Extensive Testing, Standardization and Formalization of KNSB-Based Solid Rocket Motor

Vivatsathorn Thitasirivit

Team 45: Project RADIANT

Institute of Technology (iNT), Mahidol University, Thailand

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Download at *vt.in.th/rocket*

Outlines

- Backgrounds and Introduction
- Engineering for safe, fast and reusable assembly
- Experimentation and problems with KNSB
- Standardization of Manufacturing KNSB
- Results

Our Rocket: Mana V1

- Capability: 15,000 ft [4,500 m]
- Target: 10,000 ft [3,048 m]

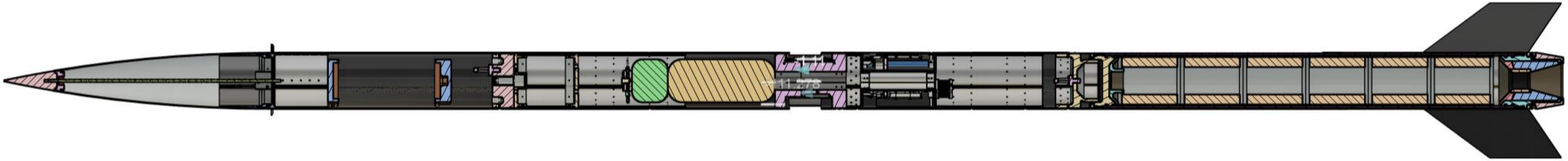
Our Rocket: Mana V1

Fully Knotless Recovery Cords

COTS Tracker | Coupler | Coupler | Motor Mount

Airframe | Fins

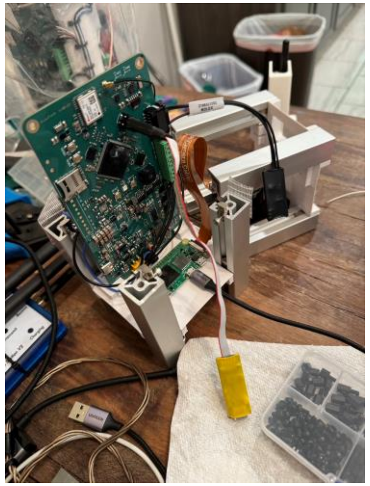
Nose Cone + Drag Ring | Payload | Piston | Parachutes | Avionics | Propulsion System



All parts are custom-made

Our SRAD Highlights

Knotless Recovery



Launch Control Unit

Payload

Drag Ring

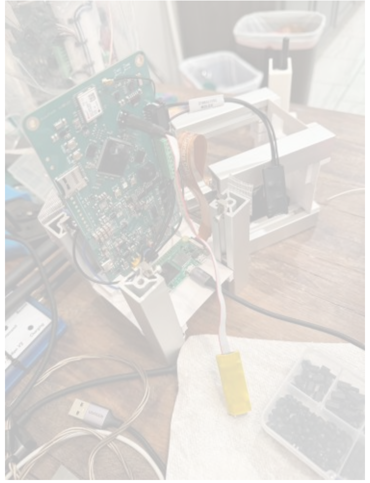
DIY Parachute

Avionics: LUNA

Propulsion: M1

Our SRAD Highlights

Knotless Recovery



Launch Control Unit

Payload

Drag Ring

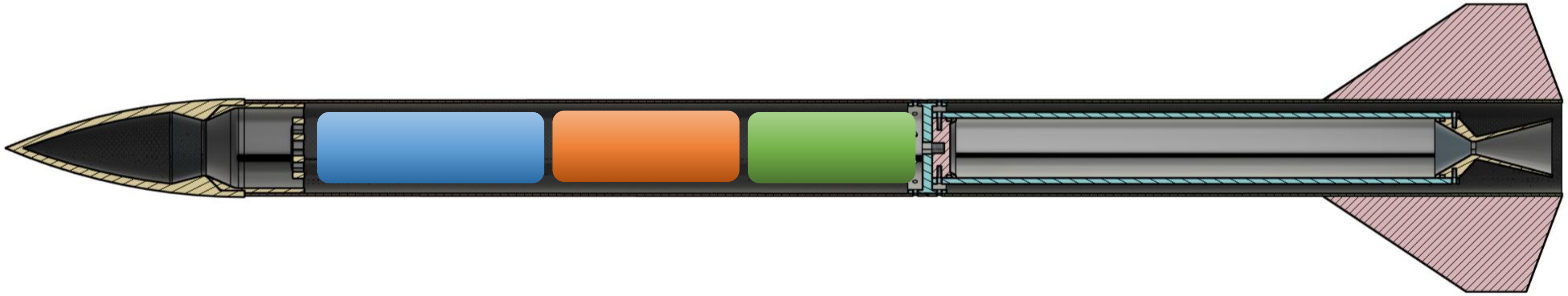
DIY Parachute

Avionics: LUNA

Propulsion: M1

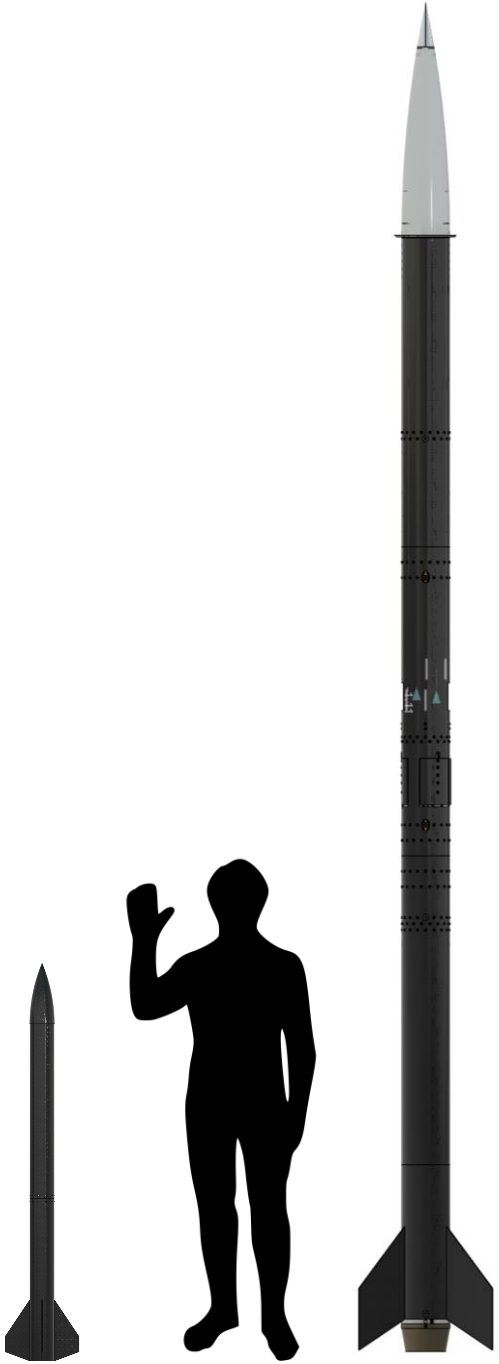
The predecessor: Juno V1

- Apogee: 3,280 ft. [1,000 m]
- KNSB-based propulsion system

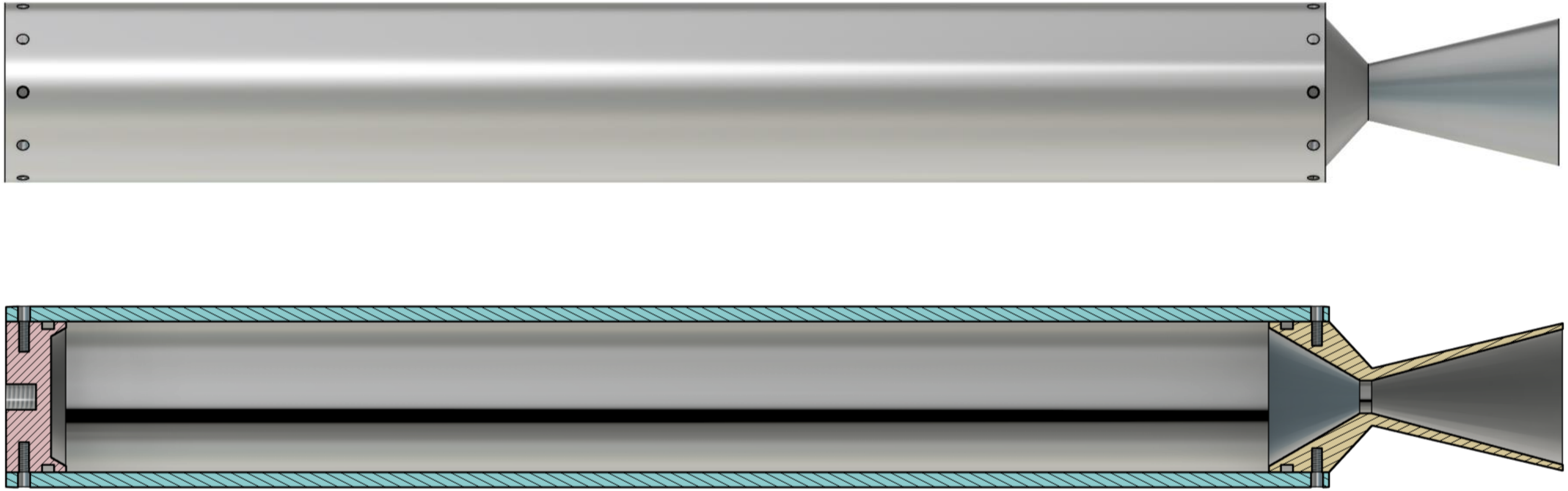


The predecessor: Juno V1

- What's the scale?
- Juno V1: 4.27 ft
  (3″ diameter)
- Mana V1: 14.36 ft
  (6″ diameter)
- Me: 5.28 ft



K1 for Juno V1 (Our first SRM)



Problems of previous designs

- Unsafe mechanical structures
  - Radial screws
  - No internal thermal insulation
  - Exposed nozzle throat outside casings
- Unreliable material and design
  - Metal was used instead of ablative material
- Part changes are required for the next launches
- Assembly process takes too long!
  - Too many screws to assemble
  - “It fits sometimes” (Most of the time it doesn’t!)

Expectations

Safe

- Safe to handle
- Safe operations

Fast Assembly

- Fast fabrication
- Fast subassembly
- Fast motor assembly
- Fast rocket assembly

Reusable

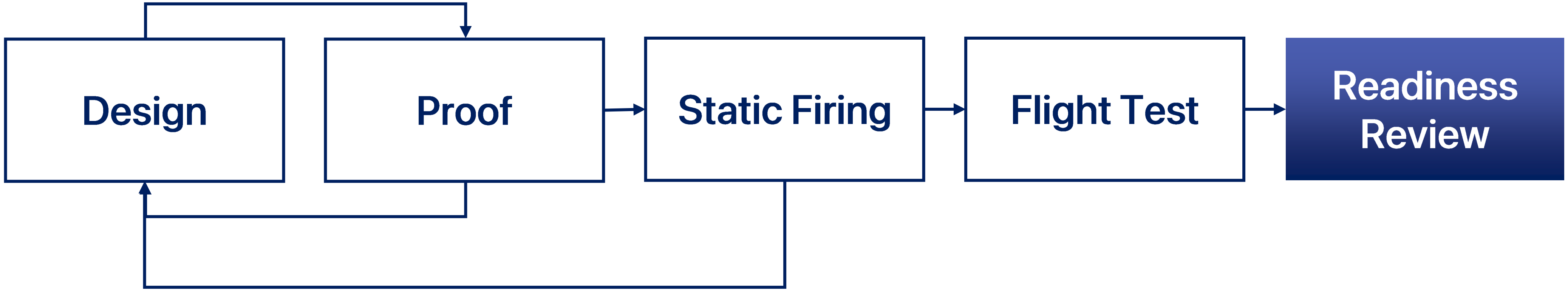
- Maximize reusability
- Minimize consumables
- Reduce cost
- Reduce resources

M1 Design Iterations

- Spoiler: M1 isn’t a M class motor at all.

