ADVANCES IN FUEL CELL BLOWERS

10th Annual SECA Workshop
Pittsburgh, PA

Sponsor: Department of Energy

Presented by: Dr. Giri Agrawal
R&D Dynamics Corporation

Date: July 16, 2009

Outline

1) *R&D Dynamics Company Overview*

2) *Foil Bearing Supported Cathode/Anode Recycle Blowers for Large MW Size SOFC Power Plants*

3) *Foil Bearing Supported Anode Gas Recycle Blower for Small Size SOFC's*

4) *Low Cost Cathode Air Blower*

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COMPANY OVERVIEW

OUR BUSINESS

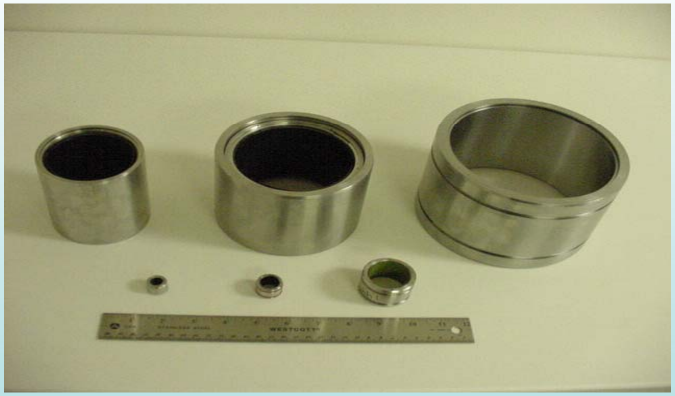
Design, Develop and Production Manufacture Oil-Free, Efficient, and Affordable Foil Bearing Supported High-Speed Turbomachinery

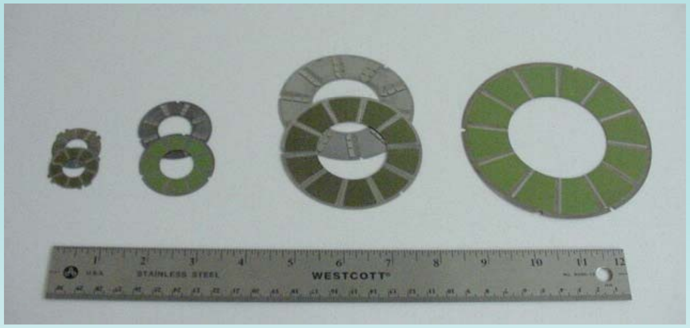
R&D Dynamics, Bloomfield, CT

World Leader in Foil Gas Bearing Technology….

FOIL BEARINGS PROVIDE-

- ✓ Oil-Free Operation
- ✓ High Rotational Shaft Speed
- ✓ Maintenance Free
- ✓ High Reliability
- ✓ High Temperature Capability





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Background

- Started in 1990
- 23,000 sq. ft. space
- 53 employees
- 50% development programs
- 50% production programs
- Quality system approved by FAA
- ISO 9001:2000 / AS9100 registered
- Major facility expansion planned for September 2009

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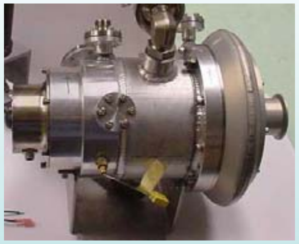
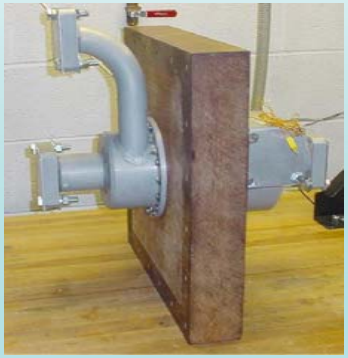
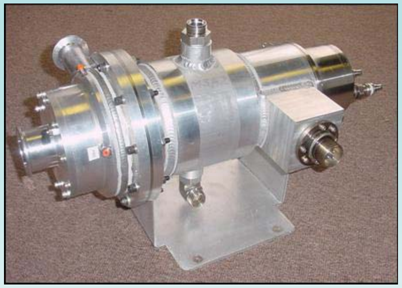
Experience

- Fuel Cell Blowers
- Motor driven gas compressors
- Turboalternators
- Turboexpanders for air separation plants
- Hydrogen turboexpander
- Refrigerant centrifugal compressors
- High temperature turbochargers



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HIGH-SPEED FOIL BEARING SUPPORTED BLOWERS PROVIDE-

- ✓ High Efficiency
- ✓ Potential for Low Manufacturing Cost
- ✓ Less Material
- ✓ Few Components
- ✓ Part Load Capability
- ✓ Variable Speed

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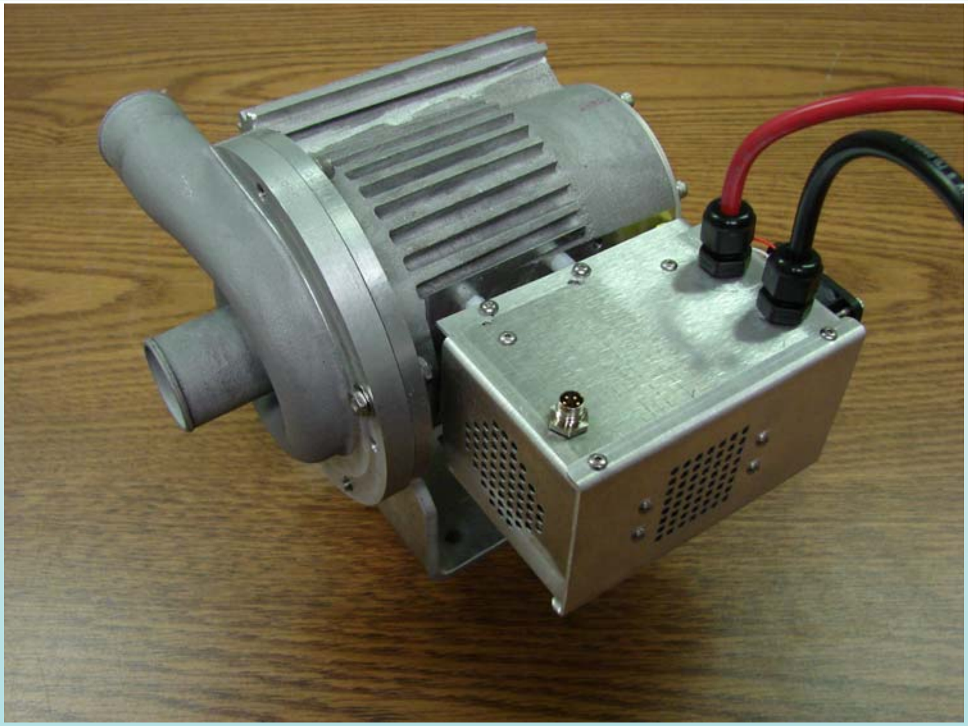
Fuel Cell Blowers

Automotive PEM Reformer Air Blower

Fuel Cell Blower (Cont'd)

Automotive PEM Air Blowers

Fuel Cell Blowers (Cont'd)



Cathode Air Blower for 5 kW SOFC APU

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Fuel Cell Blowers (Cont'd)

Cathode Air Blower

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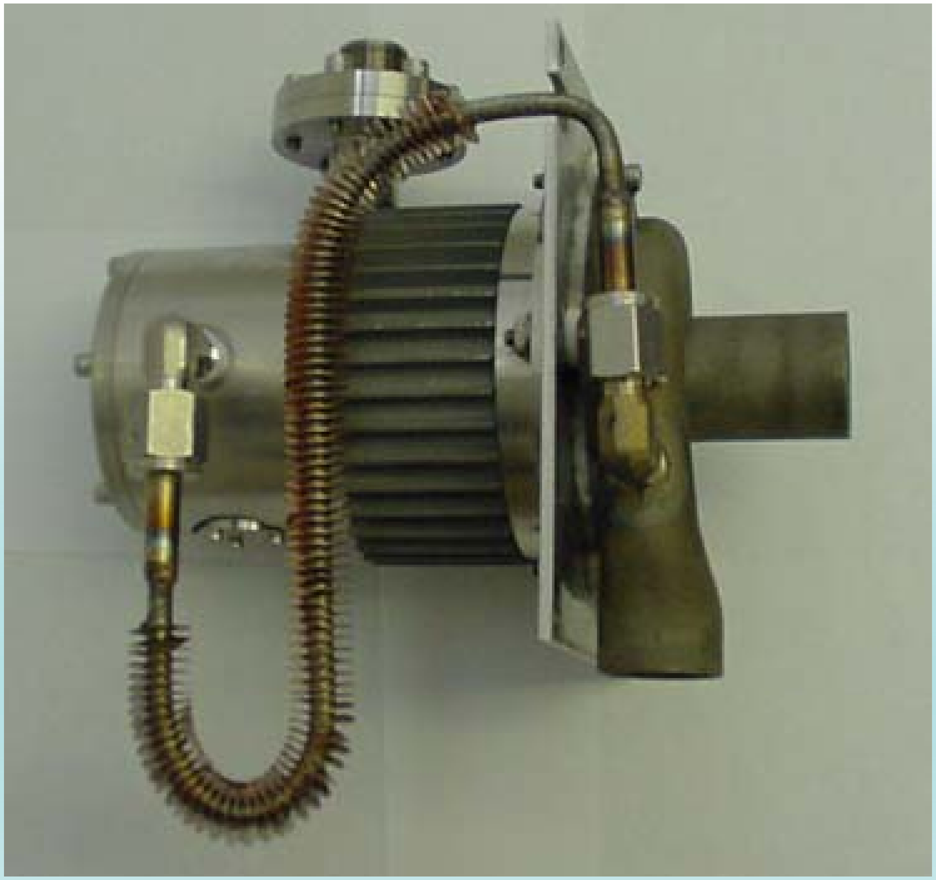
Fuel Cell Blower (Cont'd)



SOFC Anode Gas Recycle Blower

Fuel Cell Blowers (Cont'd)

SOFC Anode Gas (850^{o} C) Recycle Blower

New Facilities for R&D Dynamics
75,000 ft^2 Building Construction

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Foil Gas Bearing Supported Cathode/Anode Recycle Blowers for Large MW Size SOFC Power Plants (HT-CRB)

DOE SBIR Phase I
Contract No. DE-FG02-08ER85020

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Summary of Accomplishments

- A high temperature cathode recycle blower has been designed
  - High temperature capable (up to 800°C)
  - Highly reliable
  - Highly energy efficient (>66%)
  - Low life cycle cost
  - Oil free
  - Maintenance free
  - Higher design life (>40,000 hrs)
  - Lower noise (< 70dBa)
  - Easily scalable
  - Turn down ration up to 5:1

- A 6 inch diameter journal bearing was built and tested
  - Tested up to 15,000 rpm
  - Characteristic data were acquired

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Summary of Accomplishments (cont'd)

- Blower design successful and meets all the requirements
- Roadmap to dual use as HT-CRB or Anode Recycle Blower was developed
- Feasibility of the program was achieved by design, analysis and breadboard testing

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Design of HT-CRB
-Technical Specifications

