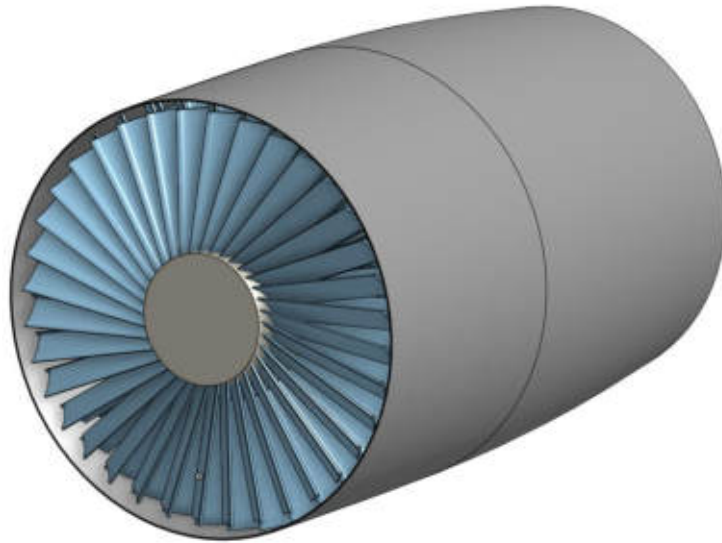


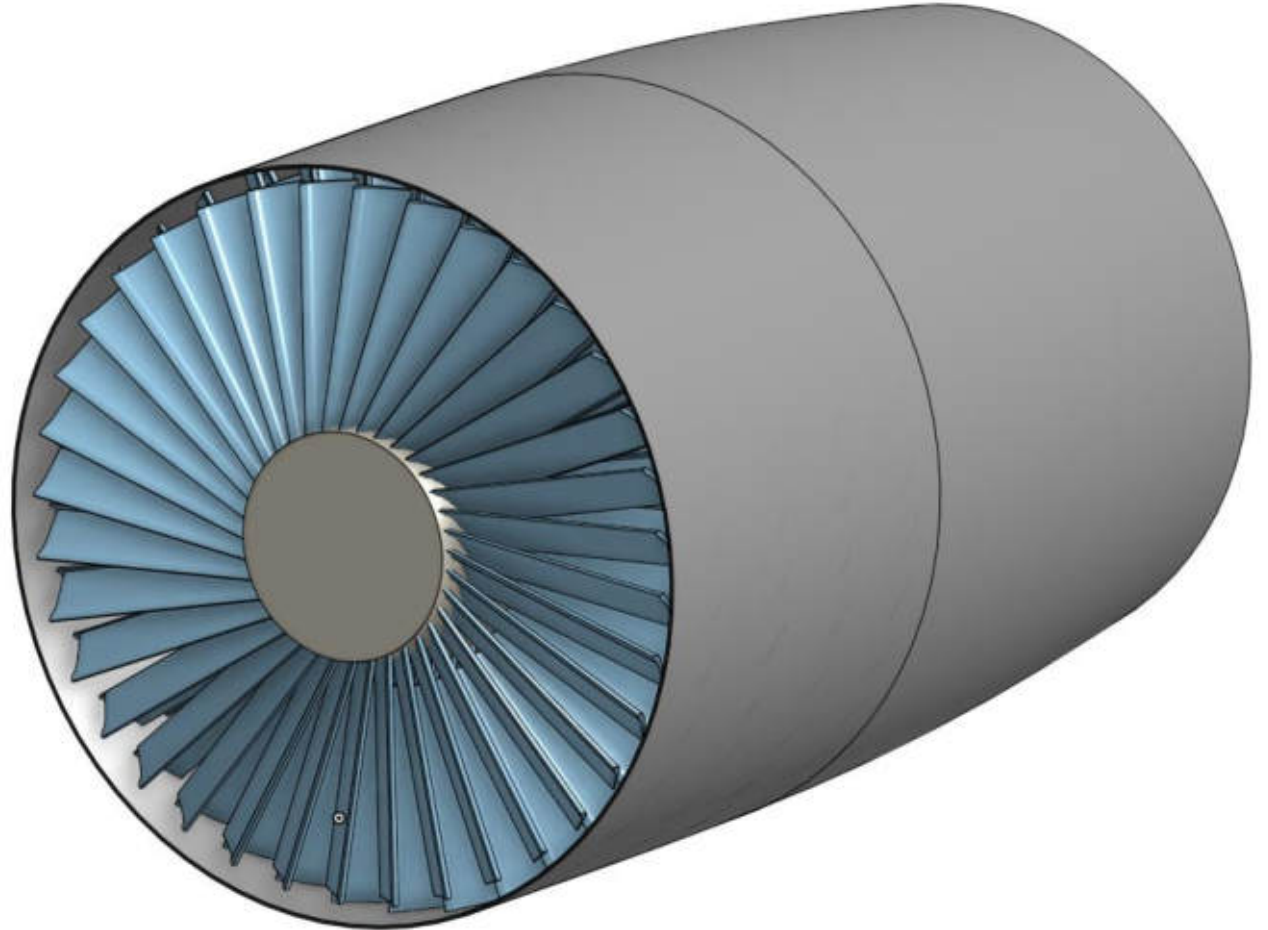
THE Compressor



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

Compressor Design

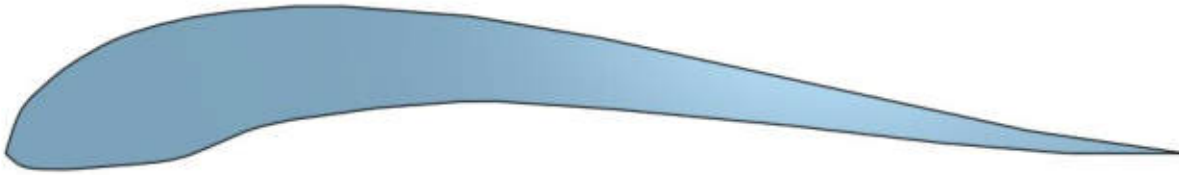
- NACA Inspired Blade Profile (NACA-8)
 - 4 stages
 - Uniform chord Length & 36 of blades per stage
- * Shell of further components shown as well (turbine, exhaust, etc.)