- A small tour of our designing-redesigning process
- Why so much changes from initial design?

M1 Design Iterations: Development Cycle



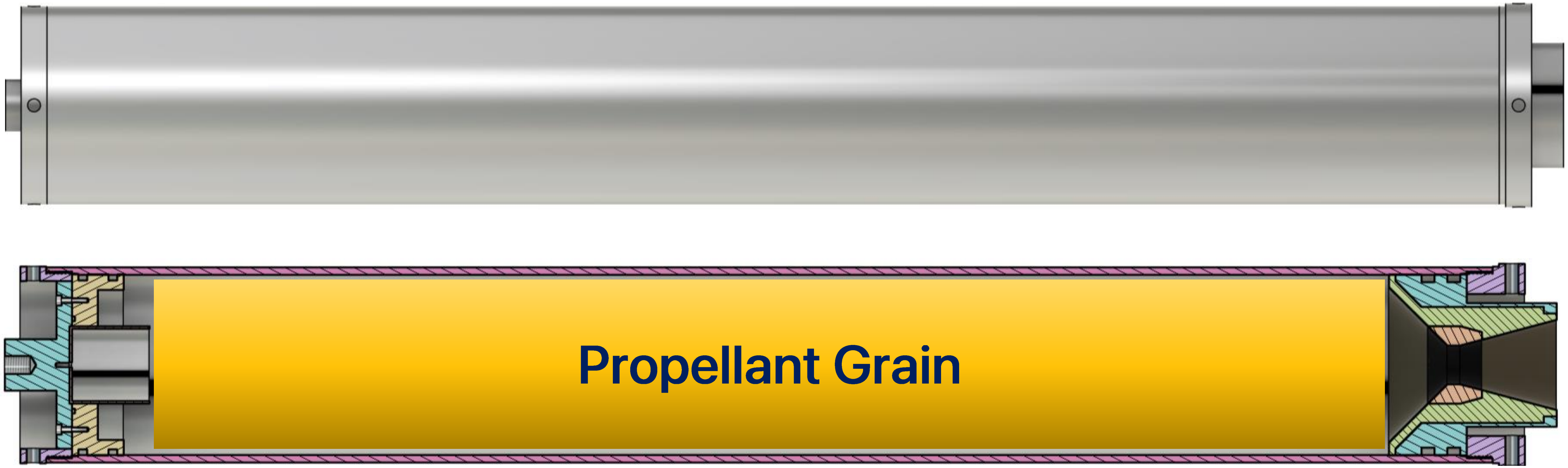
Material Selections

- Key Idea: Use appropriate material for appropriate section
  (These are standard aerospace materials.)

Structure	**AL6061-T6**: Lightweight, enough strength, moderate cost
Ablative Section	**Linen Phenolic**: Lightweight, very good ablative material
Throat	**Graphite**: Lightweight, good thermal conductivity, very low thermal expansion

M1 Design Iterations

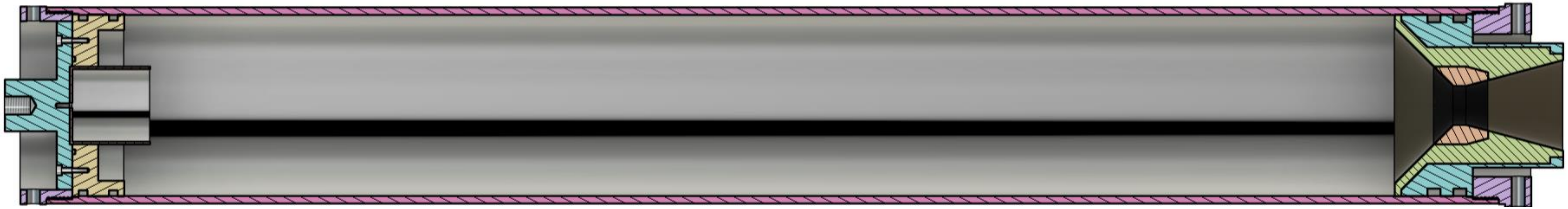
Rev.1

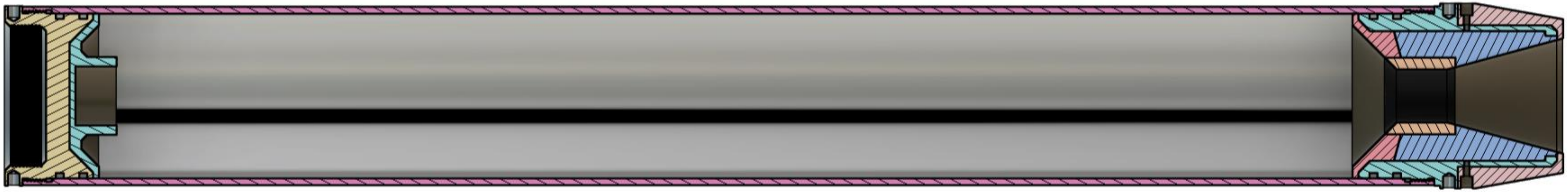


M1 Design Iterations

Rev.1 vs Rev.7

Rev.1





Rev.7

M1 Design Iterations

Rev.1

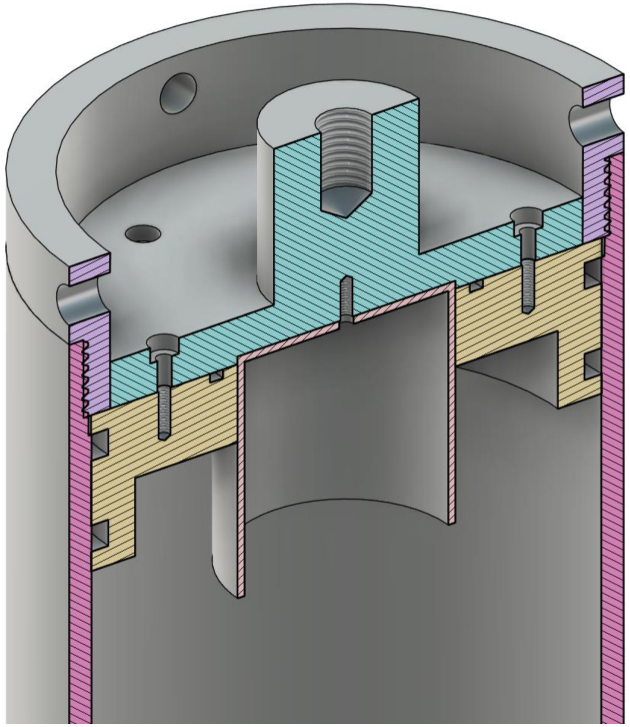
Casing

Pros
- Standard alternative way to mount nozzle and bulkhead to the motor casing
- Tremendous thread strength

Cons
- Machining process requires very large lathing machine

M1 Design Iterations

Rev.1



Bulkhead

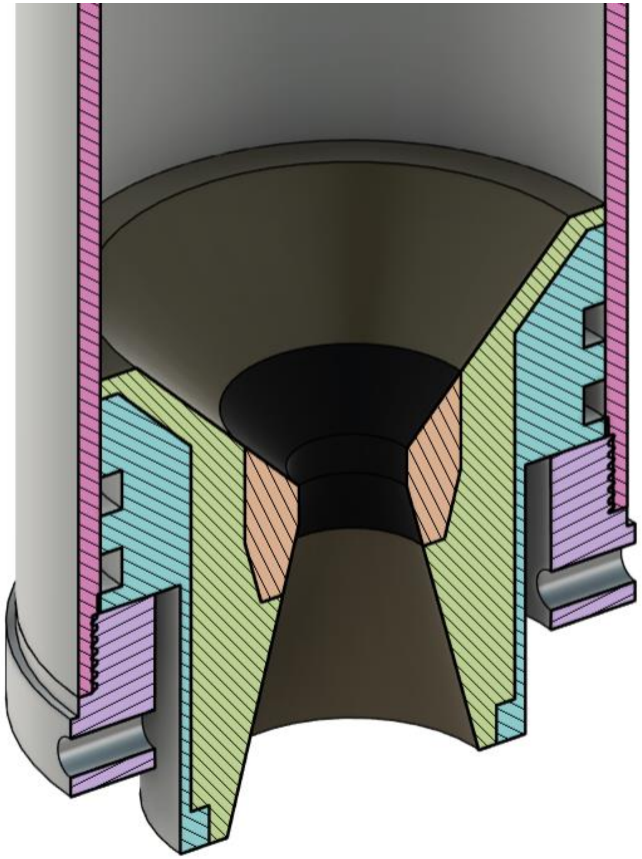
Pros
- Separate igniter loading via bulkhead
- Separate igniter charge insertion

Cons
- No insulation/ablative material
- May transfer heat to the metallic housing
- Many points of failure

M1 Design Iterations

Rev.1

Nozzle



Pros

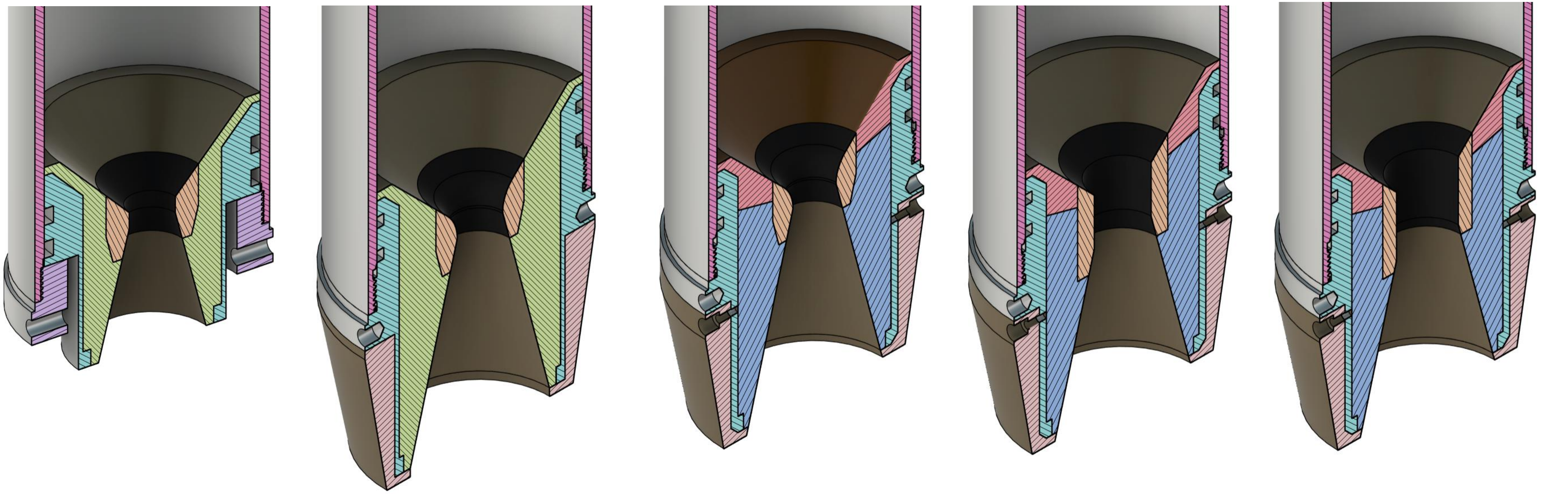
- Distinct parts, easy to change
- Lightweight (no unnecessary material)

