ROTATING INTERSHAFT BRUSH SEAL PROJECT

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U. S. AIR FORCE SMALL BUSINESS INNOVATION RESEARCH PROGRAM (SBIR)

TITLE---ROTATING INTERSHAFT BRUSH SEAL PROJECT

NASA SEAL WORKSHOP

NOVEMBER 8,2005

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The pursuit of high Mach number flight presents several challenges to the airframe and engine design engineers. Most obvious is the resulting high temperatures encountered as the aircraft approaches Mach 3 and above. The encountered high temperatures and shaft speeds of engines require rethinking in the areas of material selections, component design and component operating life.

In the area of sump compartment sealing, one of the most difficult sealing applications is the sealing of an engine's rear sump. Normally this sump will need some method of sealing ***between two rotating shafts*. This sealing operation is done with an intershaft seal.** The aft sump region also presents an additional design requirement for the intershaft seal. ***This region has to absorb the engine's thermal growth, which means that in the seal area, axial movement, on the order of 0.30 in., between the rotating shafts must be tolerated***. A new concept or new technology of sealing an intershaft sump configuration is being developed. ***This concept, called a rotating intershaft brush seal*** has key attributes that will allow this seal to perform better, in the demanding environment of sealing an aft sump with two rotating shafts, when compared to today's sealing technology of labyrinth and carbon seals.

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U. S. AIR FORCE SMALL BUSINESS INNOVATION RESEARCH PROGRAM (SBIR)

PROJECT TITLE---ROTATING INTERSHAFT BRUSH SEALS FOR SEALING BETWEEN TWO ROTATING SHAFTS

PROJECT NUMBER----FA8650-04-M-2463

OBJECTIVE----PROVIDE A SEALING FUNCTION BETWEEN TWO ROTATING SHAFTS AND ABSORB AXIAL TRANSLATION DUE TO THERMAL GROWTH

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U.S. AIR FORCE PROJECT MANAGEMENT TEAM

- 1LT. DAN DOAK, PROGRAM MANAGER
- DR. LEWIS ROSADO, TECHNICAL MANAGER

PROJECT TEAM MEMBERS

- STEPHEN KRAWIECKI, DESIGN ENGINEER, DIVERSITECH, INC
- DR. JAYESH MEHTA, AERODYNAMIST, TK ENGINEERING
- GARY HOLLOWAY, VICE PRESIDENT, DIVERSITECH, INC.

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PROGRAM SUPPORTERS AND PARTICIPANTS

- REXNORD CORP.
- GE AVIATION (GE AIRCRAFT ENGINES)
- NORTH CAROLINA A&T STATE UNIVERSITY
- LONZA CORP.
- AZTEC CORP.
- POLYCRAFT INC.
- NASA GLENN

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CONCEPT AND POTENTIAL BENEFITS

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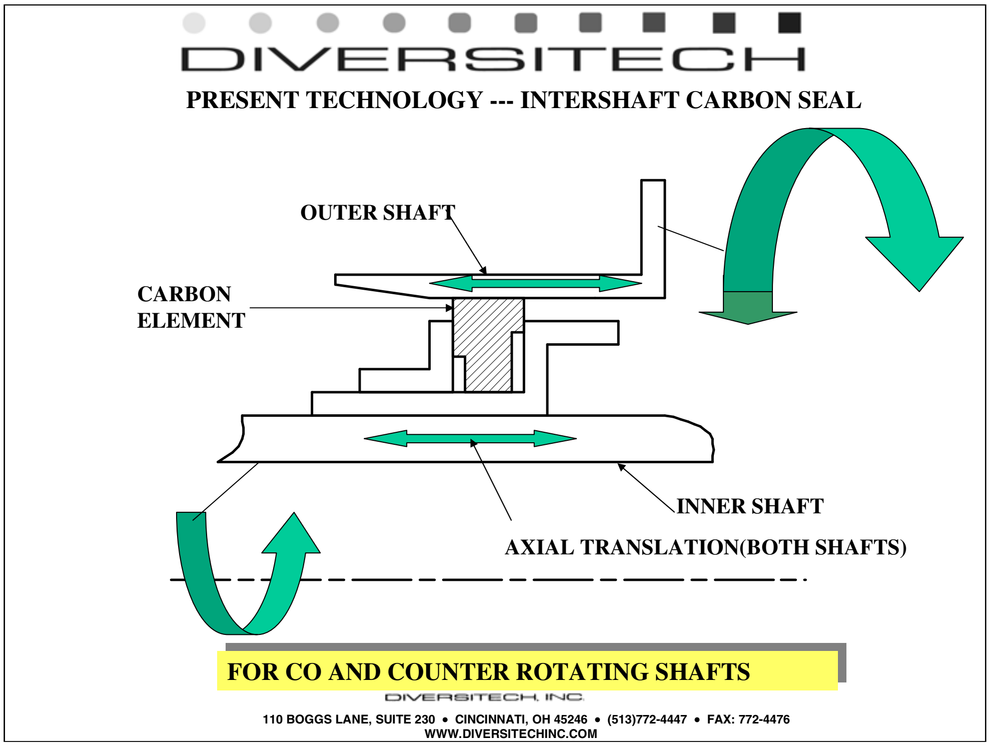
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PRESENT TECHNOLOGY --- INTERSHAFT CARBON SEAL
OUTER SHAFT
CARBON ELEMENT
INNER SHAFT
AXIAL TRANSLATION(BOTH SHAFTS)
FOR CO AND COUNTER ROTATING SHAFTS
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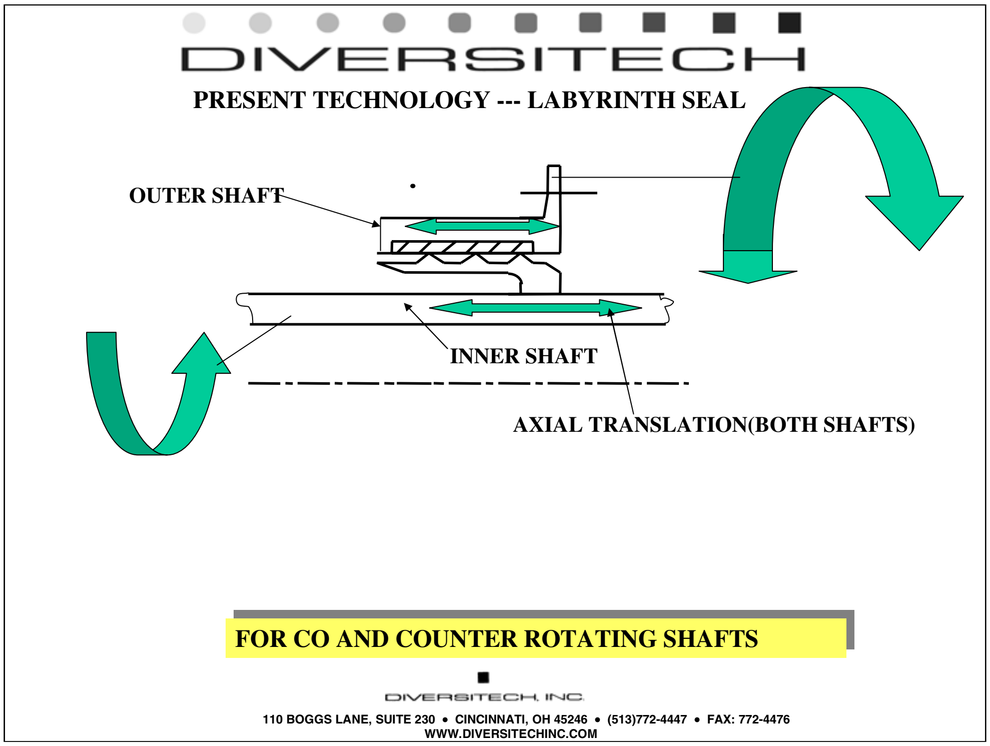
DIVERSITECH
PRESENT TECHNOLOGY --- LABYRINTH SEAL
OUTER SHAFT
INNER SHAFT
AXIAL TRANSLATION(BOTH SHAFTS)
FOR CO AND COUNTER ROTATING SHAFTS
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CARBON SEALS OFFER THE FOLLOWING ATTRIBUTES

- LOW LEAKAGE FLOW WHICH OFFERS LESS LUBRICANT CONSUMPTION AND EMISSIONS
- GOOD OPERATING LIFE
- REQUIRES HIGHLY POLISHED AND COATED SURFACES
- RUBBING SURFACES WHICH REQUIRE LUBRICANT COOLING DIRECTLY OR INDIRECTLY
- PRONE TO DAMAGE DURING HANDLING AND ENGINE ASSEMBLY DUE TO THE BRITTLE CHARACTERISTIC OF THE CARBON MATERIAL

LABYRINTH SEALS OFFER THE FOLLOWING ATTRIBUTES

- NON-CONTACTING SEALING SURFACES, ELIMINATING THE NEED TO COOL THE SEAL

HIGH LEAKAGE FLOWS, RESULTING IN HIGH LUBRICANT CONSUMPTION WHEN COMPARED TO CARBON SEALS

- GOOD OPERATING LIFE
- DOES NOT REQUIRE POLISHED SURFACES
- ROBUST DESIGN, NOT PRONE TO DAMAGE DURING HANDLING OR ENGINE ASSEMBLY

