ADVANCED SEALS FOR GE INDUSTRIAL GAS TURBINE APPLICATIONS

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Advanced Seal Applications

GT Applications

- High-Pressure Packing Brush Seals
- No. 2 Bearing Brush Seals
- 2nd Interstage Brush Seals
- Nozzle & Shroud Stationary Cloth Seals

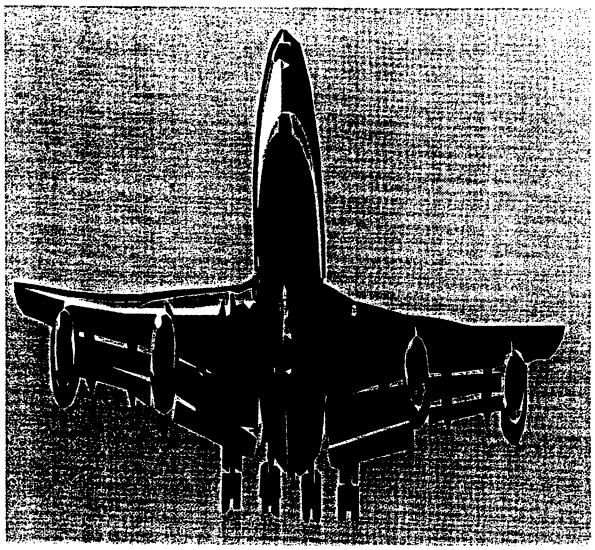
ST Applications

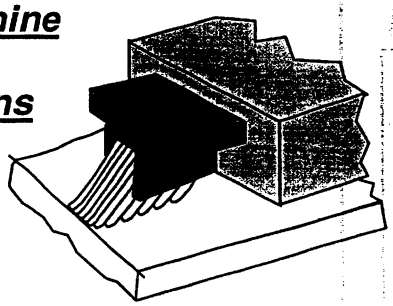
- Interstage Packing Brush Seals
- Shaft End Packings

