Phase C: Progress Presentation #4: Testing & Manufacturing Updates

Team MERCuRy - McMaster University

August 2025

Introducing Team MERCuRy: CAN-RGX VIII

= Mission Specialists

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Research Lead

Amin Nazari
Electrical Lead

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Sponsor Lead

Research Recap

Lunar Gateway [1]

[1] “Gateway,” NASA Explore. [Online]. Available: https://www.nasa.gov/mission/gateway/

Mission Motivation

- The next step of space exploration is to construct infrastructure on the Moon.
- We currently lack the suitable materials to do so
- In-situ resource utilization using lunar regolith has been recommended.

Lunar Cement

- Combining a binder with lunar soil to create cement
- Polymers are recommended for early lunar applications.
  - Goal is to minimize the amount of binder used.
- Further research is required to predict the properties on regolith cement before its used.
  - Effects of non-terrestrial gravity is of particular concern.

Figure: Lunar Cement Sample [2][3]

[2] “Simulant Development Lab,” Astromaterials Research & Exploration Science LUNAR REGOLITH SIMULANTS. [Online]. Available: https://ares.jsc.nasa.gov/projects/simulants/development-lab.html

Research Recap

MASON Mixer [3]

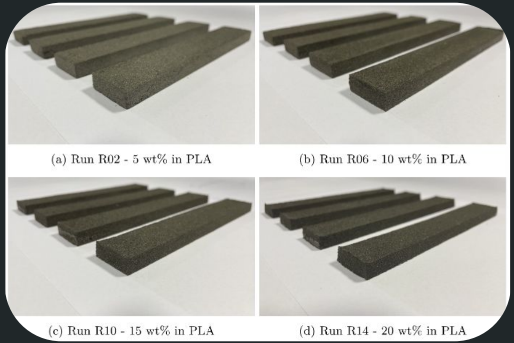
[3] MASON/Concrete Hardening - Beton im All erforschen, Emissionen auf der Erde verringern, (Feb. 03, 2022). [Online Video]. Available: https://www.youtube.com/watch?v=J2kL--y6ftk

MASON Experiment

- Study of hydraulic cement via water + JSC-1A mixture.
- A hand-powered cement mixing device, with no electrical components was designed.
- Samples were produced on the ISS by an astronaut, and compared to those created on Earth.

ESA Experiment

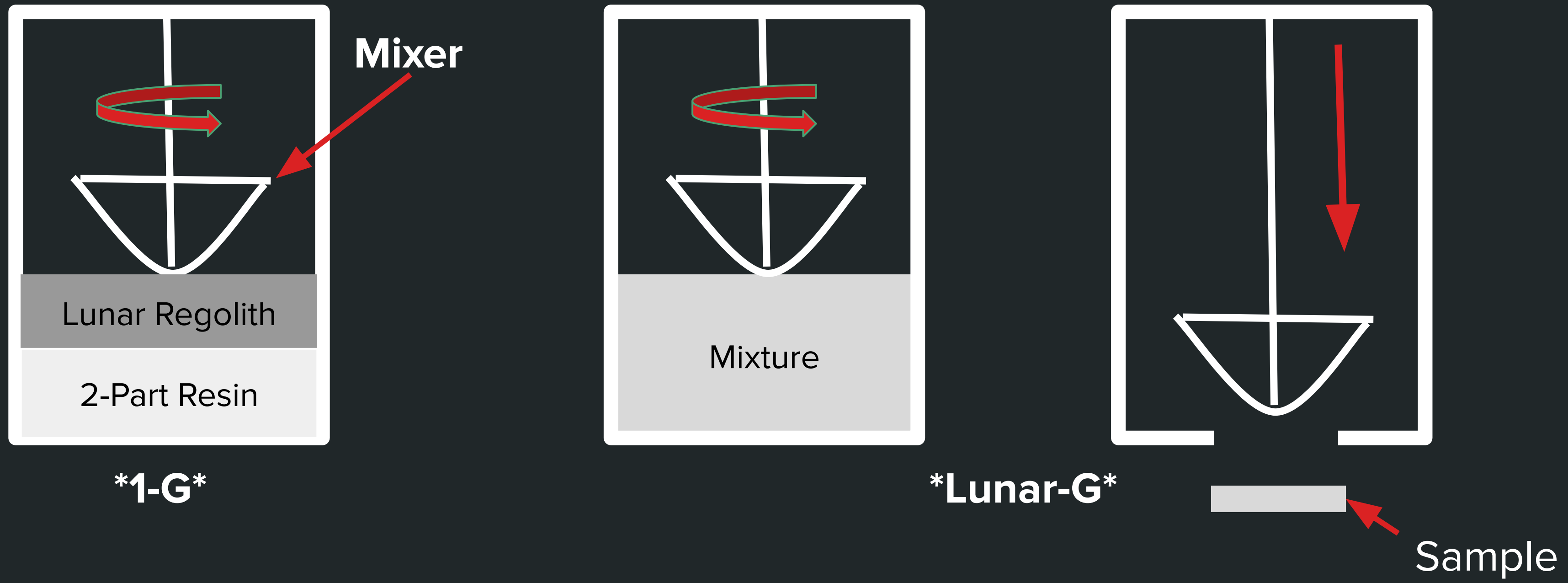
- Study of polymer cement via PLA Powder + EAC-1A mixture.
- Manually mixed and placed into molds.
- Samples were tested for flexural and compressive strength.
- Binder weight percentage, max particle size, and compaction pressure were studied.



ESA Samples [4]

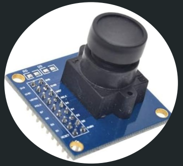
[4] R. Torre, A. Cowley, and C. G. Ferro, "Low Binder Content Bricks: A Regolith-Based Solution for Sustainable Surface Construction on the Moon," Discover Applied Sciences, vol. 6, no. 3, p. 88, Feb. 2024, doi: 10.1007/s42452-024-05717-4.

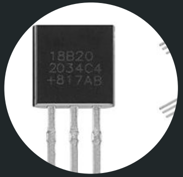
Experiment Overview



(1) Lunar regolith simulant and resin loaded into a mixing chamber.
(2) Two materials are mixed together with automated mixing device.
(3) Mixer extrudes mixture to form lunar bricks.

MERCuRy’s Scientific Objectives

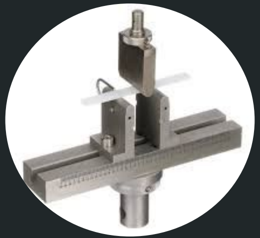




1. **Observe and log the mixing behavior and the formation of the lunar dust sample.**
    - A camera shall be used to monitor chamber flow, mixing and compression.
    - Distribution of dust and agitator quality will also be evaluated based on recordings.
    - Each camera must reach the requirement of 640p, 30 fps and function at 0-30c.
2. **Measure and log the load experienced by the sample during the pressing process.**
    - Load cells shall be used to measure the compression forces over time.
    - Must be able to measure a minimum of 500N of force with a 1 Hz sample rate and function at 0-30 c.
3. **Observe and log the temperature change during mixing and sample formation.**
    - Thermal sensors shall be used to record thermal range changes in micro-g from mixing and solidification.
    - The sensor must function at 0-30c.

MERCuRy’s Scientific Objectives

4. **Evaluate the flexural strength of the generated samples via a 3-point bending test.**
    - This goal shall be accomplished following the flight using an Instron test.
    - The increasing flexural load will be recorded to test the sample’s strength.
    - For redundancy, this can be done either at MDA Space or McMaster University.



5. **Evaluate the sample topography to study the composition and exposed surface.**
    - This goal shall be accomplished following the flight using a microscope.
    - Images will be captured of fractured samples post-flexural strength testing.
    - The images will be captured via microscopes with a minimum magnification of 100x.

MERCuRy’s Scientific Objectives

Mission Requirements

- The mission specialist shall initiate the binder entry into the chamber when in 2g ascent.
- The mixing sequence must be initiated at the start of the lunar-g period.
- The sample-forming compression process must be terminated at the end of the lunar-g period.
- All imaging and applied load data acquisition must run in the lunar-g period.
- A minimum of 6 samples must be collected per binder ratio being studied.

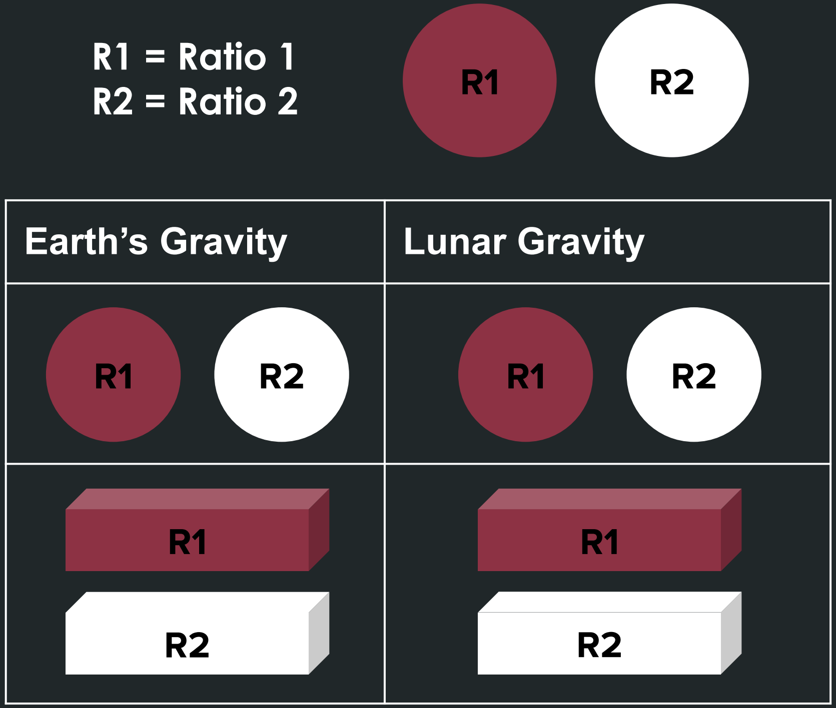
Environmental Considerations

- **Humidity**:
  - Dust bake-out prior to the flight, air-tight containers, and desiccant will be utilized.
- **Temperature**:
  - Electronics have the requirement of a minimum of 0-30 ○C operational temperature.
- **Ventilation**:
  - Workplaces must have proper ventilation with masks for dust handling.

Team MERCuRy's Experiment

"Characterizing Powder Liquid Agitation for Lunar Dust-Aided Habitation"

- Investigating polymer-regolith cement properties (Two-part resin + LSP-2).
- Test parameter of varying binder weight percentage .
  - Create samples of **two different** resin-to-powder **ratios.**
- Execute experiment on Earth and within parabolic flight to consider the **effects of lunar gravity** on sample properties.
  - Buoyancy and sedimentation phenomena.
- Produce samples for flexural testing (ASTM C239) to determine **flexural strength** of cement.
  - Study composition of sample by analyzing fractured surface.



Proposed Design - Experiment

- There will be at least 6 individual spaced out parabolas maneuvers.
  - Each lunar gravity parabola produces **two** samples in **two separate** mixing chambers, each of different resin:lunar regolith ratio.
    - Ratios will be determined through ground testing.
- Produces a total of 24 samples over two days, 12 per flight.

R1 = Ratio 1

R2 = Ratio 2

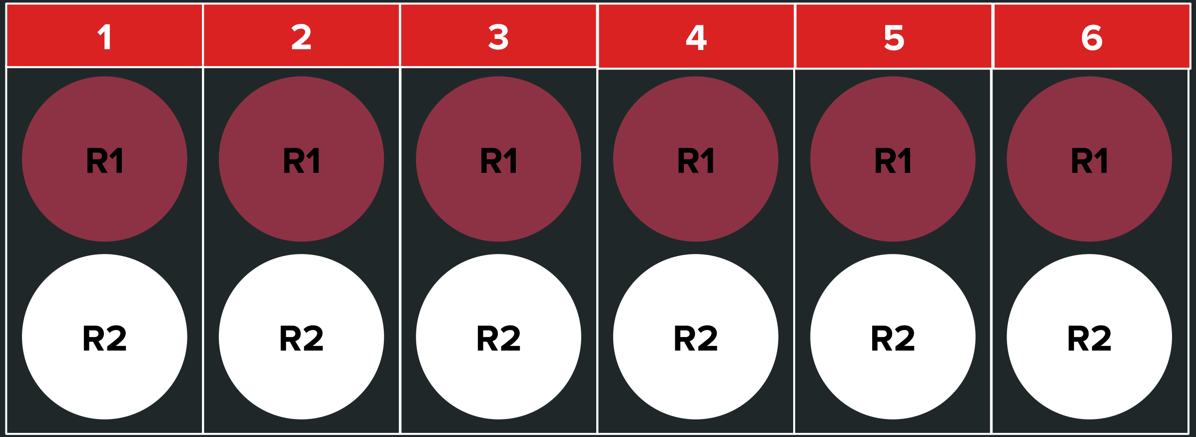
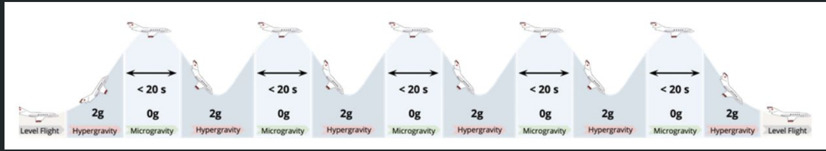


Figure: Design of Experiment

Flight Procedures



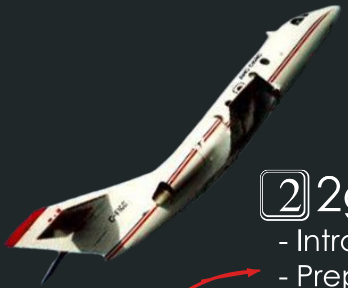
MS = "Mission Specialist"

Table: Flight Stages

Level Flight	**2-g Ascent**	**Microgravity**	**2-g Descent**
• MS1 prepares and starts the DAQ by opening the program for command. • Proper function of power supply will be confirmed. • MS1 reviews video feed to confirm proper function. • *MS2 loads next set of mixers **(2nd parabola)**.*	• MS2 triggers program to introduce binder to dust. • MS2 prepares to trigger start of mixing program and DAQ.	• Mixing program will be initiated according to count down. • Mixing initiates within chambers through motion of their agitators for total duration of 15s. • Compression mechanism will be actuated.	• MS2 pauses the program at the end of the microgravity phase and check for data completeness. • MS1 resets the program for the next cycle.

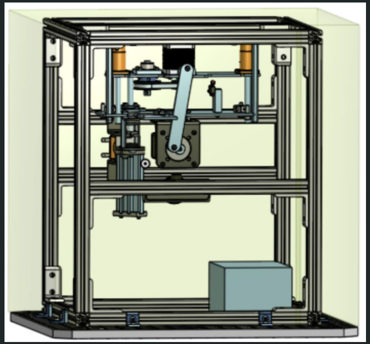
- Compression of sample in lunar gravity is to prevent movement after the lunar g phase.

Flight Profile



1️⃣Level flight✈️
- Start DAQ
- Check power/video
- Load mixers

2️⃣2g ascent🛫
- Introduce binder 🧪
- Prepare DAQ & mixer



Lunar Gravity
- Start mixing (15s) 🔁
- Trigger compression

4️⃣2g decent🛬
- Pause program
- Verify 💾✅

Pre & Post Flight Procedures Summary

Pre Flight Procedures

1. Ensure the LR simulant has been baked-out, and no moisture has been introduced during transportation using desiccant.
2. Ensure the laptop, and electrical systems are operational by running a safety check and sticking to a full charge schedule.
3. Ensure the chambers are numbered and preloaded with the correct amount of LR simulant and resin.
4. Ensure the mission specialists have a pre-prepared on-board checklist to follow, which is in progress.

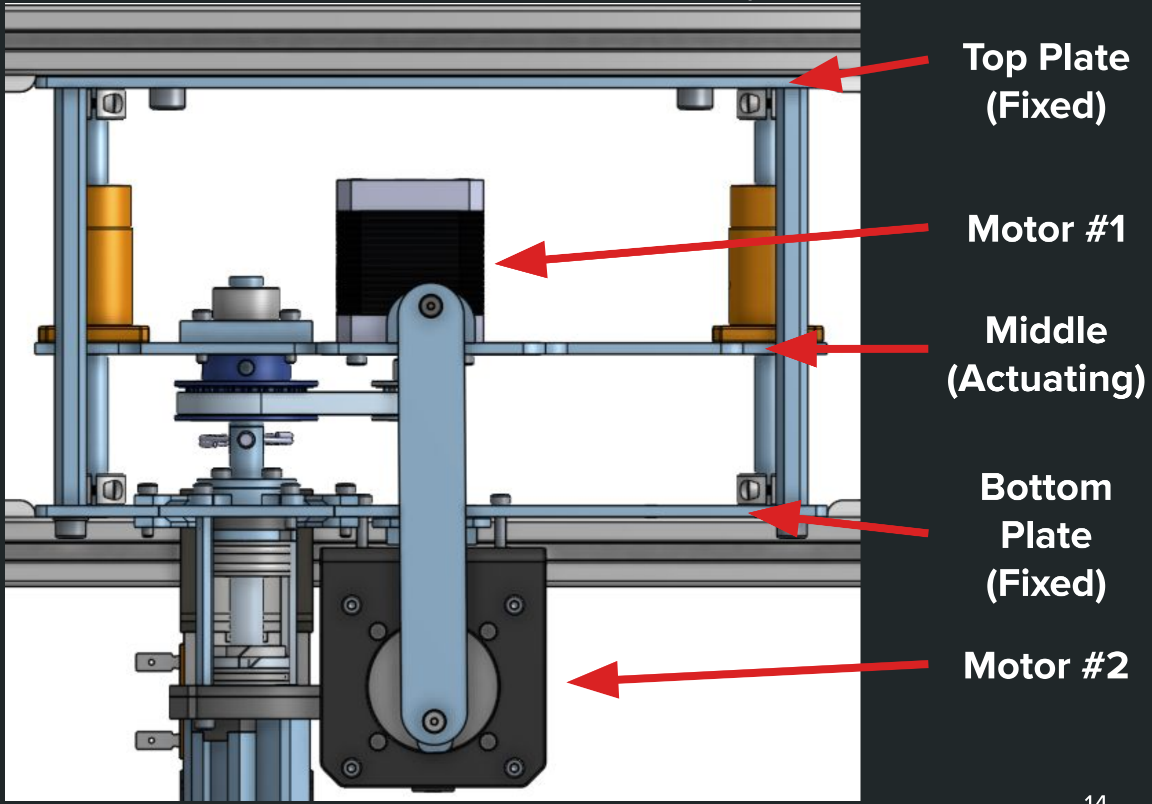
Post Flight Procedures

1. Ensure the flight data is properly collected based on conducted dry runs and saved via two methods (hard drive and USB).
2. Ensure the chamber and mold assemblies are stored properly by checking for leakage at the chamber seals.
3. Clean any surfaces that have been exposed to the LR simulant and resin, including the case, following the team's SOP.
4. Begin to process the flight data.

