SAE AeroTech Congress

The Design and Testing of a Miniature Turbofan Engine

Gary B. Cosentino
Flight Operations Engineering Branch
James E. Murray
Aerodynamics and Propulsion Branch

09ATC-0241

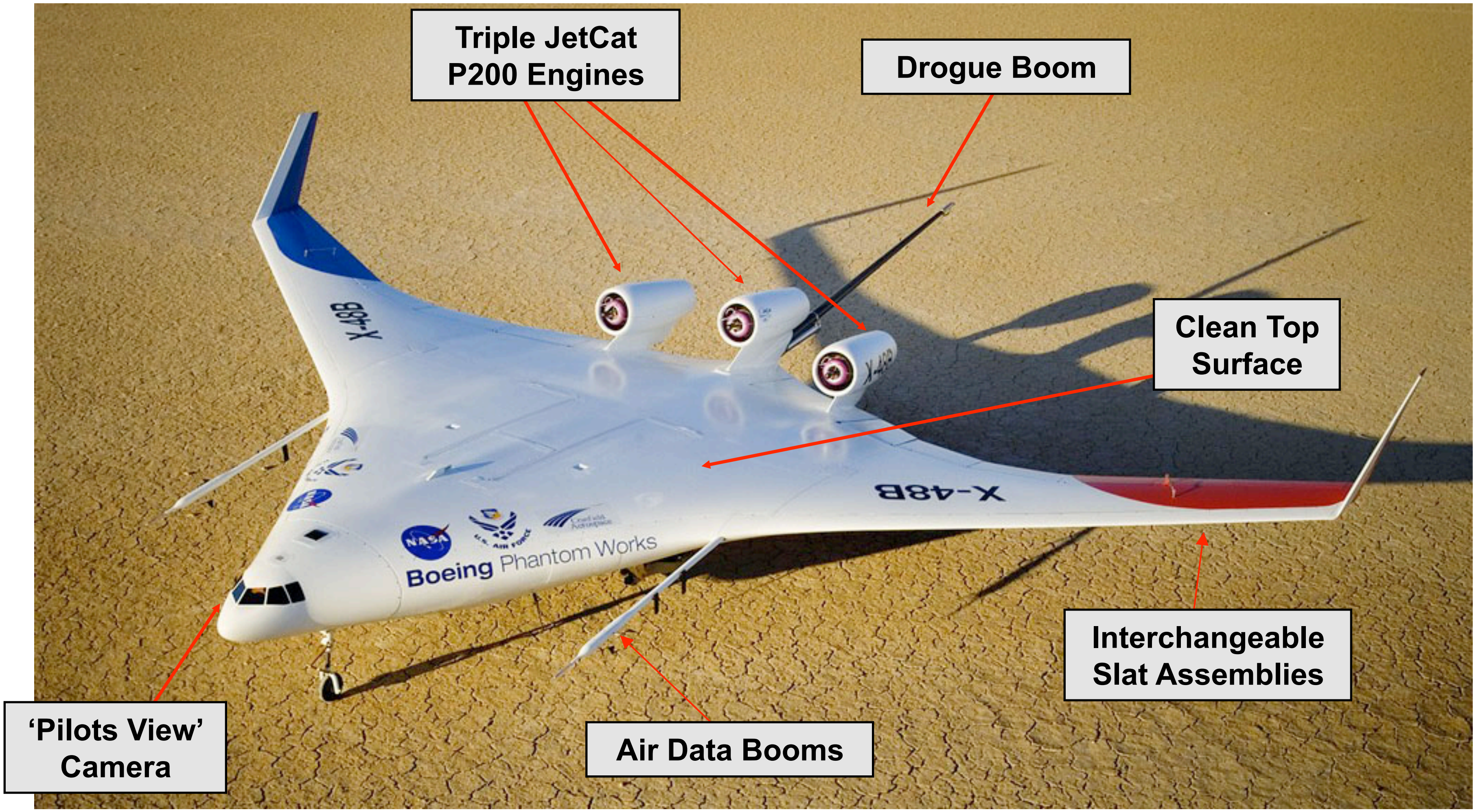
Outline

- **Motivation**
  - X-48B
  - Flight Test Efficiency
  - X-48C and Noise
- **Engine Design and Development**
  - Filling a void in what is currently available
  - Utilizing an off-the-shelf core engine as the foundation
  - Challenges
- **Engine Testing and Performance Results**
  - Static and Dynamic Testing
- **Conclusions and Q&A**

X-48B

- **Blended Wing-Body (BWB) Demonstrator Aircraft:**
  - 8.5% scale of a notional future “hybrid” wing-body cargo/tanker/transport aircraft
  - Designed and built as a remotely piloted research aircraft for controllability studies
  - Designed originally 20 years ago by McDonnell-Douglas Long Beach as future transport
  - Unusual shape promises large improvements in fuel efficiency, load capacity
  - Aerodynamically efficient way of moving a large volume through the air

X-48B Configuration – Top View

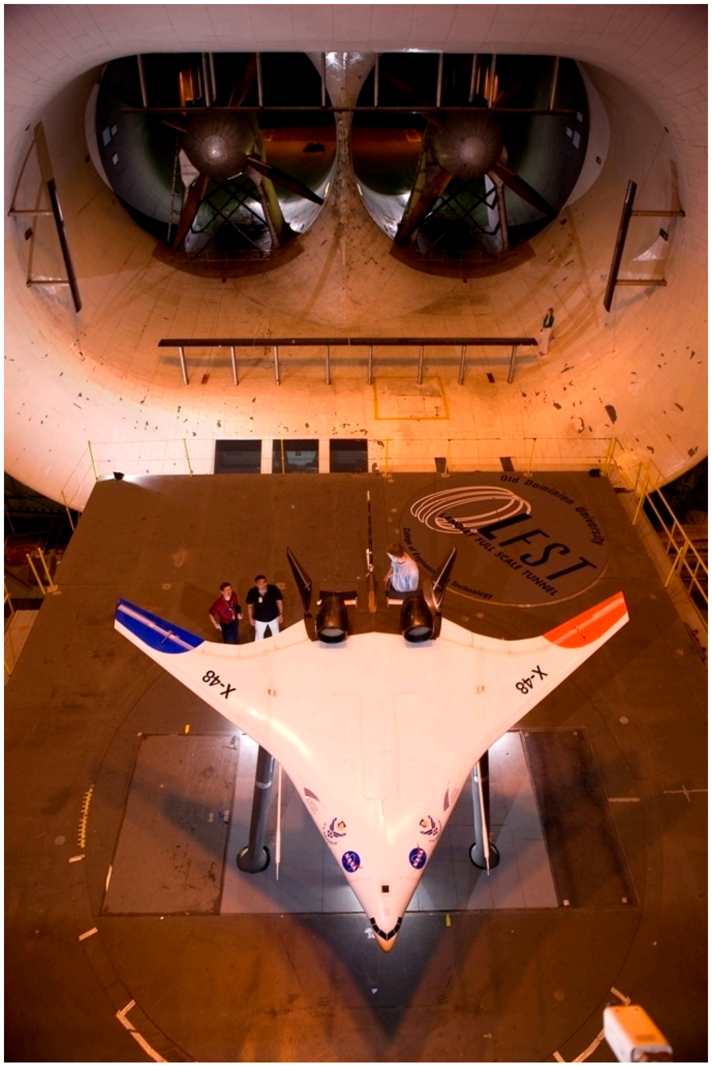


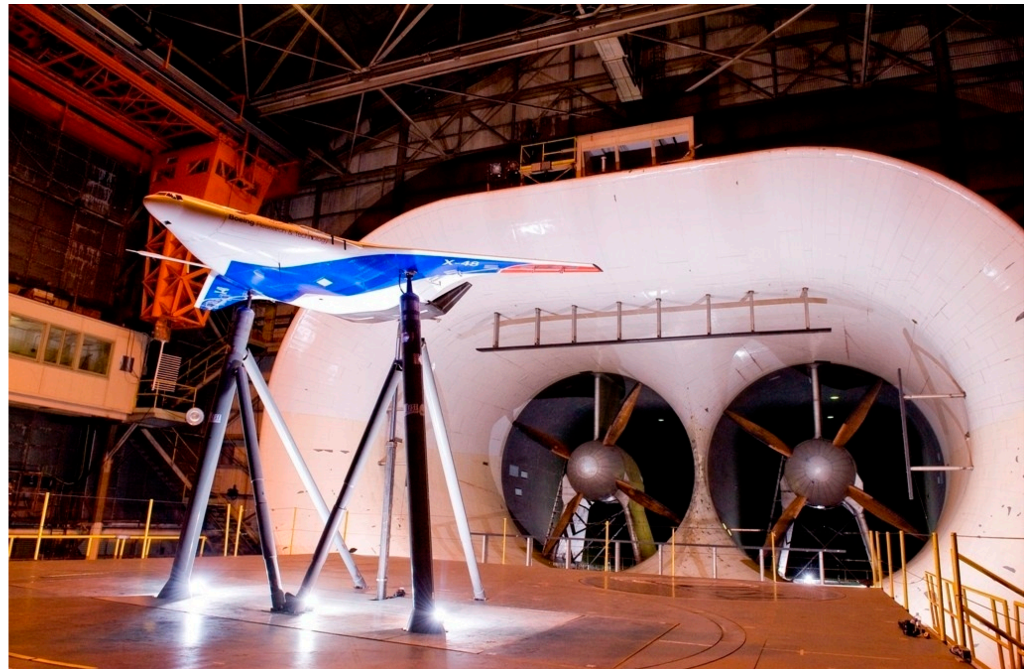
Flight Test Efficiency

- Fuel Capacity 13.3 gal. (~90 lbs.)
- Typical fuel consumption 24 oz/min at max
- Typical flight duration 35 minutes

- Bottomline: need to do a lot of flights!

X-48C





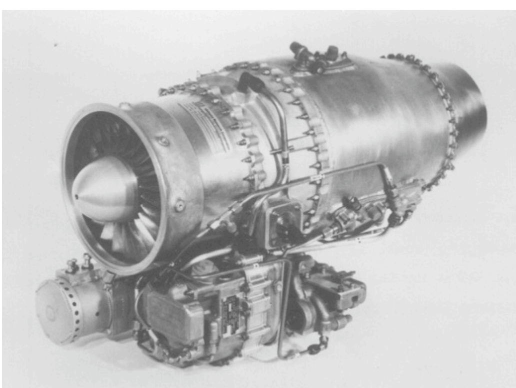
Configured as a twin – need approx. 76 lbs. thrust per engine

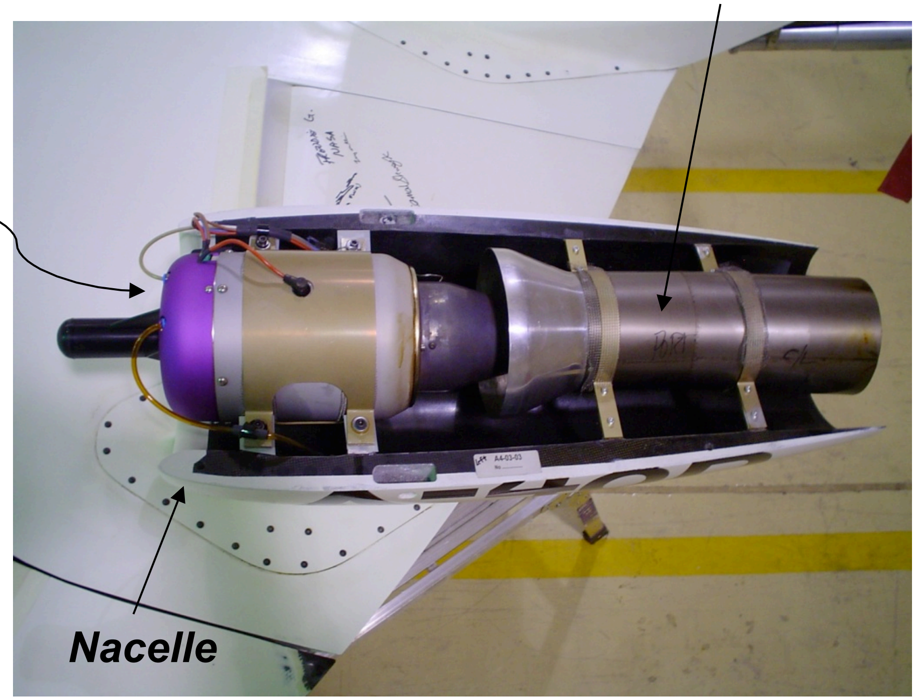
Engine Development

- **Problem – current propulsion system is very fuel-inefficient:**
  - Single compression stage turbojet
    - High SFC
    - High exhaust velocity/noise
- **Almost no alternatives in the 50 to 500 lb. thrust class available**
  - So, can we make one ???

