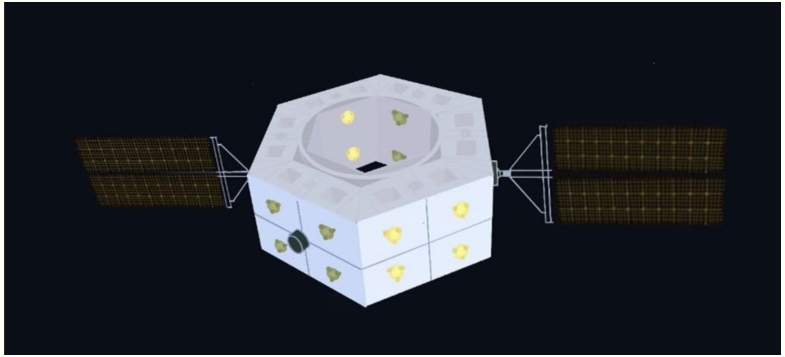
COSMIC Track 1: C3-Manufacturing

An In-Space Carbon Fiber Tube Manufacturing Payload



Rats in Space

James Glenn	Risk and Cost
Hirokuni Kakiuchi	Control/Comms/Power
Lily Mikulas	Needs to Requirements, System Concept Architecture
Oliver Roberg-Perez	Fluids Management
Aidan Timofte	Mechanical/Structural

Primary Advisor: **Dr. Majji**

https://www.halloweencostumes.com/gold-astronaut-costume-helmet.html
https://www.kindpng.com/imgv/hiTJibb_mouse-rat-png-rato-png-transparent-png/

Executive Summary

- Spacecraft component production on Earth is becoming inefficient for modern mission needs
- The idea of In-space Servicing, Assembly, and Manufacturing (ISAM) is becoming increasingly popular
- ISAM enables:
    - On-orbit construction and repair
    - Manufacturing parts in space
    - Consistent maintenance and upgrades
- Our mission focuses on manufacturing of carbon fiber tubes in space for eventual commercial use.

2.4 - Project Management Milestones

Selected program manager - 09/02/2025

Chose operations/capabilites - 10/03/2025

Defined system requirements - 10/03/2025

Completed trade studies - 10/03/2025

Finalized conceptual design - 10/28/2025

Developed a path to Preliminary Design Review - 10/28/2025

1.2 - Feasibility

- **High Feasibility:** Project designed for immediate implementation with many COTS parts

- **Cheap Space Rating:** In-house space rating replaces the need for expensive, individually rated components

- **Risk Mitigation:** Transition from piecewise rating to integrated system still satisfies NASA requirements, adding little additional mission risk.

1.4 - High Value Missions

- **Breaking Earth Constraints:** Current launch capabilities are limited in weight, placing a hard cap on the scale of space infrastructure.

- **Enabling Next-Gen Exploration:** Provides the foundation for constructing advanced systems that cannot be launched from Earth, such as:
  - Nuclear electric propulsion drive systems
  - Large structural trusses
  - Large-scale orbital habitats

3.3 - Data Handling and Comms

Operational Concept

- System operates semi-autonomously with limited ground intervention
- Ground operator required only for:
  - Start / stop commands
  - Emergency override
  - Health monitoring

Autonomy & Reliability

- Fully autonomous execution of manufacturing sequence
- Emergency stop triggered:
  - Automatically (sensor thresholds)
  - Manually (ground command within ~2 sec response)
- System continues operation during temporary comms loss

Downlink Requirements

- Continuous telemetry: ≥ 1 kbps
  - System health (temperature, pressure, power, actuator state)
- Burst data (video): ~3 Mbps (1080p @ 30 fps)
  - Used fo operation verification and anomaly detection
- Data logging onboard: ≥ 30 days storage

Uplink Requirements

- Low-rate command uplink (< 1 kbps)
- Commands:
  - Initiate manufacturing sequence
  - Pause / resume operations
  - Emergency stop

4.1 - Innovative Concepts

- **Frontal polymerization** of DCPD resin allows curing with lower thermal requirements, making it more feasible for in-space curing.
- **Microgravity resin application** needs special attention to avoid bubbles; the plunger design contributes to mitigating this.
- **Self-winding mandrel** jam cleat geometry contributes to low-waste, rapid winding of fiber that can be applied to general spooling processes.

4.2 - Technology Gaps

- **In vacuo epoxy curing** would remove the need for a pressurized environment.
- **High tensile strength carbon fiber 3D printing** would simplify the process of creating CF structures.
- **Further frontal polymerization development** would assist in understanding the processes and applications, along with risks and drawbacks.

4.3 - Biggest Challenges Encountered

- **Long term resin storage**
    - solved by using DCPD based resin

- **DCPD has a vapor pressure of ~2 mbar**
    - solved by slightly pressurizing the entire container

- **CF is usually cured using 2-part epoxy with a limited working time**
    - solved by using DCPD based resin for frontal polymerization

Design Process

Stakeholders
Identified Stakeholder Needs and Roles

Requirements Definition
Defined Requirements & Need Statements

Concept Generation
Generated & screened through multiple concepts

Solidified Concept
Chose to manufacture carbon fiber tubes in microgravity environment

System architecture development
With chosen concept (manufacturing carbon fiber tubes) built a high-level system architecture

Trade studies
Performed trade studies to determine which path would be the best to take

Detailed Design & Modeling
Designed payload & its components in CAD

Critical System Goals & Success Criteria

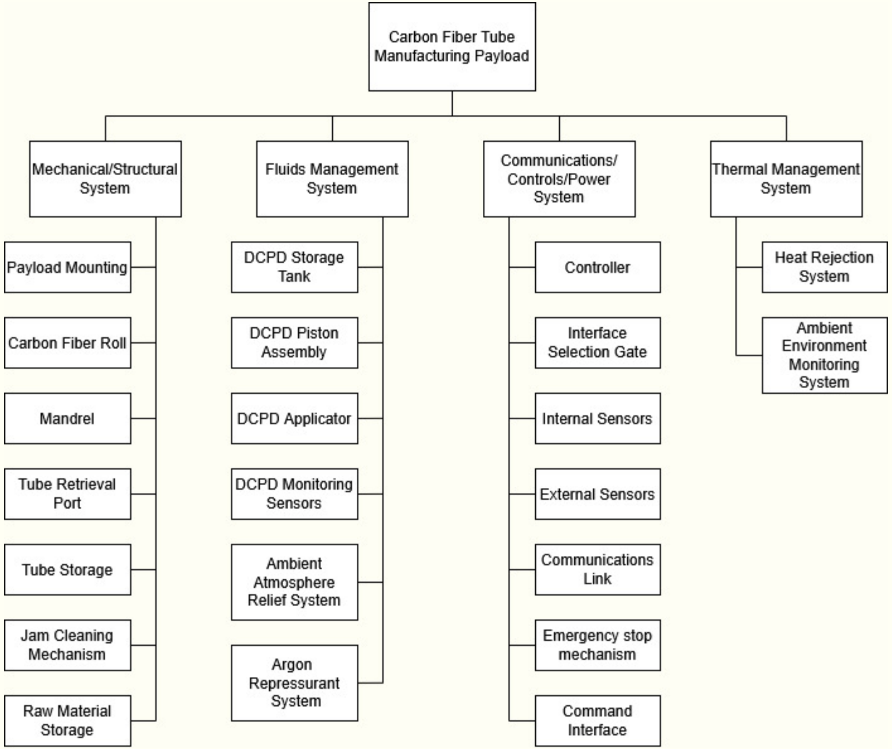
- Must fit within Arkisys’ Bosuns Locker payload volume (15.75” x 15.75” x 35.45”)
- Total system mass ≤ 400 kg
- Power constraints: ≤ 1000 W peak, ≤ 300 W sustained
- ≥ 3 operations to demonstrate carbon fiber tube manufacturing
- Must function within a microgravity environment aboard the Arkisys Port Module in LEO
- Must cure epoxy without utilizing heat for approximately zero heat transfer
    - Must withstand temperatures of ≤ 390°C from the exothermic curing process
- Must create pressurized environment of 20 mbar for vacuum injection of epoxy
- Must withstand launch loads of up to 1 G of force in tension and 6 Gs in compression

Important and Desirable Goals

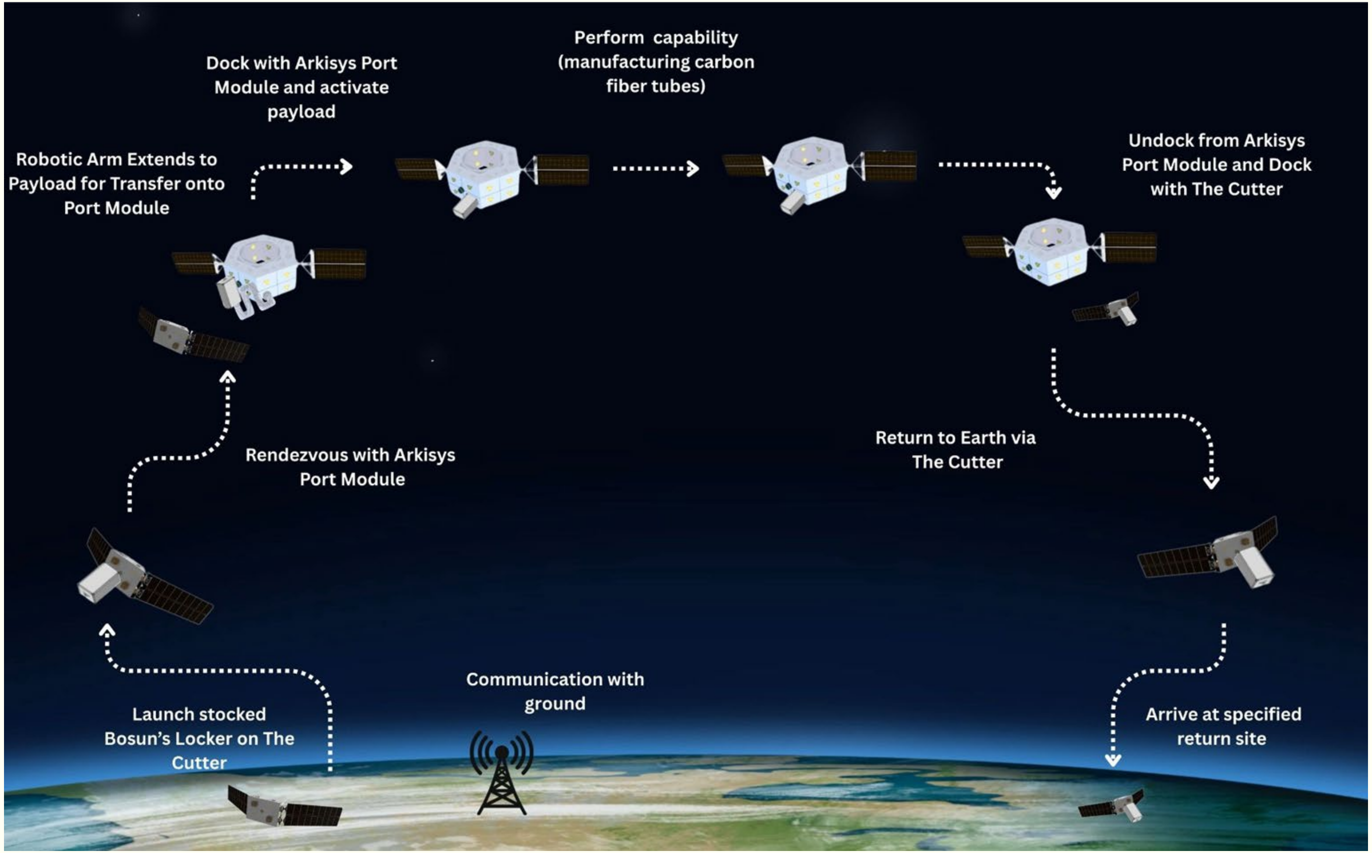
- Should have Semi-autonomous operation: ≤ 3 manual inputs
- Should be capable of producing four carbon fiber tubes
- Each tube should have the following characteristics
    - 150 mm in length
    - 25 mm internal diameter
    - Capable of supporting a 350 kN tensile load
- Might have a total production cost of $4000 USD

System Overview

- Mechanical/structural:
    - Provides support, machinery, and material handling.
- Fluids management:
    - Contains resin storage and resin delivery systems.
- Communications/controls/ power:
    - Manages sensors, power distribution, and commands.
- Thermal management:
    - Monitors and regulates heat during exothermic processes.