Design - Mechanical - Motors

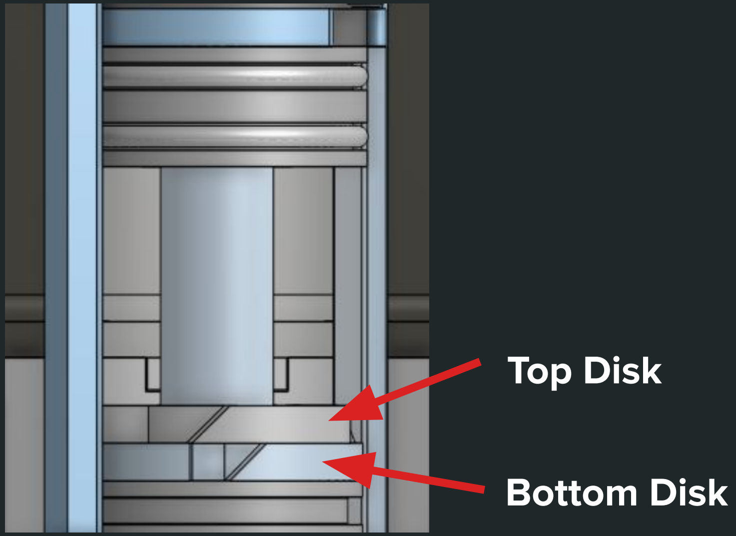
- Motor #1 (NEMA 17) provides rotational motion to disks through belt and pulleys.
- Motor #2 (NEMA 23) provides linear actuation (up and down) to the middle plate using a linkage design.
    - Middle plate can actuate due to linear rails and bearings. Top and bottom plates are fixed.

Motor Layout

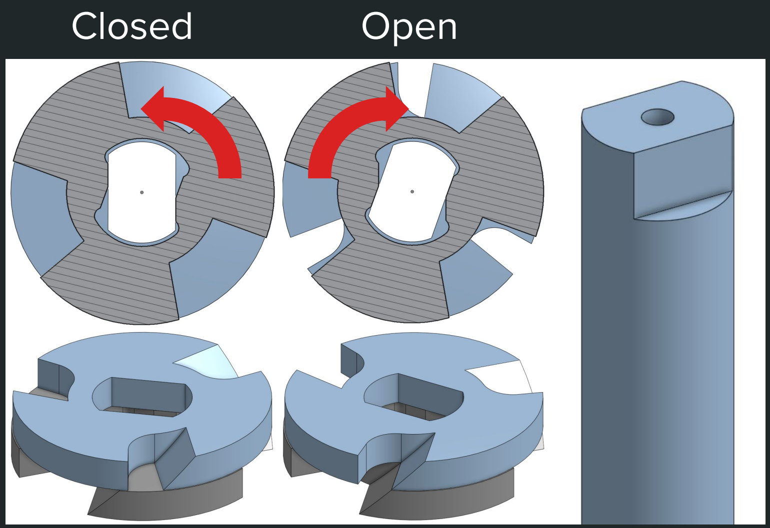


Design - Mechanical - Agitation Disks

- Top disk is directly driven by the motor and pulley system.
- Bottom disk is passively driven by interference with shaft due to internal geometry.
  - Allows direction of rotation to change from open to closed holes.

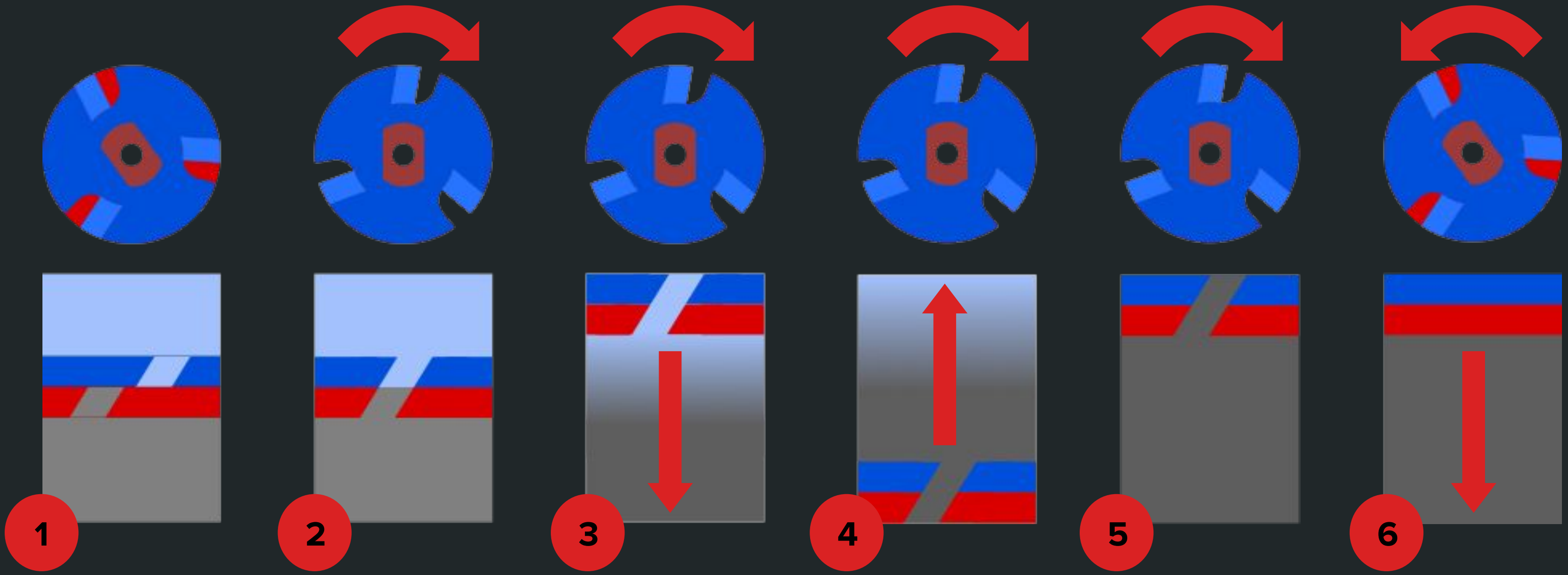


Agitation Disks



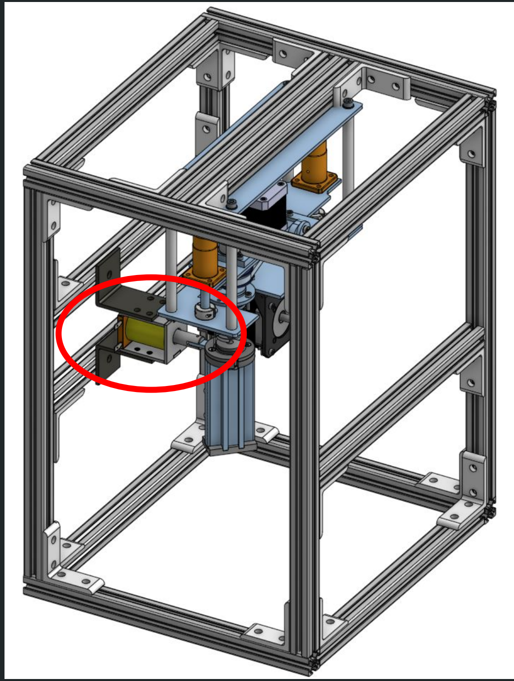
Closed and Open Mixing Disk Assembly

Design - Mechanical - Agitation Disks



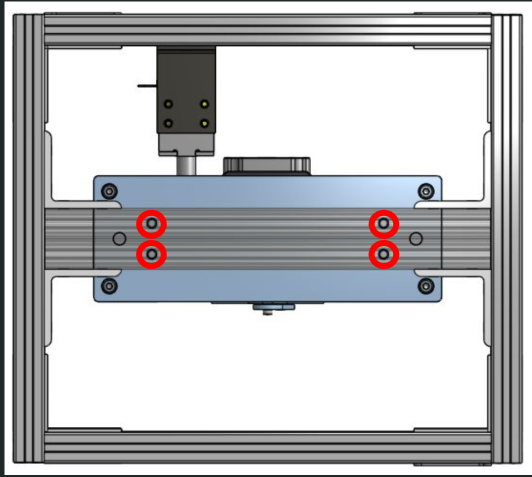
Design - Mechanical - Structure + Mounting

- 20mm Aluminum extrusion members, reinforced with aluminum brackets.
- Additional mid-section members are used to mount the valve assembly and future scope components.



Solenoid Valve Assembly Mounting

- Structure previously shown at PDR to pass static load test.

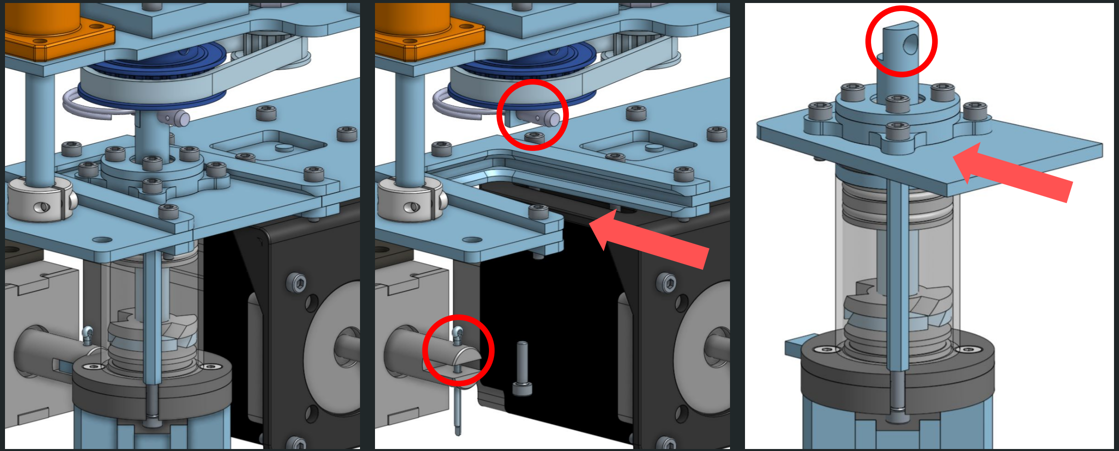


Payload Mounting

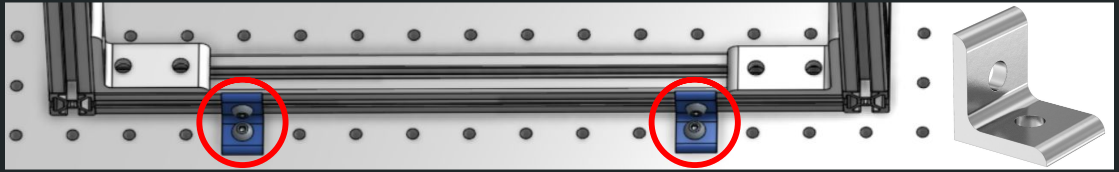
Design Update - Mechanical

1. **Shaft Coupler Design**
   a. D-shaft & clevis pin design with additional alignment for easy change out.

2. **Pelican Case Mounting**
   b. 6063 AL 20mm Corner Bracket
   Secured with 2 M5 bolts.
   c. 2 brackets used per horizontal member, (8 brackets in total).



Quick Change System



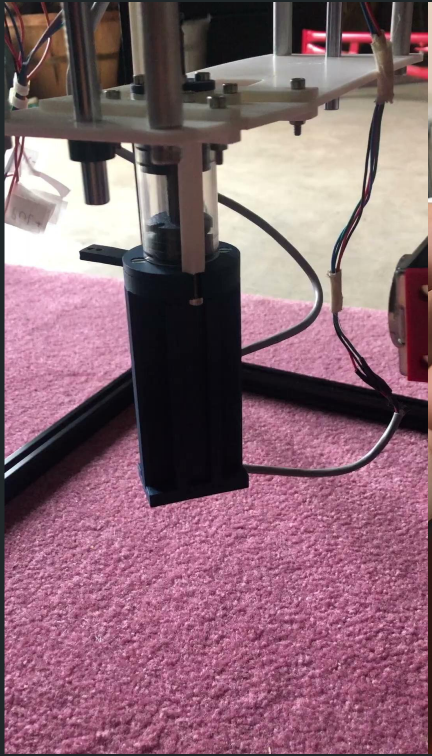
Off-the-Shelf Brackets

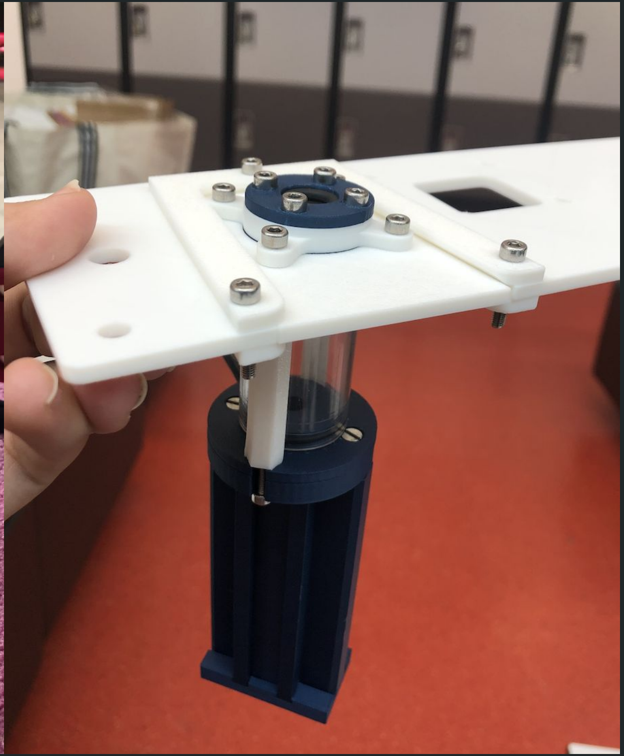
Testing Updates

Quick Disconnect Testing
The team conducted a **complete fit check** assembly with 3D printed parts prior to manufacturing, also enabling the team to successfully test the quick disconnect.

Takeaway:

- Chamber assembly was slid in and out **smoothly**.
- **‘Slide’** plate feature locates the chamber assembly to allow the pin to be placed in the D-shafts.

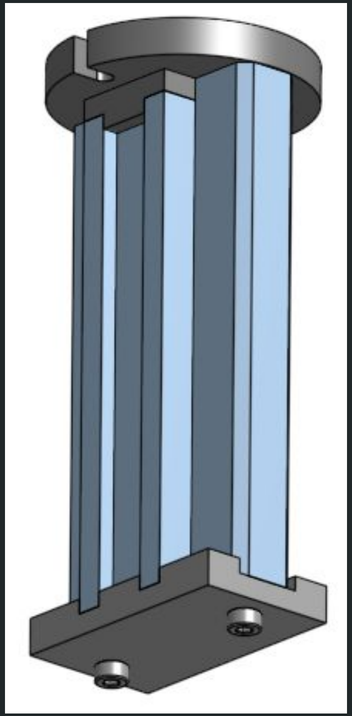




Design - Mechanical - Mold

- The mold design is based on existing concrete prism molds.
  - Designed for a 10mm x 10mm x 80mm sample volume, in a prism shape as required by ASTM standards.
- Walls are removable allowing us to extract the sample.
- **Passed a submersion test as shown at PDR.**
- **3D-printed version has also been produced and tested in curing for resource redundancy.**

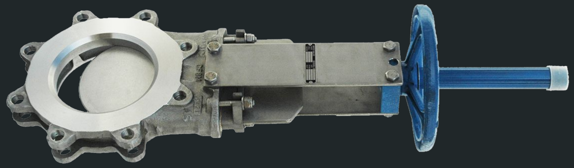
Concrete Prism Mold



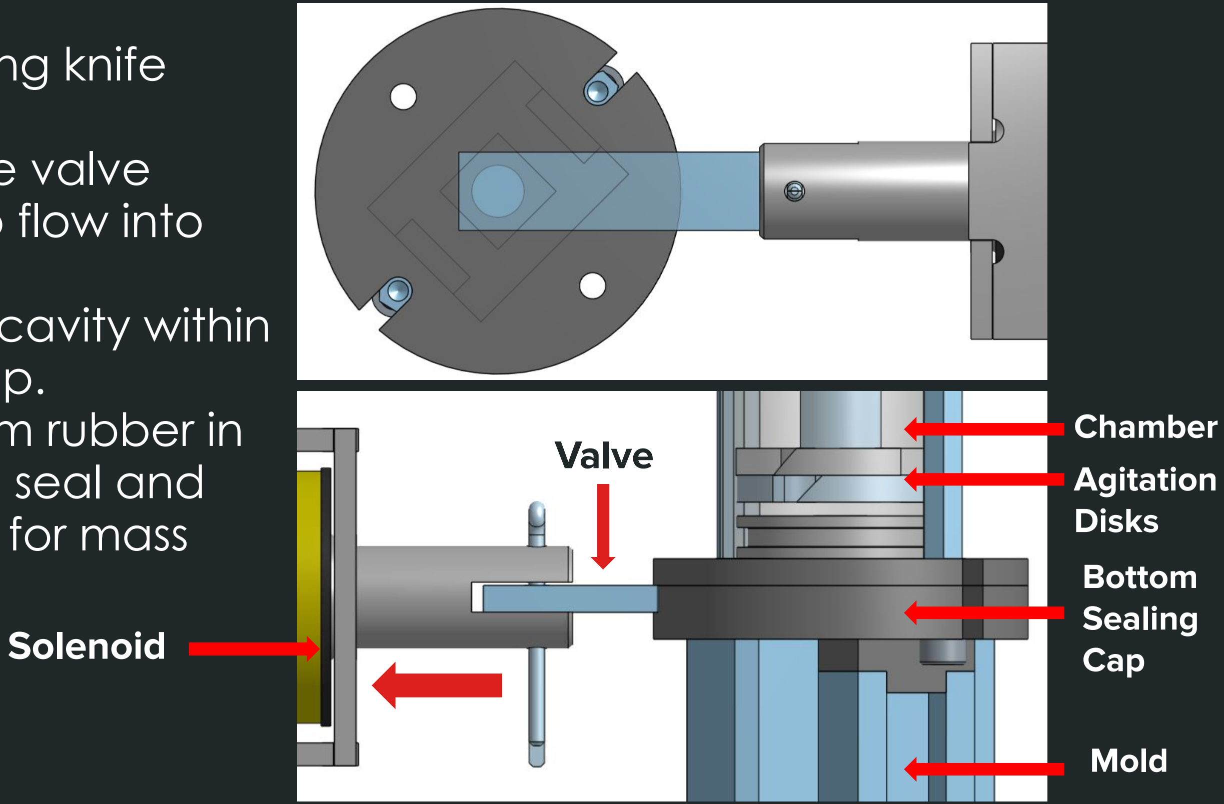
Mold Design

Design - Mechanical - Valve

- Design based on existing knife valves.
- Solenoid will retract the valve allowing the mixture to flow into the mold.
- Valve piece will exit a cavity within the Bottom Sealing Cap.
    - Manufactured from rubber in order to provide a seal and looser tolerancing for mass manufacturing.