JetCat P200

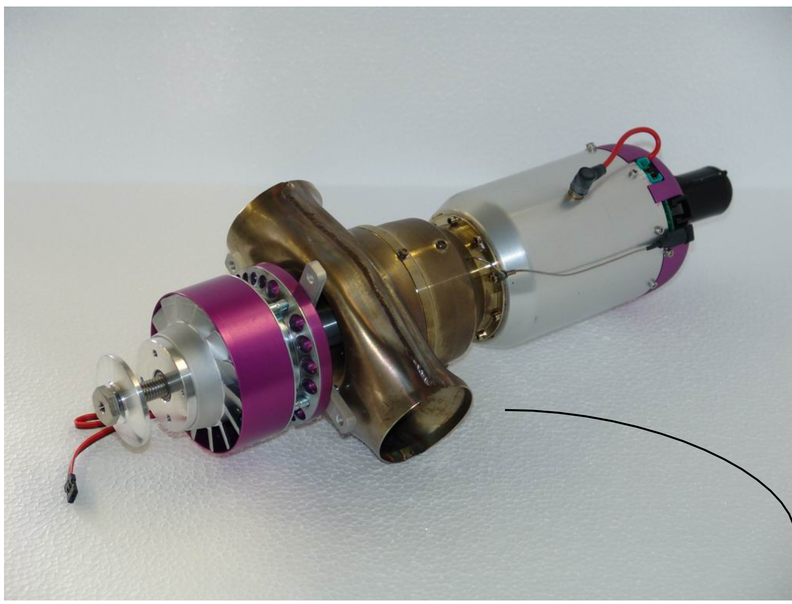
Williams WR19

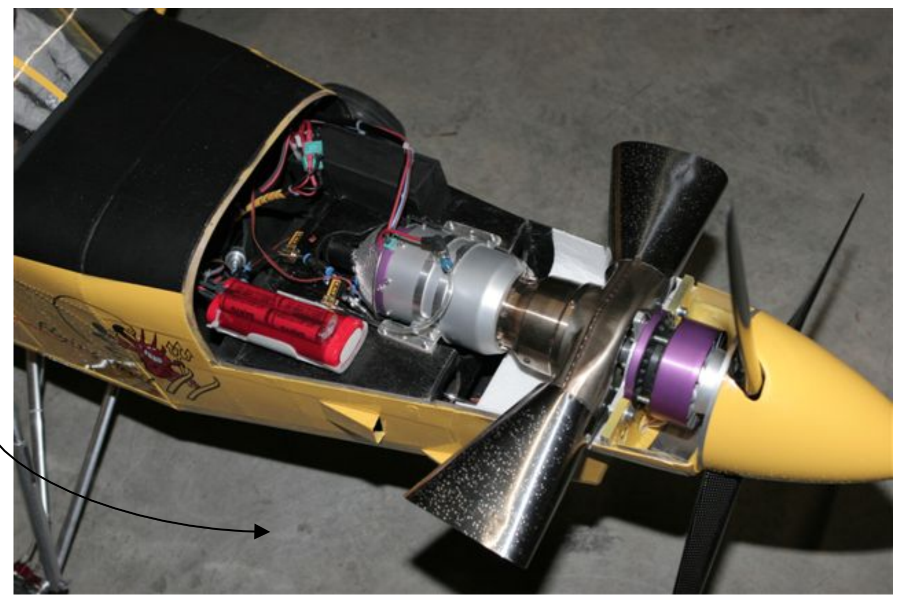




Engine Development - II

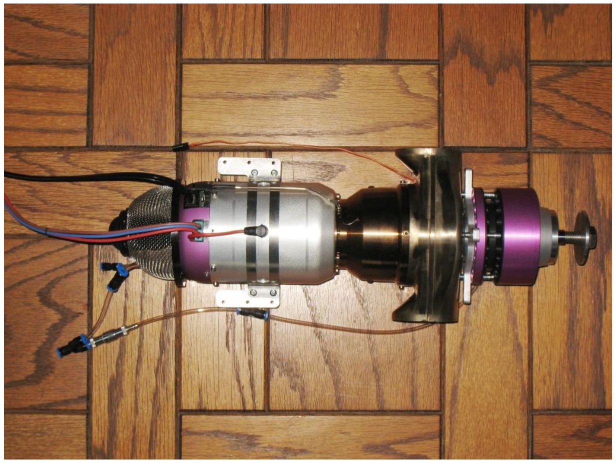
- **Available off-the-shelf turboshaft engine:**
  - Based on a much smaller gas generator than our P-200's
    - Produces about ~10 shaft horsepower at 8000 RPM
  - So, can we turn a fan instead of a prop and make about 50 lbs. of thrust ??





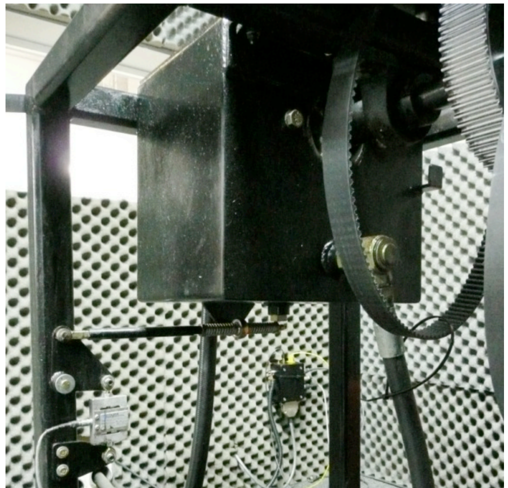
Engine Development - III

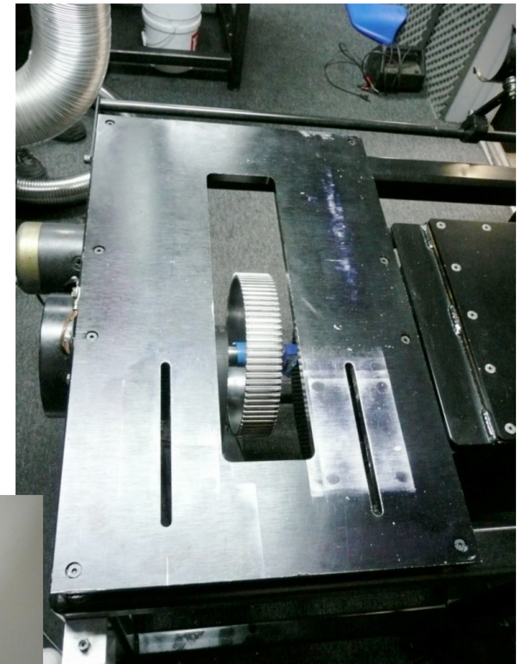
- **SPT5 Engine Specifications:**
  - Core RPM range: 50,000 (idle) to 170,000 (max) RPM
  - Rated power output: 8kW (10.5 Hp)
  - Secondary Shaft : 8750 (max) RPM
  - Rated RPM with 26” x 12” propeller: 7500 RPM
  - Power turbine to output shaft gear ratio: 8 to 1
  - EGT: 745 Deg C (warning), 750 Deg C (max)
  - Fuel Consumption: 9 fl. oz per minute at max power
  - Engine Weight: 4.8 lbs.



Engine Testing - I

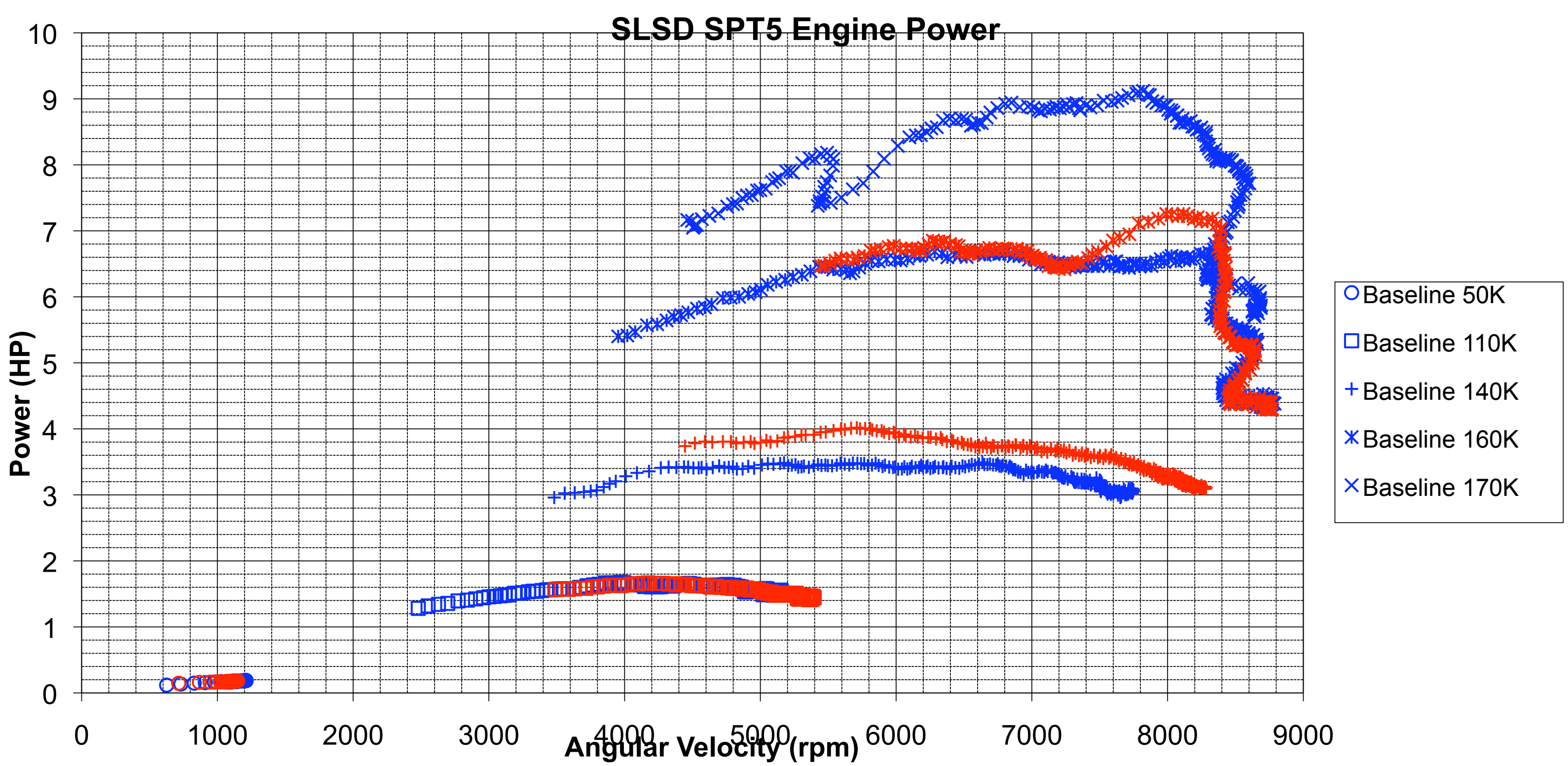
- SPT5 Dyno-tested at go-kart engine shop:



