Introduction and Purpose

Who's on team & roles

Julien MD  - Chief Design Engineer
David M    - Chief Analytical Engineer
Milo G     - Water Coolant
Kierra S   - Computational Fluid Dynamics
Introduction and Purpose

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Make a Liquid Rocket Engine for Use at Spaceport America Cup

Reach a 30,000 ft ± 300 ft target apogee
Carry a 4kg minimum payload to the apogee
Remain under 40,960 N-s (9,208 lb-s) of total impulse
Reliable
Cost Efficient
Goals

Design Goals:
- Develop lasting simulation tools.
- Full designs of injection system and regenerative/water cooled test engines.
- Validate designs using FEA

Manufacturing Goals:
- Manufacture injector test parts
- Machine final stainless steel parts for injector.
- Manufacture steel engine chamber and nozzle
- Manufacture water cooling jacket.

Testing Goals:
- Flow characterization testing of injector
- Cold flow testing of completed engine
- Hot fire testing of engine
Determination of Specifications/Flight Analysis Tool

In-house developed engine parameter selection and max apogee tool

- Altitude atmosphere simulation
- Appropriate handling of supersonic drag
- Automated Configuration parsing
Propellant Selection

Performance and thermodynamic characteristics of propellants with Rocket Propulsion Analysis (RPA) software.

Isp Performance:
- Combustion Temperature
- Combustion Pressure
- Ratio of Specific Heats

Practical Performance:
- High Impulse Density
- Lack of Corrosive Effects
- Ease of Ignition
- Stable Combustion
- Safety

Cooling:
- High Specific Heats
- High Thermal Conductivity
- High Critical Temperature

Sample Page from RPA Simulation
Propellant Selection

Why we chose Butanol

- Cleaner/Cooler than Kerosene
- Better thrust/cooling than ethanol
- Renewable Biofuel

\[
\text{H} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H} \\
\text{H} - \text{C} - \text{C} - \text{C} - \text{C} - \text{OH} \\
\text{H} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H}
\]

Why We chose liquid oxygen

- Cheaper than N2O
- Safer than N2O
- Lighter tanks

<table>
<thead>
<tr>
<th>Fuel</th>
<th>LOX &amp; Butanol</th>
<th>LOX &amp; Kerosene</th>
<th>LOX &amp; Ethanol</th>
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</thead>
<tbody>
<tr>
<td>Chamber Pressure psi</td>
<td>300</td>
<td>300</td>
<td>300</td>
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<tr>
<td>C. Pressure kPa</td>
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<td>2068.428</td>
<td>2068.428</td>
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<tr>
<td>Thrust Coefficient (Ideal)</td>
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<td>Boiling Point (C) (Fuel)</td>
<td>117.7</td>
<td>150</td>
<td>78.37</td>
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<tr>
<td>Fuel Cost (Per Gallon)</td>
<td>$4.00</td>
<td>$3.60</td>
<td>$1.31</td>
</tr>
</tbody>
</table>
Design

Propellant: Butanol & Liquid Oxygen
Combustion Pressure: 1380 kpa | 200 psi
Combustion Temperature: 3000 °C | 5480 °F
Thrust: 2.22 kN | 500 lbf
Specific Impulse (sea level): 255s
Burn Time Capability: 20 Seconds
Thrust Chamber and Nozzle Geometry

Thrust chamber and nozzle designed for manufacturing simplicity & optimized for selected materials.

- Areas determined from propellant properties, pressures, compressible flow, and desired thrust
- Nozzle is a conical shape. Easy to manufacture with a <2% efficiency compromise.
- Combustion Chamber geometry based on empirical references.
Materials Analysis

Compared >25 promising materials at range of temperatures from 800F-2000F (showing 18)

- Copper & Steel Alloys showed promising results
- Beryllium Copper shows best results.

Parameters:
- strength at high temperature
- Thermal conductivity
- Thermal expansion coefficient
- Corrosion Resistance
- Machinability
- Cost
Materials Analysis

Selected Materials:

- **Low Carbon Steel**
  - Cheap manufacturing of components
  - Corrosion may limit life span of combustion chamber in high oxidation environment

- **Pure Copper**
  - More expensive than steel
  - Better corrosion resistance
  - Superior thermal conductivity

- **Haynes 282**
  - High performance at extreme temperatures
  - Allows us to experiment with using advanced manufacturing methods
  - Low thermal conductivity
Cooling Design

Alternatives
Regen:
- No wasted fuel.
- Performance affected by flow rate, wall material and thickness.

