ESRA 30K Team: Solid Propellant Rocket Motor

2019-2020

An Informative Presentation

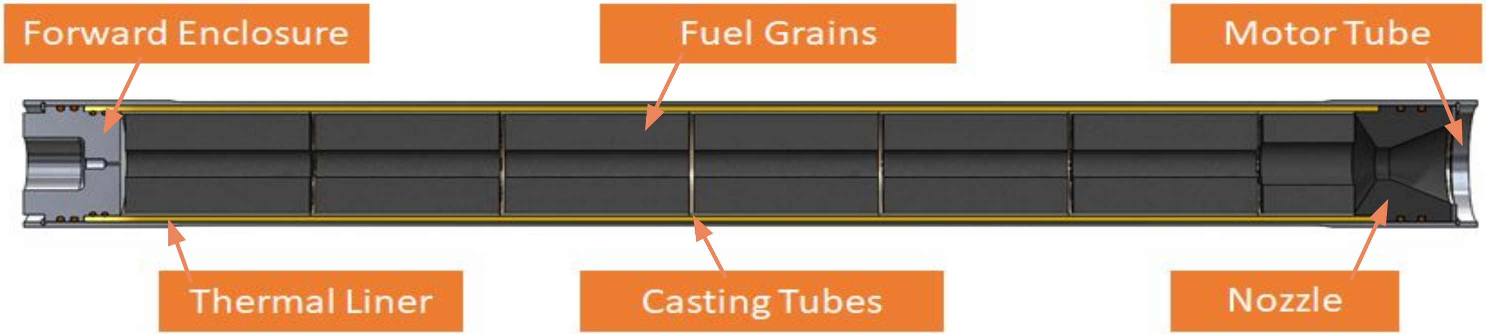
- Michael Barden
- Cole Domenico
- Tom Gerendsay
- Caspar Hendrickson
- Jon Campillo
- Carter Hazen
- Harjot Saran
- Mat Van Gordon

Oregon State University

ESRA Propulsion Topics

1. Primary Components
2. Propellant formulation
3. Characterization
4. Burnsim
5. DAQ
6. Motor Tube Design
7. CPV
8. Thermal Liner
9. Forward Enclosure
10. Nozzle
11. Testing
12. Project schedule
13. Key Takeaways & Recommendations

Primary Components



Forward Enclosure: Caps off forward end and prevent gas from getting behind thermal liner
Thermal Liner: Fiberglass Tube, Prevents the heat of the fuel from reaching motor tube
Fuel Grains: Solid Propellant that burns on interior face ate pressures (`700 psi)
Casting Tubes: Cardboard tubes that the propellant is packed into to shape it
Motor Tube: Aluminum tube that holds pressure of firing
Nozzle: Graphite nozzle that converts high pressure into supersonic flow

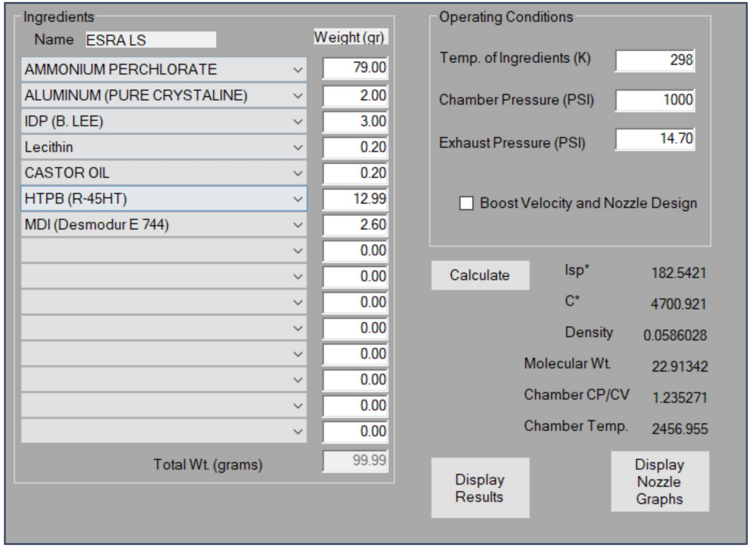
Propellant Formulation

A new chemical formulation named Liquid Schwartz (LS) was given by OROC mentor Jim Baker. Jim Baker is an experienced chemist in the aerospace industry and a mentor of OSU's solid rocket motor propulsion sub-teams. The new chemical formulation was based on previous year's composition, Orange Koolaid. The goal was to reduce the complexity of the chemical composition and to reduce total mixing time. The LS formulation consists of six primary ingredients, each with different mass fractions.