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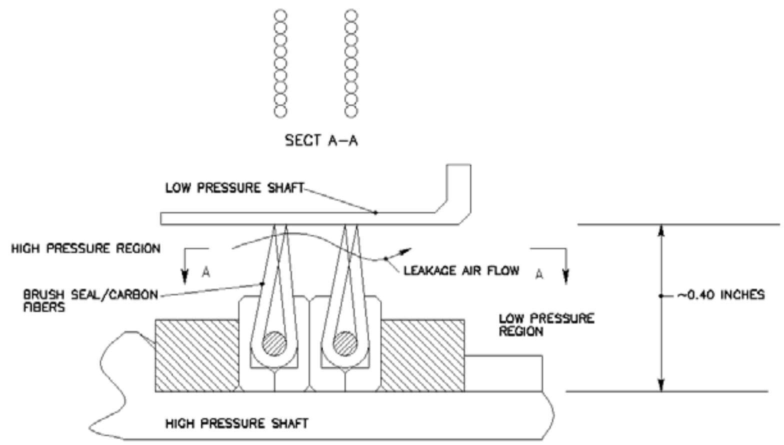
INTERSHAFT BRUSH SEAL CONCEPT

APPROACH-----USE A CARBON FIBER BRUSH SEAL BETWEEN TWO ROTATING SHAFTS



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POTENTIAL BENEFITS

- MORE ROBUST DESIGN FOR ENGINE ASSEMBLY
  - LESS CHANCE OF BREAKAGE, COMPARED TO CARBON SEAL
- POTENTIAL LESS HEAT GENERATION DUE TO REDUCED NUMBER OF RUBBING SURFACES
  - POTENTIAL USE OF HIGH CONDUCTIVITY CARBON FIBERS k~500 BTU/HR-°F-ft (Cu k~230 BTU/HR-°F-ft
  - LESS RUBBING SURFACE COMPARED TO CARBON SEAL
- ABLE TO ABSORB SHAFT AXIAL TRANSLATION BETTER WHEN COMPARED TO PRESENT TECHNOLOGY CARBON SEALS
- POTENTIALLY LESS COSTLY
- LESS LEAKAGE FLOW WHEN COMPARED TO LABYRINTH SEALS

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SEAL TECHNOLOGY COMPARISON

PARAMETER	SEAL CONFIGURATION		
	CARBON SEAL	ROTATING BRUSH SEAL	LABYRINTH SEAL
AIR LEAKAGE	LOW	MEDIUM	HIGH
OPERATING LIFE	SHORT TO MEDIUM	LONG	LONG
NEEDS POLISHED SURFACES	YES	NO	NO
RUBBING SURFACES	YES	YES	NO
ASSEMBLY DAMAGE POTENTIAL	HIGH	LOW	LOW
SEALS BETWEEN ROTATING SHAFTS	YES	YES	YES
AXIAL SHAFT TRANSLATION CAPABILITY	LOW	HIGH	HIGH
HEAT GENERATION	HIGH	MEDIUM	LOW

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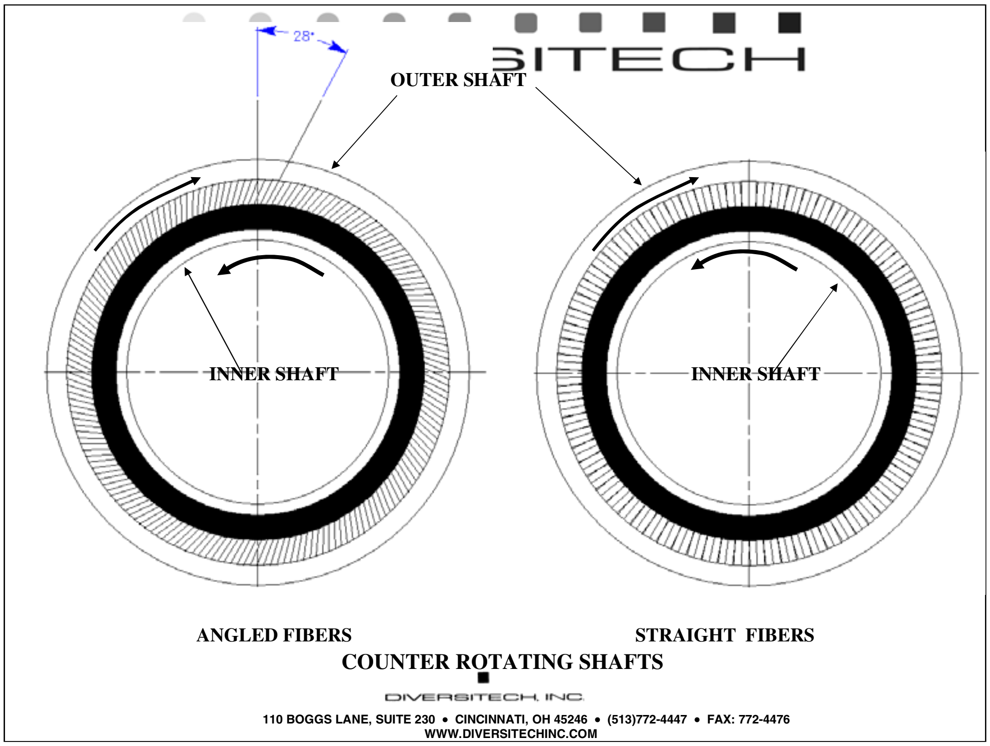
28°
OUTER SHAFT
INNER SHAFT
INNER SHAFT
ANGLED FIBERS
STRAIGHT FIBERS
COUNTER ROTATING SHAFTS
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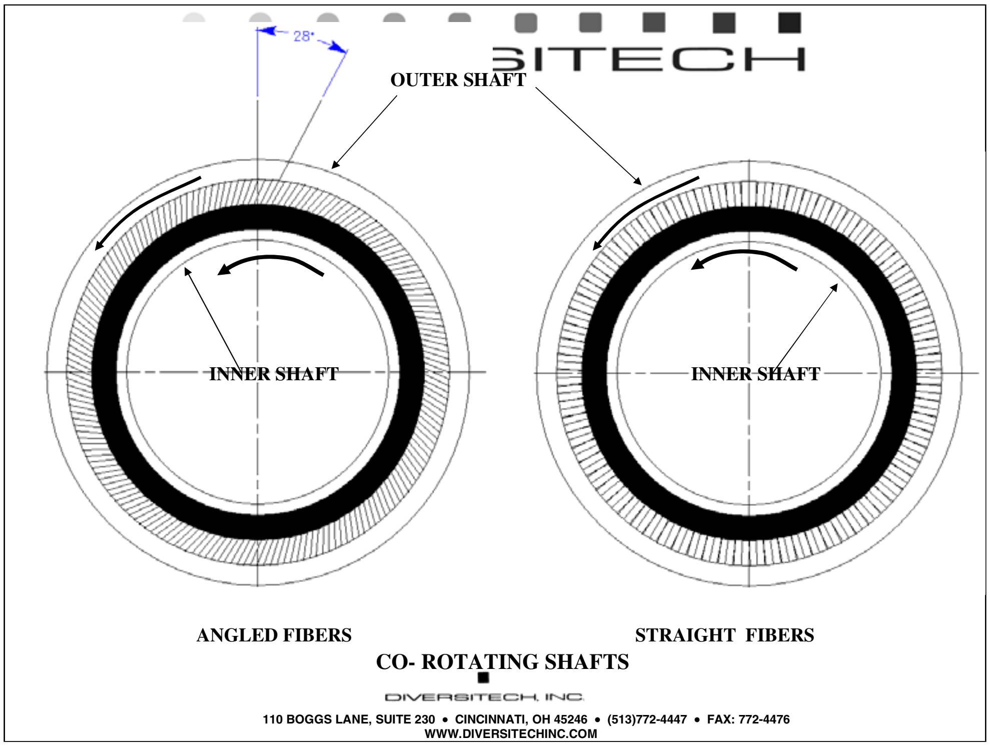
28°
SITECH
OUTER SHAFT
INNER SHAFT
INNER SHAFT
ANGLED FIBERS
STRAIGHT FIBERS
CO- ROTATING SHAFTS
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DESIGN

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PROGRAM STRUCTURE

- **FIBER RESEARCH AND SELECTION**
- **LEAKAGE AND HEAT GENERATION ANALYSIS**
- **WEAR AND LIFE ANALYSIS**
- **ROTATING BRUSH SEAL CONFIGURATION DEVELOPMENT**
- **POTENTIAL USE ANALYSIS-END USERS AND SEAL MANUFACTURERS**

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Task 1-Carbon Fiber Research
Effort undertaken to identify carbon fibers which could be used for the rotating brush seal application
Key parameters that will be used for fiber ranking
1. Fiber thermal conductivity--interface temperature impact
2. Fiber elastic modulus-fiber stiffness
3. Fiber strain capability- deflection and deformation limitations, assembly robustness
4. Fiber strength-high speed limitations
5. Fiber endurance limit -impact on fatigue life and engine cycles
5. Fiber hardness--impact on wear life
6. Tow size available-impact on fiber density and seal thickness

Task 2-Leakage and Heat Generation Analysis
Effort undertaken to analyze the brush seal performance under various speed and pressure combinations.
Will use CFD codes such as Fluent or NASA developed brush seal codes and ANSYS for seal stresses and deflections
Analysis will be undertaken for
1. Leakage flow
2. Delta p limitations
3. Fiber packing
4. Fiber stress and deflection
5.Limiting rubbing speeds due to heat generation and material temperature limits
6. Energy loss due to fiber rubbing

Task 3-Wear and Life Analysis
Analysis will undertaken to development a wear model
The wear model will account for the following interactions
1. Fiber and outer shaft material harness
2. Rubbing speeds between the fiber and shaft rubbing surface
3. Interface temperature
4. Interface friction

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PROGRAM STRUCTURE

- **FIBER RESEARCH AND SELECTION**
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- **ROTATING BRUSH SEAL CONFIGURATION DEVELOPMENT**
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Task 4-Conceptual Configuration Development
Under this task two seal configurations will be developed for manufacture under a Phase II program. The two configurations are:
•Proof of concept configuration-small scaled
 -This configuration would be used for verification of key operating parameters such as leakage performance, heat generation. This seal type could be tested at a seal vendor such as Rexnord Corp.
•Full scale configuration
 -This configuration would be a full scaled engine size that could be tested on test rigs and engines (F110 size) such as GE Aircraft Engines

