FOIL GAS BEARING SUPPORTED HIGH SPEED BLOWERS

11th Annual SECA Workshop
Pittsburgh, PA

Sponsor: Department of Energy

Presented by: Dr. Giri Agrawal (Principal Investigator)
R&D Dynamics Corporation

Date: July 29, 2010

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Outline

1. R&D Dynamics Overview Update

2. Foil Gas Bearing Supported Cathode/Anode Recycle Blowers for Large Megawatt Size SOFC Power Plants

3. Low Cost Cathode Blower

1. R&D DYNAMICS OVERVIEW UPDATE

R&D Dynamics Corporation

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OUR BUSINESS

Design, Develop and Production Manufacture Oil-Free, Efficient, and Affordable High-Speed Turbomachinery

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New Facility Inauguration

Left: Attorney General Richard Blumenthal, **Middle:** President of R&D Dynamics Dr.Giri Agrawal, **Right:** Congressman John B.Larson

Ribbon Cutting Ceremony of R&D Dynamics New 75,000 Sq.ft Facility in Bloomfield, Connecticut

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New Facility Features

- 15,000 Sq.ft of Modern Manufacturing Shop Floor
- 15,000 Sq.ft of State-of-Art Assembly & Testing Lab
- 15,000 Sq.ft of Production Floor for Blowers

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Fuel Cell Blowers Update

- R&D Dynamics is entering into supply agreements for 1,000 units of blowers per year.
- The new 75,000 Sq.ft facility will allow the set up of production line.
- Recent testing of Low Cost Blower developed using DFMA techniques has proved viability of cost effective blower solution for fuel cell applications.

High Temperature Anode Recycle Blower

- Temperature Capability (~ 850^{0}C)
- Hermetically sealed
- High Reliability
- Maintenance Free

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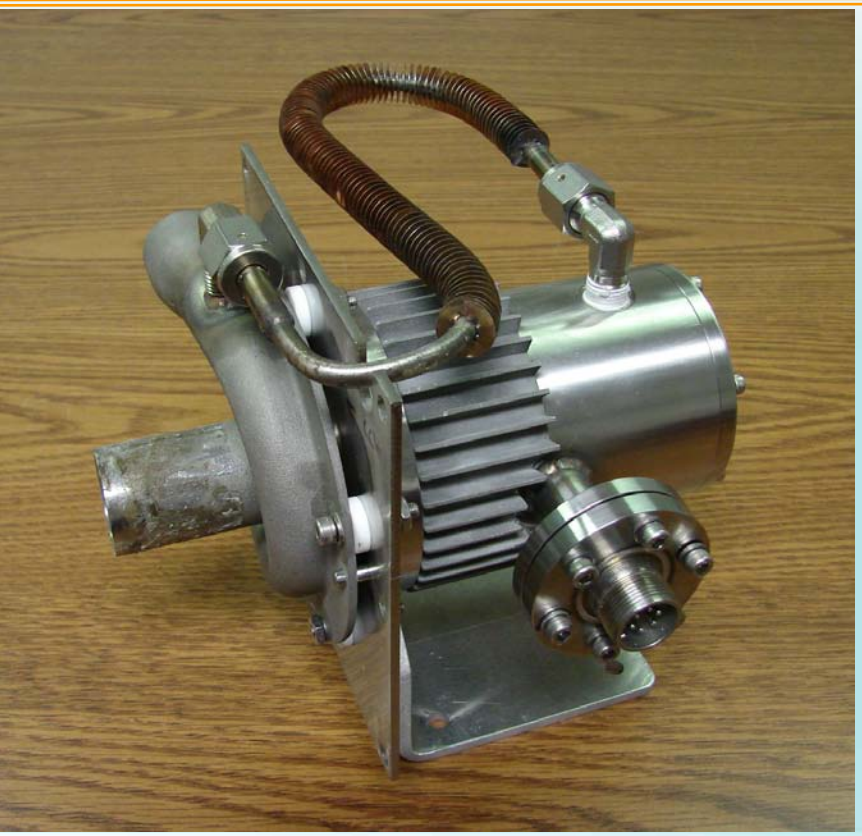
Warm Fuel Recycle Blower



- Temperature Capability (~ 250 ^{0}C)
- Hermetically sealed
- High Reliability
- Maintenance Free

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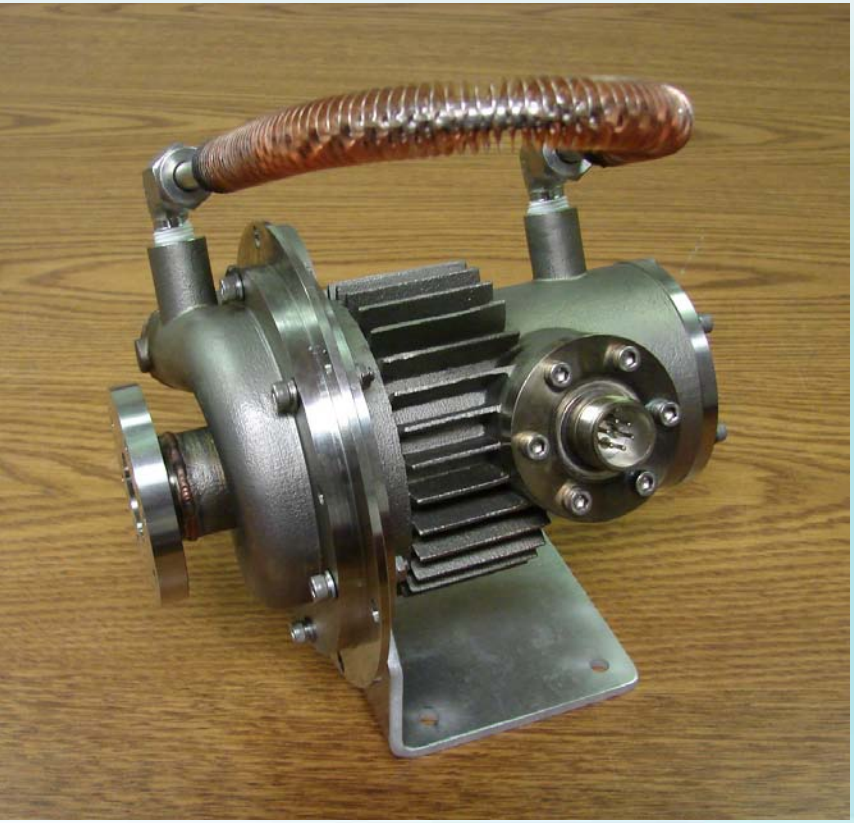
Fuel Blower for Stationary Fuel Cell Systems



- Temperature Capability (~ 160 ^{0}C)
- Hermetically sealed
- High Reliability
- Maintenance Free

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Cathode Air Blower for 5kW SOFC System

- Max Inlet Temperature (~ 60 ^{0}C)
- Integrated Motor Drive
- Compact
- Highly Efficient
- Quiet (< 80 dBa)

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Reformer Air Blower for Automotive Application

- Max Inlet Temperature (~ 40 ^{0}C)
- Compact
- Highly Efficient
- Quiet (< 80 dBa)

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Cathode Air Blower for Automotive Application

- Max Inlet Temperature (~ 45 ^{0}C)
- Compact
- Highly Efficient
- Quiet (< 80 dBa)

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Cathode Air Blower for Automotive Application

- Max Inlet Temperature (~ 60 ^{0}C)
- Liquid Cooled
- Compact
- Highly Efficient
- Quiet (< 80 dBa)

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2. FOIL GAS BEARING SUPPORTED CATHODE/ANODE RECYCLE BLOWERS for LARGE MEGAWATT SIZE SOFC POWER PLANTS

Specification

➢Process Gas	7.43% H2, 5.46% CO, 41.55% CO2, 44.13% H2O, 1.43% N2 mole fraction
➢Molecular Weight	28.31
➢Specific Heat Ratio	1.22
➢Inlet Pressure	15.31 psia
➢Outlet Pressure	15.77 psia
➢Pressure Rise	12 inches of water
➢Inlet Temperature	825 C (1517 F)
➢Flow	185 lbm/min
➢Input Voltage	480 Vac

Accomplishments

- A suitable specification was chosen for design of the blower in discussion with SECA members.
- A hermetically sealed blower concept that can be used dually as a Cathode and Anode recycle blower was developed.
- The blower being developed has following features:
  - High Temperature Capable (≥ 850 C)
  - Highly Efficient (>60%)
  - Reliable (design life > 40,000 hours)
  - Contamination Free
  - Maintenance Free
  - Variable Speed with High Turn Down Ratio (> 2:1)
  - Affordable
  - Scalable

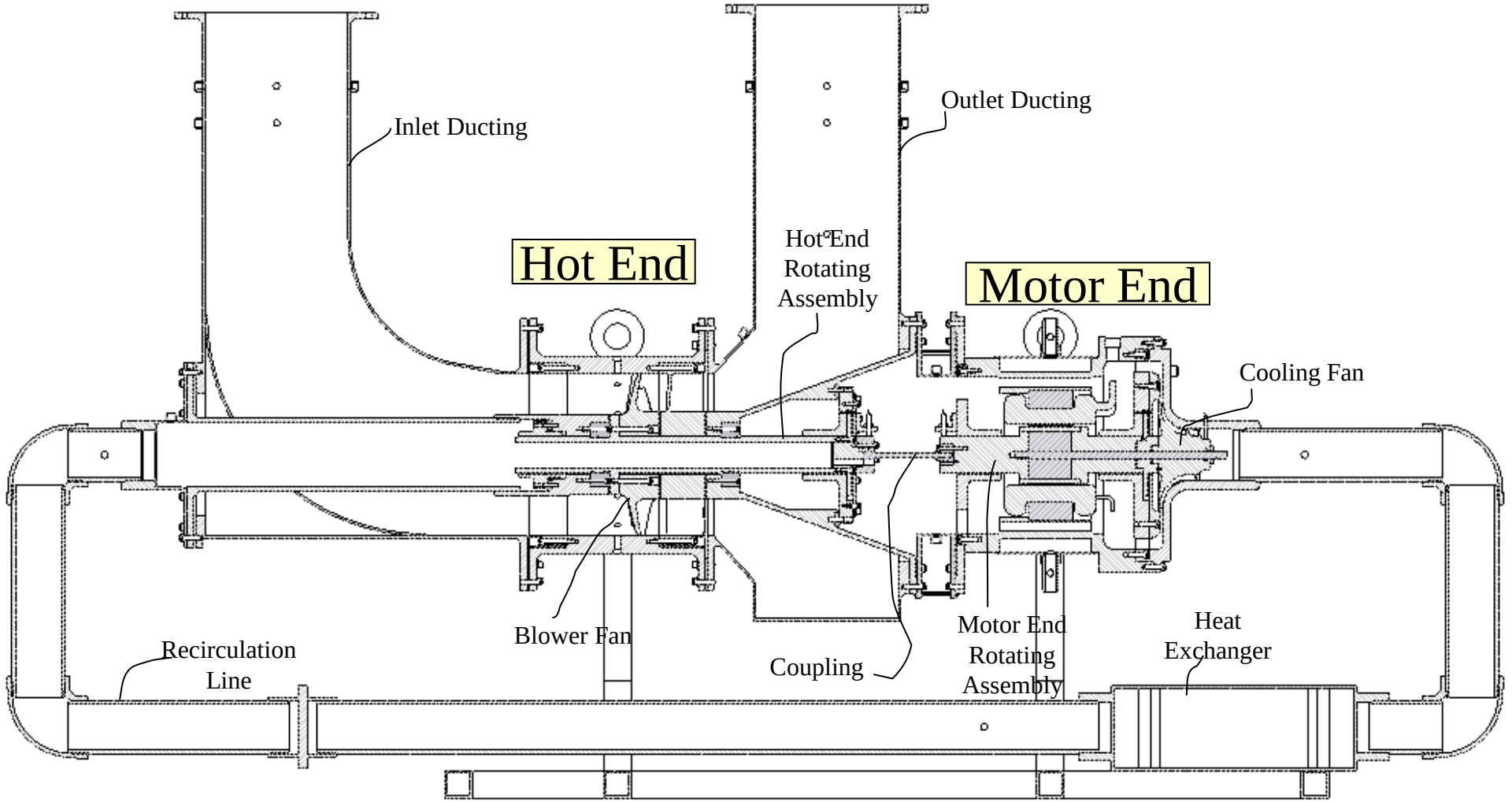
Accomplishments (Cont'd)

- Detailed heat transfer analysis of the blower completed.
- Detailed mechanical analysis and design of the blower completed.
- High temperature materials were selected from detailed analysis.
- Detailed drawings of the blower were prepared for manufacturing.
- Long lead items such as motor lamination and magnets were manufactured.
- Test plan and assembly methods are being developed for testing of the blower at end of this year.

