JetCat P100-RX Variable Geometry Nozzle

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Air Force Research Laboratory (AFRL)

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Objective

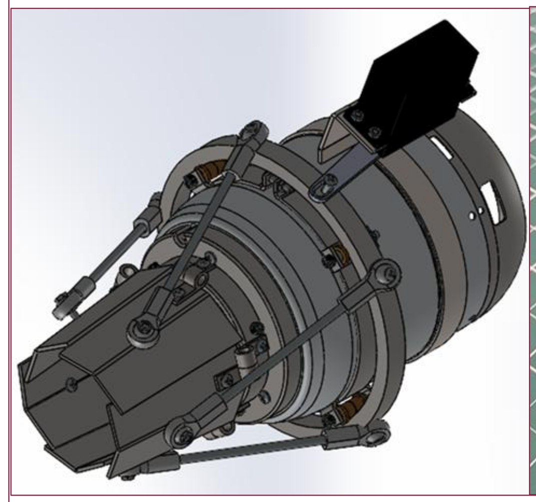
The Air Force Research Lab (AFRL) through the Aerospace Propulsion Outreach Project (APOP) is sponsoring the **design, fabrication, and implementation of a variable geometry nozzle** for a 22 lb thrust JetCat P100-RX model turbojet engine.

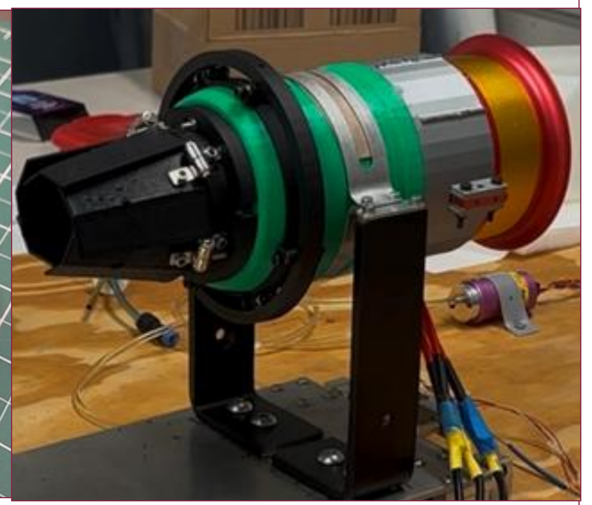
Concept Development

Prior to final selection, two designs were considered. Both designs were modeled using SolidWorks and 3D printed in ABS plastic.

Design A: Multi-Axis Petal Nozzle

- Consists of **multiple petals** each connected and simultaneously moved by a **rotating ring** controlled by an actuation mechanism.
- Opens and close much like a flower as it blooms.
- Capable of directing the thrust in multiple vectors.





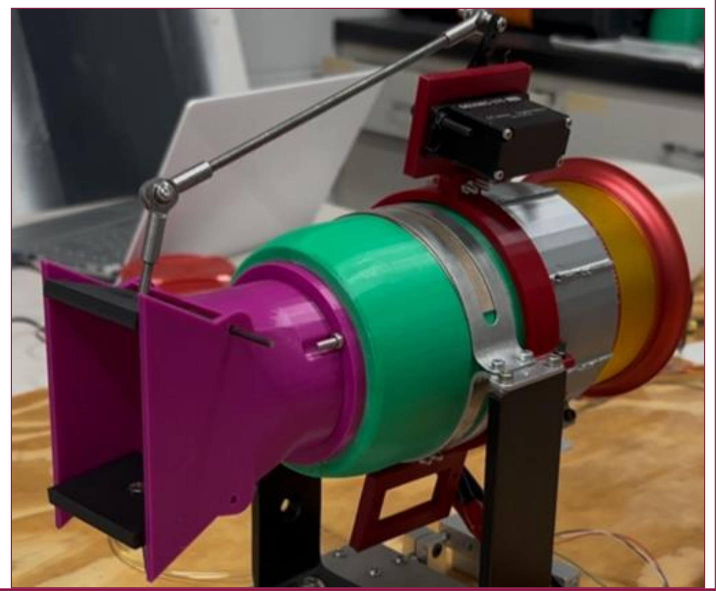
Design B: Precision Airflow Control (PAC) Nozzle

