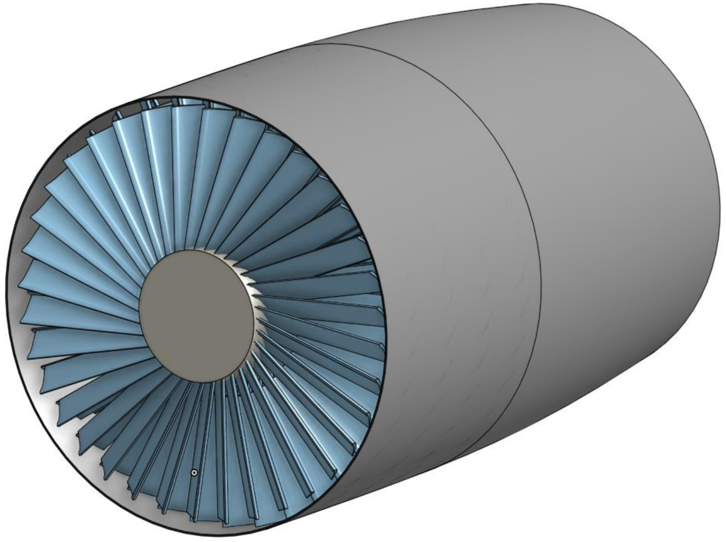
THE Compressor

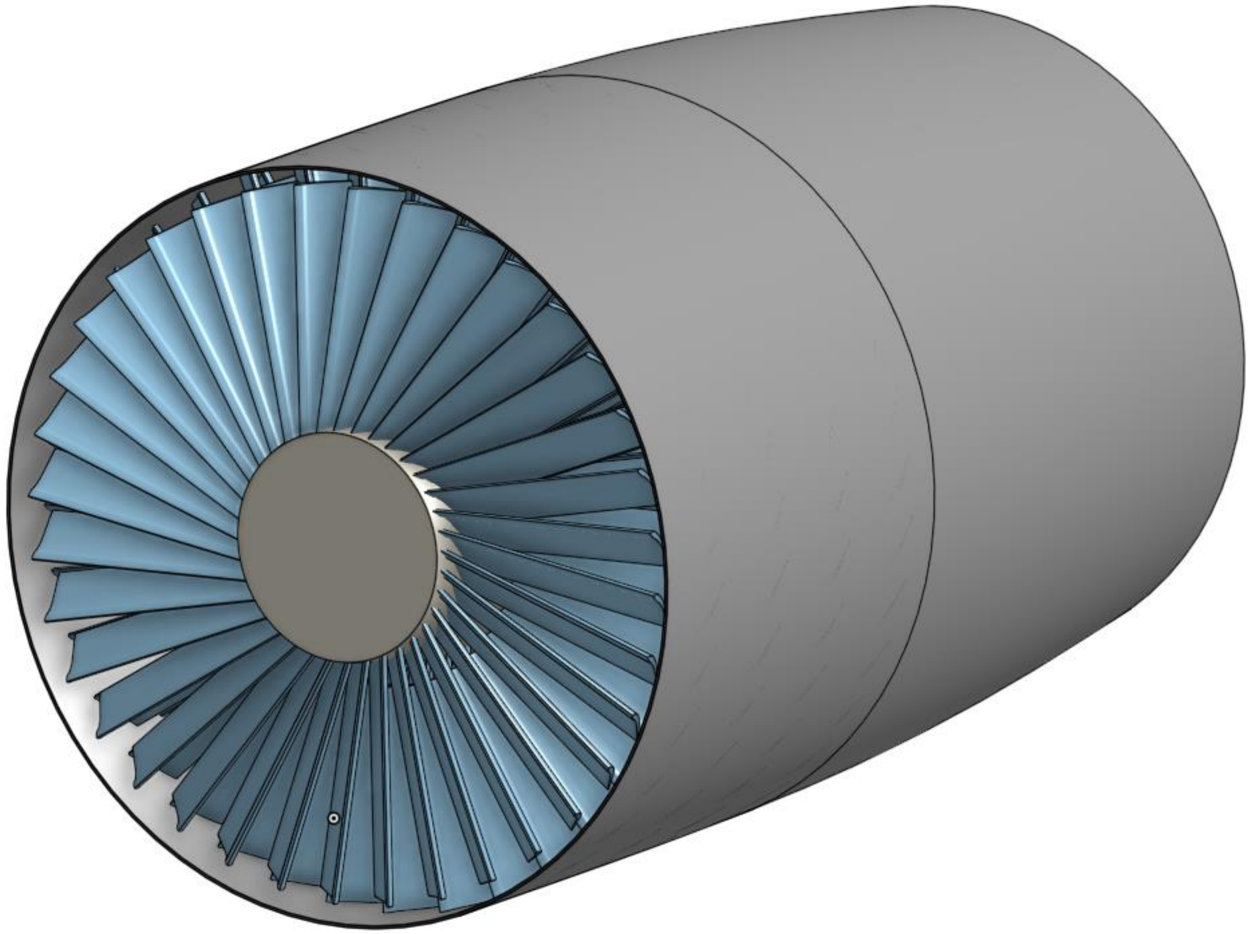


B. Bunt, B. Lee, E. Taglia, P. Sklavounos

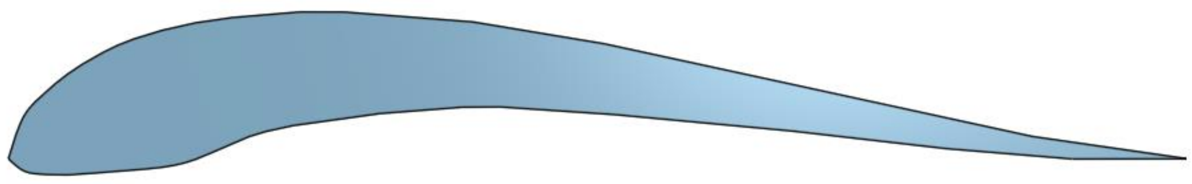
Compressor Design

- NACA Inspired Blade Profile (NACA-8)
- 4 stages
- Uniform chord Length & 36 of blades per stage