Concept of Operations



Launch stocked Bosun's Locker on The Cutter

Communication with ground

Rendezvous with Arkisys Port Module

Robotic Arm Extends to Payload for Transfer onto Port Module

Dock with Arkisys Port Module and activate payload

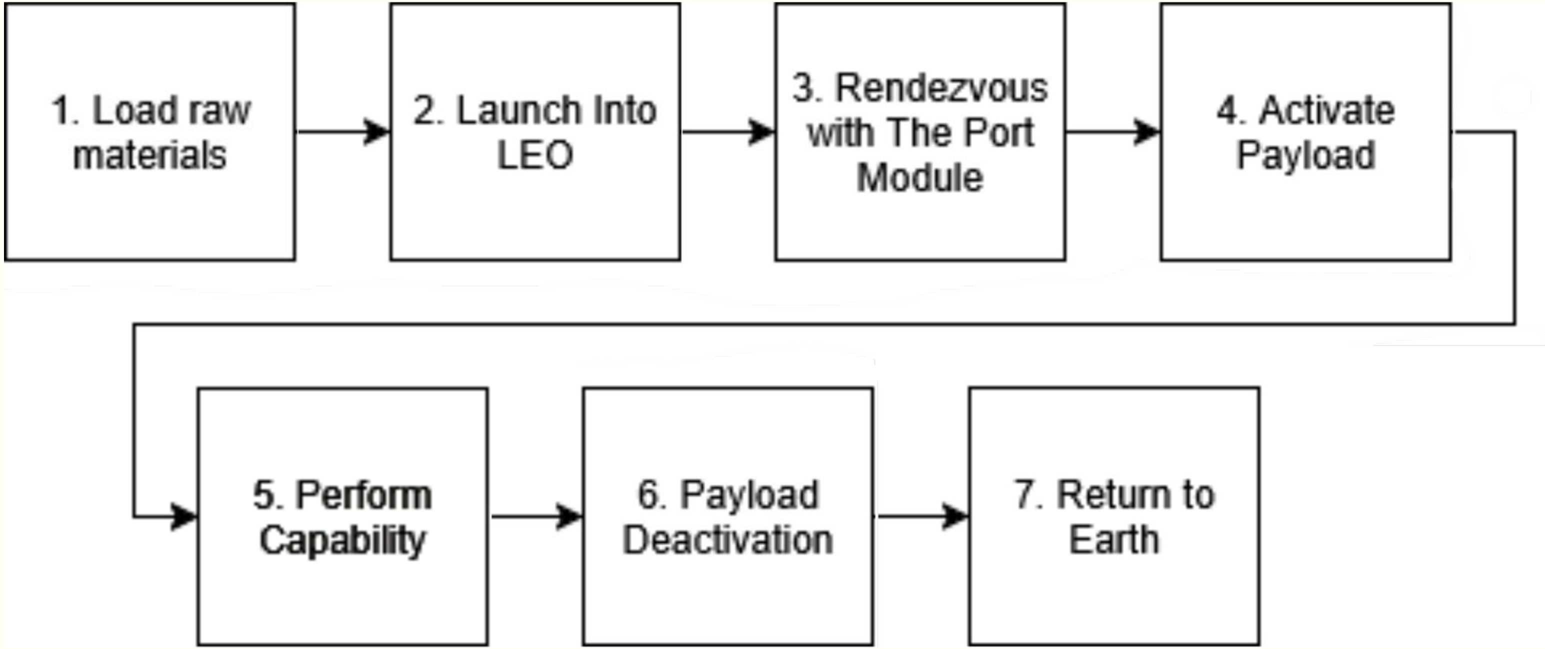
Perform capability (manufacturing carbon fiber tubes)

Undock from Arkisys Port Module and Dock with The Cutter

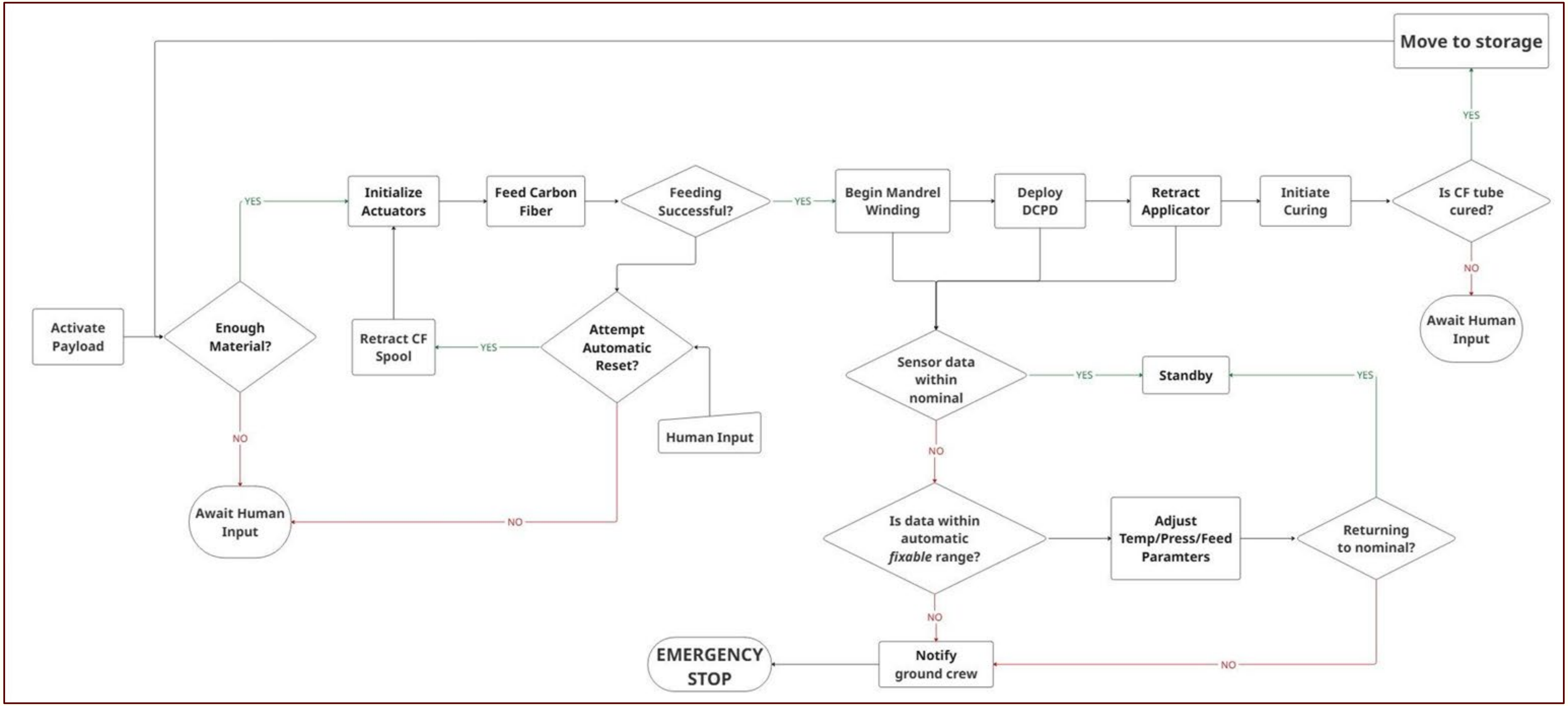
Return to Earth via The Cutter

Arrive at specified return site

Functional Flow Overview


1. Load raw materials
2. Launch Into LEO
3. Rendezvous with The Port Module
4. Activate Payload
5. Perform Capability
6. Payload Deactivation
7. Return to Earth

Functional Flow Block (Production)



Move to storage

YES

Initialize Actuators

Feed Carbon Fiber

Feeding Successful?

YES

Begin Mandrel Winding

Deploy DCPD

Retract Applicator

Initiate Curing

Is CF tube cured?

NO

Await Human Input

Activate Payload

Enough Material?

YES

Retract CF Spool

YES

Attempt Automatic Reset?

Human Input

Sensor data within nominal

YES

Standby

YES

NO

Await Human Input

NO

NO

Is data within automatic *fixable* range?

Adjust Temp/Press/Feed Paramters

Returning to nominal?