Task 5-Potential Use Analysis
Under this task, Diversitech will survey key companies about the potential benefit and interest in this technology

End Users	Seal Manufactures
GE Transportation	Rexnord Seal Company
Pratt & Whitney	Stein Seal Company
Allison Advance Development Company	Kaydon Ring and Seal
Honeywell	Perkin Elmer Corporation
Williams International	
Teledyne	

Commercialization Strategy
Based on successful development of the rotating brush seal concept the potential aircraft engine market is as follows:
- New engine applications both military and commercial
- Existing engines such as the GE-F110, GE-CFM-56

Seal Manufacturers
Potential new product line for the seal manufactures who supply the aircraft industry
- Rexnord Corp
- Stein Seal
- Kaydon Ring and Seal Company
- Perkin Elmer Corp

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SEAL PARAMETERS USED IN THIS STUDY WERE:

- INNER SHAFT RPM---------5,000 TO 20,000
- INLET TEMPERATURE-------400 ^{O}F
- INLET PRESSURE-------------60 PSIA
- SEAL Δp ---------------------5,10,15,20,25,30,35,40 PSID
- EXIT (SUMP)TEMPERATURE 300 ^{O}F
- SEAL OUTER DIAMETER--------7.55 INCHES (FIXED)
- INNER DIAMETERS---------------6.65, 7.1,7.3 INCHES

MAX. ENGINE SOAKBACK TEMPERATURE-------550^{O}F

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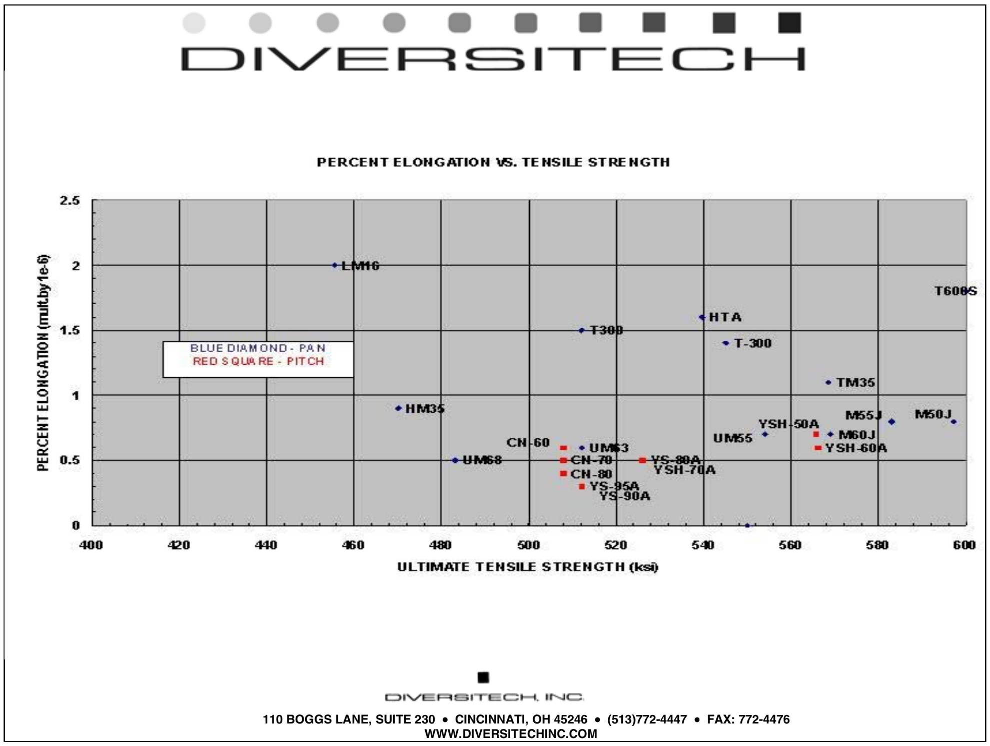
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PERCENT ELONGATION VS. TENSILE STRENGTH
PERCENT ELONGATION (mult.by1e-6)
ULTIMATE TENSILE STRENGTH (ksi)
BLUE DIAMOND - PAN
RED SQUARE - PITCH
0
0.5
1
1.5
2
2.5
400
420
440
460
480
500
520
540
560
580
600
LM16
T300
HTA
T-300
T600S
TM35
HM35
M55J
M50J
YSH-50A
UM55
M60J
YSH-60A
CN-60
UM63
UM68
CN-70
YS-80A
YSH-70A
CN-80
YS-95A
YS-90A
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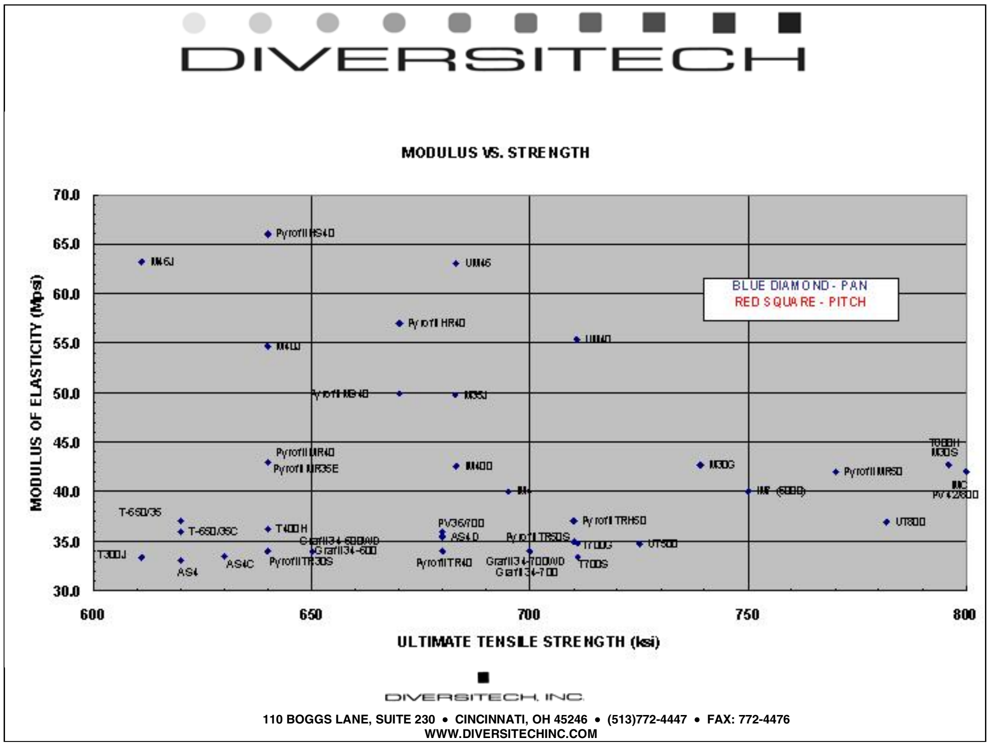
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MODULUS VS. STRENGTH
MODULUS OF ELASTICITY (Mpsi)
ULTIMATE TENSILE STRENGTH (ksi)
BLUE DIAMOND - PAN
RED SQUARE - PITCH
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
600
650
700
750
800
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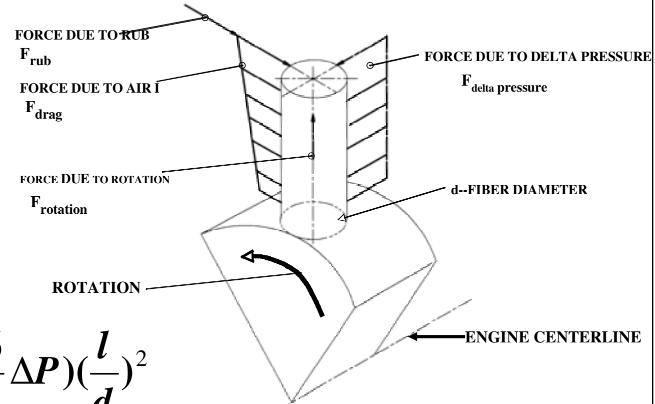
FIBER FORCE MODEL



$$\sigma_{Pressure/Bending} = (\frac{16}{\pi}\Delta P)(\frac{l}{d})^2$$

$$\sigma_{P/A} = \frac{\rho_{fiber/composite}}{2g}(R^2{}_O - R^2{}_i)(\omega)^2$$

$$\sigma_{drag/bending} = 2(C_{drag})(\frac{\rho_{air}}{\pi g})\left[(R_o + R_i)(\omega)\right]^2(\frac{l}{d})^2$$

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Vortex Shedding Frequency

$$f = 0.22(\frac{V}{D}) = 0.22(\frac{R_0 * \omega}{D_{FIBER}})(cycles / \sec ond)$$

R_o= Tip Radius of Fiber

D= Fiber Diameter

$\omega =$ Seal Rotational Speed (radians/second)

$$F_{vib} \approx (C_d \cdot \rho \frac{V^2}{2g} \cdot A) \sin(2\pi f)t = F_{DRAG} \cdot \sin(2\pi f)t$$

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FIBER VOLUME FRACTION	MATRIX MATERIAL	CARBON FIBER MATERIAL
	PT-30	T300
	TENSILE STRENGTH (PSI)	TENSILE STRENGTH (PSI)
100	0	512,000
0	5000	0
	MODULUS (PSI)	MODULUS (PSI)
100	0	33,400,000
0	400,000	0
	STRAIN (%)	STRAIN (%)
100	0	1.5
0	2	0
	DENSITY (LBS/IN^3)	DENSITY (LBS/IN^3)
------	0.0455	0.0635