Knife Valve



Solenoid Valve Assembly

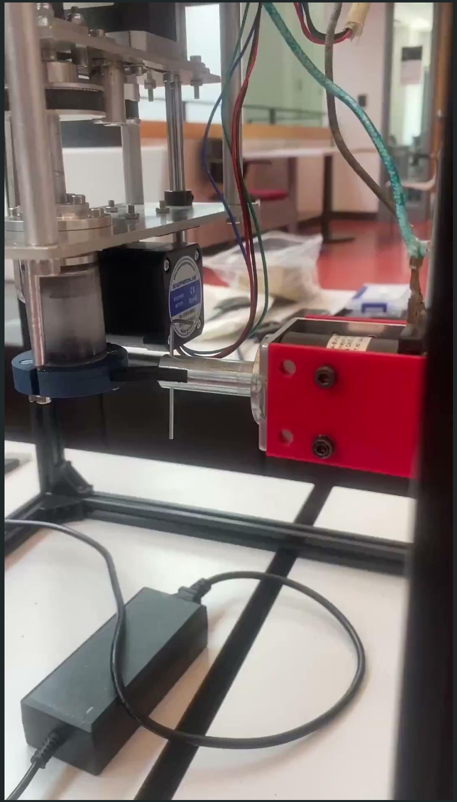
Testing Updates

Valve Testing

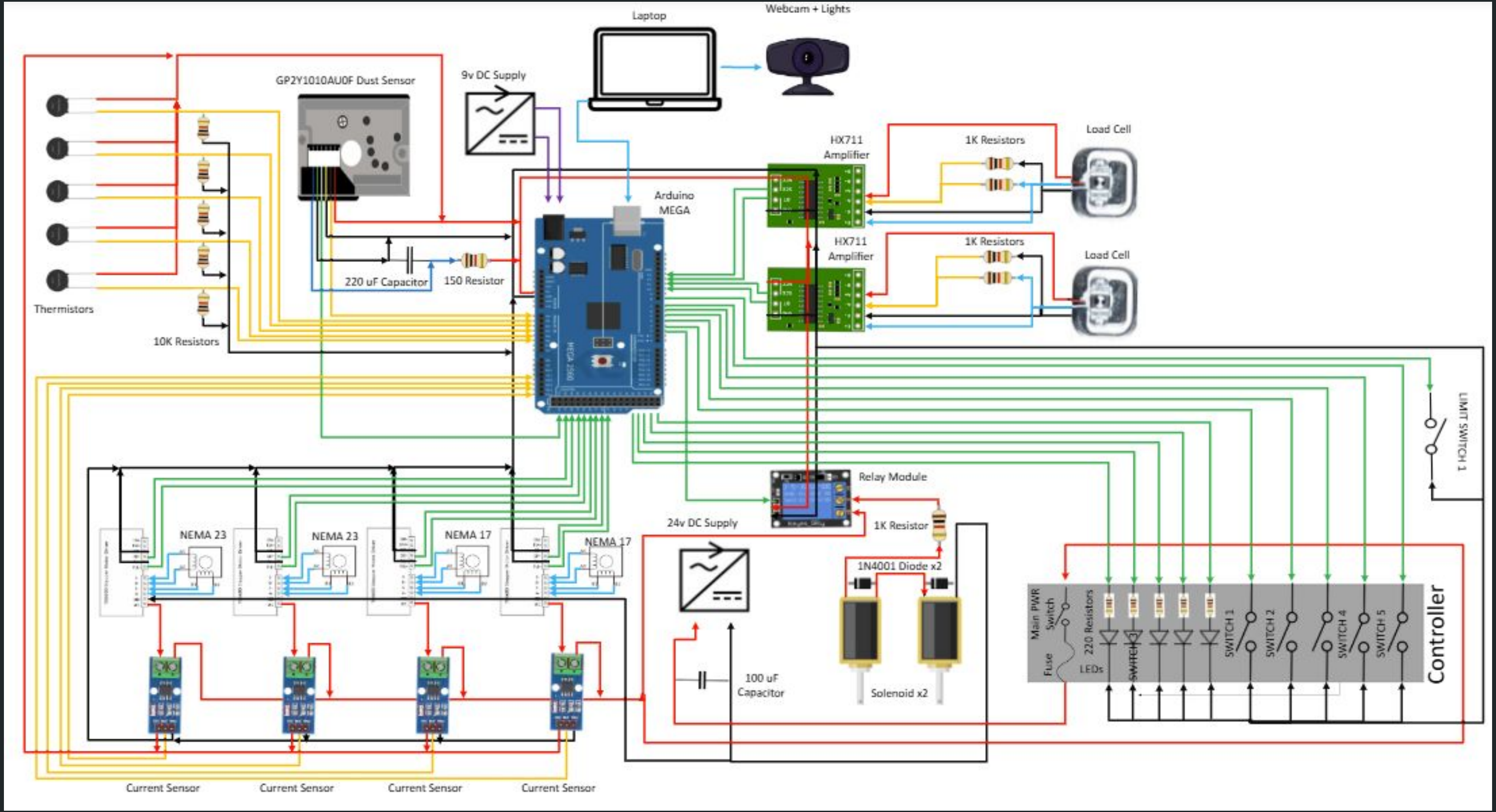
Valve was **successfully tested** during the mixing and extrusion process of the lunar regolith mixture.

Takeaway:

- **Rubber plug** addition seals all gaps to prevent leakage.
- Solenoid is able to pull the plug to **allow pass-through** of the mixture during extrusion.
- Plug is able to **withstand applied force** when the valve is closed during mixing.



Design Updates - Electrical



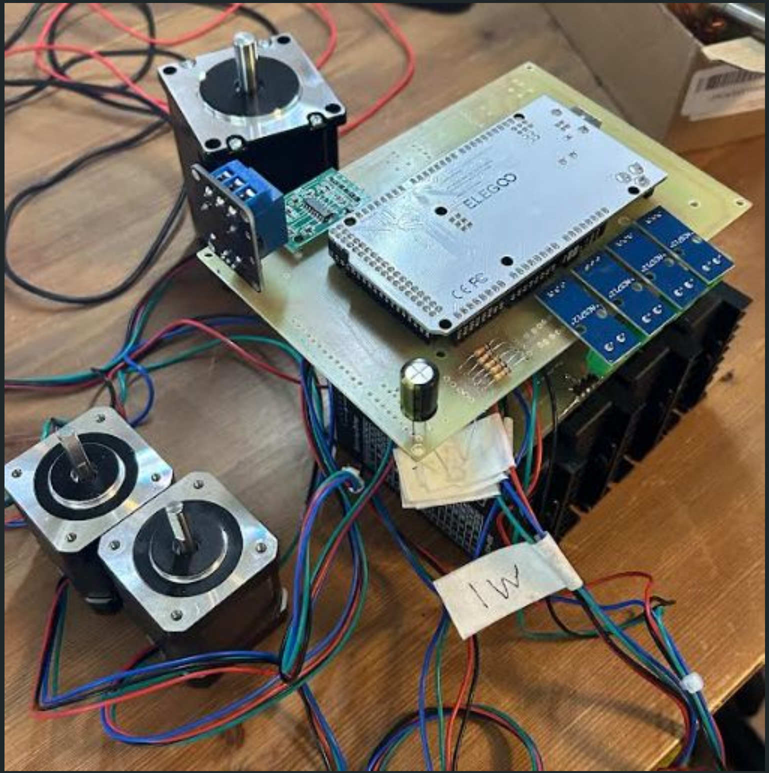
Design Updates - Electrical

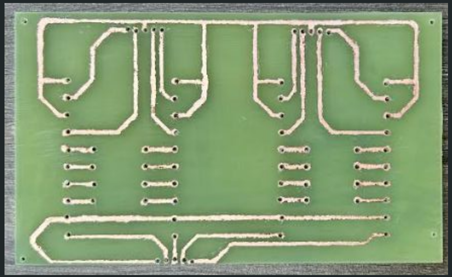
Completed:

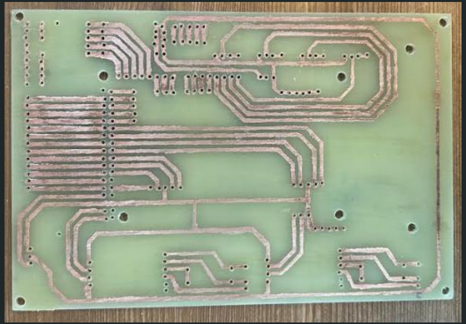
- All components purchased and on hand.
- Boards are manufactured.
- Benchtop testing of all sensors is done.

In Progress:

- Soldering components to board.
- Electrical box and controller design.







Design Updates - Software

Completed:

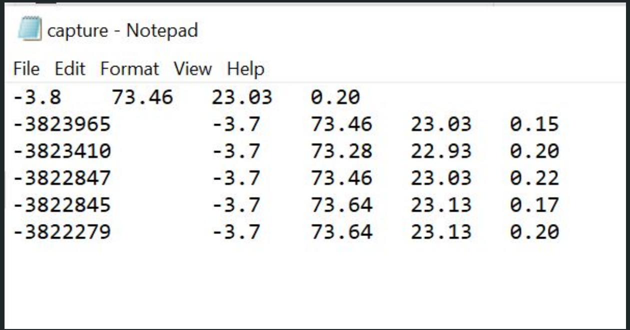
- Successful logging and saving of data using Realterm (.txt and .xlsx).

In Progress:

- Testing webcam (light, range).

Next Steps:

- Arduino code refinement for in-flight controls.
- MATLAB/Excel code for post processing.




```
-3.8      73.46    23.03    0.20
-3823965           -3.7     73.46    23.03    0.15
-3823410           -3.7     73.28    22.93    0.20
-3822847           -3.7     73.46    23.03    0.22
-3822845           -3.7     73.64    23.13    0.17
-3822279           -3.7     73.64    23.13    0.20
```

RVCM - Verification & Compliance Progress

1. Total Mass (RGX-PHY-001): **Completed** - Weighed & mass monitored via CAD.
2. Static Loading (RGX-PHY-002): **Completed -** Static Load Testing with weights.
3. Power Supply (RGX-EPS-001): **Completed** - Monitored via Power Budget.
4. Connector Type (RGX-EPS-002): **Completed** - Electrical obeys req.
5. Peak Power (RGX-EPS-003): **Completed** - Monitored via Power Budget.
6. Case Containment (RGX-SFT-001): **Completed** - CAD & Prior Testing.
7. Pelican Case Modification (RGX-SFT-001): **Completed** - Maintained.
8. Tethering (RGX-SFT-003): **Completed** - Experiment is properly secured.
9. Manual Triggering (RGX-SFT-008): **Completed -** relies on instrument triggers.
10. Materials (RGX-SFT-014): **Completed -** SOP created for experiment.
11. Fail Safe (RGX-SFT-015): **Completed -** Limit switches added to design.

RVCM - Road to FRR Verification Completion

1. Maximum Current (RGX-EPS-005): TBC before end of August.
2. Maximum Current Demo (RGX-EPS-006): TBC before end of August.
3. Ground Test (RGX-FUN-007 A/B): TBC before demo video.
4. **Scientific Objective Requirements** (self-imposed): TBC for demo video.

Points of Failure will continue to be planned and tested.

- **Power Loss:** Motor movement sensed through limit switches. Hard stops also are in place.
- **Leakage:** Multiple layers, including o-rings, mixing cylinder, bagged module, outside lexan walls, and Pelican case.
- **Thermal:** Thermal sinks to be mounted to the motors as needed.
- **Motor Mechanical Stall:** Software return to safety configuration.

Next Steps: Mechanical Production & Verification

Production Next Steps:

- Order any outstanding parts and materials (+ spares) by **Aug 15.**
- Update dimensioned drawings for manufacturing by **Aug 15.**
- Manufacture and assemble Module 1 (**Aug 18 to 24**).
  - Module 2 to follow after functional testing outlined below.

Verification Next Steps:

- Flight functional testing - includes recommended vibrational leak testing - feedback from George in TEDP Rev B (**Aug 22 to 29**).
- Sample creation and studying (**Aug 22 to 29**).
- Perform a green run of entire system (**Aug 29 to Sept 5**).
  - Practice pre-filling chambers, replacing modules, storing samples, cleaning chambers.
  - Record ground test video.

Next Steps: Electrical Production & Controls Verification

Production Next Steps:

- Solder components to circuit board by **Aug 15**.
- Build controller and electrical box by **Aug 18.**
- Integrate with mechanical system by **Aug 22.**

Controls Verification Next Steps:

- Calibrate sensors and test arduino code **(Aug 22 to 29).**
- Evaluate camera resolution and latency **(Aug 29 to Sept 5).**
- Fine tune the controls and user interface **(Aug 29 to Sept 5)**.

MERCuRy’s Timeline

Project MERCuRy Timeline			
Phase	**Milestone**	**Date Start**	**Date End**
Phase B	CDR	6/7/2025	6/21/2025
Phase B	TEDP Rev B	6/14/2025	6/28/2025
Phase C	**FRR and TEDP C Checkpoint Process**	7/7/2025	10/14/2025
Phase C	MECO Education Sessions	7/7/2025	7/31/2025
Phase C	Flight Functional Testing	7/7/2025	7/31/2025
Phase C	Flight Static Load Testing	7/21/2025	7/31/2025
Phase C	Sample Study Period	7/31/2025	8/21/2025
Phase C	Progress Presentation 4	8/21/2025	8/28/2025
Phase C	DAQ Development	8/21/2025	9/14/2025
Phase C	Ground Testing Video	9/14/2025	9/16/2025
Phase C	FRR	9/16/2025	9/28/2025
Phase C	TEDP Rev C	9/21/2025	10/14/2025

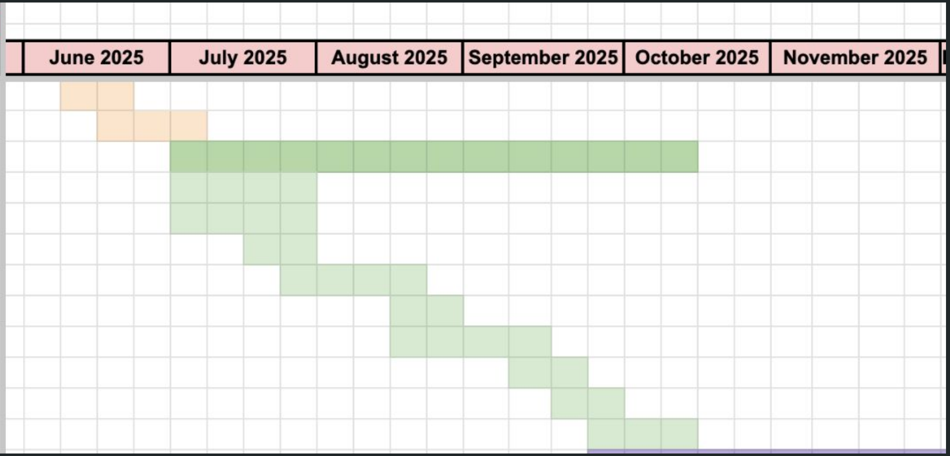


Figure: Phase C Timeline

MERCuRy’s Mission Budget

Category	Description	Notes	Purchase Amount	Sponsored Amount
Agitator Material	3D printed material to create agitator structure	**3D Printing Canada Sponsorship**	$75.00	$50.00
Bearings	Rotational and linear bearings as needed	**IGUS Sponsorship**	$200.00	$200.00
Centrifuges	Plasic for the mixing chamber structures	Hardware store polypropylene material	$100.00	$0.00
Driving Motors	Stepper motors for driving the agitation	Digikey or McMaster-Carr	$100.00	$0.00
Lunar Regolith	Lunar dust simulant for the solid mixing material	**Lunar Simulant sponsorship**	$150.00	$100.00
Load Cells	Load cells to measure compression of the material	Digikey	$20.00	$0.00
Simulation Software	Altium, ANSYS, CAD, CFD	**Available through McMaster**	$1,500.00	$1,500.00
Structure	Aluminum flight structure that houses the experiment	8020 Material	$100.00	$0.00
Thermal Instruments	Temperature monitoring instruments for the mixing and pressing process	Digikey or similar	$50.00	$0.00
Lighting	Lighting for the inner chamber and for drying the sample	Digikey or similar	$50.00	$0.00
Resin	Binder for the mixing process	*Seeking sponsorship*	$120.00	$55.00
Visual Cameras	Cameras to visually monitor testing within the chamber	Digikey or similar	$50.00	$50.00
Additional fasteners, connectors, and wiring	Any additional fasteners, connectors, and wiring required	As needed	$30.00	$0.00
Travel	Travel accomodations to the flight in Ottawa	**McMaster Engineering Sponsorship**	$1,000.00	$1,500.00
NordSpace Sponsorship	Available funds.	**NordSpace Funding**	$0.00	$500.00
MG Chemicals Sponsorship	Cleaning & sample prep products.	**MG Chemicals Product**	$0.00	$1,000.00
MMRI & SixPenny	Manufacturing services	**Free manufacturing services & resources**	$0.00	$800.00
			$3,545.00 Cost Without Funding	**$5,755.00** Funding

Figure: Mission Budget

Live Document

Project Funding Sponsors & Status

Table: Sponsor Breakdown

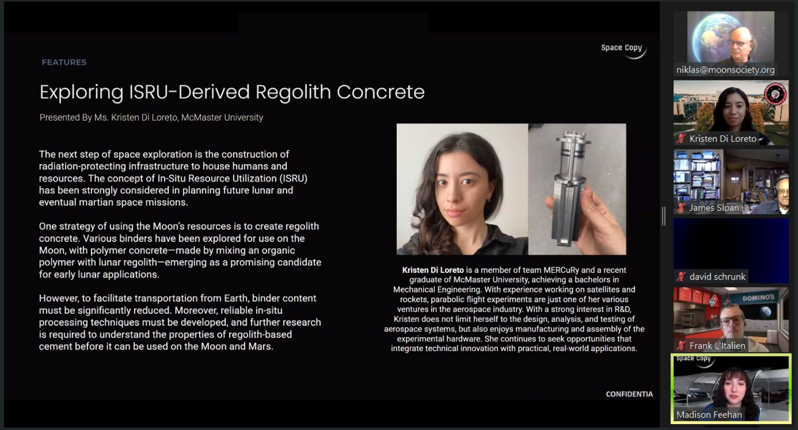
Sponsor	Value	Status
3D Printing Canada	50% off product Estimated $50 in savings	Discounted PLA & PETG in use
IGUS Canada	Free product as needed	Product discounts used
McMaster Engineering	**$1500** $500 for capstone, $1000 for travel	Capstone funding received, travelling will be expensed when needed.
MDA Space	Mentorship, cleanroom, Instron Estimated $500 in value	Mentorship & testing in 2025, further funding pending
NordSpace	**$500**	Received via e-transfer
Space Resource Tech.	**50% off** Estimated $100 in savings.	Discount code used for purchase

New Sponsors

- McMaster Manufacturing Research Institute
  - Free water jet manufacturing for aluminum plating.
  - CNC lathe and mill capabilities.
- Sixpenny:
  - Manufacturing services & McMaster-Carr purchases.
- MDA Space:
  - In addition to the previous mentorship and support, have donated $500 for team use.
- ASC Circuits:
  - PCB Manufacturing sponsorship.