		ESRA 2018 - 2019 Chemical Compositon (Orange Koolaid)	*ESRA 2019 - 2020 Chemical Compositon (Liquid Schwartz)*
Ingrediant	**Purpose**	**Mass Percentage (%)**	**Mass Percentage (%)**
Hydroxl-terminated Polybutadien (HTPB)	Resin	11.5	12.99
Isodecyl Pelargonate(IDP)	Plastisizer	3	3
Castor Oil	Chainlinking Agent	0.3	0.2
Liquid Lecithin	Viscosity Reducer	0.1	0.2
Silicon Oil	Anti-foaming Agent	0 (1drop)	0 (1drop)
Zinc	Fuel	1	N/A
Crystalline Aluminum	Fuel	0.5	2
Manganese Dioxide	Catalyst	0.5	N/A
Calcium Carbonate	Burn Rate Inhibitor	1	N/A
Ammonium Perchlorate	Oxidizer	80.1	79
Modified Isocyanate (MDI)	Curative	2	2.6

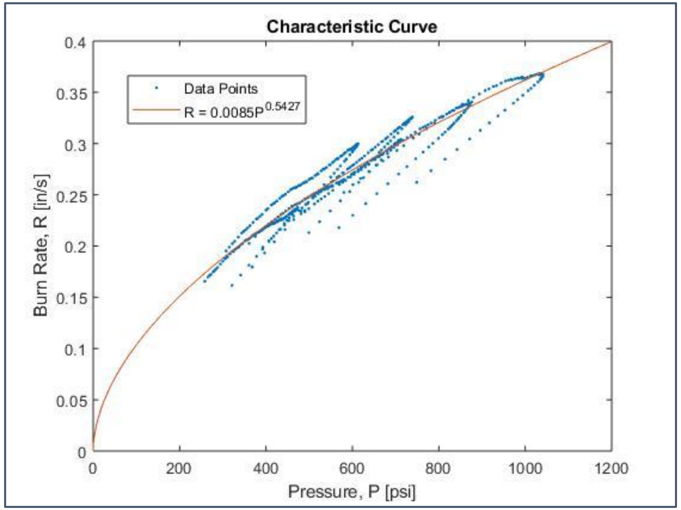
Propellant Formulation

- **Why use Propep?**
  - Propep is a propellant evaluation program used to determine the chemical composition for the combustion of a solid rocket propellant. After inputting chemical makeup and operating conditions, Propep provides theoretical performance parameters of the propellant composition.
- **Liquid Schwartz (LS) Propep Output**
  - The photo represents the chemical makeup of LS and it’s performance parameters.The parameters calculated in Propep are transferred to a separate simulation software called Burnsim.
- **Mixing Process**
  - The mixing process consists of combining all the ingredients and casting into individual propellant grains.
  - Click this link to see casting tubes.
  - Click this link to see an example of a propellant mix.
  - Click this link to see the LS Batch Sheet.
  - Click this link to see Mixing SOP.



Characterization

- **Characterization:** The process of determining the burn characteristics of solid rocket propellant using data gathered from sub-scale motor testing. (Relate P to R)
- **Why Characterize?**
  - Characterization can be used to predict the performance of full-scale motors
  - Knowing what to expect allows us to build SAFE rockets
- **What does successful characterization look like?**
  - Solve for the coefficients of Muraour's Linear Burning Rate Law (A & n)

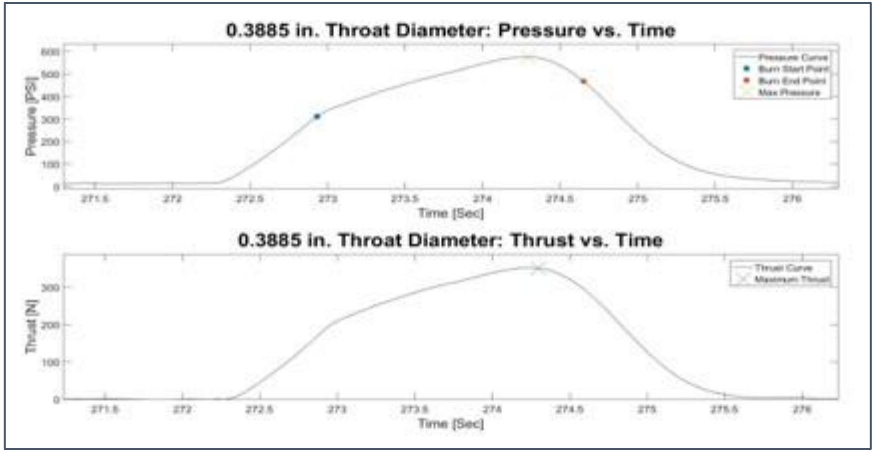


Muraour's Linear Burning Rate Law:

$$R=AP^n$$

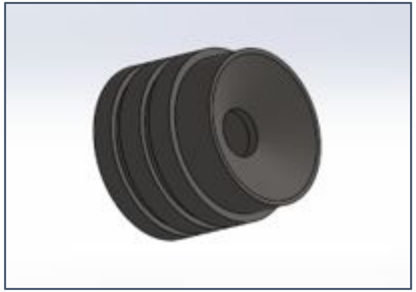
R = Propellant burn rate
P = Motor chamber pressure
A = Constant of proportionality
n = Pressure index