Cons

- Many parts to assemble,
  increased risk of assembly errors
- Complex parts, also higher failure rate

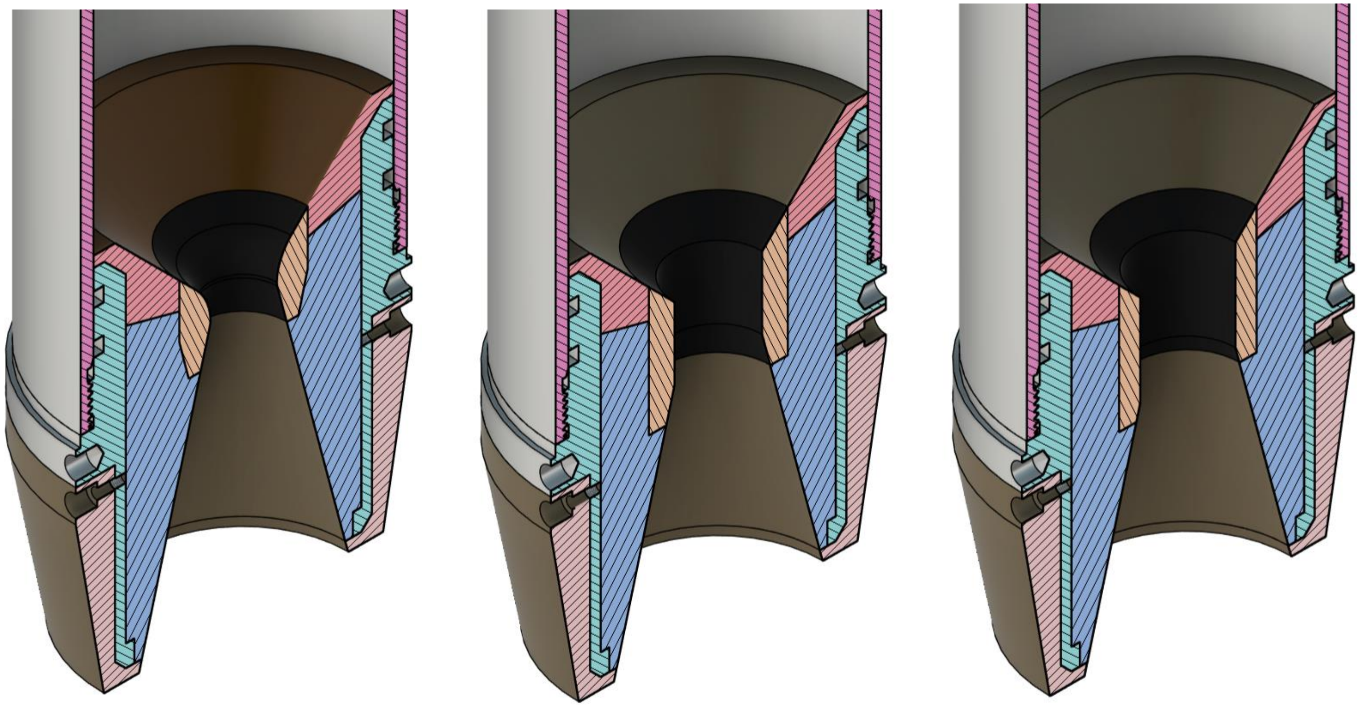
M1 Design Iterations: Nozzle Changes

Initial design | **Major redesign** | **Minor improvement** | **Throat size change** | Final design **Throat size change**



Why so much throat resizing?

35 mm [1.38″] 41 mm [1.61″] 45 mm [1.77″]



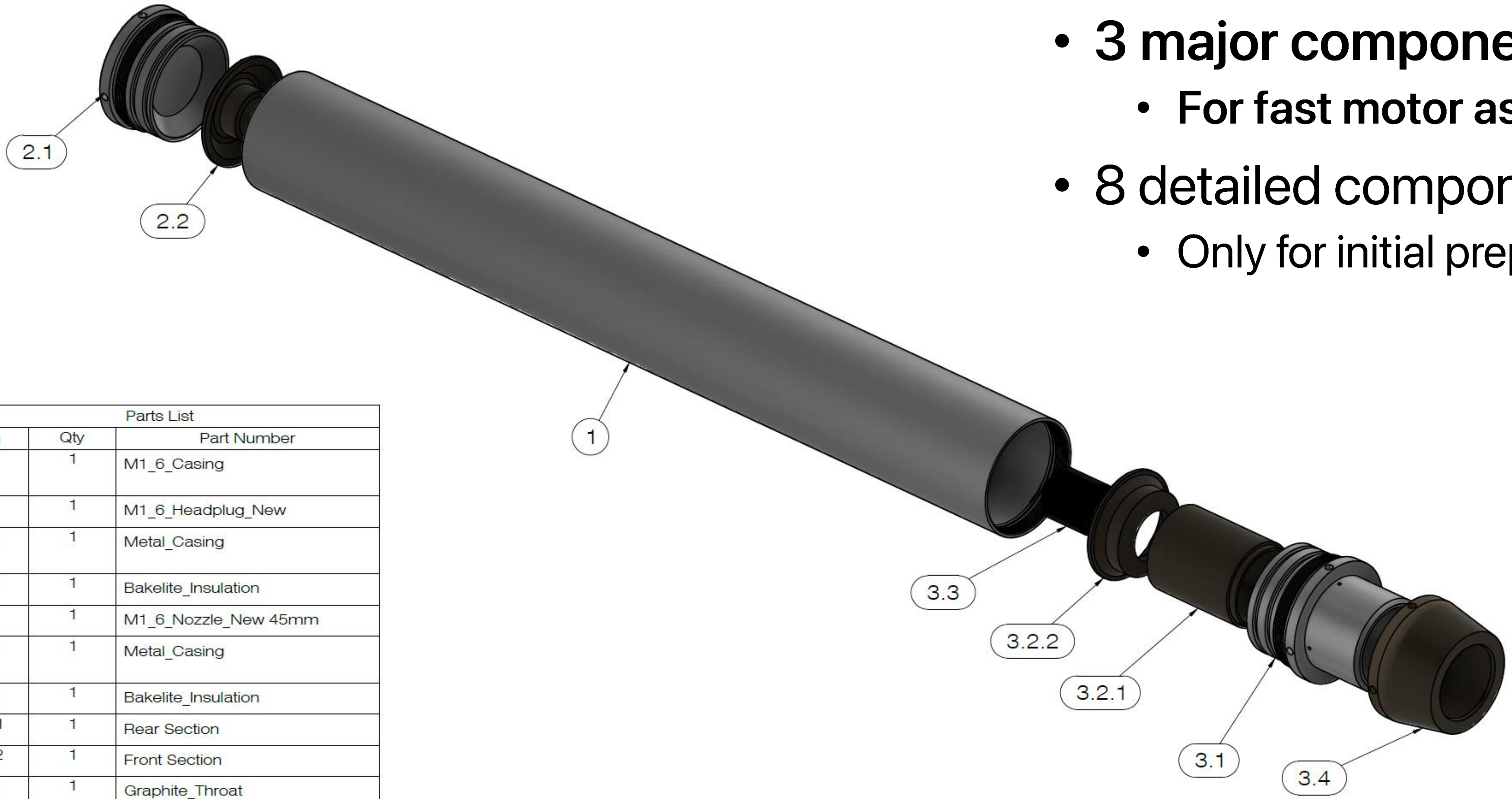
Why so much throat resizing?

- At first (during normal temperature firing
  with ambient temperature of 35°C [95°F]),
  the pressure is too high from the expected simulation results.
  - More details about simulation in later sections

- After correctly characterization, during "hot" firing
  with ambient temperature of 60°C [140°F],
  the pressure is significantly higher than normal firing.

- **As it can happen in hot weather in New Mexico,
  we increased the throat size again to ensure
  safe operating pressure.**

M1 Final Design (Rev.7)



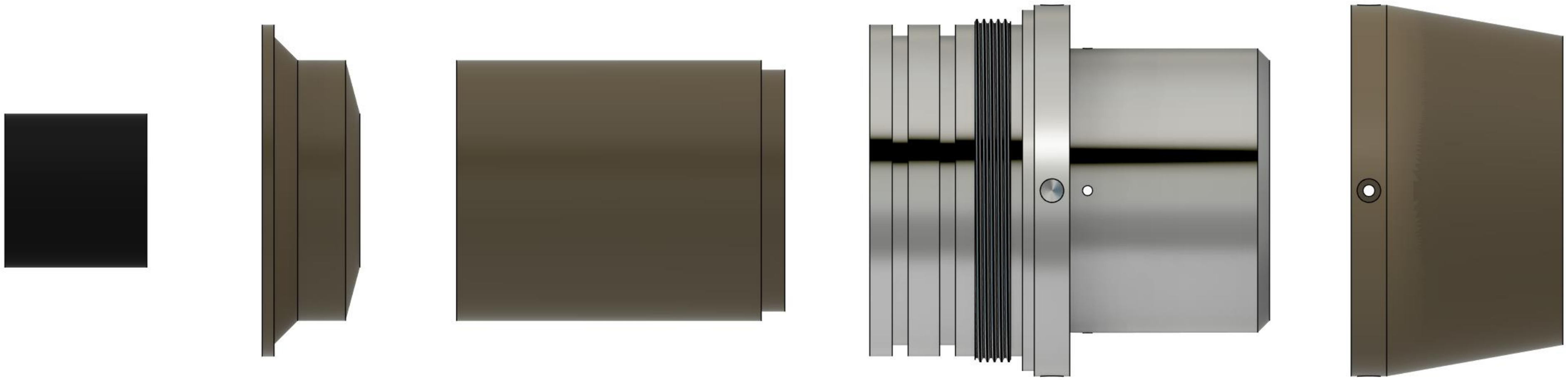
- **3 major components**
  - **For fast motor assembly**
- 8 detailed components
  - Only for initial preparation

Parts List		
Item	Qty	Part Number
1	1	M1_6_Casing
2	1	M1_6_Headplug_New
2.1	1	Metal_Casing
2.2	1	Bakelite_Insulation
3	1	M1_6_Nozzle_New 45mm
3.1	1	Metal_Casing
3.2	1	Bakelite_Insulation
3.2.1	1	Rear Section
3.2.2	1	Front Section
3.3	1	Graphite_Throat
3.4	1	Boattail

M1 Final Design (Rev.7)

Nozzle Subassembly

Throat Graphite	**Ablative Section** Linen Phenolic	**Metallic Casing** AL6061-T6	**Insulation & Boattail** Linen Phenolic

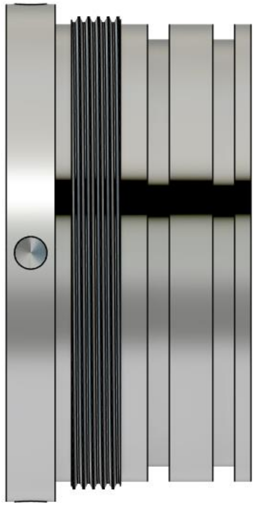


M1 Final Design (Rev.7)