* Shell of further components shown as well (turbine, exhaust, etc.)



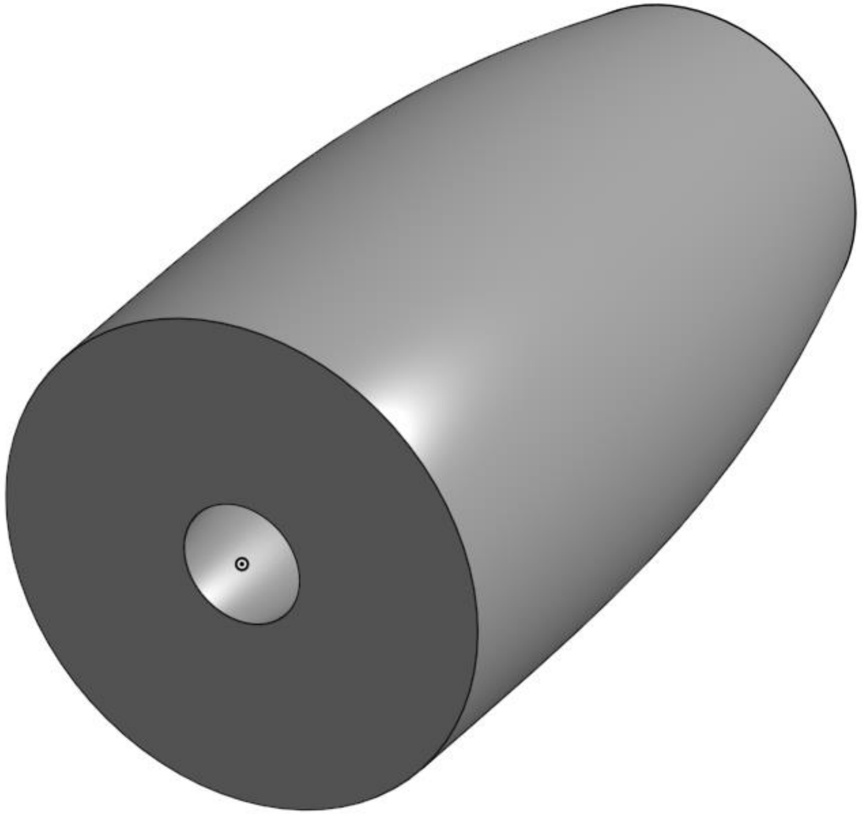
Compressor Design



NACA-8 blade

45-degree Angle of Attack

Fluid for Meshing/CFD Simulation



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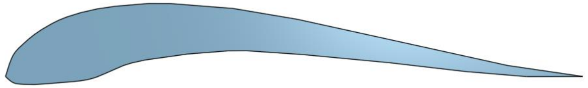