50% FIBER VOLUME COMPOSITE PROPERTIES
MATRIX/CARBON FIBER
PT-30/T300
TENSILE STRENGTH (PSI)
258,500
MODULUS (PSI)
16,900,000
STRAIN (%)
1.75
DENSITY (LBS/IN^3)
0.0545

PROPERTIES BASED ON RULE OF MIXTURES

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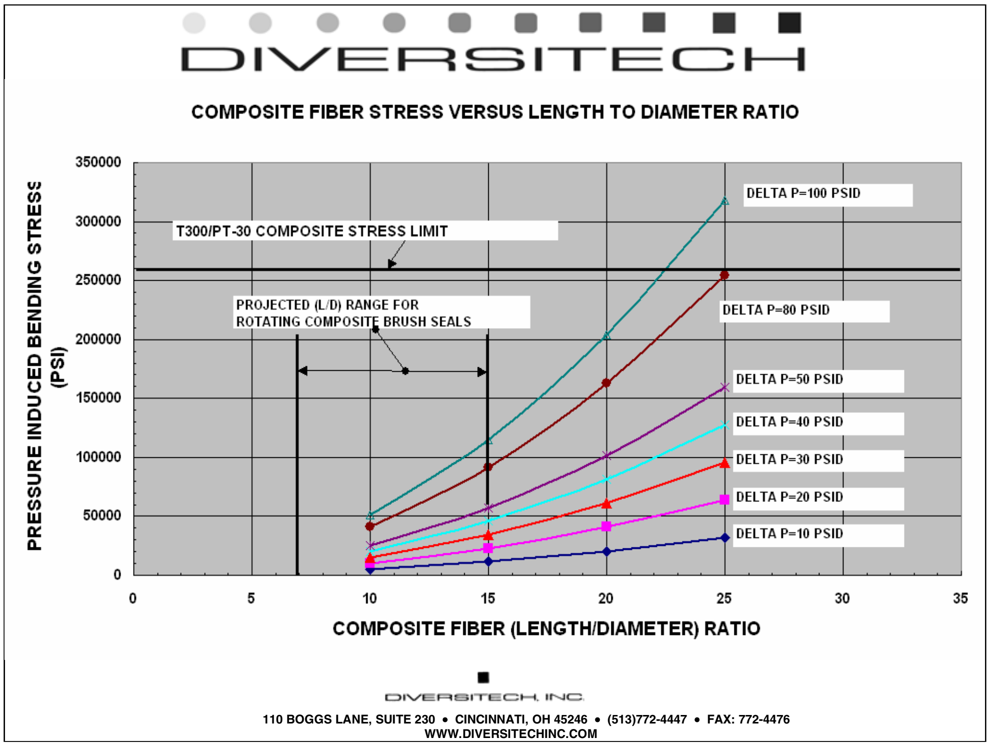
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COMPOSITE FIBER STRESS VERSUS LENGTH TO DIAMETER RATIO
PRESSURE INDUCED BENDING STRESS (PSI)
T300/PT-30 COMPOSITE STRESS LIMIT
PROJECTED (L/D) RANGE FOR ROTATING COMPOSITE BRUSH SEALS
DELTA P=100 PSID
DELTA P=80 PSID
DELTA P=50 PSID
DELTA P=40 PSID
DELTA P=30 PSID
DELTA P=20 PSID
DELTA P=10 PSID
COMPOSITE FIBER (LENGTH/DIAMETER) RATIO
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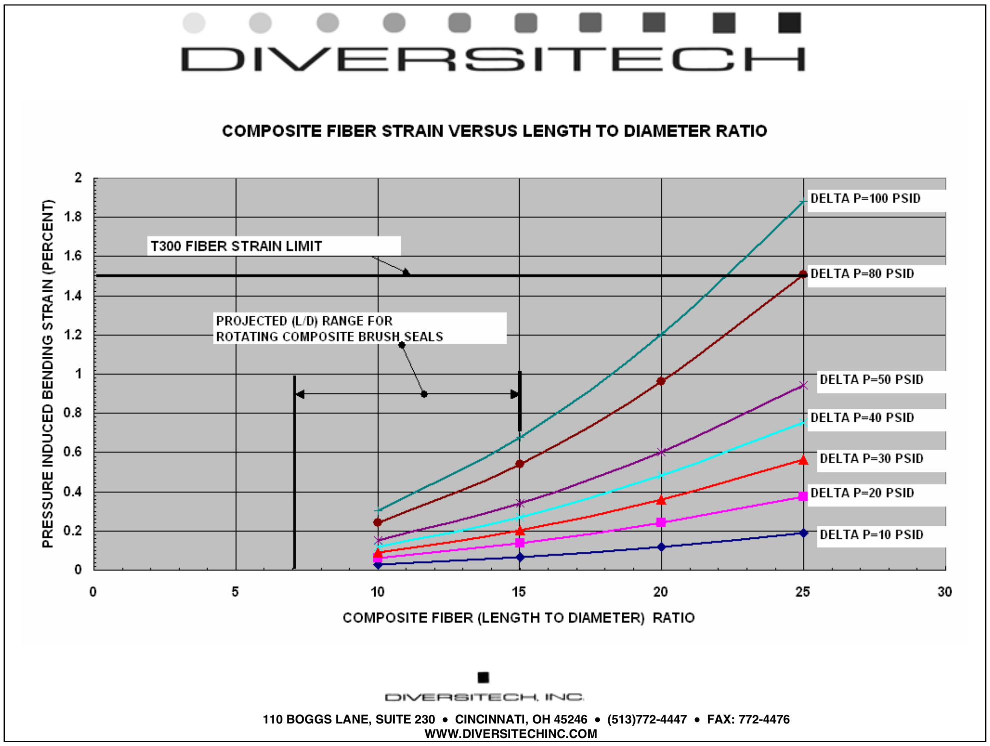
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COMPOSITE FIBER STRAIN VERSUS LENGTH TO DIAMETER RATIO
PRESSURE INDUCED BENDING STRAIN (PERCENT)
COMPOSITE FIBER (LENGTH TO DIAMETER) RATIO
T300 FIBER STRAIN LIMIT
PROJECTED (L/D) RANGE FOR
ROTATING COMPOSITE BRUSH SEALS
DELTA P=100 PSID
DELTA P=80 PSID
DELTA P=50 PSID
DELTA P=40 PSID
DELTA P=30 PSID
DELTA P=20 PSID
DELTA P=10 PSID
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
5
10
15
20
25
30
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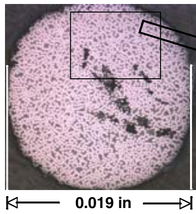
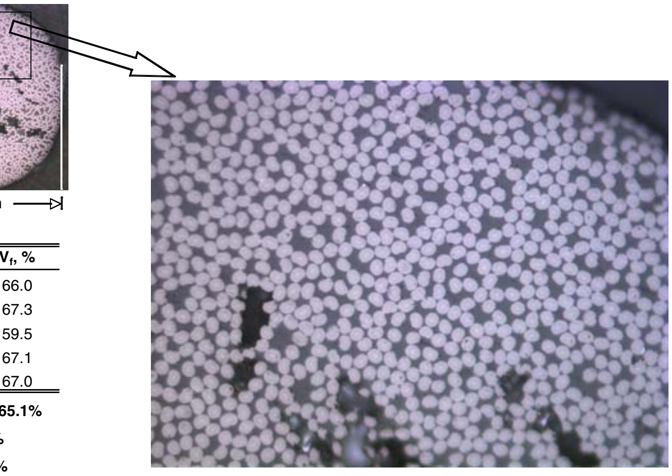
Microscopy of Fiber Distribution and Fiber Volume Fraction of T650/PT-30 Pultruded Rods





Sample #	V_f, %
1	66.0
2	67.3
3	59.5
4	67.1
5	67.0

Average = 65.1%

STD = 3.3%

CV% = 5.1%

Center for Composite Materials Research

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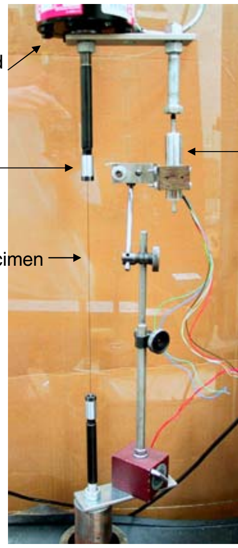
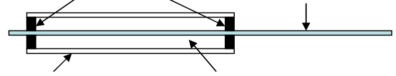
Tension Test and Results of T650/PT30 Pultruded Composites