Advance Machine

AE Applications

- GE90
- Others



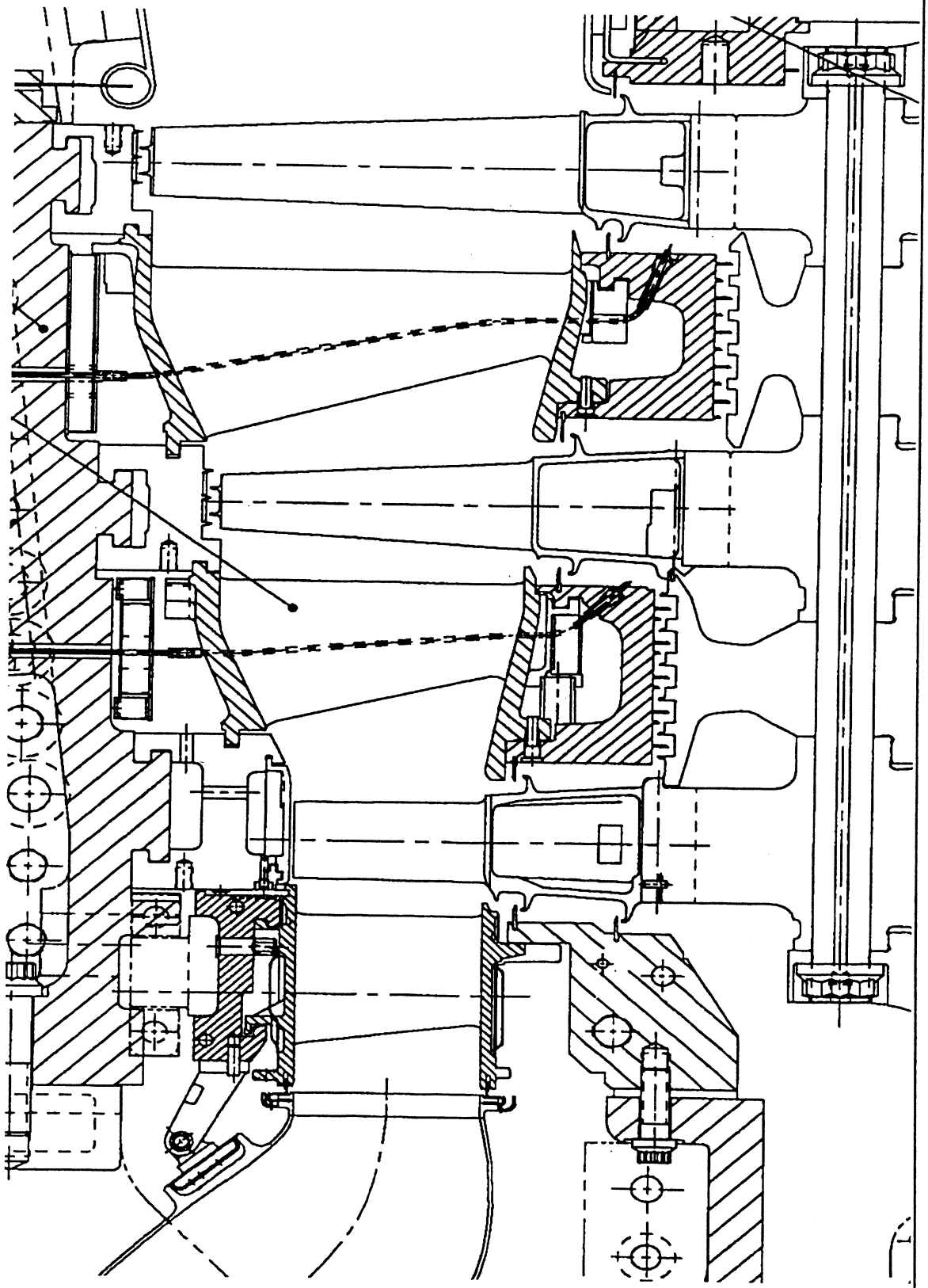


Providing You With...

Advanced Performance

- Increased Output
- Improved Heat Rate
- Sustained Performance
- Improved Reliability

7EA Gas Turbine Cross Section



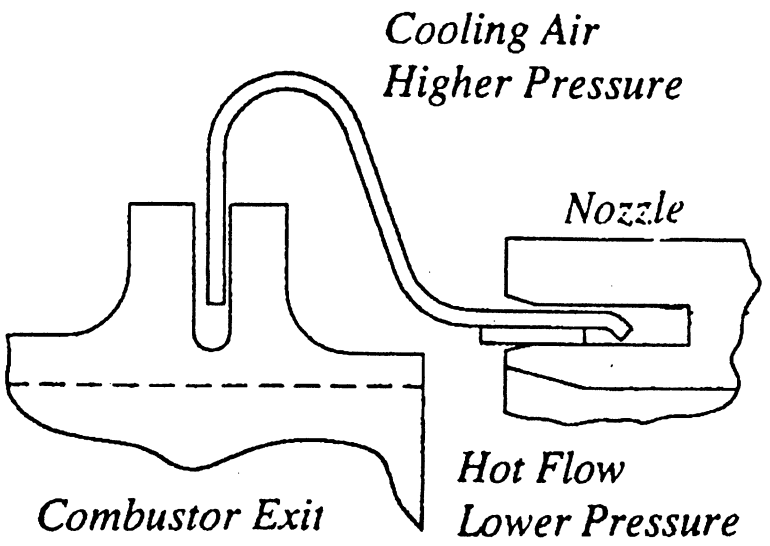
Frame Size	Output (MW) (approx)	Brush Seal Location	Commercial -ization Date
9E	123	HPP,#2 Bearing Seal	1996
7EA	85	HPP,#2 Bearing Seal	1996
6B	38	HPP	1996
52D	32	HPP,#2 Bearing Seal	1997
52C	28	HPP,#2 Bearing Seal	1997
51P	27	HPP	1997
32J	11	HPP	1997
32G	6	HPP	1997
7EA	**85**	**Interstage Diaphragm**	**1998**

Stationary Seal Applications:

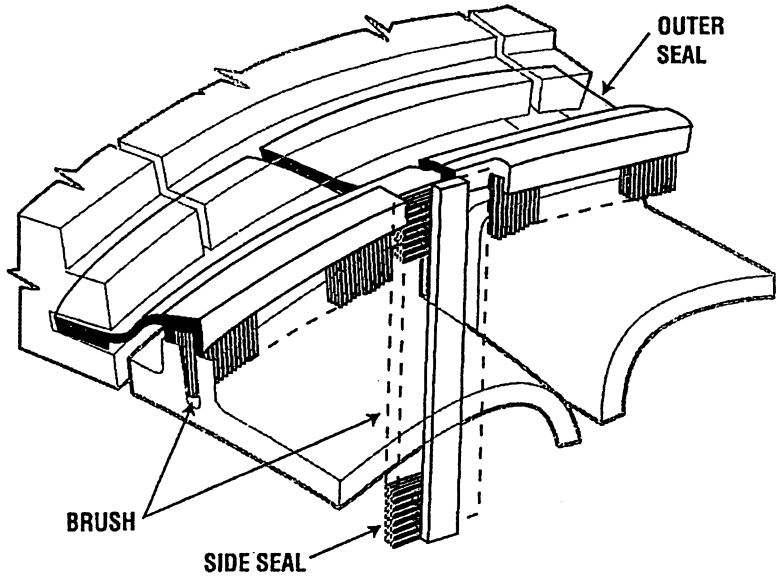
Different Sealing Arrangements

at Combustor Exit to Nozzle Junction;

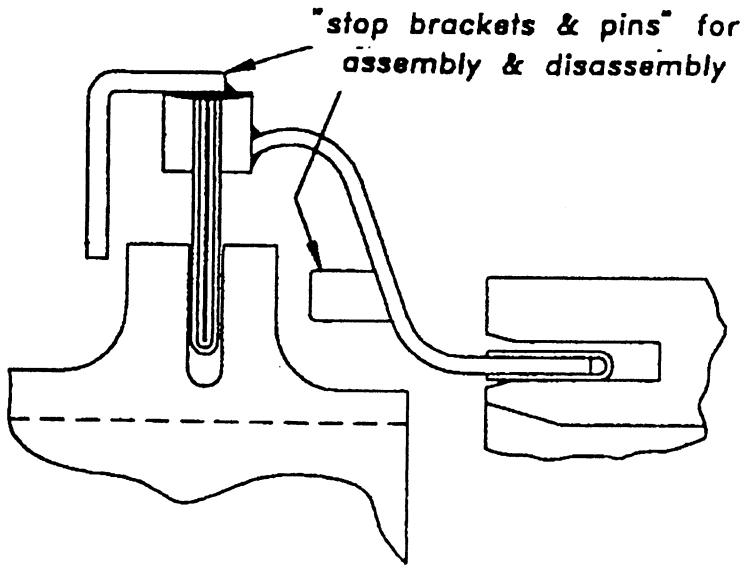
- **Current Seal Arrangement**
- **Stationary Brush Seals**
- **Stationary Cloth Seals**