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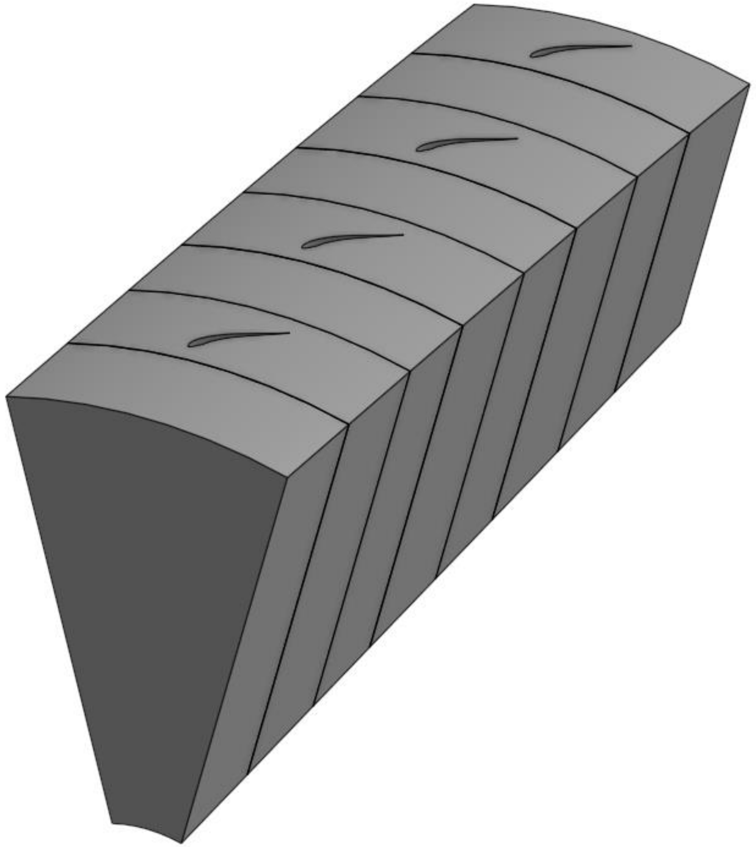
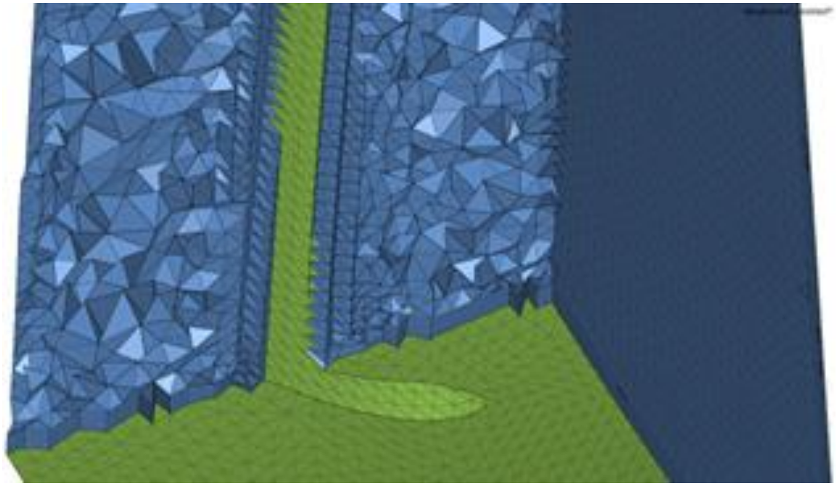
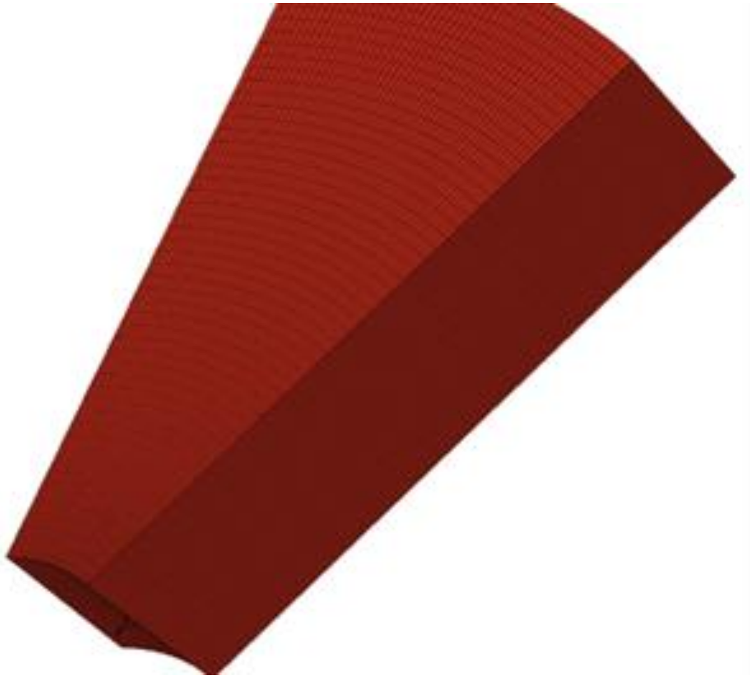
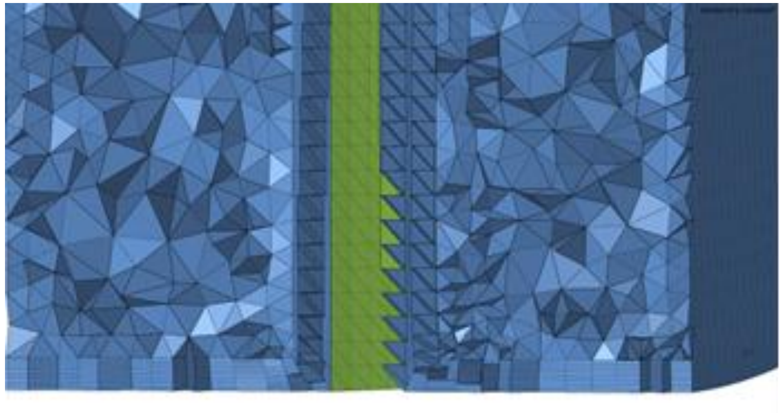