➢ SOFC Power Plant Rating	5 MW
➢ Process Gas	Air
➢ Inlet Gas Temperature (up to)	800 ^{0}C
➢ Inlet Pressure	15.6 psia
➢ Pressure Rise	12” of water
➢ Required Flow	20,000 SCFM
➢ Turn Down Ratio	2:1
➢ Design Life	>40,000 hrs
➢ Maintenance Interval	10,000 hours

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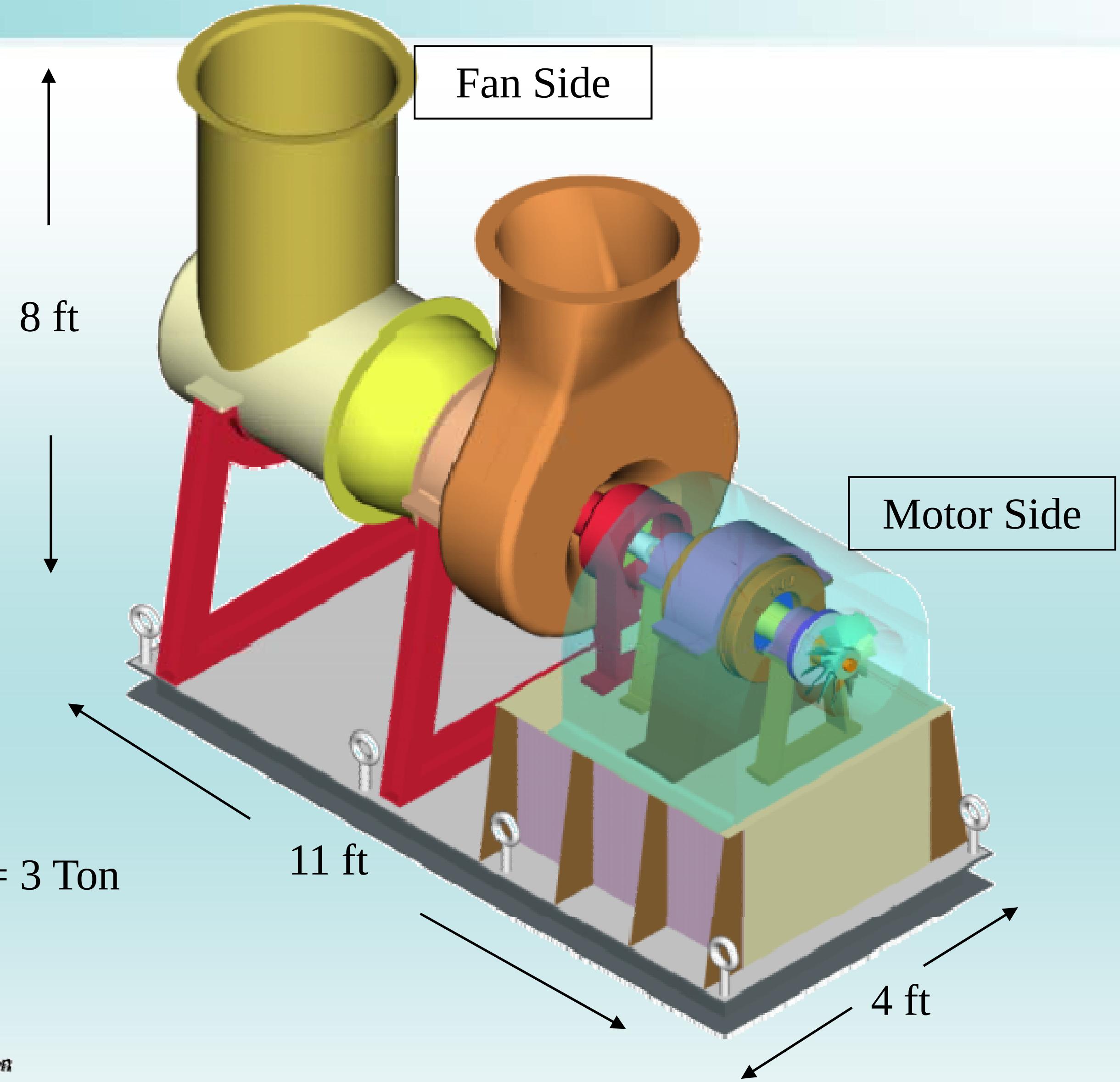
Design of HT-CRB (Cont'd)
-Key Issues

- Reliable Operation & Life of Blower at High Operating Temperature up to 800°C
- Highly Efficient
- Low Life Cycle Cost
- No Oil or Grease Contamination of Process Air
- Scalability of Design
- Low Maintenance Cost
- Low Noise
- Affordable Cost

Design of HT-CRB (Cont'd)

-Isometric View



Weight = 3 Ton

Design of HT-CRB (Cont'd)
-Technical Summary

Blower Type	Axial
Mechanical Speed	9,244 rpm
Bearing Type	Foil Gas Bearings
Motor Type	Induction Motor
Controller Type	Sensorless Controller
Overall Dimension	11ft x 8ft x 4ft
Weight	6436 lbs
Life	>100,000 hrs

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Design of HT-CRB (Cont'd)

-Performance

Inlet Temperature	800 °C
Outlet Temperature	810.5 °C
Flow Rate	1,486 lbm/min
Inlet Pressure	15.6 psia
Outlet Pressure	16.03 psia
Pressure Ratio	1.027
Fan Efficiency	80%
Bearing Efficiency	96%
Motor Efficiency	95%
Controller Efficiency	96%
Shaft Power	119.6 kW
Motor Cooling Fan Power	8.3 kW
Total Input Electric Power	144.9 kW
Overall Efficiency	66 %

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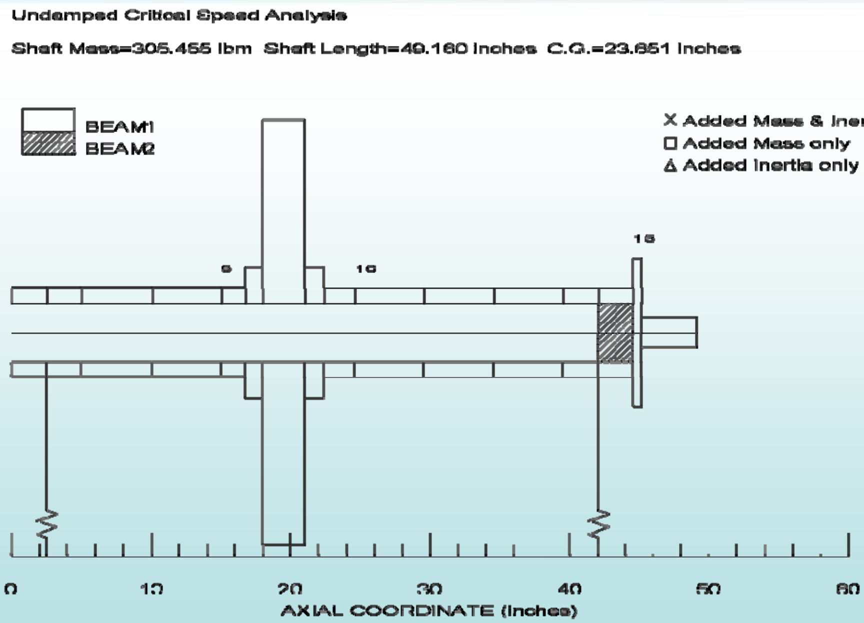
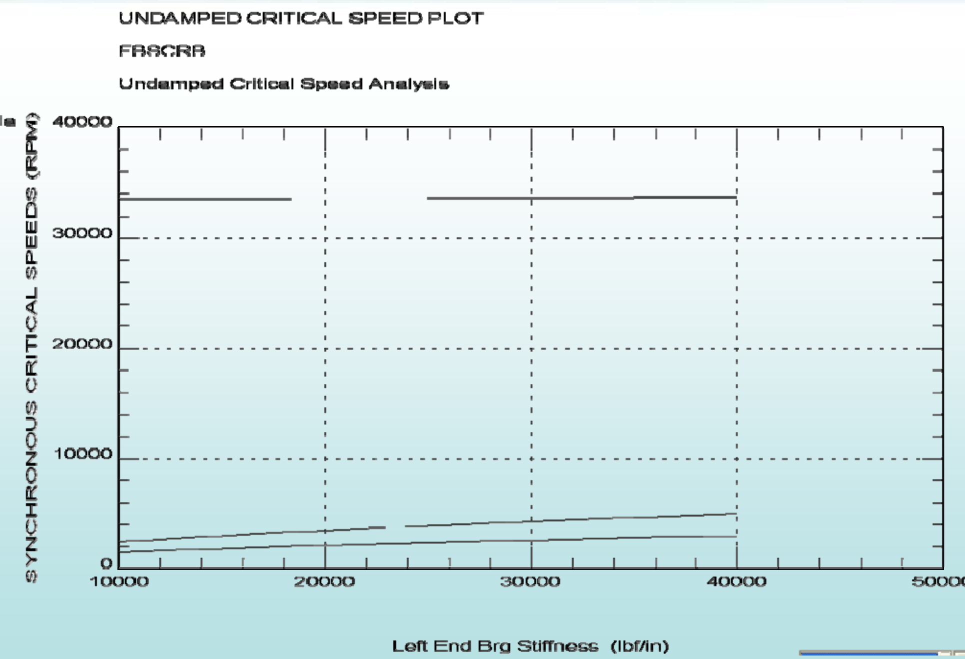
Design of HT-CRB (Cont'd)
-Technical Highlights

- High temperature capable
  - Operates at temperatures up to 800°C
- Completely Oil-free design
  - Supported on foil gas bearings
- Zero Maintenance
  - No contacting parts in the rotating assembly
- Highly Efficient
  - High efficiency fan, motor and sensorless controller
  - Foil gas bearings has low power loss
- Highly Reliable
  - Design life > 100,000 hrs
  - Start stop cycles > 35,000

Analysis

-Critical Speed Fan Shaft





- *Design speed 9,244 rpm*
- *1st Bending mode 33,677 rpm (300% margin)*
- *Fan side rotating assembly stable*

