C3 Track 1 Final Showcase Technical Report: Conceptual Design of In-Space Manufacturing of Carbon Fiber Tubes

James Glenn, Hirokuni Kakiuchi, Lily Mikulas, Oliver Roberg-Perez, Aidan Timofte

Abstract

We present a conceptual design for an in-space remote payload capable of manufacturing carbon fiber tubes for the purpose of subsequent in-space assembly of spacecraft structures. Beginning with system definitions and motivations, the process of space system design from requirement buildup to risk mitigation is detailed. In fulfilling the mission statement of the COSMIC Capstone Challenge (C3), we propose a payload design capable of manufacturing and storing carbon fiber tubes in a microgravity near-vacuum environment. By incorporating a resin capable of self-propagating a frontal polymerization reaction, we show a conceptual design for carbon fiber strut manufacturing without the use of conventional thermal curing methods. Through the implementation of this Dicyclopentadiene (DCPD) based resin, manufacturing and storage of carbon fiber tubes can be performed near-autonomously on-orbit in a feasible manner.

Introduction

Current spaceflight operations rely on the integration of two main subsystems: the spacecraft designed to complete a specific mission, and the launch vehicle capable of transporting the spacecraft out of Earth's atmosphere and into orbit. This paradigm of space missions, while effective, is not sufficient for planned missions of ever increasing scale and scope. Examples include interplanetary missions, persistent space habitation on the Moon and beyond, and larger scientific missions incapable of fitting within a single fairing of a launch vehicle. Previous missions have offered clever engineering solutions to the constraints of a launch vehicle and spacecraft system, with the origami-like James Webb Space Telescope being a prevalent example. However, it is becoming increasingly clear that the future of space depends on a shift in the way spacecraft are designed and delivered to orbit.

Recognizing an increasing need for a paradigm shift in space systems, NASA has invested resources into the development of In-space Servicing, Assembly, and Manufacturing. These three areas each target a vital need for the future of spacecraft and space mission design. With the ability to manufacture parts, assemble spacecraft from these parts, and continuously service these spacecraft in space, all parties involved in the development of space would see a huge increase in productivity and cost-effectiveness.

As the space industry continues to grow, both government and commercial sectors are showing greater interest in ISAM. There have already been several missions conducted by NASA as detailed in the ISAM State of Play, an annual document characterizing the current state of ISAM capabilities. Certain examples include the operation and maintenance of the International Space Station, the servicing and repair of the Hubble Space Telescope, and the operation of Northrop Grumman's Mission Extension Vehicle (Arney et al.). In addition to these past missions, multiple planned missions and commercial ventures will make use of ISAM capabilities. The Artemis program will construct the Gateway station in Lunar orbit, serving as an example of in-space assembly that will aid in the servicing and operation of future Artemis missions.

In particular, we focus on the concept of in-space part manufacturing. The use of carbon fiber composites is prevalent in many existing spacecraft due to a high strength-to-weight ratio, among other qualities. Currently, carbon fiber composites are used in spacecraft such as the JWST (NASA) and spacecraft subsystems such as the Canadarm in use on the ISS (Canadian Space Agency). By providing a proof-of-concept for part manufacturing at a small scale, the system will demonstrate a crucial aspect of in-space manufacturing and spacecraft assembly. Specifically, the system will manufacture wrapped carbon fiber tubes for use in spacecraft structures and subsystems, and will be contained within an Arkisys "Bosun's Locker".

Specification of Requirements

Starting with the executive summary, motivations, and definitions from the C3 Information Packet, a set of critical, important, and desirable system goals were created. This structure of tiered goals motivated a more formal definition of the system and subsystem requirements for the conceptual design. The goals are listed below in three sections: Critical, Important, and Desirable.

Critical

- The system must fit within Arkisys' Bosuns Locker payload containment unit, which has an available volume of 15.75" x 15.75" x 35.45" (5.09 ft^3), or 400.05 mm x 400.05 mm x 900.43 mm (0.14 m^3).
- The system must have a total system mass not exceeding the Bosuns Locker's payload mass capability of 400 kg.
  - Exceeding this mass may jeopardize launch safety or interfere with the Bosuns Locker's integration capabilities with the Port module.
- The system must operate below the Bosuns Locker's peak available power of 1000W and sustained available power of 300W
- The system must demonstrate 3 or more operations to demonstrate carbon fiber tube manufacturing capability.
  - An "operation" refers to an action or set of actions performed by a single device, such as extruding a polymer, moving a part, or cutting or bending a piece of material.
  - A "capability" refers to a chain of operations that performs a useful function, such as a 3D printing system extruding a polymer, moving the nozzle, and removing the finished part from the build plate.

- The system must operate within a “zero gravity” (0 g) or microgravity environment ($1x10^{-6}$ g) on board the Arkisys Port Module in low-Earth orbit, at an altitude of 2000 km or lower (COSMIC 2025).
- The system must cure carbon fiber tubes without utilizing heat, resulting in approximately 0 heat transfer into the system from its surroundings and not requiring extensive thermal management.
  - Epoxy resin cures via an exothermic reaction, so some thermal management will be required to account for the heat produced *by* the curing process. The system must withstand temperatures of up to 390°C or 663K from this exothermic process (Ran et al. 2020).
- The system must create a pressurized environment of 20 mbar for vacuum injection of epoxy resin (Brouwer et al. 2003).
  - This minimizes the risk of outgassing from the resin, reduces bubble formation within the resin, and increases the rate at which any bubbles that do form are dissolved (Brouwer et al. 2003).
- The system must withstand launch loads of up to 1 G of force in tension and 6 Gs in compression, based on data for the Space Exploration Technology Corps. (SpaceX) Falcon launch vehicle when carrying a light payload (SpaceX 2020).
  - A “light payload” is defined as any payload with a weight of under 4000 lb, or 1800 kg (SpaceX 2020).
  - The exact launch system that will be used to transport the Bosuns Locker to the Arkisys Port module has not been specified, so the SpaceX Falcon has been considered as an analogous launch system.