CFD Setup: Meshing







HONDA

Material Selection

Solid: Carbon Fiber/Graphite Composite

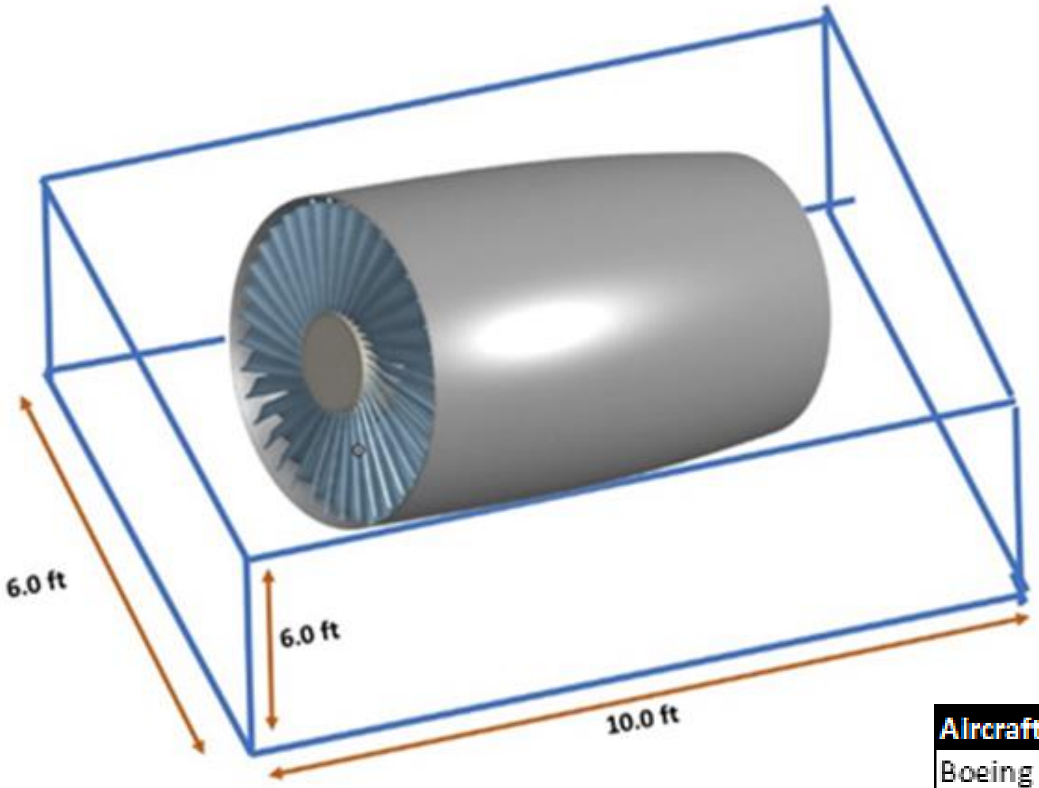
Fluid: Air (@ STP and 37000ft).