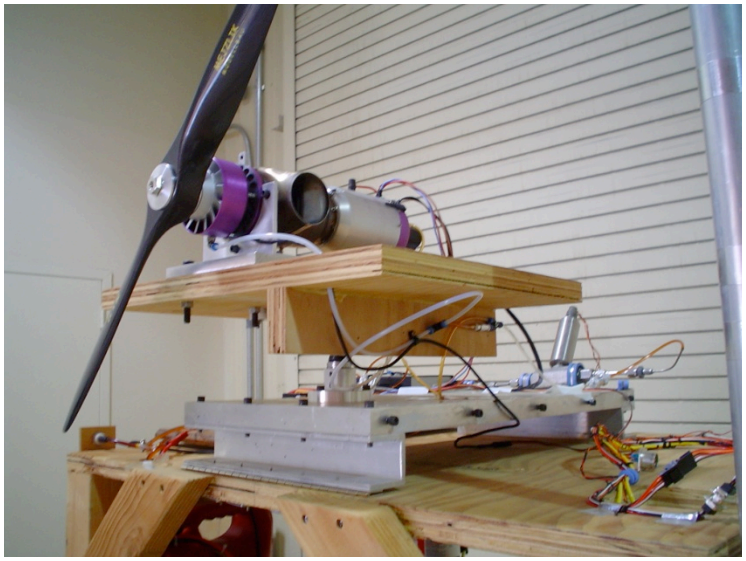


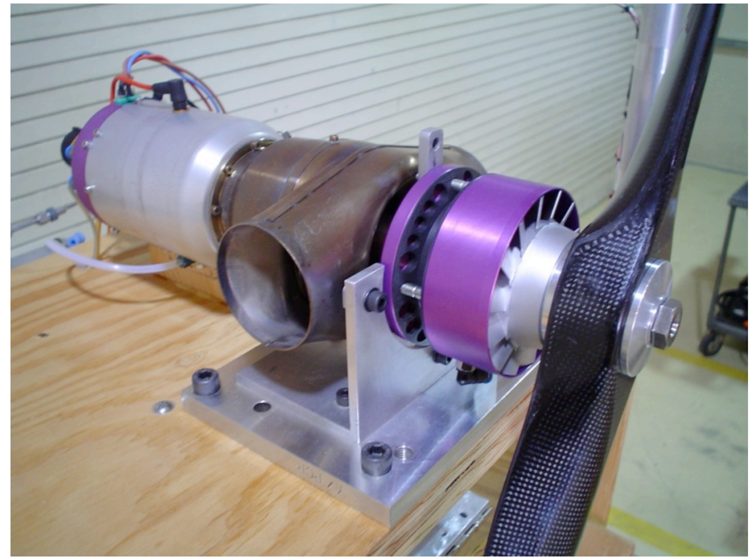
Engine Testing - II

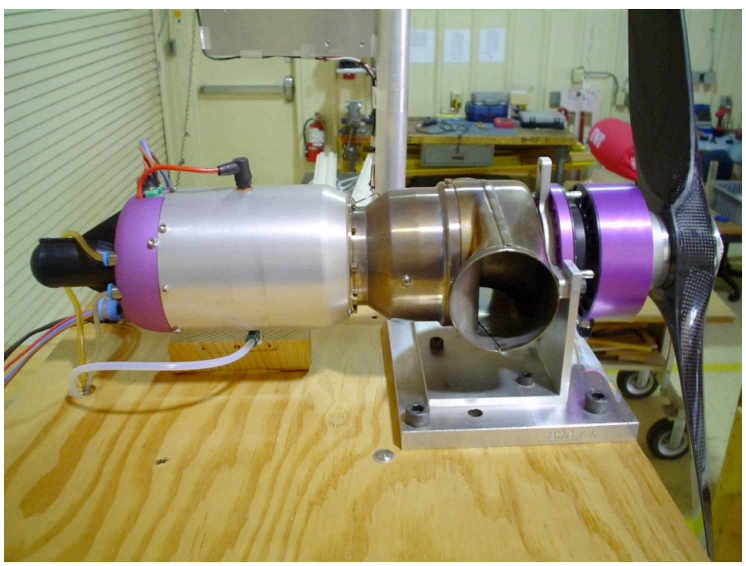
- **Characterize SPT5 performance:**
  - Run as a turboprop with a 26” x 12” carbon fiber propeller
    - Produces about 50 lbs. of thrust at 7000 RPM
  - Dyno tested to further characterize performance