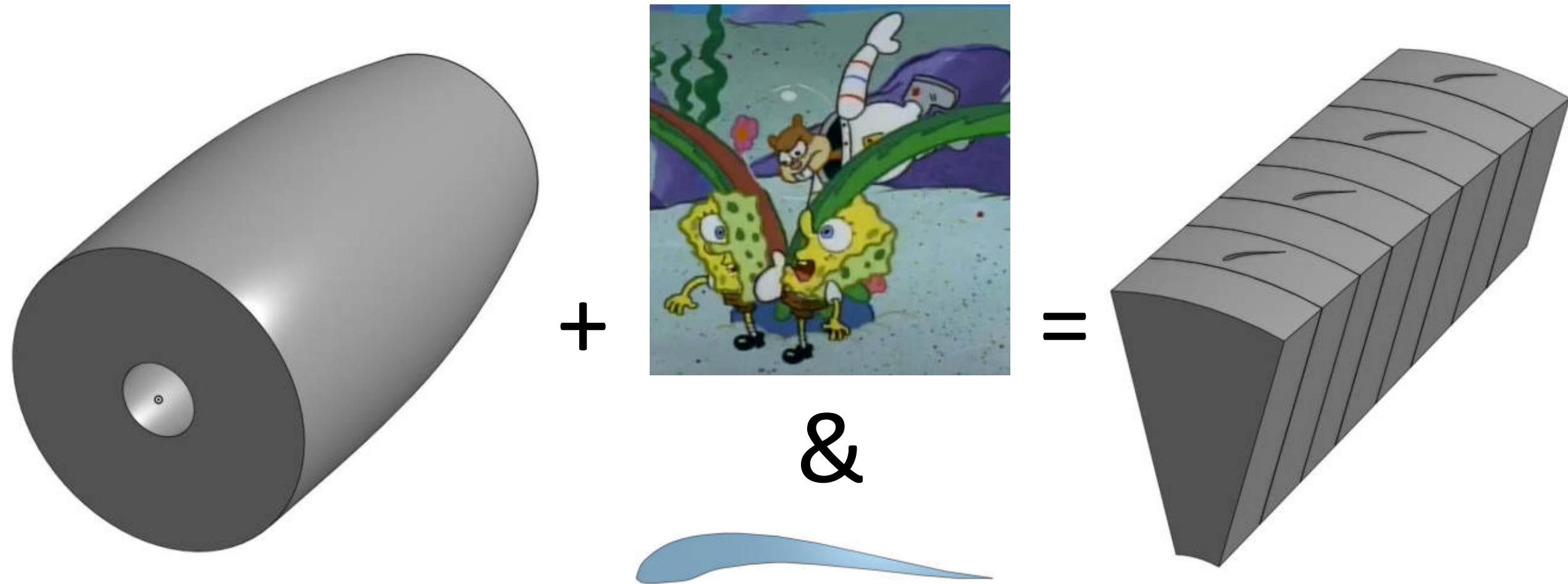
Compressor Design

NACA-8 blade

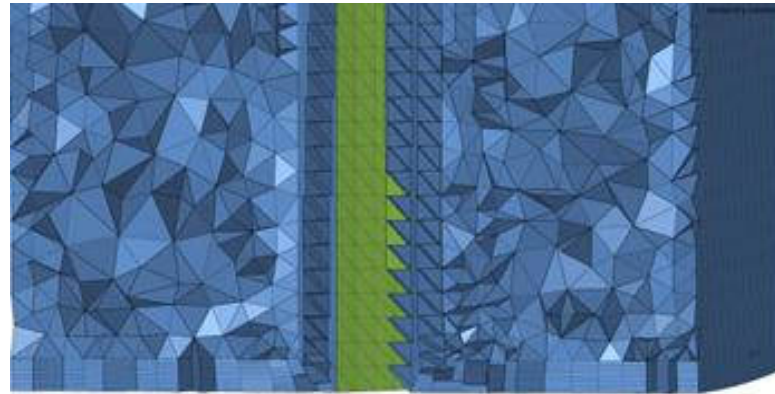