- Material properties changed in CFD program

Reasoning

- Composite can provide a weight savings of about 53 lbs in comparison to all-aluminum vanes
- Composite demonstrated better fatigue performance margins than single material vanes

Size & Weight



Part	Dry Weight (lb.)
Rotors/Stators	280
Glass Fiber Shell	373
Graphite Core	3154
Total	**3806**

Aircraft Model	Compression Ratio	Number of Compressor Stages	Compressor Weight
Boeing 737-800	30:1	13	1,560 lb (707 kg)
Airbus A320	30:1	10	1,764 lb (800 kg)
Boeing 747-8	30:1	18	6,056 lb (2,748 kg)
Airbus A380	40:1	16	6,173 lb (2,800kg)
Bombardier CRJ-700	16:1	7	327 lb (148 kg)
Embraer E170	17:1	7	462lb (210 kg)
Gulfstream G650	16.9:1	14	1,636 lb (742 kg)
Cessna Citation X+	8.5:1	2	252 lb (114 kg)
Lockheed Martin F-22 Raptor	N/A	2	1,042 lb (472 kg)
Eurofighter Typhoon	N/A	2	2,314lb (1,050 kg)

Operating Parameters

STP (~0 ft)

- "Start-up condition"
  - 0.5 s at 500 rpm
  - 0.5 s at 1500 rpm
  - 0.5 s at 2500 rpm

100 timesteps at

5 ms/timestep

High altitude (37000 ft)

- "Cruising speed condition"
  - Constant rotational speed of 20000 rpm

At most, 200 timesteps at

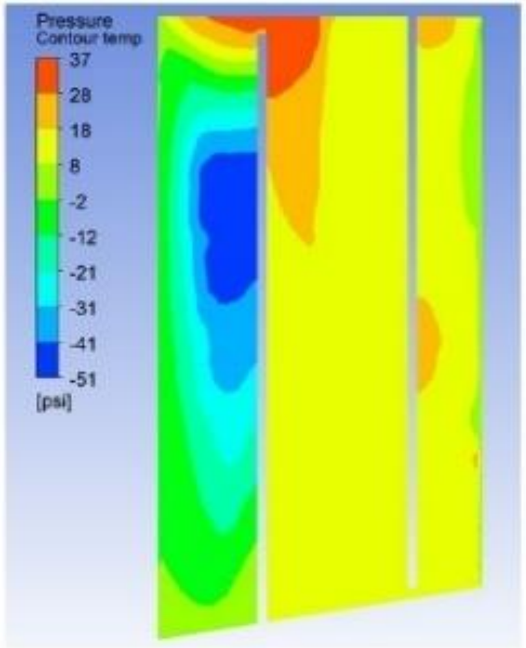
5 ms/timestep

Results (Stage 1 , Stage 2)