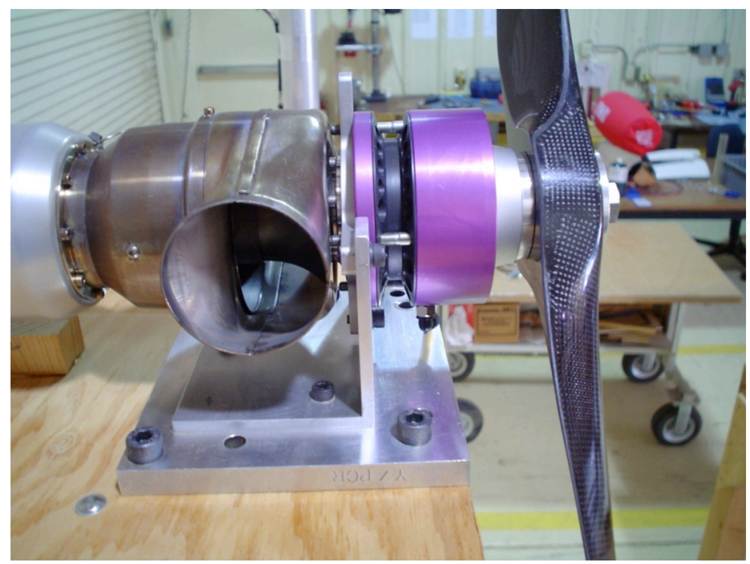


Engine Testing - III

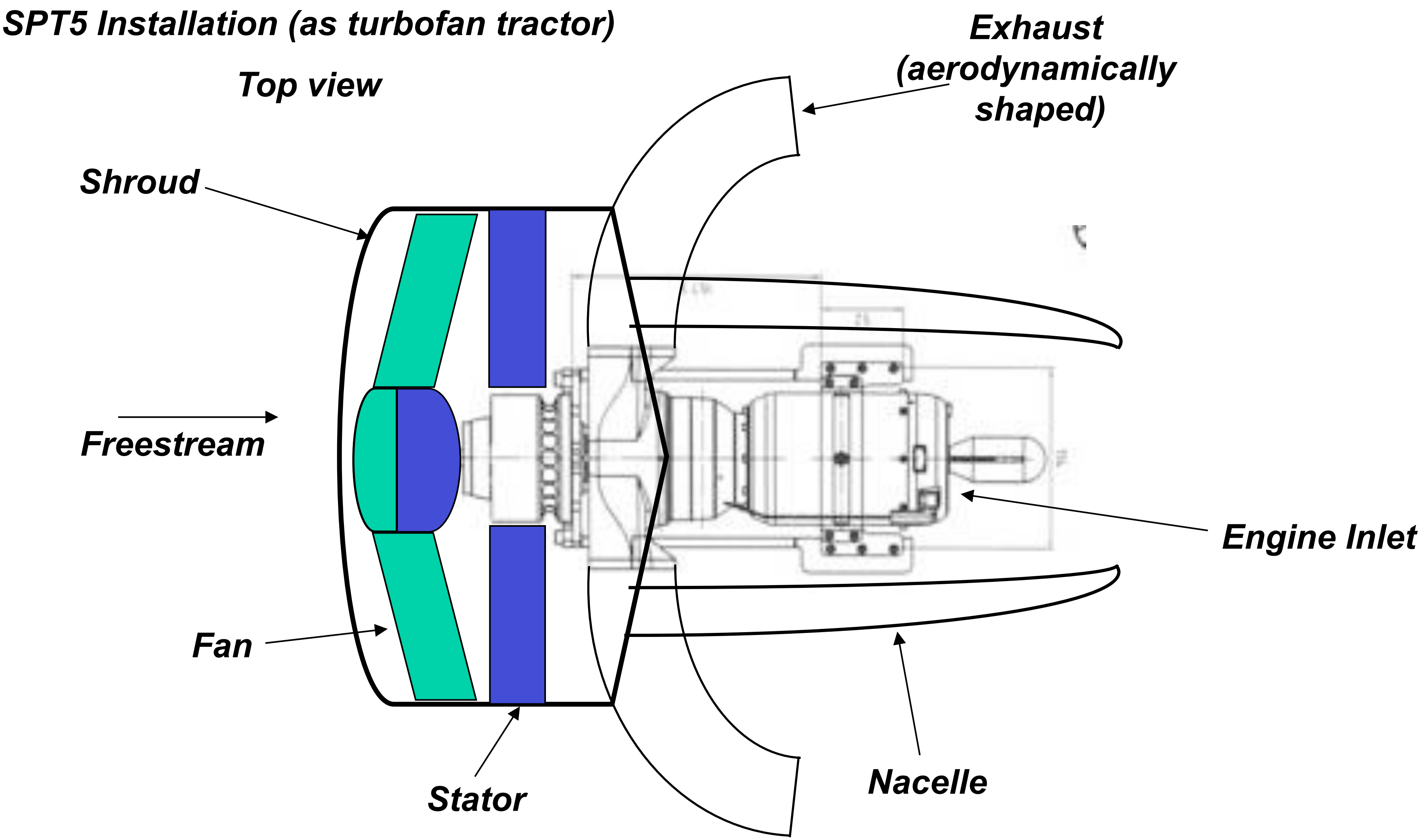




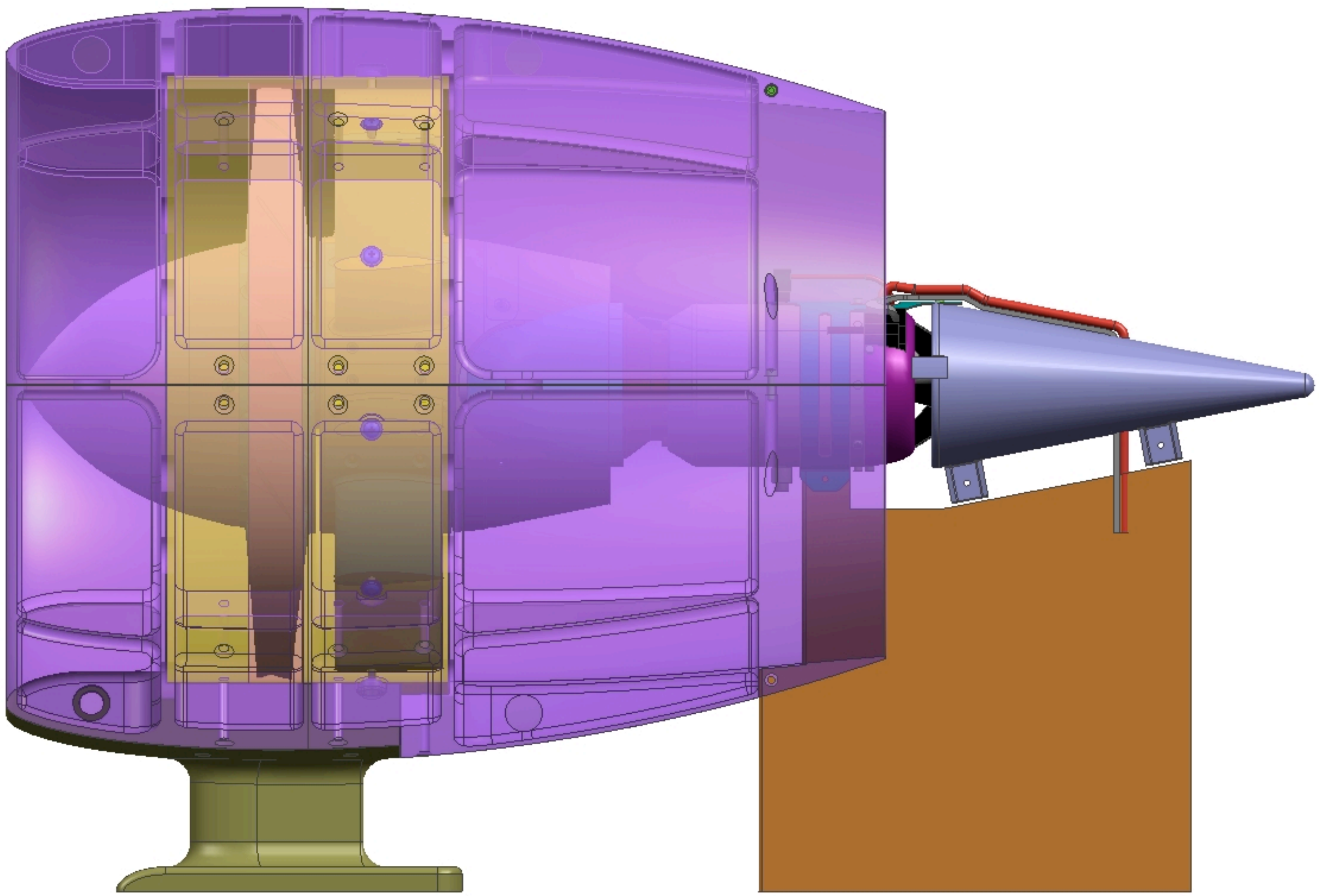




Engine Design - I

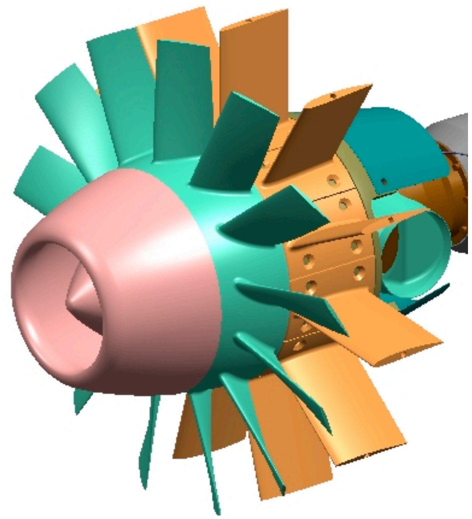


Engine Design - II



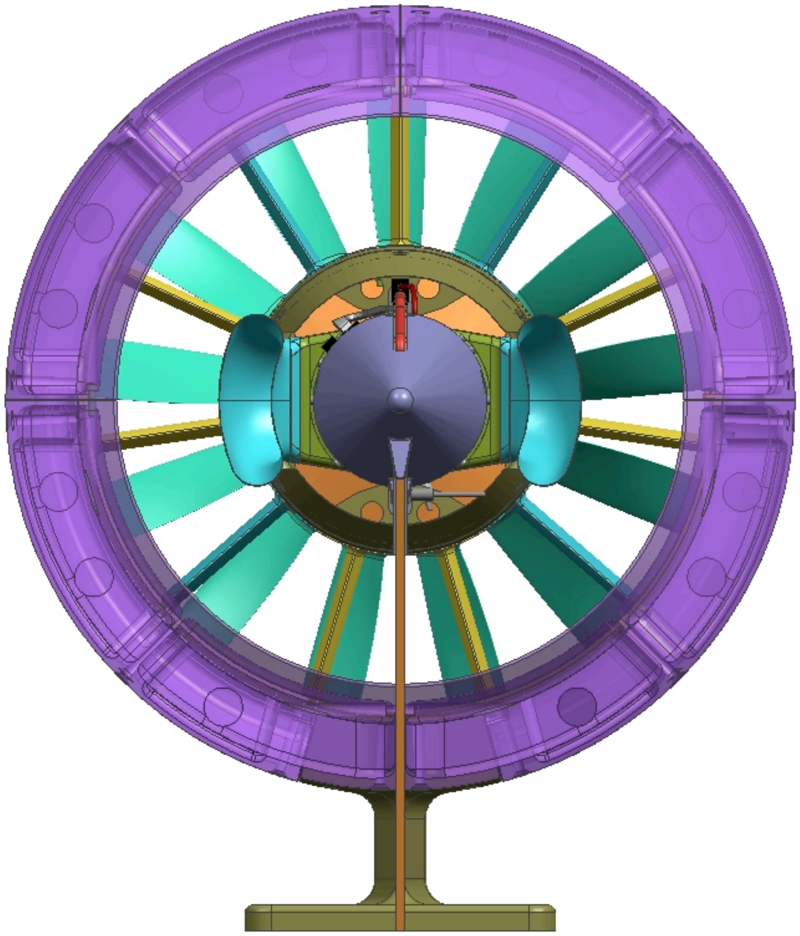
Fan Design -I

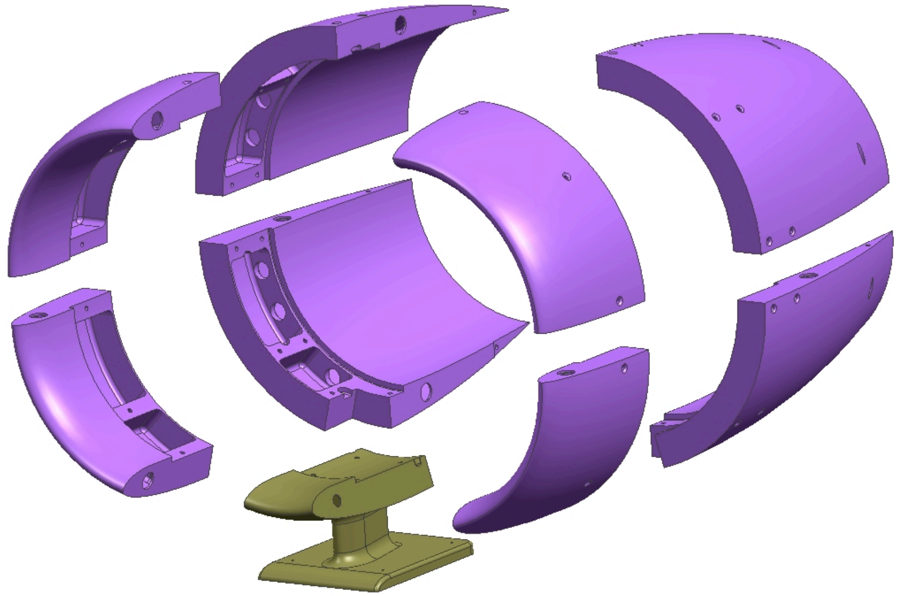
- **12” Tip Diameter, 6” Hub Diameter**
- **Assumed Low Loss Installation**
  - Flow Coefficient: 0.95
  - Thrust Coefficient: 0.95
  - Power Margin: 5 efficiency points
  - 100% Ram Recovery



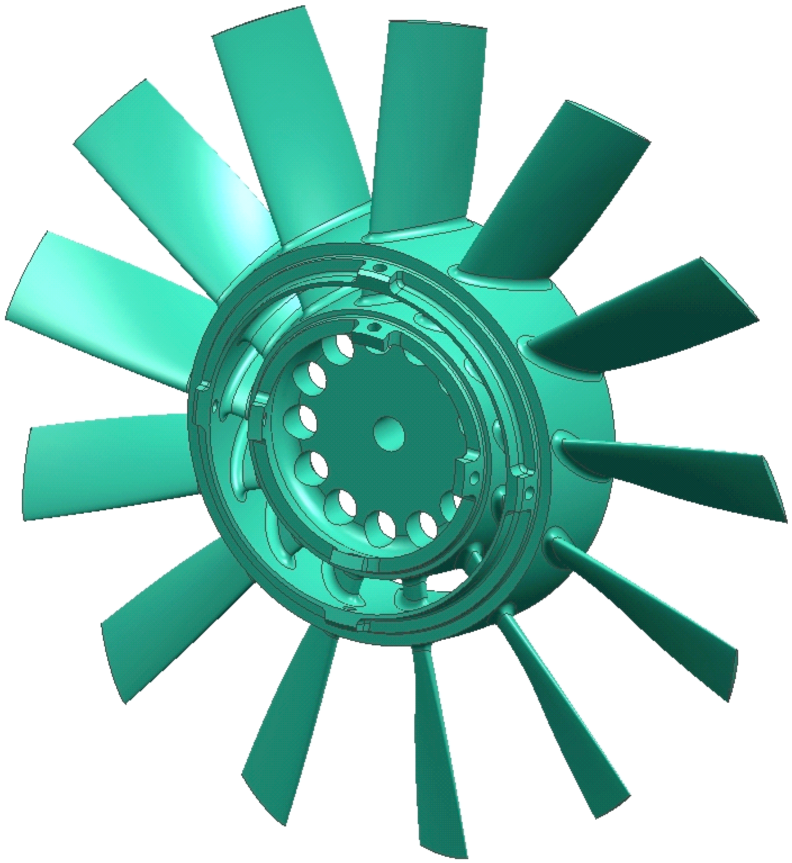
- **Sea Level Static Operation**
  - 9.70 hp Available For Thrust, 0.30 hp For Engine Cooling
  - Total Fan Pressure Ratio: 1.020, Flowrate: 8.0 lb_m/s, ~7000 rpm
  - Estimated Thrust: 44.5 lb_f
- **Altitude Cruise Operation (Assumed Thrust Sufficient To Achieve 100 KIAS)**
  - Total Fan Pressure Ratio: 1.020, Flowrate: 7.3 lb_m/s, 8750 rpm
  - Estimated (Gross or Net? Installed or Uninstalled?)Thrust: 18.1 lb_f
  - Required Power: 9.0 hp
  - Need to determine available engine power at 10,000 ft for 2nd Fan Iteration

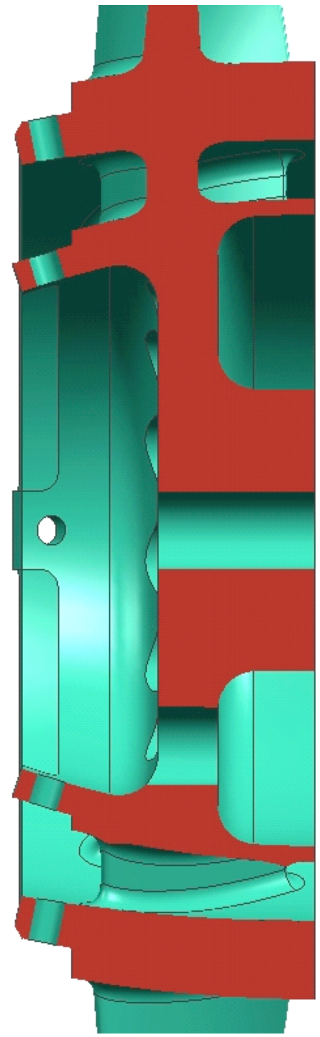
Engine Design - III





Fan Design - II





• **Cut on a 5-axis CNC mill from a solid slab of nylon**
• **Incorporates secondary flow impeller and passageway**

3-D Fan Analysis

3-D multiblock Navier-Stokes turbomachinery analysis code by R. Chima
- Node centered finite-difference formulation
- AUSM+ upwind differencing

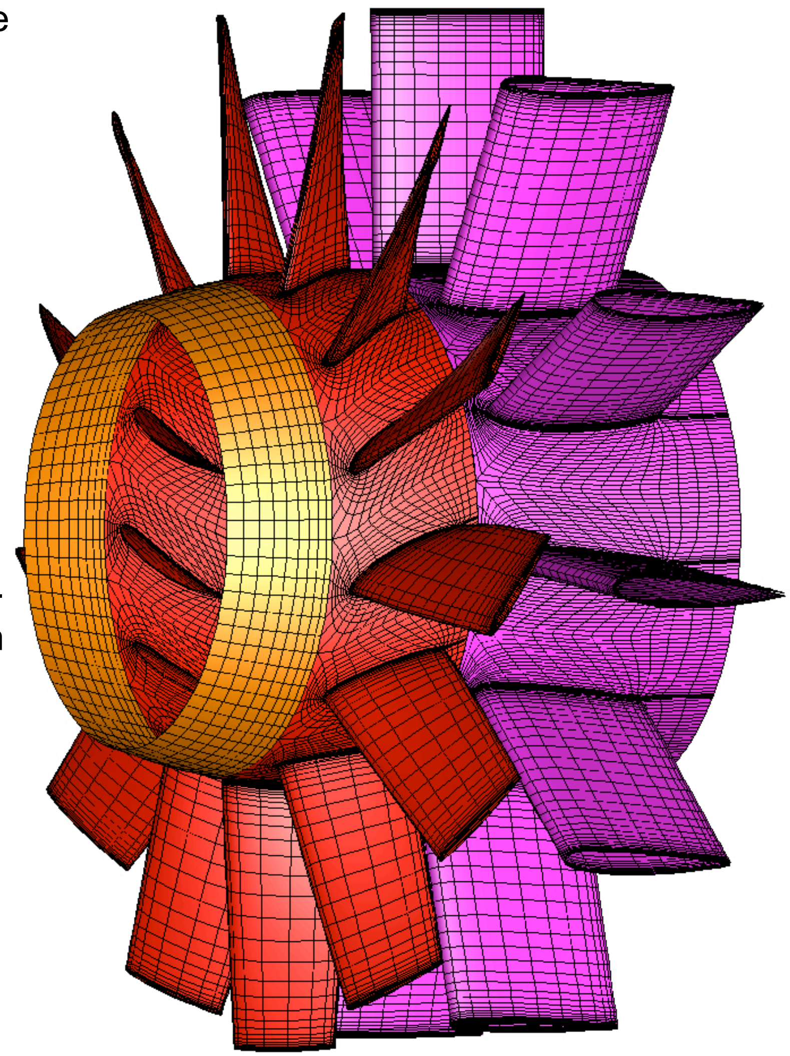
Explicit Runge-Kutta solver
- Variable Dt
- Implicit residual smoothing

Turbulence model
- Wilcox 2006 k-w turbulence model with stress limiter

Steady mixing plane model for stage calculations

TCGRID code used to define algebraic H-grid upstream, C-grids around blades, and O-grids in tip clearance region

Region	Type	Size (x, q, r)	Total points
upstream	H	45 x 38 x 93	159,030
rotor	C	193 x 62 x 93	1,112,838
rotor tip	O	145 x 13 x 13	24,505
stator	C	193 x 62 x 93	1,112,838
Total			2,409,211