Bulkhead Subassembly

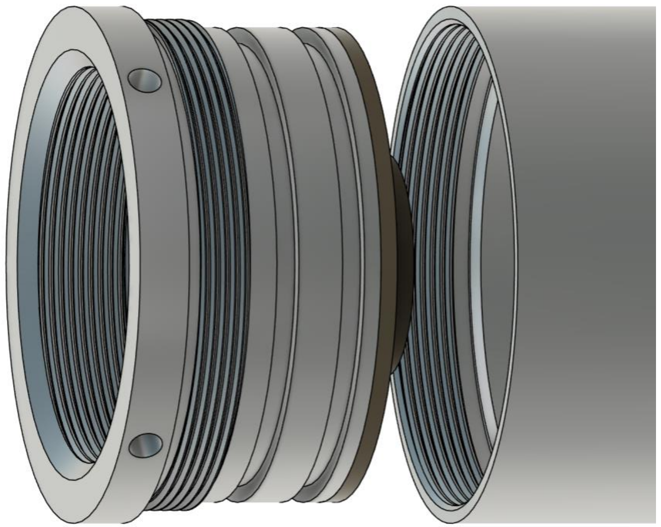
Metallic Casing
AL6061-T6

Insulation/Ablative
Linen Phenolic

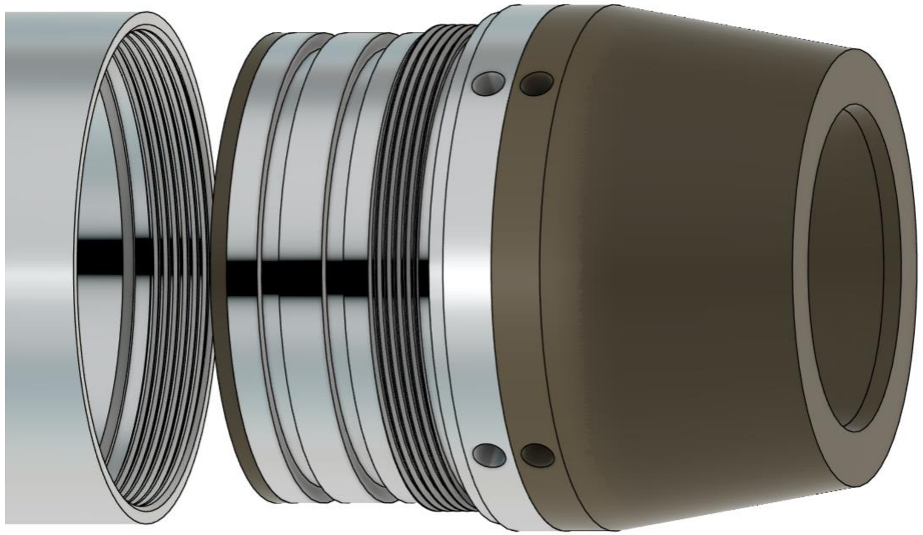


M1 Final Design (Rev.7)

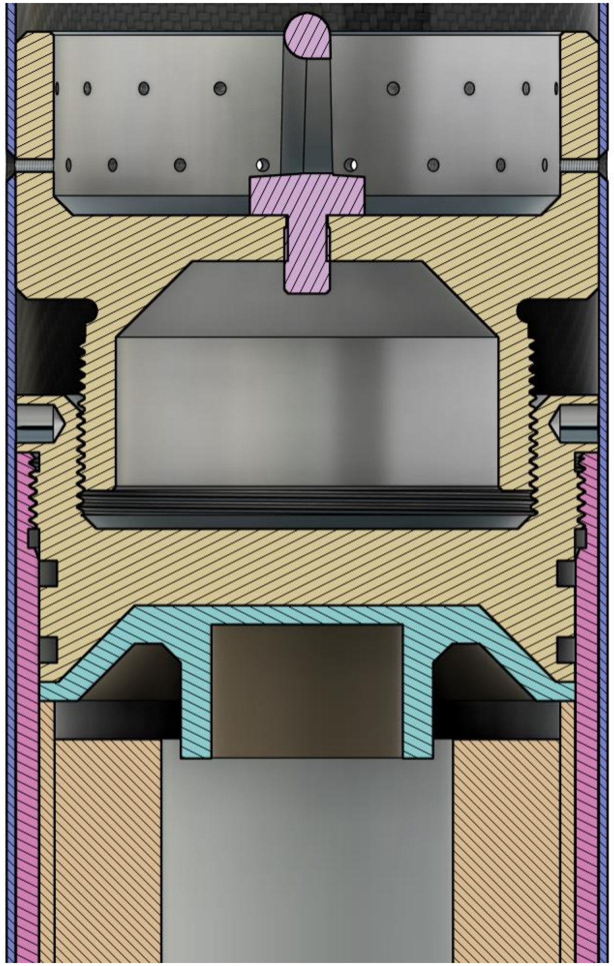
Bulkhead Assembly



Nozzle Assembly



M1 Final Design (Rev.7): Motor mount scheme



Motor Mount: Fixed to the rocket aft frame body

M120 Thread Mount:
For "screw-in" assembly and
make the distance uncertainty disappear

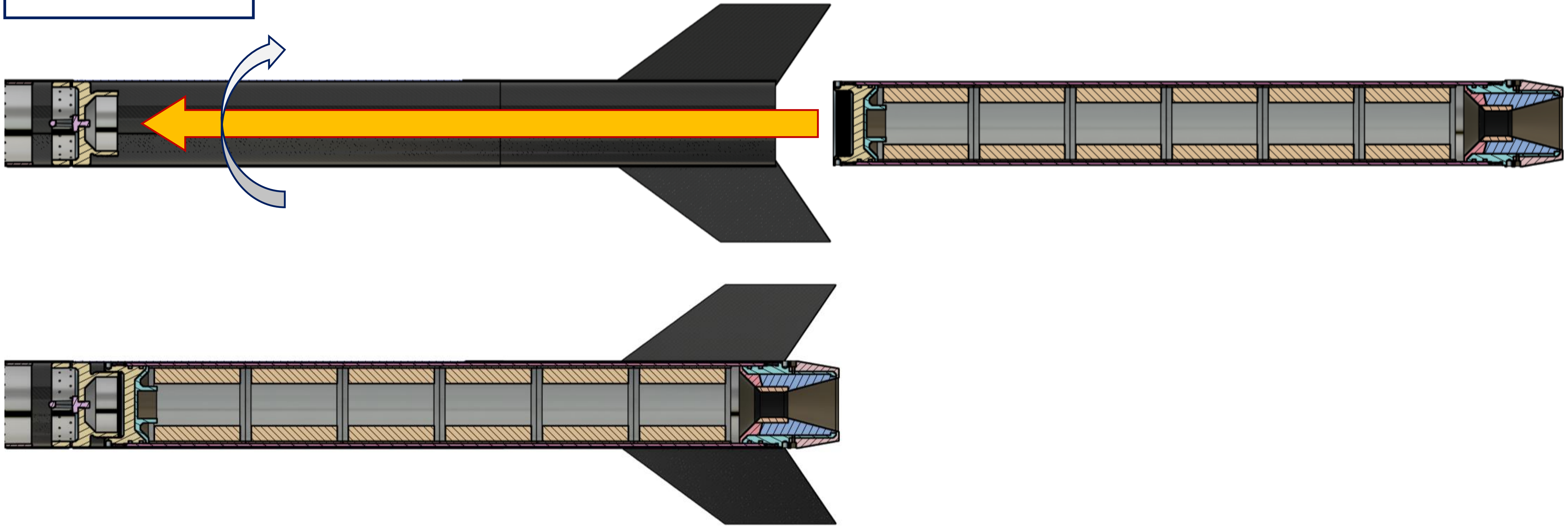
Motor Subassembly:
Same diameter as the airframe, airtight

M1 Final Design (Rev.7): Rocket Assembly

Rocket Aft Frame

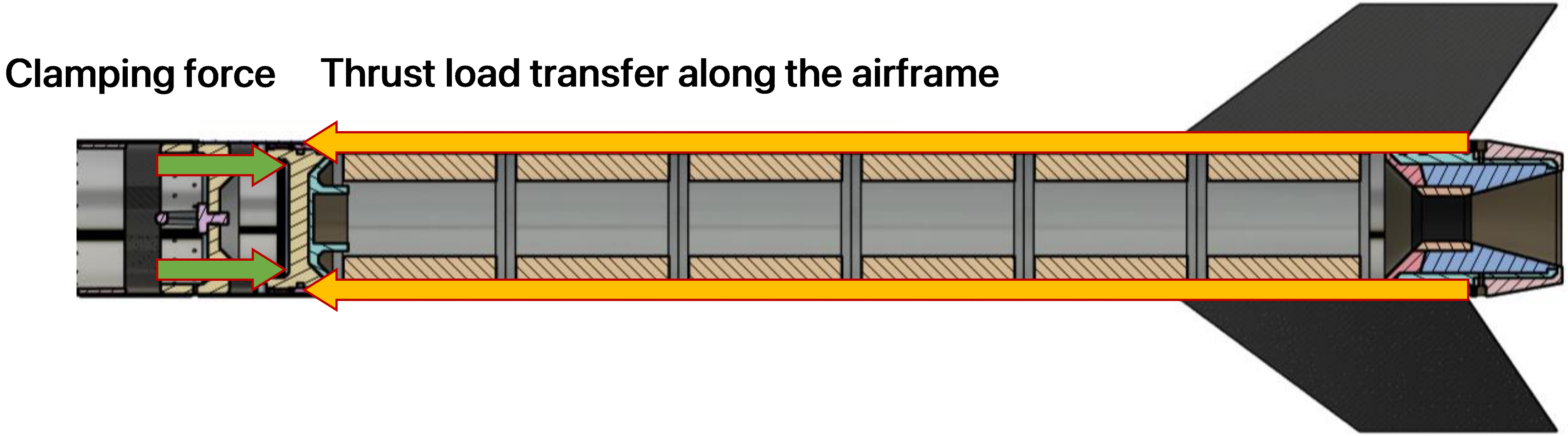
Rocket Motor

Motor Mount



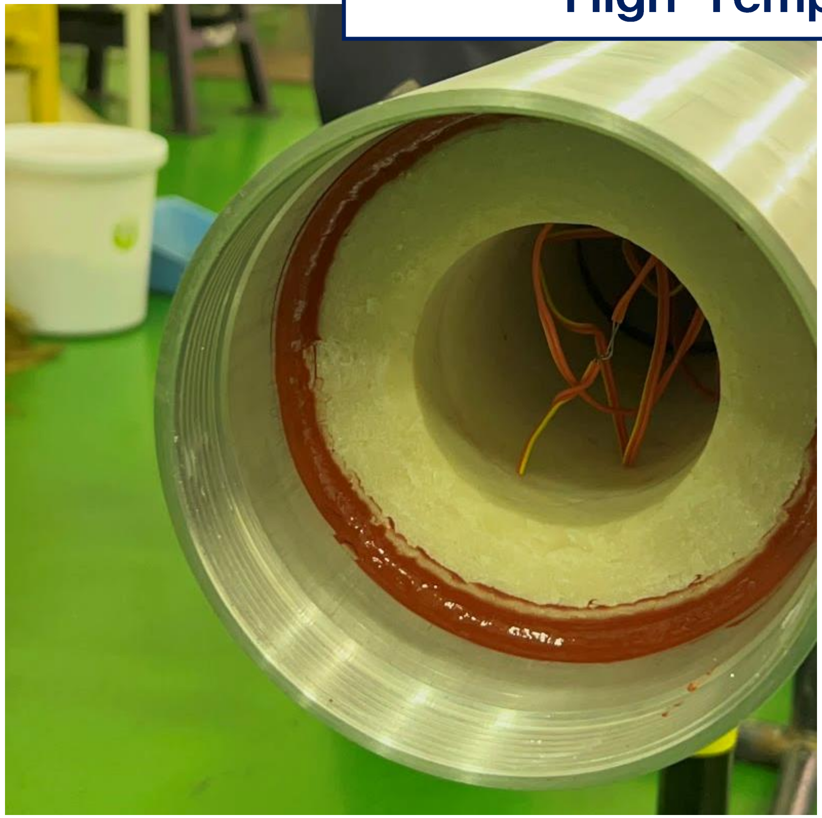
M1 Final Design (Rev.7): Rocket Assembly