NO

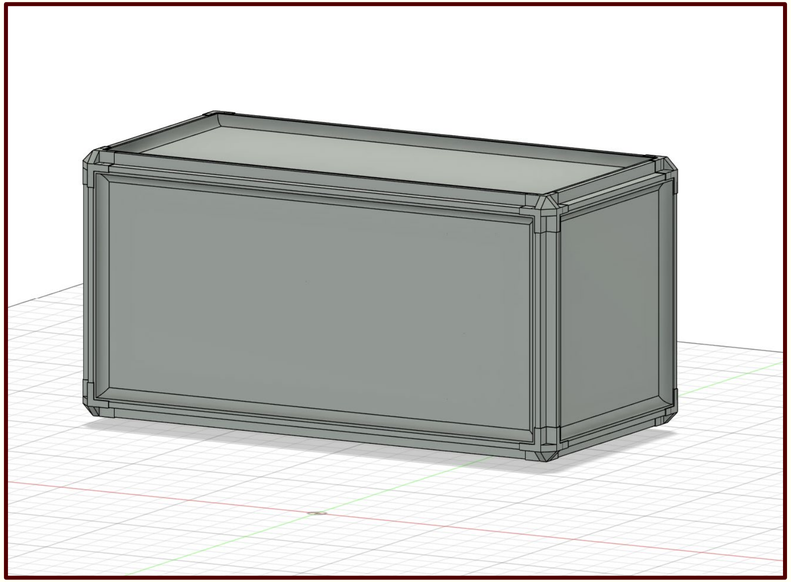
EMERGENCY STOP

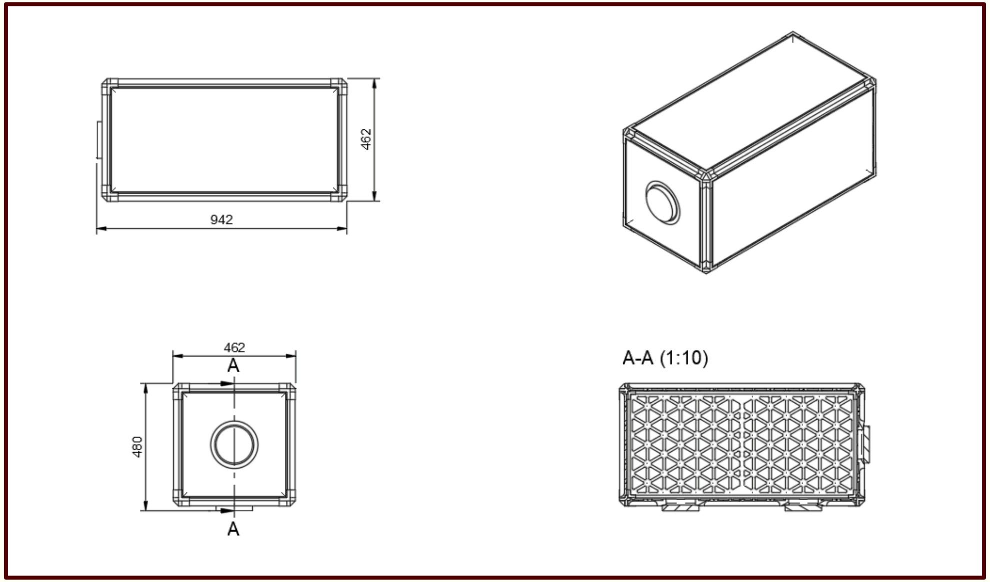
Notify ground crew

NO

System Design

- The Bosuns Locker and its CAD are provided by Arkisys

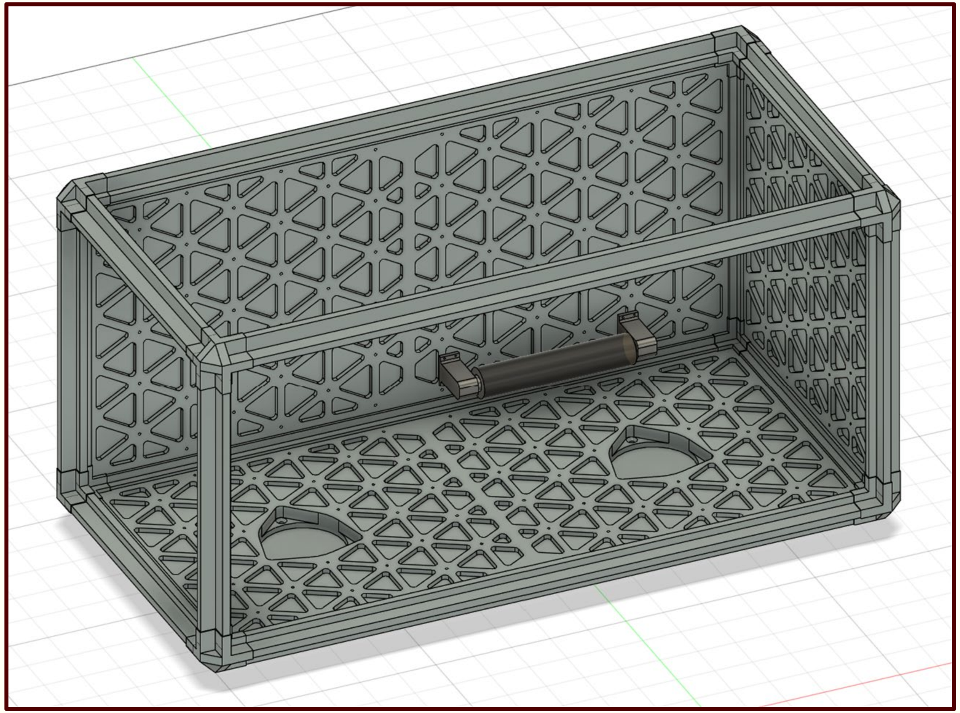




Drawings generated using Fusion360; units in mm

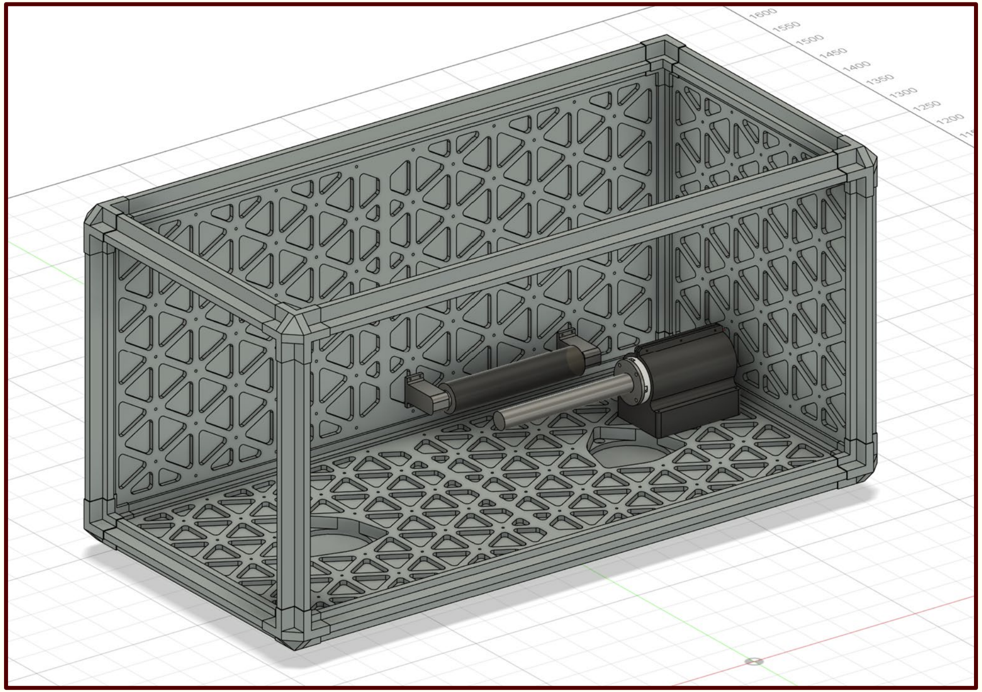
System Design

- Exterior panels have been hidden for visibility
- Initial carbon fiber spool payload is mounted to the wall of the locker
- Similar to paper towel holders – simple solution



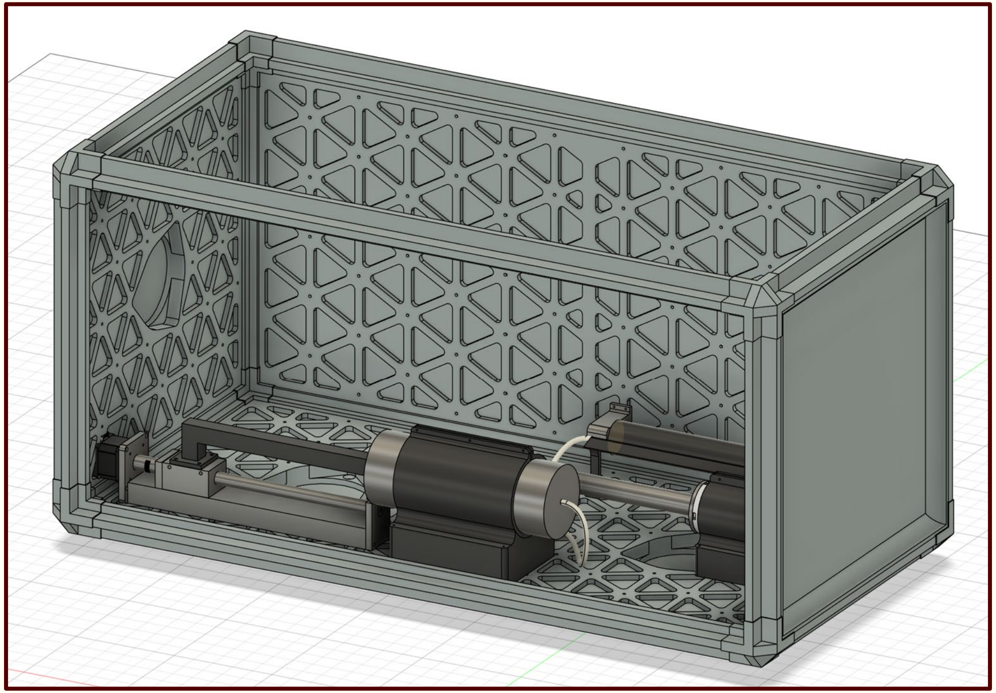
System Design

- Carbon fiber spool will be wound about a mandrel
- Mandrel is connected to a motor for rotation
    - Motor will likely be purchased COTS
- Motor is mounted to the floor of the locker with a custom bracket



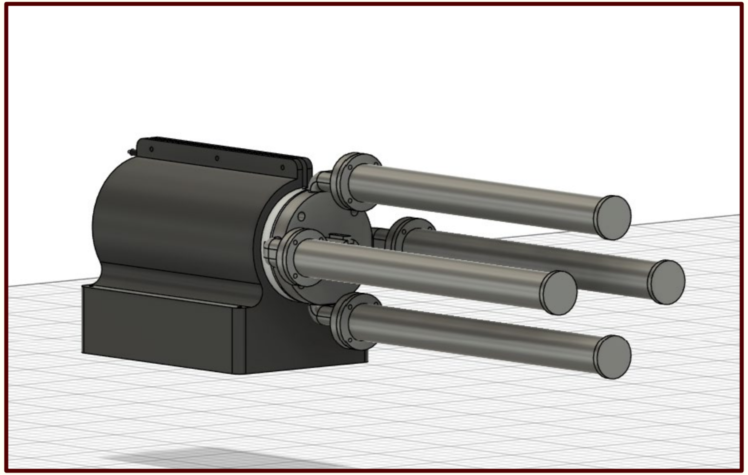
System Design

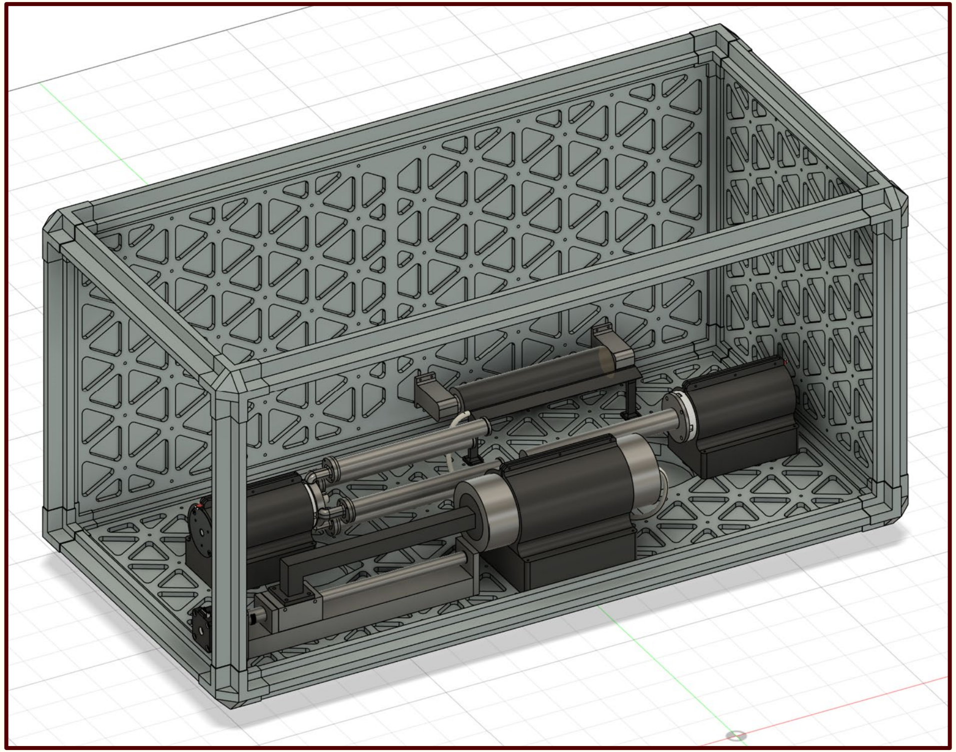
- Epoxy is stored in a polycarbonate tank
    - Polycarb is translucent in real life but the tank is represented as opaque here for visibility
- Linear actuator ejects epoxy from tank, similar to a syringe
- Epoxy is transported through a thin tube and deposited onto carbon fiber sheets