Outreach

- **Women in SEDS Conference**
  - Presented at inaugural conference.
  - Only student abstract to be accepted.
- **Space Copy Lunar Conference**
  - Invited to present with Space Copy at the Lunar Conference.
  - Continuing to work with the startup for future opportunities.
- **NEXT:** YorkU Engineering Society
  - Present workshop to encourage RGX.
- **NEXT:** FIRST STEMley Cup Event
  - Workshop + booth for K-12 participants,
- **Social Media**
  - Instagram @teammercuryproject.
    - Design & outreach updates
  - **Website Launch!**



Project Risk Management

TR1 - Airworthiness: Constant communication shall be sought with the NRC at each design milestone to ensure safety with components and LR handling.

TR2 - Background Knowledge: Fluid mechanics guidance shall be provided by Dr. Morton along with airworthiness from Dr. Gadsden, MERCuRy supervisors.

TR3 - Curing Time: An accelerant and standard resin shall be studied in the event that faster curing via a different method is required.

MR1 - Funding: Advocating for team funding shall be done with every purchase in addition to faculty networking and reaching out to current resources.

MR2 - Members Stepping Down: Minimum of one month notice shall be maintained. Connections to high schools and space education organizations help with active recruitment.

MR3 - Outreach: The team shall utilize existing connections, such as McMaster, *FIRST,* and SEDS.

SR1 -Testing Facilities: There shall be redundancy in testing facilities with proper equipment.

Project Risk Management

Table: Risk Assessment Matrix

MERCuRy Risk Assessment Matrix		Probability		
		Low	**Med.**	**High**
Severity	**High**	TR1		
	Med.	SR1, TR3, MR2	TR2	
	Low	MR1, MR3		

High Severity, Low Probability: Flight critical, but has pre-established plans in place to prevent.

Medium Severity, Low Probability: Somewhat impacts the mission, but has redundancy efforts in place.

Low Severity, Low Probability: Minimal flight impact and has already been prevented.

Medium Severity, Medium Probability: Somewhat impacts the mission, mitigation efforts ongoing.

Questions, Comments, Concerns, & Roadblocks

Questions:

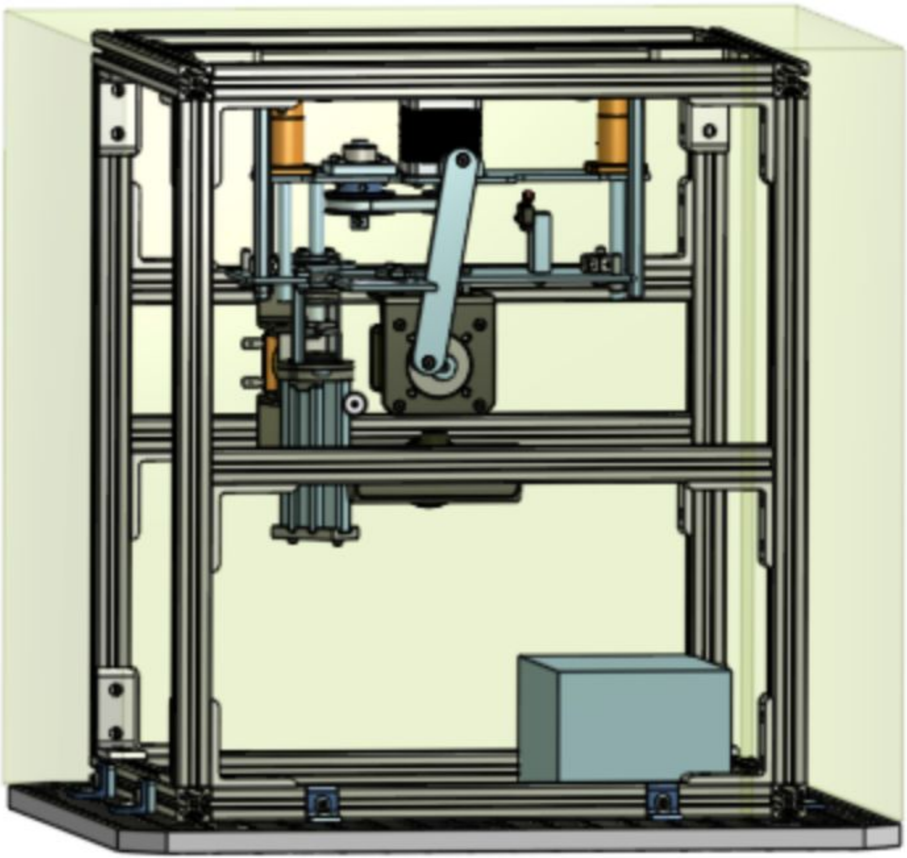
1. Submitting for CSA funding - since some of this team recently graduated, is there a risk of ineligibility?

Concerns and Roadblocks:

1. Balancing full time work.
2. Will be reaching out for feedback over the next few weeks (eg. PCB design to NRC).
3. Photos from July in MERCURY shared folder for SEDS.

Thank you.

Questions?



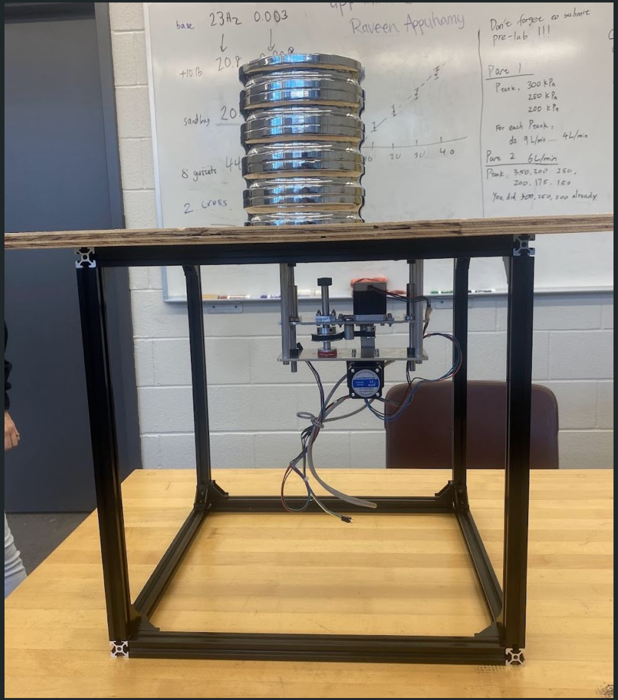
Testing Updates

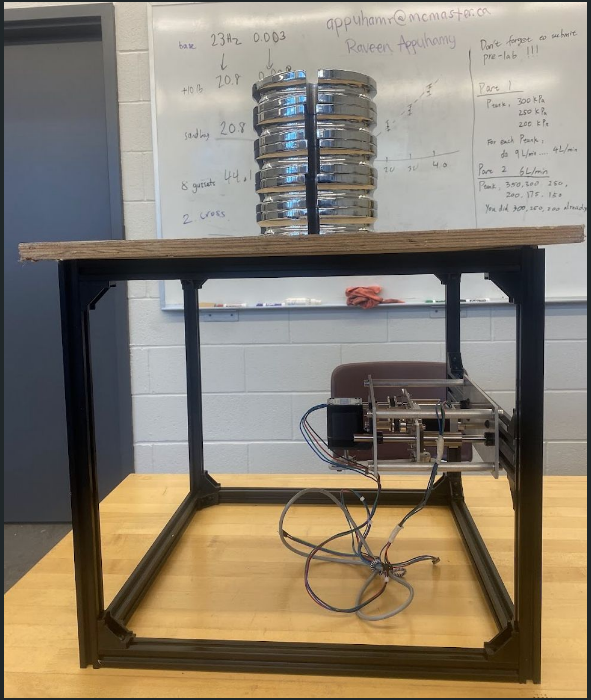
Structural Load Testing

Applied 3G load along each axis of the flight structure to meet loading requirements with specified safety factor.

Takeaway:

- No buckling or elastic bending experienced during test.
- No change throughout the 10 lbs intervals added.
- Note: amount required for testing was ultimately exceeded due to the tools available (needed 21kg, used ~23kg).





Pictured: Load Testing - Left to Stand for 1 Min

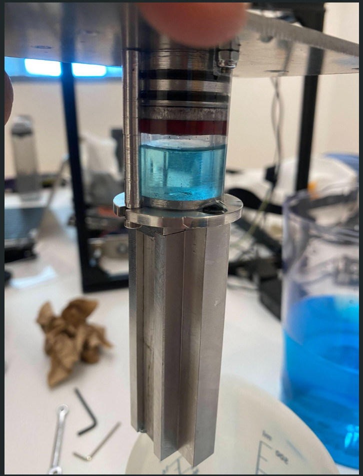
Testing Updates

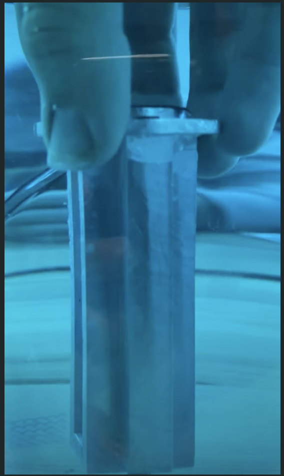
Leak Testing

To prevent leakage and free-floating matter in the case, the mold and the chamber were put through a leakage test and bubble test.

Takeaway:

- Chamber o-rings successfully prevent leakage from the chamber.
- Additional sealant was required for the mold due to the gaps in the aluminum-on-aluminum assembly.
- Passed test following modifications.





Pictured: Chamber Leak Test & Assembly Bubble Test - Left to Stand for 1 Min

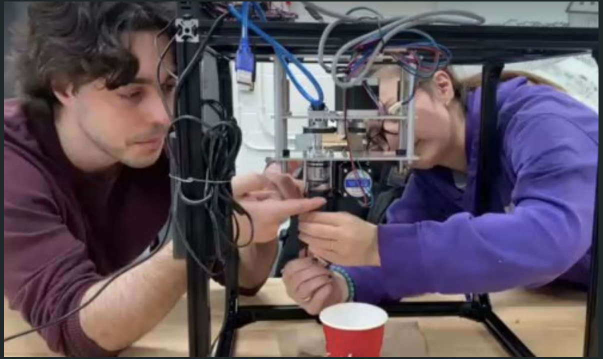
Testing Updates

Functional Testing

Functional mixing tests have begun to meet capstone deadlines. Dust is slowly being added to resin for mixing within the chamber.

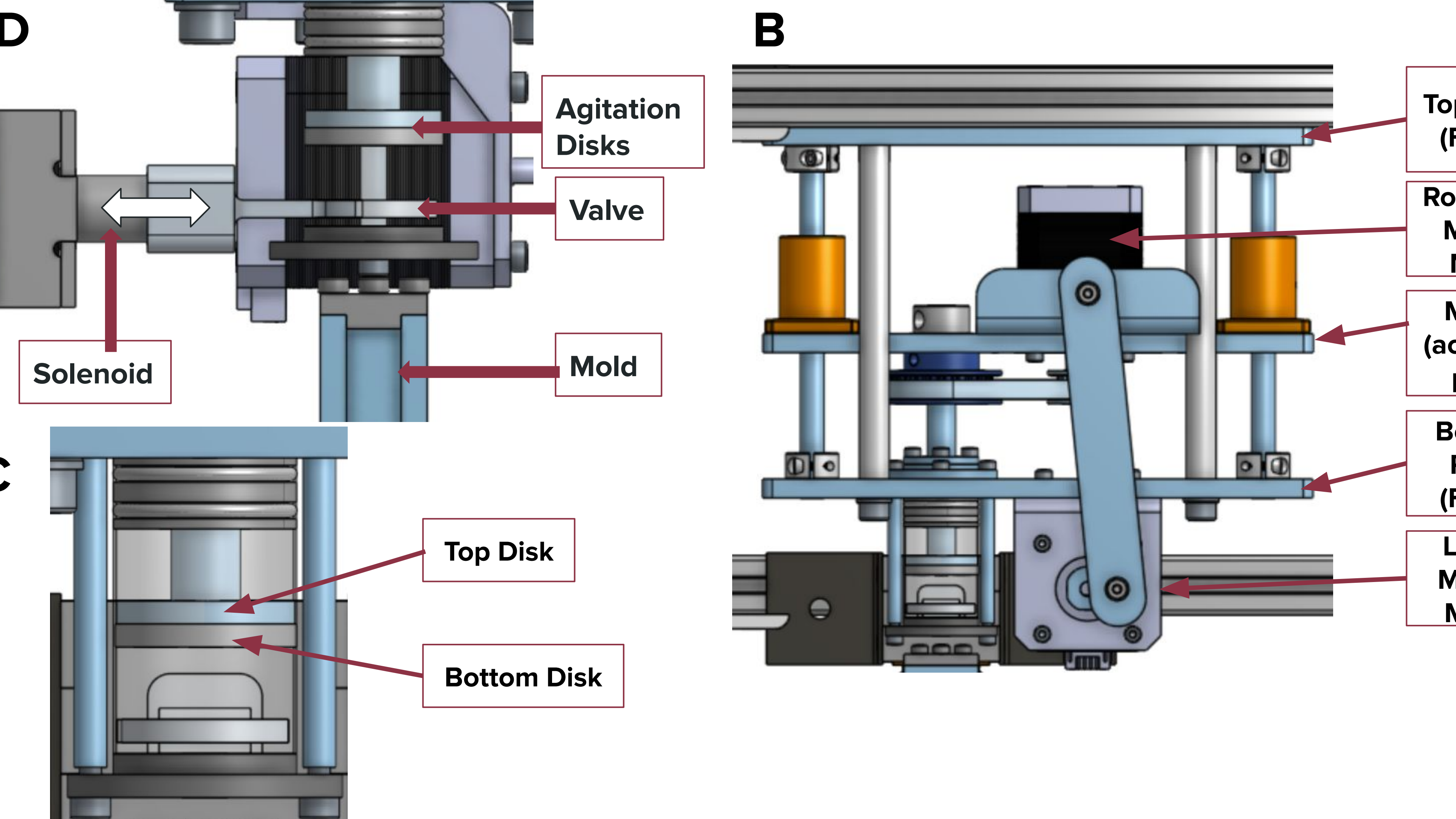
Takeaway:

- Successfully mixed with viscous liquid.
- System works for smaller amounts of dust, but need more of a ‘scoop’ motion to encourage dust to interface with the resin.
- Testing different mixing disk shapes to mitigate this torque issue.
- And just today….25% resin?

