality associated with the U.S. Air Force operations centers. To properly consider this, a trade study was conducted, aided by STK's reported line of sight accesses in terms of quantity and maximum total duration over one week.Other considerations were made for aforementioned qualities such as cost efficiency and 'level of certainty', which describes how well the past history with ground stations and the feasibility in obtaining access to such networks.

The selection of the ground station was performed in conjunction with the communications subsystem analysis. Based on the link budget analysis in the Communications section, it has been determined that the Wallops Island and White Sands ground stations provide an adequate link margin to justify neglecting consideration for a dedicated facility. Due to cost, complexity, and consistency, it is intuitive to also select the Wallops Island facility as the ground station.

In terms of automation, the Wallops NEN facility may have reduced capability and availability compared to the manning at a dedicated site. In addition to this, the complexity of operations does not dictate consistent operator interaction. The requirements for onboard systems are expected to be relatively low compared to other mission designs due to the low-level complexity of information types. This correlates to a high feasibility for use in highly automated onboard systems with minimal ground system involvement. This coincides with the ground station's requirements, which allow for non-continuous coverage at Wallops Island. This allows for the availability to perform routine visual and communications assessments to the spacecraft to verify proper operations such as receiving downlink data information and visually verifying properties such as the physical integrity of the spacecraft and orbital trajectory confirmation.

Risks

There are a number of risks that need to be considered for the mission. The first of which is slag: the hardening of molten material within the syringe. This is something that needs to be avoided because slag buildup will likely cause a jam in the syringe. A jam would mean the mission failed. To avoid slag, the syringe will be in constant motion causing the buildup of hardened material to be pushed through where it will be heated. Given the opportunity to repeat the experiment instead of performing the mission once, there would be a scraping mechanism in place to clean the syringe in between heating/cooling cycles.

It is also possible that molten material may leak out of the syringe at the injection point. If this were to occur, there could be potential damage to electrical systems and spacecraft. In the event of a leak, all openings will be sealed, and operation will be paused until the leaked material is cooled. Depending on the response of the electrical systems and readings, operation will continue, or the mission will be deemed a failure. The electrical systems may also overheat due to the heat generated by the forge. The coolant system is there to avoid this, but if the electrical systems did overheat the forge would have to be shut down until everything is operational again.

Another problem that may occur is the cylinder (solid part) getting stuck in the mold. There is a piston which should push the part out of the mold after the mission is complete, but it is possible that the piston won't be able to get a part out. If this happens, the mold itself will be analyzed after the mission and the part will have to be forcibly removed. The rest of the mission will go as planned. The piston is there for repeatability, mission SkyForge will only involve filling the mold once.

Finally, due to solar flares and other space related dangers, the payload may lose power. If there were more time to devote to this project, there would be batteries added to the payload to ensure that control of the payload is not lost. During the proof of concept, a loss of power would not be the end of the mission. The spacecraft would remain in orbit until the power eventually comes back on and then the mission would resume as normal. The heating of the forge would liquify any solid buildup in the syringe.

Future Work

Development of the Skyforge mission has required extensive research of a variety of emerging technologies. Precision injection molding and electromagnetic heating in the space environment present numerous challenges and opportunities for research. There are many ways in which Skyforge could be modified as a mission to meet additional goals or reach current goals with less risk.

As discussed, complete power failure for any reason would effectively terminate the mission. Although Stellar Solutions is willing to accept this risk by relying on the robustness of the dual solar array, backup batteries provide mitigation in the event of power loss. If hardware fails, these batteries offer a chance to continue the mission and reach critical goals. Additionally, this allows for continued operations during eclipse. In the event of solar flares, batteries can actively store power to “reboot” the payload if entering a safe mode is required.

Further improvement to Skyforge would involve effective slag removal. After several iterations of rod production, slag is likely to build up on the payload, especially in critical regions where temperatures swing. Eventually, this may terminate a mission early, and improved seals and removal techniques increase the likelihood of payload survival.

As materials science and related technologies advance, the opportunities to improve Skyforge expand greatly. The ceramic insulator used to shield electronics and other components from molten aluminum is one of the most critical pieces of hardware to improve. While ceramics are ideal for applications like these, detailed consideration is still important. A trade study of ceramic insulators would answer many remaining questions. For example, heating and cooling induce life cycle wear, and more robust insulators are desired for long flights in the space environment. Additionally, more traditional concerns arise, such as the cost, mass, and chemical compatibility of materials used. With cooling and insulation addressed, stronger and more efficient heating sources will also be desired. As research into superconducting materials grows, missions like Skyforge will have stronger and more robust magnetic heating coils at their disposal.

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