Characterization - The Process



- **Characterization Inputs:**
  - Geometry of propellant grains
  - Geometry of nozzle
  - Pressure curve from subscale testing
  - Density & mass of propellant

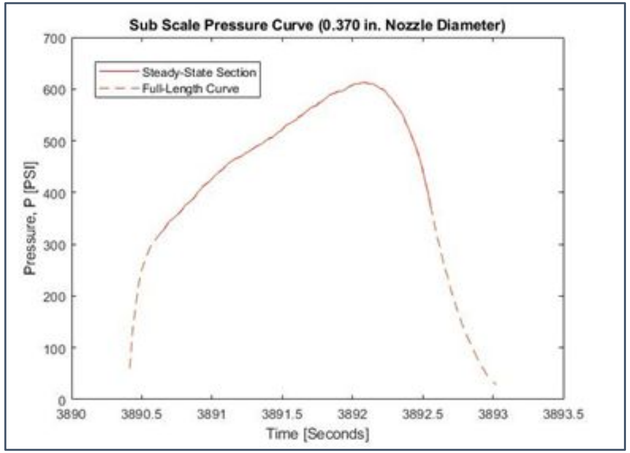
Nozzle



Propellant Grain

Characterization - The Process

- **Next steps:**
  - Determine range of steady-state (SS) burning
  - Get SS burn time
  - Calculating A & n requires burn rate. There are two different methods of determining burn rate:
    - Calculate instantaneous burn rates for each pressure data point (Richard Nakka's method)
    - Calculate average burn rate for entire test (Jim Baker's method)
  - Plot burn rate vs. chamber pressure. Then fit a line of best fit curve of the form: R = A*P^n to solve for A and n.



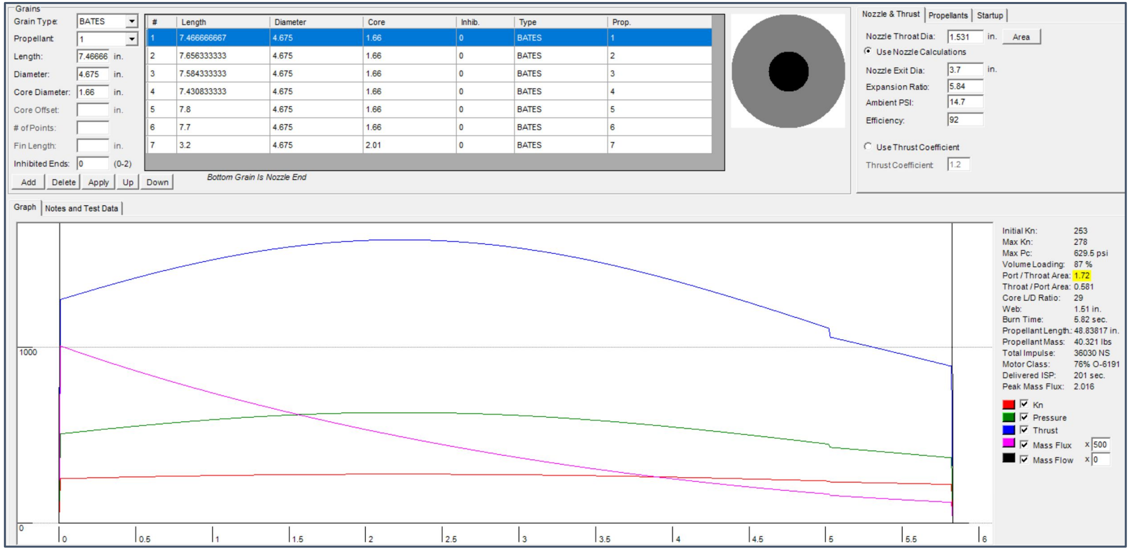
NOTE: For specifics on these methods and how to implement them, reference the ESRA Propellant Characterization guide.

Characterization - Possible Improvements

- **Increase the uniformity of propellant batches**
  - Employ vacuum casting
  - Keep ingredient sources constant
  - Keep mixing environment constant
- **Characterize propellant at three different temperatures**
  - Currently, characterization is only valid for ~40-50°F
  - Temperature affects burn rate