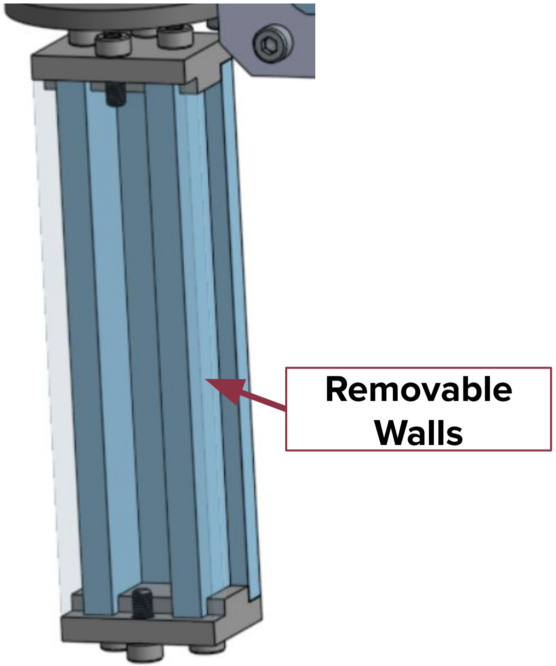


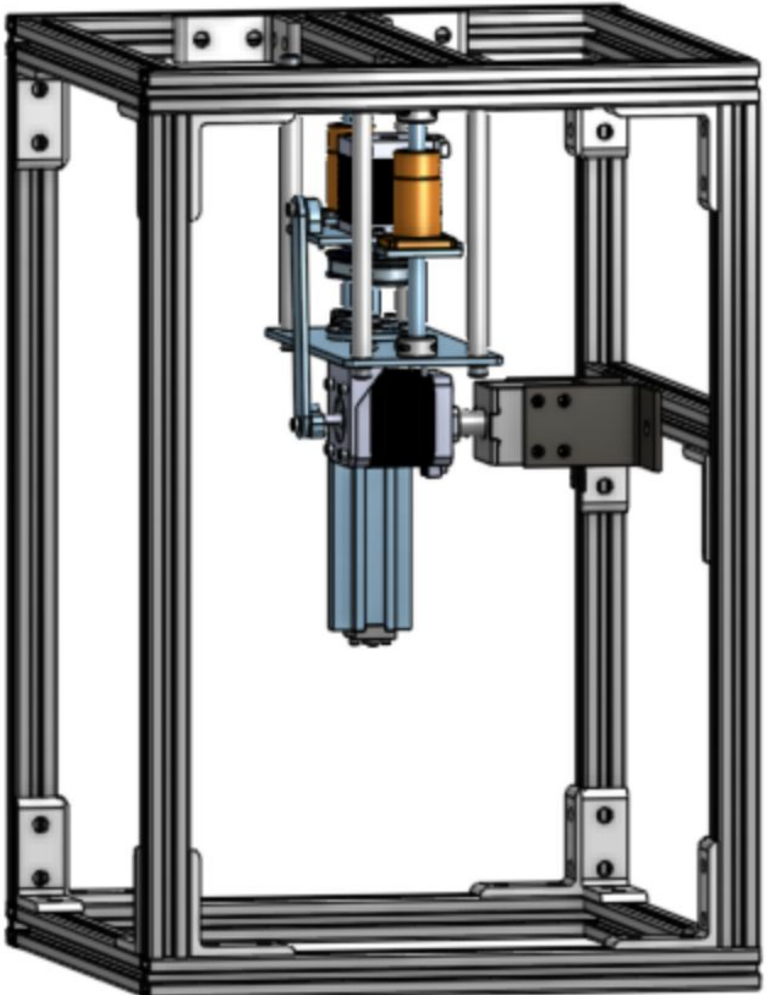
Active Mixing Taking Place with Button Controls

Testing Updates


D
Agitation Disks
Valve
Solenoid
Mold
B
C
Top Disk
Bottom Disk

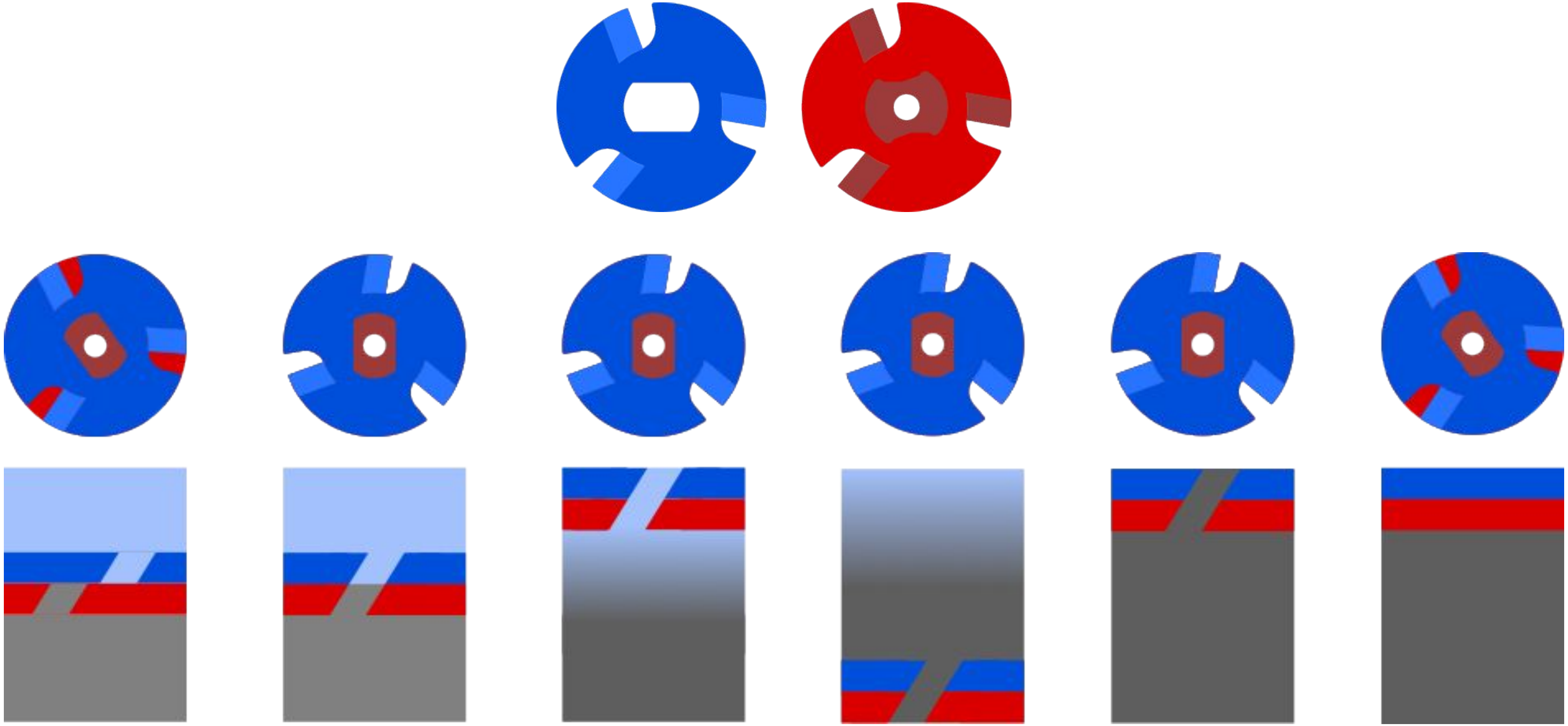
E





A

Mixing Mechanism



Speed and Torque Calcs - Theoretical

Rotation		
Name (Units)	Value	Description
r (mm)	12.315	Radius From CAD
D (in)	0.969685039	Diameter of agitator
TS (ft/min)	200	Ideal Tip Speed from Research [4]
N (rpm)	787.8266611	Rotational Speed
N (rps)	13.13044435	Rotational Speed
Q (gpm)	2.953957377	Pumping Capacity [3]
Q (cm^3/min)	11181.93979	Pumping Capacity
N_motor (rpm)	262.608887	Motor speed from 3:1 gear reduction
HP	0.000411631	Impeller Power Draw from Research [3]
P (watt)	0.30695336	Motor Power
Assuming no friction from o-rings and fluid		

Extrusion Testing Analysis		
F (lbs)	14	Force from pressure sensor
F (N)	62.22222222	Force from pressure sensor
A0 (in^2)	0.196349541	0.5in cavity of aluminum block
As (in^2)	0.069220883	19/64 nozzle diameter
A0 (mm^2)	126.6768698	Cross sectional area of billet (material being extruded)
Af (mm^2)	44.65854491	Cross sectional area of extruded product (final shape)
k	0.471121622	Using equation from [1]

Oscillation		
Name (Units)	Value	Description
y (in)	0.396	Stroke Length from CAD
x (m)	0.0100584	Moment arm from CAD
A (in^2)	0.738501313	Total area of agitator
A_h (in^2)	0.228501313	Area of agitator holes
t_piston (s)	5	Time for 1 cycle [current limitation of device]
x' (in/s)	0.0792	Piston speed
RPM	12	Rotational Speed
A0 (mm^2)	476.4515071	Cross sectional area of billet (material being extruded)
Af (mm^2)	147.4199071	Cross sectional area of extruded product (final shape)
k (Mpa)	0.471121622	Extrusion constant from testing [2]
F (N)	263.3174945	Extrusion Froce from Research [1]
T (Nm)	2.648552686	T = Force x distance
P (watt)	3.328442552	Power = Torque (Nm) x RPM / 9.5488
Neglecting effects of adding rotation during oscillation and weight of subassembly		

Speed and Torque Calcs - Theoretical

Equation Summary

Impeller Diameter (ft)

$$D = \left(\frac{6.12E7 \cdot HP \cdot 0.85}{SG \cdot N_p \cdot N^3} \right)^{0.2}$$

Torque per Equivalent Volume (in-lbs/Eq. Vol)

$$\frac{T_Q}{EqV} = \left(\frac{\frac{BHP \cdot 63025}{N}}{SG \cdot V} \right)$$

Impeller Power Draw (HP)

$$BHP = \frac{N_p D^5 N^3 SG}{6.124 \times 10^7}$$

Superficial Velocity (FPM)

$$SV = \frac{Q}{7.48\,A}$$

Pumping Capacity (usgpm)

Single Impeller

$$Q = 7.48\, N_Q N D^3$$

Dual Impellers

$$Q = 1.8 \cdot Single\,impeller$$

Equivalent Tank Diameter (ft)

Used to determine equivalent tank diameter of square or rectangular tanks

$$T_{Eq} = 1.13\sqrt{L \cdot W}$$

Impeller Tip Speed (fpm)

$$TS = \pi D N\,[FPM]$$

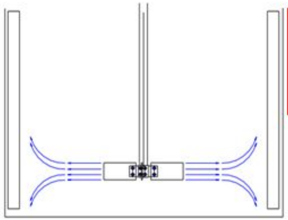
Velocity Gradient (sec^{-1})

$$G = 444\sqrt{\frac{BHP \cdot 1000}{V \cdot \mu}}$$

Where:

D is Impeller Dia in [Feet]
N is Impeller Speed [RPM]
Q is Pumping Capacity [USGPM]
HP is Nameplate Horsepower

T is Tank Dia in [Feet]
V is volume in [US Gal]
BHP is Brake Horsepower
T_Q is Torque [In-lbs]



Radial Flow Turbines

Power Number, N_P = 2.5 to 4.75
Pumping Number, N_Q = 0.95 to 1.23

Applications:

- High Shear
- Gas\Liquid Dispersion
- Liquid Liquid Dispersion
- Low Level Mixing

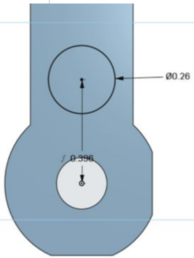
Extrusion load calculations

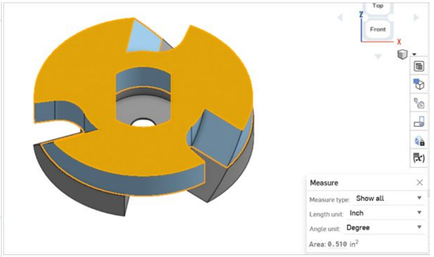
Extrusion ratio = $\left(\frac{A_0}{A_f}\right)$

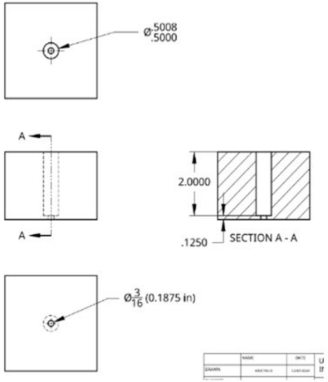
Extrusion force F in N

$$F = A_0 k ln\left(\frac{A_0}{A_f}\right)$$

Where A_0 is the area of cross-section of billet in mm^2
A_f is the area of product/extrusion in mm^2
k is extrusion constant in MPa







Power-Torque

Torque (lb.in) = 63,025 x Power (HP) / Speed (RPM)

Power (HP) = Torque (lb.in) x Speed (RPM) / 63,025

Torque (N.m) = 9.5488 x Power (kW) / Speed (RPM)

Power (kW) = Torque (N.m) x Speed (RPM) / 9.5488

Speed and Torque Calcs - Experimental

Rotation		
Name (Units)	Value	Description
r (mm)	12.315	Radius From CAD
D (in)	0.96968504	Diameter of agitator
N (rpm)	144	Rotational Speed
N (rps)	2.4	Rotational Speed
Q (gpm)	0.53992824	Pumping Capacity [3]
Q (cm^3/min)	2043.84976	Pumping Capacity
N_motor (rpm)	48	Motor speed from 3:1 gear reduction
HP	2.5136E-06	Impeller Power Draw from Research [3]
P (watt)	0.00187442	Motor Power
Assuming no friction from o-rings and fluid		

Oscillation		
Name (Units)	Value	Description
y (in)	0.396	Stroke Length from CAD
x (m)	0.0100584	Moment arm from CAD
A (in^2)	0.73850131	Total area of agitator
A_h (in^2)	0.22850131	Area of agitator holes
t_piston (s)	20	Time for 1 cycle [current limitation of device]
x' (in/s)	0.0198	Piston speed
RPM	3	Rotational Speed
A0 (mm^2)	476.451507	Cross sectional area of billet (material being extruded)
Af (mm^2)	147.419907	Cross sectional area of extruded product (final shape)
k (Mpa)	0.47112162	Extrusion constant from testing [2]
F (N)	263.317494	Extrusion Froce from Research [1]
T (Nm)	2.64855269	T = Force x distance
P (watt)	0.83211064	Power = Torque (Nm) x RPM / 9.5488
Neglecting effects of adding rotation during oscillation and weight of subassembly		

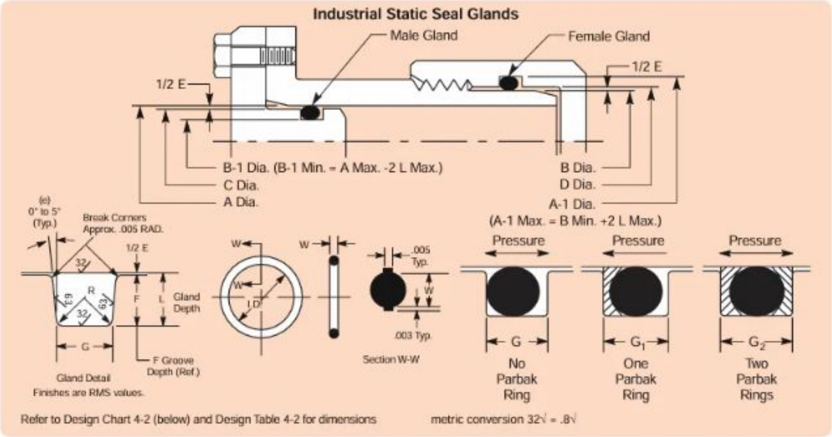
Additional Calculations: O-Ring Seal Design

Static Seal

Guide for Design Table 4-2

If Desired Dimension is Known for	Select Closest Dimension in Column	Read Horizontally in Column	To Determine Dimension for
Bore Dia. male gland	A	B-1 C G	Groove Dia. (male gland) Plug Dia. (male gland) Groove width
Plug Dia. male gland	C	A B-1 G	Bore Dia. (male gland) Groove (male gland) Groove width
Tube OD female gland	B	A-1 D G	Groove Dia. (female gland) Throat Dia. (female gland) Groove width
Throat Dia. female gland	D	A-1 B G	Groove Dia. (female gland) Tube OD (female gland) Groove width

Design Guide 4-2: Guide for Design Table 4-2



Gland Design

Known Properties

Female/Male Gland: Male Gland

- Chamber Top: Outer circumference contains O-Ring gland
- Chamber Wall: No features

Surface Finish: should not exceed 32 micro-inches (32 rms)

Known Dimension: Bore Diameter (25.4 mm) [1 in]

- Chamber walls have an ID of standard pipe

Determined Properties

O-Ring Gland

Design Table 4-2: Gland Dimensions for Industrial O-Ring Static Seals, 103.5 Bar (1500 psi) Max.

Column	Property	Dimension	Comments
A	Bore Diameter (Male Gland)	1.000 in +0.002 -0.000	- Exact dimension of 1.000in - Driving property
B-1	Groove Diameter (Male Gland)	0.900 in +0.000 -0.002	
C	Plug Diameter (Male Gland)	0.998 in +0.000 -0.001	
G	Groove Width	0.093 in +0.005 -0.000	- Other options available, smallest was chosen

Additional Calculations: O-Ring Seal Design

Static Seal

O-Ring Size

Design Table 4-2: Gland Dimensions for Industrial O-Ring Static Seals, 103.5 Bar (1500 psi) Max.

Column	Property	Dimension	Comments
O-Ring Size	Parker No. 2-	020	- Driving Property - Determined from previous step
Dimensions: ID	Internal Diameter of O-Ring	0.864 in +0.009 -0.009	
Dimensions: W	O-Ring Thickness	0.070 in +0.003 -0.003	- Other options available, smallest was chosen

Sanity Check

Chamber ID: 1.00 in
Groove Diameter: 0.900 in

Clearance:

$$(1.000 - 0.900)/2 = 0.05$$

O-Ring Thickness: 0.07 in

O-Ring Thickness > Clearance, therefore there will be squeeze.