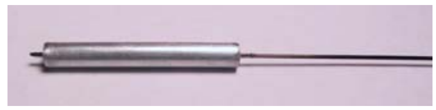
Baseline Case

Test Setup on MTS Frame



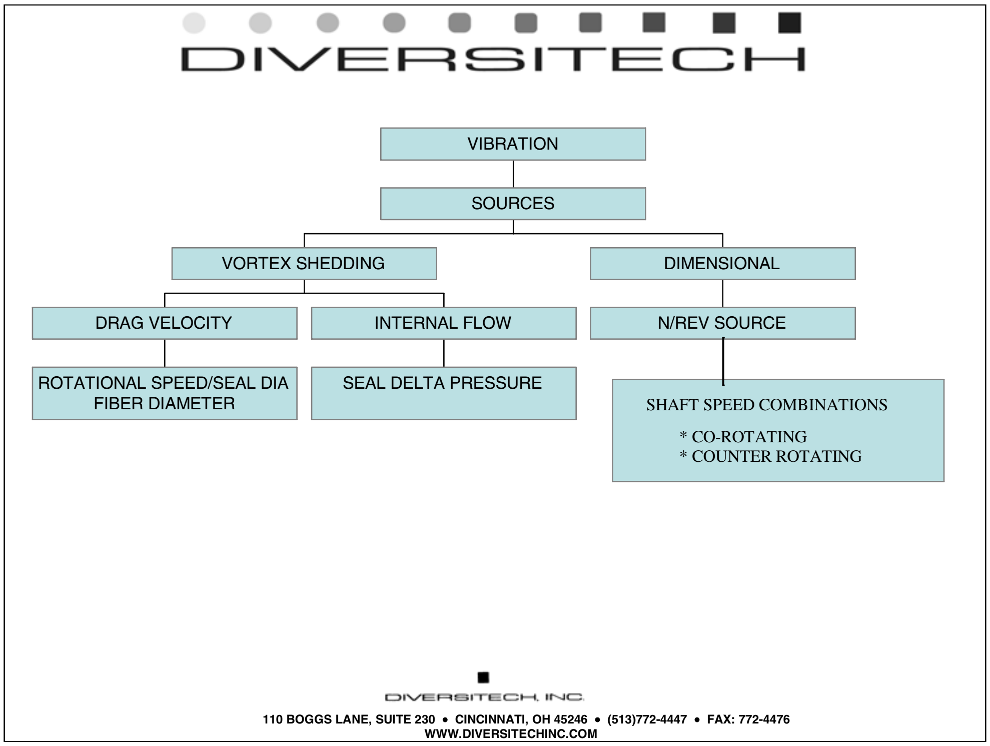
Close-up of lower collet





Specimen #	Tensile Strength (ksi)	Modulus (Msi)	Strain (%)
div-ten-BL-1	253.6	19.99	1.26
div-ten BL-2	262.7	20.16	1.30
div-ten-BL-3	257.0	20.14	1.27
div-ten BL-4	267.3	20.10	1.33
div-ten-BL-5	266.6	19.97	1.33
div-ten BL-6	250.3	20.06	1.25
div-ten-BL-7	249.7	19.59	1.27
div-ten BL-8	261.2	20.10	1.29
div-ten-BL-9	242.5	19.76	1.23
div-ten BL-10	235.1	19.93	1.17
Average	**254.6**	**19.98**	**1.27**
STD	10.5	0.18	0.05
CV (%)	**4.1**	**0.91**	**3.8**

Center for Composite Materials Research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VIBRATION
SOURCES
VORTEX SHEDDING
DIMENSIONAL
DRAG VELOCITY
INTERNAL FLOW
N/REV SOURCE
ROTATIONAL SPEED/SEAL DIA
FIBER DIAMETER
SEAL DELTA PRESSURE
SHAFT SPEED COMBINATIONS
* CO-ROTATING
* COUNTER ROTATING
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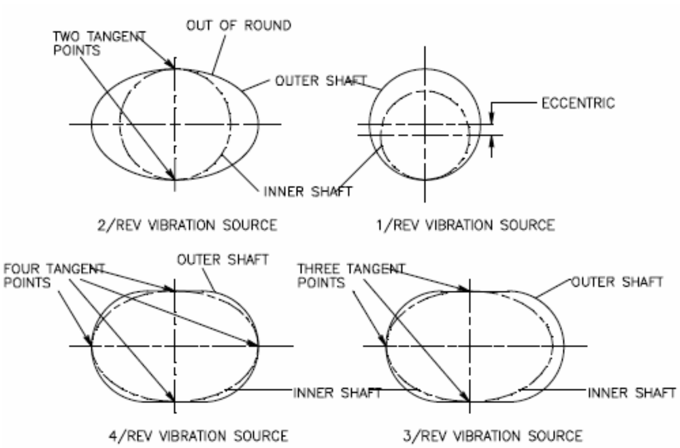
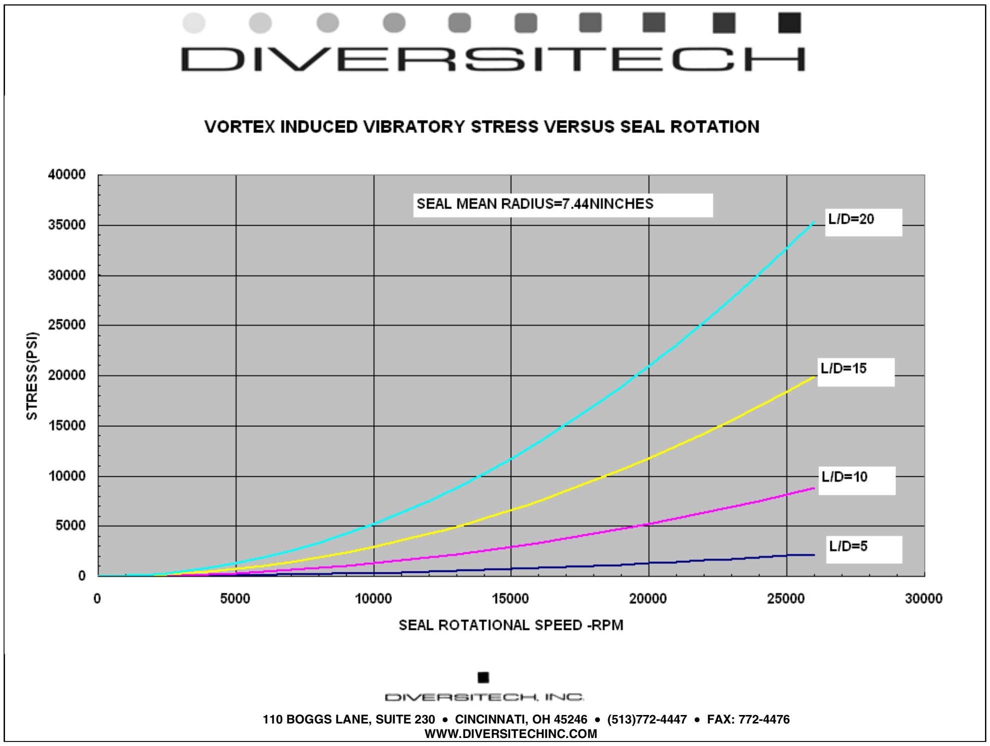
DIMENSIONAL VIBRATION SOURCES



CYCLIC INPUT	FREQUENCY INPUT FOR CO-ROTATING SHAFTS (CPS)	FREQUENCY INPUT FOR COUNTER ROTATING SHAFTS (CPS)
1/REV	$f_1=(\omega_{outer}-\omega_{inner})/60$	$f_1=(\omega_{outer}+\omega_{inner})/60$
2/REV	$f_2=2(\omega_{outer}-\omega_{inner})/60$	$f_2=2(\omega_{outer}+\omega_{inner})/60$
3/REV	$f_3=3(\omega_{outer}-\omega_{inner})/60$	$f_3=3(\omega_{outer}+\omega_{inner})/60$
4/REV	$f_4=4(\omega_{outer}-\omega_{inner})/60$	$f_4=4(\omega_{outer}+\omega_{inner})/60$

2-4476


DIVERSITECH
VORTEX INDUCED VIBRATORY STRESS VERSUS SEAL ROTATION
SEAL MEAN RADIUS=7.44NINCHES
L/D=20
L/D=15
L/D=10
L/D=5
STRESS(PSI)
40000
35000
30000
25000
20000
15000
10000
5000
0
0
5000
10000
15000
20000
25000
30000
SEAL ROTATIONAL SPEED -RPM
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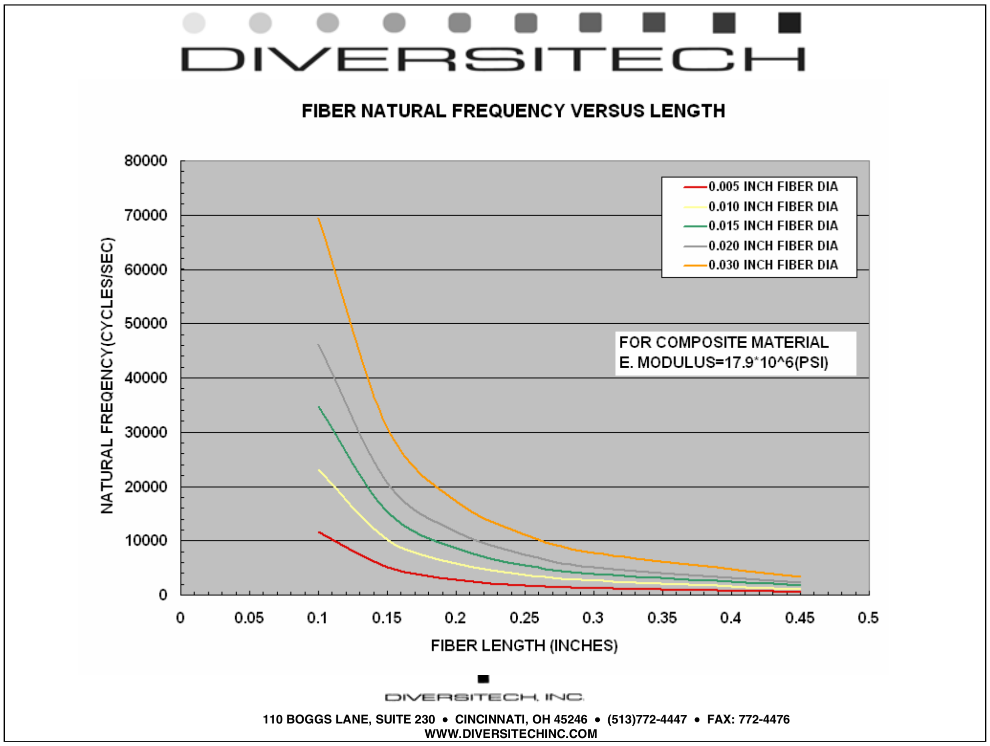
DIVERSITECH
FIBER NATURAL FREQUENCY VERSUS LENGTH
NATURAL FREQENCY(CYCLES/SEC)
FIBER LENGTH (INCHES)
0.005 INCH FIBER DIA
0.010 INCH FIBER DIA
0.015 INCH FIBER DIA
0.020 INCH FIBER DIA
0.030 INCH FIBER DIA
FOR COMPOSITE MATERIAL
E. MODULUS=17.9*10^6(PSI)
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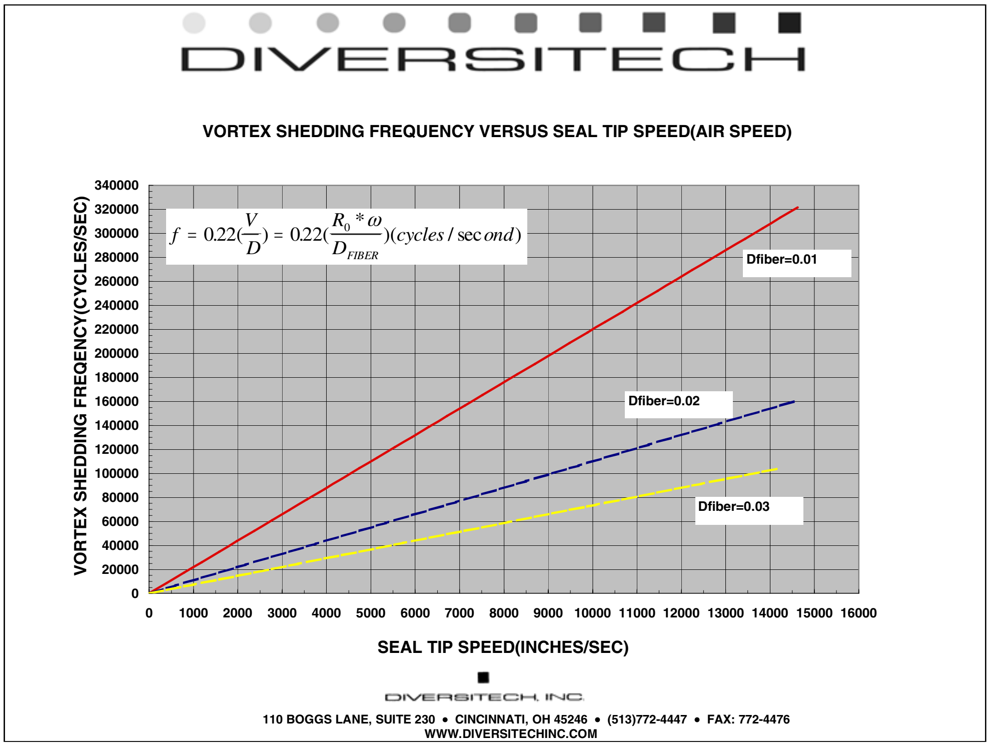