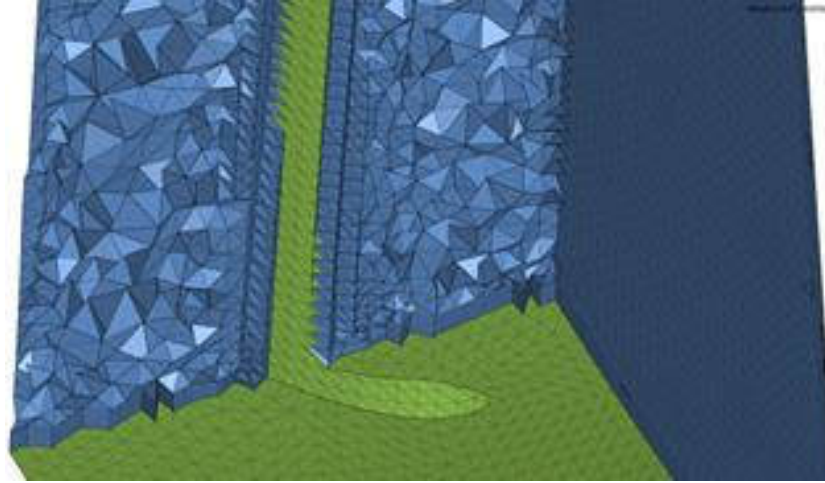
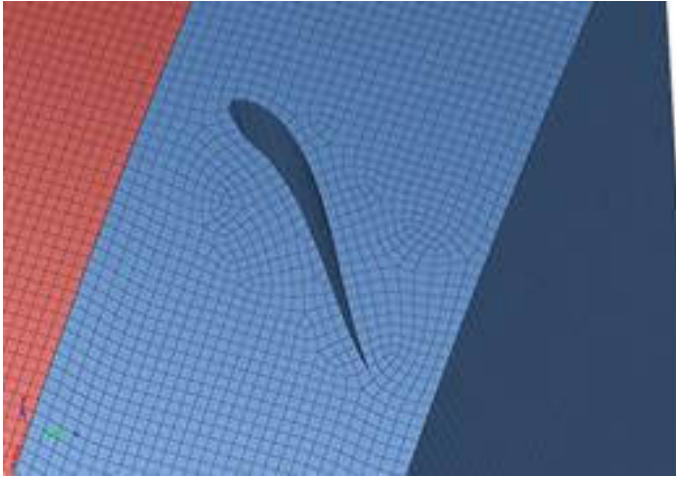
45-degree Angle of Attack



