Recap

- Testing is vital
- Oxidizer - N2O
- Fuel - Undecided (HTPB, Parrafin, Mixture, Nylon)
- Hard to make design decisions without data!
Engine Ignition/Burn

FIGURE 16-10.
Important Components/Considerations

Design Elements
- Chamber Pressure
- Chamber Temperature
- Injector
- Igniter
- Nozzle

Design Tools
- RPA Modeling
- EES Modeling
- Test Stand/Empirical Data

Big Decisions
- Casing Size/Diameter
- Fuel Grain/Overall Length
- Oxidizer Tank Size
- Dependent on Overall Weight
Chamber Pressure

- Extremely Important
- Chamber Pressure analysis is complex
- “Hard Start” Danger
- Higher Chamber Pressure $\rightarrow$ More Thrust (Generally)
- Nitrous Oxide self pressurizes around 730 psi
- Chamber pressure must be $< 600$ psi to ensure unhindered oxidizer flow and therefore stable combustion
- Use 500 psi to model at least initially
RPA Modeling

- Gas Constant
- K-Values
- Optimized Area Ratio
- Generates an Optimal Fuel Mixture Ratio for your input criteria

- Very useful for getting accurate numbers for EES Modeling

Mixture Ratio

- Optimal Mixture Ratio is still unknown
- Most likely between 7-8 (For highest specific impulse)
- RPA Modeling of N2O/HTPB predicts an optimal ratio of 7.490
- Approximately a 7.5 O/F ratio will be suitable for our rocket
- Keep this ratio in mind when selecting valves for the oxidizer injection
- A high oxidizer flow rate like this will be attainable due to a typically low regression rate
- Ratio will shift throughout the burn -> Hard to predict
EES Modeling

- Plenty of Assumptions were made
  - Assumed Burn Time (10s)
  - Assumed Initial Mass (60 lbs)
  - Constant Chamber Pressure/Temperature (500psi)
  - Ideal Compressible Flow
  - Choked Flow Throughout Burn
  - Casing Diameter (8 Inches) <- used for drag force calculation
  - No Throat Erosion/Clogging

- Initial Model predicts throat diameter of .6 inches will get us to 10500 ft with a ten second burn time after about 28 seconds
EES Refinement

- Changing Chamber Pressure
  - Testing -> More Realistic Pressure Ranges/Change -> Changing Chamber Pressure in the model

- Incorporate Chamber Pressure into the Oxidizer flow rate model

- Integrate Regression rate (found experimentally) to model the mass flow rate into the post combustion chamber and the total mass lost by the rocket

- Develop a model for chamber pressure?
Nose Cone Considerations

- Low Half Angle limits drag
- Less drag
  - Less Thrust Required
  - Lighter Rocket
- Possible Payload/Recovery System Storage
- $20^\circ = .386$, 11 inch Length
- $30^\circ = .5$, 7 inch Length

\[ C_D = 0.0112 \varepsilon + 0.162 \]

http://www.aerospaceweb.org/question/aerodynamics/q0231.shtml
Nozzle: Parameters

- Chamber length
- Chamber diameter
- Throat diameter
- Nozzle length
- Half angle
- Exit diameter
- Expansion ratio
- Contraction ratio

http://www.braeunig.us/space/pics/fig1-04.gif
Nozzle: Loss Sources

http://www.space-propulsion.info/resources/articles/Advanced_nozzles.pdf
Nozzle: Important Loss Sources

Table 1  Performance losses in conventional rocket nozzles

<table>
<thead>
<tr>
<th>Losses</th>
<th>Vulcain 1, %</th>
<th>SSME, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical nonequilibrium</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Friction</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Divergence, nonuniformity of exit flow</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Imperfections in mixing and combustion</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Nonadapted nozzle flow</td>
<td>0–15</td>
<td>0–15</td>
</tr>
</tbody>
</table>

*Other loss sources also shown in Fig. 1.

[http://www.space-propulsion.info/resources/articles/Advanced_nozzles.pdf](http://www.space-propulsion.info/resources/articles/Advanced_nozzles.pdf)
Nozzle: Important Loss Sources

- Viscous effects because of turbulent boundary layers
- Nonuniformity of the flow in the exit area
- Non adaptation of the exhaust flow to varying ambient pressures
  - Induces a significant negative thrust contribution
- Ambient pressures that are higher than nozzle wall exit pressures increase the danger of flow separation inside the nozzle
  - Results in possible generation of side loads!
Nozzle: Altitude Adaptation

- Nozzles can be complex, and be adaptive for higher performance with changing altitude.
- Simple nozzles are easy, but come with significant performance losses during off-design operation.
- Many different nozzle types exist and are suitable for a variety of scenarios.
Nozzle: Off-Design Examples

Fig. 2 Rocket nozzle flowfields during off-design operation: a) overexpanded flow RL10A-5 engine and b) underexpanded flow Saturn-1B, Apollo-7 (Photographs, United Technologies Pratt & Whitney, NASA).