Important

- The system should operate semi-autonomously with limited remote commands, with no more than 3 manual inputs required.
  - “Limited remote commands” refer to simple interactions such as initiating a sequence, interrupting a process, confirming alignment of a part, or proceeding to a following step.
- The system should contain approximately 500 grams of biaxial carbon fiber sheet with ~0.35 mm thickness and 150 mm length
- The system should contain 500 grams of DCPD resin
- The system should inject approximately 1 kg of epoxy resin per 1 kg of carbon fiber, for an approximate 50:50 ratio of epoxy to carbon fiber.
- The system should produce carbon fiber tubes consisting of 12 layers of 0.35 mm thickness, for total tube wall thickness of 4.2 mm.
- The system should produce carbon fiber tubes with internal diameter of 25 mm.
  - These dimensions are loosely modeled after 45,631-UHM tubes produced by RockWest Composites Inc (Morton et al 2024).

- The system should produce carbon fiber tubes with the same length as the stored carbon fiber sheet width
    - As the primary focus of the system is to demonstrate the capability of carbon fiber tube manufacturing, the exact dimensions of the tubes produced are less significant than demonstrating the capability of manufacturing carbon fiber tubes in general.
- The system should produce carbon fiber tubes with the ability to support a 350 kN tensile load
- The system should use the long POT life of DCPD to reduce the chance of manufacturing defects by working slowly as needed

Desirable

- The system might produce carbon fiber with areas of delamination not exceeding 5% of tube length.
- The system might have a total production cost within $4000 USD.
- The system might perform operations for a mission duration of 3-12 months on-orbit attached to the Arkisys Port module.

Below, the full requirements built up from these system goals are listed with identifiers, requirement statements, and their rationale. The system design process was actualized through satisfaction of these requirements and further subsystem requirements.

Identifier	Title	Statement	Rationale
1	Volume Constraint	The assembly in its stowed configuration shall fit within a volume with dimensions of 15.75” x 15.75” x 35.45”.	The packing efficiency needs to be optimized for launch
2	Launch Mass Constraint	The total mass of the payload (excluding the locker) shall have a mass at or below 400 kg.	Allotted mass budget for launch.
3	Power Constraint	The total continuous power draw from the Arkysis station must be equal to or less than 300 W with a peak power draw no greater than 1000 W.	Exceeding the station’s power delivery could result in damage to the payload, the station, or both.
4	Thermal Constraint	The heat produced shall not exceed 300 W unless a custom heat rejection system is developed.	It is assumed that there is sufficient heat rejection for the approved sustained power draw.

5	Scalability	The payload shall be capable of producing four tubes internally.	Given the power, volume, and mass constraints it is not expected that the payload is capable of producing large quantities of tube. However, the payload must still demonstrate ISAM capabilities.
6	Orbital Debris	The payload shall retain the extruded carbon fiber tube in such a way that there is minimal risk of the creation of orbital debris.	The Inter-Agency Space Debris Coordination Committee (IDAC) has designated any orbital altitude below 2000km as the LEO protected region.
7	Autonomy	The payload shall be capable of production without the direct instructions from ground personnel.	The C3 competition requires the payload to "operate on its own with limited remote commands".
8	Communication	The payload shall be capable of both receiving and sending data using pre-defined communication protocols.	Uplink of instructions will allow for emergency stop edge-case scenarios which were not covered under autonomy. Downlink allows for data collection and monitoring.
9	Monitoring	The payload shall contain at least one engineering camera connected to the communication system.	Real-time video downlink allows for the determination if human intervention is required even if none of the onboard sensors determine the situation to require an emergency stop.

10	Emergency Stop	The manufacturing process shall include an emergency stop which can be triggered both automatically and manually through the use of the data uplink.	In the event an irrecoverable fault is detected the system needs to be capable of a complete shutdown in order to preserve the payload and the Arkisys station.
11	Internal Sensors	The payload shall contain sensors for internal monitoring. These include but are not limited to: positioning, thermal, and power.	Internal monitoring is required for safe operation of autonomous processes.
12	External Sensors	In addition to the internal sensors listed above, the payload shall have the ability to deploy external sensors to monitor heat rejection through the siding of the Bosuns locker.	The accurate measurement of heat dissipation is crucial for the continued operation of electrical systems in a vacuum in order to prevent overheating.
13	Jam Cleaning	The payload shall be capable of clearing the production system in the event an emergency stop is called.	In the event of production error, the ability to reset the system to a known state is instrumental in replicating the fault and troubleshooting solutions.

14	Carbon Fiber Tube Storage	The payload shall contain adequate volume to store six full-length carbon fiber tubes.	An extension of Req5, if the device is unable to demonstrate scalability through length it will need to be capable of producing multiple. Additionally, if it is deemed that the payload will operate as a fully self-contained unit with no passthrough capability Req. 14 will additionally solve Req. 5 The requirement of six tubes allows for at least two failed and cleared construction attempts for the target of four successful tubes.
15	Subsystem Mounting Profile	The payload shall have the capability to mount to the isogrid layout found on the interior of the Bosun's Locker.	The payload must be secured to the walls of the Bosuns Locker during launch, internal deployment of systems, and production.