Key Issues

- High Temperature Capable (up to 850 C)
- Affordable
- Highly Efficient
- No Anode Gas Leakage
- No Metal Outgassing
- Low Lifecycle Cost
- No Oil or Grease Contamination of Process Gas
- Scalable to other Sizes
- Maintenance Free
- Low Noise

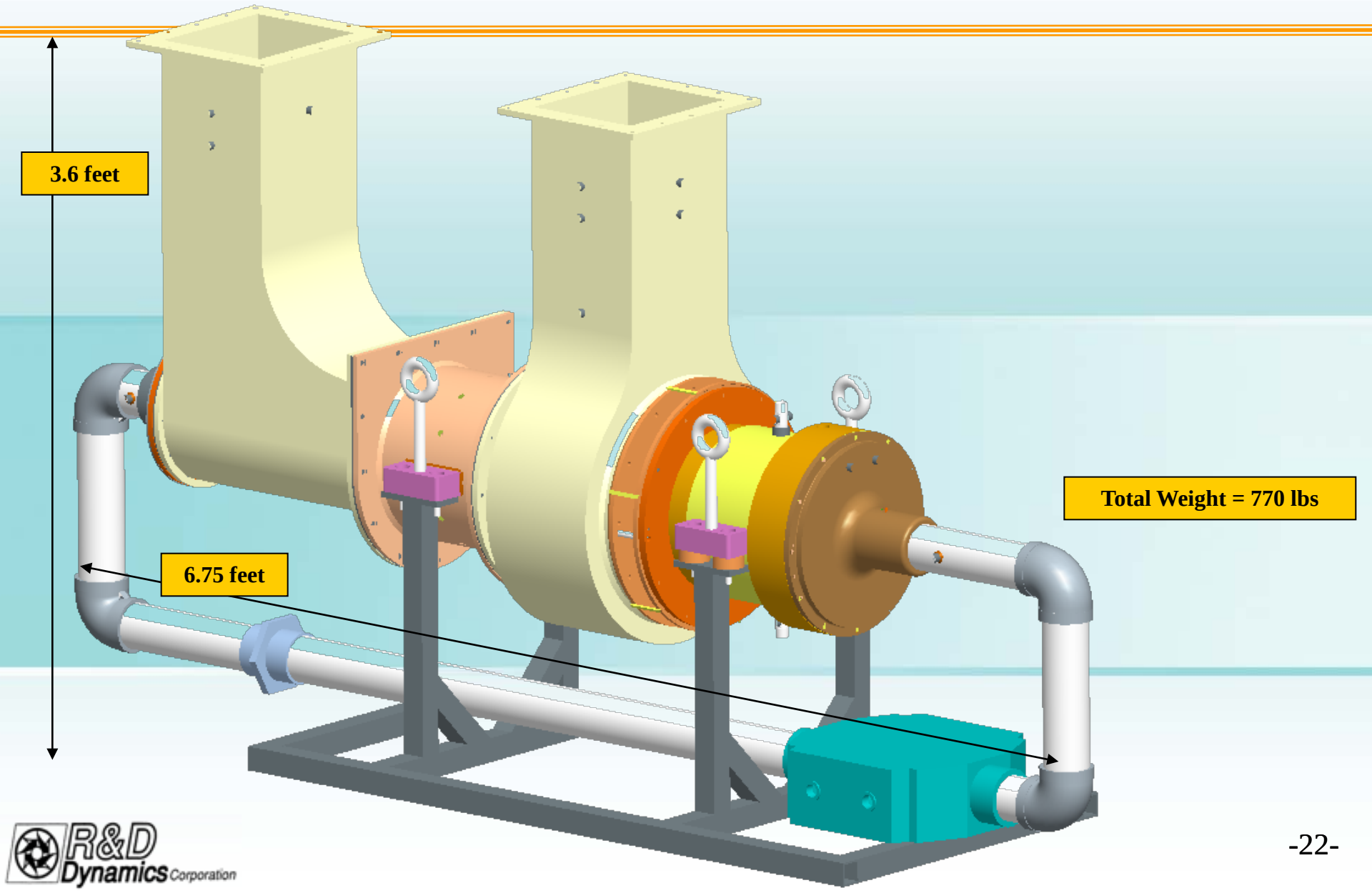
Blower Concept



Technical Summary

Rotor Type	Axial
Speed	26,520 rpm
Tip Diameter	8.8 inches
Pressure Ratio	1.03
Isentropic Power	13.57 kW
Impeller Efficiency	80%
Bearing Type	Foil Gas Bearings
Motor Type	PM Synchronous
Controller Type	Sensorless
Design Life	>40,000 hours
Maintenance	None
Overall Efficiency	>60%

3-d View of Blower



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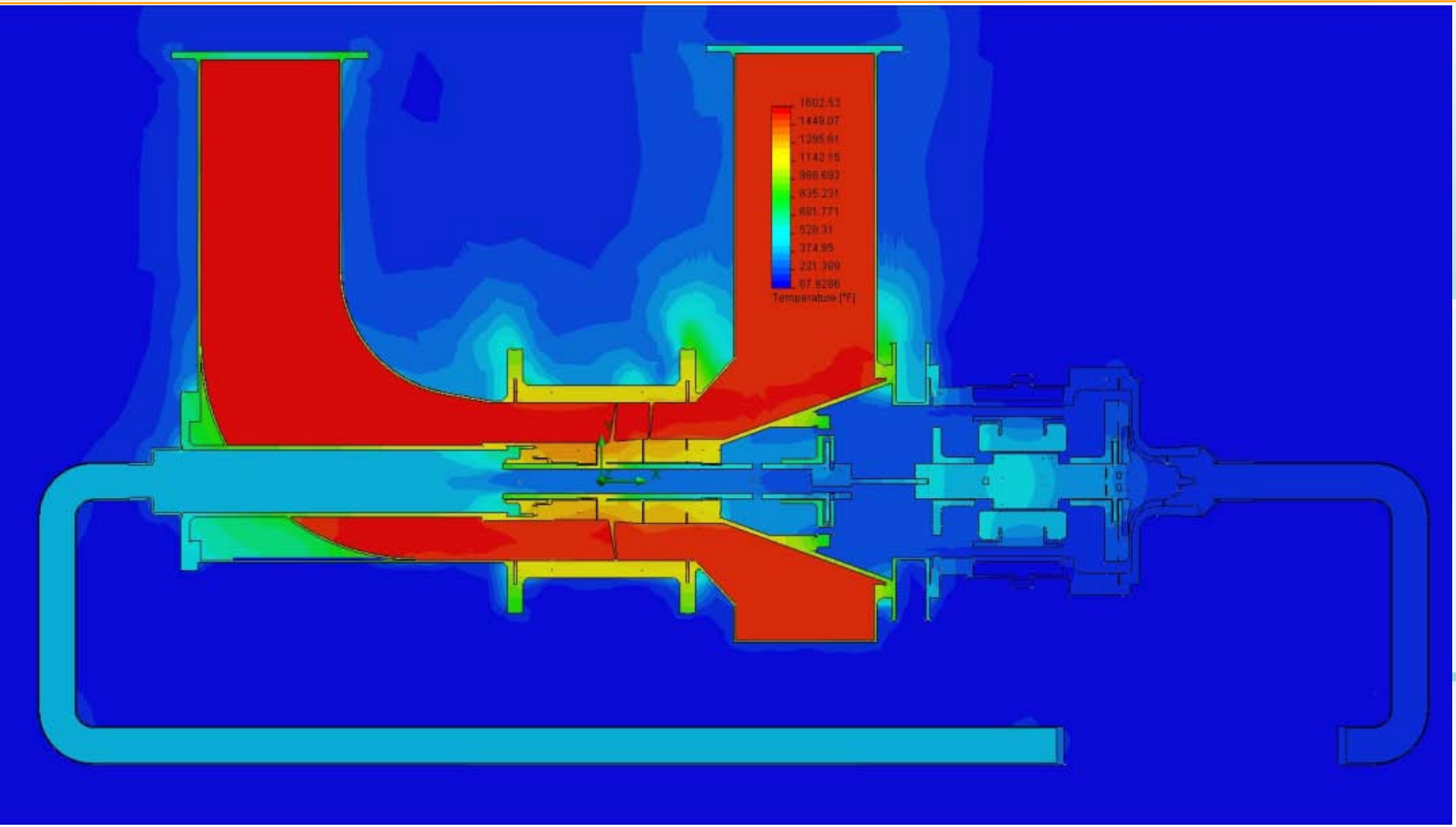
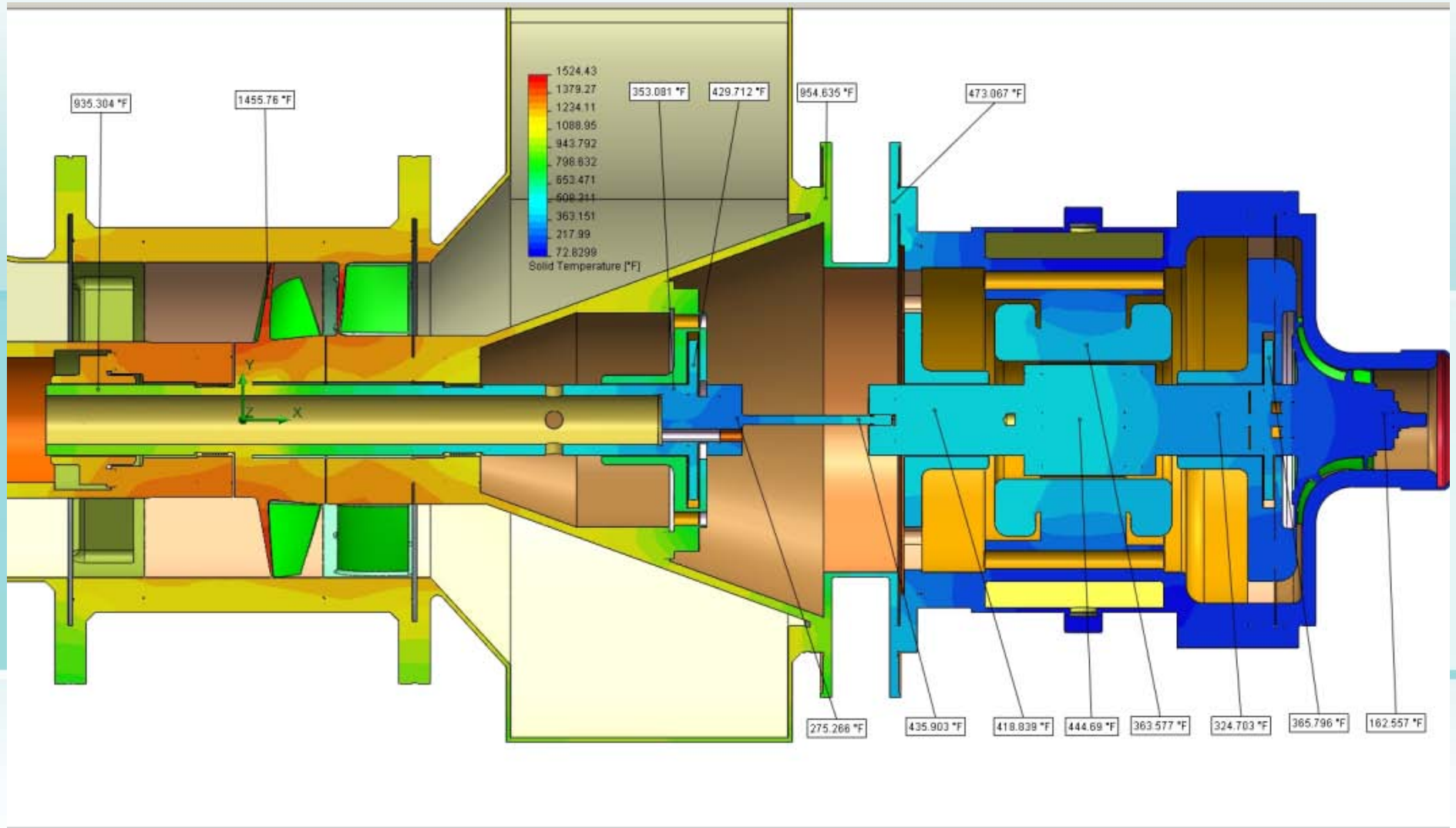
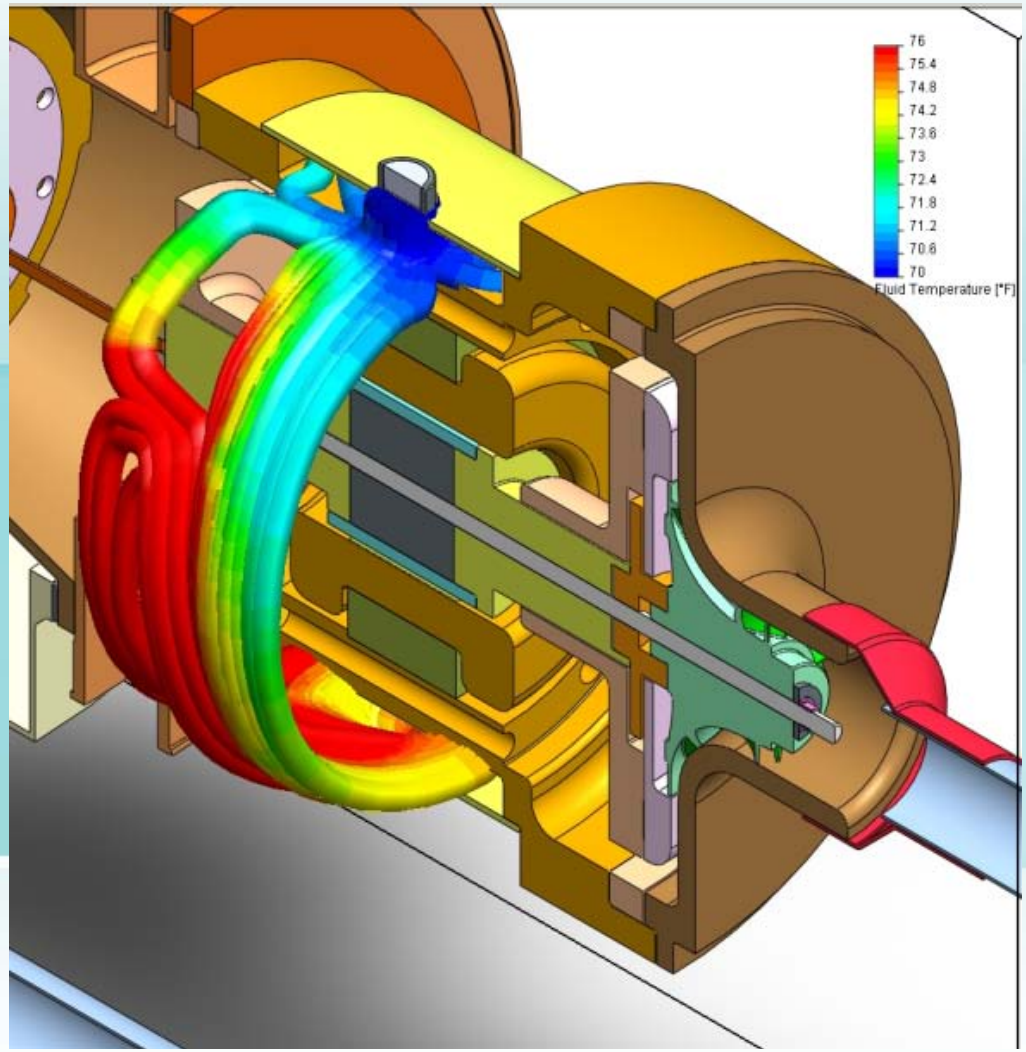
Heat Transfer Analysis