<u>Compression Ratio : Stage 1 @ 37kft, 20krpm</u>

Rotor Inlet

6.21psi



Stator Outlet

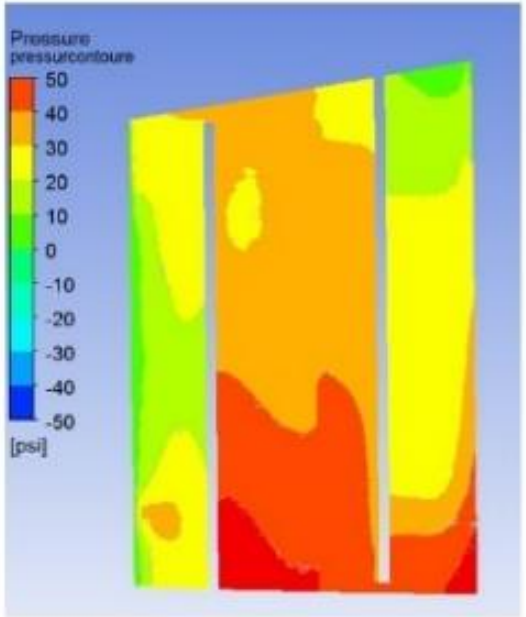
12.91psi

Compression: 2.08

<u>Compression Ratio : Stage 2 @ 37kft, 20krpm</u>