DIVERSITECH
VORTEX SHEDDING FREQUENCY VERSUS SEAL TIP SPEED(AIR SPEED)
$f = 0.22(\frac{V}{D}) = 0.22(\frac{R_0 * \omega}{D_{FIBER}})(cycles / second)$
Dfiber=0.01
Dfiber=0.02
Dfiber=0.03
VORTEX SHEDDING FREQENCY(CYCLES/SEC)
SEAL TIP SPEED(INCHES/SEC)
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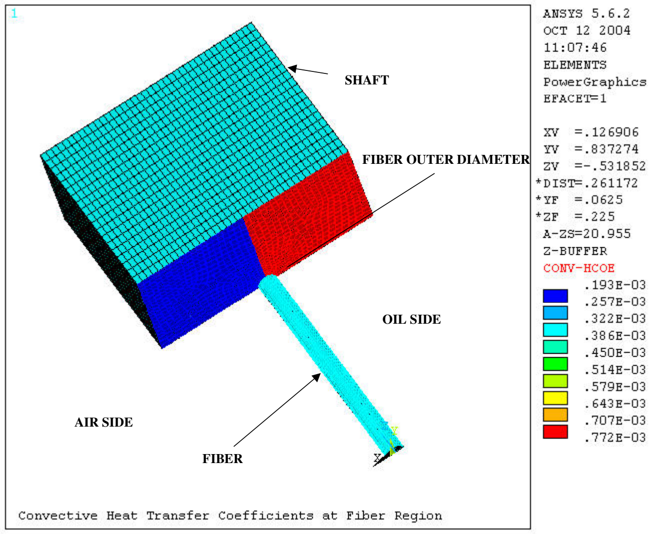

FIGURE 333

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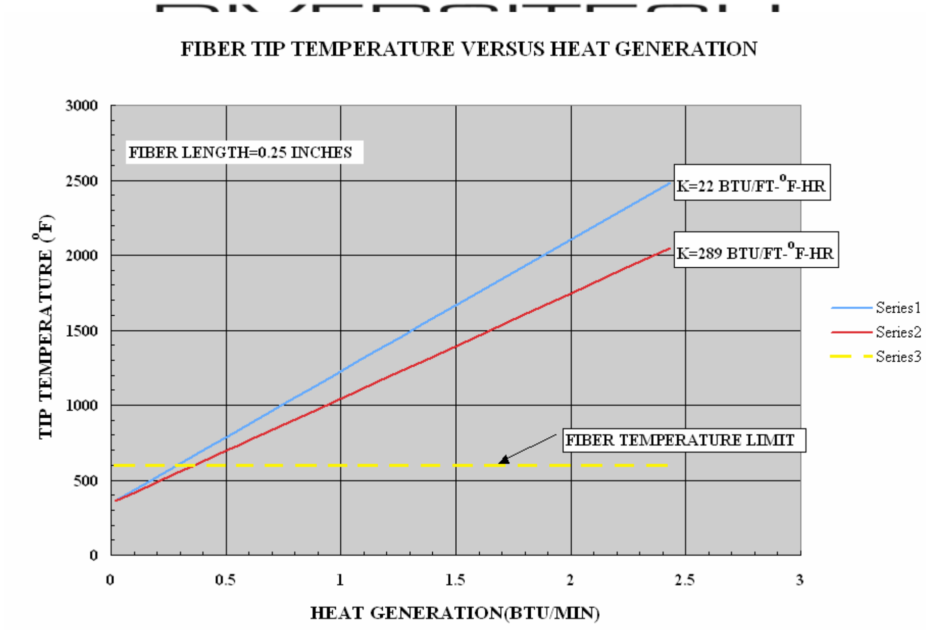

FIGURE 333

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<u>PROBLEM</u>

•HEAT GENERATION WILL CAUSE TEMPERATURE TO EXCEED MATERIAL LIMITS

<u>SOLUTION</u>

•MINIMIZE RUBBING CONTACT BY DESIGNING FOR CLEARANCE OPERATION

<u>BENEFITS</u>

• LOW WEAR AND HIGHER SPEED CAPABILITY

• MINIMIZES VIBRATION INPUTS AND FATIGUE DAMAGE

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AERO DESIGN

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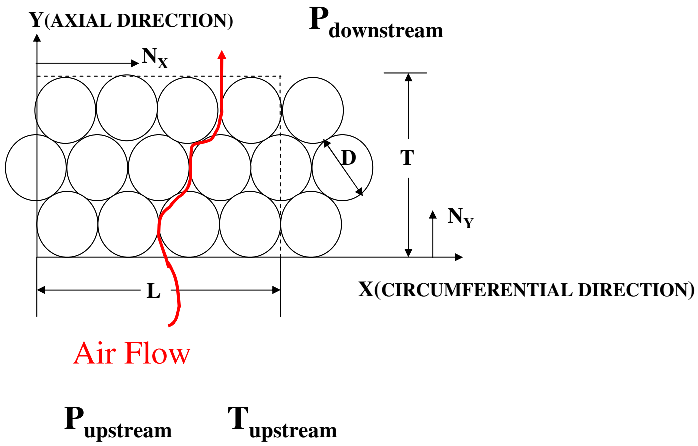

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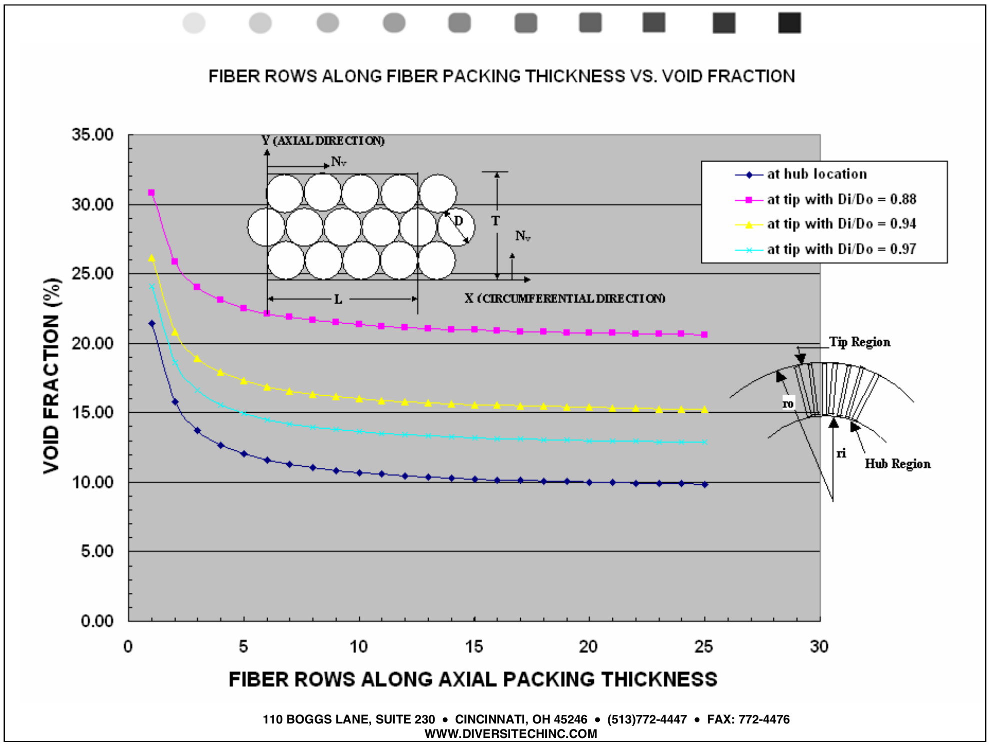