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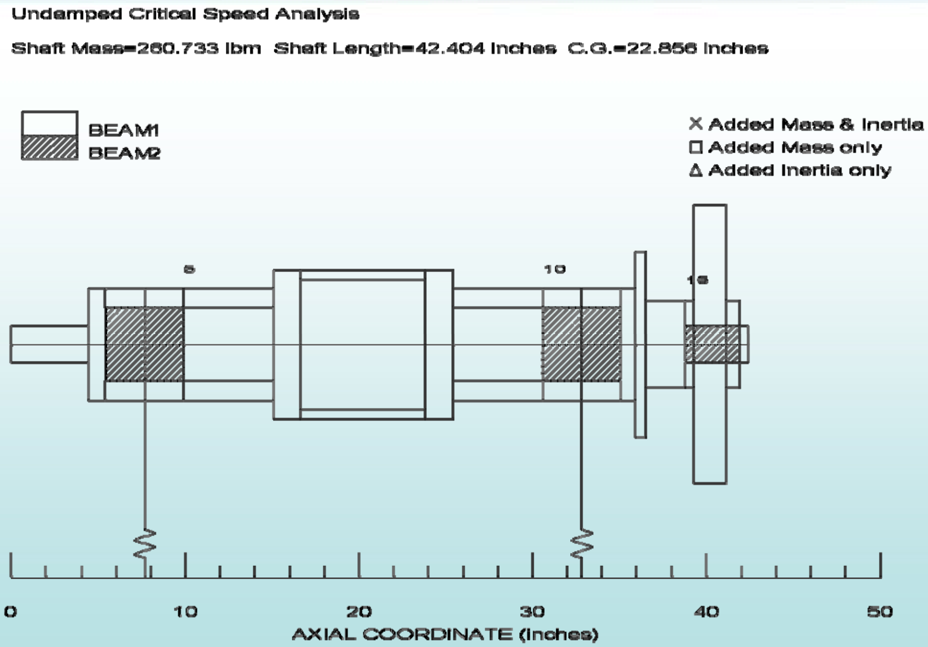
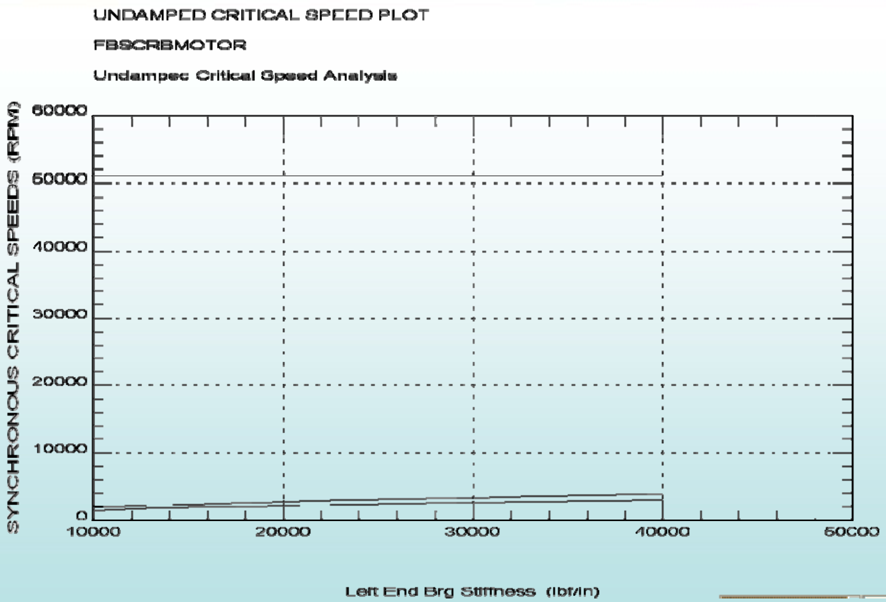
Analysis (Cont'd)

-Critical Speed Motor Shaft





- *Design speed 9,244 rpm*
- *1st Bending mode 51,919 rpm (500% margin)*
- *Motor side rotating assembly stable*

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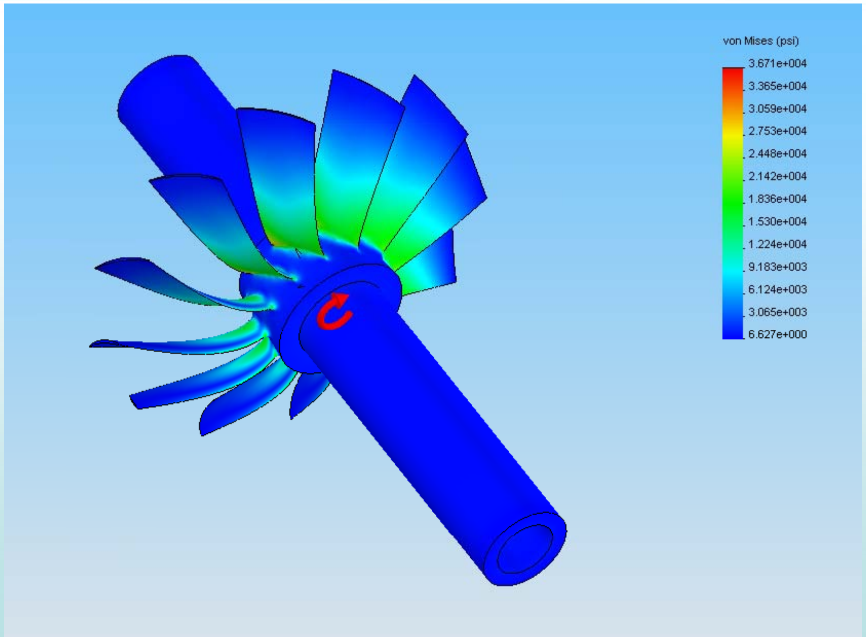
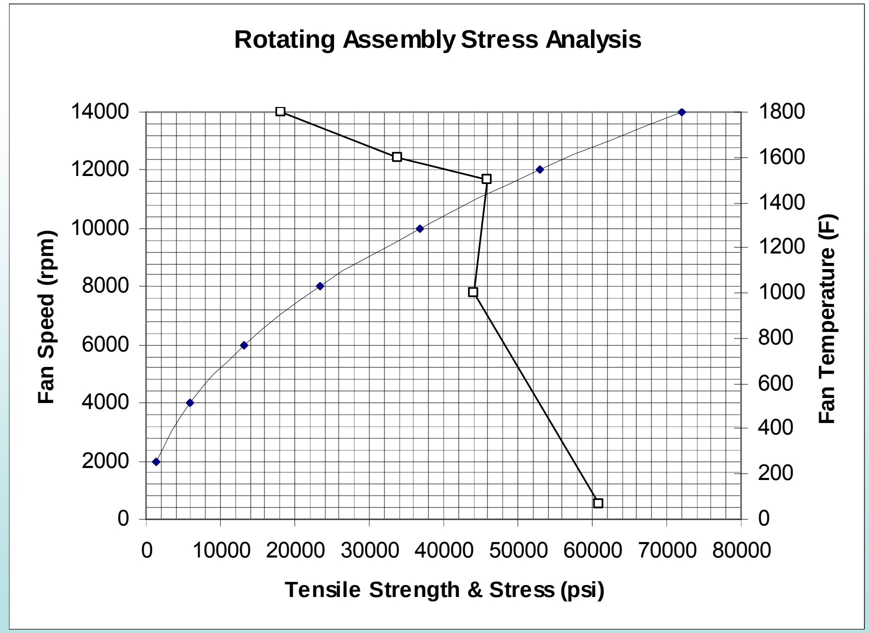
Analysis (Cont'd)

-Fan Shaft Stress





- *Fan rotor maximum stress 36,710 psi*
- *Hastealloy @ 1500 °F has 46,000 psi tensile strength*
- *Shaft stress less than 3000 psi*
- *Rotating assembly design safe*

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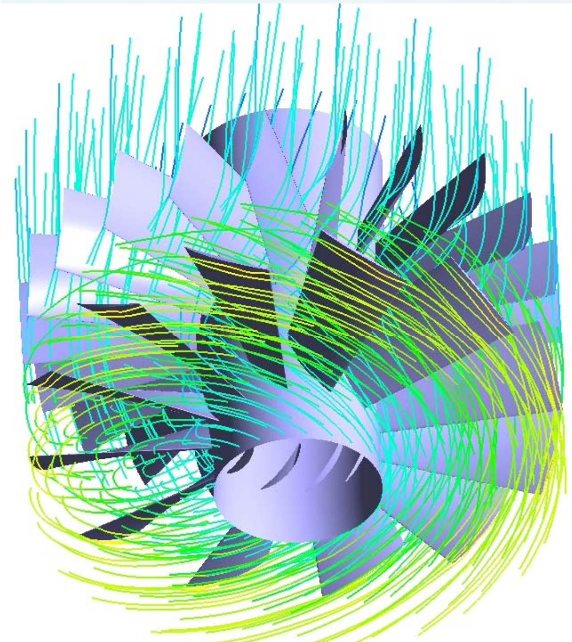
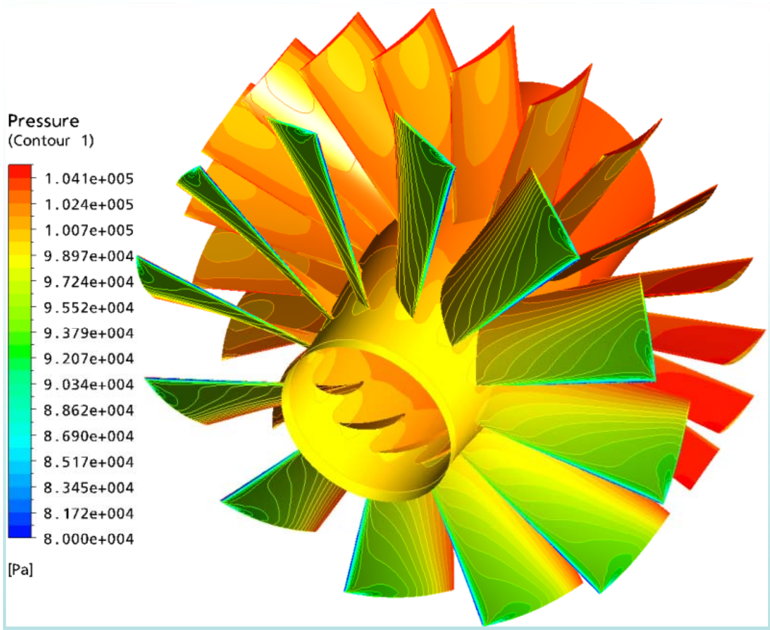
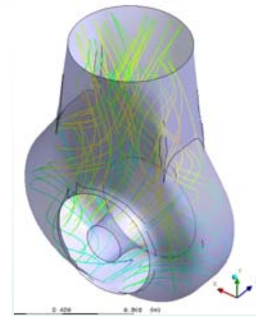
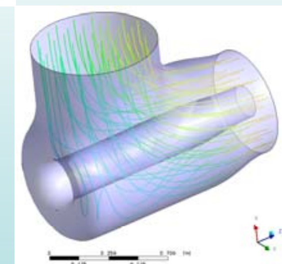
Analysis (Cont'd)