(a) Previous sealing arrangement



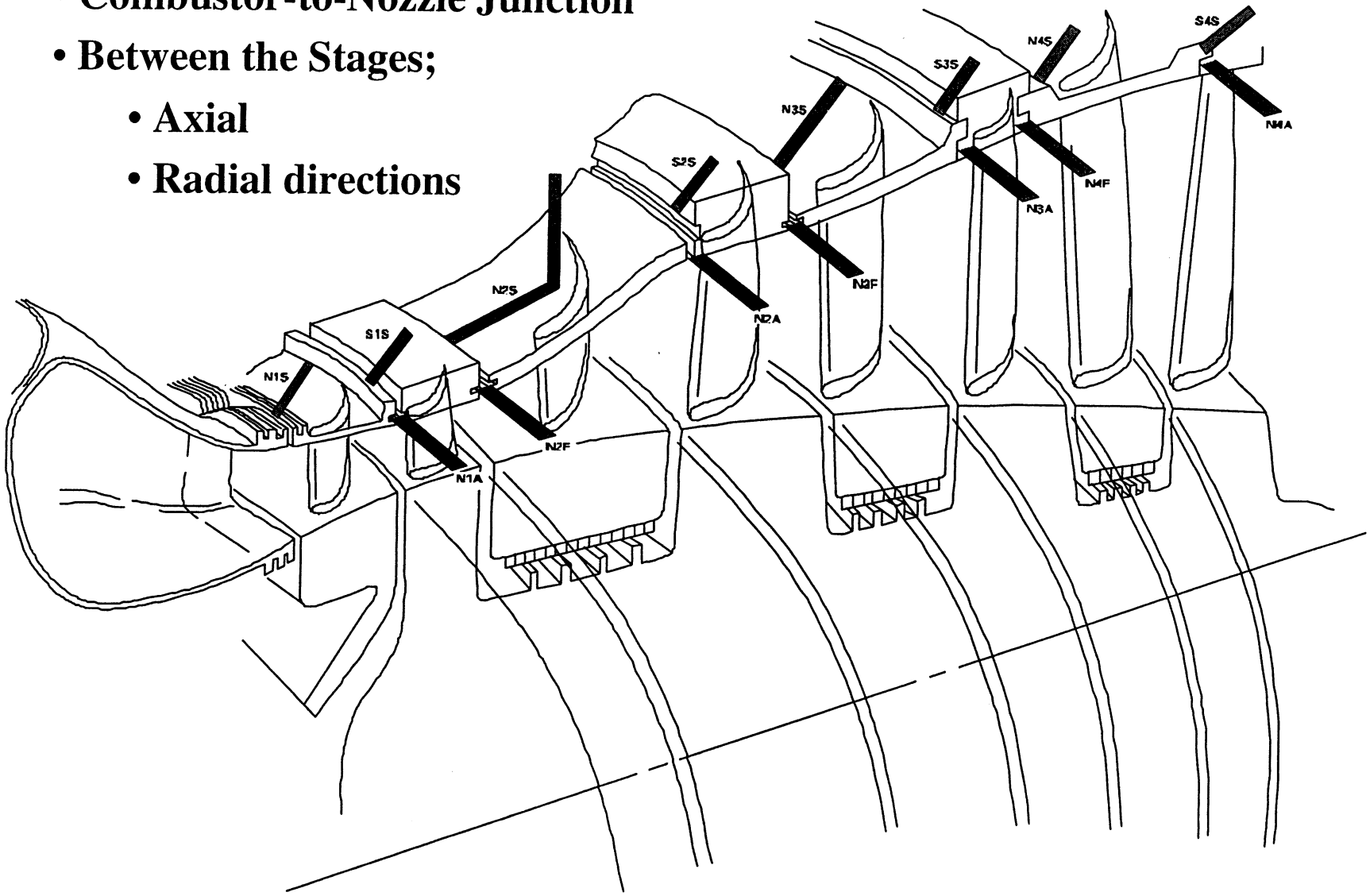
(b) Sealing arrangement with stationary brush seals



(c) Sealing arrangement with cloth seals

Cloth Seals at Turbine Hot Gas Path:

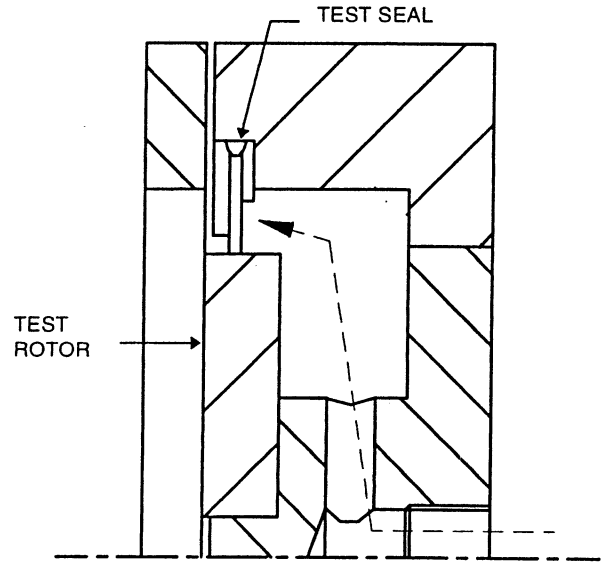
- Combustor-to-Nozzle Junction
- Between the Stages;
  - Axial
  - Radial directions