FIBER ROWS ALONG FIBER PACKING THICKNESS VS. VOID FRACTION
VOID FRACTION (%)
FIBER ROWS ALONG AXIAL PACKING THICKNESS
at hub location
at tip with Di/Do = 0.88
at tip with Di/Do = 0.94
at tip with Di/Do = 0.97
Y (AXIAL DIRECTION)
X (CIRCUMFERENTIAL DIRECTION)
Tip Region
Hub Region
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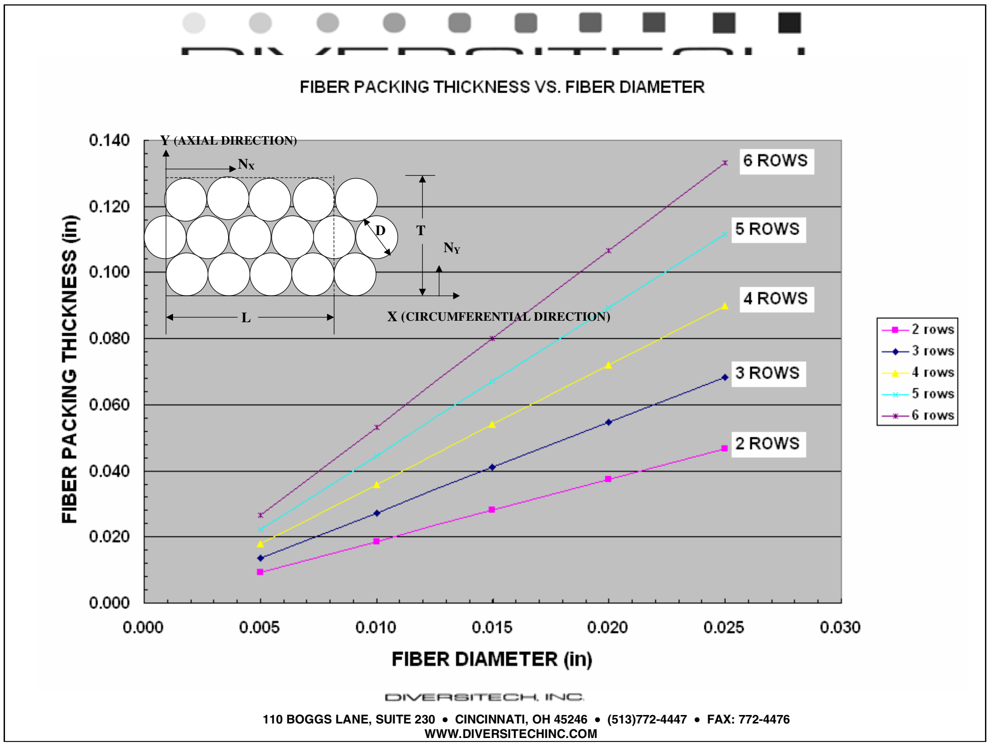
FIBER PACKING THICKNESS VS. FIBER DIAMETER
FIBER PACKING THICKNESS (in)
FIBER DIAMETER (in)
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Y (AXIAL DIRECTION)
X (CIRCUMFERENTIAL DIRECTION)
D
T
L
6 ROWS
5 ROWS
4 ROWS
3 ROWS
2 ROWS
2 rows
3 rows
4 rows
5 rows
6 rows
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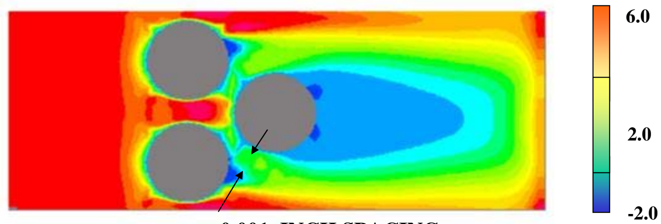
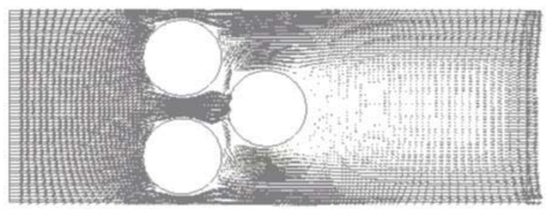
CONCERT Based Velocity Contours And Velocity Vectors
Six Rows – Do = 7.18 Inches, Di = 6.782 Inches, Pu = 60 psia, Pu/Pd = 2.0



0.001 INCH SPACING

Velocity Contours for Three Rows – Velocity In Ft/Sec.



Velocity Vectors for Three Rows

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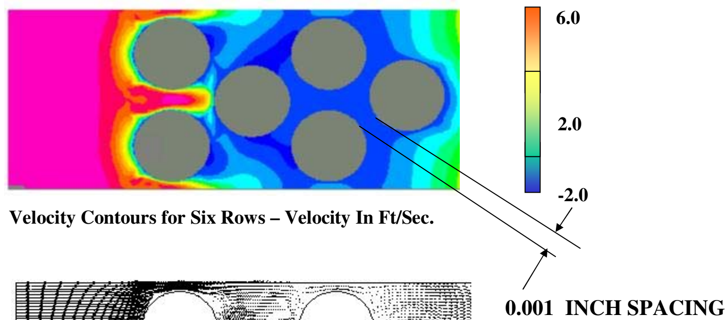
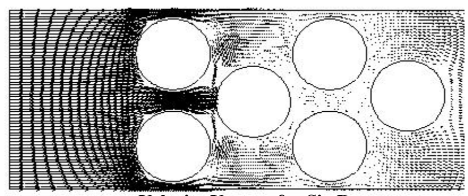
CONCERT Based Velocity Contours And Velocity Vectors
Six Rows – Do = 7.18 Inches, Di = 6.782 Inches
Pu = 60 psia, Pu/Pd = 2.0



Velocity Contours for Six Rows – Velocity In Ft/Sec.



Velocity Vectors for Six Rows

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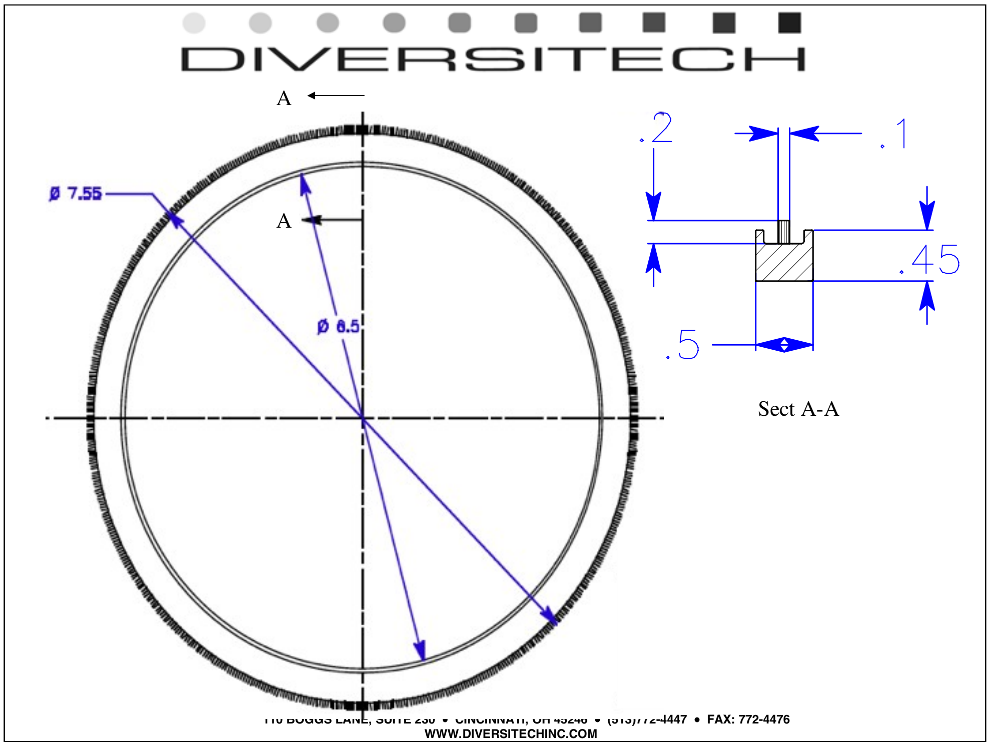
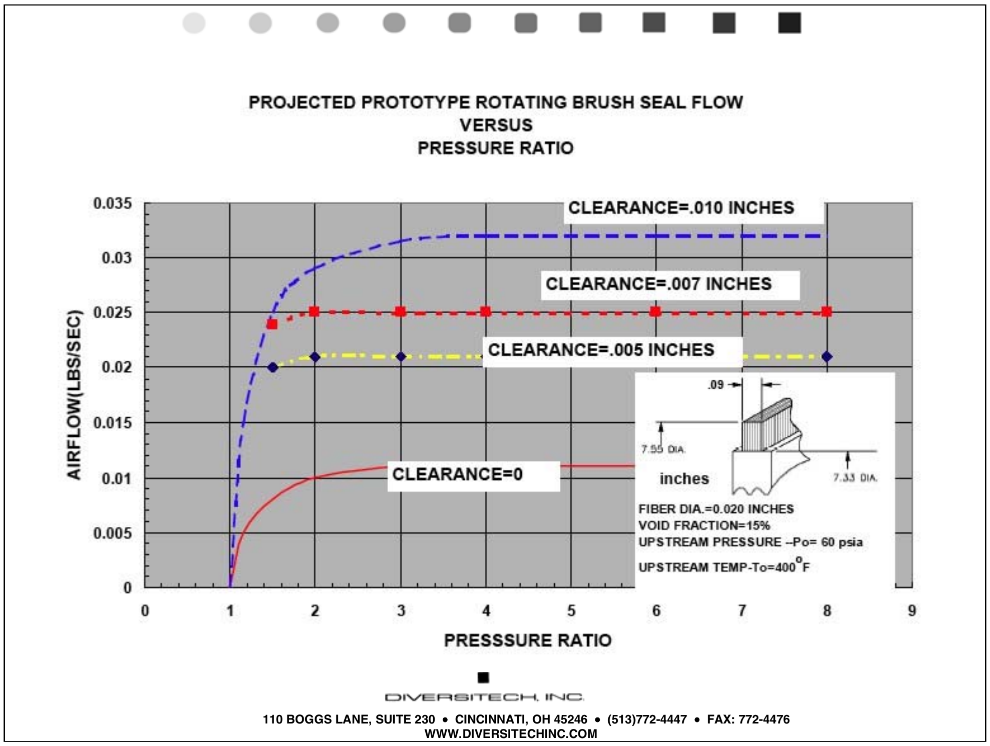