- Inspired by **Lockheed Martin's F-22 Raptor**, which channels an "eye-lid" type variable nozzle and can produce more thrust than any current fighter engine.
- Stationary nozzle body **transitions from a circular to rectangular cross section** and expands out into divergent side wants. Throughout the transition, the percent variation in cross-sectional area does not exceed 4%.
- Two symmetric flange doors flush against side walls and open and close in circular path about pivot points to vary the exit area.

Proof of Concept Testing

To rapidly iterate through different designs, verify theoretical understanding, and gather data on the nozzle's performance, a cold flow test device was constructed using ABS plastic 3D printed parts and a **12 lb thrust 90mm JP Hobby EDF** (electric ducted fan).

- **Multi Axis Petal:** Revealed that mechanical interference and leakage significantly impacted overall performance and reliability.
- **PAC:** Negligible leakage, close tolerances, and simplicity of only two actuation points reduced potential points of failure.
  - Overall more versatile, can achieve a wider area range.



Manufacturing

The nozzle was 3D printed using **Selective Laser Sintering (SLS) metal powder printing** using **316 stainless steel** chosen due to complex geometry of transition from circular to rectangular cross section.

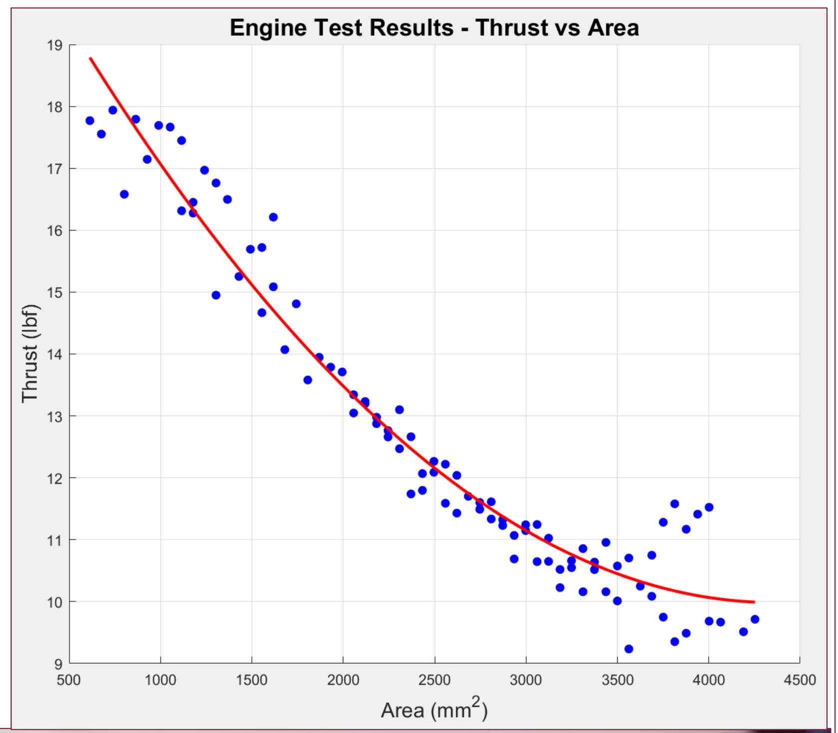
Final Design & Test Results

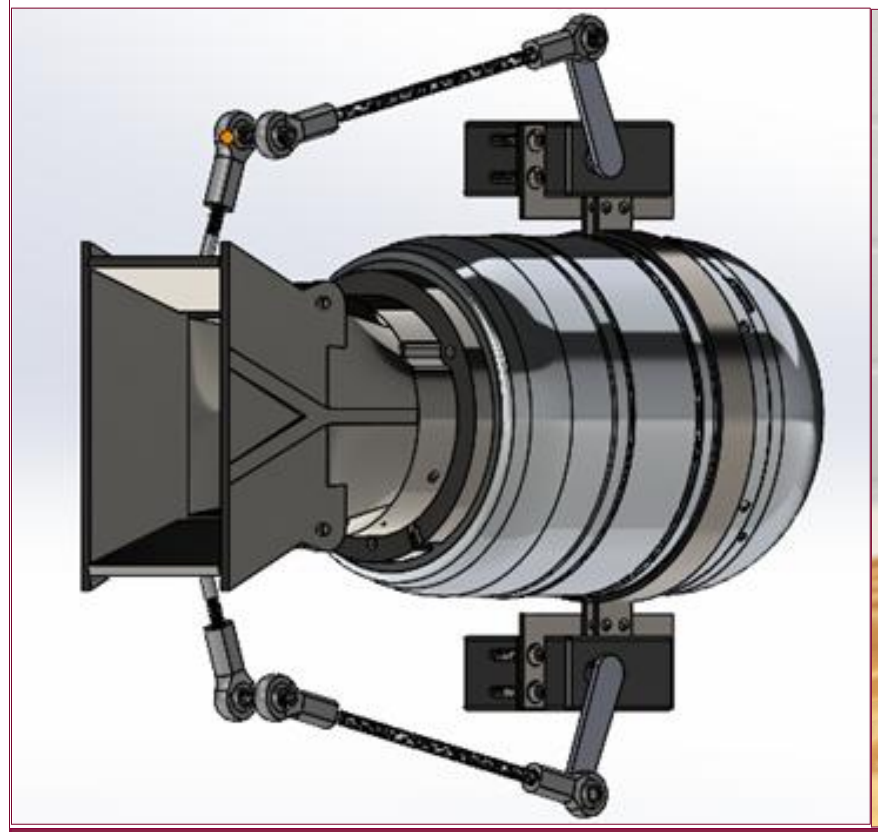
After cold flow testing and theoretical analysis, design alterations included:

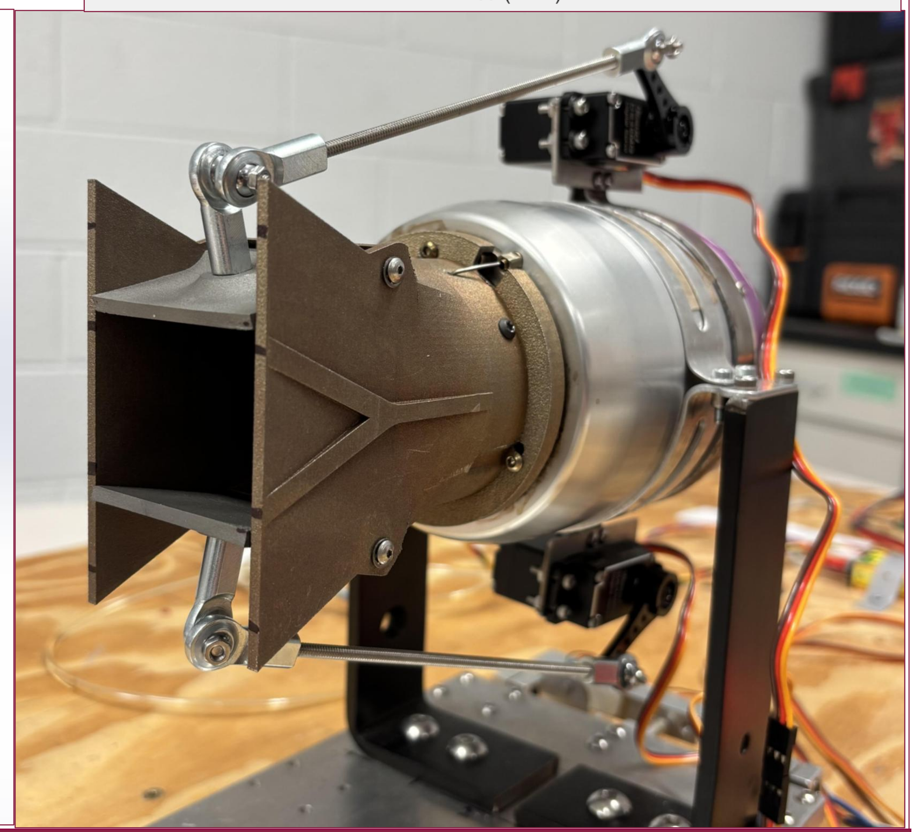
- Shortened axial length of nozzle to diffuse flow gently and avoid low pressure flow separation regions that cause suction and drag.
- Set thickness to 2 mm to mitigate thermal expansion and increase durability.
- Added ribs on walls for structural support and pocketed flanges to reduce weight.
- Reduced play between connections by swapping a ball joint for a swing bolt.