Concept of Operations

Here, the system decomposition and concept of operations for the proposed system are detailed. The concept of operations, or ConOps, specifies the broad function of the system in its intended environment over a series of high-level mission phases. The system decomposition specifies the various subsystems and their subsequent components for the conceptual design.

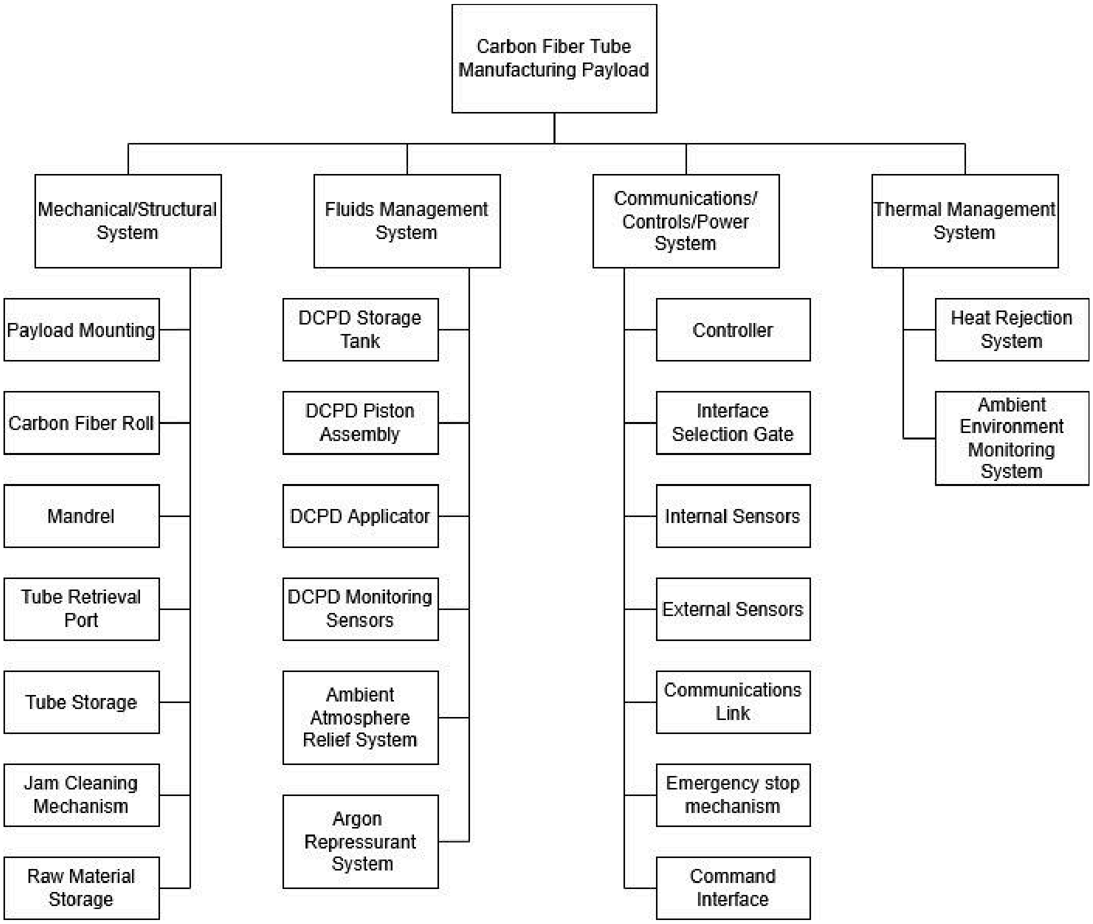


Figure 1: *Bosun's Locker System Decomposition*

Shown above in Figure 1 is a level 2 system decomposition of the carbon fiber manufacturing payload. This system is composed of four major subsystems: the mechanical and structural system, the fluids management system, the communications, controls, and power system, and the thermal management system. The mechanical and structural system is made up of the following major components: payload frame, the carbon fiber loom, the mandrel, the tube storage, the tube retrieval port, the jam cleaning mechanism, and the raw material storage. The fluids management system is composed of the following: the DCPD storage tank, the DCPD piston assembly, the DCPD applicator, the DCPD monitoring sensors, the ambient atmosphere relief system, and the argon repressurant system. The communications, controls, and power system consists of the following components: the controller, the interface selection gate, the internal sensors, the external sensors, the communications link, the emergency stop mechanism, and the command interface. The thermal system is composed of the following: the heat rejection system and the ambient monitoring system. Below, the individual steps of the ConOps are listed in detail.