Resulting Seal From Phase 1 Design Effort


PROJECTED PROTOTYPE ROTATING BRUSH SEAL FLOW
VERSUS
PRESSURE RATIO
AIRFLOW(LBS/SEC)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
CLEARANCE=.010 INCHES
CLEARANCE=.007 INCHES
CLEARANCE=.005 INCHES
CLEARANCE=0
.09
7.55 DIA.
7.33 DIA.
inches
FIBER DIA.=0.020 INCHES
VOID FRACTION=15%
UPSTREAM PRESSURE –Po= 60 psia
UPSTREAM TEMP-To=400°F
0 1 2 3 4 5 6 7 8 9
PRESSSURE RATIO
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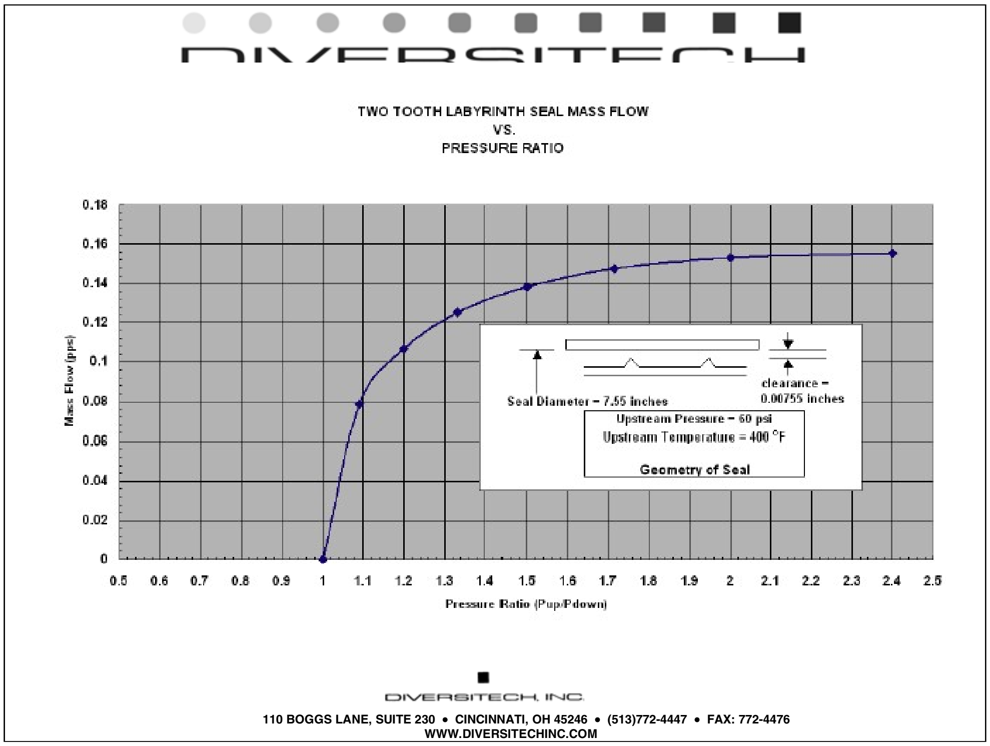
DIVERSITECH
TWO TOOTH LABYRINTH SEAL MASS FLOW
VS.
PRESSURE RATIO
Mass Flow (pps)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2 2.1 2.2 2.3 2.4 2.5
Pressure Ratio (Pup/Pdown)
Seal Diameter = 7.55 inches
clearance = 0.00755 inches
Upstream Pressure = 60 psi
Upstream Temperature = 400 °F
Geometry of Seal
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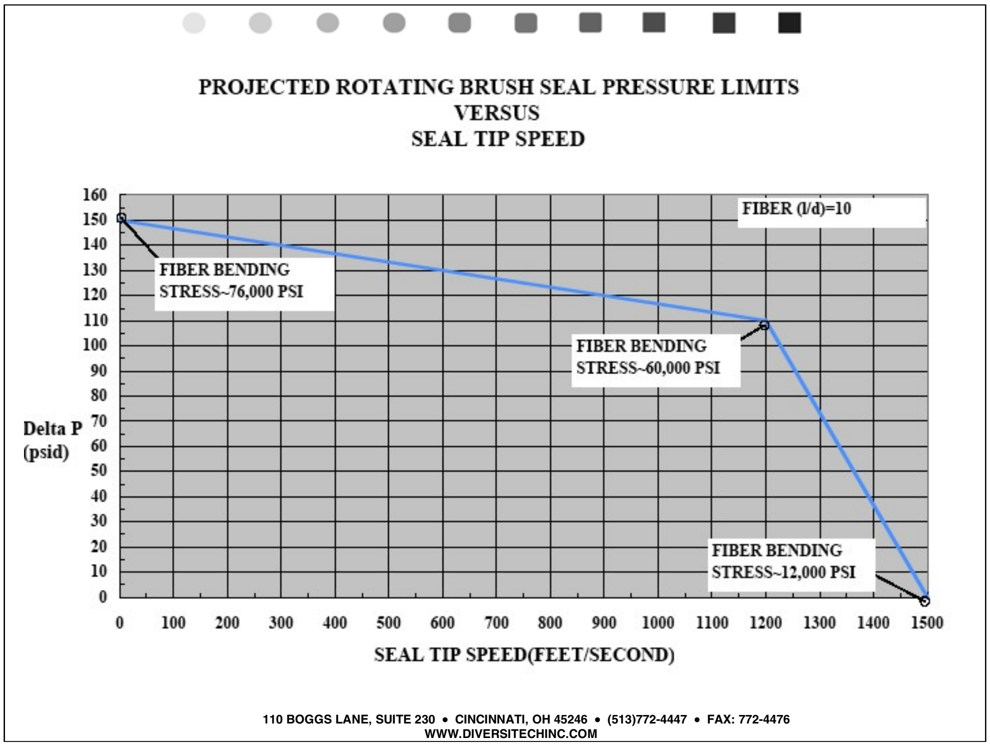
PROJECTED ROTATING BRUSH SEAL PRESSURE LIMITS
VERSUS
SEAL TIP SPEED
FIBER (l/d)=10
FIBER BENDING
STRESS~76,000 PSI
FIBER BENDING
STRESS~60,000 PSI
FIBER BENDING
STRESS~12,000 PSI
Delta P
(psid)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
SEAL TIP SPEED(FEET/SECOND)
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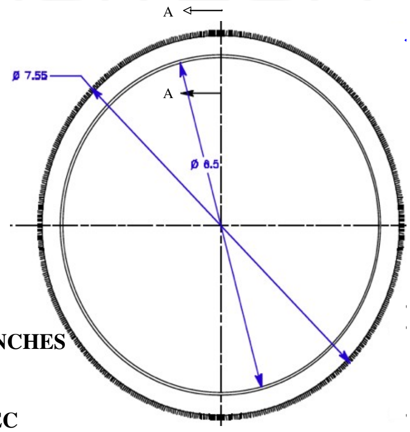

RESULTING SEAL DESIGN

- **NON-CONTACTING**
- **COMPOSITE ROD DIAMETER---0.020 INCHES**
- **TEMPERATURE CAPABILITY -600 ^{o}F**
- **TIP SPEED CAPABILITY-->= 1200 FT/SEC**
- **DELTA P CAPABILITY> 100PSID**
- **AXIAL TRANSLATION CAPABILITY**
- **SEALS BETWEEN CO OR COUNTER ROTATING SHAFTS**
- **COMPACT SPACING**

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- US AIR FORCE AFRL/PRTM -WRIGHT PATTERSON AFB---CONCEPT SUPPORT AND PROGRAM FUNDING
- REXNORD CORP.- CONCEPT SUPPORT AND SEAL TESTING
- GE AVIATION (GE AIRCRAFT ENGINES)- CONCEPT SUPPORT AND SEAL TESTING(COUNTER ROTATING) AND BEARING CONTAMINATION TESTING
- NORTH CAROLINA A&T STATE UNIVERSITY-MATERIAL EVALUATION AND RESIN CONSULTATION
- LONZA CORP.-HIGH TEMPERATURE RESIN
- AZTEC CORP.-PULTRUDED COMPOSITE ROD MANUFACTURE
- POLYCRAFT INC.-COMPOSITE SEAL MANUFACTURE
- NASA GLENN- SEAL SOFTWARE USE

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