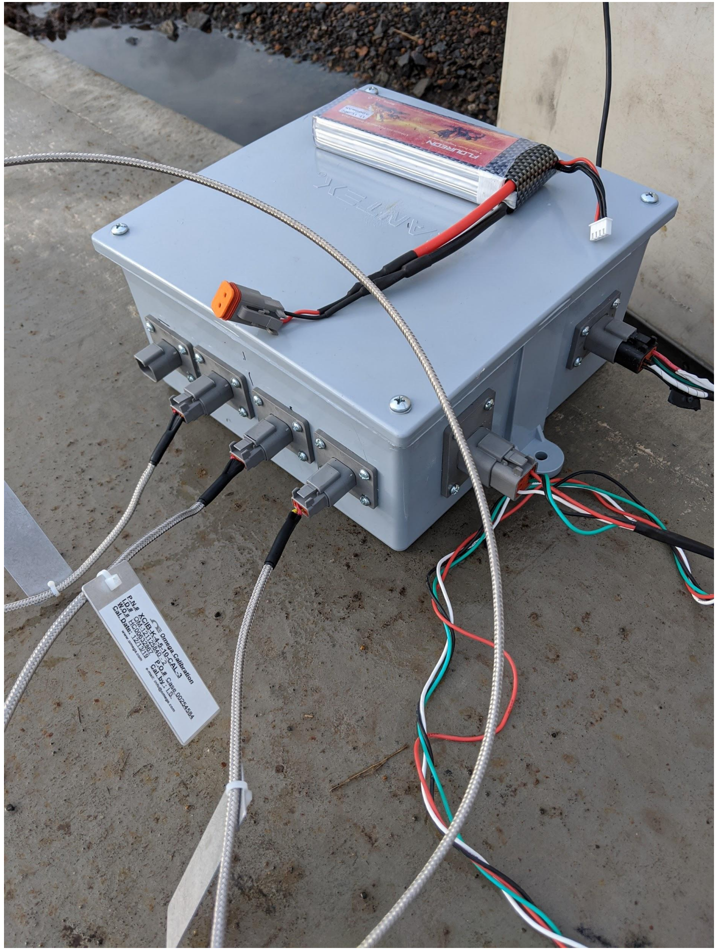
BurnSim

- **Why use BurnSim?**
  - Simulation program used to predict the performance characteristics of a solid propellant rocket motor.
  - Aids in calculating theoretical nozzle geometry.
- **Burnsim Program Inputs**
  - **Propellant characteristics**
    - A and N values
    - Propellant density
    - Characteristic velocity
  - **Grain Geometry**
    - Grain Length
    - Grain Diameter
    - Grain Core Diameter
  - **Nozzle Geometry**
    - Nozzle throat diameter
    - Nozzle exit diameter
    - Nozzle efficiency
    - Ambient pressure



DAQ

- **DAQ 3.0**
  - Pressure, thrust, and thermal data is collected with the data acquisition system.
  - Manual can be found here: [DAQ 3.0 Manual]
- **What sensors do we have?**
  - Futek PFP350 (0-3000psi) pressure transducer
  - OMEGA LCM 305 (0-10,000N) load cell
  - OMEGA XCIB-K-4-5-10 Thermocouples (x6)
  - Read the DAQ 3.0 manual to learn how to operate it. The DAQ works with mV/V sensors and Type K thermocouples.
- **Next Prototype**
  - DAQ 4.0 was created spring of 2020.
    - Compatible with various sensor output types:
      - mV/V
      - 0-5V or 0-3.3V
      - 4-20mA
    - Compatible with (K, J, N, R, S, T, E, and B) thermocouples.
    - Improved precision.