Consistent results achieved across three tests, with similar trends to the theoretical analysis and the following relationship between thrust and area is visualized. It is best approximated by a quadratic regression model with a coefficient of determination $R^2 = 0.95$. From official testing on Wright-Patterson AFB:

- **Maximum thrust: 19.4 lbf ~ 615 mm²**
- **Minimum thrust: 11.1 lbf ~ 3500 mm²**
- **Flow separation after ~ 3000 mm²** results in a quadratic relationship and greater variation in data at low areas

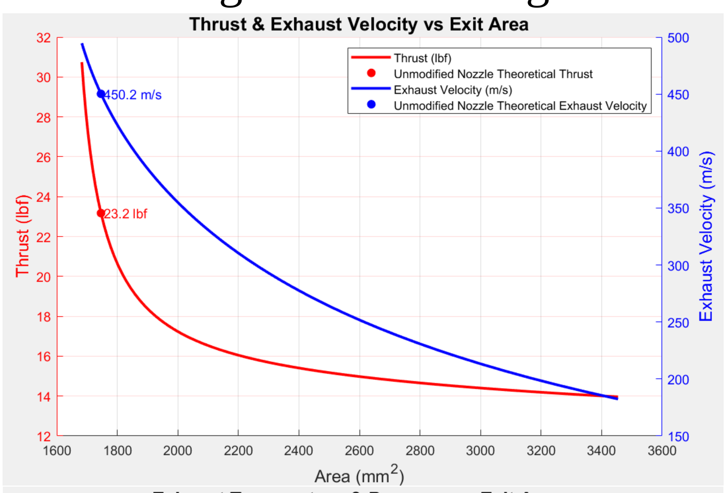


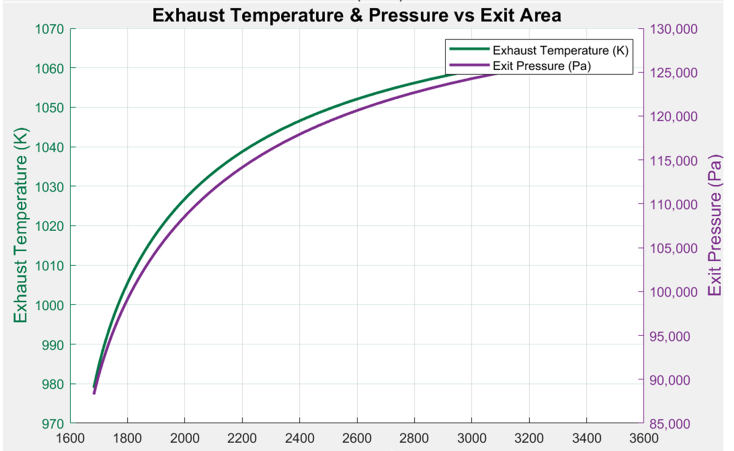




Parametric Cycle Analysis

A parametric cycle analysis (PCA) was performed to establish the relationship between the JetCat P100-RX's design parameters, component efficiencies, exit area, and thrust to define a target exit area range that maximizes the thrust range.