Key Component Temperatures



Motor Stator Cooling



- Min cooling flow 3 gpm to keep motor under 400 F.
- $\Delta T = 6$ @ 3 gpm.
- Motor cooling design safe.

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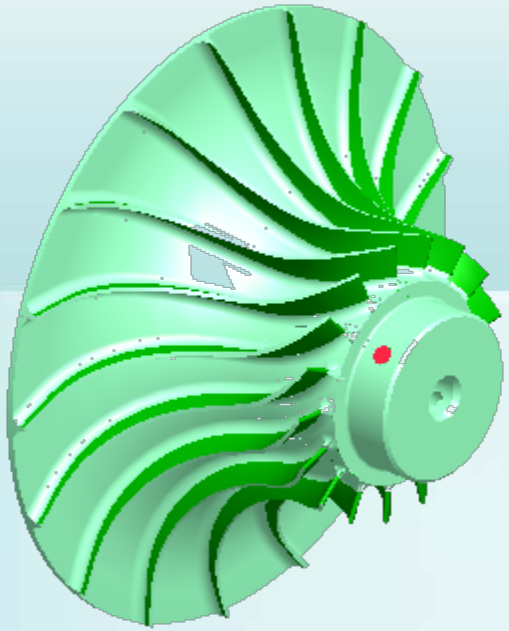
Cooling Fan Design

Rotor Type	Centrifugal
Specific Speed	80
Speed	26,520 rpm
Tip Diameter	5.98 inches
Inlet Pressure	16 psia
Outlet Pressure	20 psia
Pressure Ratio	1.25
Inlet Temperature	100 F
Outlet Temperature	135.3 F
Flow	12 lbm/min
Isentropic Power	1.8 kW



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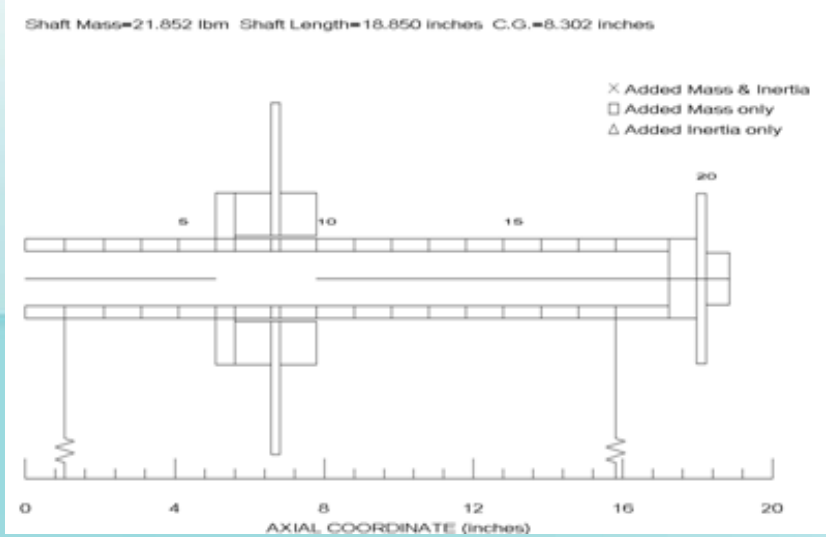
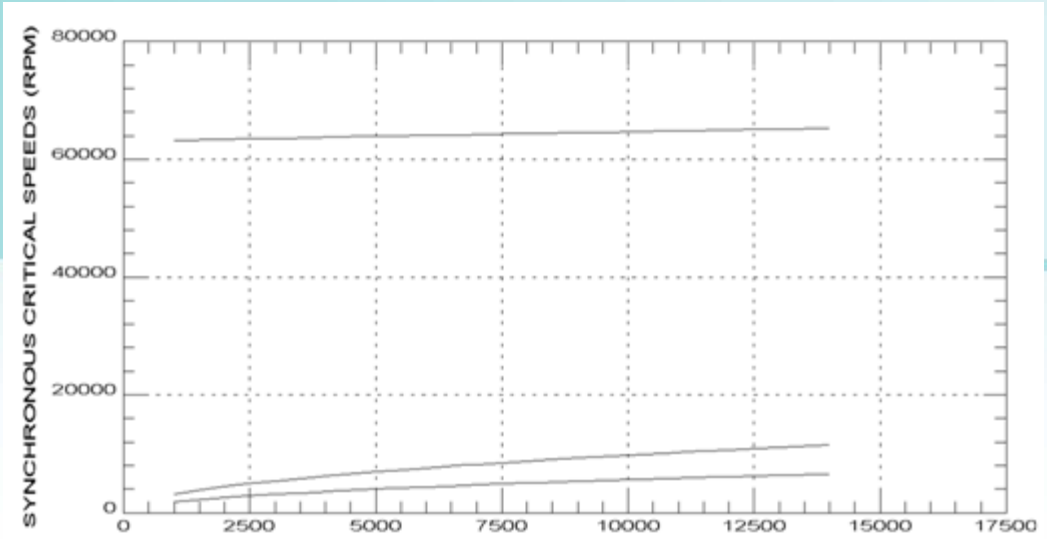
Hot End Rotating Assembly Critical Speed Analysis



E (Youngs modulus)	20,200,000
G (Shear modulus)	7,590,000
Poissons Ratio	0.33
1st Bending Mode	63,259
Design Speed	26,520 rpm
Margin	130 %



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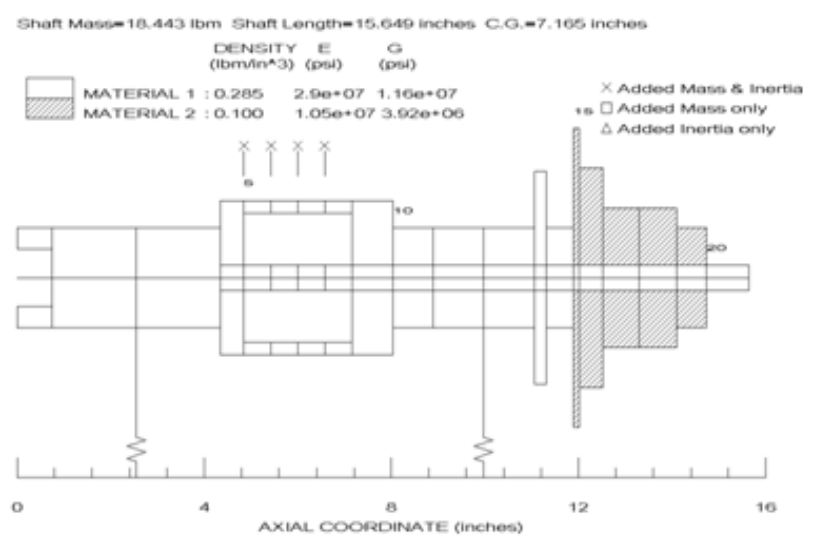
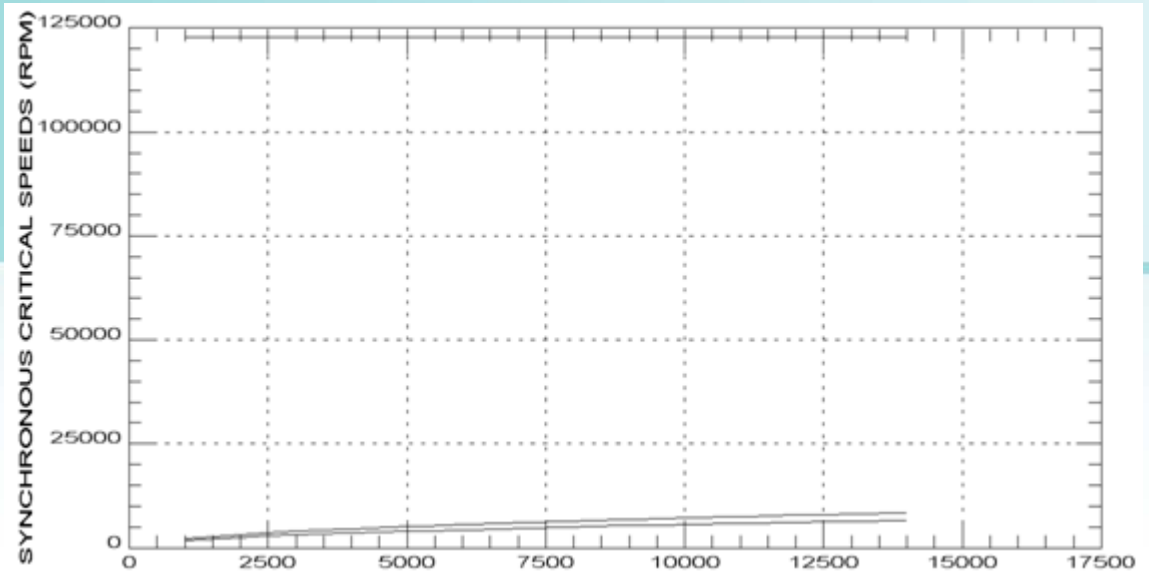
Motor End Rotating Assembly Critical Speed Analysis