Rotor Inlet

0.99psi

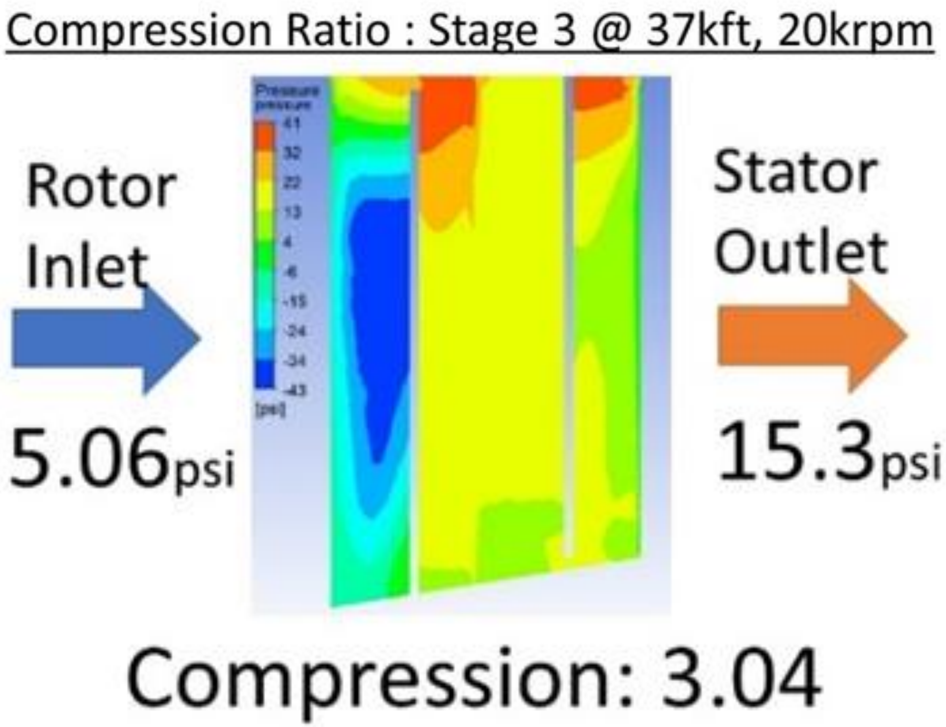


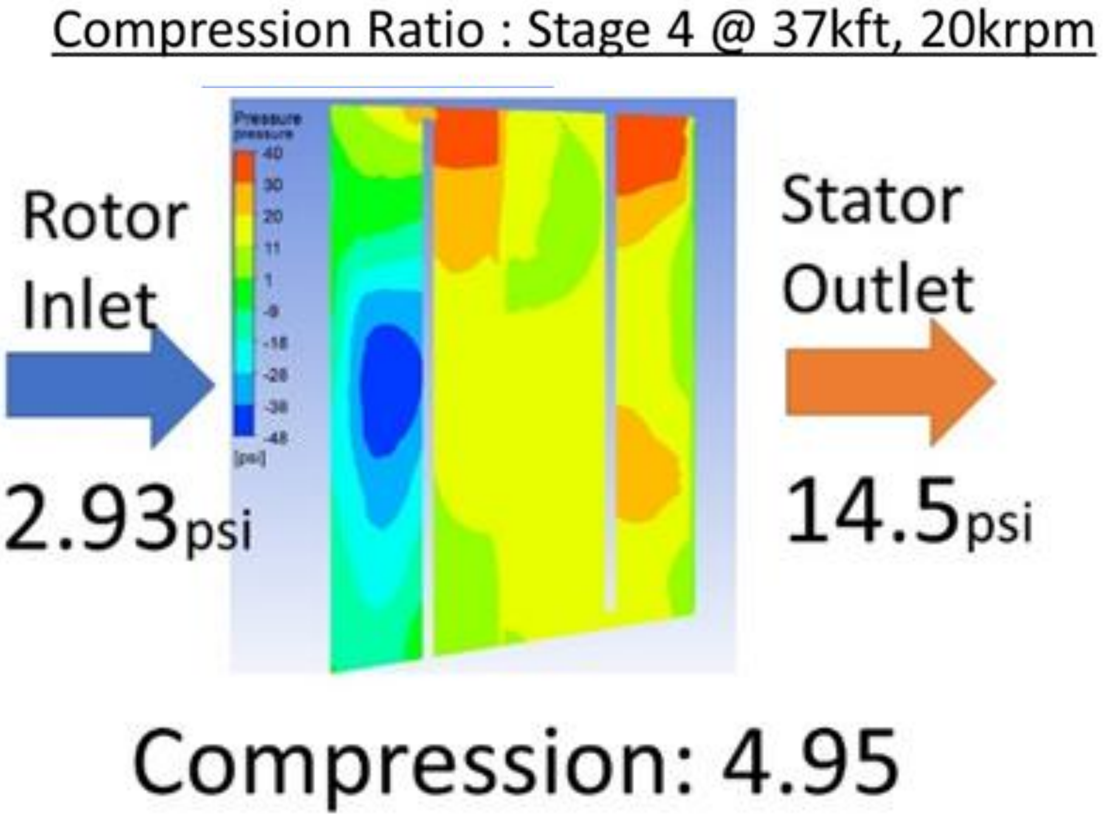
Stator Outlet

2.43psi

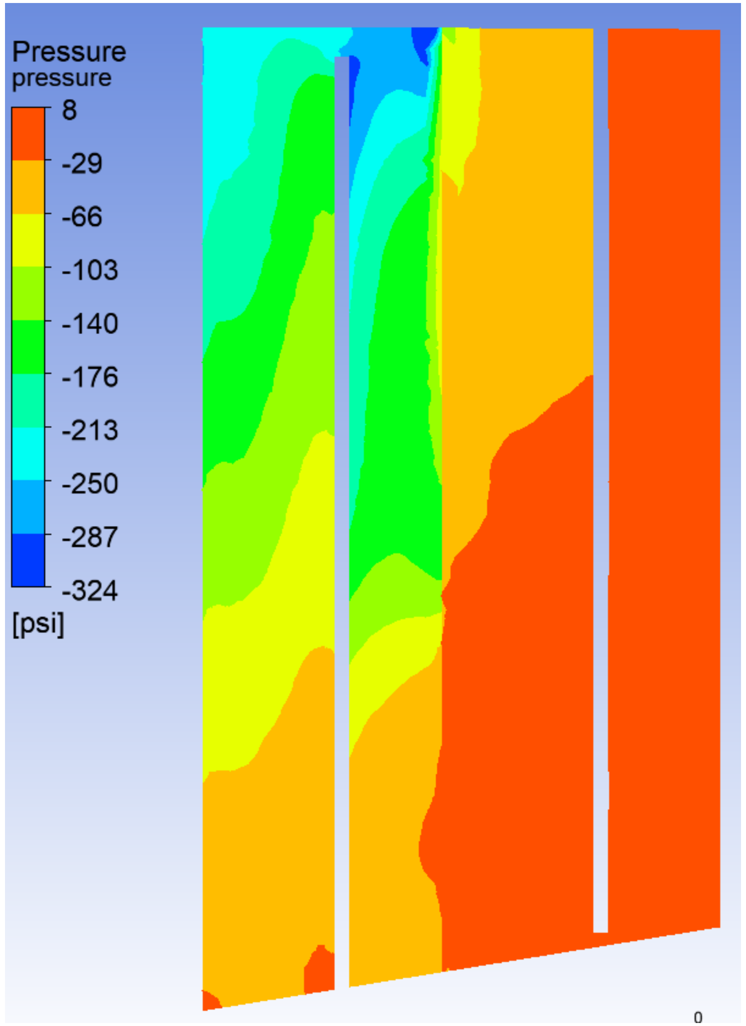
Compression: 2.43

Results (Stage 3, Stage 4)