Fluid for Meshing/CFD Simulation



CFD Setup: Meshing



Material Selection

Solid: Carbon Fiber/Graphite Composite

Fluid: Air (@ STP and 37000ft).

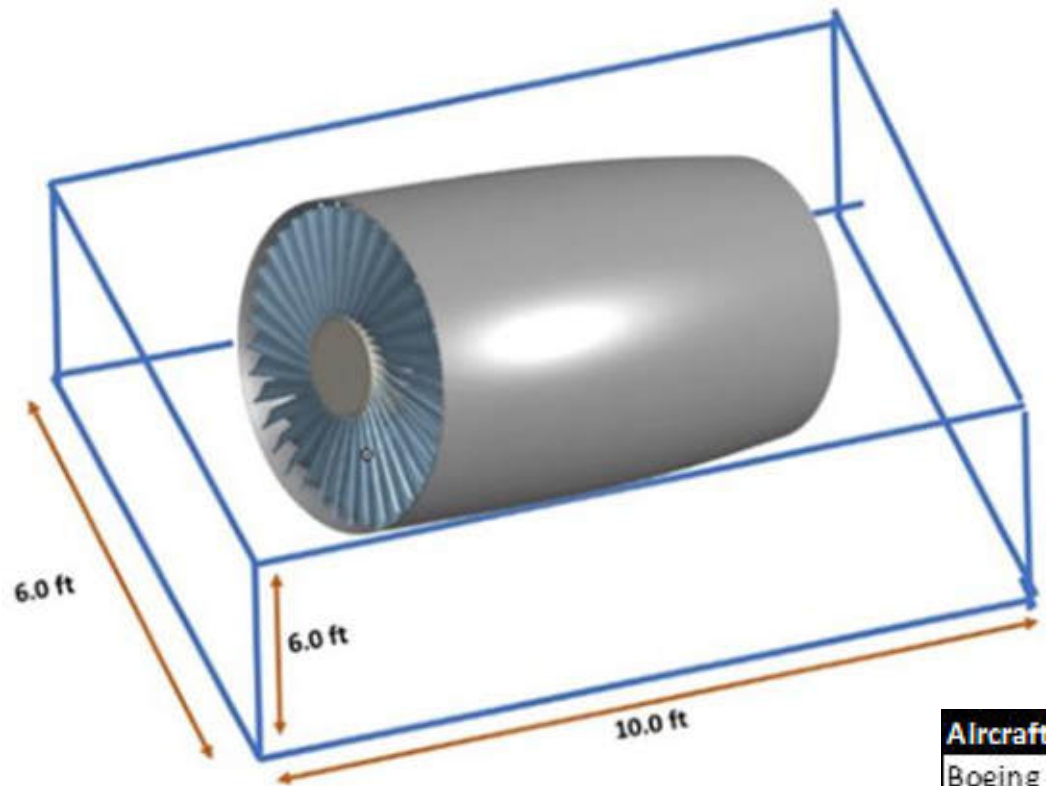
- Material properties changed in CFD program