1st Bending Mode	122,780 rpm
Design Speed	26,520 rpm
Margin	350 %



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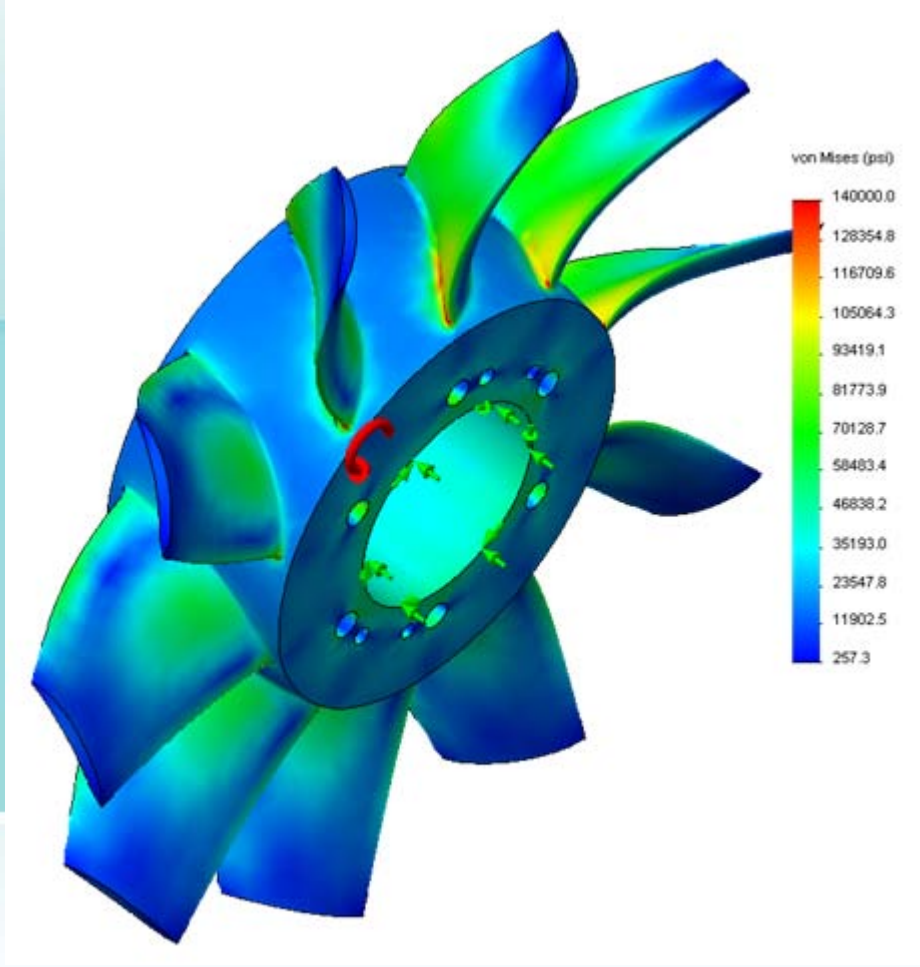
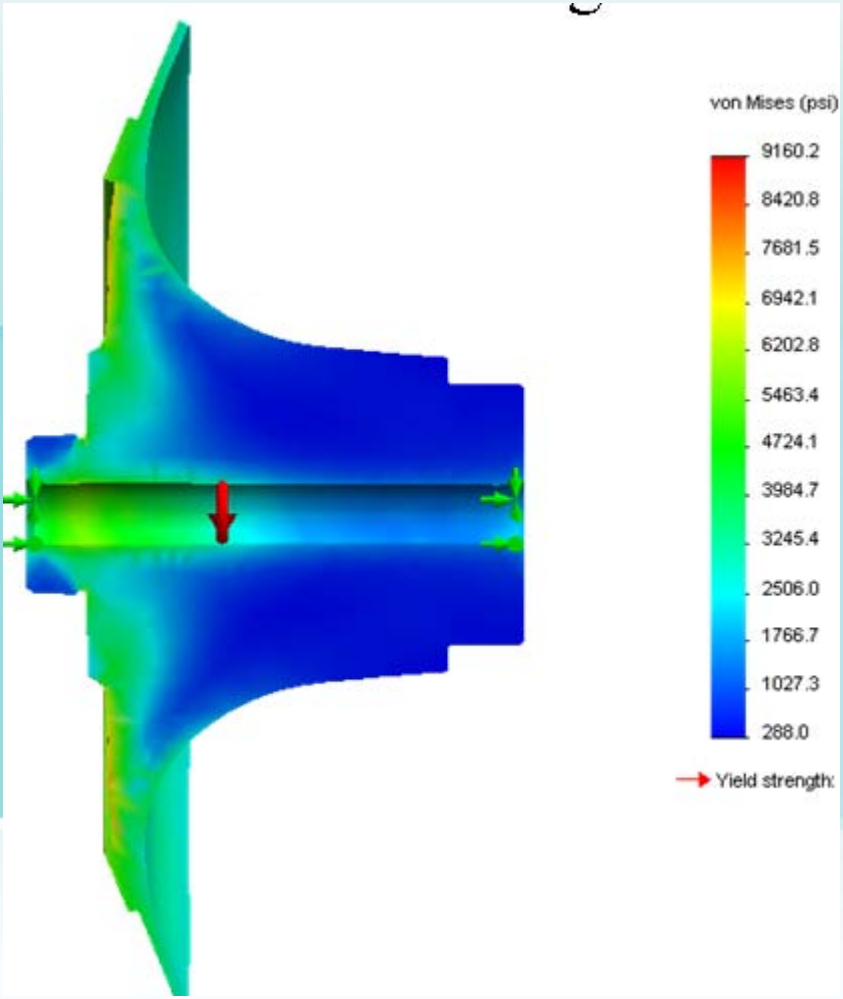
Fan Rotor Stress Analysis



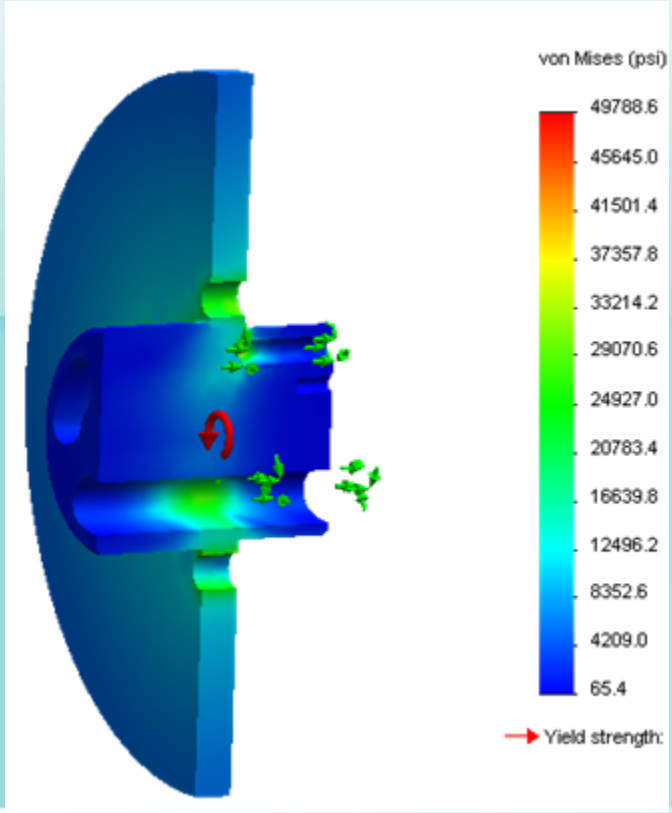
- Maximum stress below yield strength.
- Rotor structurally safe.
- Maximum thermal growth 0.088”.
- Maximum centrifugal growth 0.018”.
- Total radial growth 0.124”.

Cooling Fan Stress Analysis



- Max stress 9,206 psi @ 27,000 rpm
- Factor of safety 4.8
- Max disc radial growth 0.001”
- Max axial displacement 0.004”

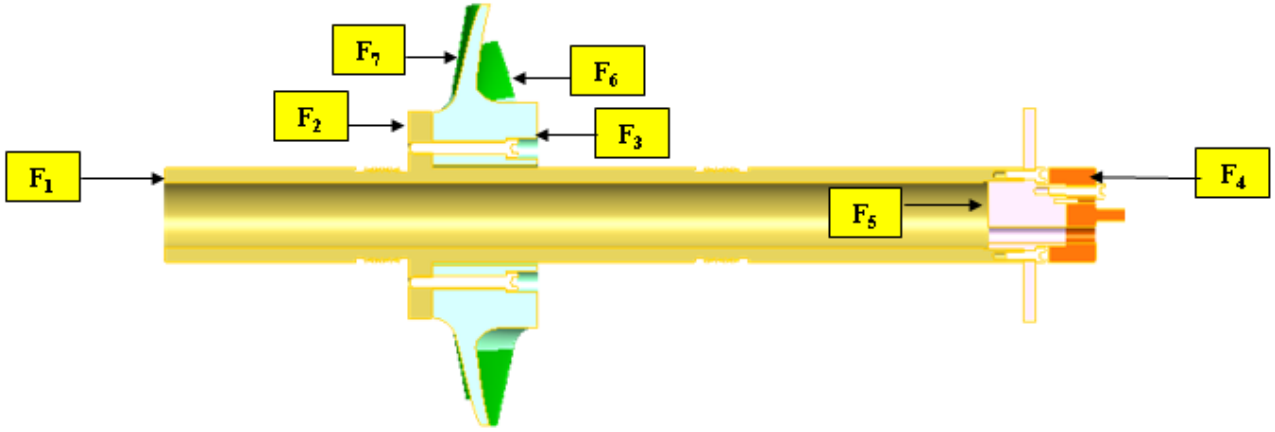
Thrust Disc Stress Analysis



- Max stress 49,788 psi @ 27,000 rpm
- Inconel 718 has 100,000 psi tensile strength @ 1400 F
- Factor of safety 2
- Max disc radial growth 0.0005”
- Max axial displacement 0.0001”