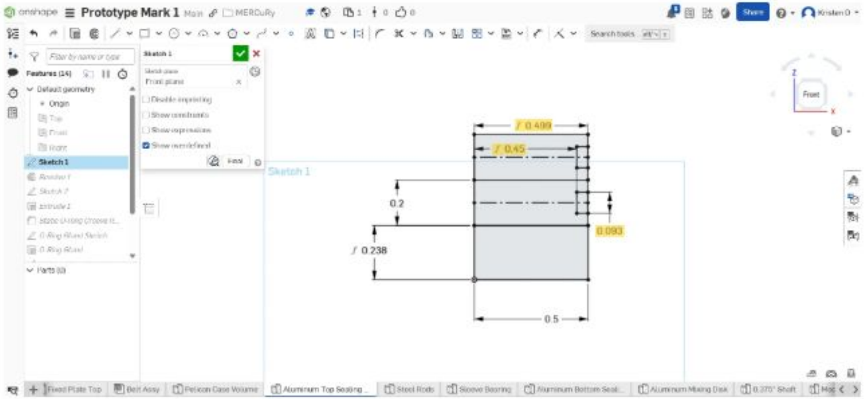
Design Chart 4-2: For Industrial O-Ring Static Seal Glands

Column	Property	Dimension	Comments
O-Ring 2-Size	AS568B-	004 through 050	- Driving Property - Determined from previous steps
W	Nominal Cross-Section	1/16	
W	Actual Cross-Section	.070 in +0.003 -0.003	
L	Gland Depth	.050 to .052 in	
Squeeze	Actual Squeeze	0.015 to 0.023 in	
Squeeze	Percent Squeeze	22% to 32%	
E	Diametral Clearance	0.002 to 0.005 in	
G	Groove Width - No Parbak Ring	0.093 to 0.098 in	
R	Groove Radius	0.005 to 0.015 in	

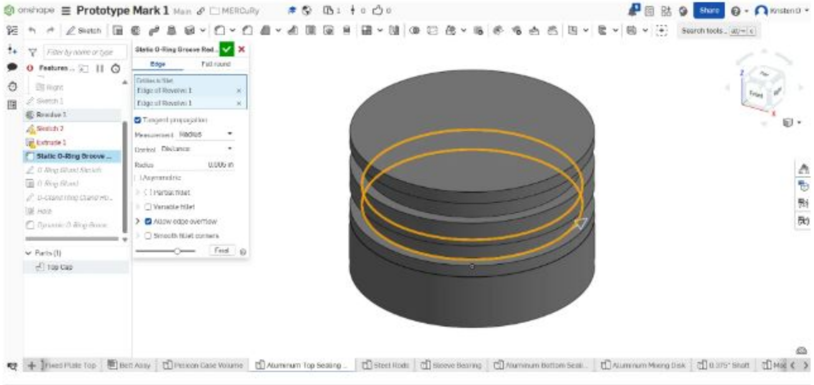
Additional Calculations: O-Ring Seal Design

Static Seal

- The following dimensions were defined using the design charts *within the part sketch*
  - Plug Diameter: 0.998 in
    - Plug Radius: 0.998/2 in = 0.499in
  - Groove Diameter: 0.9 in
    - Groove Radius: 0.9/2 in = 0.45 in
  - Groove Width: 0.093 in

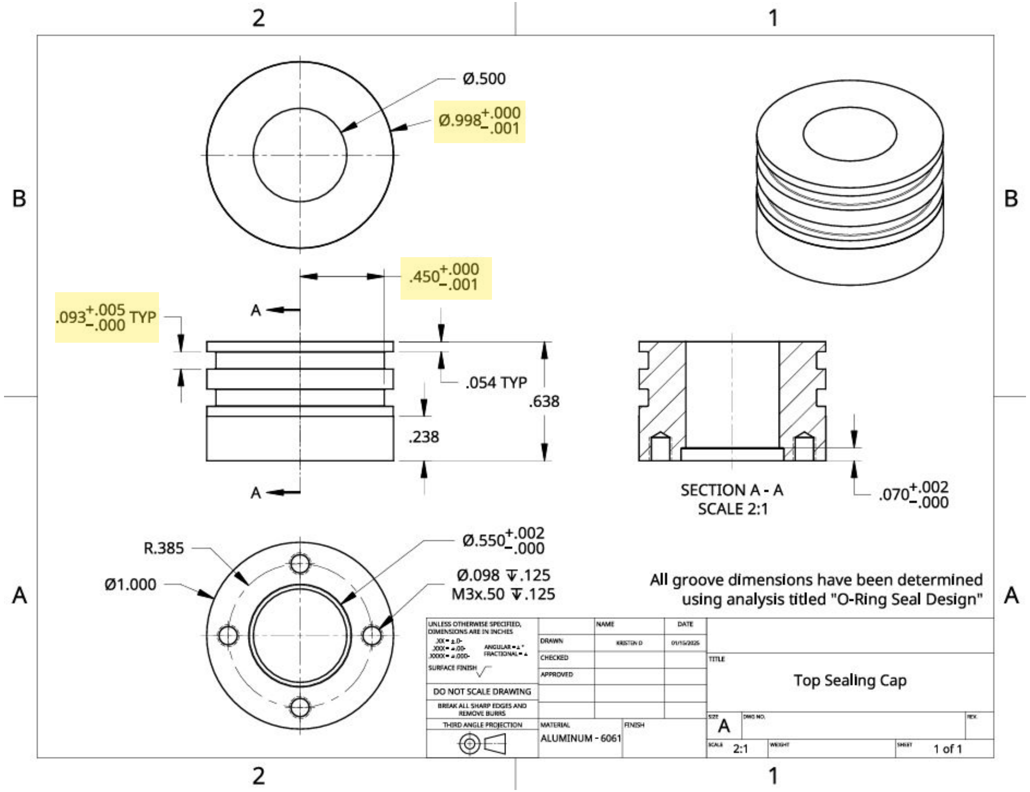


- The groove radius was *implemented as a fillet*
  - Groove Radius: 0.005 in



Additional Calculations: O-Ring Seal Design

Static Seal



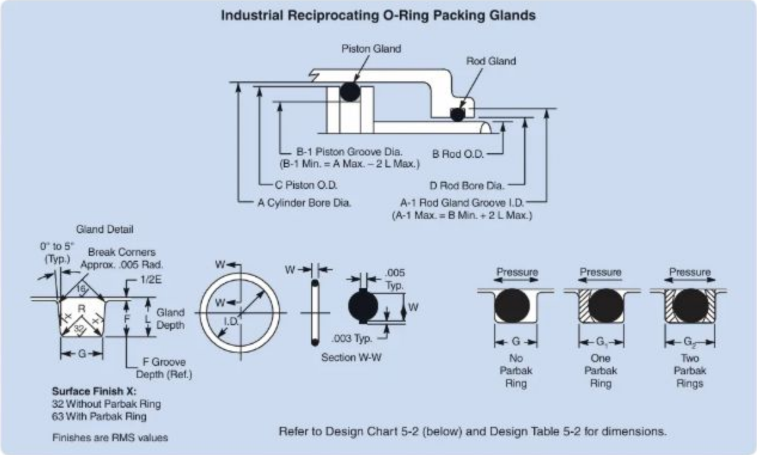
Additional Calculations: O-Ring Seal Design

Dynamic Seal

Guide for Design Table 5-2

If Desired Dimension is Known for	Select Closest Dimension in Column	Read Horizontally in Column	To Determine Dimension for
Bore Dia of cylinder	A	B-1 C G	Groove Dia of piston OD of piston Groove width
OD of piston	C	A B-1 G	Bore Dia of cylinder Groove Dia of piston Groove width
OD of rod	B	A-1 D G	Groove Dia for rod Bore ID for rod Groove width
Bore Dia for rod	D	A-1 B G	Groove Dia for rod OD of rod Groove width

Design Guide 5-2b: Guide For Design Table 5-2



Gland Design

Known Properties

Piston/Rod Gland: Rod Gland

- Shaft: No features
- Top Cap: inner groove contains O-Ring gland

Surface Finish: should not exceed 32 micro-inches (32 rms)

Known Dimension: OD of Rod [0.375 in]

Determined Properties

O-Ring Gland

Design Table 5-2: Gland Dimensions for Industrial Reciprocating O-Ring Seals, 103.5 Bar (1500 psi) Max.

Column	Property	Dimension	Comments
B	Outer Diameter (Rod)	0.374 in +0.000 -0.002	- Closest *undersized* dimension to 0.375 in - Driving property
A-1	Groove Diameter (Rod Gland)	0.550 in +0.002 -0.000	
D	Bore Diameter (Rod)	0.376 in +0.000 -0.001	
G	Groove Width	0.140 in +0.005 -0.000	- Other options available, second smallest was chosen for ease of manufacturing

Additional Calculations: O-Ring Seal Design

Dynamic Seal

O-Ring Size

Design Table 5-2: Gland Dimensions for Industrial Reciprocating O-Ring Seals, 103.5 Bar (1500 psi) Max.

Column	Property	Dimension	Comments
O-Ring Size	Parker No. 2-	110	- Driving Property - Determined from previous step
Dimensions: ID	Internal Diameter of O-Ring	0.362 in +0.005 -0.005	
Dimensions: W	O-Ring Thickness	0.103in +0.003 -0.003	- Other options available, smallest was chosen

Sanity Check

Rod OD: 0.375in
Groove Diameter: 0.550in

Clearance:

$$(0.550 - 0.375)/2 = 0.0875$$

O-Ring Thickness: 0.103 in

O-Ring Thickness > Clearance, therefore there will be squeeze

Design Chart 5-2-a: Design Chart for Industrial Reciprocating O-Ring Packing Glands

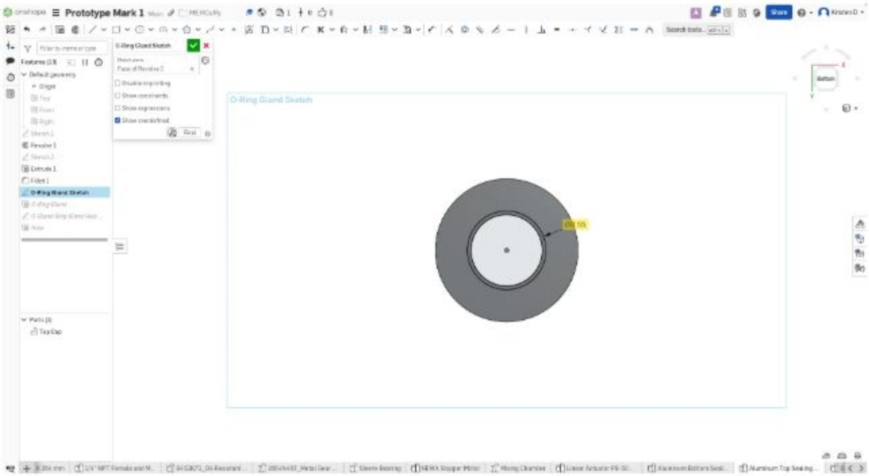
Column	Property	Dimension	Comments
O-Ring 2-Size	AS568B-	104 through 116	- Driving Property - Determined from previous steps
W	Nominal Cross-Section	3/32	
W	Actual Cross-Section	.103 in +0.003 -0.003	
L	Gland Depth	.088 to .090 in	
Squeeze	Actual Squeeze	0.010 to 0.018 in	
Squeeze	Percent Squeeze	10% to 17%	
E	Diametral Clearance	0.002 to 0.005 in	
G	Groove Width - No Parbak Ring	0.140 to 0.145 in	
R	Groove Radius	0.005 to 0.015 in	

Additional Calculations: O-Ring Seal Design

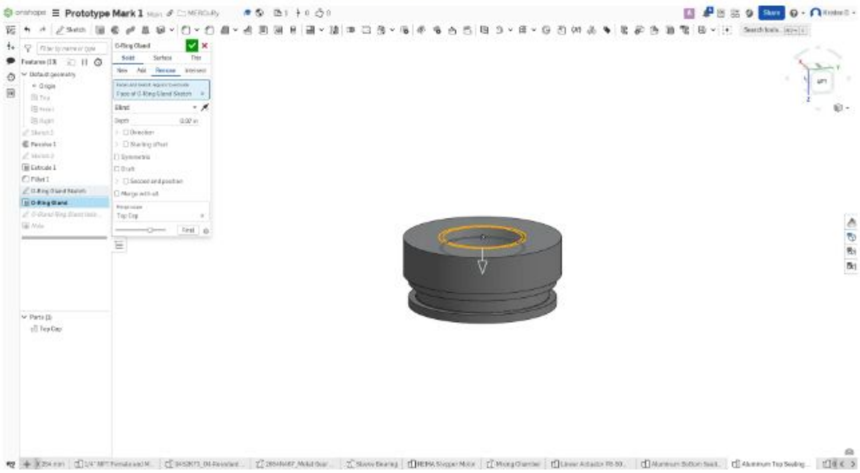
Dynamic Seal

Top Sealing Cap

- The following dimensions were defined using the design charts *within the part sketch*
  - Groove Diameter: 0.550 in

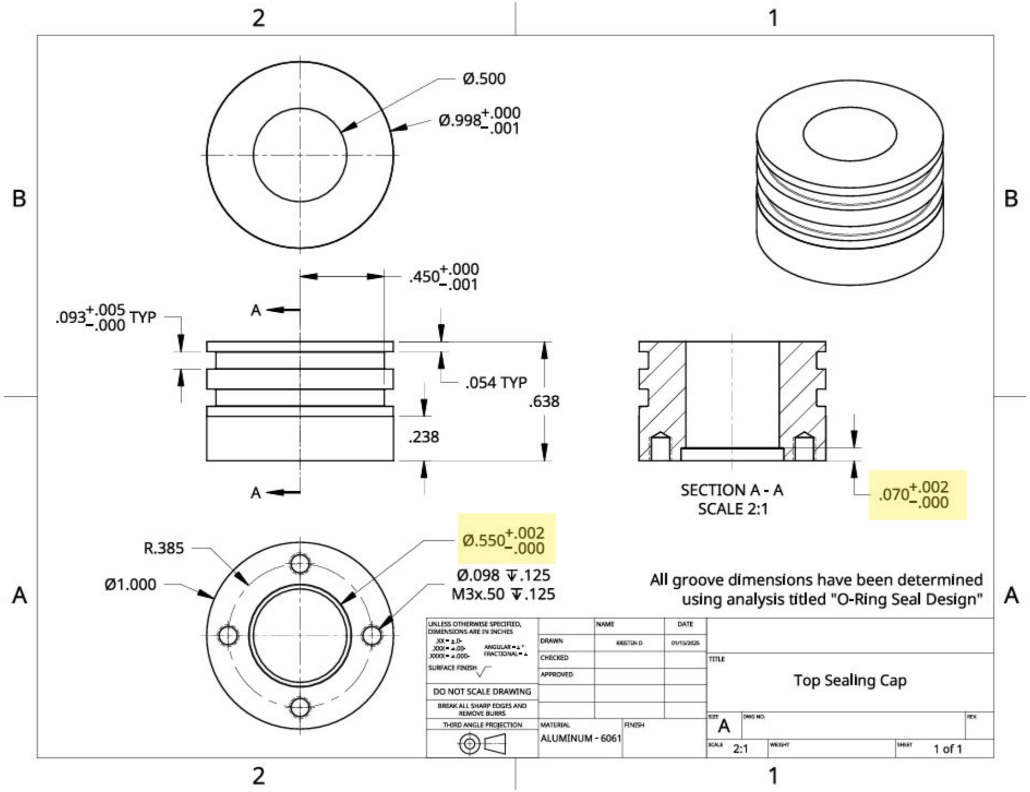


- *Half of* the groove width was *removed* from the part geometry
  - Groove Width: 0.140in
    - Half of Groove Width: 0.140in/2 = 0.07in



Additional Calculations: O-Ring Seal Design

Dynamic Seal



Additional Calculations: O-Ring Seal Design

Mixing Tool

⚠️

- In retrospect, prior to calculating the dynamic O-ring and groove required for this component, the amount of material left in the mixing tool should have been calculated. Since these calculations it is apparent that the mixing tool is not large enough to support and O-ring groove.

Mixing Tool Features

Hole Diameter: 3mm

Maximum D-Shaft Diameter: 9.525mm

Outer Diameter: 24.63 mm

Material Remaining:

$$(((24.63 - 9.525)/2) - 3)/2 = 2.28$$

If there were no additional features such as an O-ring seal, the remaining material on each side of the hole pattern is about 2.28 mm. Thus adding an O-ring groove will remove too much material risking the manufacturability and structural integrity of the mixing tool.

Gland Design

Known Properties

Piston/Rod Gland: Piston Gland

- Mixing Tool: Outer circumference contains O-Ring gland
- Chamber Wall: No features

Surface Finish: should not exceed 32 micro-inches (32 rms)

Known Dimension: Bore Diameter (24.630 mm) [0.969685 in]

- Chamber walls have an ID of standard pipe

Additional Calculations: O-Ring Seal Design

Mixing Tool

Iteration 1:

Determined Properties

O-Ring Gland

Design Table 5-2: Gland Dimensions for Industrial Reciprocating O-Ring Seals, 103.5 Bar (1500 psi) Max.

Column	Property	Dimension	Comments
A	Bore Diameter (Cylinder)	0.937 in +0.002 -0.000	- Closest *undersized* dimension to 0.969685 in - Driving property
B-1	Groove Diameter (Piston)	0.761 in +0.000 -0.002	
C	Outer Diameter (Piston)	0.935 in +0.000 -0.001	
G	Groove Width	0.140 in +0.005 -0.000	- Other options available, smallest was chosen

O-Ring Size

Design Table 5-2: Gland Dimensions for Industrial Reciprocating O-Ring Seals, 103.5 Bar (1500 psi) Max.