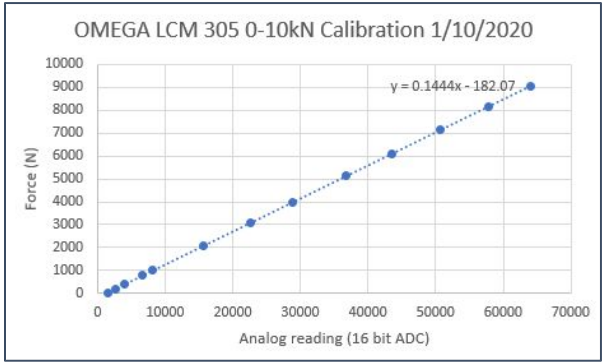


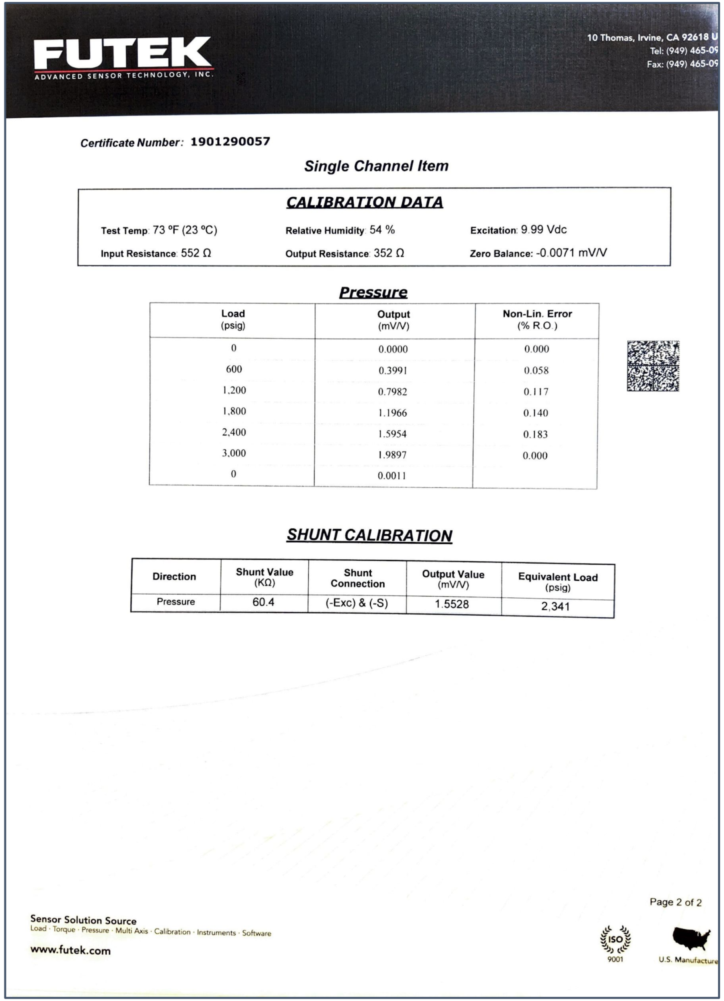
DAQ - Testing setup

- Pressure transducer is connected to forward enclosure by copper tubing for ease of connection, and to protect the sensor from heat.
- Motor sits on top of load cell to gather thrust data to predict altitude.
- Subscale thrust data is used as a double check when calculating burn rate.

DAQ - Calibration

- FUTEK pressure transducer calibration was supplied by FUTEK. The calibration is applied in the DAQ 3.0 code, so pressure channel is reported in PSIA.
- Load cell was calibrated using the INSTRON.





FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 U
Tel: (949) 465-09
Fax: (949) 465-09

Certificate Number: 1901290057

Single Channel Item

CALIBRATION DATA

Test Temp: 73 °F (23 °C) Relative Humidity: 54 % Excitation: 9.99 Vdc

Input Resistance: 552 Ω Output Resistance: 352 Ω Zero Balance: -0.0071 mV/V

Pressure

Load (psig)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0000	0.000
600	0.3991	0.058
1,200	0.7982	0.117
1,800	1.1966	0.140
2,400	1.5954	0.183
3,000	1.9897	0.000
0	0.0011	

SHUNT CALIBRATION

Direction	Shunt Value (KΩ)	Shunt Connection	Output Value (mV/V)	Equivalent Load (psig)
Pressure	60.4	(-Exc) & (-S)	1.5528	2,341

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Sensor Solution Source
Load · Torque · Pressure · Multi Axis · Calibration · Instruments · Software

www.futek.com

ISO 9001 U.S. Manufacture

DAQ - Calibration

- Thermocouples don't require calibration. K type output can be correlated to temperature from lookup table: [Lookup Table]
- Accuracy can be slightly increased by individually calibrating each probe.
- DAQ outputs the calibrated temperature. No need to use any of this.

OMEGA™

Form: NJ-MET-FRM-004 Rev. A

Certificate Of Calibration

for

Oregon State University

Cust. P.O. #: Case 00254584
Test Item: XCIB-K-4-5-10-CAL-3

Report #: OM- 121125840
WO : HC00632867

Recal Date: Per System Application

Ref. I.D.: WNW0165287

CAL-3

Omega Engineering, Inc. certifies that the above instrumentation has been calibrated and tested to **meet or exceed** the published specifications. This calibration and testing was performed using instrumentation and standards that are traceable to the **National Institute of Standards and Technology**. Calibration has been performed in compliance with ISO 10012-1, ISO 9001 and ANSI/NCSL Z540-1-1994 as well as ASTM E 230 and ANSI MC96.1. This Certificate/Report shall not be reproduced, except in full, without written consent of Omega Engineering Inc.

Test Conditions: Temperature 73°F Relative Humidity 32%
Procedure used: QAP-2100
The maximum calibration uncertainty is calculated to be 0.3C from -25C to 500 C and 0.55C from 500C to 1100C.
INSTRUMENTS USED:

MODEL	SERIAL#	CAL DUE DATE	N.I.S.T. NUMBERS
Agilent 34401A	MY41015106	04/10/20	NNDM-100-11
DP251	1292-007-484	08/21/20	NNPT-100-02
DP251	1325031708	02/22/20	NNPT-100-06
TRCIII	I-0014	03/14/20	NNIP-100-07
RTD (Burns)	765566	09/19/20	NNPR-100-06
RTD (ASL)	S184	02/26/20	NNPR-100-09
RTD (Burns)	724312	04/03/20	NNPR-100-12

Probe No.	Nominal Temperature	Actual Test Temperature	Indicated Temperature
1	212°F	212.0°F	212.6°F
1	392°F	392.0°F	393.4°F
1	752°F	752.0°F	753.5°F
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Metrology Technician
Calibration Date: 12-13-19