Load Transfer



M1 Final Design (Rev.7): Rocket Assembly

High-Temp RTV Silicone

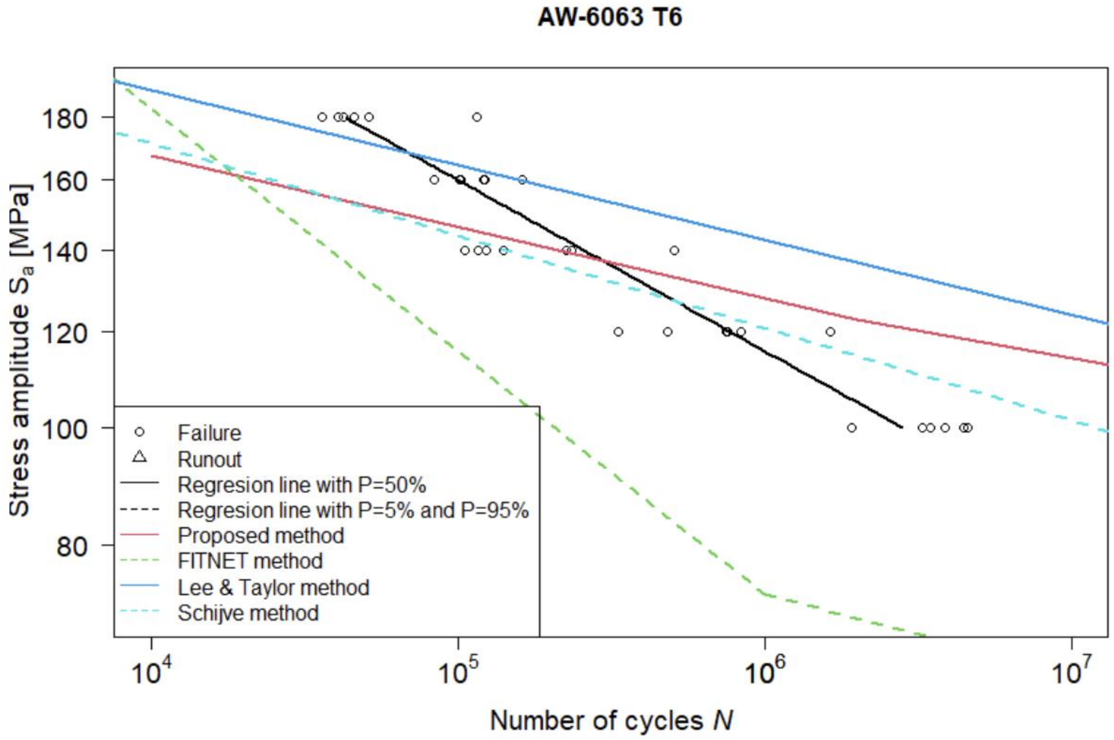


M1 Final Design (Rev.7): Rocket Assembly

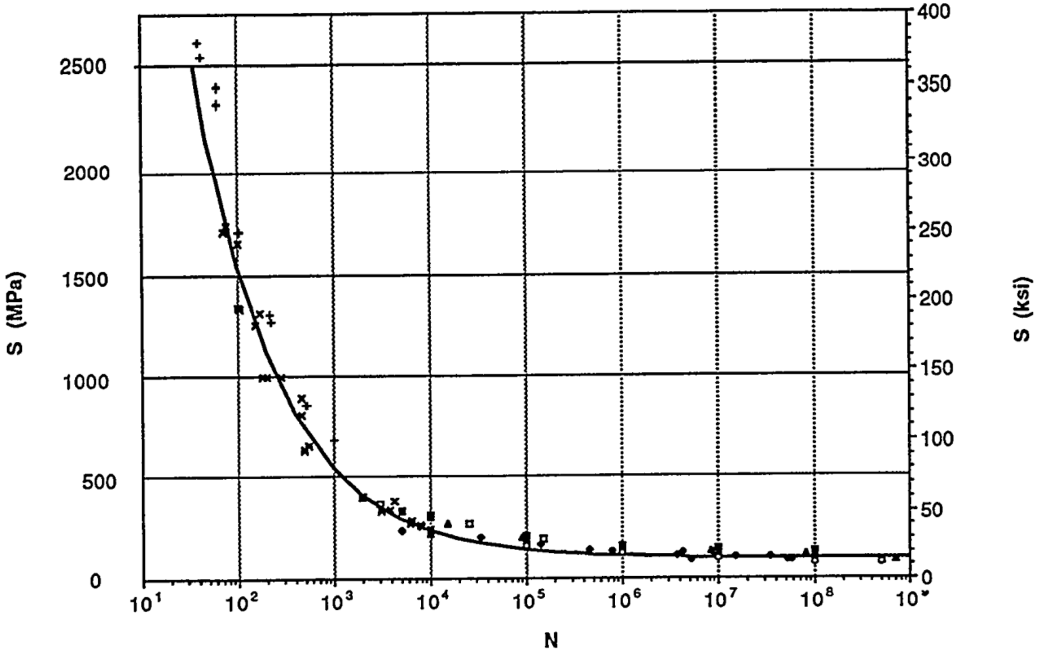
Safety Earth Cable

Material Reusability Analysis (S-N Curve, Material Fatigue)

In short, should be good for 10+ launches



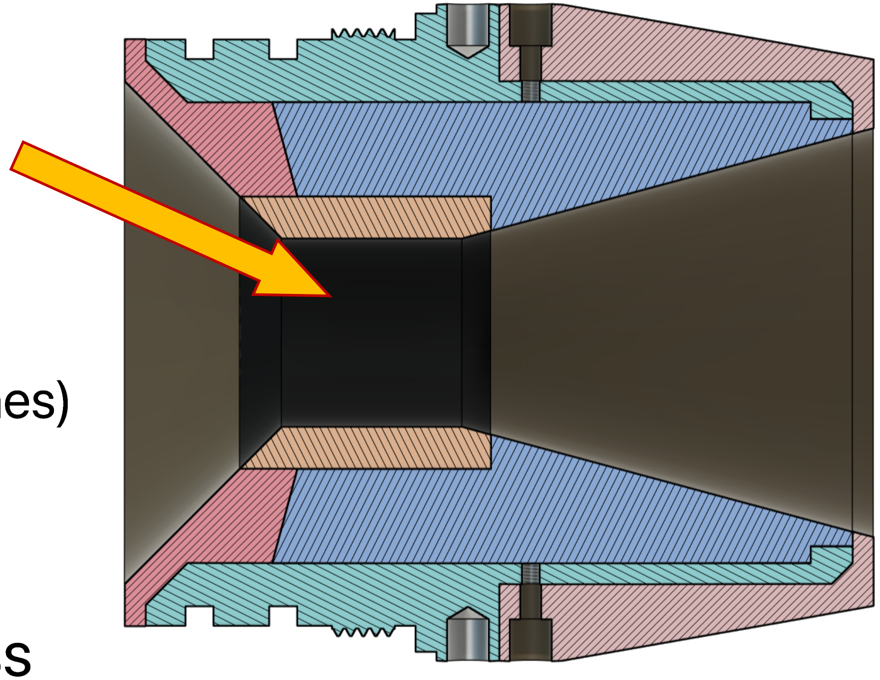
S-N Curve for AL6063-T6
10.1051/matecconf/202133801026

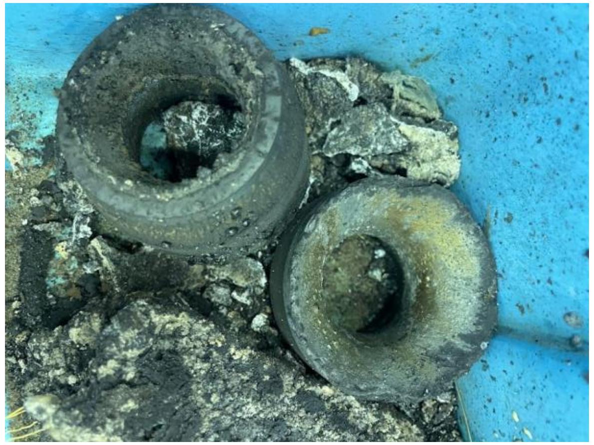


S-N Curve for AL6061-T6
https://www.osti.gov/servlets/purl/10157028

M1 Reusability: What to do for the next launch?

- Clean all parts
- Swap out
  - 1x Graphite throat
  - 4x O-rings
  - All linen phenolic (after many launches)
- No need to change metallic parts unless there are significant mechanical failures, e.g., cracks





The Propellant

Why KNSB?

- KNSB (65% Potassium nitrate + 35% Sorbitol)

- We have some “unofficial” experiences manufacturing KNSU (sucrose-based).
  - The melting temperature is very high (and very close to ignition temperature).
  - Unless it reaches its melting point, the paste is VERY viscous (sticky).
  - Curing it takes time. There are also high risk of air bubbles.
  - But, KNSU has very good and consistent performance.

- Official experiences using KNSU
  - have utilized provided KNSU in the local rocket competition.

Our first trials with KNSB

- Of course we did it wrong!

Propellant Manufacturing

- There are many ways to manufacture sugar propellant.

- Problems with sugar propellant (regarding mfg.)
  - Characterization (chemical grades)
  - Manufacturing (blending, melting, casting, curing)

- How to get consistent results
- What we have come up so far
- More problems?

Propellant Manufacturing
Getting consistent results

- We have tried and tested many methods from naïve to sophisticated methods for mixing, melting, casting, and curing.
- We have come up with standardized method (factory-like) to manufacture KNSB with very good consistency.

- Standardization & Formalization
  - **Hardware**: to reduce technical failures
  - **Process**: to reduce human errors

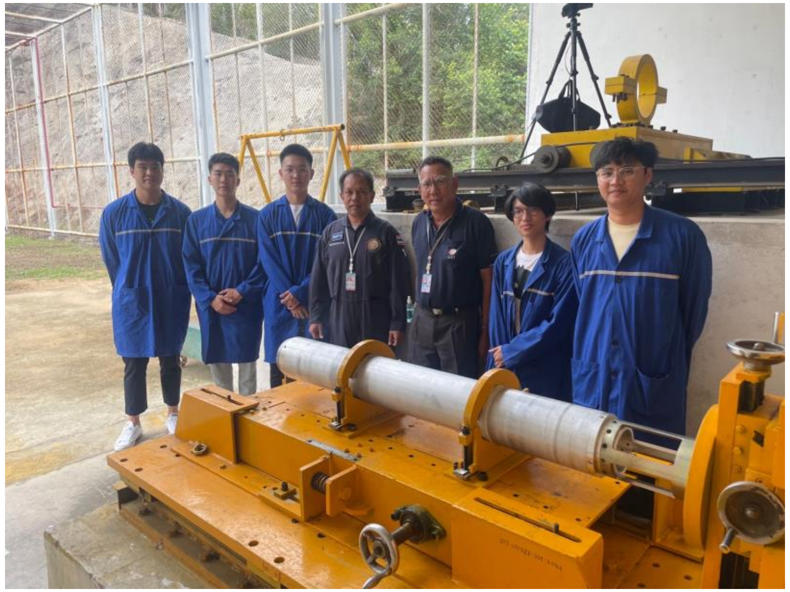
Tests/Experiments

Static firing

Hydrostatic pressure

Flight Test

Tests/Experiments
Static firing tests



Tests/Experiments

Static firing tests

Tests/Experiments
Static firing tests

Tests/Experiments

Static firing tests: Post-firing conditions

Tests/Experiments

Static firing tests: Post-firing conditions

Tests/Experiments

Static firing tests: Problems with KNSB (1)