Hot End Thrust Load Model

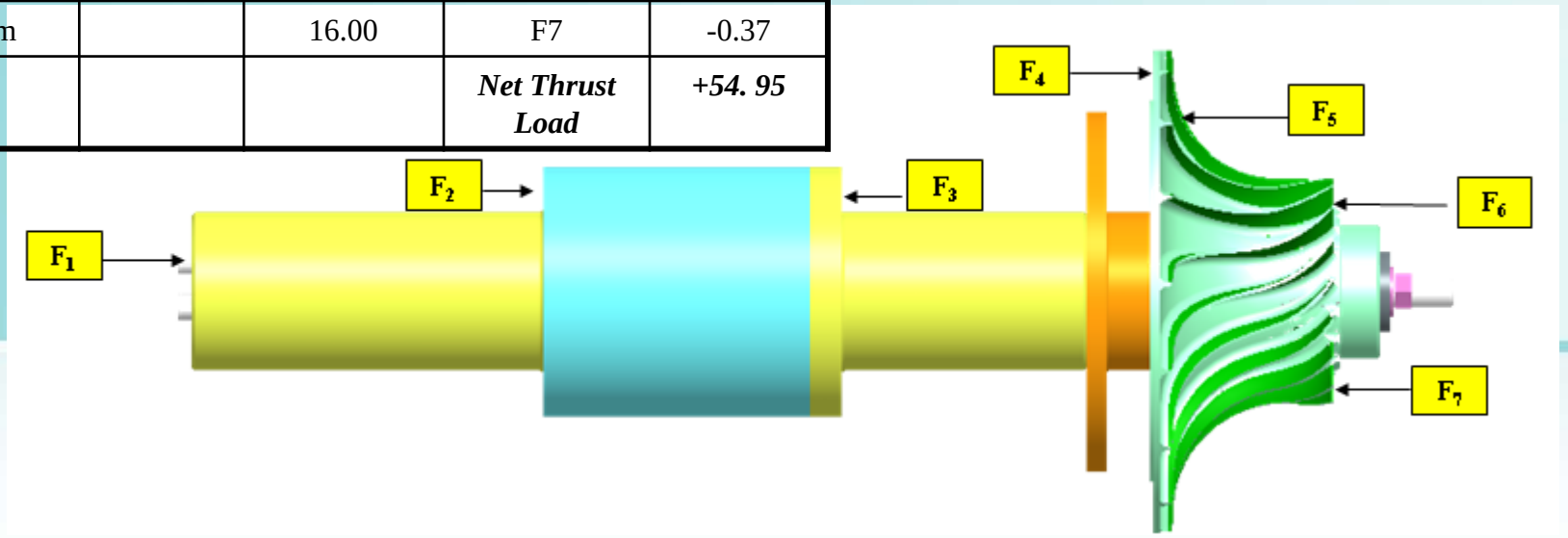
Location	Area (in^2)	Pressure (psia)	Force	Force (lbf)
Hot End	1.65	16.56	F1	+27.32
Fan Inlet	57.67	15.31	F2	+882.92
Fan Outlet	57.67	15.74	F3	-907.72
Coupling End	2.08	19.29	F4	-40.12
Shaft ID	0.89	17.33	F5	+15.42
Inlet Momentum	46.29	15.31	F6	+43.84
Outlet Momentum	43.47	15.74	F7	-45.69
			Net Thrust Load	***-24. 03***



- Net thrust load 2.4 psi, fan side thrust bearing design safe.

Motor End Thrust Load Model

Location	Area (in^2)	Pressure (psia)	Force	Force (lbf)
Left Shaft	2.49	19.29	F1	+48.03
Left Sleeve	4.15	19.27	F2	+79.97
Right Sleeve	4.15	19.53	F3	-81.04
Behind Fan	25.11	20.00	F4	+502.22
Fan Shroud	21.97	18.00	F5	-395.46
Eye Diameter	6.15	16.00	F6	-98.4
Momentum		16.00	F7	-0.37
			Net Thrust Load	***+54. 95***



➢Net thrust load 5.16 psi, motor side thrust bearing design safe.

Program Summary & Future Plans

- Program is on schedule and all tasks were accomplished as planned.
- Blower is being manufactured for testing.
- A prototype unit will be assembled in November-2010.
- A test plan will be developed and the prototype unit will be tested in December-2010.
- Field testing will be conducted in 2011.
- The blower will be cost reduced and commercialized for future large size SOFC systems.

3. LOW COST CATHODE BLOWER

Specification

Working Fluid	Air
Pressure Ratio	1.1 to 1.2
Volume Flow	1500 slpm
Turn-Down Ratio	5:1
Overall Efficiency	>60%
Design Life	>40,000 hrs
Maintenance Interval	10,000 hrs
Target Cost	$100 @ 50,000 units/yr
Noise Level	<70 dBa
Contaminants	None, Oil-free

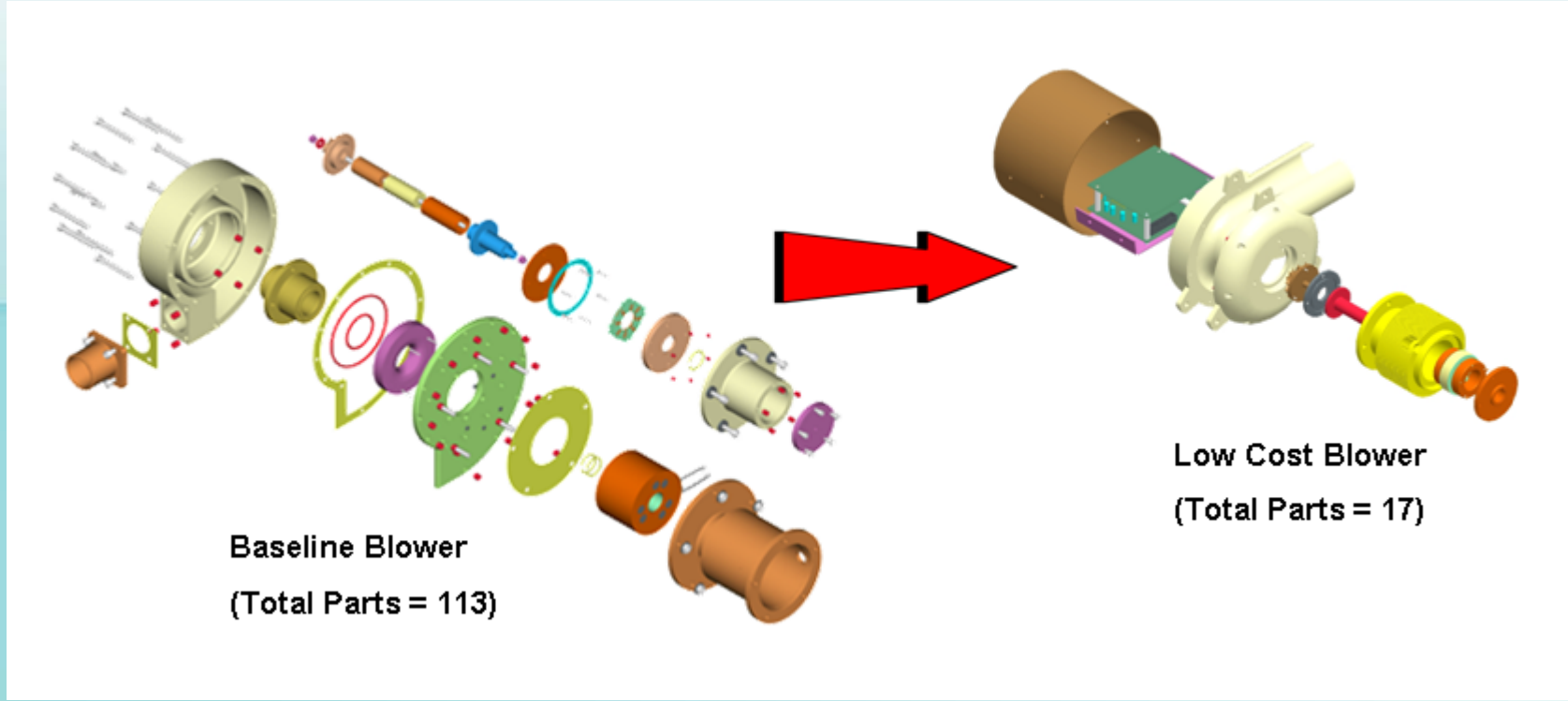
Accomplishments

- A Low Cost Cathode Blower (LCCB) with only 17 parts was developed.
- The blower developed has following features:
  - Low Cost
  - High Efficiency
  - High Reliability (design life > 40,000 hours)
  - Contamination Free
  - Maintenance Free
  - Compact and Lightweight
  - Variable Speed with High Turn Down Ratio (> 5:1)
  - Scalability to different Sizes
- Detailed design was done and drawings were prepared for manufacturing.
- Prototype units were manufactured by machining and investment casting.

Accomplishments (Cont'd)

- Prototype units were assembled for performance testing.
- A performance test rig was fabricated for testing.
- The blower units were tested and test data analyzed.
- Acoustic testing of the blower was completed.
- Preliminary quotes were received for pre-production quantities and vendor base were developed for volume production.
- SECA members were informed of advancements made in developing the low cost blower and support from SECA members was received for system testing the blower after completion of development.

Low Cost Blower Concept

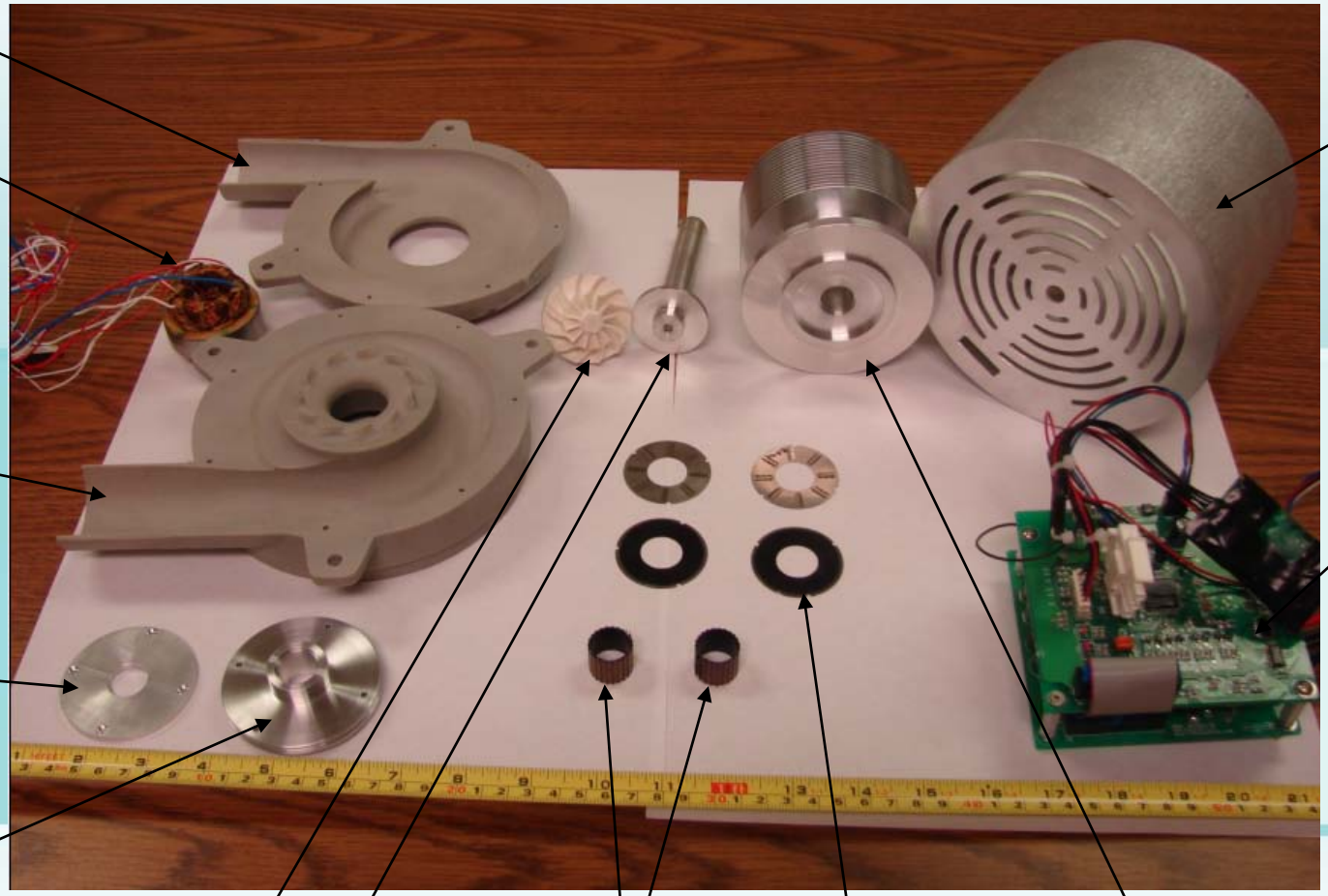


- Less number of parts hence low cost.
- Less weight, compact and cheaper material hence low cost.