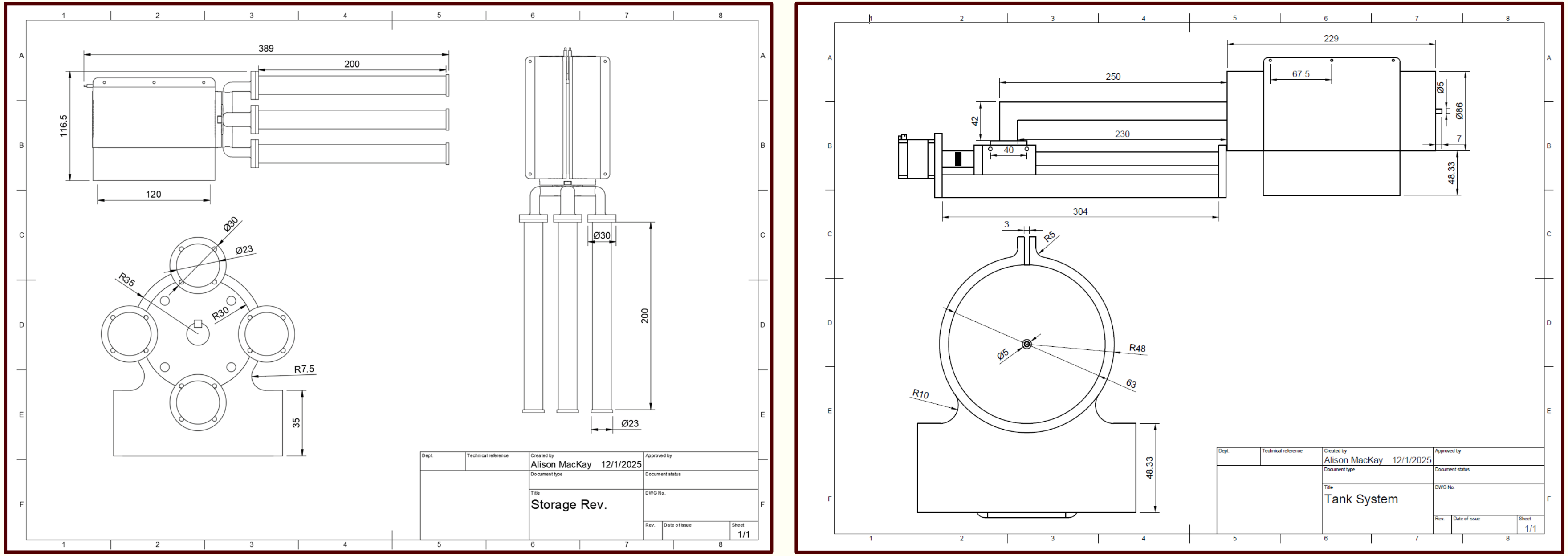
System Design

- Finished tubes are deposited onto a storage "carousel"
- Rotates to hold up to 4 tubes





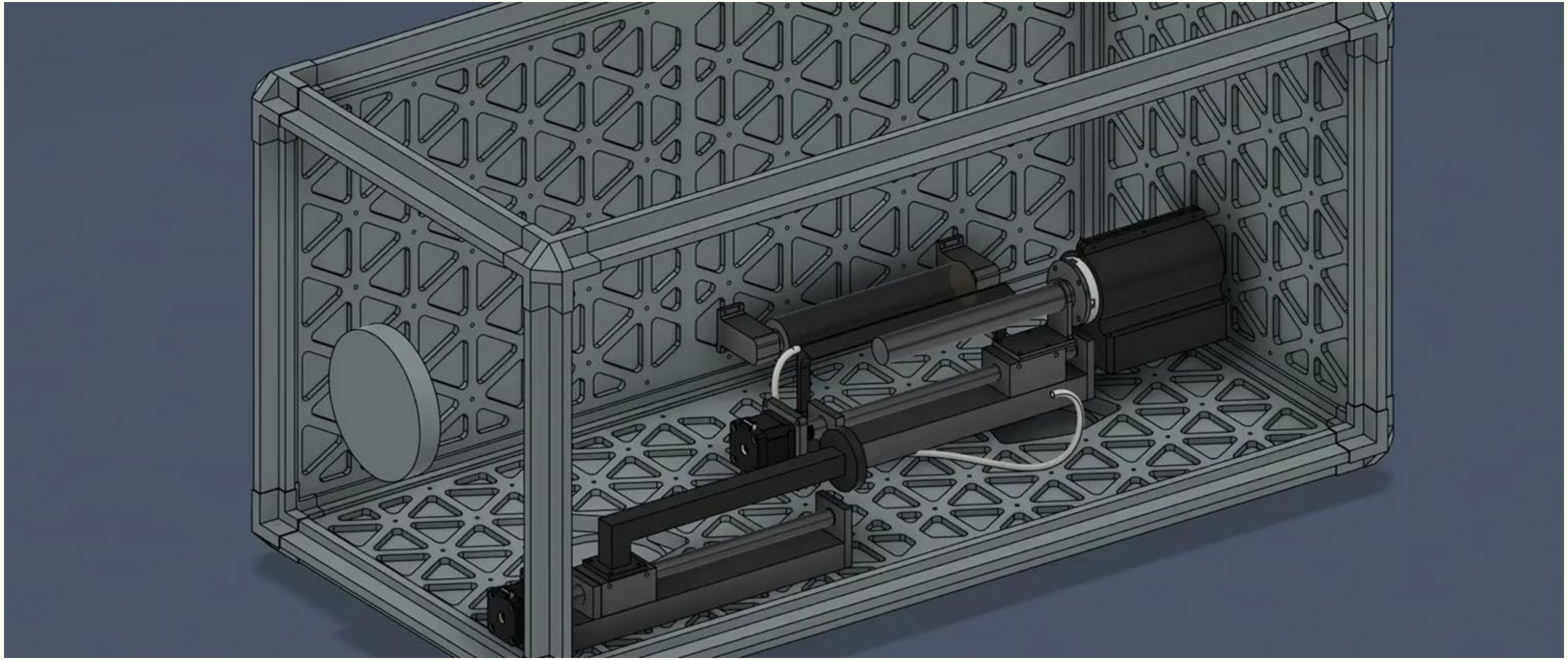
System Design



Tube storage carousel (L), epoxy storage tank (R), all dimensions in mm

System Design

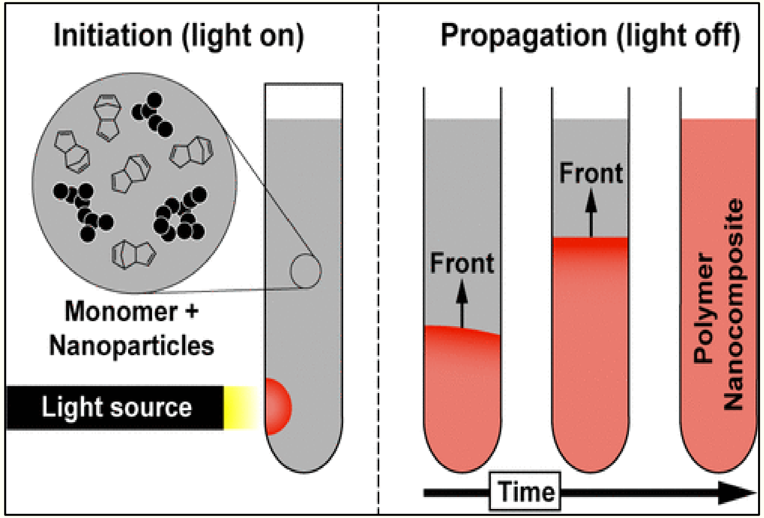
- CF Tube deposition system



Preliminary Sizing and Trade Studies

Mechanical/Structural: Curing Method

- Power requirements make typical autoclave cure methods impractical
  - Prepreg CF Sheets
  - Two-Part Epoxy Curing
- Instead, sizing focused on alternate polymerization methods
  - UV Radical Polymerization (UVRP)
  - Frontal Polymerization (FP)
- We chose **Frontal Polymerization**



Photoinitiation of Frontal Polymerization of DCPD resin.
Image Source: Dean et al., 2020.

Preliminary Sizing and Trade Studies

Thermal Management: Heat Rejection

- Passive technologies dominate small spacecraft thermal design
    - Coatings, sunshields, radiators, etc.
- Active control methods are more effective for high heat loads
    - Thermoelectric coolers (TECs), fluid loops, cryocoolers, etc.