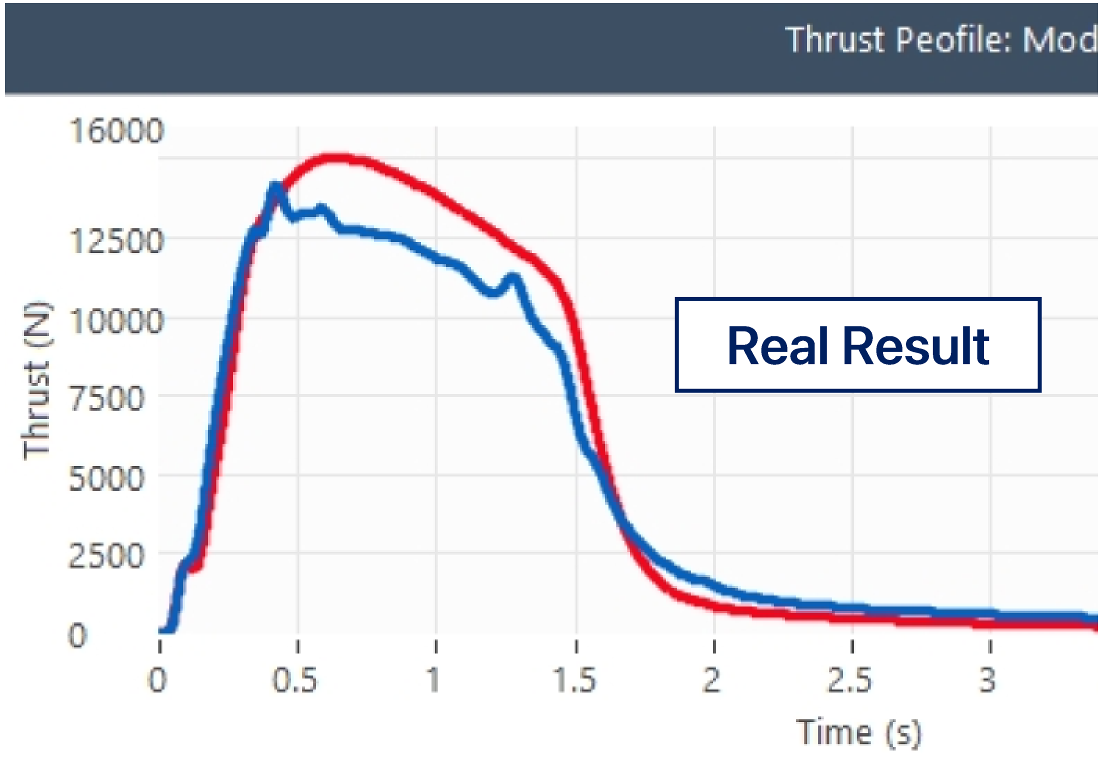
- Throughout our tests, our KNSB compound real static firing test thrust profile does not match openMotor simulation.
  - Burn time and pressure amplitude are both different.
  - Total impulse is relatively similar
  - Note: openMotor’s KNSB data is from Richard Nakka.

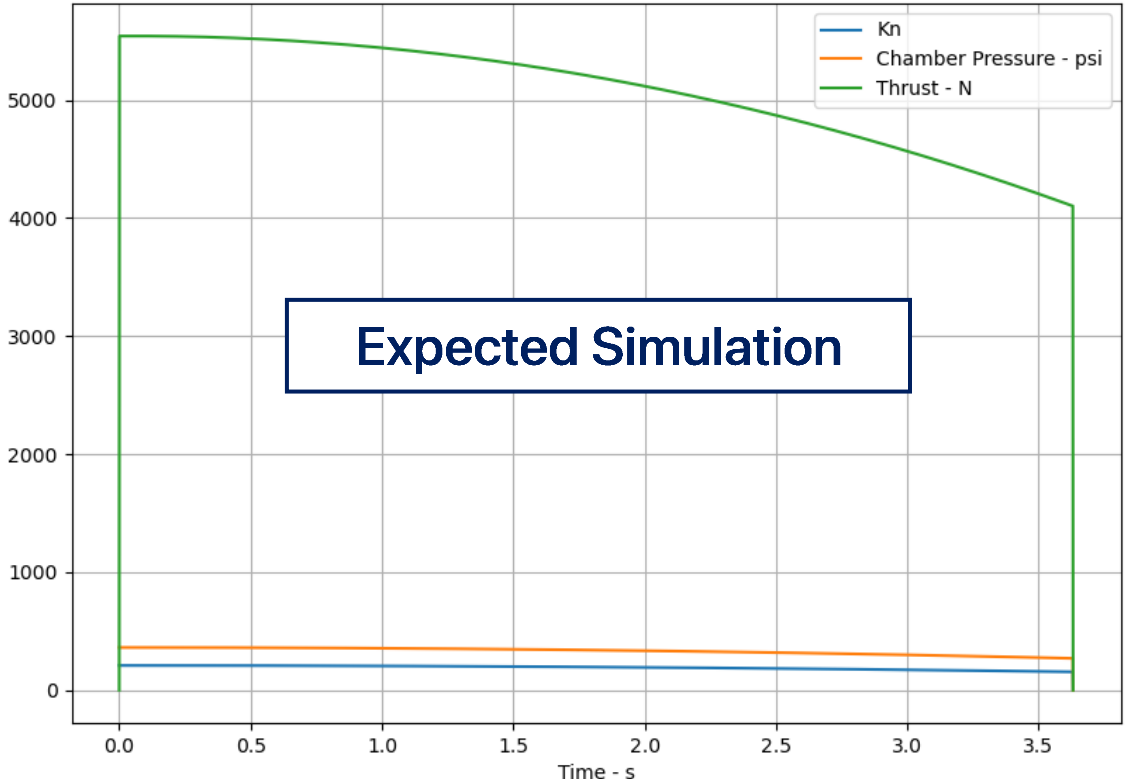
- Might be mainly from different impurities and partially from grain configurations.

Tests/Experiments

Static firing tests: Problems with KNSB (1)

- After parameter (burn rate) adjustment from the BEM.

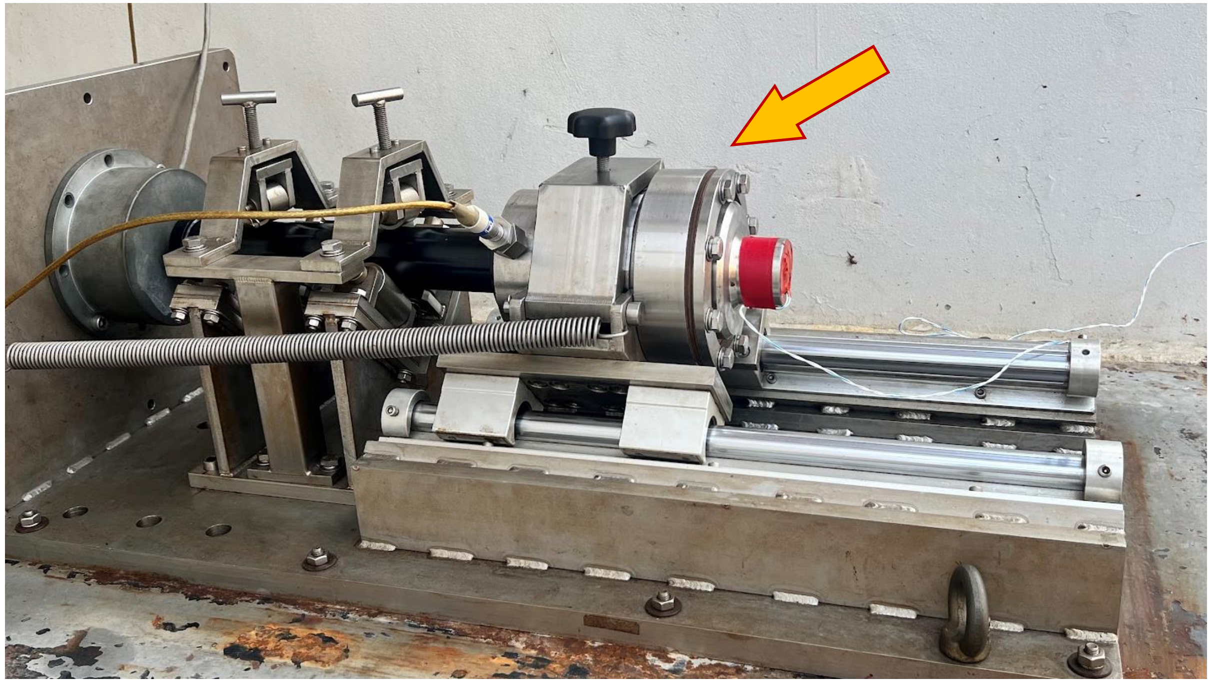




Tests/Experiments

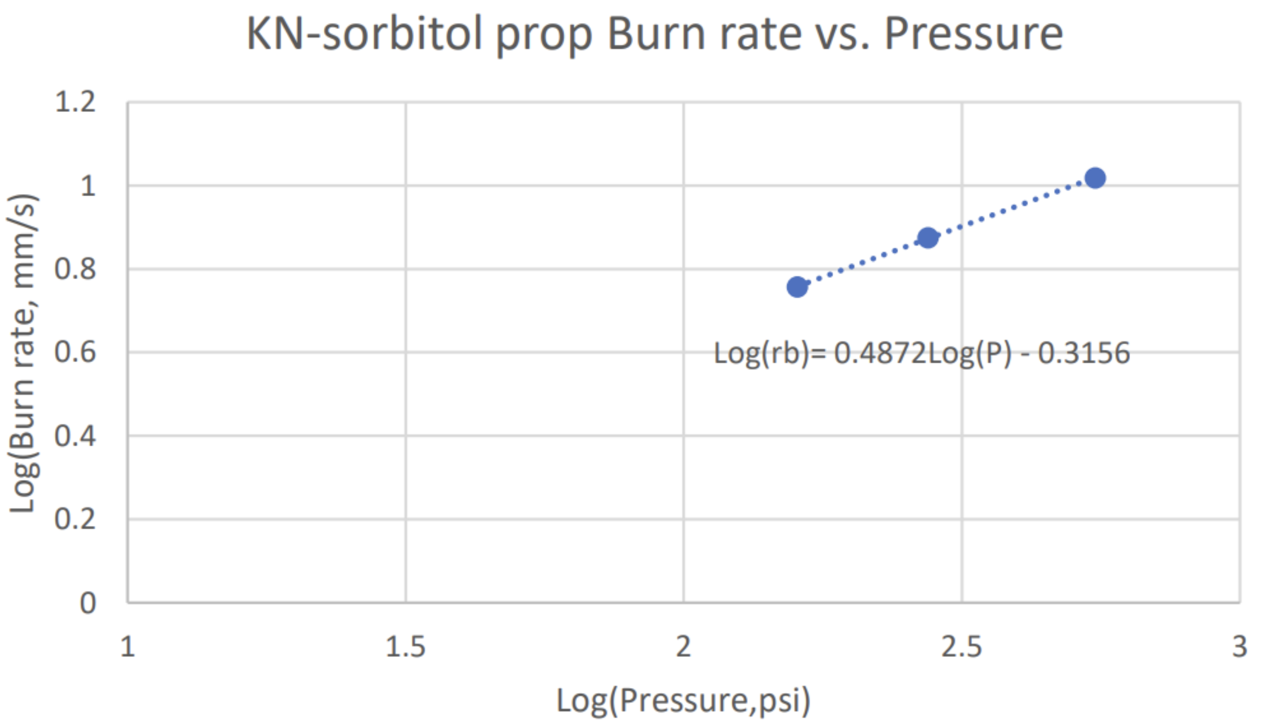
Static firing tests: Ballistic Evaluation Motor

- BEM is a calibrated SRM test unit to accurately characterize burning characteristics of a propellant.