Technical Summary

➢Blower Type	Centrifugal
➢Mechanical Speed	80,000 rpm
➢Weight	5.3 lbm
➢Bearings	Foil Gas Bearings
➢Motor Type	Permanent Magnet Motor
➢Controller Type	Sensorless Controller
➢Input Electric Power	769 watt
➢Overall Efficiency	61.6 %
➢Estimated Cost	$102.86 (@50,000 units/yr)
➢Life	>40,000 hrs
➢Turn Down Ratio	>5:1
➢Contaminants	None
➢Maintenance	None

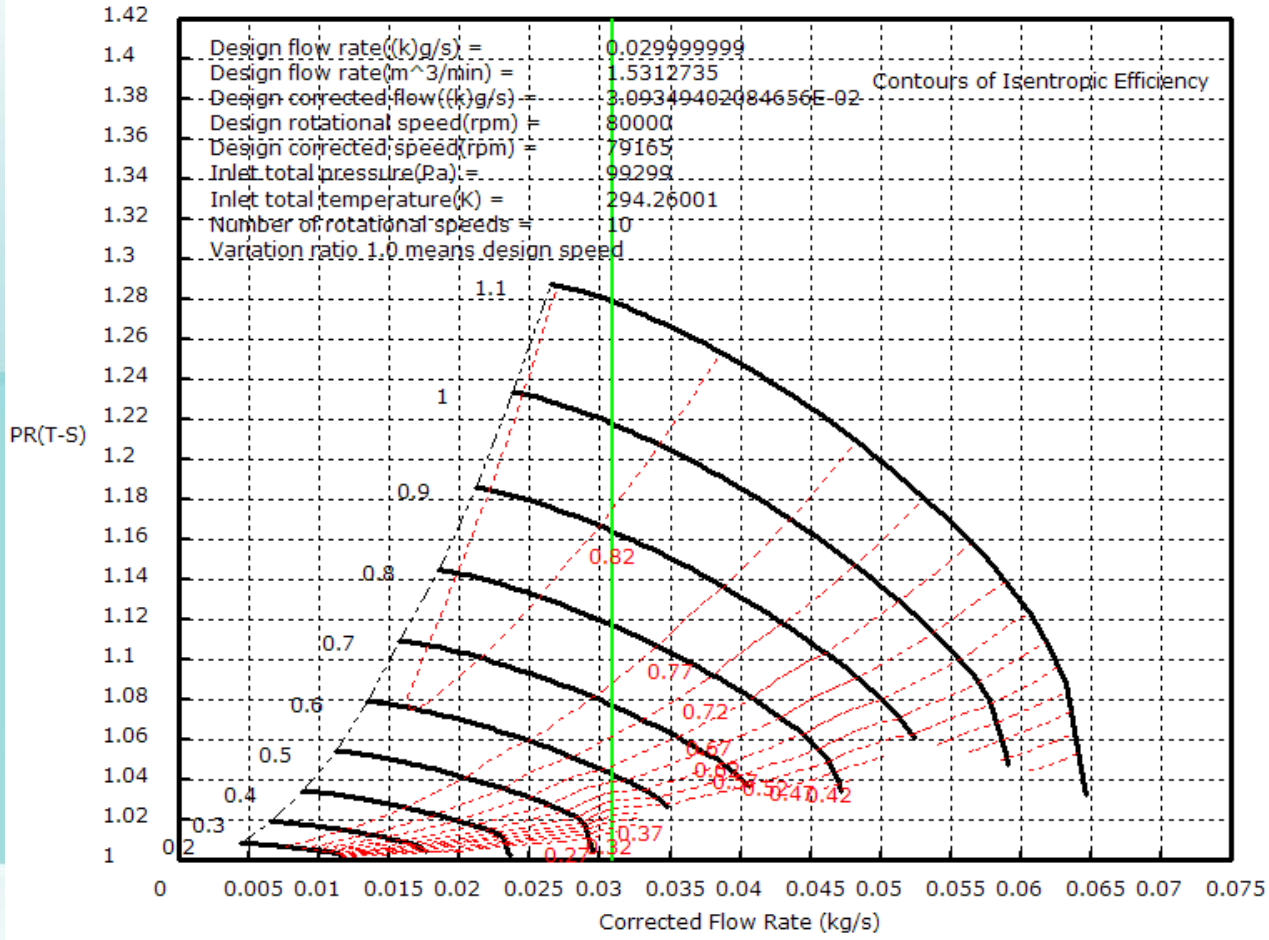
Blower Parts



Assembled Prototype Units

- 3 prototype units were assembled for testing.
- Motor driven is integrated part of blower assembly.

Aerodynamic Performance



- Blower aerodynamic design meets flow and pressure rise target.
- Low solidity diffuser vanes designed for higher efficiency.

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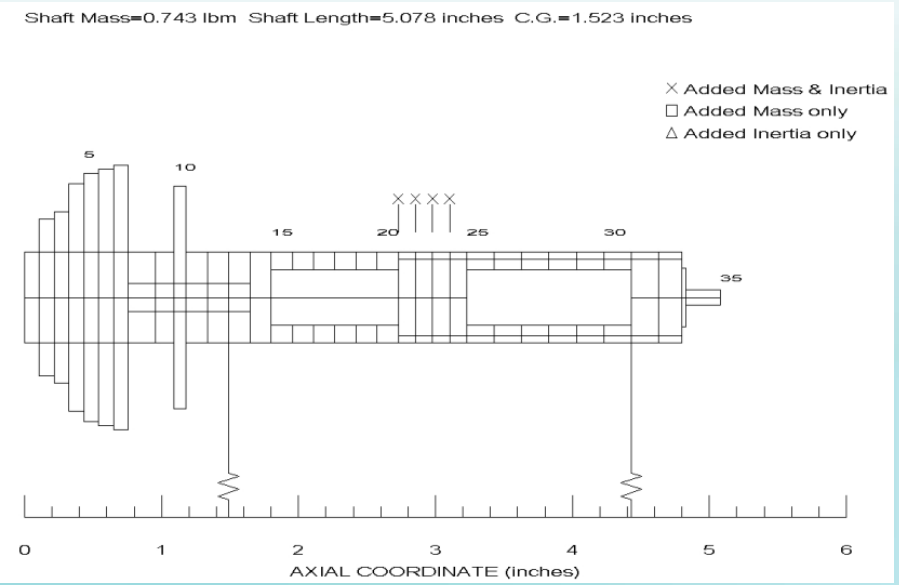
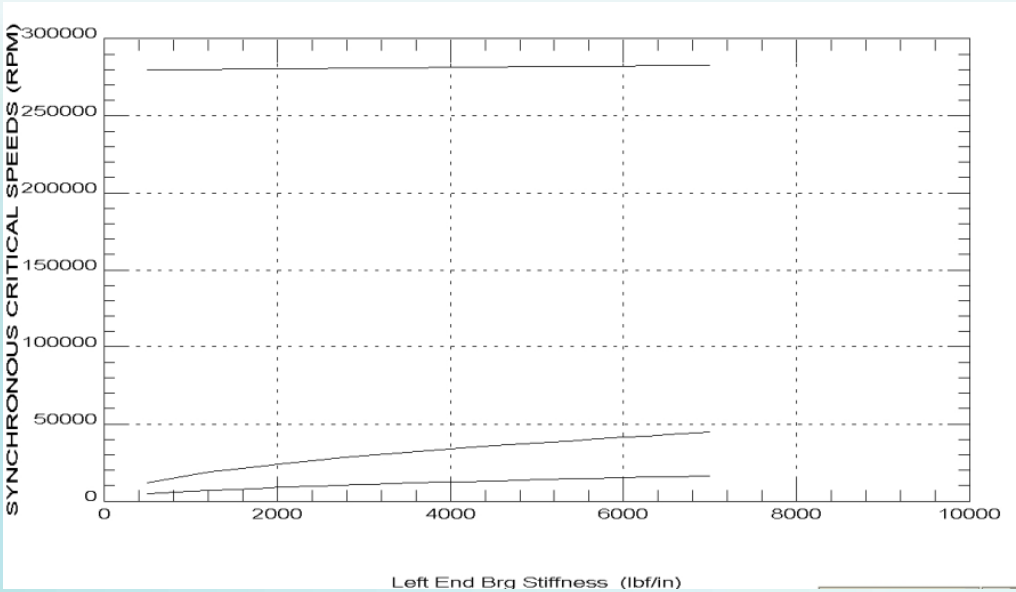
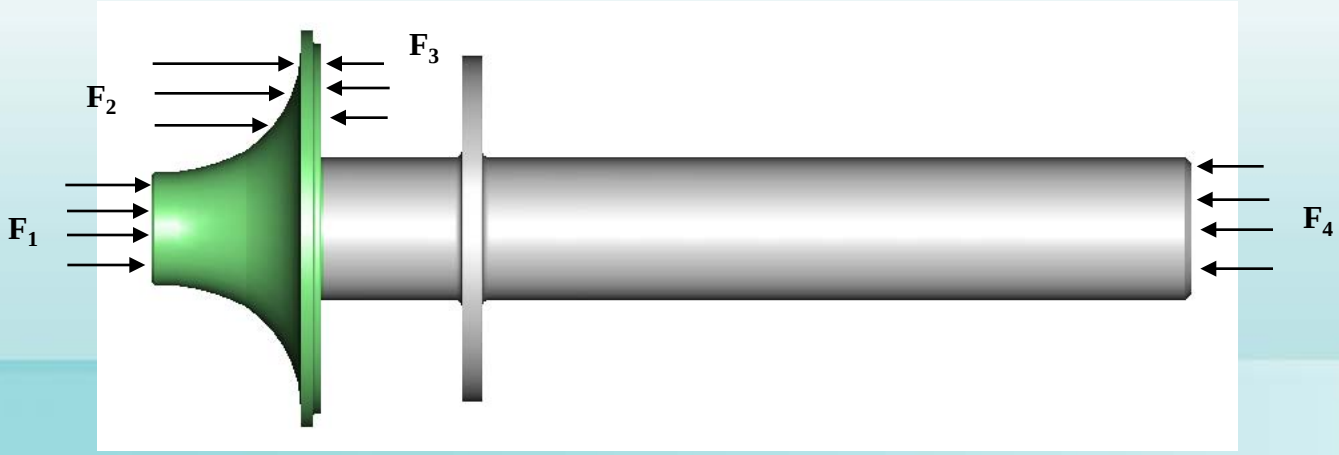
Critical Speed Analysis





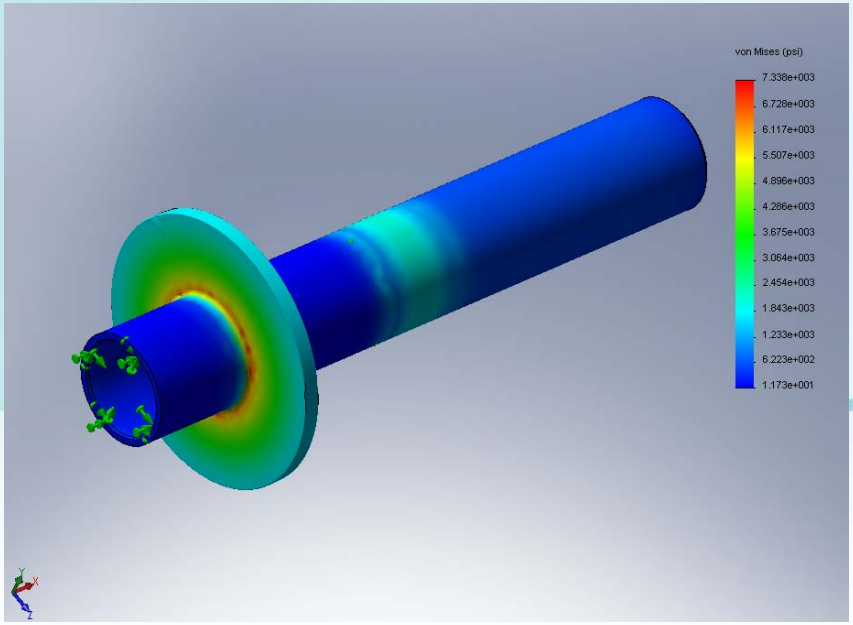
- 1st Bending mode @ 260,000 rpm (design speed 80,000 rpm).
- Design has more than 300% margin.
- Rotating assembly design is safe.