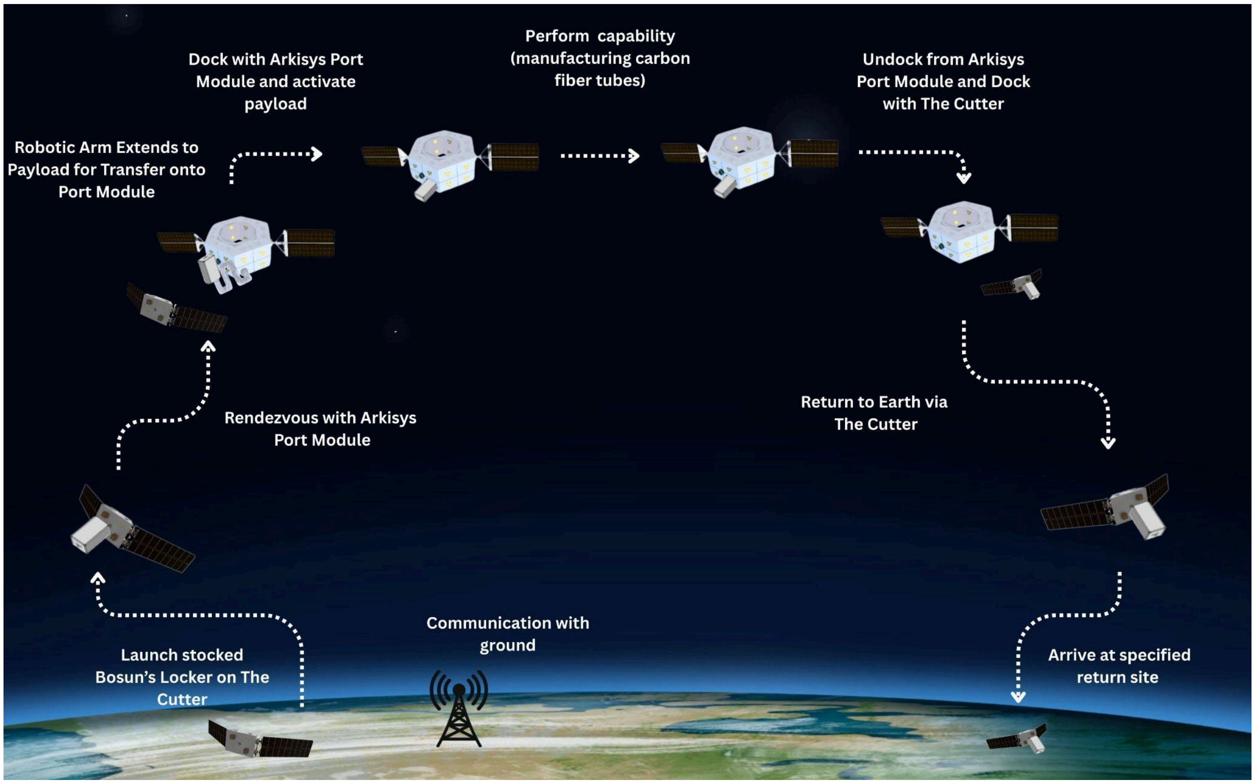


Figure 2: *Concept of Operations for Bosun's Locker*

1. Launch from Earth and Rendezvous with Arkisys Port Module

Prior to Launch, the Bosun's locker will be stocked with raw materials used to manufacture carbon fiber tubes in orbit. The payload will be transported into orbit by a rideshare launch vehicle, also known as The Port Cutter, into Low Earth Orbit (LEO), and then transported by an Orbital Transfer Vehicle (OTV) to the Arkisys Port Module (also referred to as "The Port").

2. Docking and Integration with Arkisys Port Module

When the payload has made a successful rendezvous with The Port, it will connect to a Port Module using the two payload interfaces that are in use, depending on the payload requirements: (1) Through the Universal Device Adapter (UDA) or (2) through the Intelligent Space Systems Interface (iSSI). Each Port Module is equipped with a mechanical lock as well as a robotic arm to move payloads around as necessary.

3. Payload Activation

Upon docking the Port Module the payload's interface ensures that the payload is securely attached to the Port Module. Given that the payload is secure, power generated from the Port Module will power the payload. System checks will be performed on the payload to ensure all components are functioning properly before operation can begin.

4. Payload Operation

During operation, the payload will remain attached to the Port Module. The payload will then begin its capabilities, namely manufacturing carbon fiber tubes out of raw materials sent up with the locker from Earth.

5. Sustainment and Duration

This system is designed to remain attached to the Port Module and in operation for approximately 6 months. Regular maintenance checks are performed to ensure that the locker is still functional.

6. Payload Deactivation and Return to Earth

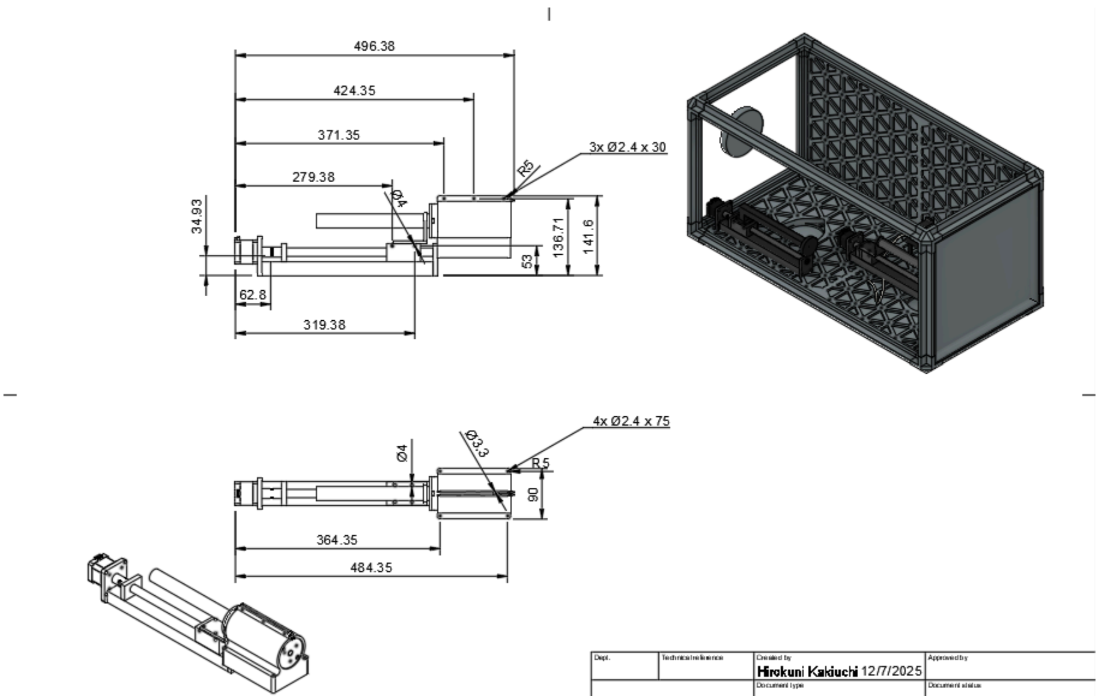
After the payload has performed its capability, power will gradually be reduced and data collected during its lifespan will be collected and stored. The payload will be assisted by the robotic arm and moved onto the Port Cutter. The Port Cutter will descend back down to Earth in a controlled manner in order to ensure that the payload makes it back safely. The Port Cutter will land at a predetermined landing site and the payload may be retrieved for further analysis. The carbon fiber tubes may then be extracted from the locker for further analysis.