Fig. 4 Flow phenomena for a conventional rocket nozzle.

http://www.space-propulsion.info/resources/articles/Advanced_nozzles.pdf
Nozzle Types

- Nozzles with inserts for controlled flow separation
- Two-position nozzles
- Dual-bell nozzles
- Dual expander/dual throat nozzles
- Expansion-deflection nozzles
- Plug nozzles

Fig. 11 Performance characteristics of a dual-bell nozzle. Performance is compared with two baseline bell-type nozzles as function of flight altitude (baseline nozzle 1: same area ratio as dual-bell base nozzle; baseline nozzle 2: same area ratio as nozzle extension).
Nozzle Selection

- Our design - 10,000ft.
- Only a small area expansion ratio is required
- We can neglect “aspiration” drag at such low altitudes and small areas, its effects will be minor
- Optimizing at one altitude will get the job done
- Options
  - Conical
  - Single bell contour
Injector

- Consists of holes, orifices, and passageways
  - Cross flow area
  - Flow rate
- Self-pressurizing oxidizer
- Design considerations
  - Two phase flow
  - Combustion Stability
  - Hole diameter
  - Hole inlet geometry
- Designs
  - Stanford 3” 9,600ft
  - Fintels 5” 15,000ft

http://aa.stanford.edu/events/50thAnniversary/media/Karabeyoglu.pdf
Injector - Self Pressurization

Oxidizer

- N2O - high vapor pressure
  ○ no pumps or pressurization system
  ○ = 730 psi @ room temp
- Problems
  ○ Dynamic and thermodynamic properties difficult to predict
- Flow rate affected by
  ○ vapor volume
  ○ heat and mass transfer

Figure 3: Still images from a video of a cold flow test. The white numbers at the bottom indicate the normalized time for each image.

http://spase.stanford.edu/Self-Pressurizing_Propellant_Dynamics.html
Injector - Two Phase Flow

- Static pressures within injector reach values below vapor pressure
  - Cavitation occurs
  - Flash vaporization
  - Decreases bulk fluid density
- Homogeneous Equilibrium Model (HEM)
  \[
  m_{\text{HEM}} = A \rho_2 \sqrt{2(h_1 - h_2)}
  \]
  - Assumptions
    - liquid and vapor phases in thermal equilibrium
    - no velocity difference between phases
    - flow is isentropic in injector

Figure 3: Conceptual injector pressure history as adapted from work by Dyer et al.\textsuperscript{11} showing a low vapor pressure propellant (left) and a high vapor pressure propellant (right) with flow from left to right.

Injector - Combustion Stability

- Chamber pressure lower than 80% of vapor
  - Decrease chamber pressure
  - Increase vapor pressure
- Increase temperature of oxidizer

Figure 12. Mass flow rate vs. the ratio of chamber pressure to oxidizer saturation pressure ($P_2/P_v$). Data is presented for the flow of nitrous oxide through a sample injector over a range of supercharge values. Details of the injector design and the cold flow test apparatus used to make these measurements can be found in Ref. 5.

Injector - Hole Diameter

- Discharge Coefficient decreases as hole diameter increase

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Figure 15. $C_d$ in the single-phase region vs. supercharge for injectors number 1, 2 and 5 with nitrous oxide.

Injector - Hole Inlet Geometry

- Square is significantly lower
- Rounded slightly higher than chamfered
- Extra effort to round edges is not worth the slight improvement

Figure 18: $C_d$ in the single phase region vs. supercharge for injectors number 1, 2 and 5 with nitrous oxide.

Injector - Stanford Design

- Showerhead-style 1/16” thick copper injector plate
  - Minimal weight
  - Copper is oxidizer-safe
  - Easily optimized flow
- 13-hole pattern
  - At .5” and 1” circles
- 0.067” hole diameter
  - Compromise between atomization and avoidance of cavitation

http://web.stanford.edu/~hultgren/HybridRocket.pdf
Injector - Fintels Design

5" Diameter Rocket

Forward Bulkhead

Inlet

Injector Plate

x8 .125"

http://www.thefintels.com/aer/hr5.htm
Injector - Fintels

- 3 pounds of Nitrous Oxide

http://www.thefintels.com/aer/hr5.htm
Igniters

Priority of requirements:
● Specified Performance
● Specified Reliability
● Lowest Possible Cost
Igniters

3D Printed Rocket Restart Test

Stop and Start Igniter
- Competition only requires one flight
- Stop and start igniter would be too complicated and unnecessary

Stop Start Igniter

https://www.youtube.com/watch?v=W_idSgO0jIQ
Igniters

Ematches

Igniters

Pyrogen
- Nitrocellulose (NC) Lacquer
  ○ Acetone
  ○ Ping-Pong balls
  ○ 2:3 ratio of Acetone to Ping-Pong
- Black Powder

Igniters

Penn Hybrid Rocket, https://sites.google.com/site/pennhybridrocket/design-1/igniter-and-pyro-grain
Igniters

FIGURE 14-13. Simple diagrams of mounting options for igniters. Grain configurations are not shown.
Arduino/MicroController

- Flight Controls
  - Altimeter
  - GPS
  - Oxidizer Valve Control
  - Ignition Power
- Develop Models to know when to cut the oxidizer (Prevent Overshooting 10,000)
Arduino Choice

**UNO-Atmega328**
- 16MHz
- Standard board
- More Prebuilt libraries
- Built-in power jack
- 7-12 volt

**NANO-ATmega328**
- 16MHz
- Half the size
- Light weight
- 7-9 volt
Problem

- Idea voltage 3-5 volt (DC)
- Electric Valve 24-120 volt

Solution

- Use a transistor
- Use a Voltage divider
Testing

Testing Data:
- Average Regression Rate
- Burn Time
- Pressures on the Casing
- Oxidizer Amount/Flow rate Needed for Burn
- Temperatures for chamber and Throat

Equipment Needed:
- Thermocouples
- Pressure Transducers
- Data Acquisition System
- Flow Rate Sensors
- Load Cells
- Test Stand
Summary

- Stuck on many decisions without experimental data
- Modeling should help lighten the design load after testing
- One time ignition only -> Ematches
- Arduino board should be enough for avionics
- Injector -> Valve/“Showerplate”