Thrust Load & Stress Analysis

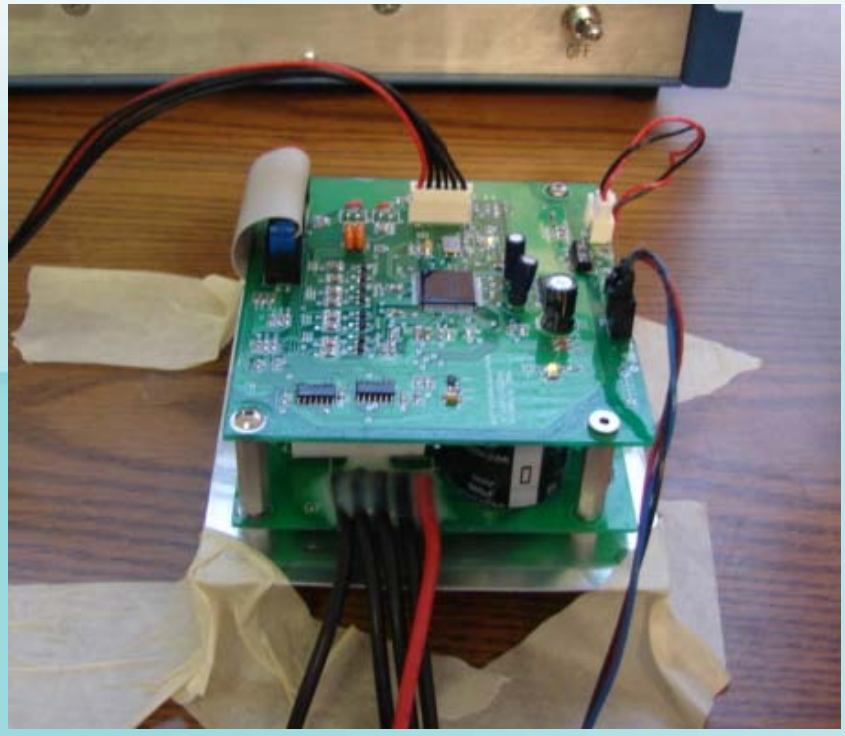


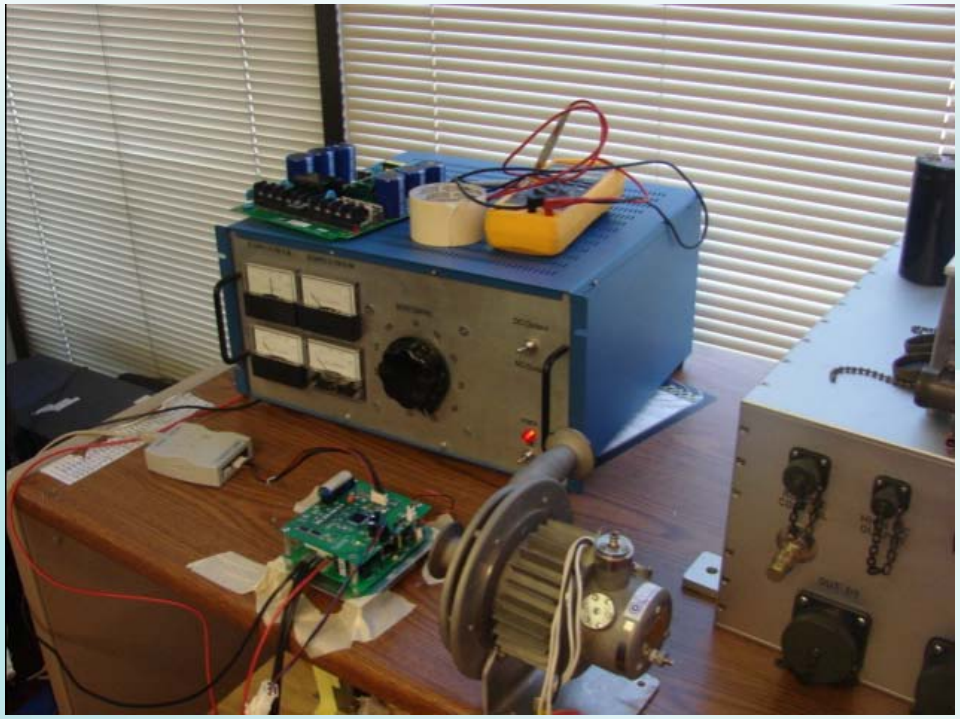
F_1	=13.67 lbf
F_2	=23.30 lbf
F_3	=-35.58 lbf
F_4	=-4.51 lbf
Net	=-2.81 lbf

- Net thrust load 1.9 psi, thrust bearing design safe
- Max stress 7400 psi, 6061 Aluminum has 40,000 psi yield strength.
- Rotating assembly design is safe.



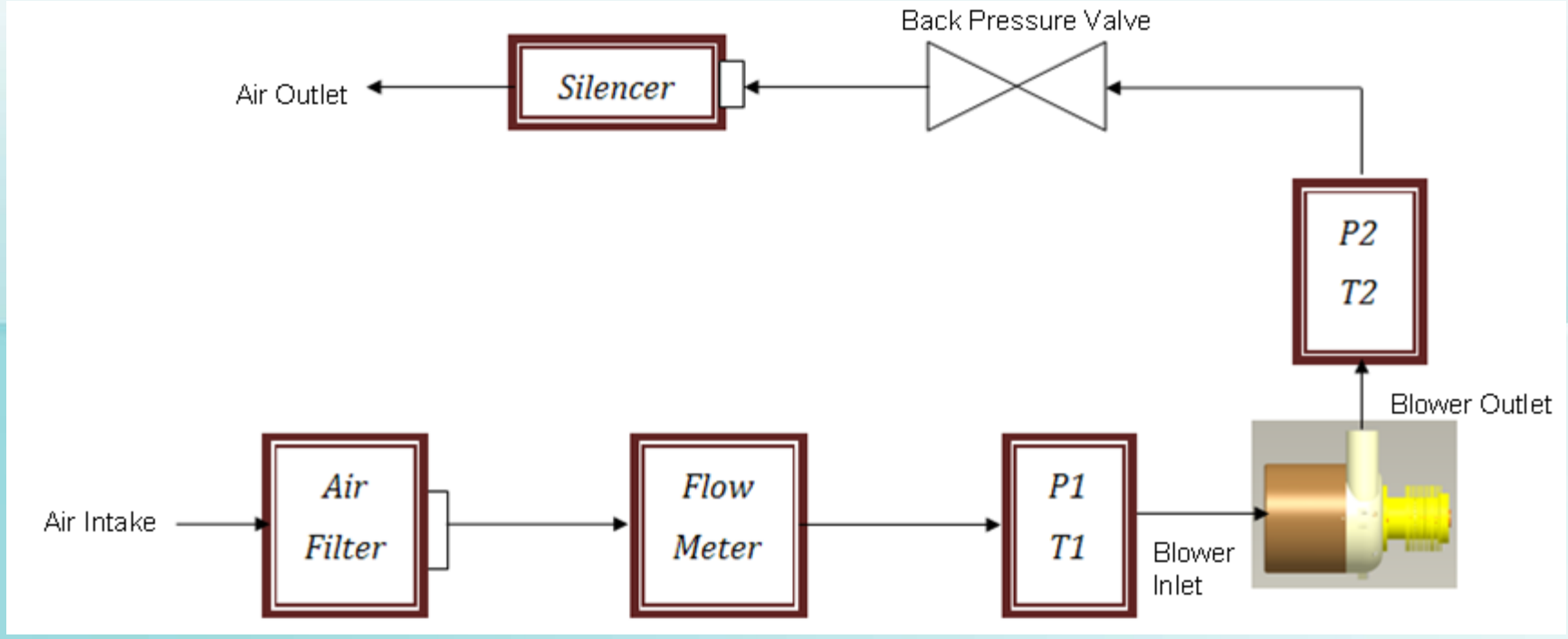
Low Cost Controller Development





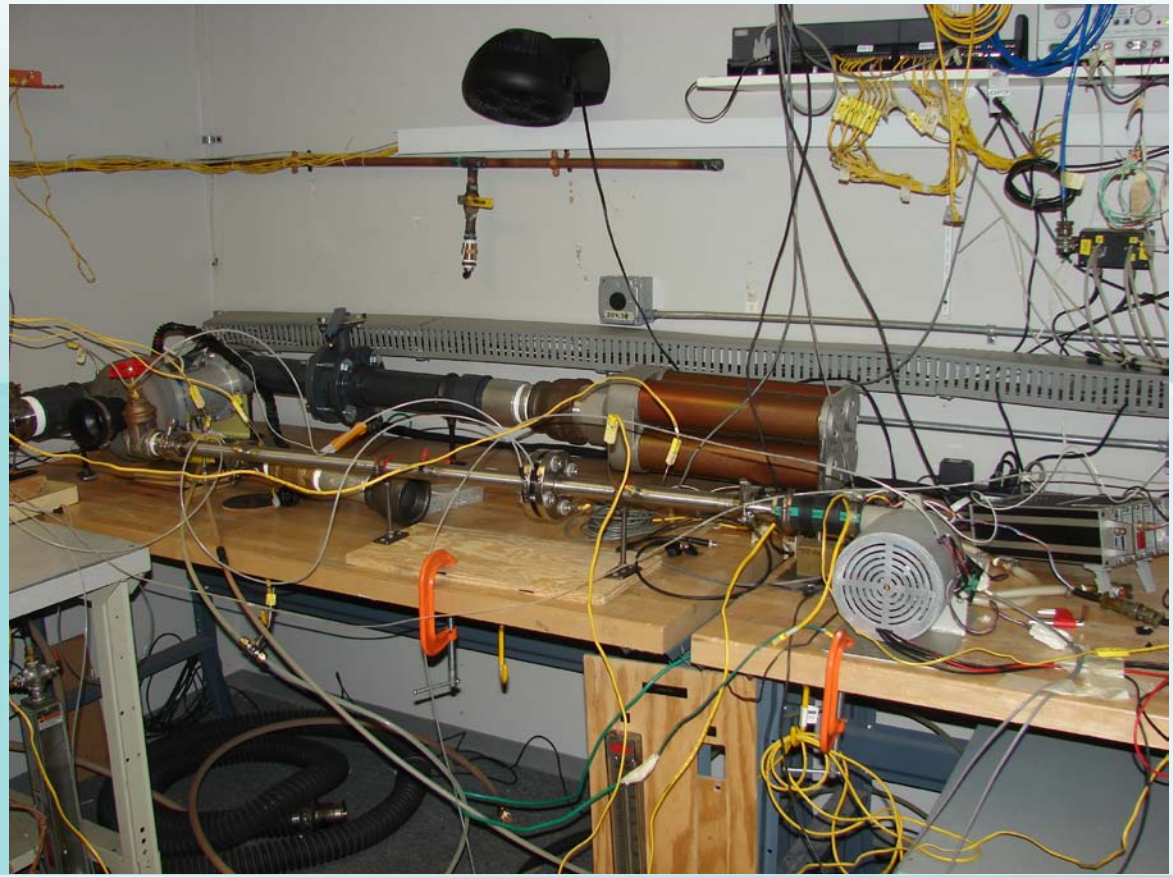
- A low cost controller was developed.
- Controller developed using appliance components to reduce cost.
- Controller tested successfully above 100,000 rpm.