System Design

Mechanical and Structural System Design

The mechanical and structural subsystem enables the handling, forming, curing, removal, and storage of carbon fiber tubes inside the Arkisys Bosuns Locker. Initially, its purpose is to physically support subsystem hardware during launch while remaining within the limited volume envelope provided by the locker. Once in orbit, this hardware must allow composite layup, Frontal Polymerization (FP) curing, and transfer of completed tubes without gravity. The mechanical subsystem therefore serves three main functions: load-bearing support during launch, geometric control during manufacturing, and controlled transfer and storage of finished products.

In order to satisfy the locker's space constraints, the entire subsystem integrates into a rectangular structural frame occupying 400 mm × 400 mm × 900 mm. The frame interfaces directly with the locker's internal mounting surfaces using rigid bolted connections rather than suspending hardware from secondary brackets. This prevents unwanted shock or micro-shift of components during ascent, particularly for rotating assemblies such as the mandrel and spool. The frame is organized around a single structural axis, along which raw material payout, mandrel rotation, resin deposition, curing, and tube removal occur. Using one central axis reduces tolerance stacking between subsystems, minimizes tooling, and ensures alignment remains consistent after launch vibrations.



Communications/Control System Design

The Communications/Control subsystem encompasses all electronic components and processes required to carry out the operation of other subsystems. The two sections of this subsystem each handle a core aspect of the subsystem. Communication involves the transfer of data, logging, and commands to and from the system and a ground control station. Control involves the monitoring, management, and commanding of the different sensors and actuators in the system. In fulfilling each of these functions, the subsystem makes use of various electronic components and protocols. Thus, the system design for this subsystem is composed primarily of the trade selection of these components and protocols.

Due to the relative abundance of electronic components and the relative difficulty of designing dedicated electronic systems, it was decided that any necessary components would be bought rather than made. The trades for each necessary component are thus performed based on a metric of various different quantities: performance, power draw, operating temperature range, and sensor resolution are a few of the most important specifications analyzed.

Thermal Management

Small spacecraft face several challenges in regards to thermal control while in orbit. The limited volume and power availability create difficulties in isolating thermal zones, powering electronics for the purpose of thermal management, and implementing hardware in the available space. However, maintaining a stable thermal environment remains essential to the performance, safety, and longevity of small spacecraft systems. In LEO, the spacecraft experiences a wide range of temperatures as it transitions in and out of the path of the Sun’s rays, with temperatures being high while facing the Sun, and very low while in shadow. This extreme temperature variation places stress on mechanical structures, can lead to failure of electronic components, and in the case of the carbon fiber tube manufacturing application, can compromise the performance of the tubes produced by the system. In the worst case scenario, thermal runaway caused by the exothermic DCPD curing process could even cause damage to structures beyond the Bosuns Locker, such as the Arkisys Port Module itself. A method to provide effective thermal control for the Bosuns Locker is therefore necessary to prevent unnecessary damages that could disrupt or jeopardize not just the carbon fiber tube production system, but neighboring Lockers' systems or the host Port Module as well.

According to a NASA report on state-of-the-art small spacecraft technology, the majority of thermal design for small spacecraft is therefore dominated by passive techniques, which are lower in volume than their active counterparts and do not require any powered equipment to function (2024). On account of the Bosuns Locker's limited sustained power supply of 300W, passive methods were the first technologies considered for the purpose of thermal management to counter the heat produced by the exothermic curing process of DCPD.

Fluid Management

The goal of the Fluids Management subsystem is to contain, transport, and apply DCPD as well as provide pressurization to the locker. A majority of the systems can be bought as commercial-off-the-shelf parts or synthesized from multiple (such as the repressurant system). The main focus of this subsystem is on accurate physical manipulation of DCPD with pressurization as a means to an end of preventing the resin from boiling.

Pressurization

The first main hurdle was calculating what pressure would be safe to be contained in the locker, a rectangular pressure vessel. The initial hand calculations were done by treating the flat plate walls as a 2-D being beam problem. The locker was approximated as the minimum thickness value with no internal support webbing, this was done to ensure a highly conservative estimate on the strength. At 20mbar the maximum stress using this method was found to be on the order of 200 kPa. Using Ansys' finite element analysis it was found to be closer to 180 kPa.

Repressurization

The parts selection for maintaining atmosphere inside the locker was largely driven simply by part compatibility with the unique environment present with cost being a secondary factor. The repressurization system onboard will be a one liter tank of argon gas pressurized to 1 atm and a pressure regulator. This system must maintain the output pressure within 10% of the expected value, operate even with no power present, and have the ability to repressurize the entire locker to 20 mbar at minimum 25 times. The exact tank is a lower priority and will be selected later on in development (1 liter at 1 atm is capable of refilling the tank around 50 times).