Film:
- Excess fuel along walls forms barrier.
- Some wasted fuel, reduced performance

Ablative:
- Inexpensive but limits engine reuse

Selected regen for performance and reusability.
Incorporated film cooling for added safety factor.
Cooling Design

- Coaxial Shell
  - Works well for our requirements
  - Easier to manufacture

- Channel Wall
  - Higher Strength
  - Hard to Manufacture
3D Printed Engine

- Channel-wall cooling channel design for extra strength.
- Designed for DMLS.
- Made from Haynes 282
- Allows comparison of heavily simplified manufacturing of regenerative cooling jacket.
Regenerative Cooling Analysis

- 1D Steady State Axisymmetric Analysis
- Compressible Flow Modeled
- Used for all material types (shown is for Haynes 282)
- Heat fluxes Compared to allowable stresses
Regenerative Cooling Analysis
Regenerative Cooling Analysis

Heat Flux Across the Engine

- Bartz (Btu/in^2-s)
- Cinjarew (Btu/in^2-s)
- Pavli (Btu/in^2-s)

Distance Relative to Throat (in)
Regenerative Cooling Analysis

Stress Across the Engine

- Bartz SF
- Cinjarew SF
- Pavli SF

Stress (psi) vs. Distance Relative to Throat (in)
Water Cooled System

- For initial testing and validation of engine.
- Excessively cooled with water. Large pipe for easy manufacturing and instrumentation.
- Instrumentation support for pressure, temperature, thrust, and natural combustion frequency.
Injector Design

Flat plate ("showerhead") vs pintle:
- Flat plate (doublet, coaxial, etc.) - better performance/mixing
- Pintle - better combustion stability, easier to manufacture, easier to adjust or throttle

Pintle Injector Elements:
- Outer annulus
- Inner Annulus
- Pintle
Pintle Injector Design

- Geometry based on required flow rate, pressure drop, and momentum ratio (radial to axial).
- Pintle screw to adjust flow rates on the fly for testing.
- Chose oxidizer centered to increase ease of flow rate adjustment, engine survivability.

Injector Geometry Tool
FEA Stress Validation

Injector:

- Worst Case Loadings
- Primary stress from pressure
Manufacturing

- Aluminum and Steel test pieces
- CNC of most complicated injector pieces
- Pintle and other delicate or simple pieces machined by hand
Manufacturing

- Collaborated with Quality Machined Products to make engine in two parts.
- Welding done with assistance of OIT/KCC welding instructors and class.
- Post weld heat treating
Manufacturing
Testing

Spray pattern characterization pre-testing with low pressure water
- Measurement of spray angles
- Uniformity
- Mixing (colored water)
What’s Happening Now

- Insurance
- High ΔP mixture & cold flow testing (water and liquid nitrogen)
- Manufacturing of spares and copper engine
- Further preparations for Hot-Fire
What’s Happening Now

Development of chemical electroplating device and process for cost effective engine development
What’s Happening Now

Simplification and improvement of inhouse design & analysis tools.
What’s Happening Now

Teaching new OTRA members what we have learned
Questions?
Regenerative Cooling Jacket

Engine cooled by fuel on route to injector.

Thin channels for high flow velocities.

Jacket made from nickel plated steel rather than aluminum to limit galvanic corrosion with the copper while maintaining low cost and easy machinability.

Jacket made in two halves. Early test article bolted together to allow disassembly for inspection. Final engines welded.
Acoustic Analysis

Longitudinal vs tangential vs radial mode severity

Potential approaches for addressing instabilities: injector mixing, modifying natural frequencies - acoustic absorbers, internal baffles to break wave propagation.

<table>
<thead>
<tr>
<th>Modes or Natural Frequencies of Combustion Chamber</th>
<th>c (m/s)</th>
<th>Lambda</th>
<th>LOX &amp; Butanol</th>
<th>GOX &amp; Butanol</th>
<th>GOX &amp; Ethanol</th>
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<tbody>
<tr>
<td>1-Longitudinal</td>
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</tbody>
</table>
Lessons Learned

- Engineering: A rocket engine from A to B
  - Challenges with Design Tools
  - Manufacturing
  - Testing

- Administrative
  - Manufacturing
  - Insurance