Quality Assurance Inspector

OMEGA™

Form: NJ-MET-FRM-004 Rev. A

Continued Report # OM- 121125840

Probe No.	Nominal Temperature	Actual Test Temperature	Indicated Temperature
2	212°F	212.0°F	211.9°F
2	392°F	392.0°F	391.5°F
2	752°F	752.0°F	752.7°F
-----------	-----------	-----------	-----------
3	212°F	212.0°F	211.9°F
3	392°F	392.0°F	391.3°F
3	752°F	752.0°F	752.6°F
-----------	-----------	-----------	-----------
4	212°F	212.0°F	212.6°F
4	392°F	392.0°F	392.6°F
4	752°F	752.0°F	752.8°F
-----------	-----------	-----------	-----------
5	212°F	212.0°F	212.0°F
5	392°F	392.0°F	391.3°F
5	752°F	752.0°F	752.6°F
-----------	-----------	-----------	-----------
6	212°F	212.0°F	211.9°F
6	392°F	392.0°F	391.3°F
6	752°F	752.0°F	752.7°F
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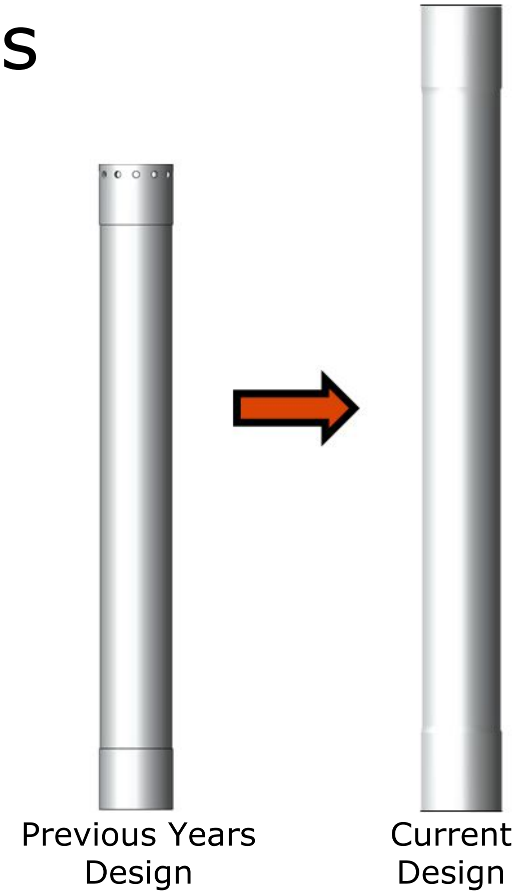
OMEGA Engineering, Inc. | Pureland Industrial Park | One Omega Circle | Swedesboro, NJ 08085 omega.com WCS-0638A_rev0218

Motor Tube

- **What is a motor tube?**
  - The motor tube is the component that gives structure to the overall motor assembly and is the main component in containing the pressure during operation.
- **Dimensions**
  - 60” length
  - 6” outer diameter
  - 5.5” inner diameter
  - 0.25” thick on ends
  - 0.175” thick in the middle
- **Safety Factor**
  - Calculated to approx. 4.1 during operational pressures of 600 psi.
- **Material Selection**
  - Aluminum 6061-T6, selected over aluminum 7071 due to its availability, cost, and manufacturability
- **Machining**
  - Currently, OSU does not have the capabilities to accommodate a 60” tube on any of their lathes or CNC machines
  - Utilized P&J Machining to have the motor tubes manufactured out-of-house
    - https://www.pnjmachining.com/

Motor Tube - Design Changes

- **Length**
  - Increased to 60” from the previous years 48” to allow for the greatest volume of propellant
- **External shoulder**
  - Created curved shoulders instead of a sharp step down to the smaller diameter to reduce stress concentrations
- **Extended length of full thickness sections at ends**
  - The temperature is highest at the shoulder where the nozzle presses up against the thermal liner, so the motor tube’s thickest points were extended over this weak point
- **Snap rings instead of radial bolts**
  - Reduces manufacturing effort on both the motor tube and forward enclosure
  - Integration time is reduced drastically