Static firing tests: BEM Results

- BEM at 30°C [86°F]
- Web thickness = 24 mm



$$\log_{10} \text{burn rate} = 0.4872 \log_{10} P - 0.3156$$

Pressure (psi)	Burn time (s)	Burning Rate (mm*s^-1)
550	2.3	10.4
275	3.2	7.5
160	4.2	5.7

Burn rate = 14 mm*s^-1
Burn rate exp. (n) = 0.4872
Burn rate coeff. = 0.000006 m*s^-1*Pa^-n

Tests/Experiments

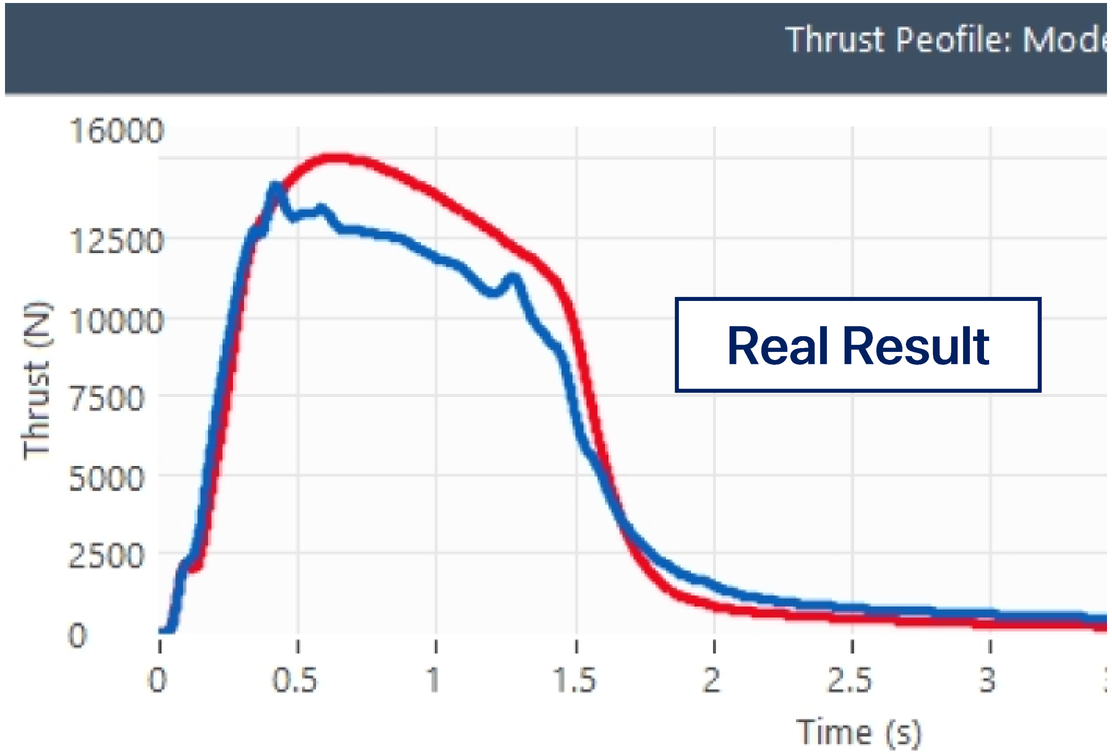
Static firing tests: openMotor configurations

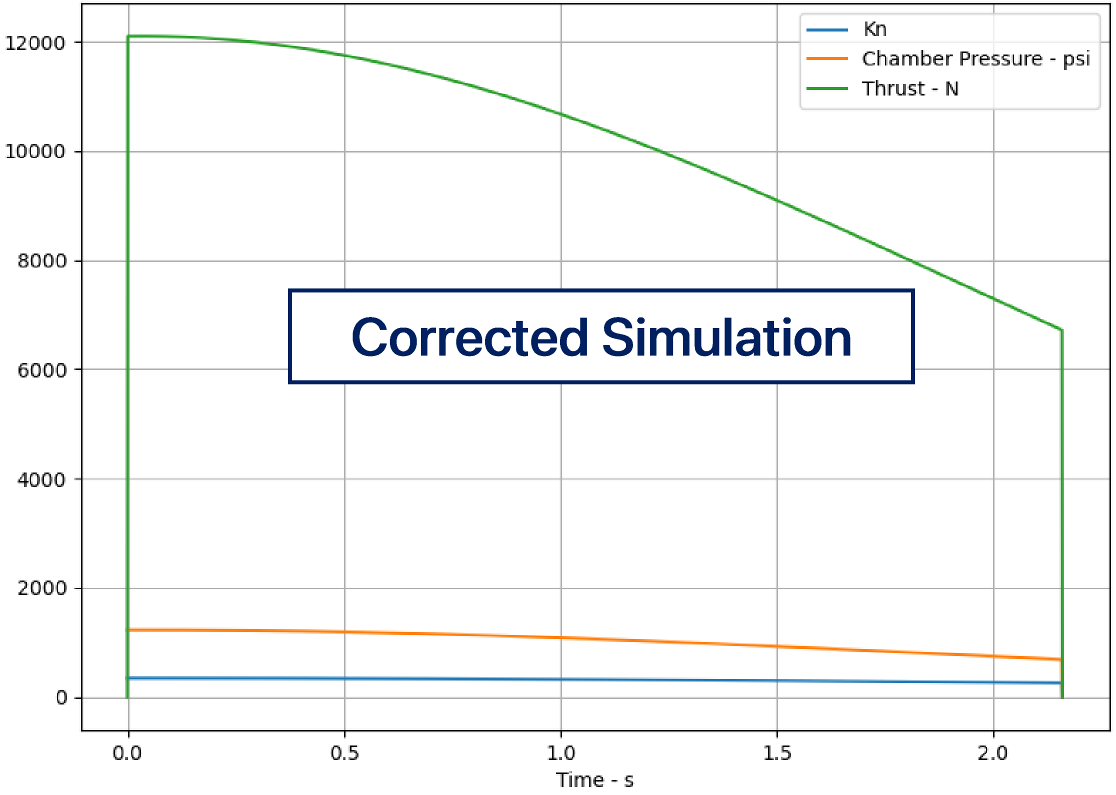
Name:	RADIANT KNSB 2024	
Density:	1.950000 g/cm^3	
Properties:	Minimum Pressure:	0.000000 psi
	Maximum Pressure:	1500.000000 psi
	Burn rate Coefficient:	0.000006 m/(s*Pa^n)
	Burn rate Exponent:	0.487200
	Specific Heat Ratio:	1.136100
	Combustion Temperature:	1520.000000 K
	Exhaust Molar Mass:	39.900000 g/mol
	Characteristic Velocity: 885151 mm/s	

Tests/Experiments

Static firing tests: Problems with KNSB (1) solved!

- After parameter (burn rate) adjustment from the BEM.

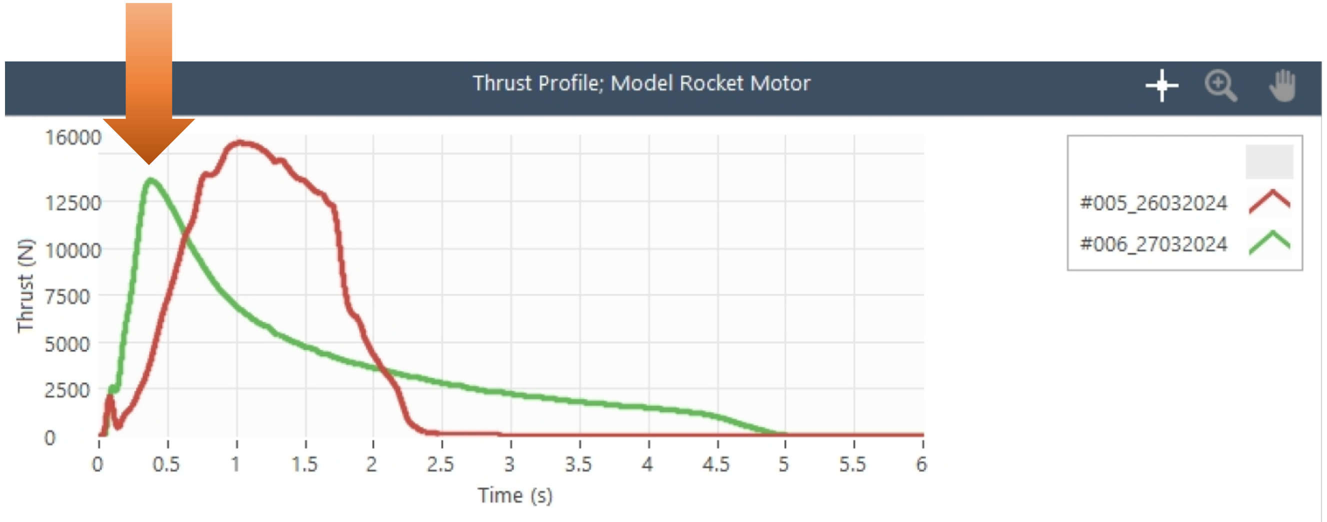


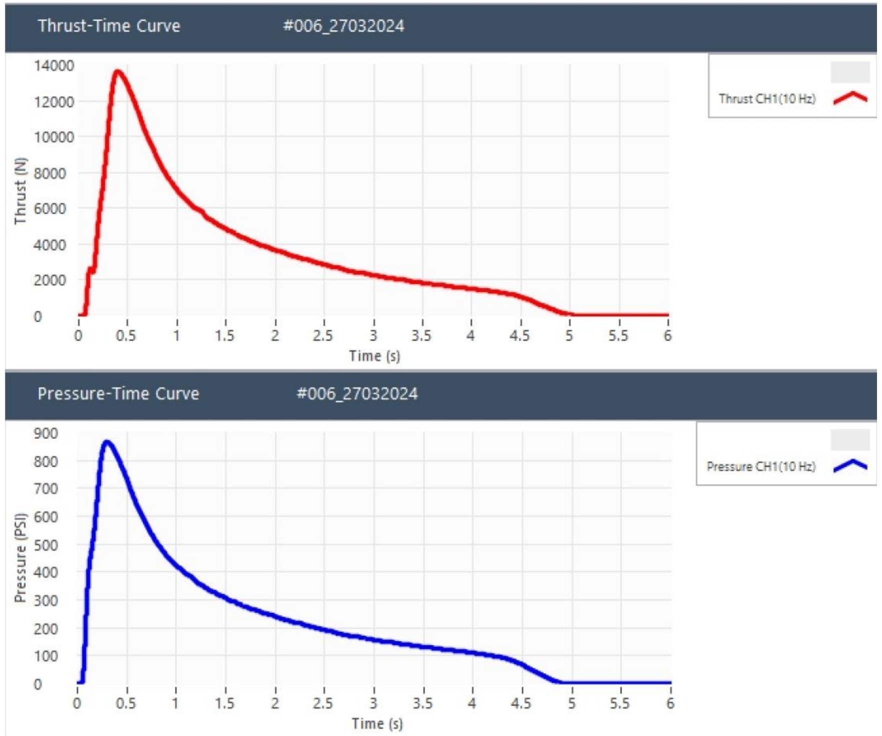


Tests/Experiments

Static firing tests: Problems with KNSB (2)

- In our very last static firing tests,
  we encountered weird mountain thrust curve.