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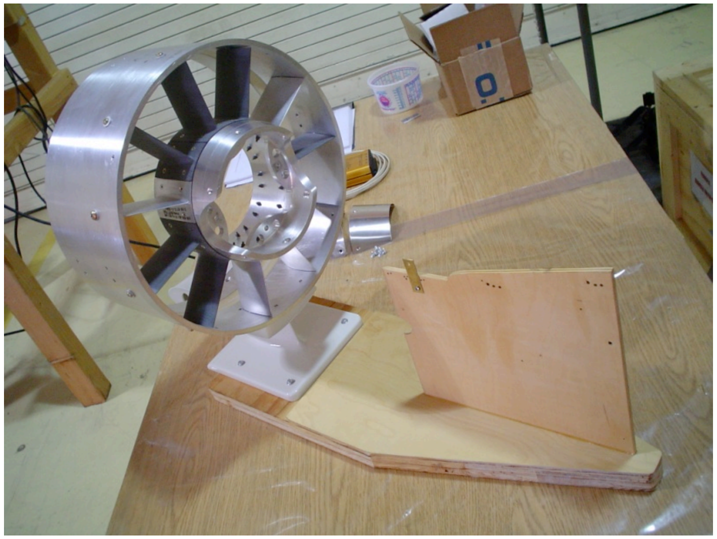
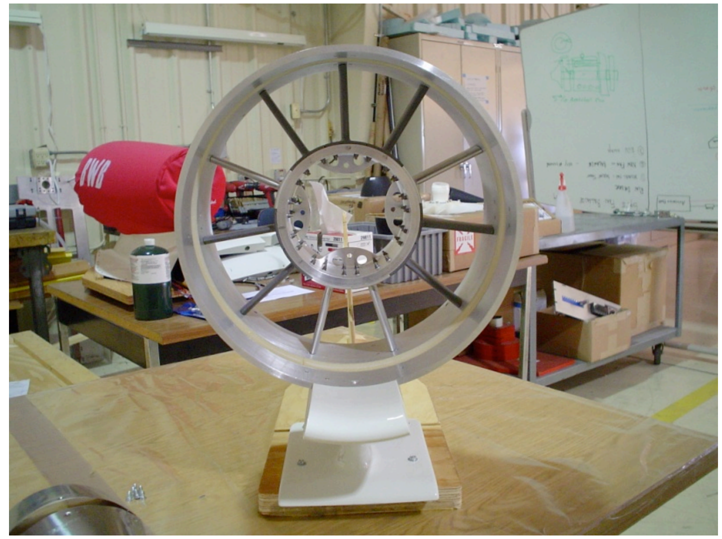
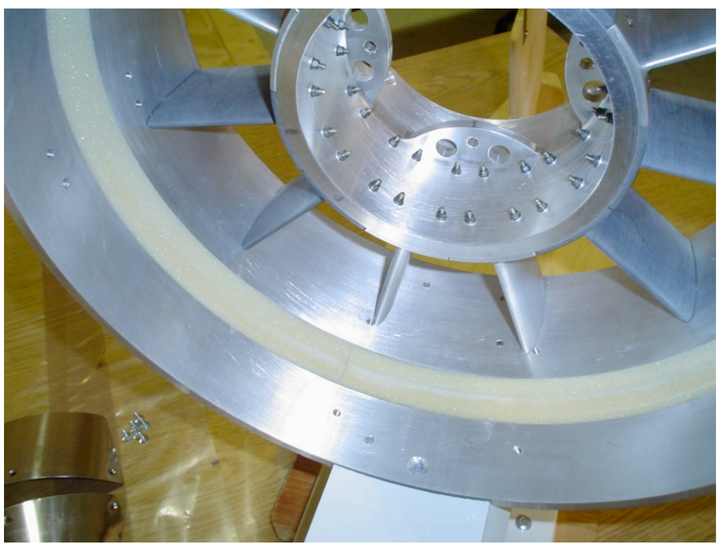
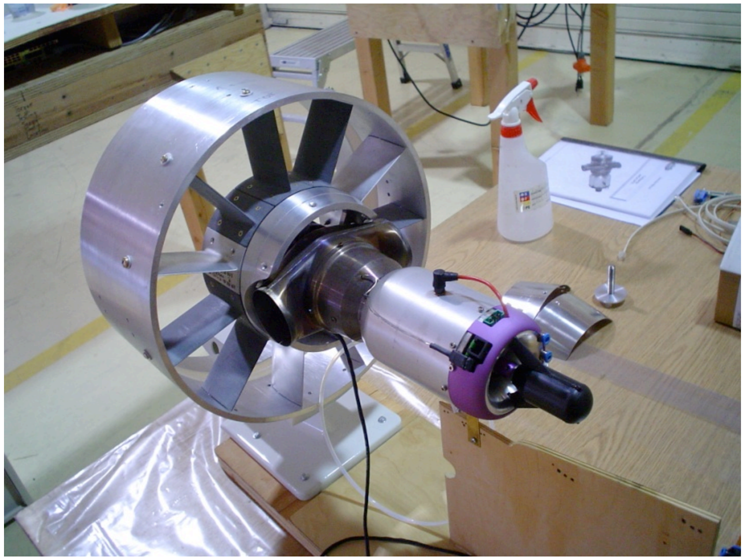
Engine Assembly - I

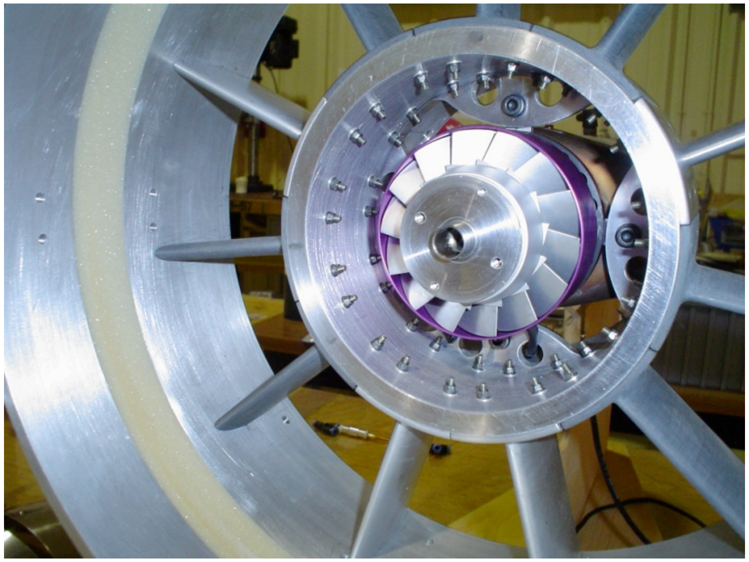


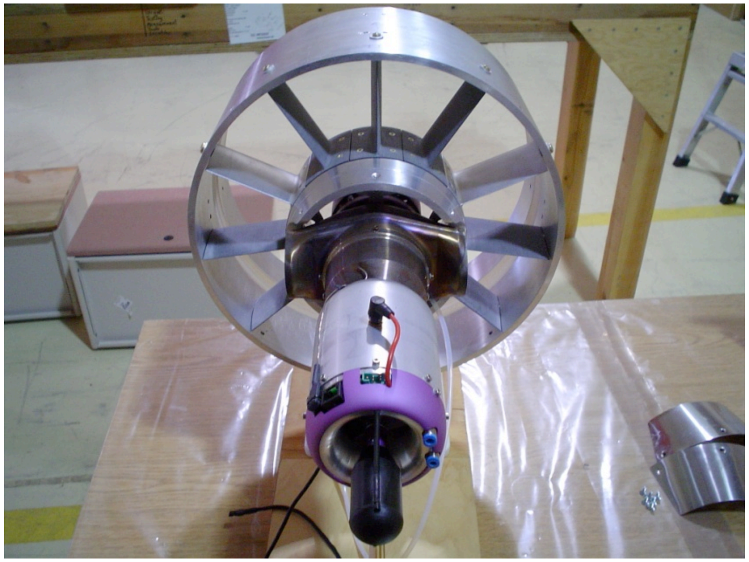




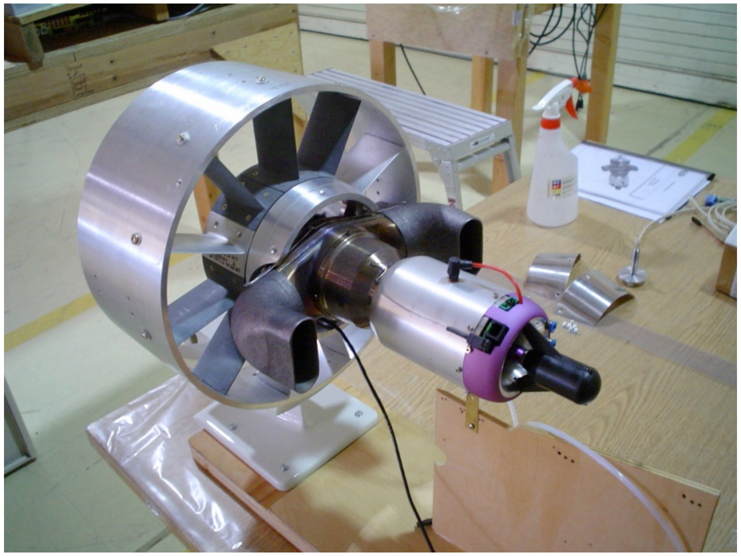
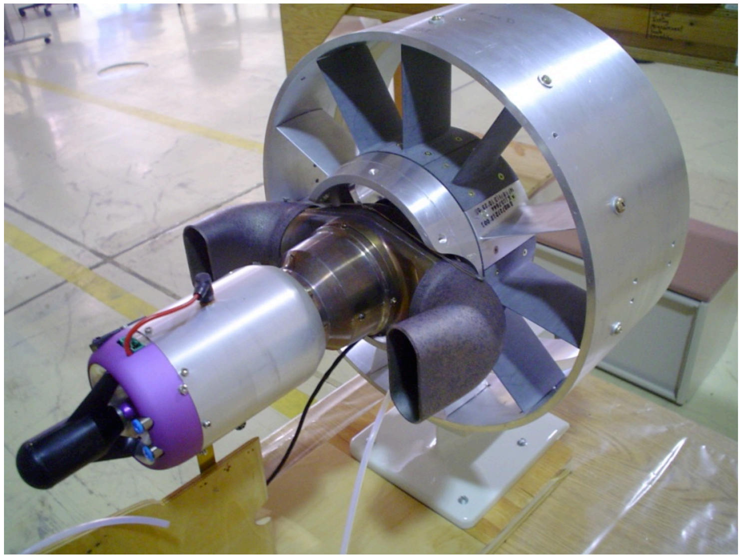
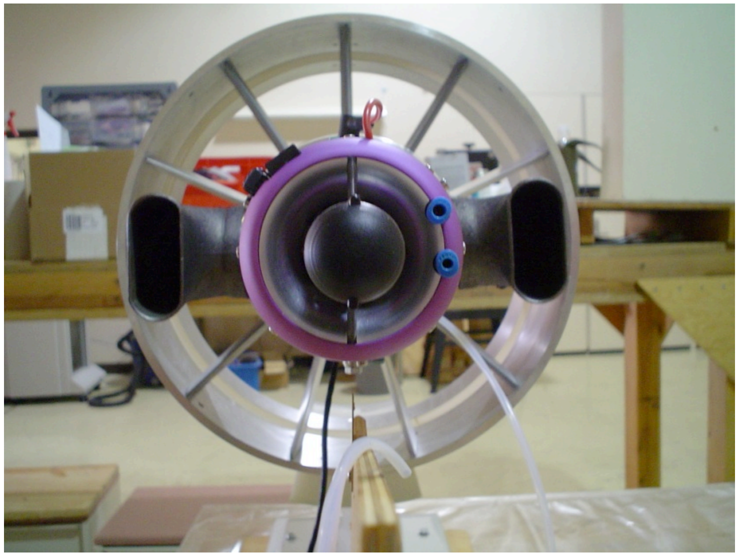
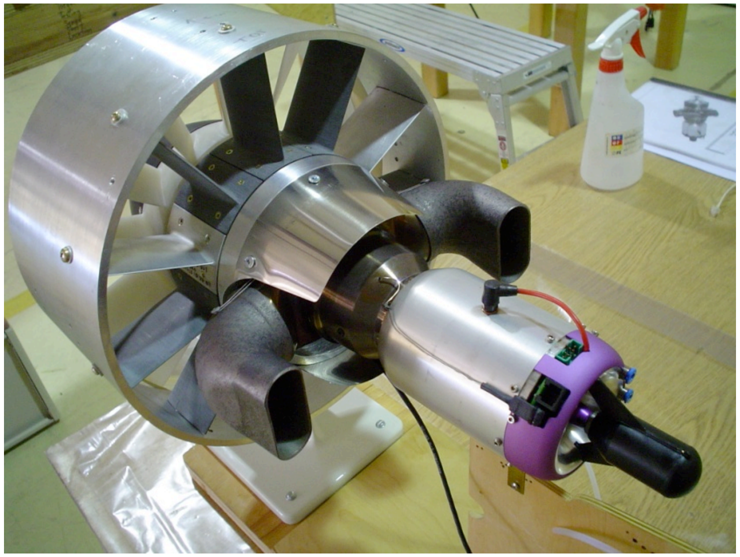
Engine Assembly - II