Relief Valve

In addition to the repressurization system a relief valve must also be chosen to equalize pressure as the payload ascends on a rocket. The payload locker will be loaded and sealed with 1 atm of argon and then bleed off argon until the internal pressure is at the desired 20 mbar. This relief valve must maintain pressure at no lower than 20 mbar and no higher than 40 mbar. The strict lower cutoff is required to reduce the risk of DCPD boiling due to the ambient pressure dropping below its vapor pressure. Additionally the relief valve needs to operate in the same fashion regardless of the outside environment whether it is waiting on the launch pad, during ascent, or on orbit. Much like the pressure regulator the relief valve must also operate with a complete loss of power. A few candidates were chosen and are tabulated below. Extreme accuracy is required to maintain a pressure difference of only 20 mbar, resulting in the relief valve being our most expensive part.

Piston Drive System

Aside from just keeping the DCPD compound from boiling off, fluid management is also responsible for the overall control of how DCPD is used and stored. It was determined early on that conventional methods such as pump systems would not have the reliability we required.

DCPD Storage System

The DCPD storage tank will be preloaded at 20 mbar of internal pressure, requiring a design which is capable of handling just under 1 atm of inward pressure. Additionally the material it is constructed out of must be transparent to allow onboard engineering cameras to see inside for monitoring both piston depression and the integrity of the DCPD itself. A few materials were considered, a selection of which have been tabulated below (not the top three materials, just ones which show a wide spread of properties). Ansys FEA simulations were also performed with the lower mesh fidelity runs netting the most similar results to those found in hand calculations.

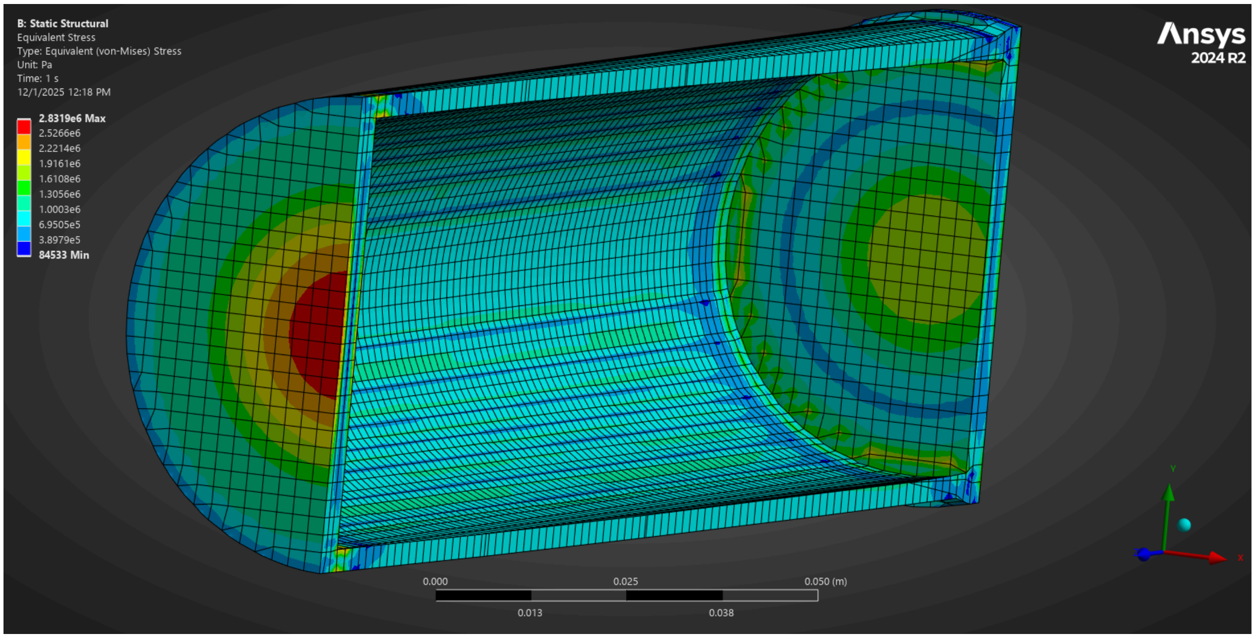
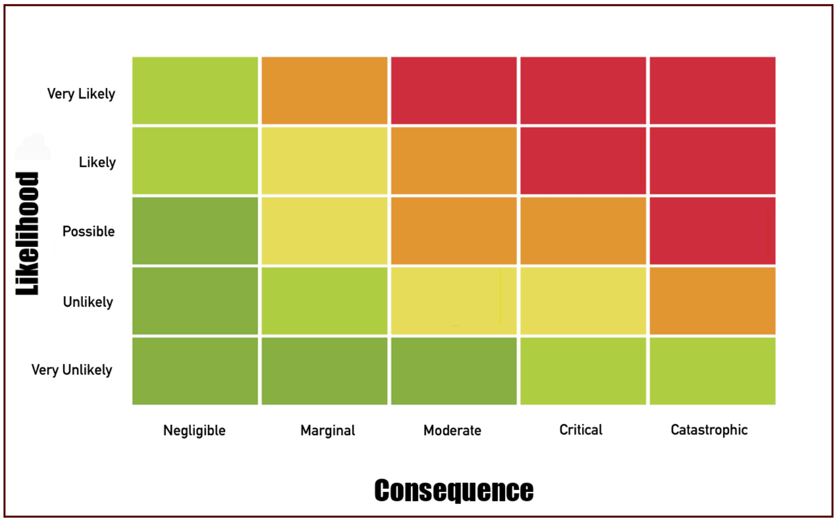