Motor Tube - Possible Improvements

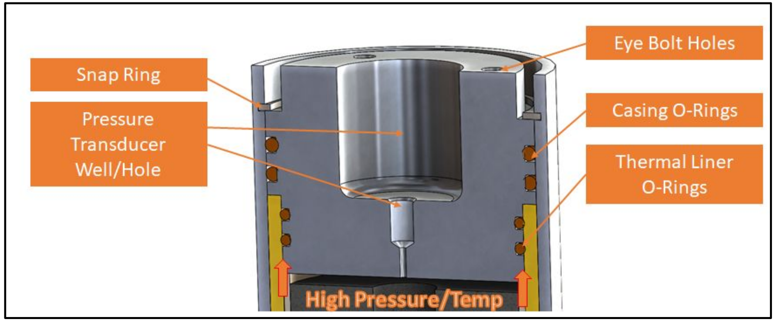
- **Length**
  - With a better formulation for the propellant, the motor tube’s length can most likely be reduced now that there is reliable data to more accurately simulate the required volume of propellant.
- **Thickness of material at forward enclosure end**
  - The temperatures recorded at the forward enclosure are not extreme enough to make the thicker sections as necessary. This means that more of the tube can be a thinner diameter to save on weight.
- **Material**
  - If a reliable aluminum 7071 supplier is found, it is a much better material in terms of its properties. A long time was spent attempting to source any, but all the options that were found were extremely expensive with a very low amount of material in stock. So, while it has the capability of being a drastic improvement, unless a source is found that has a large inventory with decent prices, stick to aluminum 6061.
  - If possible, continue the deal with P&J Machining to acquire material and machine through them. Online Metals is an option that previous teams have used to purchase motor tube stock, but there are more frequent issues with defects in their product that is hard to identify without the proper tools. So, it is helpful to have professionals who verify the stock first and know what to watch out for.
- **Boat Tail Integration**
  - Incorporate design features in the motor tube to secure the boat tail of the rocket sooner. The motor tube was adapted later on in the project to make this attachment point possible, but it would have made integration into the rest of the rocket smoother if there had been attachment points in the design from the beginning.

Thermal Liner

- **Why Use a Thermal Liner?**
  - A layer of insulating material will allow for a reduction of the rate at which heat may be diffused into the casing walls. The idea is to use a material that won't completely burn away after a single usage.
- **Material Selection**
  - We used fiberglass thermal liners to protect the Aluminum 6061-T6 from the propellant.
  - Fiberglass was durable and amazing with how well it handled the massive temperature change. Transfers almost no heat to the aluminum.
- **Our Advice**
  - Fiberglass is heavy! A large portion of the motor's weight is the liner. We cautiously recommend looking into experimentation with thermal liner.
  - If there is no need for change in material, look for a reduction of the thickness so you don't have to spend time sanding down the fiberglass. Or look into possibly laying up your own fiberglass liner.
- **Link for Thermal Liner We Used**
  - https://www.centekmarine.com/product-category/exhaust-tubing/?number=90

Forward Enclosure

- **Why Use a Forward Enclosure?**
  - The forward enclosure caps off forward end of the rocket using multiple sets of O-rings to prevent the combustion gasses from circulating behind the thermal liner or escaping the end of the motor.
- **Material Selection**
  - 6061-T6 was chose due to its availability and price point as material strength is not a concern for this part.
- **Our Advice**
  - This design works well but could be optimized for weight and additional sensors could be added.
  - The machining process takes a long time if this can be done on a CNC lathe you will save your self days.

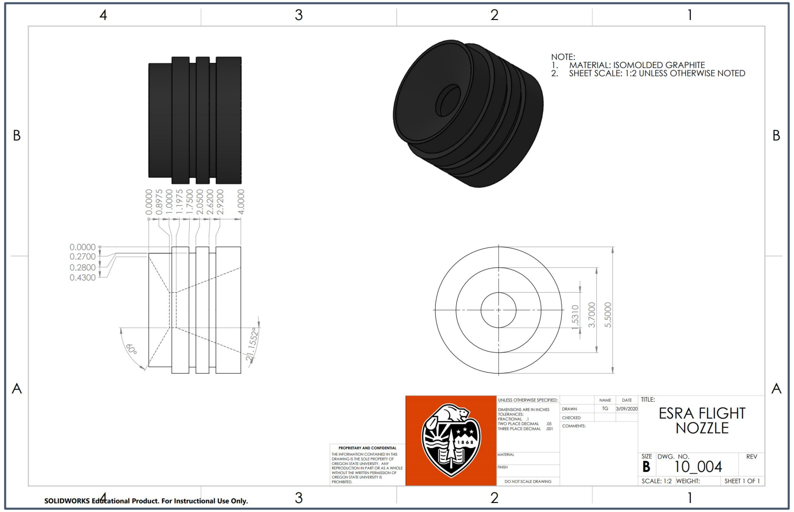


Design Features:

- Snap Ring
  - Prevents FE from moving axially
- Pressure Transducer
  - ¼ in NPT threaded hole for pressure transducer
- Eye Bolt Holes
  - Holes to connects parachute eye bolts and rest
    rocket
- Thermal Liner O-Rings
  - Primary O-ring set prevent hot gasses from circulating behind the thermal liner
- Casing O-Rings
  - Secondary set of O-rings to provide fail-safe to thermal liner O-rings