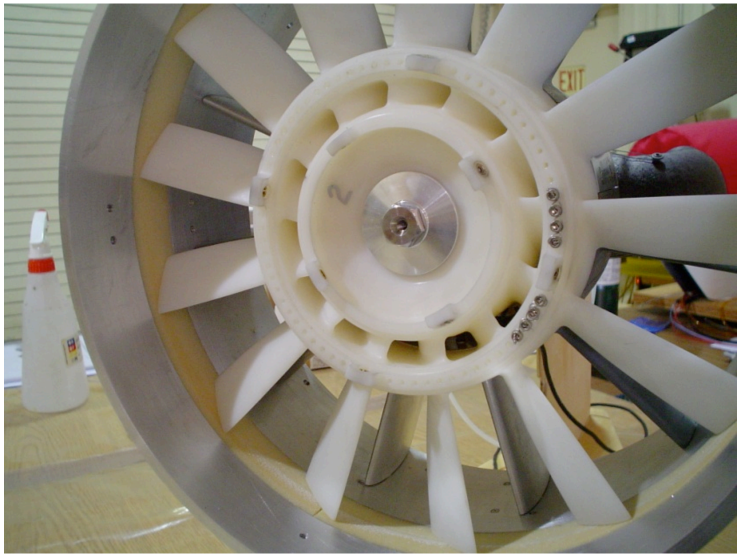


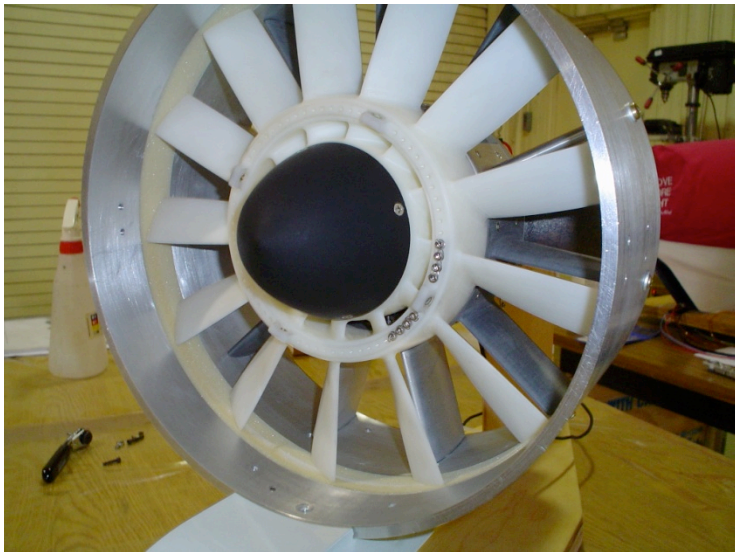


Engine Assembly - III

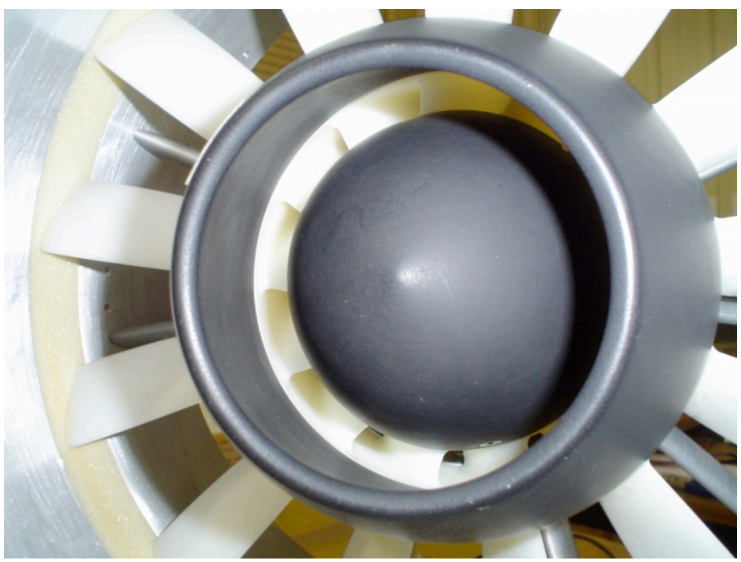





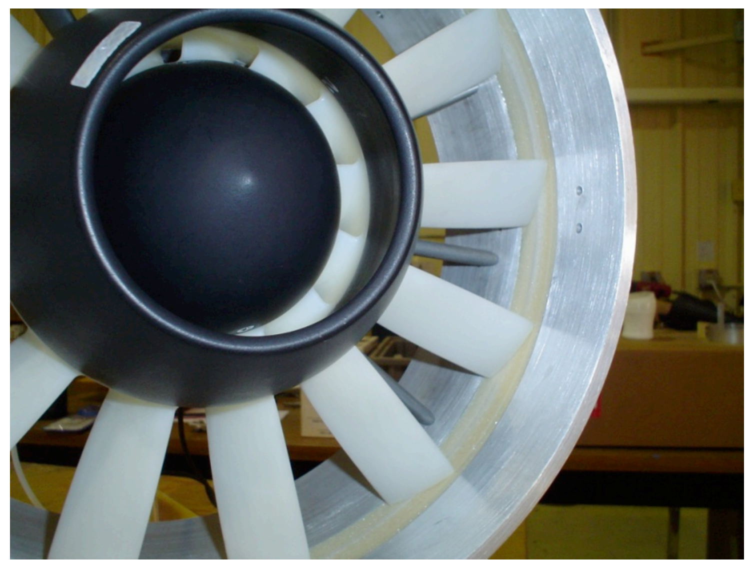
Engine Assembly - IV



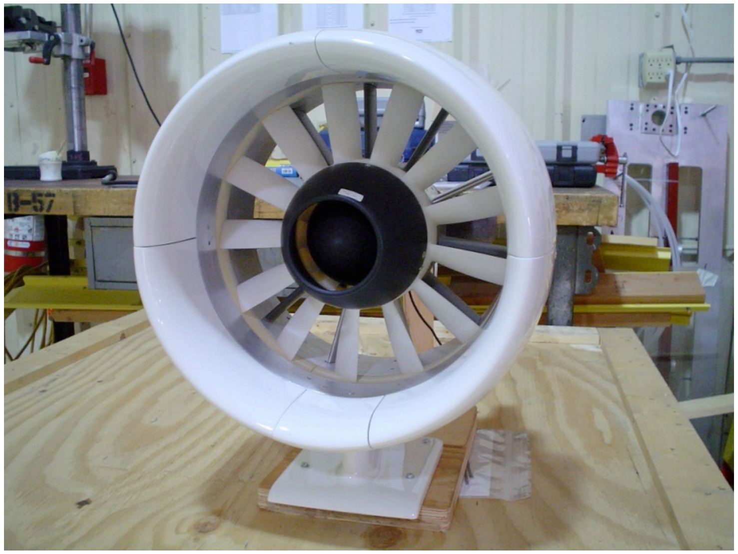


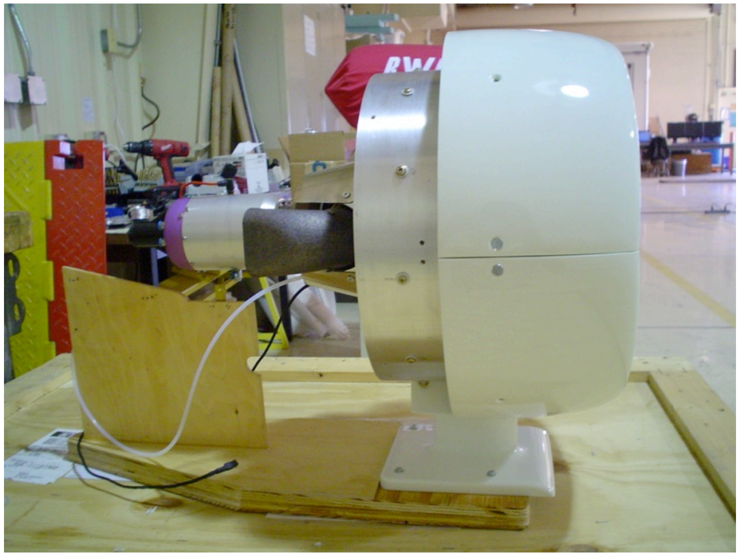
Engine Assembly - V

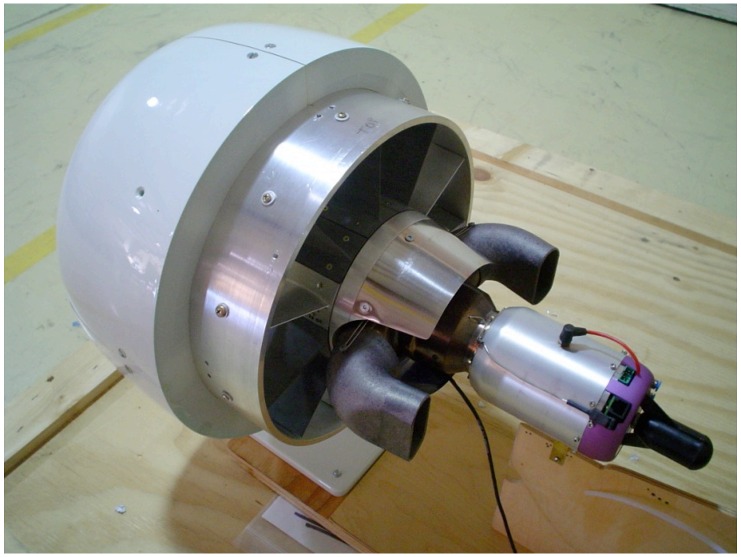


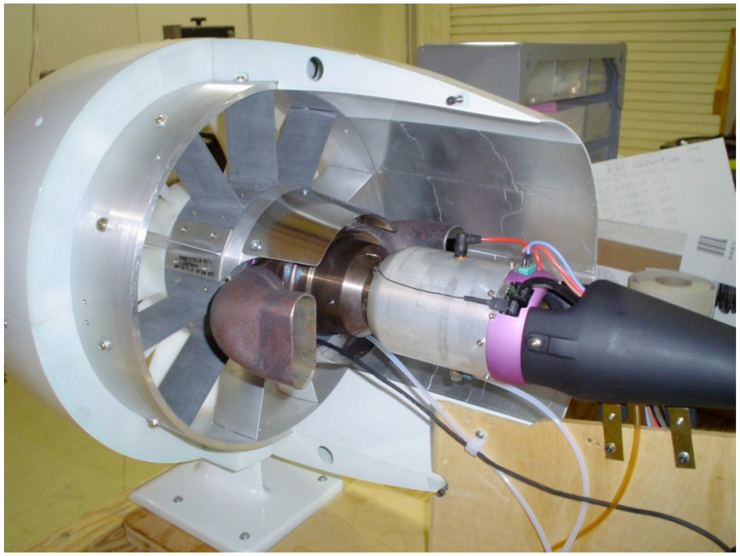


Engine Assembly - VI

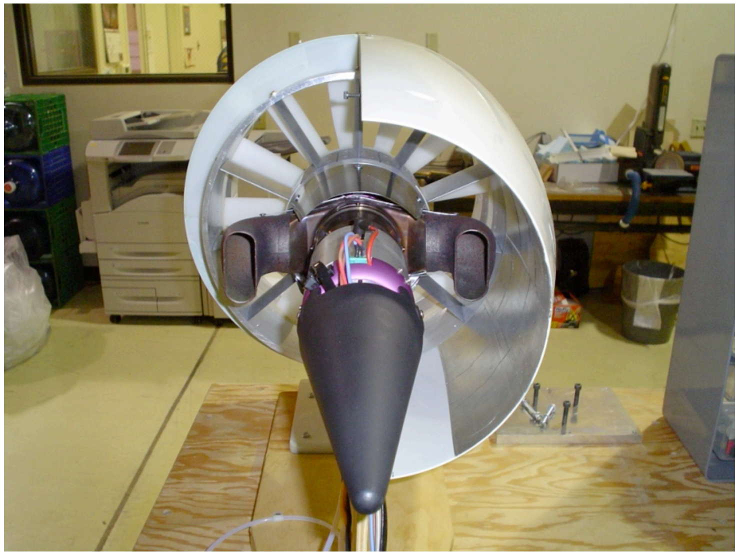
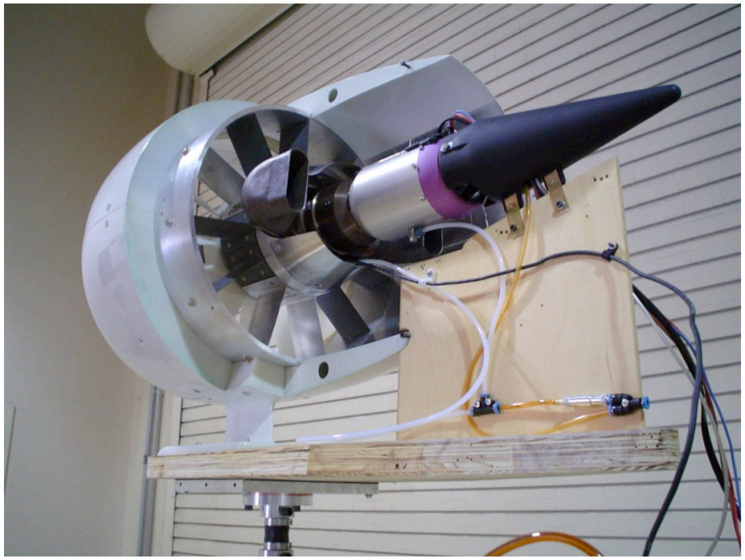
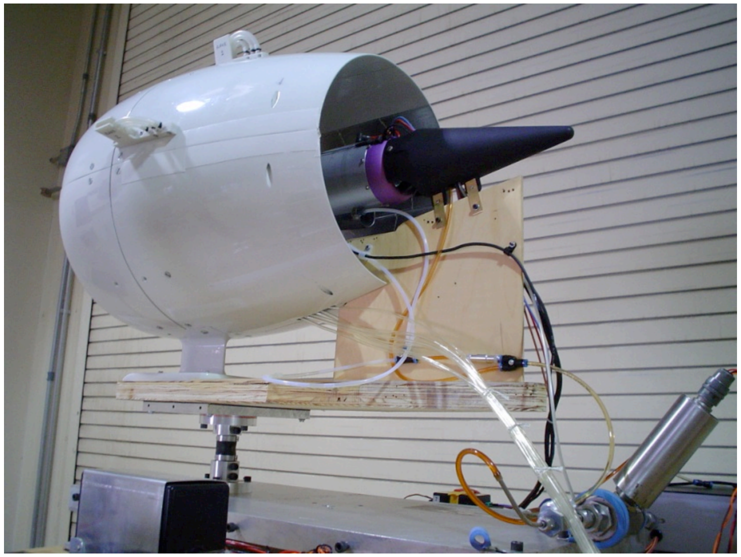
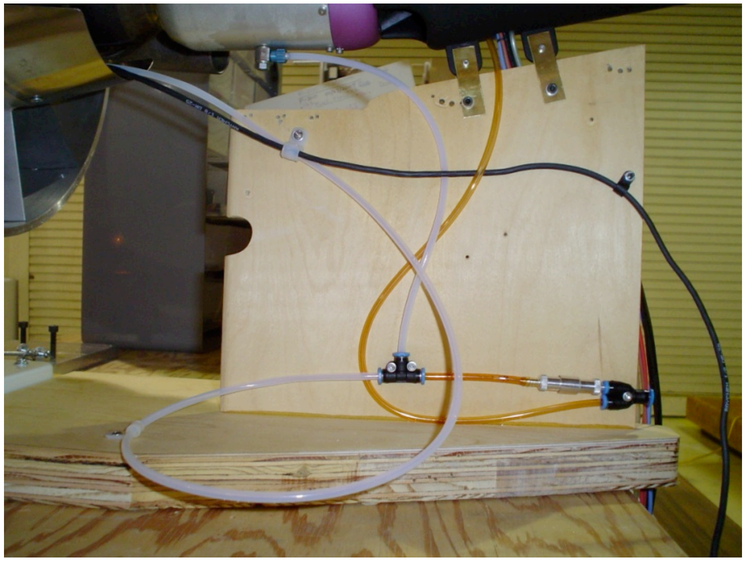