-Aerodynamics





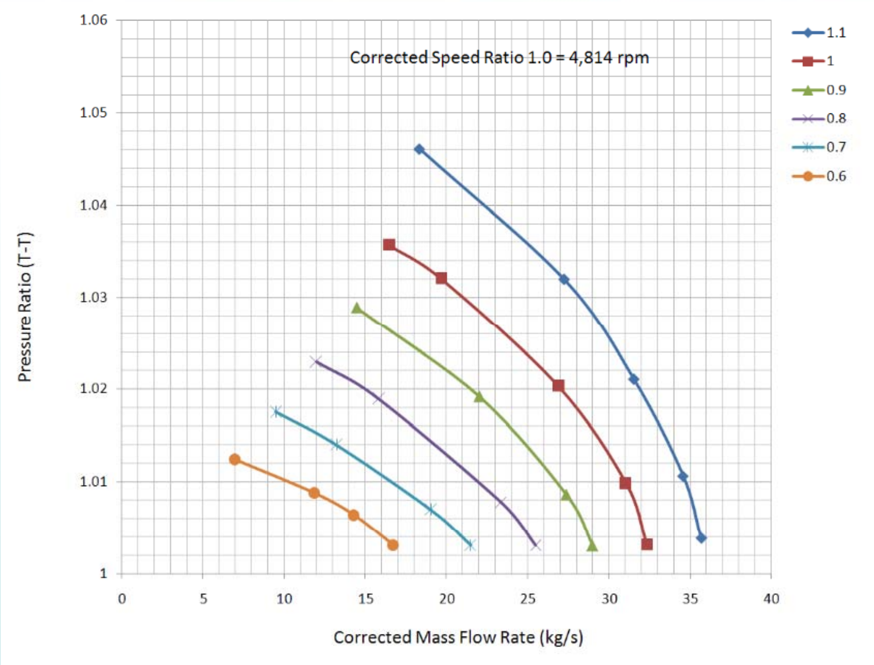


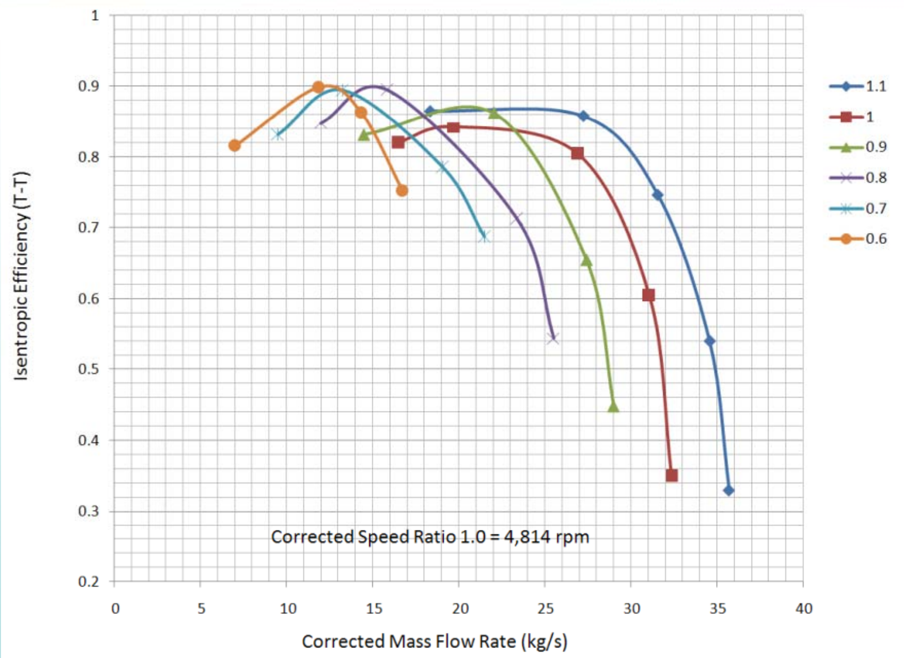


- *High efficiency blades designed with CFD tools*
- *Uniform pressure profiles obtained for high efficiency*
- *Inlet and outlet geometry optimized*

Analysis (Cont'd)

-Fan Performance Map





- *Aerodynamic design meets design point flow and pressure rise*
- *Predicted efficiency meets target > 80%*

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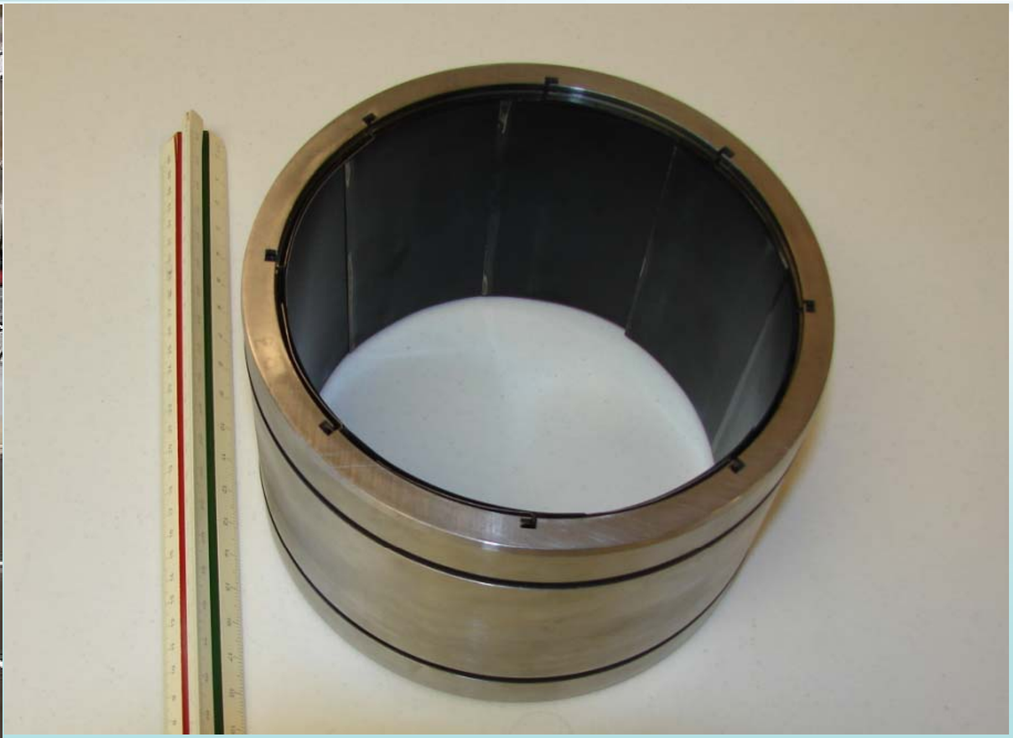
Testing of 6” Bearing
-Hardware



- *Left picture shows the test rig used for testing the bearing*
- *Right picture shows the 6” bearing manufactured and tested for HT-CRB*

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Testing of 6” Bearing (Cont’d)
-Conclusions

- Test proved feasibility of a new high temperature 6” diameter journal bearing design suitable for HT-CRB application
- Bearing tested up to 15,000 rpm (50 % more than design speed)
- Running torque low, hence better overall blower efficiency
- An optimum bearing design was identified for this application

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Dual Use of HT-CRB

-Need for Anode Recycle Blower

- *In discussion with SECA members, need for high temperature Anode Recycle Blower also exists for large power plants*

- *HT-CRB has been designed such that it can be modified to use as High Temperature Anode Recycle Blower (HT-ARB)*

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Phase II Workplan
-Technical Objectives

- *Continue working with SECA members on blower specifications and requirements*
- *Perform detailed analysis and prepare detailed drawings for manufacturing*
- *Manufacture the blowers and conduct performance testing at R&D Dynamics facility*
- *Test the blowers in an actual fuel cell system of SECA members and collect performance data*
- *Cost reduce the design for manufacturing of blowers in large quantities for commercialization*

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Foil Gas Bearing Supported High-Speed Centrifugal Anode Gas Recycle Blower (AGRB)

DOE SBIR Phase II
Contract No. DE-FG02-05ER84210

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Technical Summary

Blower Type	Centrifugal
Impeller Dia	31.6mm
Mechanical Speed	98,600 rpm
Pressure Rise	1-2.5 KPa (4-10 in of H_2O)
Flow	1.54 g/s
Size	195mm x 197mm x 204mm
Volume	0.85 Liter
Weight	6.5 Kg
Bearings	Foil Gas Bearings
Motor Type	Permanent Magnet Motor
Controller	Sensor-less
Operating Temperature	850° C
Input Electric Power	~60 Watts
Overall Efficiency	45.6 %

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Highlights

- Testing in 2008 limited maximum recycle gas temperature up to 719 ^{o}C.

- Improvements to AGRB design now allows recycle gas temperature operation of up to 850 ^{o}C

Accomplishments

- Reduced number of parts for cost reduction
- Upgraded materials to reach $850^{0}C$
- High speed motor redesigned
- Modified 100krpm rotor-shaft assembly for high temperature application
- Tested in laboratory rig up to 850 ^{o}C
- R&D Dynamics applied for 2009 R&D 100 Award

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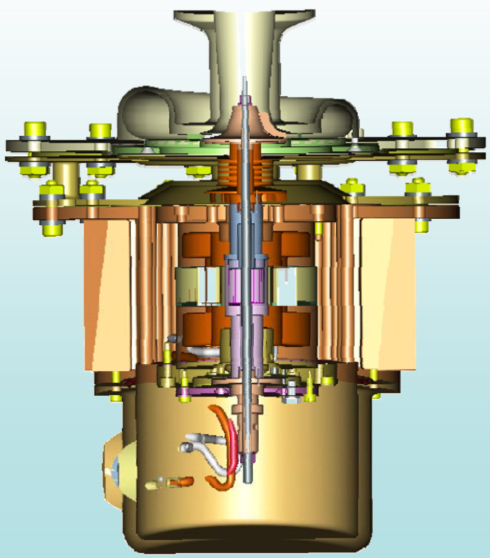
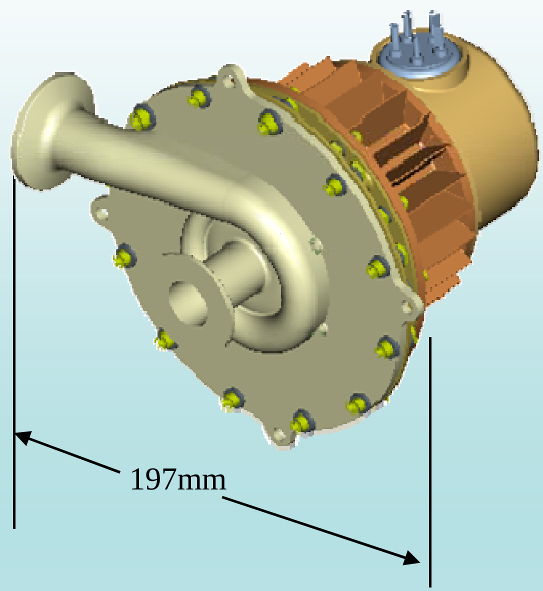
Improved AGRB Design

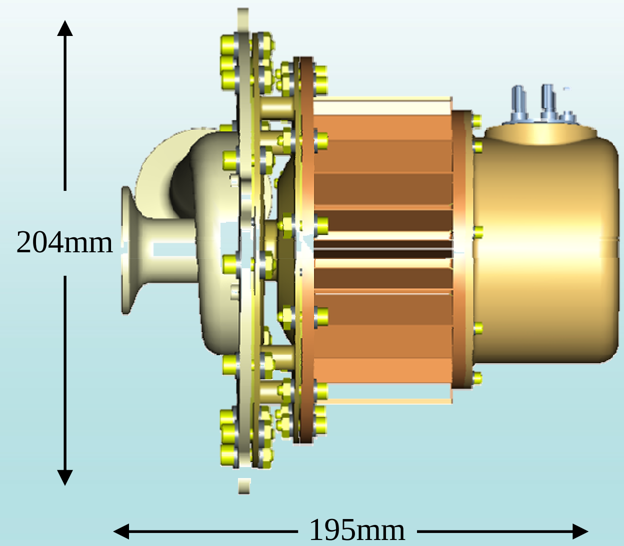
- Simplified volute housing design
- Merge two thermal choke plates into one
- Diffuser attachment on to the volute housing was changed to avoid warping of vanes
- Merge inner and outer motor housings into one piece housing. Cooling flow channels are provided instead of internal fins to enhance heat transfer
- Added hermetic connector to the end cover for motor leads
- Several others changes were made to simplify the design