- **Thrust and exit velocity decrease with exit area:** As expected from the continuity equation, for subsonic flow, as the exit area decreases, velocity—as well as Mach number and thrust—increases. Target area range identified: **1500 - 3500 mm²**.
- **Exit temperature and pressure increase with exit area:** Based on the assumption of isentropic flow through the nozzle and the ideal gas law, pressure, density, and temperature decreases with velocity; increasing with area.

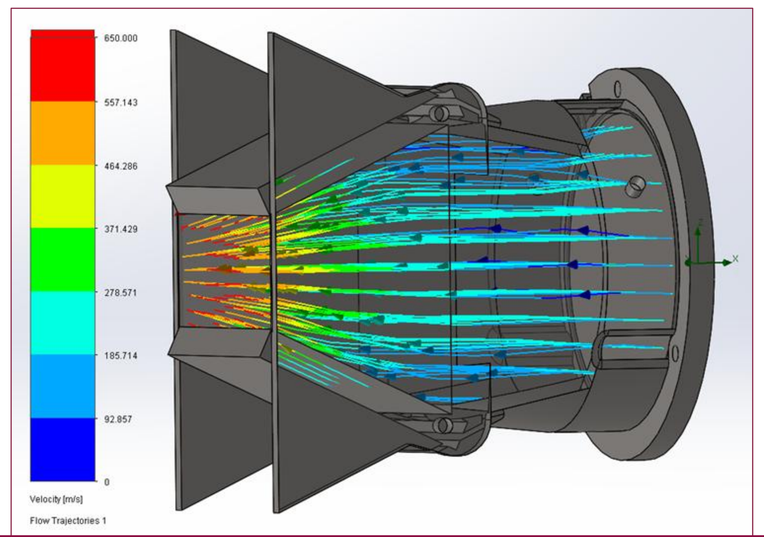
These four output variables of interest are **heavily interdependent** on one another. Thrust equation:

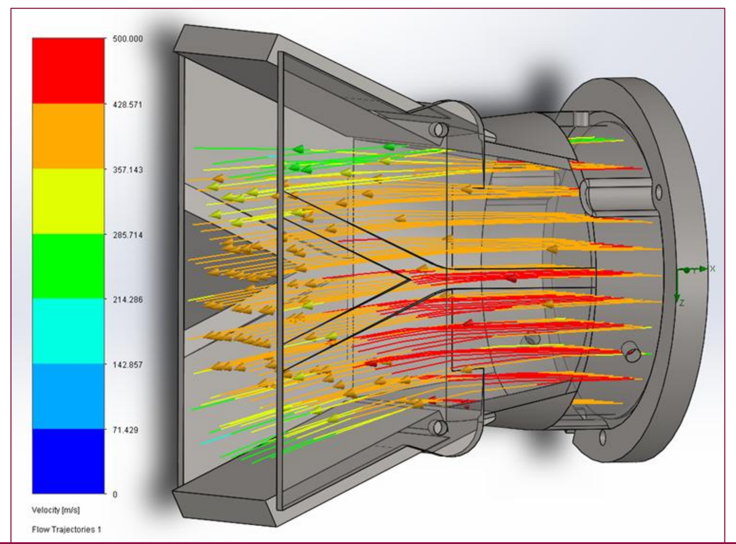
$$F = \frac{1}{2}\frac{a_0^2}{g_c}\rho_9 A_0((1+f) - M_0 + (1+f)\frac{R_t T_9/T_0}{R_c V_9/a_0}\frac{(1-P_0/P_9)}{\gamma_c})^2$$

CFD Analysis & Flow Visualization

Two flow simulations were conducted on the model, each with the nozzle being in a different configuration with the exhaust velocity given by the manufacturer, 434 m/s

- **Closed Configuration**: Average exit velocity increased to **603.3 m/s**
- **Open Configuration:** Although average exit velocity varied little at 421.6 m/s, flow separation regions are visualized where velocity decreases to about **250 m/s**