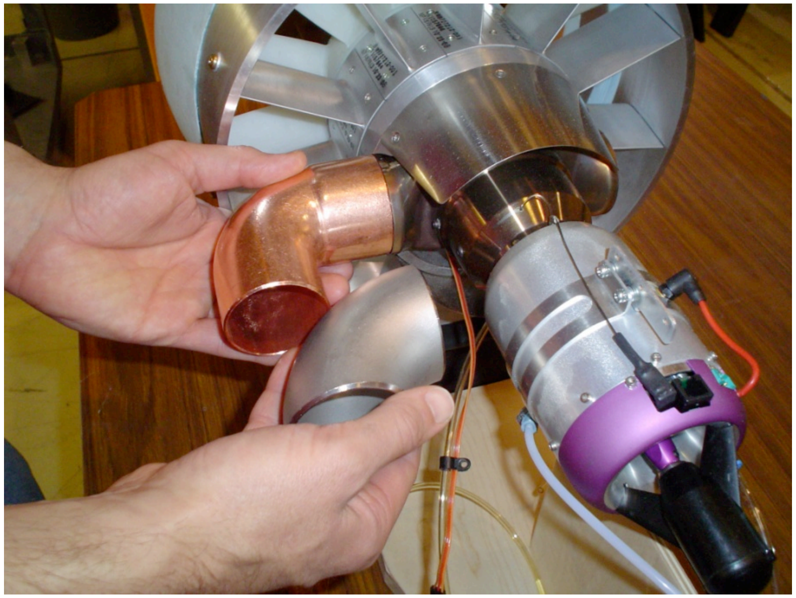




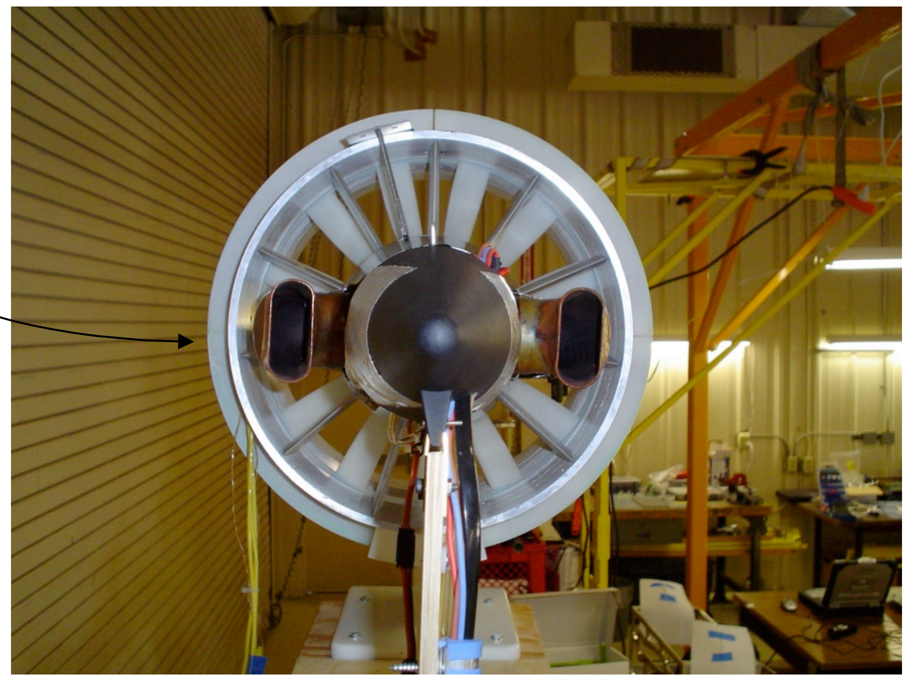
Engine Assembly - VII

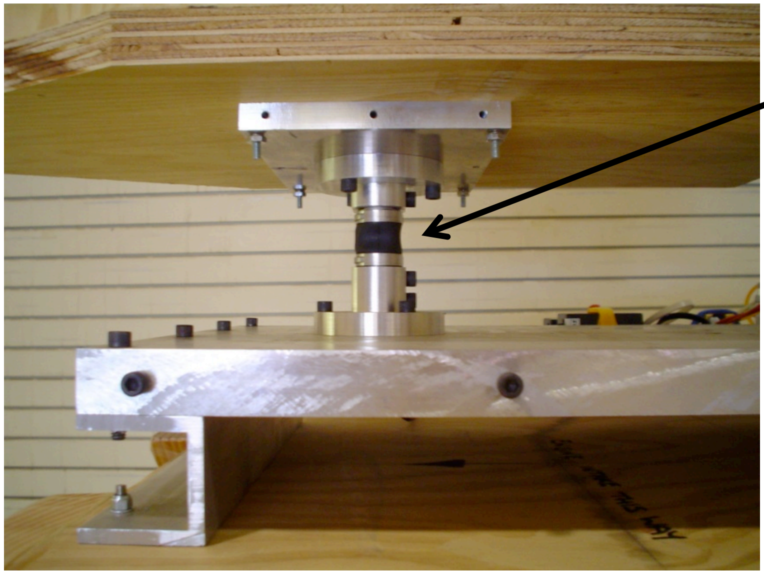
Engine Development - V



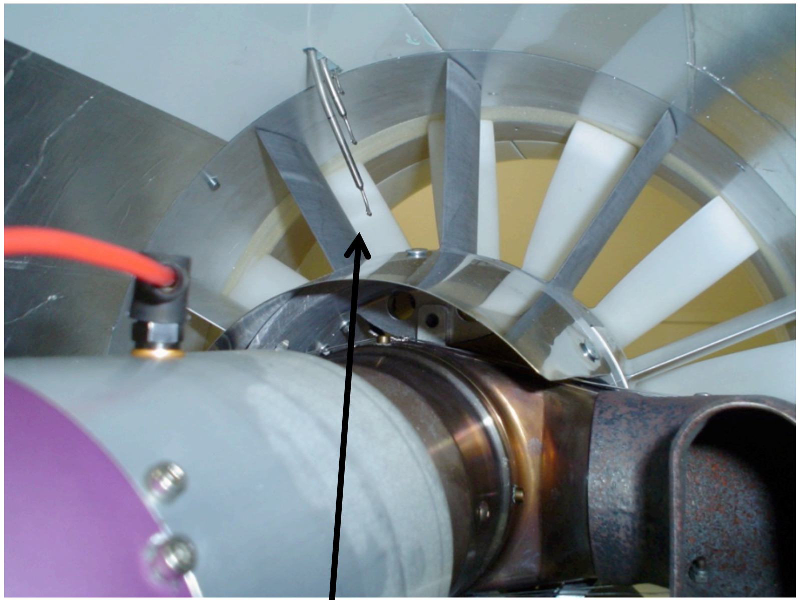
Some basic challenges, like turning the exhaust…without blocking too much of the fan flow…

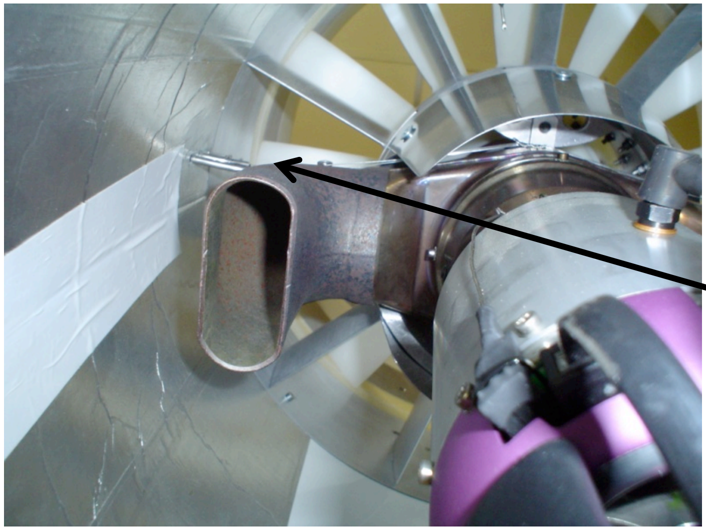


Test Instrumentation - I



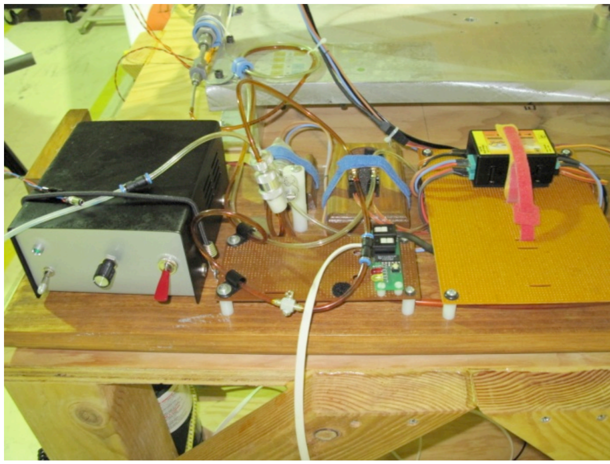
Force balance strain gauge



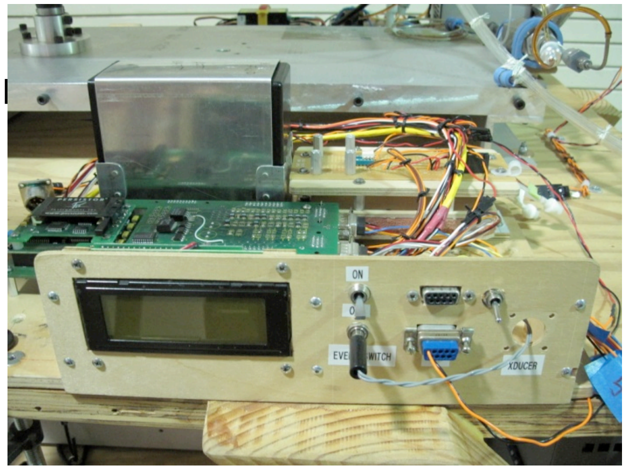


Kiel probes – 2 rakes with 3 probes each (total pressure)