Improved AGRB



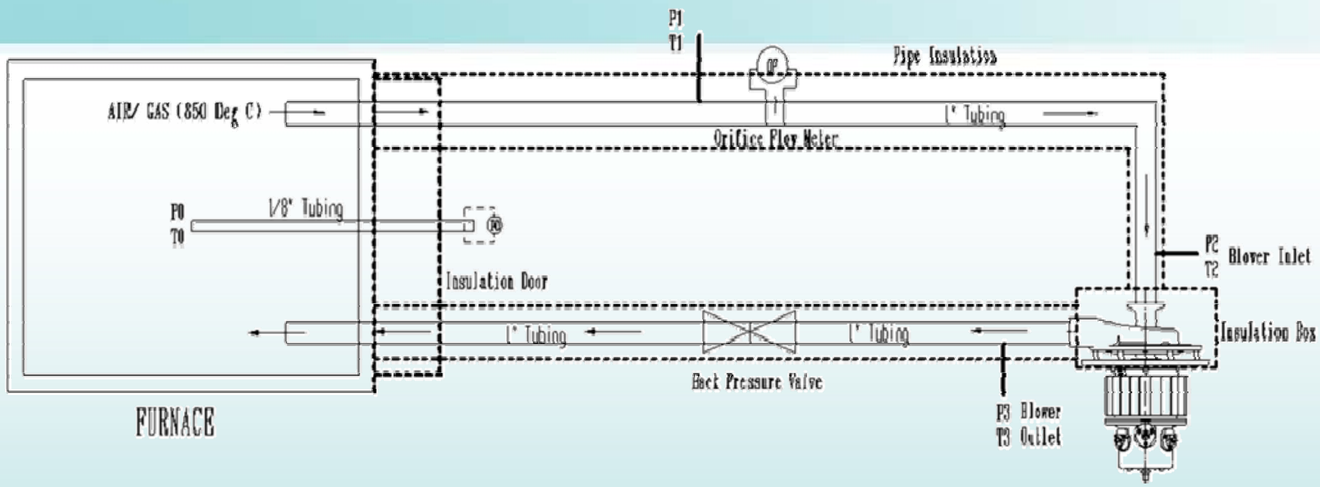
Vertical Section





Total Assembly Weight = 6.51kg

Test Rig



- The test cycle is based on closed loop system
- Hot air is circulated via Furnace heated up to 850^{0}C
- Flow to the compressor measured through orifice flow meter
- Back pressure valve is used to back pressure the compressor to generate compressor map
- All the plumbing connections and pipings are fully insulated for a minimal heat loss
- The blower hot side is enclosed in an insulation box for minimal heat loss

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Foil Gas Bearing Supported High Speed Centrifugal Cathode Air Blower

(Low Cost Cathode Blower)

(LCCB)

DOE SBIR Phase II

Contract No. DE-FG02-06ER84616

Phase I

-Accomplishments

- A low cost blower with only 16 number of parts was concepted
- An efficient low cost cathode air blower was designed
  - Oil free
  - Highly efficient (>61%)
  - Highly reliable
  - Maintenance free
  - Easily scalable
- A cost model targeting $100 was developed
- Bread board test was conducted to prove structural strength of plastic impeller concept
- Feasibility of program was achieved

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Phase I

-Specifications

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

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Phase I

-Key Issues

- Low Cost
- High Efficiency
- High Reliability
- Oil-free

Phase I

-Technical Summary

Blower Type	Centrifugal
Mechanical Speed	80,500 rpm
Weight	1.45 kg (3.2 lbm)
Bearings	Foil Gas Bearings
Motor Type	Permanent Magnet Motor
Controller Type	Sensorless Controller
Input Electric Power	769 watt
Overall Efficiency	61.6 %
Total Blower Cost	$105.11 [@ 50,000 units/year]
Life	>40,000 hrs

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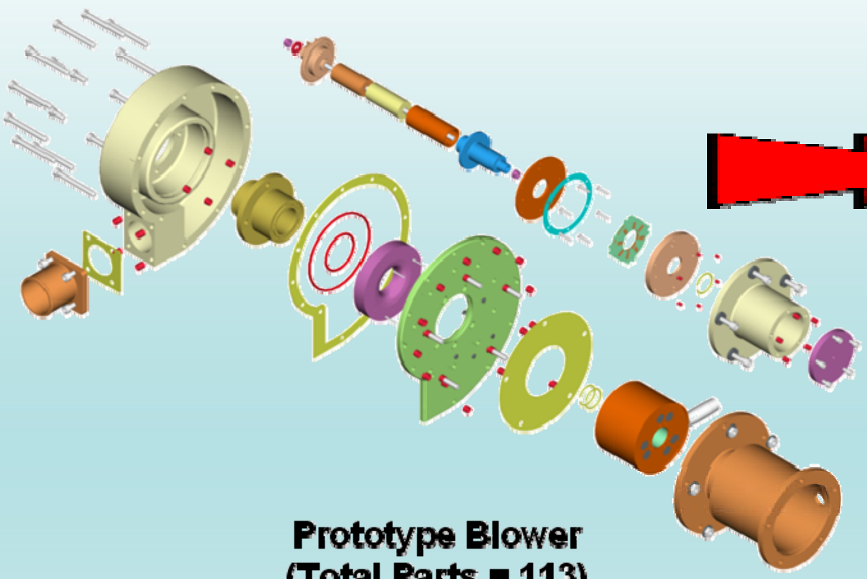
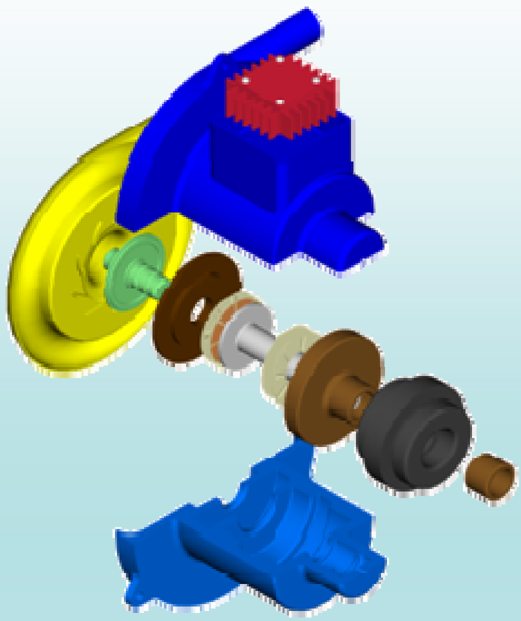
Phase I

-Design



Prototype Blower
(Total Parts = 113)



Low Cost Cathode Air Blower
(Total Parts = 16)

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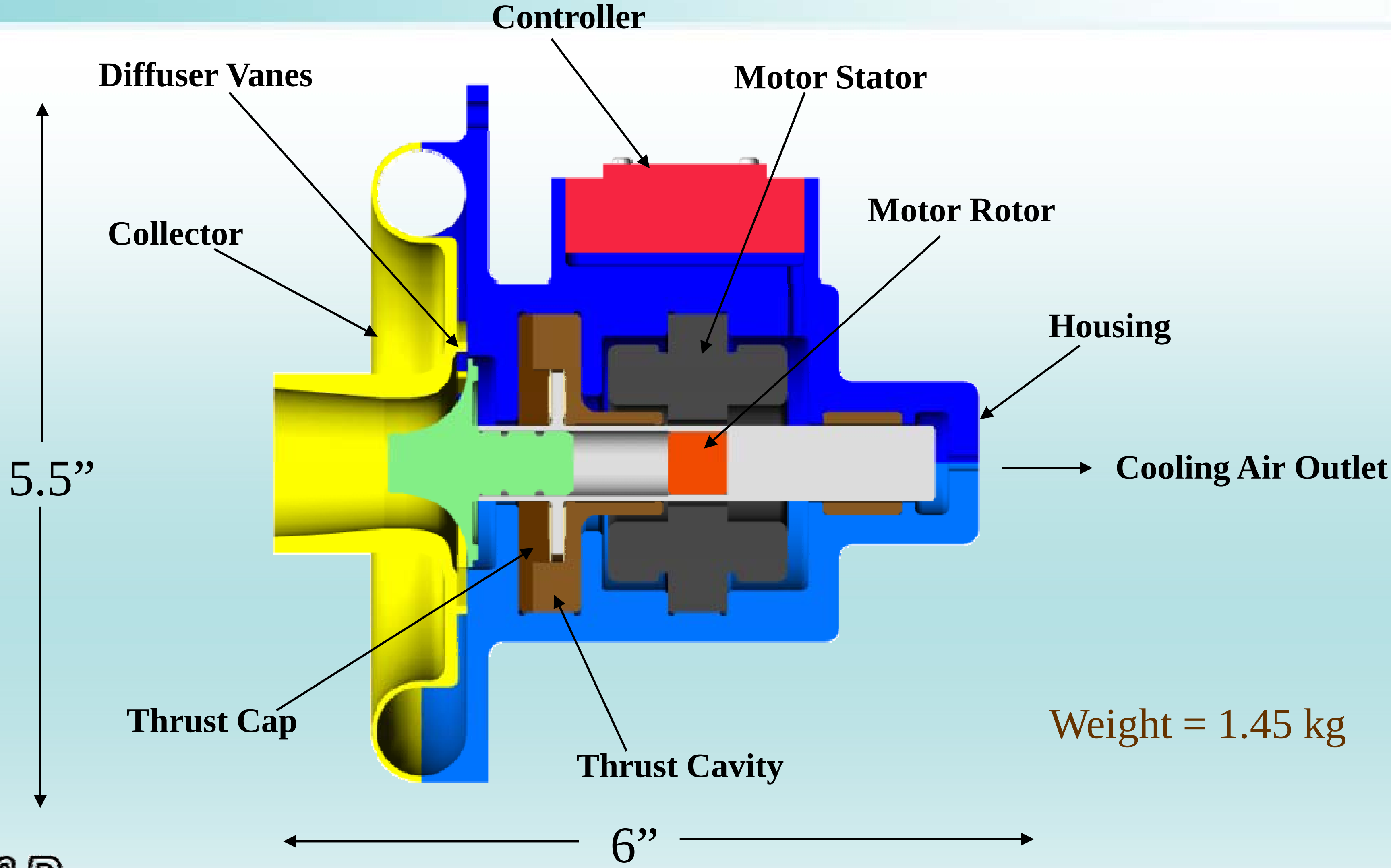
Phase I