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	<u>3806</u>

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

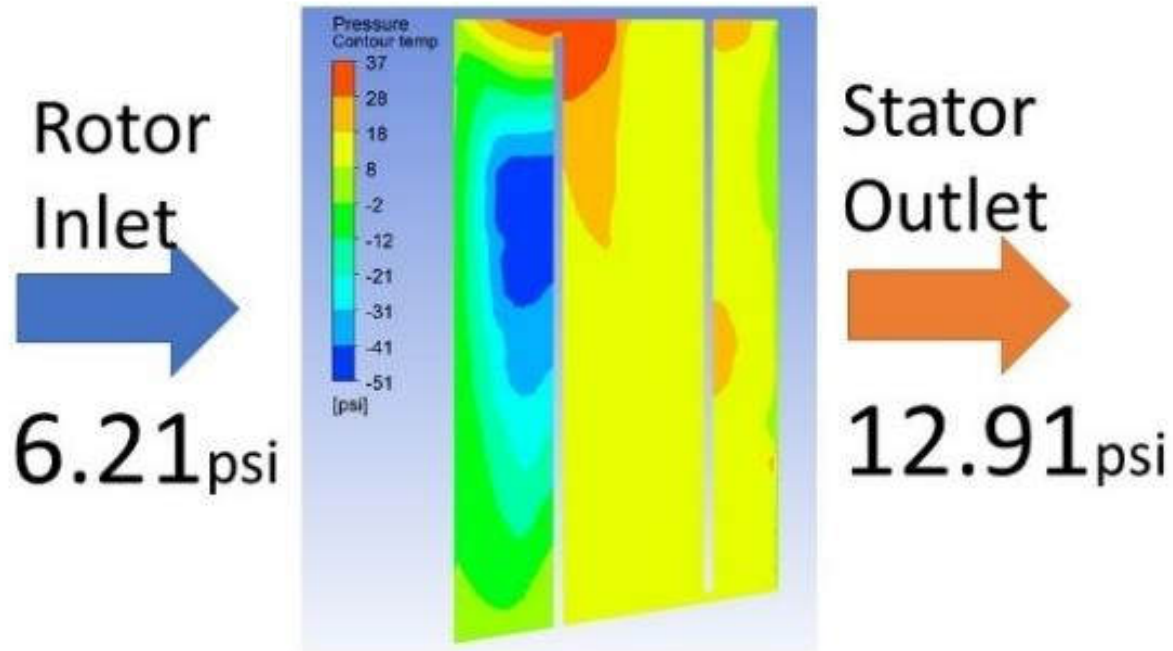
High altitude (37000 ft)

- “Cruising speed condition”
 - Constant rotational speed of 20000 rpm

At most, 200 timesteps at
5 ms/timestep

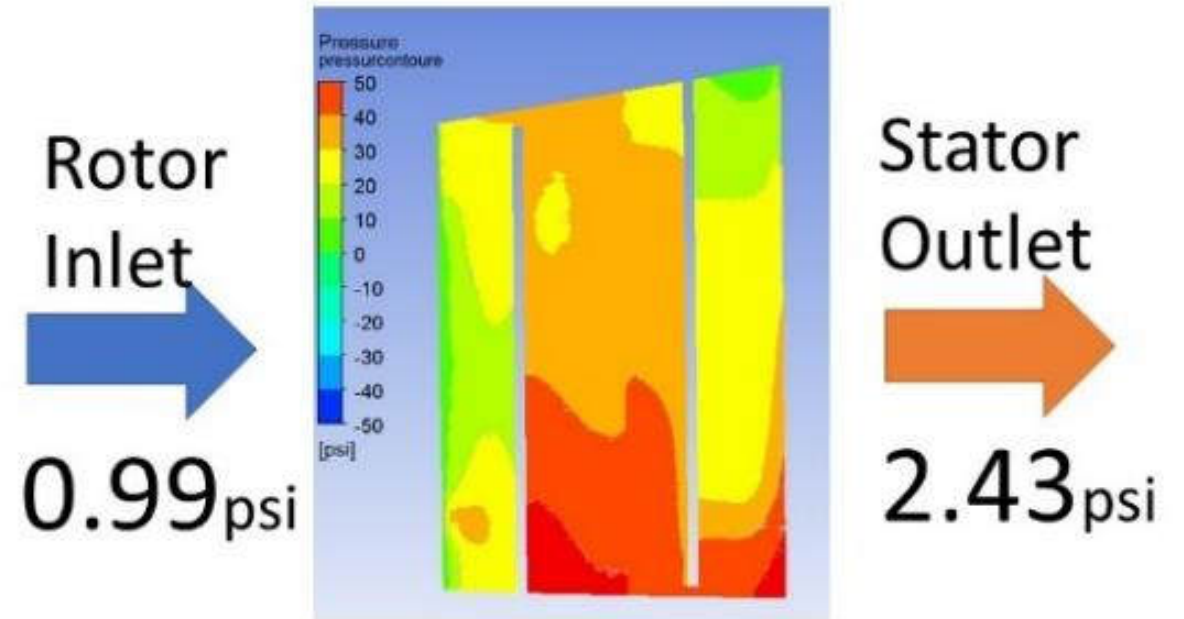
Results (Stage 1 , Stage 2)