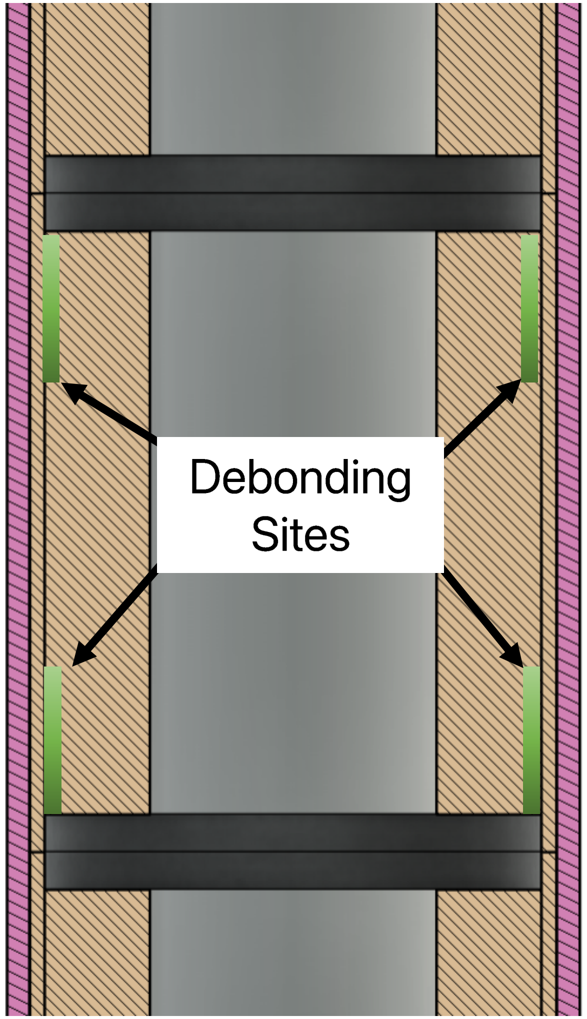
- At first, we suspected it might be from very little grain spacing, so, we increase the spacing and the problem was still seen.
- We later found out that it is from propellant grain "debonding."

Tests/Experiments

Static firing tests: Problems with KNSB (2)

- Debonding happens when the propellant grain detaches itself from the liner material.
  - In this case, KNSB and paper tube.

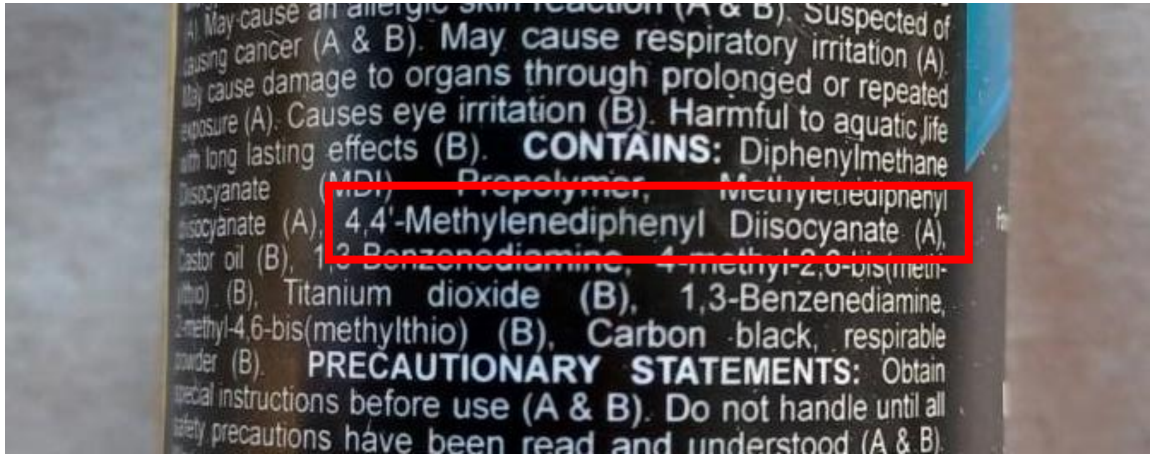
- There are two possible fixes (as we know as of now)
  - Pressing the propellant cast cap after casting it. (poses another problem)
  - Add isocyanate compound to help adhering/binding KNSB and paper tube together. (haven’t tried yet, will be trying this launch!)



Tests/Experiments

Static firing tests: Problems with KNSB (2)

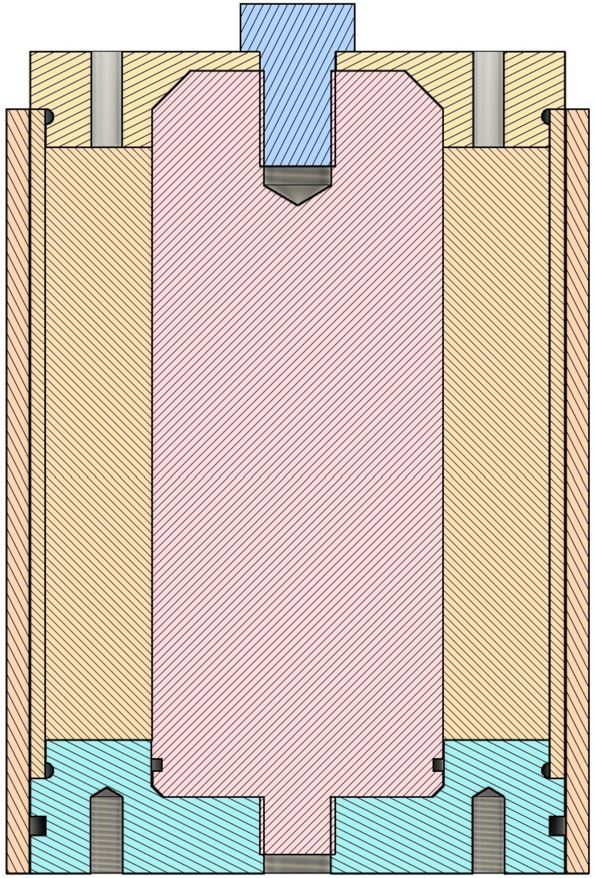
“A” Component: MDI, pMDI



Propellant Manufacturing

The Hardware

Tightening bolt/screw	For pressing the propellant grain to its nominal density
Pressuring cap	
Grain	Paper liner to use, target product
Core rod	BATES Core
Base	Base
Casing	For alignment and prevent liner deformation



Propellant Manufacturing
The Hardware

Standardized Propellant Manufacturing

The Process (1/2): Casting

- Prepare the paper liner by applying –isocyanate to the inner side
- Measure 65% KNO_3 and 35% Sorbitol (or appropriate ratio)
- Mix using a V-blender
- Lubricate the mold
- Melt it using a saucepan + heating pad
    - Fire stove or induction stove is not recommended due do its uncontrolled nature
- Pour it into the casting mold slowly to reduce air bubble formation
- Use rubber hammer to thump (hit) on the side to remove air bubbles
- Leave it to dry and cool down naturally at room temperature for 12 – 24 hr.

Standardized Propellant Manufacturing

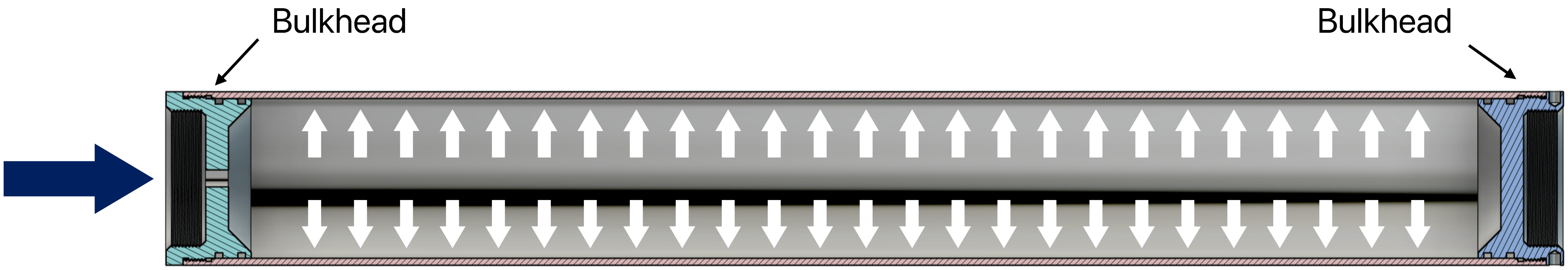
The Process (2/2): Post-processing

- After fully dried, remove the grain and trim excessive edges.
- Confirm the final weight.
- Clean the grain with 99% isopropyl alcohol
- Dehumidify the grain for 12 – 24 hr.
- Coat the propellant grain with dough-like black powder on top and bottom sides and leave it for 12 – 24 hr.
- Store it in a dry environment.
- Voila!

Tests/Experiments

Hydrostatic pressure test

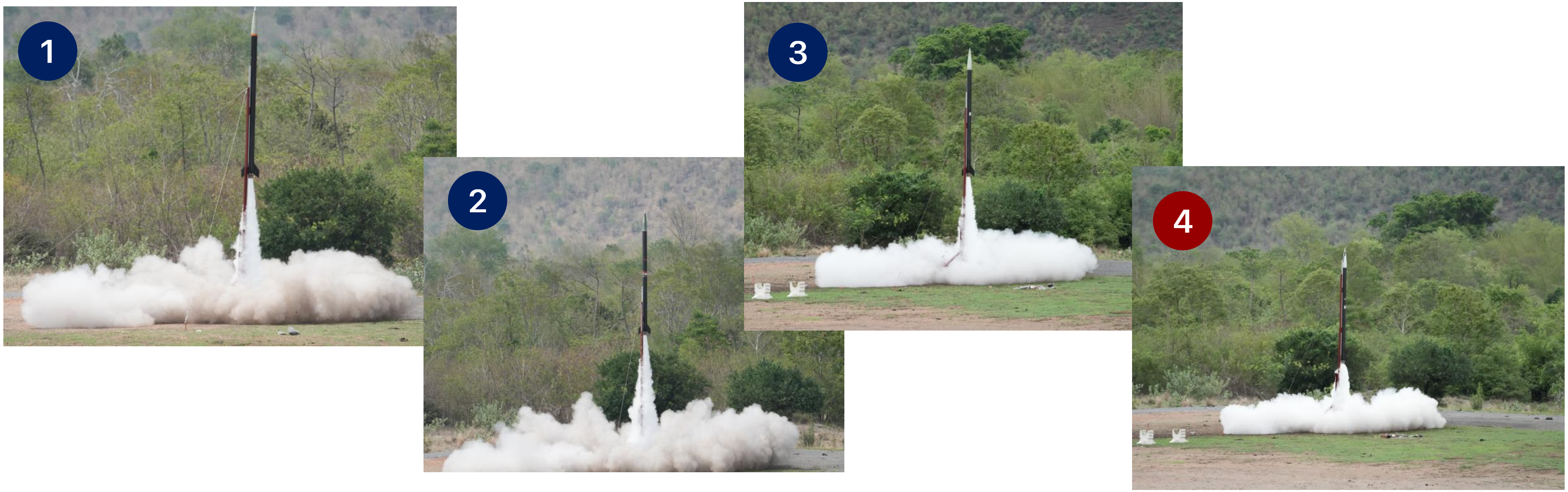
- To ensure that the casing and configurations can operate at least 2 times of the Maximum Expected Operating Pressure (MEOP).



Tests/Experiments

Dynamic (flight) tests

- Out of 4 flights,
  - 3 of 4: performs exactly like the simulation
  - 1 of 4: found propellant “cracks” and “debonding (disbonding)”



That’s just a small part of our journey.
Thailand’s high power rocketry spin-off.

Download at
vt.in.th/rocket

Thank you for all the supports!