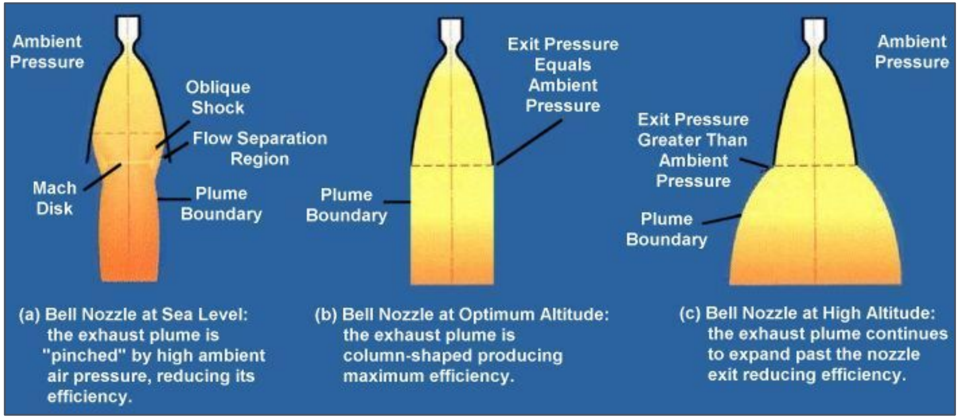
Nozzle

- **Why use a Nozzle?**
    - The purpose of a isomolded graphite de laval nozzle is to channel and accelerate the flow of combustion gasses to a supersonic velocity.
- **Importance?**
    - The nozzle design dictates:
        - The thrust produced by the rocket motor.
        - The internal chamber pressure experienced by the rocket motor.
        - The rate at which the propellant will burn.
- **The Goal?**
    - The goal of the nozzle is to maximize the velocity of the exhaust gasses without over-pressurizing the aluminum 6061 motor casing.
- **Material Selection**
    - Isomolded graphite is used to manufacture the nozzle.
        - Graphite is easy to manufacture using the OSU Summit lathe.
        - Graphite is a structurally reliable material in high heat applications.
        - Graphite is affordable.
    - Graphite is ordered from the Graphite store. Click [here.]



Nozzle

- **Avoiding Inefficiencies**
    - There are two expansion behaviors that induce inefficiencies in nozzle performance: Over-expanded flow and under-expanded flow.
        - **Over-expanded Flow:** Occurs when the ambient pressure is higher than the nozzle exit pressure. This type of expansion behavior results in constricted flow of combustive gasses. Over-expansion can be mitigated by shortening the length of the nozzle or decreasing the diverging angle to decrease the nozzle exit area to a point where the nozzle exit pressure is equal to the ambient.
        - **Under-expanded Flow:** Under-expanded flow occurs when the ambient pressure is less than the nozzle exit pressure. This type of expansion behavior results in an expanded flow of combustive gasses. Under-expansion can be mitigated by increasing the length of the nozzle or increasing the diverging angle to a point where the nozzle exit pressure is equal to the ambient.



Testing

1. **SUB-SCALE**

   Essentially a miniature version of the motor used for collecting data about the propellant. Multiple subscale tests are used to characterize the propellant and discover the A and n values.

2. **HYDROSTATIC**

   Using the full scale motor, water is pumped in until the motor is full and is then sealed by a second forward enclosure. A grease gun is then used to pressurise to 1.5x the operational pressure and held there for several minutes. This ensures that the motor is unlikely to fail during a full-scale test fire. See link for procedure here.

3. **INTEGRATION**

   Completely assemble the full-scale motor. This is a dry run to make sure all components integrate correctly and the motor is ready for full-scale static testing. See link for procedure here.

4. **FULL-SCALE**

   The full-scale motor is statically test fired to gather thrust, pressure, and temperature data. Data is collected into test report. See example here.

Project Schedule

- Fall Term:
  - Chemical formulation
    - Design the formula
    - Mix sub-scale batch
    - Design and build sub-scale test stand
    - Design and build sub-scale ignition system
    - Gather data from subscale static fire
    - Characterized formula from static fire data. (We repeated these steps a few times before we were satisfied with the data).
  - Design full-scale motor assembly
    - Forward enclosure
    - Motor tube
    - Nozzle
    - Thermal liner
    - Casting tubes
- Winter Term:
  - Validate motor design
    - Full-scale static test fire
    - Mix full-scale motor
    - Finish manufacturing motor assembly
    - Design and build full-scale test stand
    - Design and build full-scale ignition system
    - Gather data from full-scale static test fire
    - Repeat if necessary. (We repeated to get a faster ignition.)

Project Schedule

- Winter Term - Continued:
  - Prepare for test flight
    - Build full-scale motor
    - Design and build igniter for rocket on the rail
    - Design and build a system to log pressure data while in flight
    - Conduct test integration of motor into rocket
- Spring Term:
  - Build additional motors for further testing and competition
  - Support other sub-teams
  - Document work
  - Develop equipment for future ESRA years

Key Takeaways & Recommendations

- Follow safety procedures at all times.
- Measure twice, cut once.
  - Always reference CAD modeling when manufacturing and integrating components.
- Make sure to research completely and make informed, justified decisions.
  - Recommend reading Solid Rocket Propellant Technology
- Seek low-risk design changes to reduce weight of rocket motor.
  - Phenolic Nozzle
  - Vacuum Casting Grains
  - Reduce thickness of fiberglass liner
- Aim to complete subscale testing by the end of fall term.
- Always seek help and ask questions. Our mentors are outstanding!

Thank You!