Figure 3: *FEA simulation results for the DPCD storage tank*

Risk Identification & Mitigation

There are inherent risks associated with the proving of novel concepts, and the development of this technology is not free from risks. To evaluate risk, the team employed a standard 5 by 5 Risk Matrix as seen below in Figure 4**.**



Likelihood	Negligible	Marginal	Moderate	Critical	Catastrophic
Very Likely	🟩	🟧	🟥	🟥	🟥
Likely	🟩	🟨	🟧	🟥	🟥
Possible	🟩	🟨	🟧	🟧	🟥
Unlikely	🟩	🟩	🟨	🟨	🟧
Very Unlikely	🟩	🟩	🟩	🟩	🟩

Consequence

Figure 4: *Risk Matrix*

Risks are individually evaluated on a scale of 1-5 for each of Likelihood and Consequence. Descriptions of the quantifications of each value are provided below, in Tables 1 and 2.

Table 1: *Description of Likelihood Quantifiers*

Likelihood		Description
5	Very Likely	All but certain.
4	Likely	Expected at least once during operation.
3	Possible	May occur during operation.
2	Unlikely	Improbable, but not impossible.
1	Very Unlikely	Near-impossible. Assumed not to occur.

Table 2: *Description of Consequence Quantifiers*

Consequence		Description
5	Catastrophic	Irreparable mission failure.
4	Critical	Fails to meet 1 or more **Critical** System goals. The nonoperational system requires immediate attention.
3	Moderate	Fails to meet 1 or more **Important** System goals, OR a recoverable major error occurs.
2	Marginal	Fails to meet 1 or more **Desired** System goals. Mission continues with reduced performance.
1	Negligible	Minor inconvenience, may require a system reset or a small loss of time.

The risk identification process focused on identifying failure modes that could threaten mission safety and Critical System Goals, in that order. Four significant technical system risks have been identified, and through the application of risk identification, quantification, and mitigation strategies, the residual risk profile for each risk has been reduced to acceptable levels.

The most prevalent mechanical risk was identified to be a Tube Ejection Jam, classified as a Likely (4) Critical (4) risk before mitigation. This failure mode involves one of the following: the carbon fiber tube adhering to the mandrel during the protrusion phase as the DCPD resin is applied; or the carbon fiber tube drifting off-axis as it is ejected from the mandrel into the storage roll. The primary driver for the first failure mode is the adhesive properties of the DCPD resin. If the resin were to seep through the carbon fiber roll and cure adhered to the mandrel, it would be very difficult to detach the two and the mission would be halted. To combat this, a Polytetrafluoroethylene (PTFE/Teflon) coating will be applied to the mandrel to minimize friction and prevent adhesion during the curing process. The second failure mode is driven by the microgravity environment and the needed precision to bring the tube to the storage roll. A high-precision linear actuator is used to ensure consistent, accurate force application during the dispensing process, lowering the risk. These strategies reduce the Tube Ejection Jam likelihood to 1: Very Unlikely, and consequence to 3: Critical. This residual risk is acceptable and correctable, and future mitigation strategies will be assessed to lower it further.

A second major risk is an Atmosphere Leak. The locker requires a stable 20-40 mbar atmosphere for operation, and a loss of this environment would prove disastrous. This was classified as a Possible (3) Catastrophic (5) risk due to the known challenge that is atmosphere management in the harsh environment of space. Arkisys claims that atmospheric containment will not be an issue; however, to further mitigate this known risk, absolute pressure sensors will identify pressure leaks, triggering a backup Argon tank to provide pressure top-offs. These mitigation strategies bring the residual risk to an Unlikely (2) Marginal (2) risk, which is acceptable.

The thermal issues present in this manufacturing process are considered in the Nozzle Cure Creep risk, a Possible (3) Critical (4) risk. The curing process of DCPD resin via FP is exothermic, creating a risk that the reaction could propagate upstream, resulting in cured epoxy in the dispensing nozzle. This would render the fluid management system inoperable. Controls for this risk include active thermal sensing with an IR thermal camera to monitor the thermal gradient near the nozzle to determine if production needs to be halted due to high temperatures; and a dedicated Jam Cleaning Mechanism which will be determined later to clear any loosely cured resin. These mitigation strategies lower the likelihood of the risk to Very Unlikely (1), but it is still Critical (4), and further strategies will be assessed to handle this risk.

Finally, a Winding Initiation Failure may occur during the carbon fiber transfer process from the supply spool to the mandrel. If there is a miscalibration between the spool and the mandrel, the fiber could be mis-seated in the mandrel, causing loose carbon fiber to spill into the payload volume, clogging the volume and hindering motors and sensors. Before mitigation, this was identified as a Possible (3) Critical (4) risk due to the precision needed to maintain calibration and the mission-halting characteristics it brings. To mitigate the risk, the mandrel design features a serrated jam cleat geometry designed to catch the fiber on the first rotation. There is also active tension monitoring to verify fiber anchoring before winding commences. These techniques lower the risk to a Very Unlikely (1) Critical (4) risk, which is acceptable.

All risks have been mitigated out of the “High Risk” sector of the Risk Matrix–denoted by the color red–into the “Low Risk” green areas. Further risk identification and mitigation strategies will be discussed to continue to lower the severity of these risks.

Lessons Learned

During the development of the conceptual design, the team ran into multiple innovations and challenges that motivated the design. Detailed below are our most innovative concepts, technology gaps that were identified, and the biggest challenges in the design process.