Compression Ratio : Stage 1 @ 37kft, 20krpm



Compression: 2.08

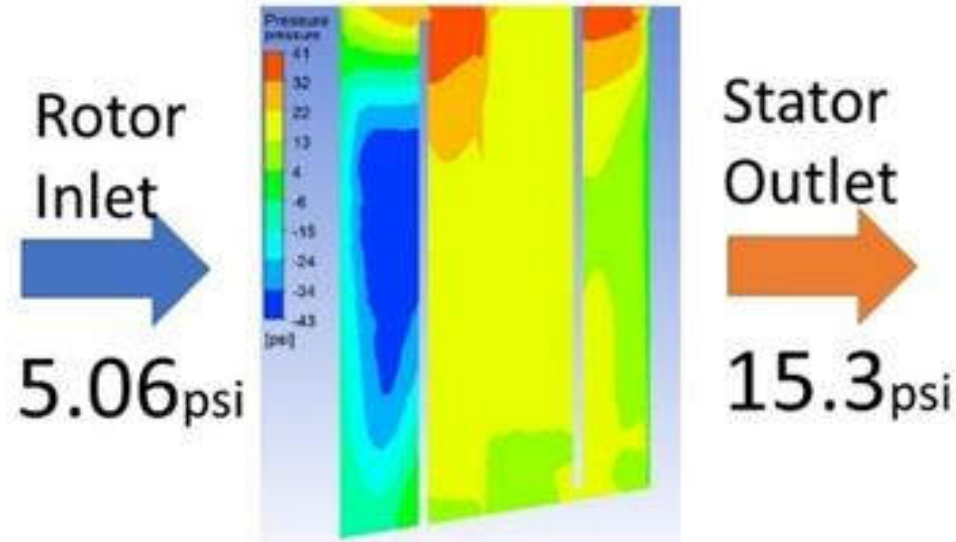
Compression Ratio : Stage 2 @ 37kft, 20krpm



Compression: 2.43

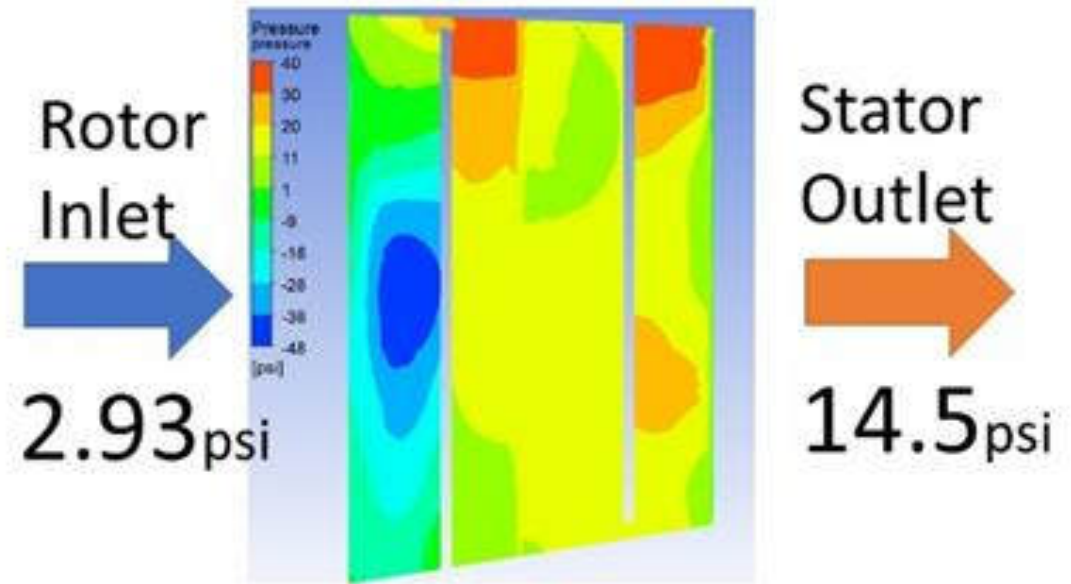
Results (Stage 3, Stage 4)