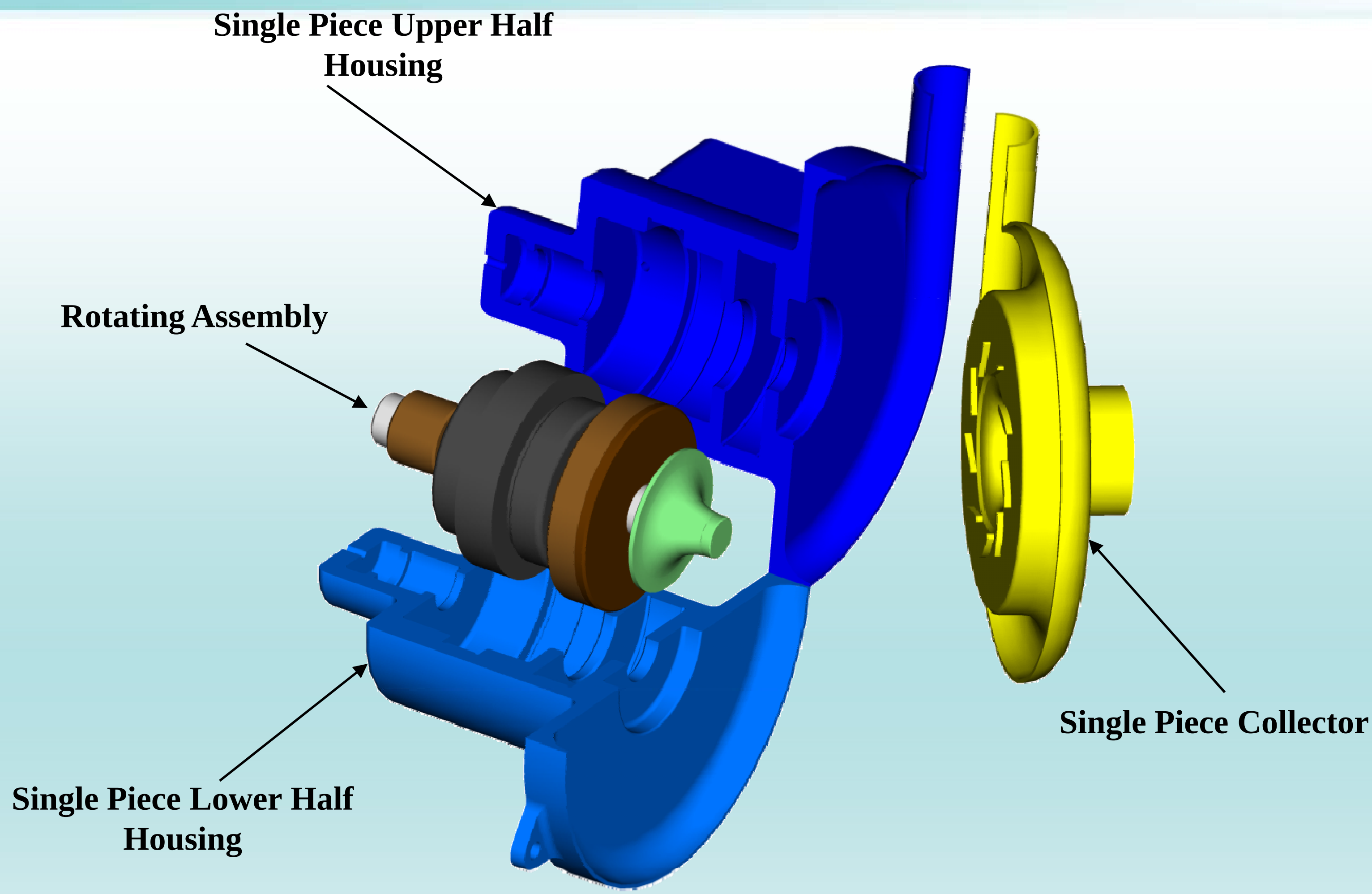
-Cut Section



Weight = 1.45 kg

Phase I

-Innovative Split Housing Design



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Phase I

-Cost Model

Low Cost Cathode Air Blower Cost Model			
Component	**Cost**	**Material**	**Manufacturing Processes**
Upper Half Housing	$4.79	Nylon	Injection mold
Lower Half Housing	$4.79	Nylon	Injection mold
Journal Bearing	$1.24	Inconel	Stamping
Thrust Bearing	$15.32	Inconel	Stamping, Welding
Bearing Sleeves	$2.03	Aluminum	Rolling
Shaft	$3.49	Aluminum	Machining, Anodizing
Impeller	$1.32	PPS Plastic	Injection mold
Thrust Cap	$2.14	Aluminum	Casting, machining
Collector	$1.58	Nylon	Injection mold
Shims, fasteners & screws	$0.00	-	-
Total Part Cost	$36.70		
Manufacturing Tooling & Assembly Tool	$3.35		
Labor Cost	$1.54		
Sub Total	$41.59		
Motor	$8.95		
Controller	$54.57		
Cathode Air Blower Total Cost	**$105.11**		

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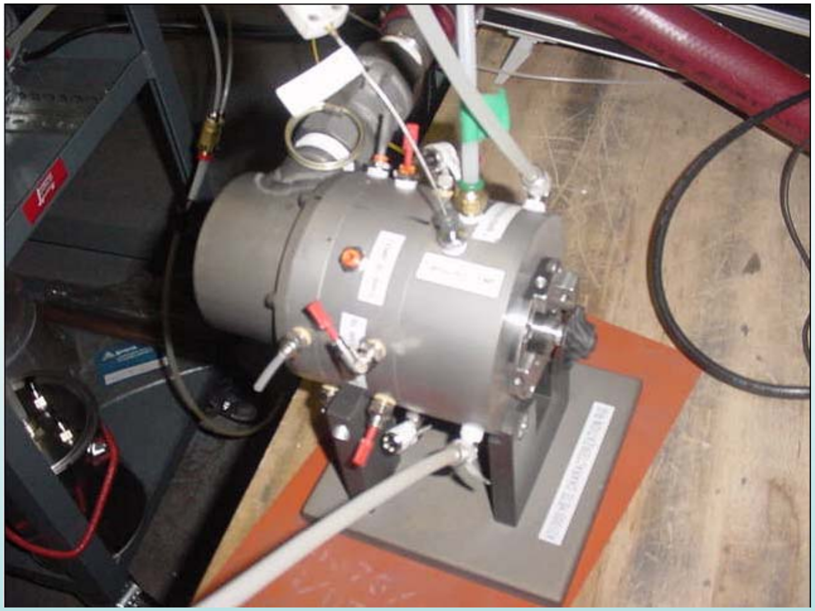
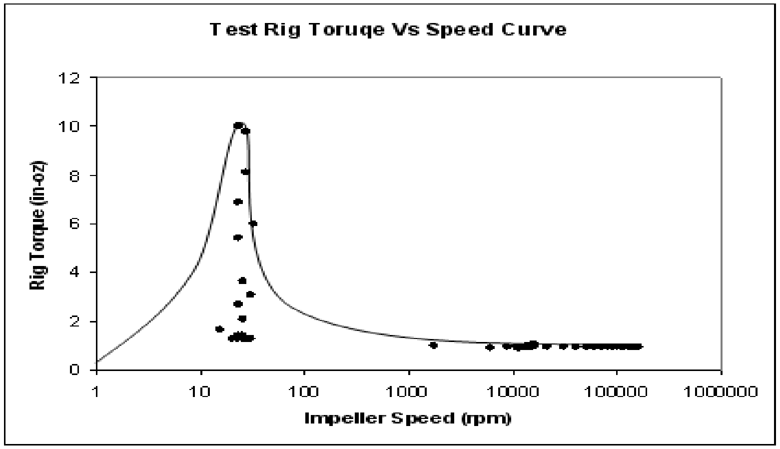
Phase I

-Plastic Impeller Testing





- *Tested up to 155,000 rpm (850 ft/sec)*
- *Cathode blower design tip speed 612 ft/sec*
- *Structurally very strong, withstood gyroscopic loads, needs no balancing*

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Phase II

-Ojectives

- *Detailed design of low cost cathode air blower*
- *Develop and test a low cost sensorless controller technology*
- *Manufacture a “hog out” low cost design blower*
- *Assemble and performance test at R&D Dynamics facility*
- *Test in SECA member’s actual SOFC system*
- *Optimize design with SECA members feedback*
- *Identify U.S. suppliers for high volume manufacturing*

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Phase II

-Accomplishments

- *Phase I design was revisited and blower design was optimized*
- *Detailed design and analysis of blower was completed*
- *A low cost controller design was developed & tested*
- *Detailed drawings were prepared*
- *Vendors are being identified for manufacturing of low cost design*

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Phase II

-Comparative Motor Study

Type of Motor	Development Time	Efficiency	Size	Part Count	Assembly	Rank
Rare Earth Surface PM	1	1	1	5	5	13
Rare Earth Interior PM	4	2	2	3	3	14
Switch Reluctance	6	4	3	2	2	17
Regular Induction	1	5	6	3	3	18
Solid Rotor Induction	5	6	5	1	1	18
Ceramic Surface PM	3	2	4	5	5	19

- *Rare earth surface PM motor ranks top (lower cost & highest efficiency)*
- *Single tooth winding identified cost effective for stator manufacturing*

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Phase II

-Comparative Shaft Study

Parameter	304 Shaft	Aluminum Shaft	Zinc-Aluminum Shaft
Critical Speed	265,000 rpm	224,000 rpm	176,000 rpm
Cost	$1.02 / ft^3	$0.75 / ft^3	$0.15 / ft^3
Electrical Conductivity	15% of copper	59% of copper	28% of copper
Thermal Conductivity	16	113	113
Density	0.29	0.1	0.25
Yield Strength	29,700 psi	23,900 psi	27,459 psi
Die Cast Tolerance	NA	+ / - 0.002	+ / -0.0015
Die Castable Thickness	NA	0.06”	0.03”

- *Die casting most suitable to produce low cost shaft*
- *Al or Zn-Al casting will meet the needs for low cost cathode air blower*