Many innovative concepts were explored in the design, but three were of particular note. The usage of a resin “brush” allowed for the application of resin to a carbon fiber sheet in a microgravity, near-zero pressure environment. Then, a motorized mandrel connected to the carbon fiber sheet enabled autonomous carbon fiber tube rolling and storage. Most importantly, the usage of DCPD resin and the frontal polymerization method allowed for a carbon fiber curing process without the need for thermal curing that would be infeasible in the space environment.

During the design process, multiple technological areas were considered that would make the design easier to implement. Further advances in the method of frontal polymerization would make the design more feasible and easy to accomplish. Additionally, advances in in-vacuo epoxy curing would aid in the analysis of the design. Finally, advances in the tensile strength of carbon fiber materials would allow for a cheaper process and less material requirements.

Noted here are the three biggest challenges encountered in the design process. It was assumed that any thermal load generated inside or outside the system can be adequately controlled by sufficient heat expulsion from the Bosun’s Locker. Another challenge not considered was the long term storage and handling of the polymer resin. Finally, a large challenge that contributed to the design considerations was the difficulties in manufacturing carbon fiber parts in a low pressure environment, where offgassing and other factors must be considered.

References

Arkisys Inc. (2025). *Bosuns Locker family: Interface control document (ICD)* (Version 2.4) (PORT-BLICD-2025-V2.4) Arkisys Inc. https://cosmicspace.org/wp-content/uploads/2025/07/Bosuns-Locker-Prelim-ICD-7.9.pdf

A. Sethi, V. Thakurta, N. Gajanur, B. S. Cheela, K. S. Sadasivan and R. Hosangadi, "Implementation of COTS components for CubeSat applications," *2017 IEEE Aerospace Conference*, Big Sky, MT, USA, 2017, pp. 1-11, doi: 10.1109/AERO.2017.7943808.

Brouwer, W. D., van Herpt, E. C. F. C., & Labordus, M. (2003). Vacuum injection moulding for large structural applications. *Composites Part A: Applied Science and Manufacturing*, *34*(6), 551–558. doi:10.1016/S1359-835X(03)00060-5

Consortium for Space Mobility and ISAM Capabilities (COSMIC). (2025, July). *2025–26 COSMIC Capstone Challenge: Information packet (Rev. A, Document No. COSMIC-E01-WD005-2025-A)*. https://cosmicspace.org/c3

Elweteedy, Ahmed & Elmaihy, Ali & Elhefnawy, Ahmed. (2021). Small Satellite Operational Phase Thermal Analysis and Design: A Comparative Study. INCAS BULLETIN. Volume 13. 59-74. 10.13111/2066-8201.2021.13.4.6.

How does a thermoelectric cooler (TEC) work? [Photograph of a thermoelectric cooler]. (n.d.). *Thermal Book*. https://thermalbook.wordpress.com/how-does-a-thermoelectric-cooler-tec-work/

Inter-Agency Space Debris Coordination Committee. (2025, January). *IADC space debris mitigation guidelines* (IADC-02-01, Rev. 4). www.iadc-home.org/documents_public

Morton J, Hodges G, Pankow M, Lamberson L. Hypervelocity impact investigations of composite truss tubes for in orbit assembly risk assessment. *Journal of Composite Materials*. 2024;59(3):331-342. doi:10.1177/00219983241292787

NASA Lyndon B. Johnson Space Center, Loads and Structural Dynamics Branch. (2024, March 20). *JSC-65829 Rev B: Loads and Structural Dynamics Requirements for Spaceflight Hardware*. NASA.

NASA & Northrop Grumman. (2008, December 11). *The James Webb Space Telescope sunshield outstretched* [Photograph]. European Space Agency. https://www.esa.int/Science_Exploration/Space_Science/Super-tough_sunshield_to_fly_on_James_Webb_Space_Telescope

Nader, Ronnie. (2011). SEAM/NEMEA A SPACE ENVIRONMENT ATTENUATION MANIFOLD MLI SHIELD.

National Aeronautics and Space Administration. (2024). Small spacecraft technology state of the art report: Thermal systems (Chapter 7). NASA. https://www.nasa.gov/smallsat-institute/sst-soa

Pojman, J. (2001). Frontal Ring-Opening Metathesis Polymerization of Dicyclopentadiene. Macromolecules. https://doi.org/10.1021/MA0106999

Ran, Z., Liu, X., Jiang, X., Wu, Y., & Liao, H. (2020). Study on curing kinetics of epoxy-amine to reduce temperature caused by the exothermic reaction. *Thermochimica Acta*, *692*, 178735. doi:10.1016/j.tca.2020.178735

Rottländer, H., Umrath, W., & Voss, G. (2016). Fundamentals of Leak Detection (Leybold GmbH, Ed.). https://www.leyboldproducts.com/media/pdf/90/c7/87/Fundamentals_of_Leak_Detection_EN.pdf

Sarkar, Sumon. (2025). Carbon fiber in space systems. 10.13140/RG.2.2.16286.86081. https://www.researchgate.net/publication/391497587_Carbon_fiber_in_space_systems

Space Exploration Technologies Corp. (SpaceX) (2020, April). *Falcon user's guide*. https://spacex.relayto.com/e/spacex-falcon-user-s-guide-oc92qkoxzo1jf

Weinberger, D. (2019, February 16). Choosing the right video bitrate for streaming HLS and DASH. *Bitmovin*. https://bitmovin.com/blog/video-bitrate-streaming-hls-dash/

Wilson, A. N., Gupta, K. A., Koduru, B. H., Kumar, A., Jha, A., & Cenkeramaddi, L. R. (2023). Recent Advances in Thermal Imaging and its Applications Using Machine Learning: A Review. IEEE Sensors Journal, 23(4), 3395–3407. doi:10.1109/JSEN.2023.3234335