Compression Ratio : Stage 3 @ 37kft, 20krpm



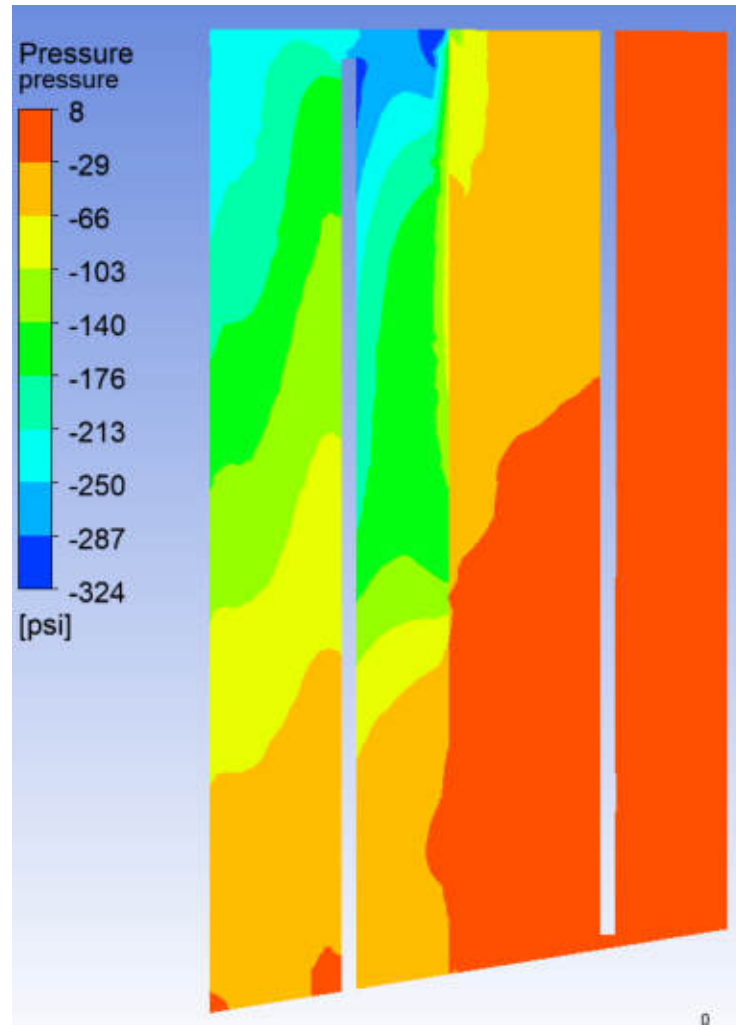
Compression: 3.04

Compression Ratio : Stage 4 @ 37kft, 20krpm



Compression: 4.95

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

$$T_1 = 80^\circ F, P_1:P_2 = 1:20$$

And

$$P_1 = 1 \text{ atm}, P_2 = 20 \text{ atm}$$

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

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

$$T_2 = 679.17 \text{ F}$$

At 37,000 ft:

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

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

Lapse rate: $-3.57^\circ F$ per 1,000 ft

$$T_{37,000 \text{ ft}} = 80^\circ F + \frac{-3.57 \cdot 37000}{1000} = -70^\circ F$$

$$\Gamma = \frac{c_p}{c_v} = 1.4$$

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

Approximate Power Approximation

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

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

$$W_{actual} = 2 \frac{lb}{s} * 0.24 \frac{BTU}{lbm * R} (1075 - 901) = 84 \text{ kg} \frac{m^2}{s^2}$$

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

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

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

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

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

$$\eta = 0.82$$

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, results will converge even with same settings



Design Time Estimate

>360 hours



Questions?