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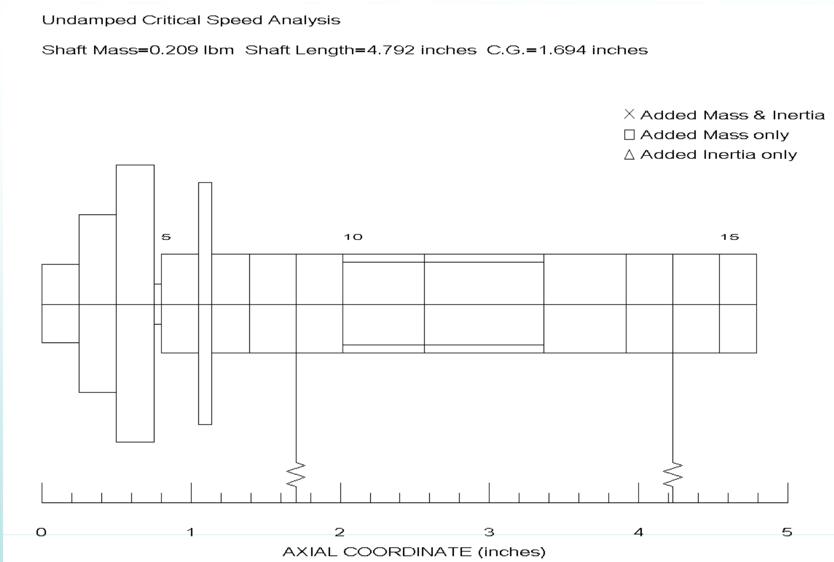
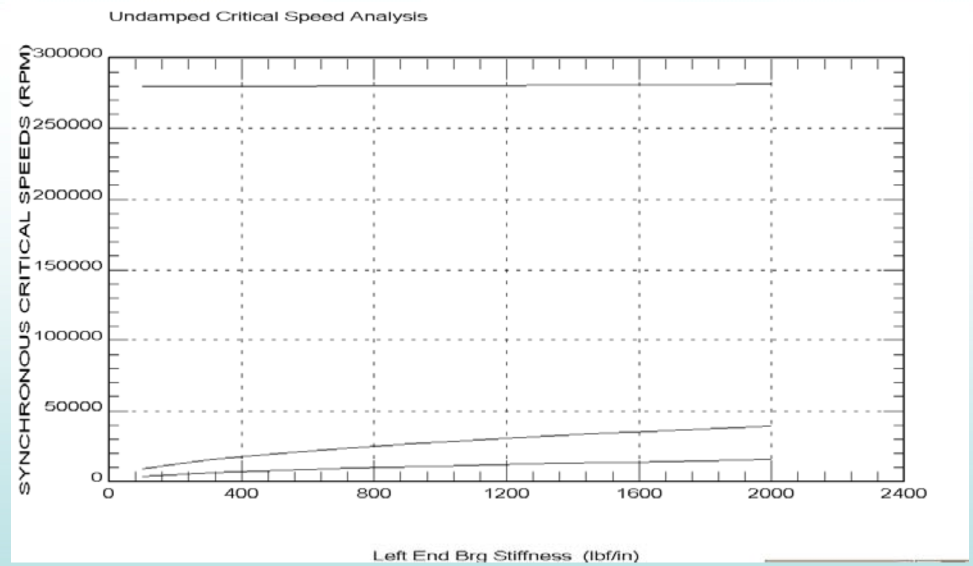
Phase II

-Shaft Critical Speed





- *Shaft 1st bending mode speed (>200,000) 2 times higher than design speed (80,500rpm)*
- *Shaft assembly stable*

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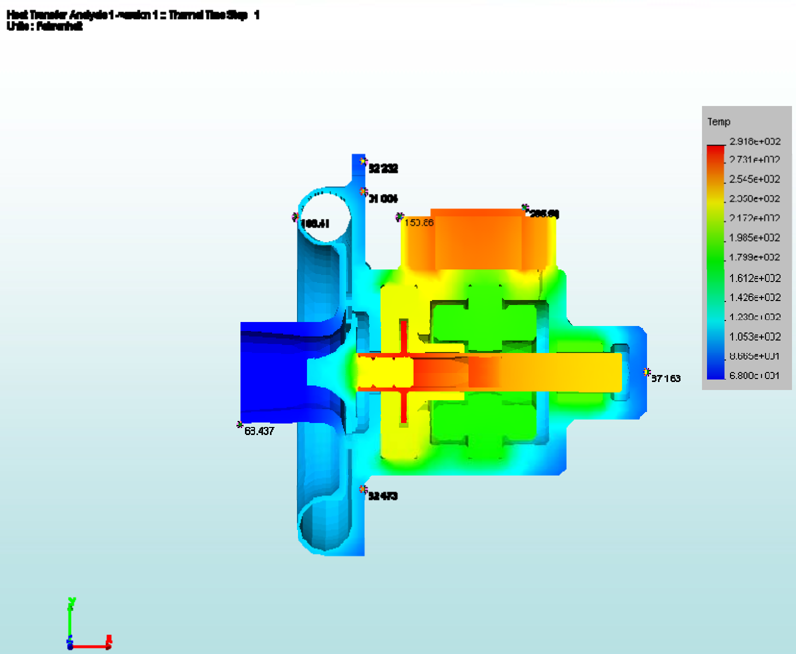
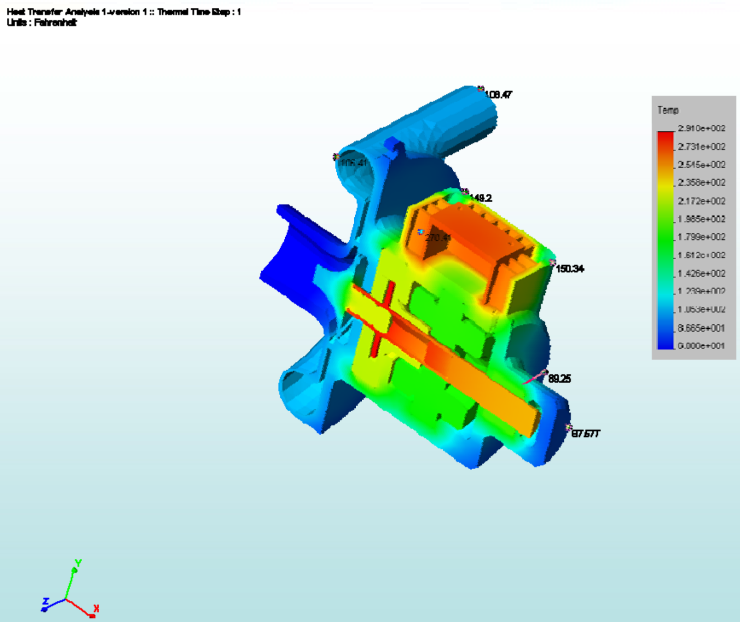
Phase II

-Heat Transfer

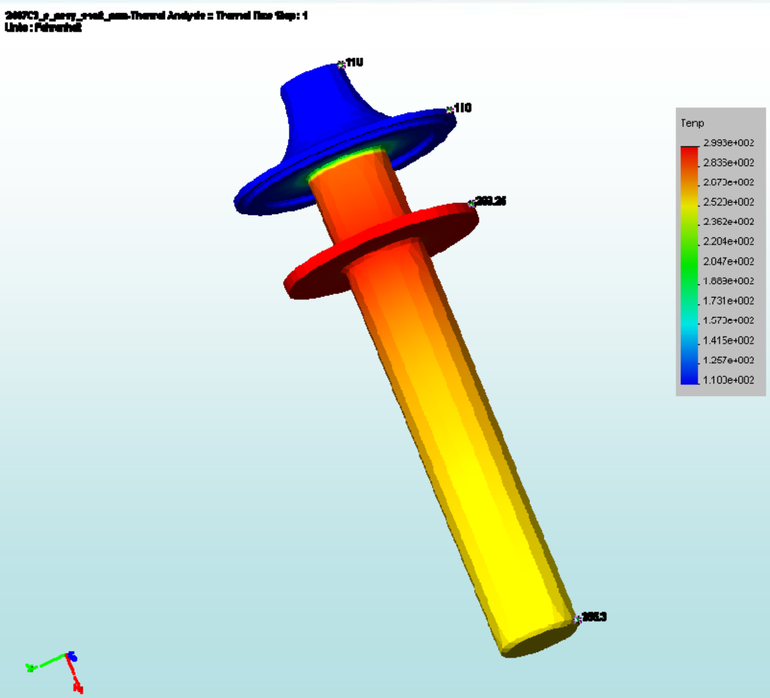


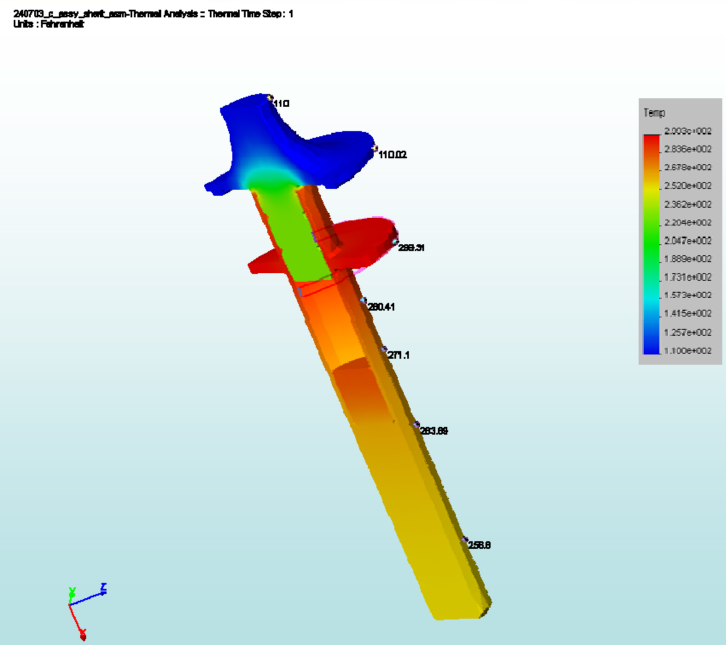


- *All components max operating temperature 50% below melting point.*
- *Thermal growth very meager*
- *Materials properly chosen*

Phase II

-Shaft Heat Transfer





- *Thermal growth very meager*
- *Windage, motor loss & bearing loss properly cooled*
- *Motor rotor & impeller press fit fail proof*

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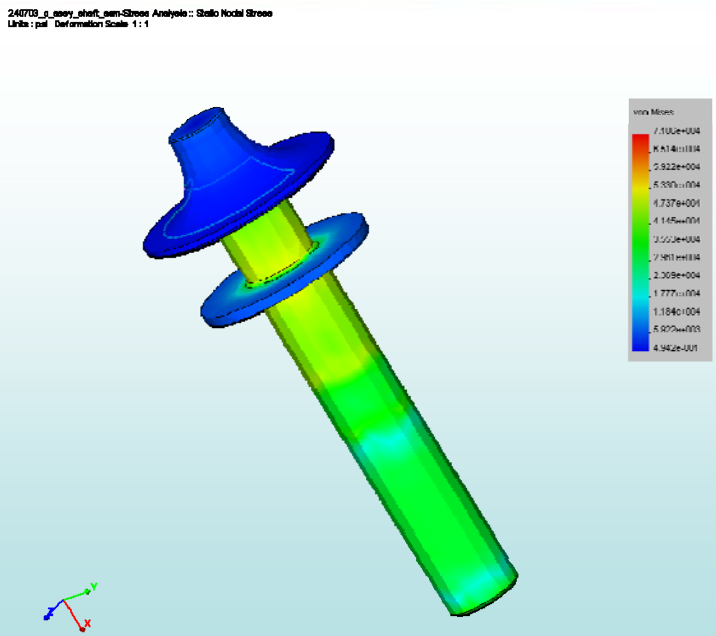
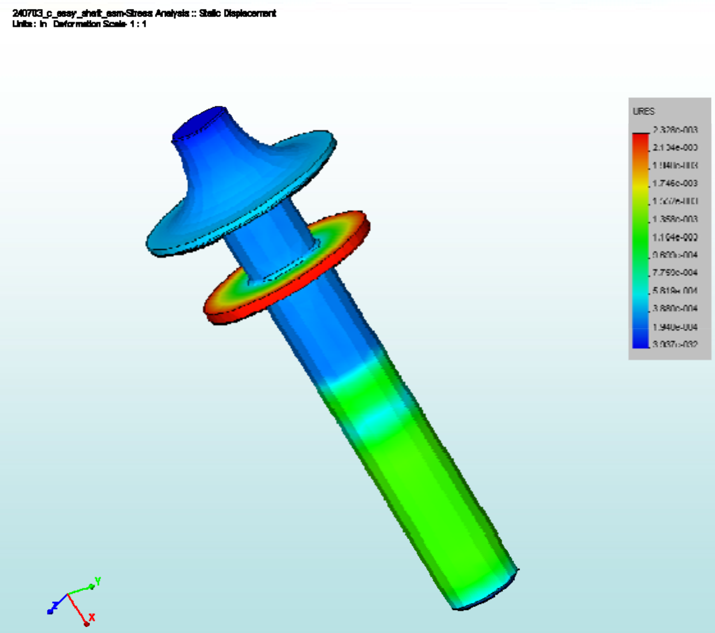
Phase II