Test Rig Design



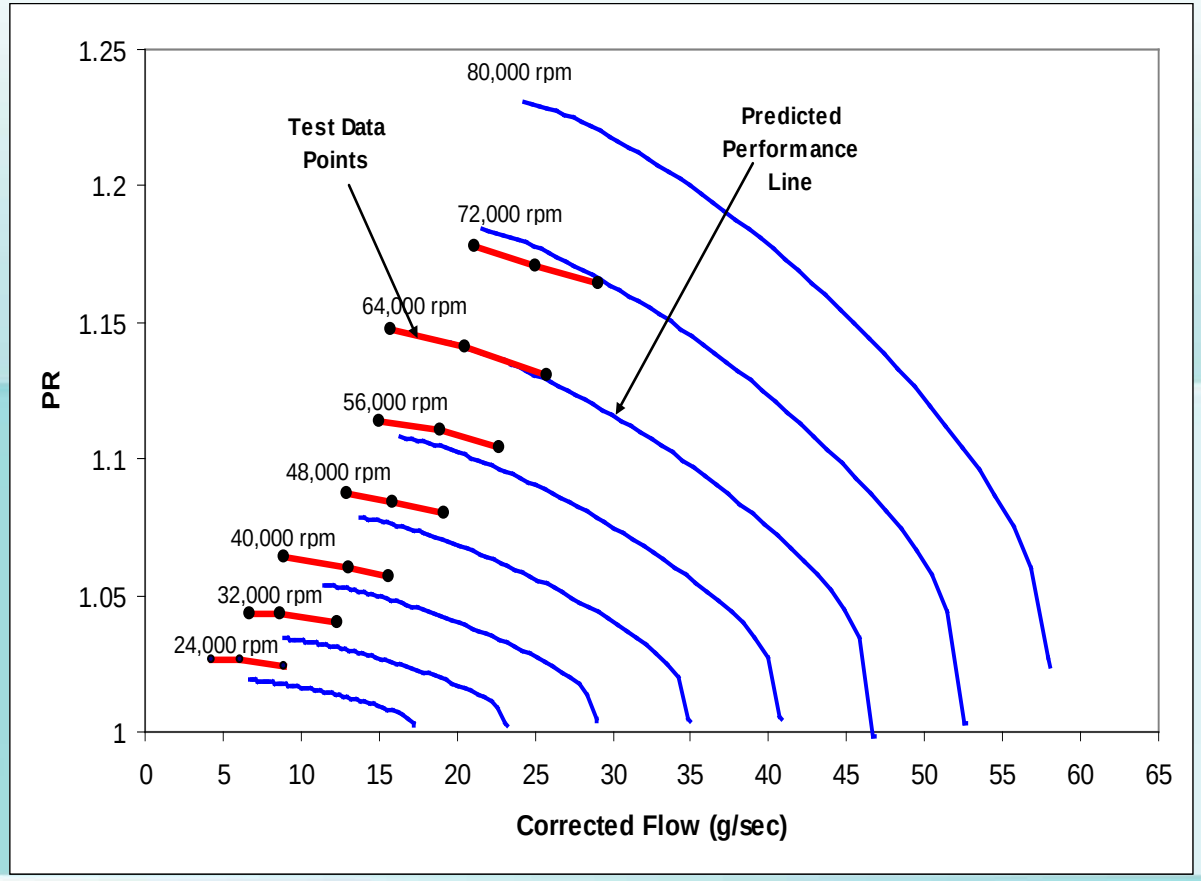
- A test rig was developed for testing the blower.
- Orifice type flow meters were used to measure flow.
- Pressure transducers were used to measure pressures and magnetic type probes were used to measure speed.

Testing



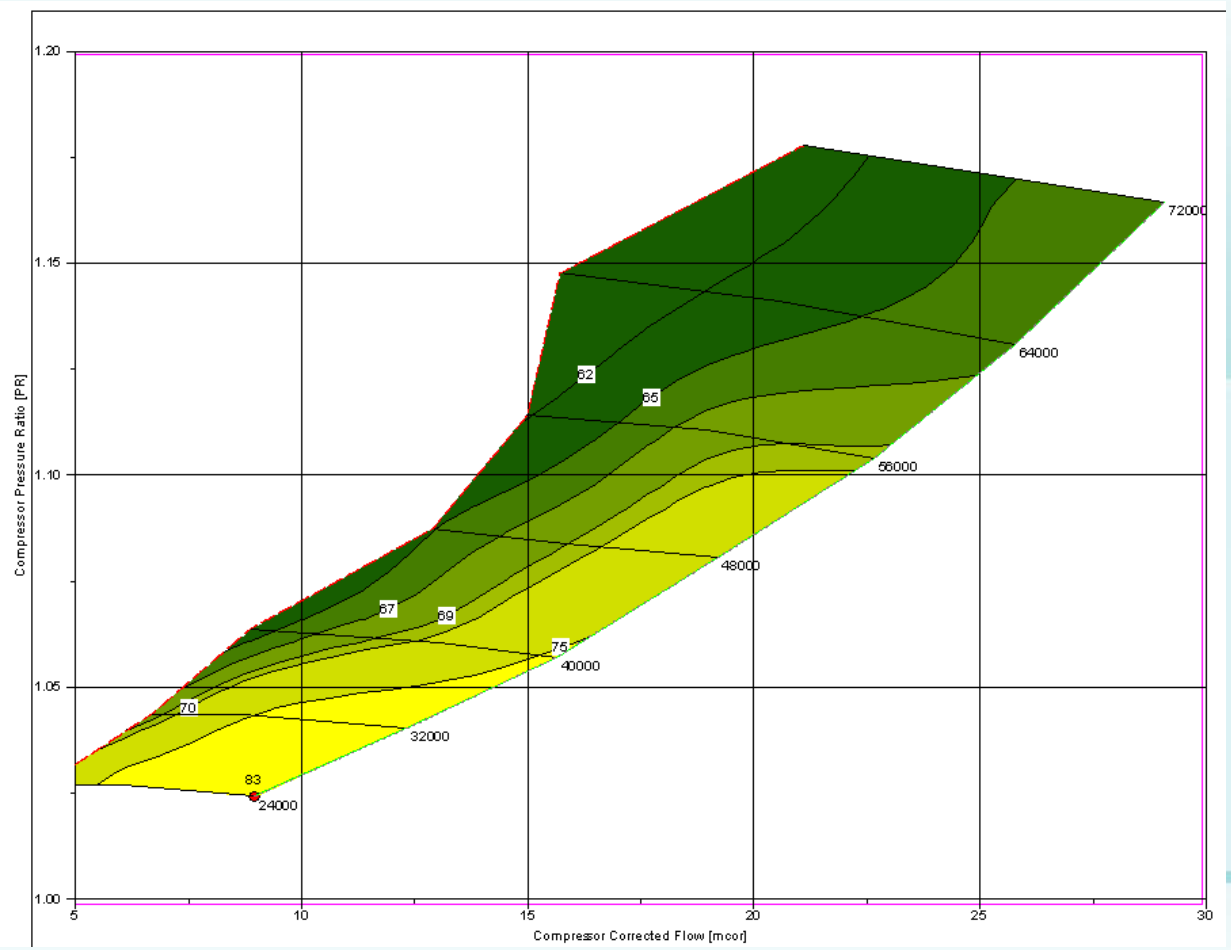
- Testing was done to measure blower performance.
- Test data were acquired using automated LabView system.
- Control valve operates the blower at various flow and pressure rise conditions.

Performance Data



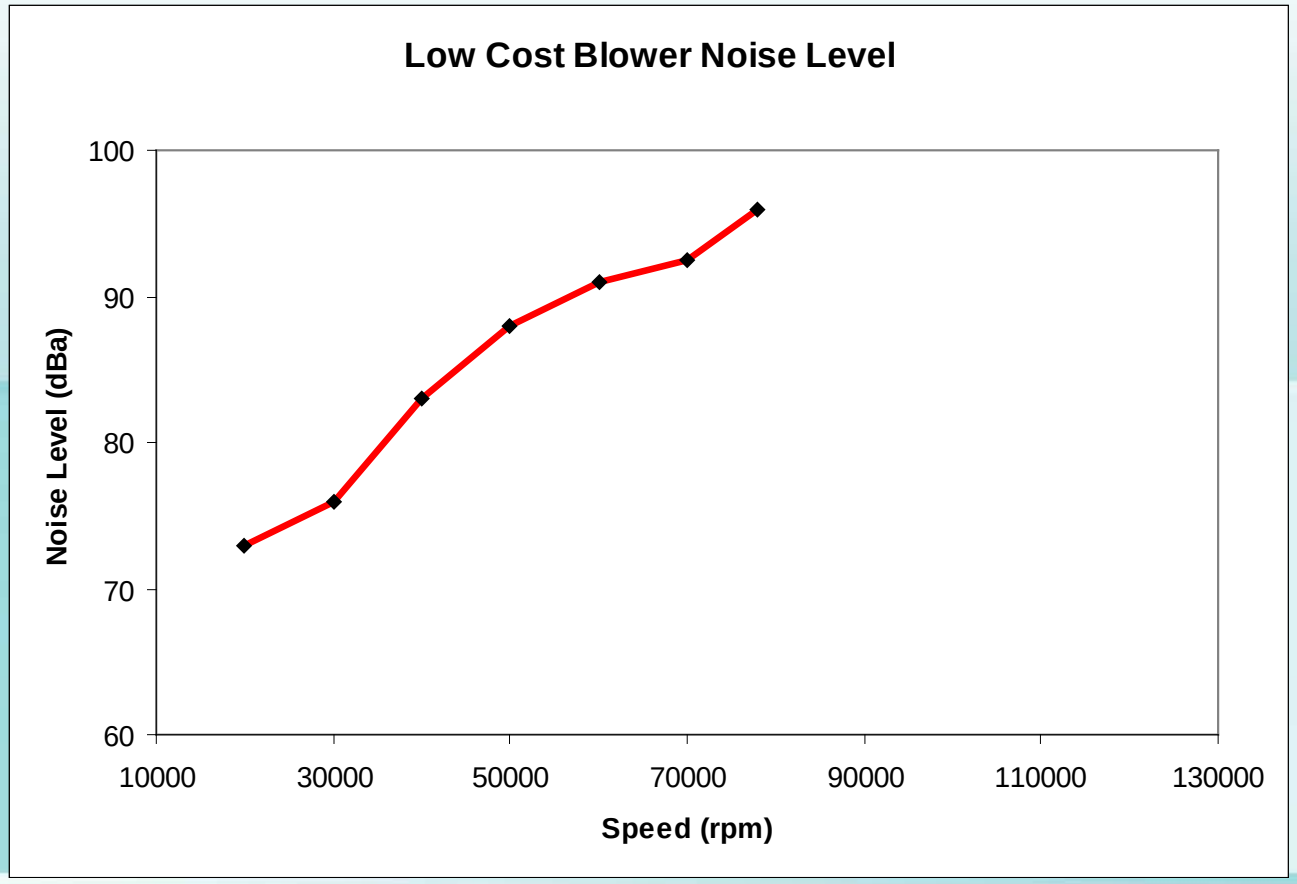
- Blower performed as predicted.
- Further testing being done for performance mapping at off-design operating lines.

Performance Data (Cont'd)



- Aerodynamic efficiency higher than 75%.
- Design meets efficiency target.

Acoustic Test Data



- Blower comparatively quieter than roller type bearing blowers.
- By further optimizing air flow path noise can be reduced to <70 dBa.

Program Summary & Future Plans

- The blower development and testing has proved viability of a reliable, energy efficient and low cost blower for SOFC systems.
- Further optimization of the blower is being performed to improve performance and to meet all specifications.
- SECA members have extended their support to test the blower in their SOFC systems.
- The further optimized blower will be system tested and commercialized.

Overall Conclusion

- R&D Dynamics has become a complete blower solution provider for all fuel cell system industry.
- Particularly in last 5 years working closely with DOE and SECA members the phase is shifting from prototype manufacturing to volume production.
- R&D Dynamics blowers have been field tested successfully for thousands of hours all around the world.
- R&D Dynamics blowers provide energy efficient, reliable, contamination free and maintenance free operation.

Overall Conclusion (Cont'd)

- Currently R&D Dynamics is working on setting up production line in the new 75,000 Sq.ft facility and establishing vendor supply base for volume manufacturing.
- R&D Dynamics is committed to deliver quality blowers for fuel cell system manufacturers which meets their performance and cost goals.

Acknowledgement

R&D Dynamics would like to thank DOE and SECA members for their continued support.