Column	Property	Dimension	Comments
O-Ring Size	Parker No. 2-	116	- Driving Property - Determined from previous step
Dimensions: ID	Internal Diameter of O-Ring	0.737 in +0.009 -0.009	
Dimensions: W	O-Ring Thickness	0.103 in +0.003 -0.003	- Other options available, smallest was chosen

Additional Calculations: O-Ring Seal Design

Mixing Tool

Design Chart 5-2-a: Design Chart for Industrial Reciprocating O-Ring Packing Glands

Column	Property	Dimension	Comments
O-Ring 2-Size	AS568B-	104 through 116	- Driving Property - Determined from previous steps
W	Nominal Cross-Section	3/32	
W	Actual Cross-Section	.103 in +0.003 -0.003	
L	Gland Depth	.088 to .090 in	
Squeeze	Actual Squeeze	0.010 to 0.018 in	
Squeeze	Percent Squeeze	10% to 17%	
E	Diametral Clearance	0.002 to 0.005 in	
G	Groove Width - No Parbak Ring	0.140 to 0.145 in	
R	Groove Radius	0.005 to 0.015 in	

Sanity Check

Chamber ID: 0.970 in
Groove Diameter: 0.761 in

Clearance:

$$(0.970 - 0.761)/2 = 0.1045$$

O-Ring Thickness: 0.103 in

O-Ring Thickness < Clearance, therefore there will not be squeeze, need to iterate with thicker O-ring or a smaller

- Multiple iterations were required:
  - Iteration 2: Thicker O-Ring
    - Squeeze would be possible, however thickness of 0.139” was larger than our anticipated disk thickness of 0.125”
  - Iteration 3: Custom O-Ring Gland
    - Was able to calculate a groove diameter that would allow for squeeze

Additional Calculations: O-Ring Seal Design

Mixing Tool - Seal Disk Design

- Iteration 4:
    - Rather than using an O-ring, we could produce the mixing disk out of PTFE
    - Determined dimensions using the O-Ring design tables

Seal Outer Diameter

Known Dimension:

Bore Diameter: 25.4mm [1.00 in]

- Chamber walls have an ID of standard pipe

$$Squeeze = (OD_{seal} - ID_{chamber})/2$$

$$OD_{seal} = 2 \times Squeeze + ID_{chamber}$$

$$OD_{seal} = 2 \times (0.25mm) + 25.4mm$$

$$OD_{seal} = 25.90mm$$

Disk Thickness: 3.175 mm [0.125 in]

Disk Thickness: 3.175 mm [0.125 in]

- I will design the seal as if it were an O-ring with a cross-section of 0.103in (~2.6mm), referencing *Design Chart 5-2a*

Industrial Reciprocating O-Ring Packing Glands

O-Ring 2-Size AS568A-	W Cross-Section Nominal	W Cross-Section Actual	L Gland Depth	Squeeze Actual	Squeeze %	E(a) Diametral Clearance	G-Groove Width: No Parbak Ring(G)	G-Groove Width: One Parbak Ring(G_1)	G-Groove Width: Two Parbak Rings(G_2)	R Groove Radius	Max. Eccentricity (b)
006 through 012	1/16	.070 ± .003	.055 to .057	.010 to .018	15 to 25	.002 to .005	.093 to .098	.138 to .143	.205 to .210	.005 to .015	.002
104 through 116	3/32	.103 ± .003	.088 to .090	.010 to .018	10 to 17	.002 to .005	.140 to .145	.171 to .176	.238 to .243	.005 to .015	.002
201 through 222	1/8	.139 ± .004	.121 to .123	.012 to .022	9 to 16	.003 to .006	.187 to .192	.208 to .213	.275 to .280	.010 to .025	.003
309 through 349	3/16	.210 ± .005	.185 to .188	.017 to .030	8 to 14	.003 to .006	.281 to .286	.311 to .316	.410 to .415	.020 to .035	.004
425 through 460	1/4	.275 ± .006	.237 to .240	.029 to .044	11 to 16	.004 to .007	.375 to .380	.408 to .413	.538 to .543	.020 to .035	.005

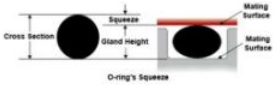
(a) Clearance (extrusion gap) must be held to a minimum consistent with design requirements for temperature range variation.
(b) Total indicator reading between groove and adjacent bearing surface.

Design Chart 5-2-a: Design Chart for Industrial Reciprocating O-Ring Packing Glands

Actual Squeeze: 0.01in (0.254mm) to 0.018in (0.4572mm)

- Design for minimum squeeze ~0.25mm

- The following equation is adapted for a solid seal, as the original equation only considers the difference in seal thickness and gland depth
    - This equation considers the squeeze in terms of the outer diameter of the seal rather than the thickness

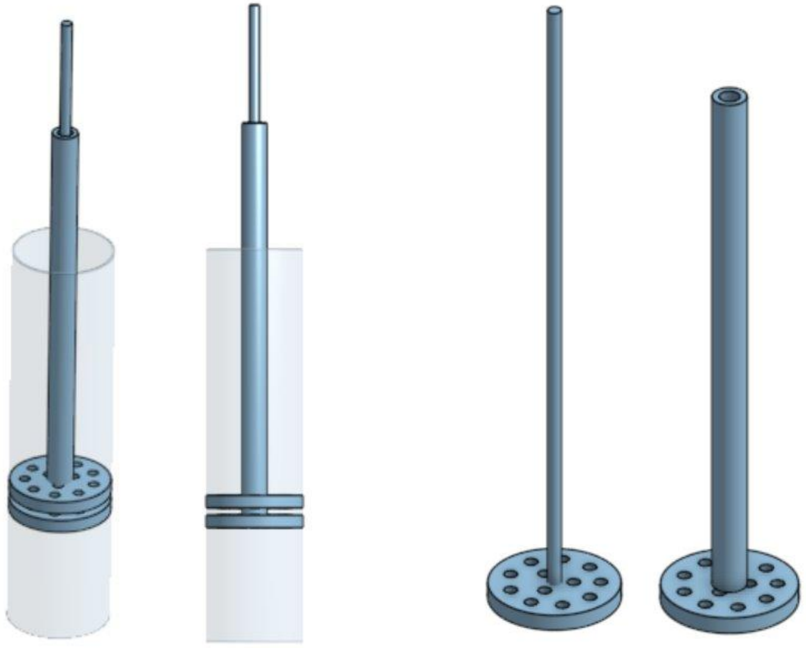


O-Ring Groove (Gland) Design: A Detailed Guideline - WayKen

Additional Calculations

Mixing Shaft Analysis

- In our initial design concepts we explored using concentric shafts in order to allow for independent rotation of the mixing disks
- We assumed this design would be prone to buckling/ torsion so further analysis was recommended



Additional Calculations

Mixing Shaft Analysis - Buckling

📖 Reference: Shigley's Mechanical Engineering Chapter 4: Deflection and Stiffness

$I = Ak^2$

I = moment of inertia

A = cross-sectional area

k = radius of gyration

$P_{cr} = C\pi^2 EI/l^2$

C = end condition constant

E = Young's Modulus

l = length of column

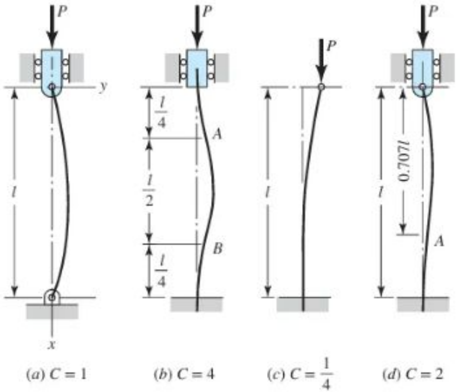
Table 4–2 End-Condition Constants for Euler Columns [to Be Used with Equation (4–43)]

Column End Conditions	End-Condition Constant C: Theoretical Value	Conservative Value	Recommended Value*
Fixed-free	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
Rounded-rounded	1	1	1
Fixed-rounded	2	1	1.2
Fixed-fixed	4	1	1.2

*To be used only with liberal factors of safety when the column load is accurately known.

Figure 4–18

(*a*) Both ends rounded or pivoted; (*b*) both ends fixed; (*c*) one end free and one end fixed; (*d*) one end rounded and pivoted, and one end fixed.



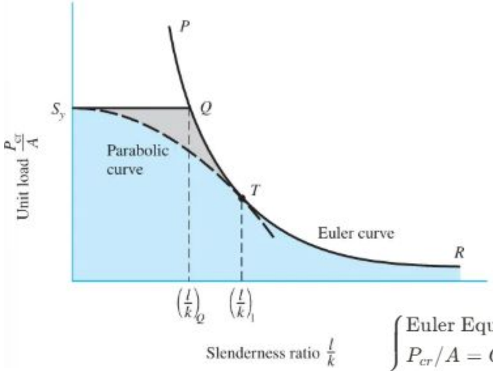


Figure 4–19

Euler curve plotted using Equation (4–43) with $C = 1$.

$$\begin{cases} \text{Euler Equation} & \\ P_{cr}/A = C\pi^2 E/(l/k)^2 & \text{if } (l/k) \le (l/k)_1 \\ \text{Parabolic Equation} & \\ P_{cr}/A = S_y - (lS_y/2\pi k)^2(1/CE) & \text{if } (l/k) > (l/k)_1 \end{cases}$$

Additional Calculations

Mixing Shaft Analysis - Buckling

Euler Equation

- Given a column of round cross section with diameter d:

$A = \pi d^2/4$

$I = \pi d^4/64$

$k = (I/A)^{1/2}$

$k = [(\pi d^4/64)/(\pi d^2/4)]$

$k = d/4$

$P_{cr}/A = C\pi^2 E/(l/k)^2$

$P_{cr}/(\pi d^2/4) = C\pi^2 E/[l/(d/4)]^2$

- Solving for d yields: $d = (64P_{cr}l^2/\pi^3 CE)^{1/4}$

- Given a hollow column with outer diameter D and inner diameter d:

$A = \pi(D^2 - d^2)/4$

$I = \pi(D^4 - d^4)/64$

$k = (I/A)^{1/2}$

$k = [(\pi(D^4 - d^4)/64)/(\pi(D^2 - d^2)/4)]$

$k = \sqrt{(D^2 + d^2)}$

$P_{cr}/A = C\pi^2 E/(l/k)^2$

$P_{cr}/(\pi(D^2 - d^2)/4) = C\pi^2 E/[l/\sqrt{(D^2 + d^2)}]^2$

- Solving for D yields: $D = ((\pi^3 d^4 CE + 4l^2 P)/\pi^3 CE)^{1/4}$

Parabolic Equation

- Given a column of round cross section with diameter d:

$A = \pi d^2/4$

$I = \pi d^4/64$

$k = (I/A)^{1/2}$

$k = [(\pi d^4/64)/(\pi d^2/4)]$

$k = d/4$

$P_{cr}/A = S_y - (lS_y/2\pi k)^2(1/CE)$

$P_{cr}/(\pi d^2/4) = S_y - (lS_y/2\pi(d/4))^2(1/CE)$

- Solving for d yields: $d = 2(P_{cr}/\pi S_y + S_y l^2/\pi^2 CE)^{1/2}$

- Given a hollow column with outer diameter D and inner diameter d:

$A = \pi(D^2 - d^2)/4$

$I = \pi(D^4 - d^4)/64$

$k = (I/A)^{1/2}$

$k = [(\pi(D^4 - d^4)/64)/(\pi(D^2 - d^2)/4)]^{1/2}$

$k = \sqrt{(D^2 + d^2)}/4$

$P_{cr}/A = S_y - (lS_y/2\pi k)^2(1/CE)$

$P_{cr}/(\pi(D^2 - d^2)/4) = S_y - (lS_y/2\pi\sqrt{(D^2 + d^2)}/4)^2(1/CE)$

- D must be solved with an iterative solver
  - Can use Goal Seek if you set the following equation with the
    - To find an initial guess can use the DESMOS graph to find solution

$(P_{cr}/(\pi(D^2 - d^2)/4)) - (S_y - (lS_y/2\pi\sqrt{(D^2 + d^2)}/4)^2(1/CE)) = 0$

Additional Calculations

Mixing Shaft Analysis - Buckling

Buckling Analysis	**Solid Shaft**						
*This spreadsheet is used to **determine the diameter of the column** from a given critical load, material and length. First the calculation is completed with the Euler Method, but if this is not applicable, the Parabolic Method will be recommended.*						Input	
						Conditional Formatting	
						Output	
End Condition Constraint (C)	1		**Euler Equation**			**Parabolic Equation**	
			Diameter of Column (d) [m]	0.0187		**Diameter of Column (d) [m]**	0.0190
Material Properties			Diameter of Column (d) [mm]	18.74		Diameter of Column (d) [mm]	19.02
Young's Modulus (E) [Pa]	2.07E+11						
Yield Strength (S_y) [Pa]	5.00E+08		Moment of Inertia (I) [m^4]	6.06E-09		Moment of Inertia (I) [m^4]	1.78E-05
			Cross-Sectional Area (A) [m^2]	2.76E-04		Cross-Sectional Area (A) [m^2]	2.84E-04
Geometric Properties			Radius of Gyration (k) [m]	0.005		Radius of Gyration (k) [m]	0.25
Length of Column (l) [m]	0.375						
Length of Column (l) [mm]	375		**Assumption Check**			**Assumption Check**	
			Critical Slenderness Ratio (l/k)_1	90.4		Critical Slenderness Ratio (l/k)_1	90.40
Load Conditions			Slenderness Ratio (l/k)	80		Slenderness Ratio (l/k)	1.5
Safety Factor (n)	4		**Recommended Method**	**Parabolic**		**Recommended Method**	**Parabolic**
Maximum Load (P) [N]	2.20E+04						
Critical Load (P_cr) [N]	8.80E+04						

Additional Calculations

Mixing Shaft Analysis - Buckling

*This spreadsheet is used to **determine the maximum applied load to the column** from a given diameter, material and length. Reference the recommended method to determine what outputs are relevant.*

				Input	
				Conditional Formatting	
				Output	
End Condition Constraint (C)	0.25	**Geometric Calculations**		**Euler Equation**	
		Moment of Inertia (I) [m^4]	4.04E-10	Critical Load (P_cr) [N]	8.43E+06
Load Conditions		Cross-Sectional Area (A) [m^2]	7.13E-05	**Maximum Allowable Load (P) [N]**	8.43E+06
Safety Factor (n)	1	Radius of Gyration (k) [m]	0.002	**Check for Failure**	**Pass**
Applied Load [N]	1300				
		Assumption Check		**Parabolic Equation**	
Material Properties		Critical Slenderness Ratio (l/k)_1	1229.3	Critical Load (P_cr) [N]	1.60E+04
Young's Modulus (E) [Pa]	6.89E+13	Slenderness Ratio (l/k)	38	**Maximum Allowable Load (P) [N]**	1.60E+04
Yield Strength (S_y) [Pa]	2.25E+08	**Recommended Method**	**Parabolic**	**Check for Failure**	**Pass**
Geometric Properties					
Length of Column (l) [in]	3.553				
Length of Column (l) [m]	0.0902462				
Length of Column (l) [mm]	90.2462				
Diameter of Column (d) [in]	0.375				
Diameter of Column (d) [m]	0.009525				
Diameter of Column (d) [mm]	9.525				

Additional Calculations

Mixing Shaft Analysis - Buckling

Buckling Analysis	**Hollow Shaft**					
This spreadsheet is used to ***determine the outer diameter of the column*** *from a given critical load, material and length. First the calculation is completed with the Euler Method, but if this is not applicable, the Parabolic Method will be recommended.*					Input	
					Conditional Formatting	
					Output	
End Condition Constraint (C)	1		**Euler Equation**		**Parabolic Equation**	
			Outer Diameter of Column (D) [m]	0.0193	**Initial Guess:**	
Material Properties			Outer Diameter of Column (D) [mm]	19.28	**Outer Diameter of Column (D) [m]**	0.0249
Young's Modulus (E) [Pa]	2.07E+11				Outer Diameter of Column (D) [mm]	24.93
Yield Strength (S_y) [Pa]	5.00E+08		Moment of Inertia (I) [m^4]	3.79E-10		
			Cross-Sectional Area (A) [m^2]	8.27E-06	Moment of Inertia (I) [m^4]	1.26E-08
Geometric Properties			Radius of Gyration (k) [m]	0.007	Cross-Sectional Area (A) [m^2]	2.05E-04
Length of Column (l) [m]	0.375				Radius of Gyration (k) [m]	0.008
Length of Column (l) [mm]	375		**Assumption Check**			
			Critical Slenderness Ratio (l/k)_1	90.4	Optimization Equation	-9.39E-06
Inner Diameter of Column (d) [m]	0.019		Slenderness Ratio (l/k)	55		
Inner Diameter of Column (d) [mm]	19		**Recommended Method**	**Parabolic**	**Assumption Check**	
					Critical Slenderness Ratio (l/k)_1	90.40
Load Conditions					Slenderness Ratio (l/k)	48
Safety Factor (n)	4				**Recommended Method**	**Parabolic**
Maximum Load (P) [N]	2.20E+04					
Critical Load (P_cr) [N]	8.80E+04					

Additional Calculations

Mixing Shaft Analysis - Buckling

This spreadsheet is used to ***determine the maximum applied load to the column*** *from a given diameters, material and length. Reference the recommended method to determine what outputs are relevant.*

Input	
Conditional Formatting	
Output	

End Condition Constraint (C)	1
Load Conditions	
Safety Factor (n)	3
Applied Load [N]	30000
Material Properties	
Young's Modulus (E) [Pa]	2.07E+11
Yield Strength (S_y) [Pa]	5.00E+08
Geometric Properties	
Length of Column (l) [m]	0.375
Length of Column (l) [mm]	375.00
Inner Diameter of Column (d) [m]	0.019
Inner Diameter of Column (d) [mm]	19.00
Outer Diameter of Column (D) [m]	0.0249
Outer Diameter of Column (D) [mm]	24.93

Geometric Calculations	
Moment of Inertia (I) [m^4]	1.26E-08
Cross-Sectional Area (A) [m^2]	2.05E-04
Radius of Gyration (k) [m]	0.008
Assumption Check	
Critical Slenderness Ratio (l/k)_1	90.4
Slenderness Ratio (l/k)	48
Recommended Method	**Parabolic**

Euler Equation	
Critical Load (P_cr) [N]	1.83E+05
Maximum Allowable Load (P) [N]	6.09E+04
Check for Failure	**Pass**
Parabolic Equation	
Critical Load (P_cr) [N]	8.80E+04
Maximum Allowable Load (P) [N]	2.93E+04
Check for Failure	**Fail**

Additional Calculations

Mixing Shaft Analysis - Torsion

📖 Reference: Shigley's Mechanical Engineering Chapter 3: Load and Stress Analysis

$\theta = Tl/GJ$

θ = angle of twist

T = torque

l = length

G = modulus of rigidity

J = polar second moment of area

$\tau = T\rho/J$

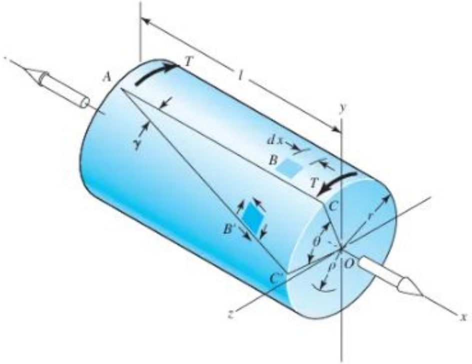
τ = shear stress

T = torque

ρ = radius

J = polar second moment of area

- Shear stress is maximum at the radius of the outer-most surface



Assumptions:

- Bar experiences pure torque, sections under consideration are remote from the point of application of the load and from change in diameter
- Material obeys Hooke's law
- Adjacent cross sections originally plane and parallel remain so after twisting, and any radial line remains straight
- Equation only applies to circular cross-sections