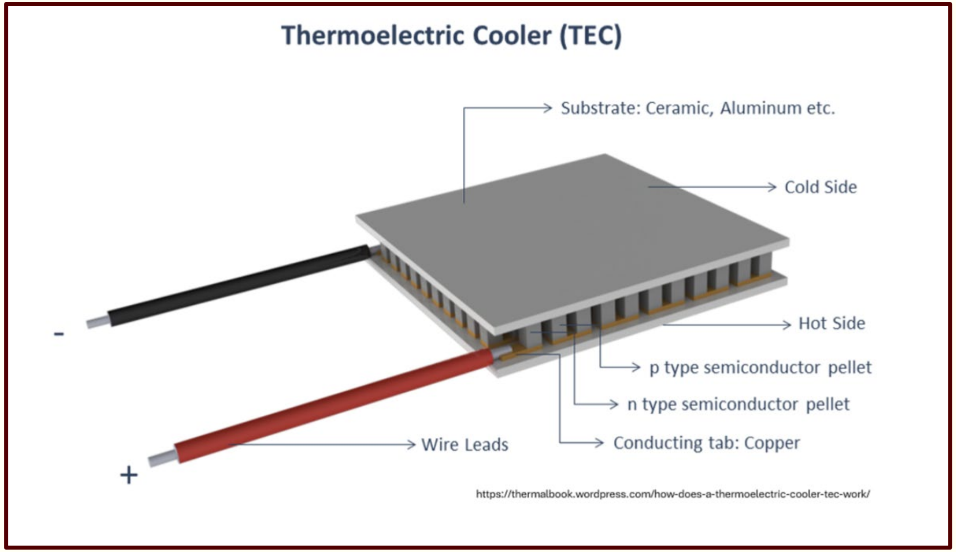
(NASA, 2024)

https://www.esa.int/Science_Exploration/Space_Science/Super-tough_sunshield_to_fly_on_James_Webb_Space_Telescope

Preliminary Sizing and Trade Studies

Thermal Management: Heat Rejection

- TECs provide cooling via electric current
- TECs are:
    - Simple, no moving parts
    - Reliable
    - Lightweight and compact



https://thermalbook.wordpress.com/how-does-a-thermoelectric-cooler-tec-work/

Preliminary Sizing and Trade Studies

Thermal Management: Monitoring

- 3 methods of heat transfer:
  - Conduction
  - Convection
  - Radiation
- Only radiation works in a vacuum (like outer space)

Preliminary Sizing and Trade Studies

Thermal Management: Monitoring

- Thermal imaging cameras detect infrared radiation
- Portable and low cost
- Standard accuracy of ±2°C (Wilson et al., 2023)

https://www.infratec-infrared.com/thermography/industries-applications/medicine/

Preliminary Sizing and Trade Studies

Fluids Management: Pressurization

- Internal Atmosphere Composition
    - Pressure - 20 mBar
    - Molecular makeup - Inert
- Individual Component Pressurization Requirements
    - Liquid subsystems
    - Curing subsystems
    - Leakage failsafe

Preliminary Sizing and Trade Studies

Pressure Vessel	**Cost**	**Locker Integrity**	**Mass**	**Max Safe Operating Pressure**
Airlock System	$1,000-3,000	Nominal under standard use	Up to 10 kg	Over 1 bar
Pressurize Entire Volume	Up to $200 depending on sealing method	Abnormal due to additional stress caused by pressure containment	1-2 kg max for sealing locker	Capable of 2000 Pa (20 mBar)

Pressurizing Gas	Cost ($/ft^3)*	Relative Reactivity
Nitrogen	18.64	Low
Argon	28.57	Lowest
Air	~Free	Highest

*at STP

Preliminary Sizing and Trade Studies

Fluids Management: Delivery

- Environment Compatibility
  - Microgravity
  - Rarefied atmosphere (20 mbar)
- Leakage Risk
  - Prioritize minimizing leak chance

Preliminary Sizing and Trade Studies

Fluid Feed Type	**Cost**	**Viability in 0g**	**Power Consumption**	**Driving System Leakage Risk**
Gas Pressurization	$10-100	NO	None	Highest
Gas Driven Piston	$700	Yes	None	High
Hydraulic Driven Piston	>$1000*	Yes, requires additional fluid conditioning	~	High
Electrically Driven Piston	$1000	Yes	<300 W	None

*includes pump and scrubbing system cost

Preliminary Sizing and Trade Studies

Fluids Management: Storage

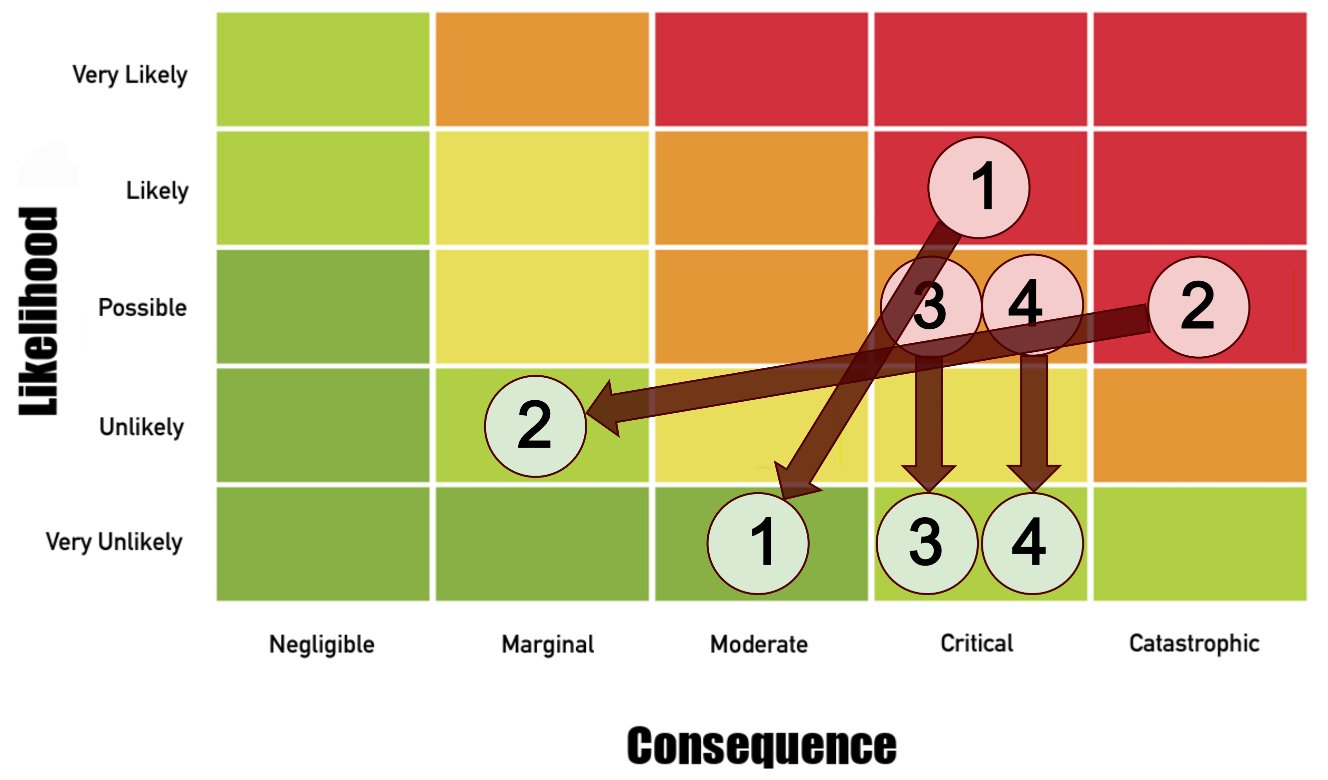
- Geometry
  - Piston compatible
  - Common sealing methods

- Cylindrical Storage Tank
  - O-rings and gaskets
  - Common in practical applications

Risk Assessment

Risk	Scenario	L/C	Mitigation	Residual L/C
1: Ejection Jam	The tube sticks to the mandrel or drifts off-axis during ejection.	Likely **(4)** Critical **(4)**	• Linear actuator for dispensing • Teflon coating	Very Unlikely **(1)** Moderate **(3)**
2: Atmosphere Leak	Locker seal failure causes pressure to drop below the requirement.	Possible **(3)** Catastrophic **(5)**	• Backup Argon • Pressure monitoring	Unlikely **(2)** Marginal **(2)**
3: Nozzle Cure Creep	Conductive heat travels up the feed tube, curing in-tube resin.	Possible **(3)** Critical **(4)**	• Onboard sensors • Jam clearing mechanism	Very Unlikely **(1)** Critical **(4)**
4: Winding Initiation Failure	Fiber fails to seat in the mandrel properly, causing the system to unspool loose fiber.	Possible **(3)** Critical **(4)**	• Jam cleat geometry • Active tension monitoring	Very Unlikely **(1)** Critical **(4)**

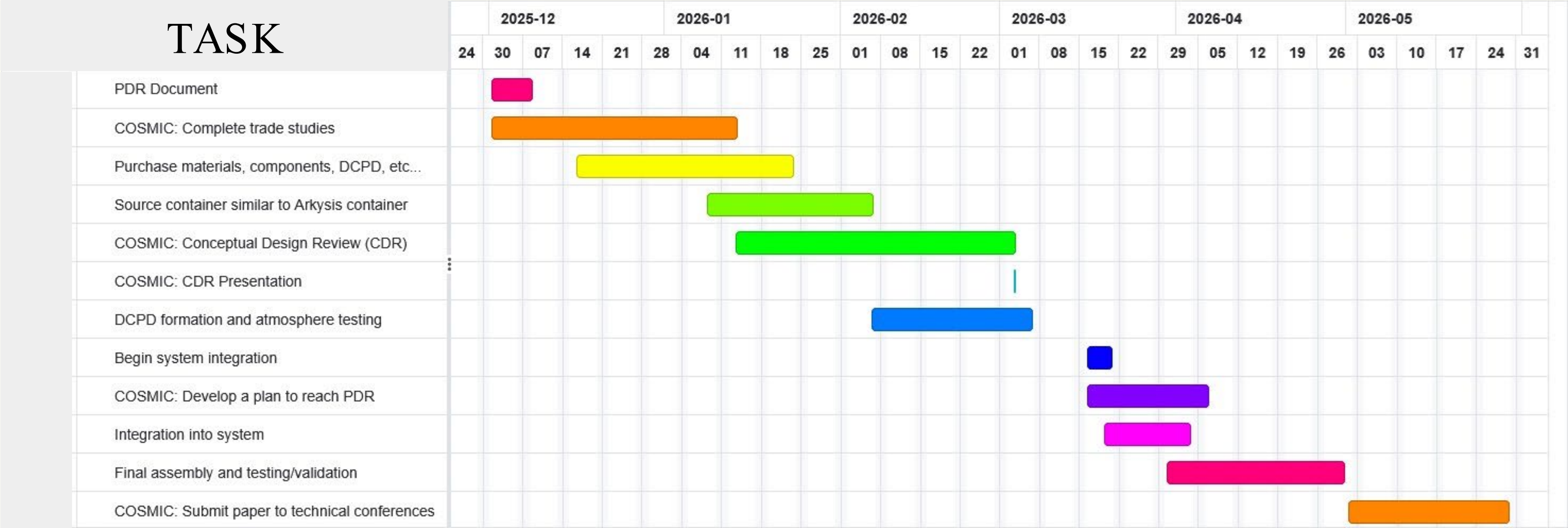
Risk Assessment



Risks

1. Ejection Jam
1. Atmosphere Leak
1. Nozzle Cure Creep
1. Winding Initiation Failure

Project Schedule



TASK

- PDR Document
- COSMIC: Complete trade studies
- Purchase materials, components, DCPD, etc...
- Source container similar to Arkysis container
- COSMIC: Conceptual Design Review (CDR)
- COSMIC: CDR Presentation
- DCPD formation and atmosphere testing
- Begin system integration
- COSMIC: Develop a plan to reach PDR
- Integration into system
- Final assembly and testing/validation
- COSMIC: Submit paper to technical conferences

Summary

- The project clearly demonstrates ISAM capabilities

- The project is well within feasibility
    - Constructed mostly from COTS parts
    - Protoype already designed

The full design process has been documented in a report following the C3 competition guidelines

Questions?