Results (examples at STP/sea level)



Compressor Performance

At 37,000 ft & constant speed of 20,000 rpm

Stage	Inlet gage	Outlet gage	Compression ratio
1	6.21	12.91	2.08
2	0.99	2.43	2.43
3	5.06	15.36	3.04
4	2.94	14.53	4.95
TOTAL			75.97

Compressor Performance

At 37,000 ft & constant speed of 20,000 rpm

Stage	Inlet gage	Outlet gage	Compression ratio
1	0.17	0.87	5.00
2	0.12	0.69	5.62
TOTAL			28.11

(and beyond!)

Calculated Entrance and Exit Temperatures

Assumption: ideal gas, adiabatic process
Given: Inlet temperature is 25 C, Pressure Ratio is 20:1 (outlet pressure = 20x larger)

At Sea Level:

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{\Gamma-1}{\Gamma}}$$

Where

$$T_1 = 80°F,\ P_1 : P_2 = 1:20$$

And

$$P_1 = 1\,atm,\ P_2 = 20\,atm$$

$$\Gamma = \frac{c_p}{c_v} = \frac{1}{0.718} = 1.4 \text{ at STP}$$

$$T_2 = \cdot \left(\frac{20\,atm}{1\,atm}\right)^{\frac{1.4-1}{1.4}}$$

$$T_2 = 679.17\ F$$

At 37,000 ft:

$$T_{altitude} = T_{sea\ level} + (Lapse\ Rate \cdot Altitude)$$

Tropopause sublayer that has a temperature that decreases linearly with altitude:

Lapse rate: -3.57°*F* per 1,000 ft

$$T_{37{,}000\ ft} = 80°F + \frac{-3.57 * 37000}{1000} = -70°F$$

$$\boldsymbol{\Gamma = \frac{C_p}{C_v} = 1.4}$$

$$\boldsymbol{T_2 = 213K \cdot \left(\frac{20\,atm}{1\,atm}\right)^{\frac{1.4-1}{1.4}} = 501.3K = 442.67F}$$

Approximate Power Approximation

$$P_{is} = 2.31 \cdot \frac{\gamma}{\gamma - 1} \cdot \frac{T_2 - T_1}{M} \dot{m}$$

$$W_{actual} = \dot{m} c_p \left(T_{03} - T_{02}\right)$$

$$\boldsymbol{W_{actual} = 2\frac{lb}{s} * 0.\frac{24BTU}{lbm * R}(1075 - 901) = 84\,kg\frac{m^2}{s^2}}$$

$$W_{adiabatic} = c_p T_{02} \left[\left(\frac{P_{03}}{P_{02}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$W_{actual} = W_{adiabatic} \cdot \eta_c$$

$$\eta_c = \frac{84}{143} = 0.58$$

$$\eta_t = \frac{W_{adiabatic}}{W_{actual}} = 1.7$$

$$\eta = \frac{T_{04} - T_{02}}{c_p T_{03} - c_p T_{02}} \cdot \frac{1}{PR^{\frac{\gamma-1}{\gamma}}} \cdot \frac{1}{\eta_c \eta_t}$$

$$\eta = 0.82$$

Actual Power Calculations

Compression ratio	Operating speed(rpm) @ 1st 0.5s	Operating speed(rpm) @2nd 0.5s	Operating speed(rpm) @3rd 0.5s	Power (kW)
At least 20:1	500	1500	2500	21.5
76:1	20,000	20,000	20,000	172.3

(at least...)

Design Benefits:

1. Specified pressure ratio of $\geq$20:1 achieved

2. Outermost diameter no bigger than 6 ft

3. Reasonable weight

4. Reasonable efficiency (~82%)
    - On average, efficiency between 70% & 85%

Lessons from CFD Simulations

- Start with more stages than likely needed, cut back if applicable
  - Original design had 6 – removed 2
- Rerun simulation if results diverge
  - Sometimes, <u>results will converge even with same settings</u>

Design Time Estimate

≥360 hours

Questions?