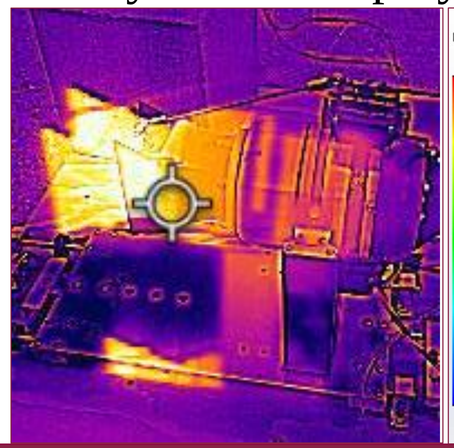


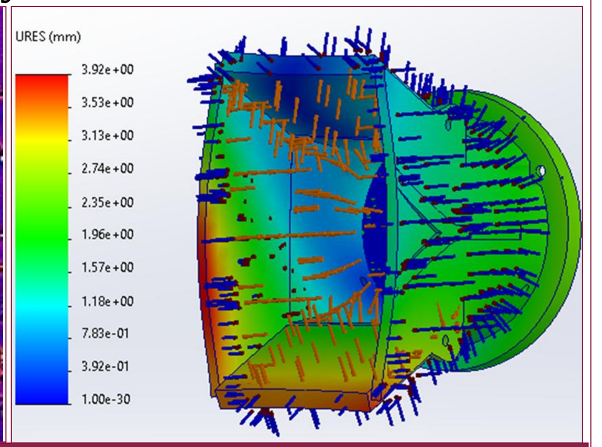


Thermal Analysis

To ensure minimal thermal expansion given the material (316 stainless steel) and visualize hot gas impingement, a **FLIR TG267** thermal camera and a SolidWorks thermal analysis was employed.

- Executed using an exit temperature of 900 K, and an ambient temperature of 273 K.
- The **maximum displacement** was found to be **3.97 mm**

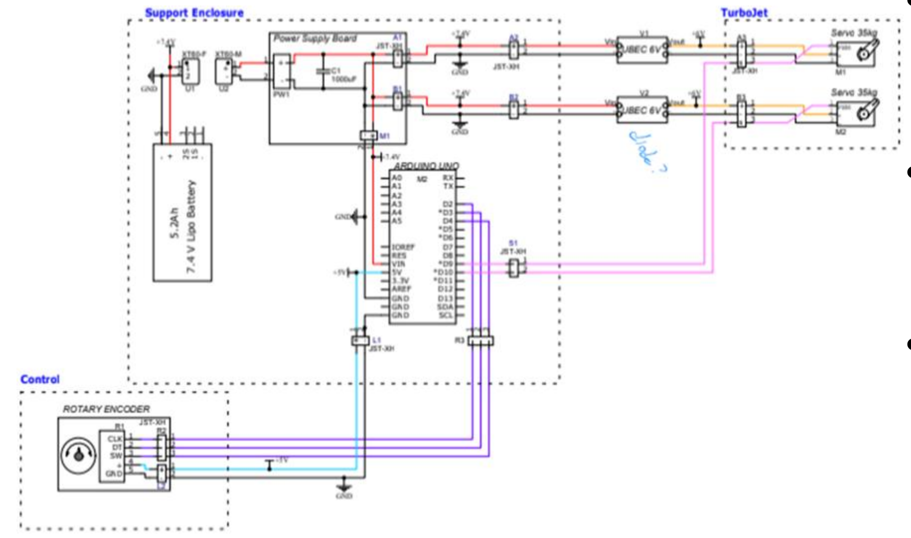




Control System & Assembly

To acuate the nozzle, two **35 kg servos** are connected to the flange doors via threaded push rod with ball joints. Flanges can pivot **±10 degrees** to vary the nozzle exit area, achieving an area range of **600 - 4000 mm²**.

- The servos and an Arduino Uno receive power from a 2S LiPo battery through a 6 V BEC regulator.
- A rotary encoder in control room connects via DB9 cable to Arduino near engine



- Turning the encoder dial "sweeps" flanges from closed to open positions
- Arduino limits servo travel to the optimized min-max range based on test data
- A LED indicator on control will show relative flap position to user

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