Backup Slides

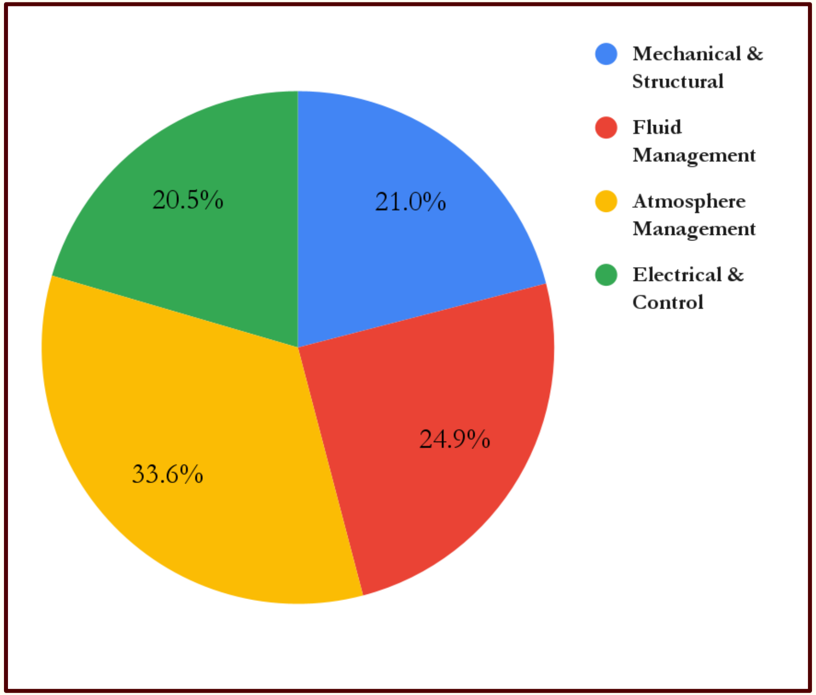
Cost Estimate Methodology & Scope

- Methodology: Bottom-Up Estimation
    - Cost derived from individual parts
    - Part costs based on vendor quotes and historic estimates

- Scope: Pre-Launch Costs
    - Launch and Operation costs are covered by Arkisys, so the cost estimate includes raw materials, COTS components, hardware, and custom machining

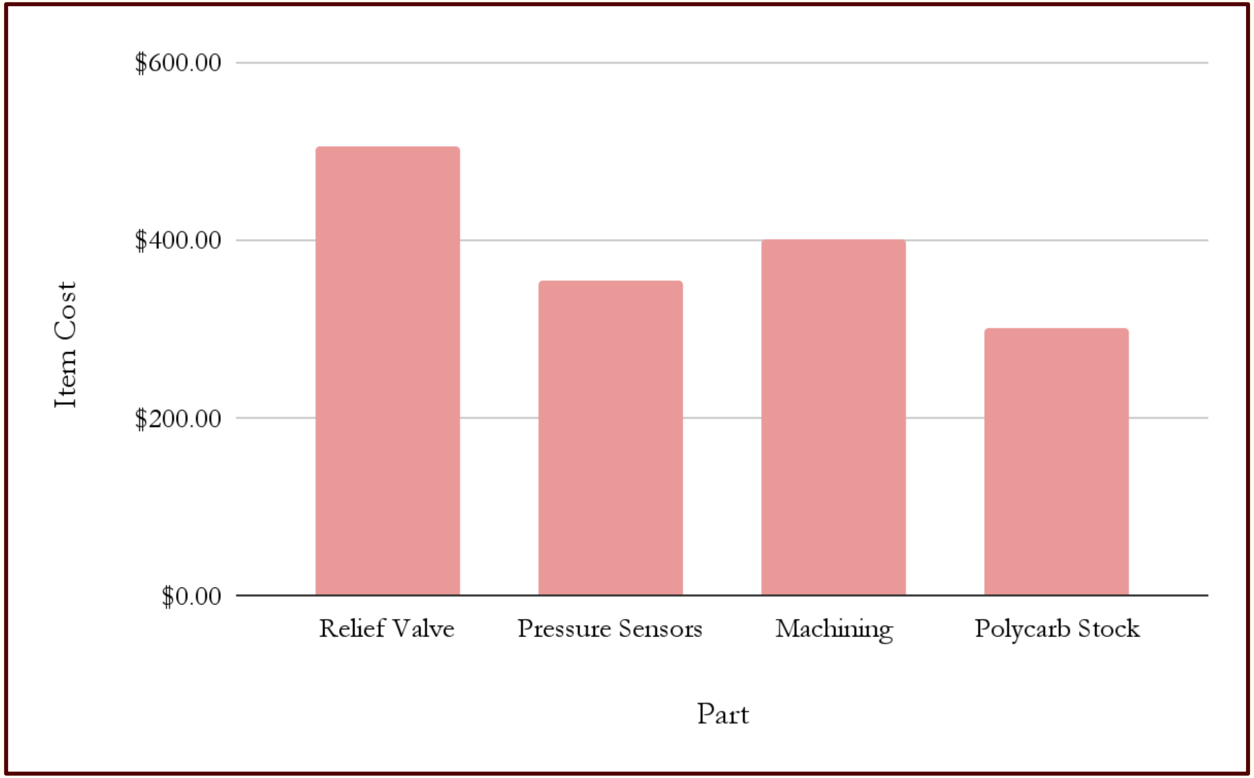
Cost Estimate

Subsystem	Estimated Cost
Mechanical & Structural	$550.00
Fluids Management	$653.36
Atmosphere Management	$881.27
Electrical & Control	$536.66
Hardware Subtotal	$2,621.29
30% Contingency	$786.39
TOTAL ESTIMATE	**$3,407.68**



Major Procurement & Cost Drivers

- 60% of total cost from 4 items
- These high-quality COTS parts mitigate risk through sensors and prevention



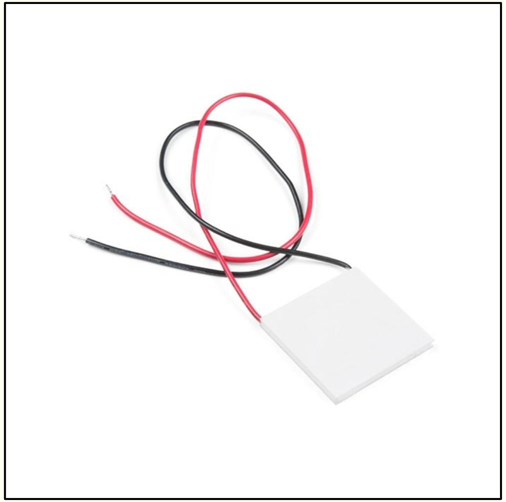
System Design: Thermal Management

- Thermal Management involves heat transfer and expulsion
- We chose to **Buy** components for this subsystem
- The Arkisys I/O port provides an output for heat expulsion
- Thermoelectric coolers (TECs) and heat piping will be used for heat transfer and expulsion
- These components will be bought based on power, heat transfer capacity, and cost

System Design: Thermal Management

Heat Expulsion & Transfer

- TECs provide heat transfer with no moving parts or fluids
- Less powerful than conventional heat pumps, but will satisfy thermal requirements
- The **TEC112707** provides a small, inexpensive option for solid-state heat transfer



System Design: Electrical & Control

- This subsystem handles power, control, and monitoring
- We chose to **Buy** components for this subsystem
- Commercial-Off-The-Shelf (COTS) electrical components can satisfy our requirements in LEO
- Components are selected based on power draw, processing power, memory, sensor resolution, and cost

System Design: Electrical & Control

Microcontroller Architecture

- Selected microcontroller must satisfy requirements:
  - Capable of running PX4 framework
  - I2C, UART, and CAN-Bus compatible
  - Capable of operating in -40 - 60 °C
- The **STM32 L-series** microcontroller satisfies these requirements at low power and cost

System Design: Electrical & Control

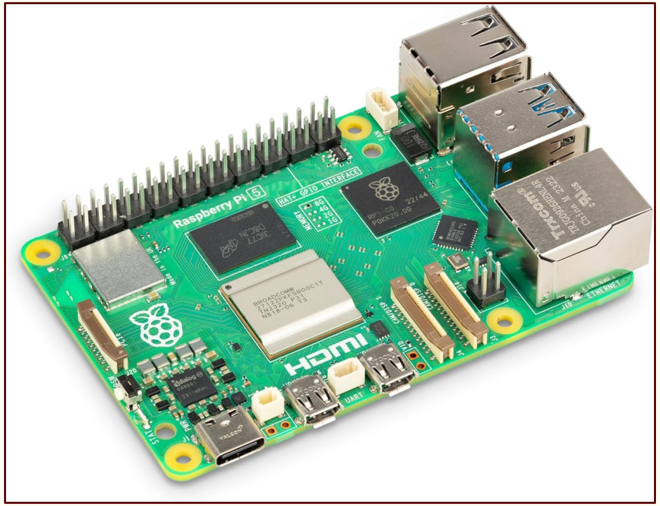
Microcontroller Architecture

Name	Operating Temp (°C)	Voltage Draw (V)	Clock Speed (MHz)	Flash Memory (KB)	Peripheral Connections	Dedicated PCB	Cost/Unit ($)
STM32-L5	-40 - 85	1.71 - 3.6	110	512	UART, I2C, CAN	No	7.52

System Design: Electrical & Control

Onboard Computer

- The Onboard Computer (OBC) will house the cFS mission planning framework
- Must be OS-capable with sufficient specs for mission scheduling & logging
- The **Raspberry Pi 5** is a staple COTS option for a Single-Board computer



System Design: Electrical & Control

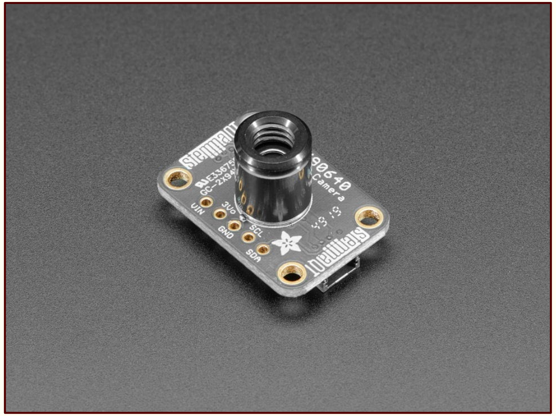
Onboard Computer

Name	Clock Speed (GHz)	Memory (GB)	Power Draw (W)	Inboard MCU	Cost/Unit ($)
Raspberry Pi 5	2.4	2	25	No	49.95
BeagleBone Black	1.0	4	10	Yes	69.95

System Design: Electrical & Control

Thermal Sensors

- Due to near-vacuum environment, atmosphere-based thermal sensors are ineffectual
- Thermal infrared cameras directly measure heat radiation in any environment
- We chose the **MLX90640 IR Thermal Camera**