Solid Shaft

$J = \pi d^4/32$

d = diameter

Hollow Shaft

$J = \pi(D^4 - d^4)/32$

D = outer diameter

d = inner diameter

Additional Calculations

Mixing Shaft Analysis - Torsion

Torsion Analysis	**Solid Shaft**			Input
*This spreadsheet is used to determine the **maximum shear stress on the column** from a given diameter, material and length.*				Conditional Formatting
				Output
Load Conditions		**Geometric Calculations**		
Safety Factor (n)	1	Polar Second Moment of Area (J) [m^4]	8.08E-10	
Applied Torque (T) [Nm]	0.43			
Allowable Torque (T_all) [Nm]	0.43	**Angle of Twist (theta) [rad]**	0.00	
		Angle of Twist (theta) [deg]	0.00	
Material Properties				
Shear Strength (T_y) [Pa]	2.07E+08	**Maximum Shear Stress (tau) [Pa]**	2.53E+06	
Shear Modulus (G) [Pa]	2.60E+13	**Check for Failure**	**Pass**	
Geometric Properties				
Length of Column (l) [in]	3.553			
Length of Column (l) [m]	0.090			
Length of Column (l) [mm]	90.2462			
Outer Diameter of Column (D) [in]	0.375			
Outer Diameter of Column (D) [m]	0.010			
Outer Diameter of Column (D) [mm]	9.525			

Additional Calculations

Mixing Shaft Analysis - Torsion

Torsion Analysis	**Hollow Shaft**					Input
*This spreadsheet is used to determine the **maximum shear stress on the column** from a given diameter, material and length.*						Conditional Formatting
						Output
Load Conditions			**Geometric Calculations**			
Safety Factor (n)	2		Polar Second Moment of Area (J) [m^4]		6.38E-08	
Applied Torque (T) [Nm]	50					
Allowable Torque (T_all) [Nm]	100		**Angle of Twist (theta) [rad]**		0.29	
			Angle of Twist (theta) [deg]		16.63	
Material Properties						
Shear Strength (T_y) [Pa]	5.00E+08		**Maximum Shear Stress (tau) [Pa]**		1.18E+07	
Shear Modulus (G) [Pa]	2.70E+07			**Check for Failure**	**Fail**	
Geometric Properties						
Length of Column (l) [m]	0.010					
Length of Column (l) [mm]	10					
Outer Diameter of Column (D) [m]	0.030					
Outer Diameter of Column (D) [mm]	30					
Inner Diameter of Column (D) [m]	0.020					
Inner Diameter of Column (D) [mm]	20					

Additional Calculations

Slider-Crank Mechanism

📖 Reference: Dynamics and Mechanisms Design for Technology Students

Displacement Analysis

- Slider Crank mechanism is composed of the following components:

Linkage 1	- Connected to the point of rotation - Radius of circular motion
Linkage 2	- Connects slider to Linkage 1
Slider	- Restricted to travel linearly

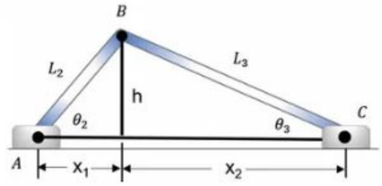


Figure 3.2

- Linkages create a triangle
    - Link 1 and 2 are constrained by a common height

L_2 = Length of linkage 1

L_3 = Length of linkage 2

x = Stroke length of slider

Linkage 1

$$sin(\theta_2) = h/L_2$$
$$h = L_2 sin(\theta_2)$$
$$x_1 = L_2 cos(\theta_2)$$

Linkage 2

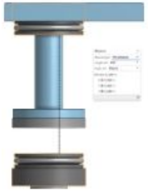
$$sin(\theta_3) = h/L_3$$
$$h = L_3 sin(\theta_3)$$
$$x_2 = L_3 cos(\theta_3)$$

$$h = L_2 sin(\theta_2) = L_3 sin(\theta_3)$$
$$sin(\theta_3) = (L_2/L_3) sin(\theta_2)$$
$$\theta_3 = sin^{-1}[(L_2/L_3) sin(\theta_2)]$$

$$x = x_1 + x_2$$
$$x = L_2 cos(\theta_2) + L_3 cos(\theta_3)$$

Linkage Design

Properties



Mixing Chamber Internal Height: 0.99in

- Related to chamber height

Stacked Disk Height: 2(0.125in) = 0.25 in

- Related to thickness of mixing disks

Stroke Length: 0.74in

$$0.99in - 0.25in = 0.74in$$

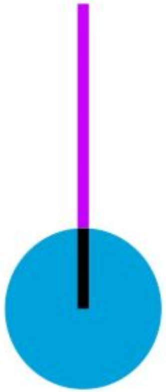
Additional Calculations

Slider-Crank Mechanism

Linkage 1

Problem Statement: Want to determine length of linkage 1 (L_2) using the required stroke length (x)

Maximum Displacement

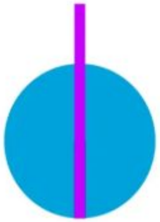


- Takes place at $\theta_2 = 0^\circ$

$$\theta_3 = sin^{-1}[(L_2/L_3)sin(\theta_2)]$$
$$\theta_3 = sin^{-1}[(L_2/L_3)sin(0^\circ)]$$
$$\theta_3 = sin^{-1}[0]$$
$$\theta_3 = 0^\circ$$

$$x = L_2cos(\theta_2) + L_3cos(\theta_3)$$
$$x = L_2cos(0) + L_3cos(0)$$
$$x_{max} = L_2 + L_3$$

Minimum Displacement



- Takes place at $\theta_2 = 180^\circ$

$$\theta_3 = sin^{-1}[(L_2/L_3)sin(\theta_2)]$$
$$\theta_3 = sin^{-1}[(L_2/L_3)sin(180^\circ)]$$
$$\theta_3 = sin^{-1}[0]$$
$$\theta_3 = 0^\circ$$

$$x = L_2cos(\theta_2) + L_3cos(\theta_3)$$
$$x = L_2cos(180) + L_3cos(0)$$
$$x_{min} = -L_2 + L_3$$

$$x_{stroke} = x_{max} - x_{min}$$
$$x_{stroke} = L_2 + L_3 - (-L_2 + L_3)$$
$$x_{stroke} = 2L_2$$
$$L_2 = x_{stroke}/2$$

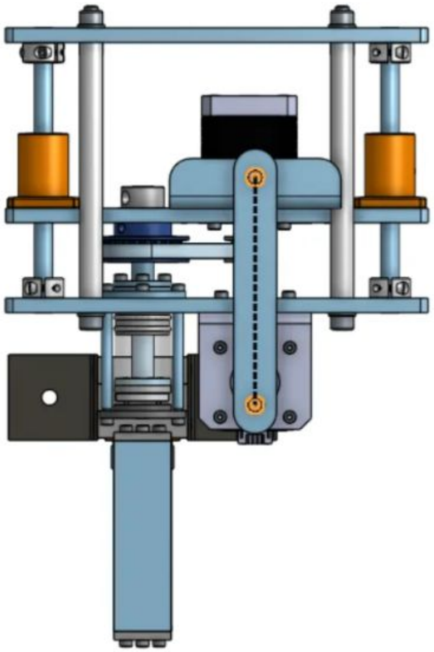
$$x_{min} = -L_2 + L_3$$
$$x_{max} = L_2 + L_3$$

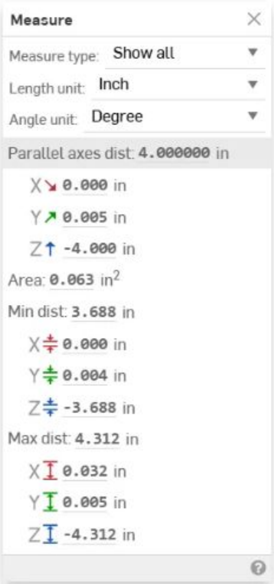
Additional Calculations

Slider-Crank Mechanism

Linkage 2

- Length is defined from the distance between the mounting holes at the lowest position
    - This is also when the plunger should be at its lowest state
- This dimension will be measured directly from the CAD file





Additional Calculations

Mold Wall Tolerances

Table A–13

A Selection of International Tolerance Grades—Inch Series (Size Ranges Are for *Over* the Lower Limit and *Including* the Upper Limit. All Values Are in Inches, Converted from Table A–11)

Basic Sizes	Tolerance Grades IT6	IT7	IT8	IT9	IT10	IT11
0–0.12	0.0002	0.0004	0.0006	0.0010	0.0016	0.0024
0.12–0.24	0.0003	0.0005	0.0007	0.0012	0.0019	0.0030
0.24–0.40	0.0004	0.0006	0.0009	0.0014	0.0023	0.0035
0.40–0.72	0.0004	0.0007	0.0011	0.0017	0.0028	0.0043
0.72–1.20	0.0005	0.0008	0.0013	0.0020	0.0033	0.0051
1.20–2.00	0.0006	0.0010	0.0015	0.0024	0.0039	0.0063
2.00–3.20	0.0007	0.0012	0.0018	0.0029	0.0047	0.0075
3.20–4.80	0.0009	0.0014	0.0021	0.0034	0.0055	0.0087
4.80–7.20	0.0010	0.0016	0.0025	0.0039	0.0063	0.0098
7.20–10.00	0.0011	0.0018	0.0028	0.0045	0.0073	0.0114
10.00–12.60	0.0013	0.0020	0.0032	0.0051	0.0083	0.0126
12.60–16.00	0.0014	0.0022	0.0035	0.0055	0.0091	0.0142

Table A–14

Fundamental Deviations for Shafts—Inch Series (Size Ranges Are for *Over* the Lower Limit and *Including* the Upper Limit. All Values Are in Inches, Converted from Table A–12)

Basic Sizes	Upper-Deviation Letter c	d	f	g	h	Lower-Deviation Letter k	n	p	s	u
0–0.12	−0.0024	−0.0008	−0.0002	−0.0001	0	0	+0.0002	+0.0002	+0.0006	+0.0007
0.12–0.24	−0.0028	−0.0012	−0.0004	−0.0002	0	0	+0.0003	+0.0005	+0.0007	+0.0009
0.24–0.40	−0.0031	−0.0016	−0.0005	−0.0002	0	0	+0.0004	+0.0006	+0.0009	+0.0011
0.40–0.72	−0.0037	−0.0020	−0.0006	−0.0002	0	0	+0.0005	+0.0007	+0.0011	+0.0013
0.72–0.96	−0.0043	−0.0026	−0.0008	−0.0003	0	+0.0001	+0.0006	+0.0009	+0.0014	+0.0016
0.96–1.20	−0.0043	−0.0026	−0.0008	−0.0003	0	+0.0001	+0.0006	+0.0009	+0.0014	+0.0019
1.20–1.60	−0.0047	−0.0031	−0.0010	−0.0004	0	+0.0001	+0.0007	+0.0010	+0.0017	+0.0024
1.60–2.00	−0.0051	−0.0031	−0.0010	−0.0004	0	+0.0001	+0.0007	+0.0010	+0.0017	+0.0028
2.00–2.60	−0.0055	−0.0039	−0.0012	−0.0004	0	+0.0001	+0.0008	+0.0013	+0.0021	+0.0034
2.60–3.20	−0.0059	−0.0039	−0.0012	−0.0004	0	+0.0001	+0.0008	+0.0013	+0.0023	+0.0040
3.20–4.00	−0.0067	−0.0047	−0.0014	−0.0005	0	+0.0001	+0.0009	+0.0015	+0.0028	+0.0049
4.00–4.80	−0.0071	−0.0047	−0.0014	−0.0005	0	+0.0001	+0.0009	+0.0015	+0.0031	+0.0057
4.80–5.60	−0.0079	−0.0057	−0.0017	−0.0006	0	+0.0001	+0.0011	+0.0017	+0.0036	+0.0067
5.60–6.40	−0.0083	−0.0057	−0.0017	−0.0006	0	+0.0001	+0.0011	+0.0017	+0.0039	+0.0075
6.40–7.20	−0.0091	−0.0057	−0.0017	−0.0006	0	+0.0001	+0.0011	+0.0017	+0.0043	+0.0083
7.20–8.00	−0.0094	−0.0067	−0.0020	−0.0006	0	+0.0002	+0.0012	+0.0020	+0.0048	+0.0093
8.00–9.00	−0.0102	−0.0067	−0.0020	−0.0006	0	+0.0002	+0.0012	+0.0020	+0.0051	+0.0102
9.00–10.00	−0.0110	−0.0067	−0.0020	−0.0006	0	+0.0002	+0.0012	+0.0020	+0.0055	+0.0112
10.00–11.20	−0.0118	−0.0075	−0.0022	−0.0007	0	+0.0002	+0.0013	+0.0022	+0.0062	+0.0124
11.20–12.60	−0.0130	−0.0075	−0.0022	−0.0007	0	+0.0002	+0.0013	+0.0022	+0.0067	+0.0130
12.60–14.20	−0.0142	−0.0083	−0.0024	−0.0007	0	+0.0002	+0.0015	+0.0024	+0.0075	+0.0154
14.20–16.00	−0.0157	−0.0083	−0.0024	−0.0007	0	+0.0002	+0.0015	+0.0024	+0.0082	+0.0171

Additional Calculations

Mold Wall Tolerances

Table 7.9:

Type of Fit: Clearance, Sliding Fit (H7/g6)

"Where parts are not intended to run freely, but must move and turn freely and locate accurately"

Hole Tolerances

Table A-13:

Tolerance Grade: IT7

Basic Sizes 0.12-0.24

$\Delta D = 0.0005in$

$$D_{max} = D + \Delta D$$
$$= 0.1875 + 0.0005$$
$$D_{max} = 0.188in$$

$$D_{min} = D$$
$$D_{min} = 0.1875in$$

Shaft Tolerances

Table A-13:

Tolerance Grade: IT6

Basic Sizes: 0.12-0.24

$\Delta d = 0.0003in$

Table A-14:

Upper deviation letter: g

Basic Sizes: 0.12-0.24

$\delta_f = -0.0002in$

$$d_{max} = d + \delta_f$$
$$= 0.1875 - 0.0002$$
$$d_{max} = 0.1873in$$

$$d_{min} = d + \delta_f - \Delta d$$
$$= 0.1875 - 0.0002 - 0.0003$$
$$d_{min} = 0.187in$$

Assume shaft diameter (wall thickness) is fixed to 0.1875in:

Maximum Clearance

$$D_{max} - d_{min} = 0.188in - 0.187in$$
$$= 0.001in$$

Minimum Clearance

$$D_{min} - d_{max} = 0.1875in - 0.1873in$$
$$= 0.0002in$$

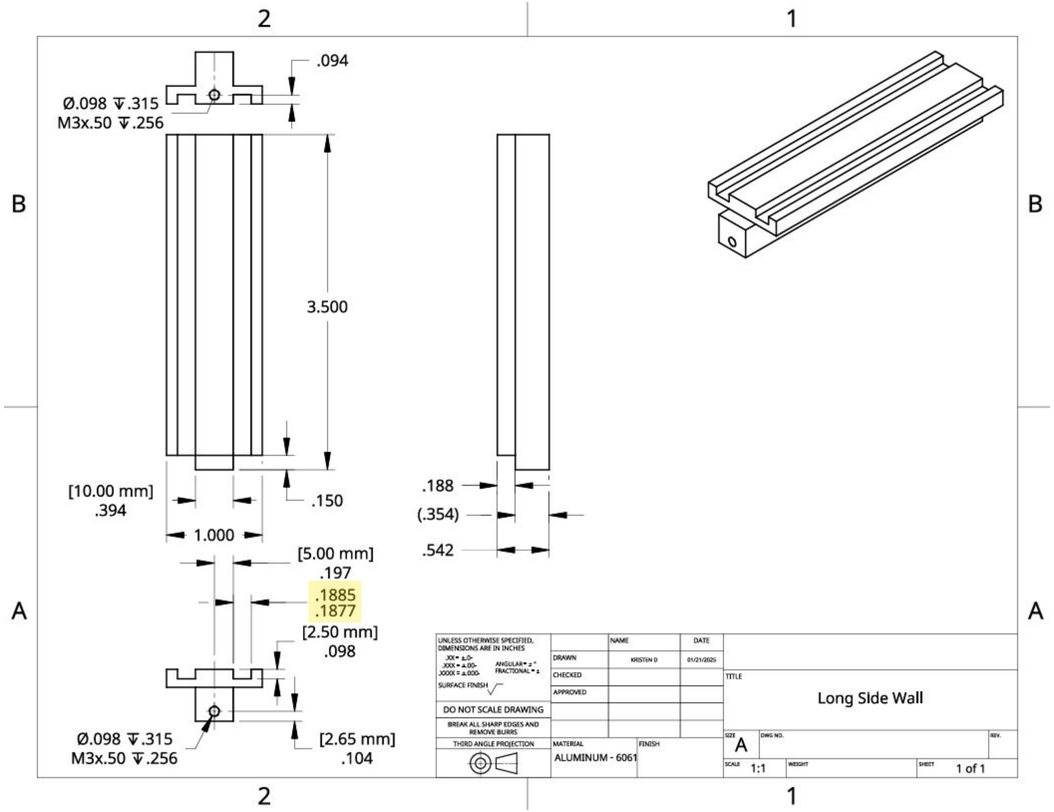
$$d = 0.1875in$$

$$D_{min} = 0.1875in + 0.0002 = 0.1877in$$

$$D_{max} = 0.1875in + 0.001 = 0.1885in$$

Additional Calculations

Mold Wall Tolerances



Power Budget

Table 1: Power budget template

Component	QTY	Voltage [V]	Current [A]	Idle Operation Duty Cycle [%]	Idle Operation Power [W]	Science Operation Duty Cycle [%]	Science Operation Power [W]	Verification Method	Note(s)
NEMA 17 Stepper	1	24 VDC	1.5	0	0	100	36	E	Neglecting inrush current
NEMA 23 Stepper	1	24 VDC	2	0	0	100	48	E	Neglecting inrush current
Arduino	1	9 VDC	0.05	100	0.45	100	0.45	E	
Webcam	1	5 VDC	0	0	0	0	0		Powered by laptop
Laptop	1	12 VDC	1.3	100	15.6	100	15.6	E	
Voltage Measurement Unit	2	24 VDC	0.1	0	0	100	2.4	E	
Load Cell	1	5 VDC	0.1	0	0	100	0.5	E	
Thermal Sensors	2	5 VDC	0.1	0	0	100	0.5	E	
Solenoid	1	12 VDC	1	0	0	100	12	E	
Total Power Consumed: [W]					16.05		115.45		
Total Available Power [W]					600.00		600.00		
Power Margin [W]					+583.95		+484.55		