Test Instrumentation - II

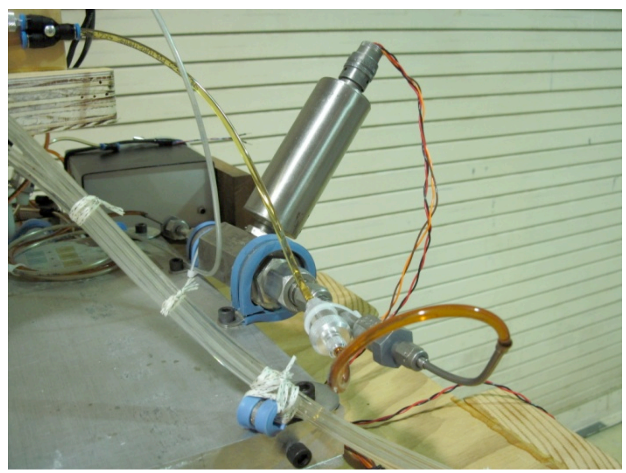


Engine Control Unit



Data Acquisition System

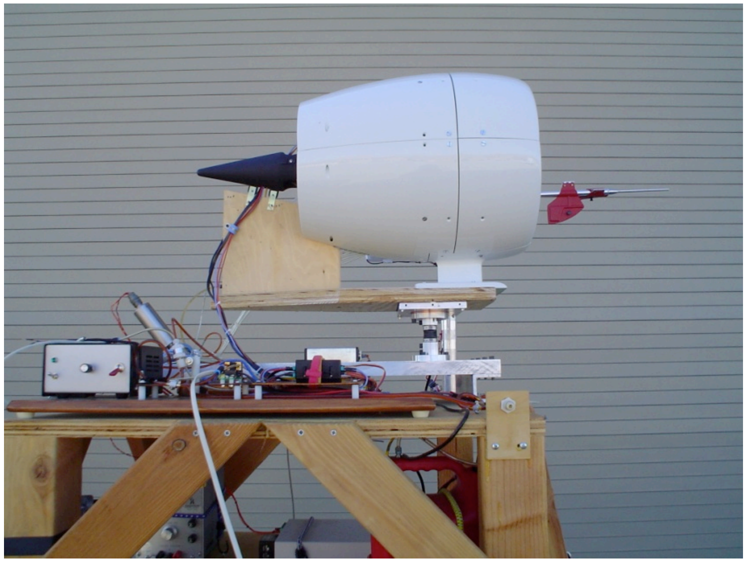
Airdata probe (pitot, static, alpha, beta)



Volumetric fuel flowmeter

Not shown:
- OAT
- Fuel Temperature
- Core RPM
- Shaft RPM
- EGT

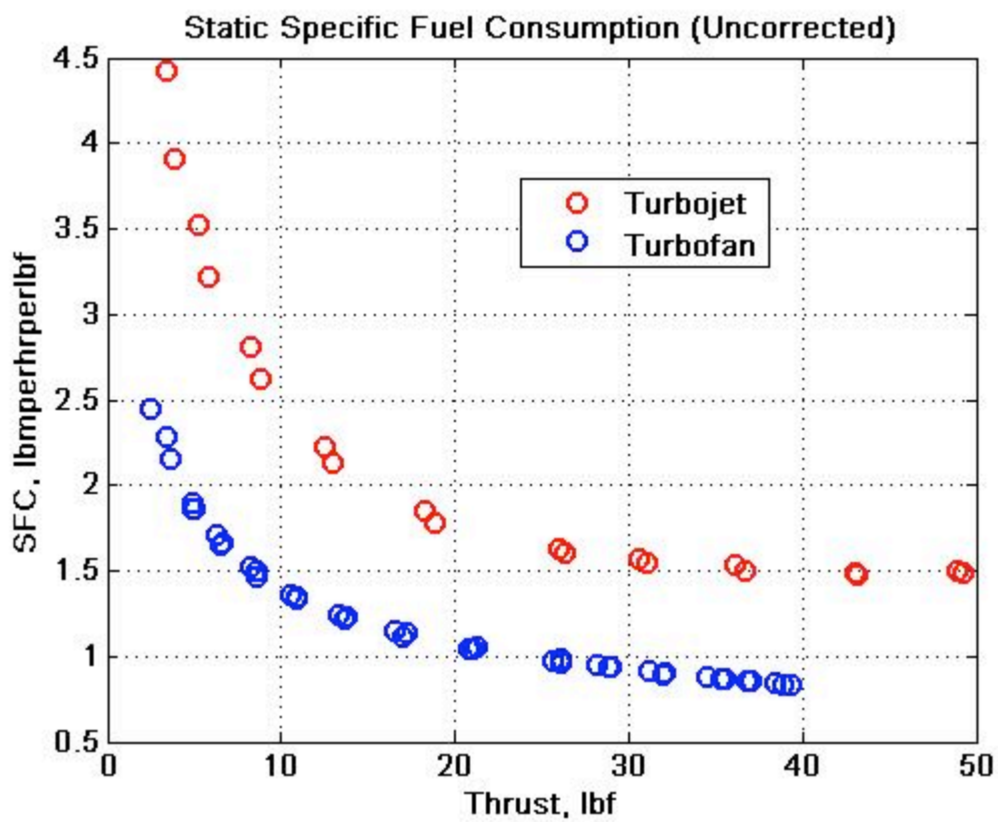
Engine Testing - I



Engine Testing - II

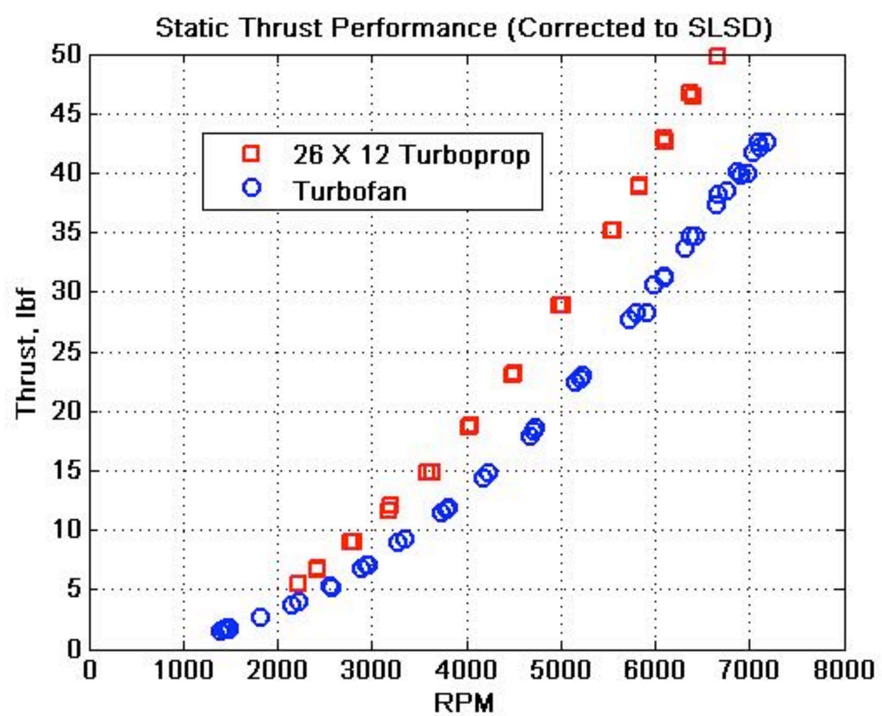
Engine Testing (Static) - V

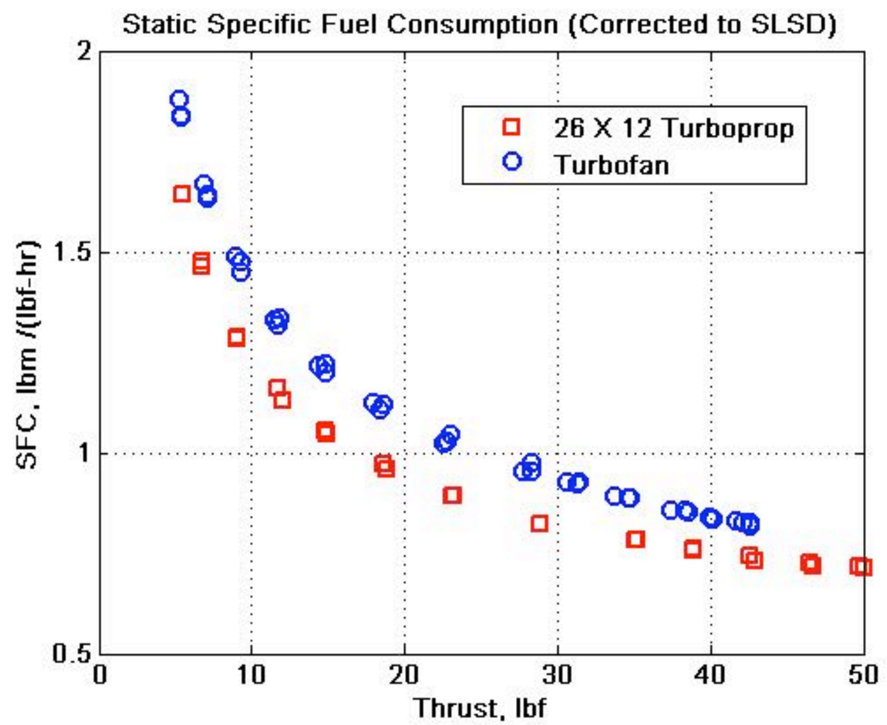
- **Characterize P240 turbojet and SPT5 turbofan performance:**
  - 44% reduction in SFC at turbofan max thrust



Engine Testing (Static) - VI

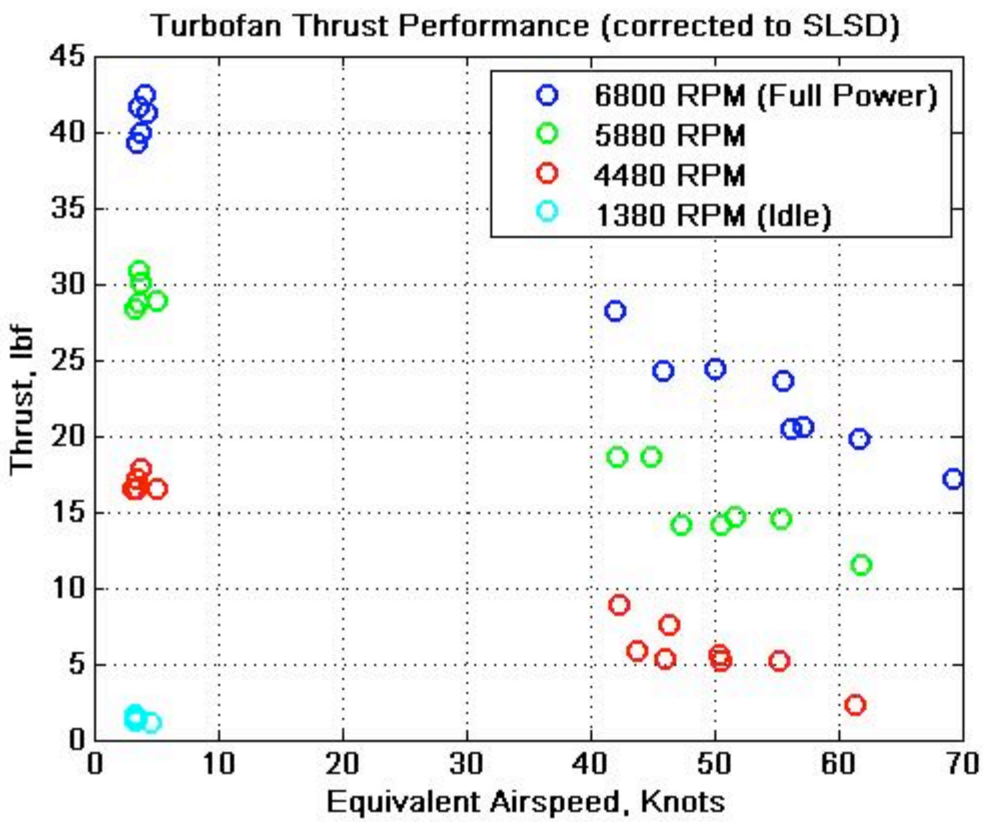
- **Characterize SPT 5 turboprop and turbofan performance:**
  - Turboprop thrust and SFC performance exceed that of turbofan
  - Turboprop static, sea level thrust approximately 50 lbf at 6700 RPM
  - Turbofan static, sea level thrust approximately 43 lbf at 7200 RPM





Engine Testing - VII

- **Characterize SPT 5 turbofan performance at flight-representative airspeeds:**
  - Significant thrust lapse with airspeed



Conclusions

- **Off-the-shelf jet propulsion in the 50 – 500 lb thrust class sparse**
- **A true twin-spool turbofan in this range does not exist**
- **Adapting an off-the-shelf turboshaft engine is feasible**
  - However the ~10 Hp SPT5 can't quite make 50 lbs. of thrust
  - Packaging and integration is challenging, especially the exhaust
- **Building on our engine using a 25 Hp turboshaft seems promising if the engine becomes available**
- **Test techniques used, though low cost, adequate for the purpose**

Future Work

- Dyno-test SPT15 engine when it becomes available
- Run another design iteration of fan with SPT15 data
- Target is 75 lbf thrust Sea Level

Acknowledgements

Boeing Colleagues:

Mark Kuehn – Boeing Mesa
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Timothy Brewer – Boeing Mesa

Norman Princen – Boeing Huntington Beach
Michael Kisska – Boeing Huntington Beach
Robert Briester – Boeing Huntington Beach

NASA Colleagues:

Timothy Risch – NASA Dryden
Ronald Chima – NASA Glenn

Questions ?

Gary B. Cosentino
NASA Dryden Flight Research Center
Lead Flight Operations Engineer
Science and UAV's
gary.b.cosentino@nasa.gov