System Design: Electrical & Control

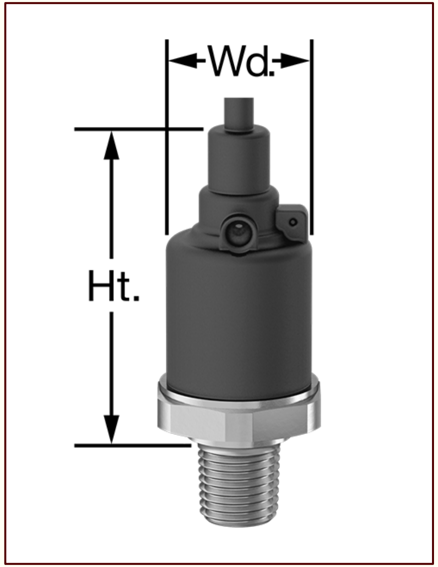
Thermal Sensors

Name	Measurement Type	Temperature Range (°C)	Resolution (px)	Cost/Unit ($)
AMG8833	FLIR	0 - 80	8x8	49.95
MLX90640	FLIR	-40 - 300	32x24	69.95
MCP9808	Conduction	-40 - 125	N/A	4.95

System Design: Electrical & Control

Pressure Sensors

- Once again, low pressure environment exceeds typical resolution of gauge pressure sensors
- Absolute pressure transducers, capable of measuring from a vacuum, are needed
- The **McMaster-Carr Absolute Pressure Transmitter** is capable of vacuum to ambient pressure measurement



System Design: Electrical & Control

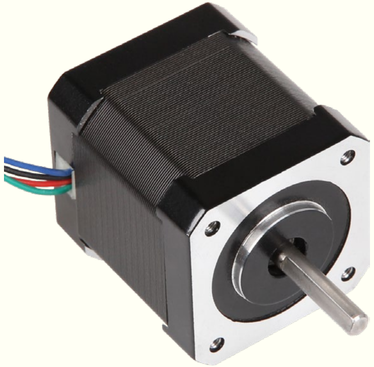
Pressure Sensors

Name	Pressure Range (bar)	Temperature Range (°C)	I2C Compatible	Cost/Unit ($)
McMaster-Carr 3861N11	0 - 1.034	-40 - 124	No	352.90
Adafruit LPS22	0.23 - 1.26	-40 - 120	Yes	6.95

System Design: Electrical & Control

Motor Drivers/Microcontrollers

- Currently system have two stepper motors (NEMA17) and 2 DC motors for the mandrel
- Stepper motors will be controlled through Arduino + Stepper Motor Drivers
- DC motors will be controlled by main computer (raspberry pi5) with DC motor driver



System Design: Electrical & Control

Stepper Motor Drivers/Microcontrollers

Name	Clock Speed (GHz)	Memory (KB)	Power Draw (W)	Inboard MCU	Cost/Unit ($)
Arduino Nano	0.016	32	0.095	No	6.34
Arduino Uno	0.016	32	0.25	ATmega328P	27.60

Name	Operating Temp (C)	Cost/Unit ($)
Leadshare motor driver	0 - 65	53.69
MybotOnline Motor driver	-10 - 65	22.50

System Design: Electrical & Control

DC Motor Drivers/Microcontrollers

Name	Clock Speed (GHz)	Memory (GB)	Power Draw (W)	Inboard MCU	Cost/Unit ($)
Raspberry Pi 5	2.4	2	25	No	49.95

Name	Inboard Driver	Supply Voltage	Mex Peak Current	Price ($)
BTS7960 43A High-Power H-Bridge Driver Module	BTS7960 dual H-bridge driver	6 V - 27V	43A	4.50
HiLetgo L298N DC Dual H-Bridge Motor Driver Module	L298N dual H-bridge driver	5 V - 35V	2A	6.99

System Design: Fluid Management

- This subsystem handles both DCPD and atmospheric functions
- We chose to **Buy** *most* components for this subsystem
- The parts which will be **Built** are the piston head and DCPD container
- The Non-COTS parts are subject will require machining/tooling of material
- Purchased parts were selected primarily on their compatibility with the locker environment

System Design: Fluid Management

DCPD Storage

- Withstand an *inward* pressure of 1 bar at launch
- Construction material must be non-reactive with DCPD
- Design must be transparent to onboard engineering cameras

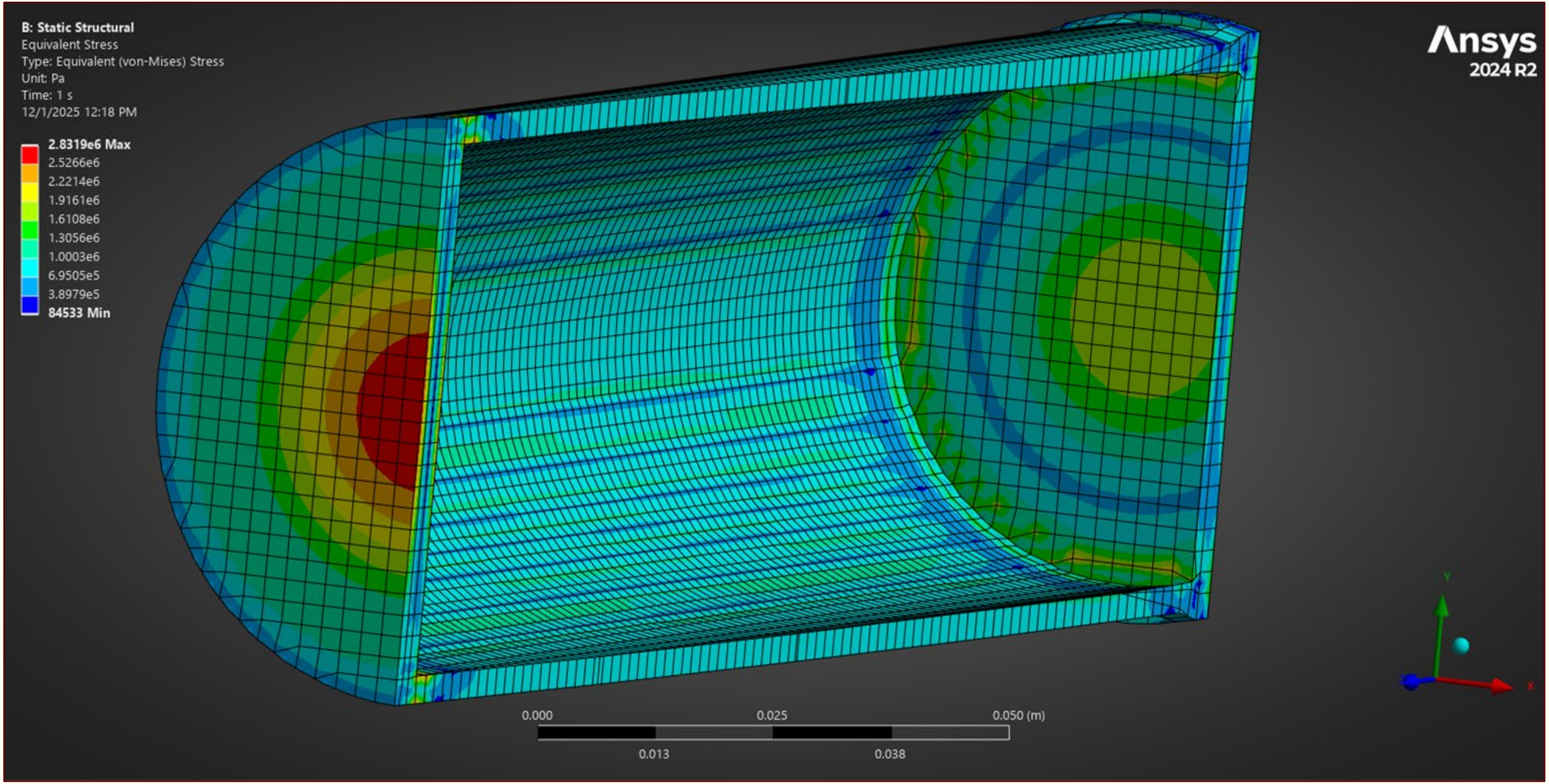
ID: 57 mm
IL: 200 mm
-From CF tube requirements

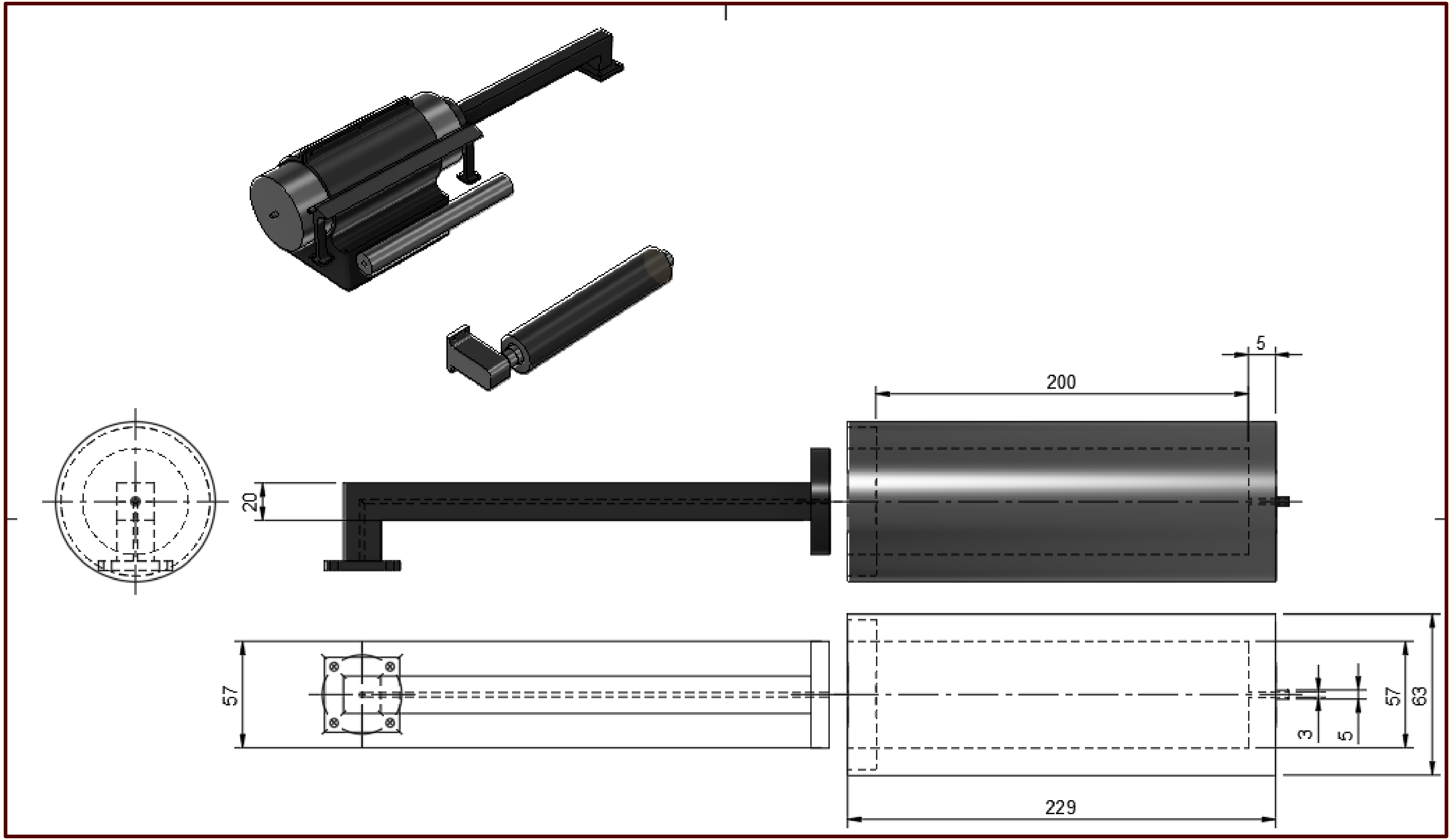
OD: 63 mm
OL: 210 mm
Wall Thickness: 3mm
-From material properties