-Stress Analysis

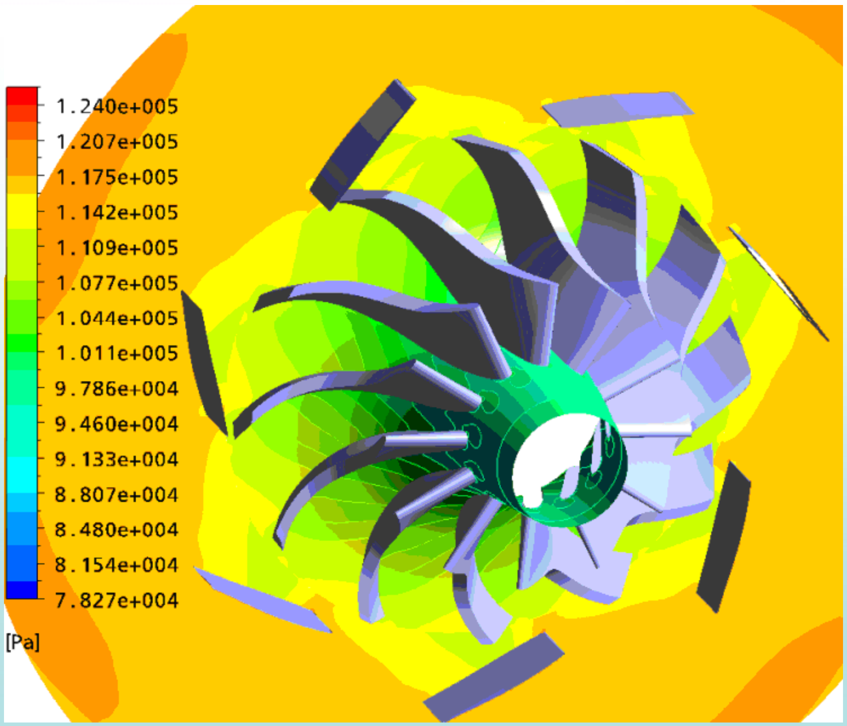


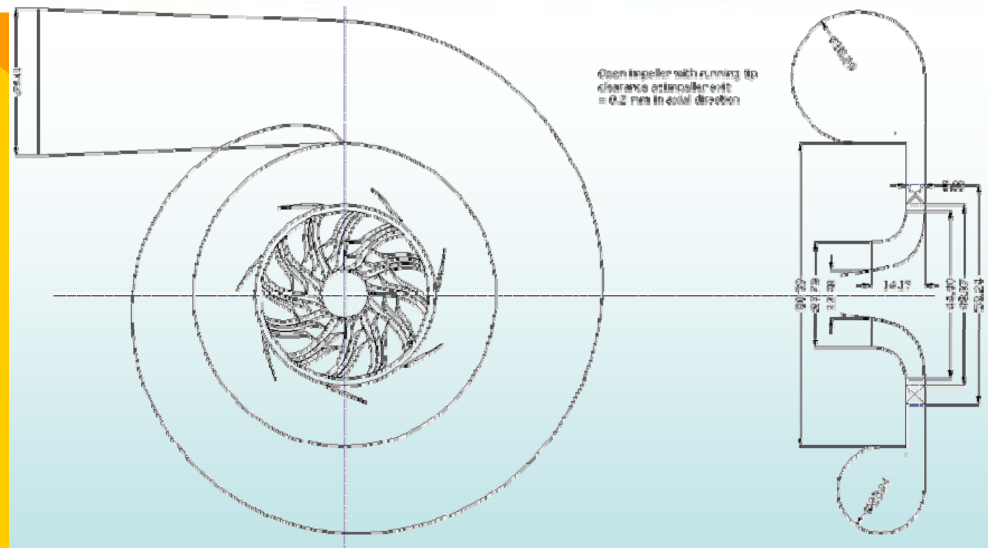


- *Max Von Misses stress 50 % lower than material strength*
- *Shaft assembly very stable at design speed*

Phase II

-Aerodynamic Design





- *Low cost injection moldable blades designed*
- *High efficiency obtained with low solidity diffuser vanes*

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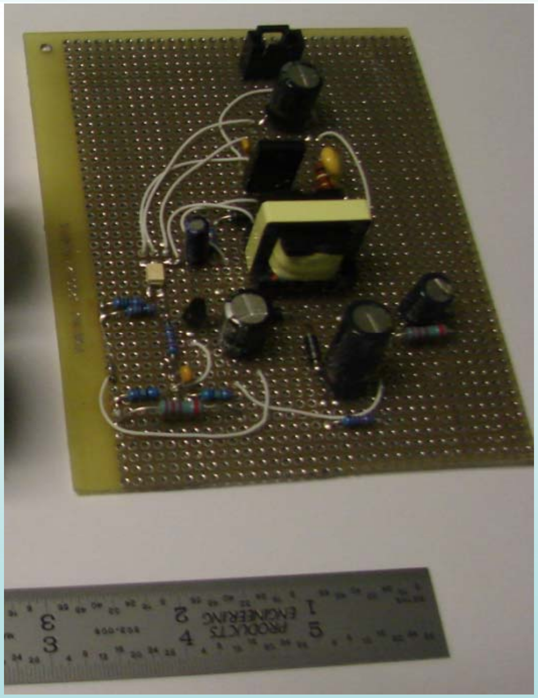
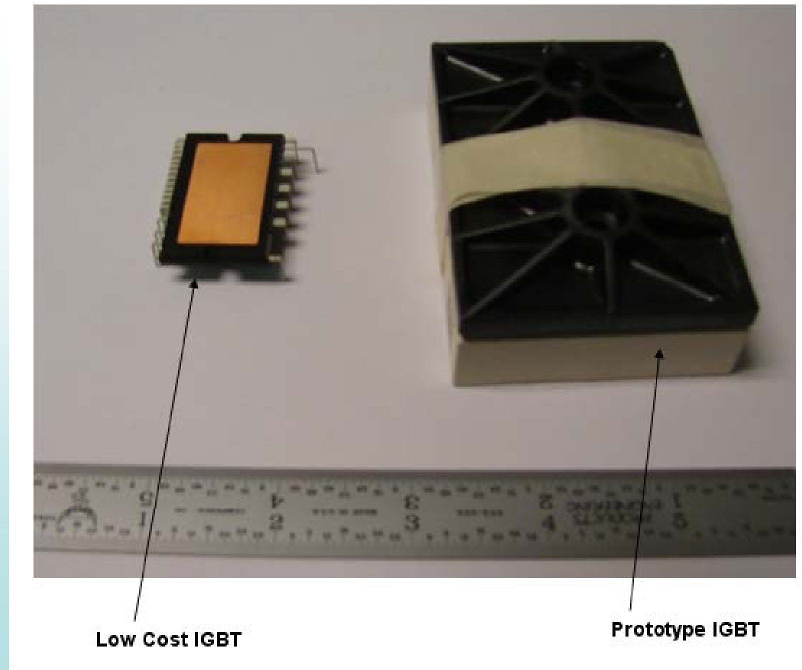
Phase II

- Controller Cost Reduction





- *Left picture shows low cost DC-DC converter developed for the controller*
- *Right picture shows commercial IGBT identified for low cost design*

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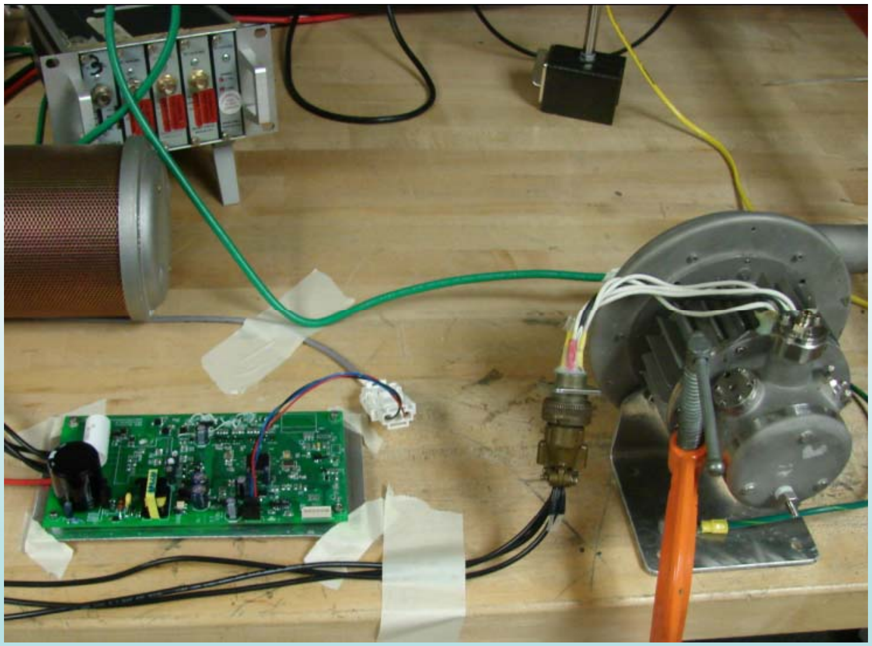
Phase II

-Controller Testing



- *Left picture shows low cost controller being tested using a test blower*
- *Right picture shows uniform controller output current measured during testing*

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Phase II

-Low Cost Controller Conclusions

- *An existing blower was used to test the low cost controller*
- *Controller operated successfully above design speed (>80,500 rpm)*
- *Controller cost < $100 for few thousand units*
- *Low cost controller technology developed successfully*

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Overall Concluding Remarks

Conclusions

✓ Component and SECA member system testing have shown that foil bearing supported blowers will meet…

- High efficiency
- Low volume/weight
- High reliability
- Oil free operation
- Maintenance free operation

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Conclusions (cont'd)

- ✓ DFMA analysis have shown that production cost target of SECA members will be met

- ✓ Pricing of limited production units will require partnership among…

    - ❖ R&D Dynamics
    - ❖ SECA Members
    - ❖ Department of Energy

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Acknowledgement

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