System Design: Fluid Management

DCPD Storage

Material	Required Wall Thickness (mm)	DCPD Compatible	Transparent	Cost/kg ($)
Polycarbonate	3	Yes	Yes	2.50-3.50
Acrylic	2.5	No, reacts	Yes	1.50-2.00
Aluminum	<1	Yes	No	1.80-3.00

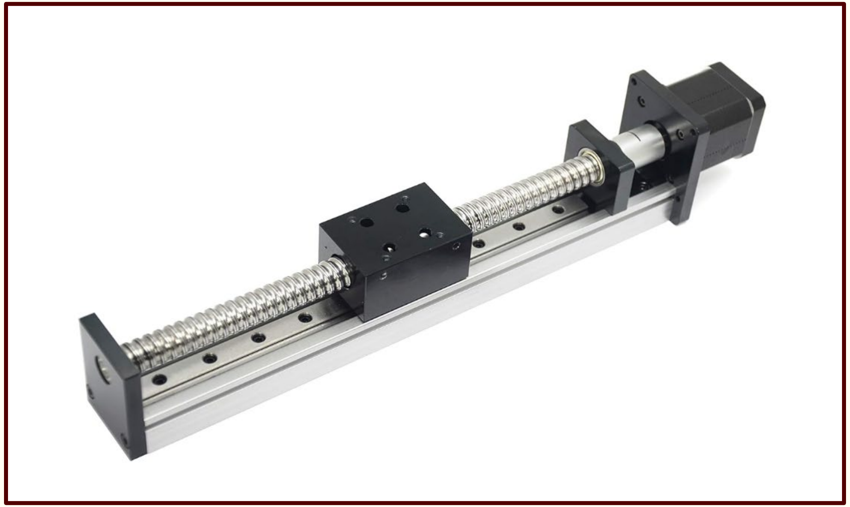

B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1 s
12/1/2025 12:18 PM
2.8319e6 Max
2.5266e6
2.2214e6
1.9161e6
1.6108e6
1.3056e6
1.0003e6
6.9505e5
3.8979e5
84533 Min
Ansys
2024 R2
0.000
0.025
0.050 (m)
0.013
0.038
Y
X


5
200
20
57
3
5
57
63
229

System Design: Fluid Management

Piston Assembly

- Driving Mechanism
  - Capable of 0.1 mm/s drive speed
- O-ring sealing
  - Δp of 1 bar is trivial for sealing
- Piston Head
  - Depth will be determined by O-ring selection



System Design: Fluid Management

Applicator

- Non-reactive with DCPD
- Operate in microgravity
- Allow for a flow rate of 0.1 cc/s

- Bristle Brush
  - Uses surface tension to spread DCPD evenly
- Silicone Squeegee
  - Force DCPD onto carbon fiber

System Design: Ambient Atmosphere Control

Repressurization System

- Survive in 20 mbar ambient atmosphere
- Maintain output pressure within 10% of expected value
- Failsafe operation
    - Still performs nominally with total loss of power
- Refill locker volume a minimum of 20 times

System Design: Ambient Atmosphere Control

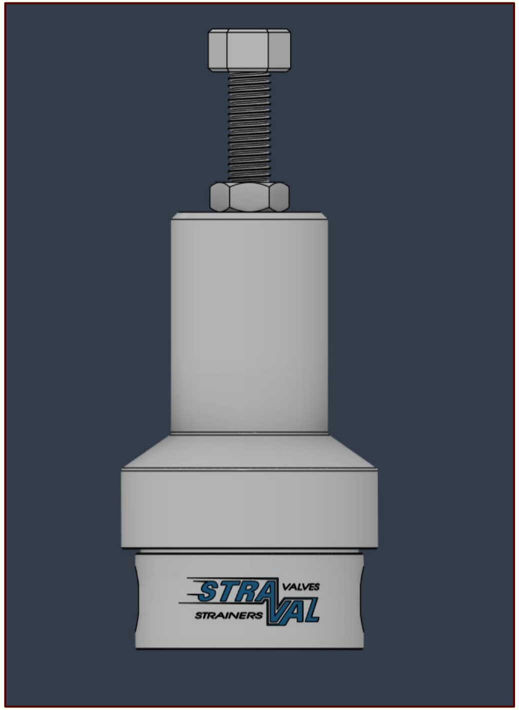
Repressurization System (Regulator)

Manufacturer	Output Pressure Range (mbar)	Accuracy	Cost (USD)	Mechanism
McMaster-Carr	0-140	±0.01%	185	Mechanical
Aircom	20-150	<5%	250	Mechanical
Equilibar QPV	0-70	±0.7 mbar	Quote Required	Electronic

System Design: Ambient Atmosphere Control

Relief Valve

- Accuracy
  - Maintain internal pressure at no lower than 20 mbar
  - And no greater than 40 mbar
- Operate regardless of outside environment
  - Operating mode should be the same whether payload is on the launch pad or on orbit
- Failsafe operation
  - Still performs nominally with total loss of power



System Design: Ambient Atmosphere Control

Relief Valve

Manufacturer	Target Pressure (mbar)	Cost (USD)	Material	STEP file?
Accu-Glass (PRV)	35-140	444.00	Al, SS, “Viton”	No
Stra-Val (RVi)	21-90	505.50	303-SS	Yes
Stra-Val (RVL)	21-90	518.00	303-SS	No

Stakeholders

- The stakeholders were identified by investigating:
  - What organizations will be directly involved with our mission?
    - Arkysis, NASA.
  - What Entities have authority over the certification, safety, and mitigation of our mission?
    - NASA, Composite Overwrapped Pressure Vessel (COPV) Manufacturers, Inter-Agency Space Debris Coordination Committee (IADC).
  - Customers that will benefit from our system's outputs.
    - These will benefit from the technology developed by proving that carbon fiber tubes can be successfully manufactured in space.
    - Orbital tug companies, deep space missions, orbital resupply companies.

Lily Mikulas

Stakeholders

Stakeholder	Role	Needs
Arkysis	Provides transportation to and from the host Port Module.	System follows volume/mass/power requirements & does not interfere with adjacent payloads.
Inter-Agency Space Debris Coordination Committee (IADC)	Issues debris mitigation guidelines for LEO/	Compliance with the IADC guidelines.
NASA	Potential mission partner & ISAM standardization.	demonstrates the feasibility of in-space carbon fiber manufacturing processes.

Stakeholder	Role	Needs
Composite Overwrapped Pressure Vessel (COPV) Manufacturers	Reference groups for the manufacturing process of a COPV.	Collected data should help in the evaluation of whether in-space manufacturing of CF tubes could eventually match or closely resemble terrestrial processes.
Orbital Resupply Companies	Supplies Carbon Fiber restocks to the payload.	Project may in the future demonstrate the ability to scale ISAM CF manufacturing for future market opportunities.
Deep Space Missions	Users of large structures	Payload should provide experimental data to determine whether or not in-space manufacturing is feasible.
Orbital Tug Companies	Interest in long-term applicability of technology for future use	Present mission provides the baseline research that may guide the future of CF tube use in orbit.

Preliminary Sizing and Trade Studies

Curing Method: Decision Matrix

Curing Method	**Autoclave Heat Curing**	**CF Layering Compatibility**	**Mixing Complexity**	**UV Degradation**
Prepreg Sheets	Yes	High	None	Medium
Epoxy	Yes	Medium	Medium	Medium
UV Epoxy	No	Low/None	Medium	Low
Frontal Polymerization	**No**	**Medium**	**High**	**Medium**

Preliminary Sizing and Trade Studies

Mechanical/Structural: Interior Layout

- Manufacturing requires pressurized environment
- Is a dedicated pressure vessel needed?
- Based on different resin vapor pressures, requirement of 20 mbar
- We chose **No Pressure Vessel**
- Instead, the Bosuns' Locker will contain the required atmosphere of inert gas

Preliminary Sizing and Trade Studies

Subsystem 2 Requirement 1: External Communication

Category	Example System	Weight/Complexity	Stability	Bandwidth	Decision
In-House	Custom RF + custom framing	Low–Medium	Low	0.5–5 kbps	Not Selected
Open Source	CCSDS over S-Band	Medium	High	1 kbps–3 Mbps	Selected
Commercial	KSAT / AWS Relay	Medium–High	Very High	Varies	Future Upgrade Option

Preliminary Sizing and Trade Studies

Subsystem 2 Requirement 2: System Framework

Architecture	Strengths	Weaknesses	Outcome
PX4 Only	Deterministic real-time control	Weak autonomy/logging	Not Selected
cFS Only	Strong telemetry/logging/scheduling	Not real-time control	Not Selected
Hybrid PX4 + cFS	Real-time control + traceable autonomy	Requires supervisory bridge	Selected

Preliminary Sizing and Trade Studies

Subsystem 2 Requirement 3: Fault Detection, Isolation and Recovery

Fault Type	PX4 Response	cFS Response	Result
Jam Detected	Stop feed + retract	Log event + operator alert	Prevents mechanical damage
Thermal Overrun	Slow/stop curing cycle	Transmit warning + safe hold	Prevents runaway heat
Emergency Stop	Zero all actuator outputs	Record stop event	Satisfies ≤ 2 second safety requirement
Execution Stall	Watchdog auto-reset	Log reset reason	Maintains autonomous recovery

Preliminary Sizing and Trade Studies

Subsystem 2 Requirement 4: Power Distribution & Duty Cycle

Component	Typical Power Draw	Duty Cycle	Strategy
PX4 Controller	1–3 W	Continuous	Always-on control core
cFS Supervisor	2–5 W	Continuous	Low-duty mission sequencing
High-Compute SBC	5–15 W	On-demand only	Software power-gated
S-Band Radio	5–20 W	Scheduled	Enabled only during downlink windows
Sensor Suite	1–4 W	Continuous	Staggered polling minimizes instantaneous draw

Preliminary Sizing and Trade Studies

Subsystem 2 Requirement 5: Sensor Suite

Sensor Type	Purpose	Criticality	Status
Encoders	Extrusion length + jam detection	Critical	Selected
Thermal Sensors	Cure reaction + electronics monitoring	Critical	Selected
Pressure Sensors	Vacuum verification	Critical	Selected
Current Sensors	Motor stall / overload detection	Critical	Selected
IR Thermal Camera (Optional)	Heat rejection monitoring	Helpful	Optional Upgrade