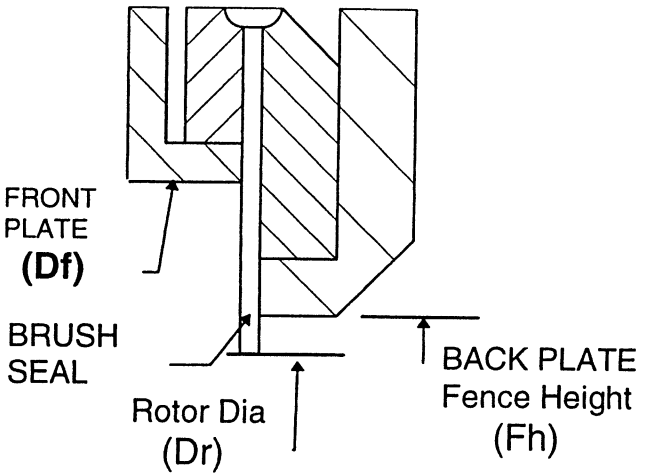
Rotational Seals: Brush Seal Development

Brush Seal Testing: Fundamentals

- **Brush Seal Testing Configurations**



Schematic of Static Test Rig



Test Seals with Interchangeable Front and Back Plates

Design Variables:

Seal	Wire Size inches	Bristle Density wires per inch
A	.0028	*A*
B	.004	*.73A*
C	.004	*1.47A*
D	.0056	*.53A*

Fh= 0.01, 0.05, 0.06, 0.073, 0.98, 0.123, 0.201

Dr= 5.10, 5.09, 5.80, 5.069

Seal Clearances= Line-to-line, 0.005", 0.01", 0.015"

R_f (D_f/2)= 0.796", 0.579", 0.451", 0.204"

Brush Seal Testing: Fundamentals

1. The characteristic curve of a brush seal is a function of the pressure drop across the seal

Fig.1. Effective Clearance for Seal B against Pressure Ratio (Fh=0.123")

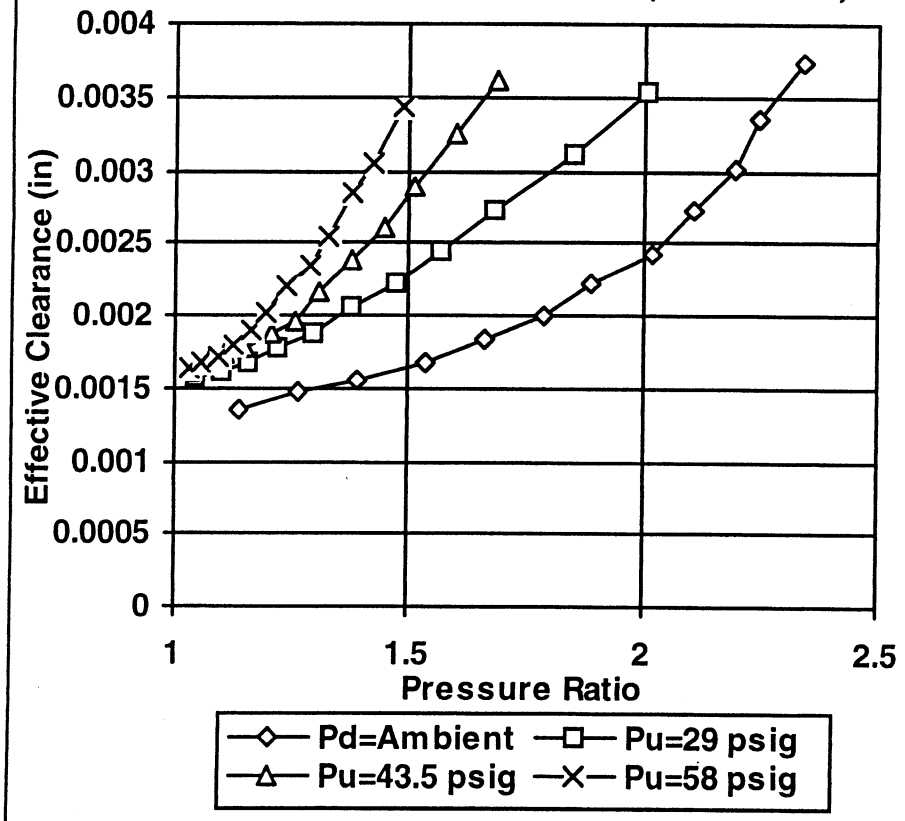
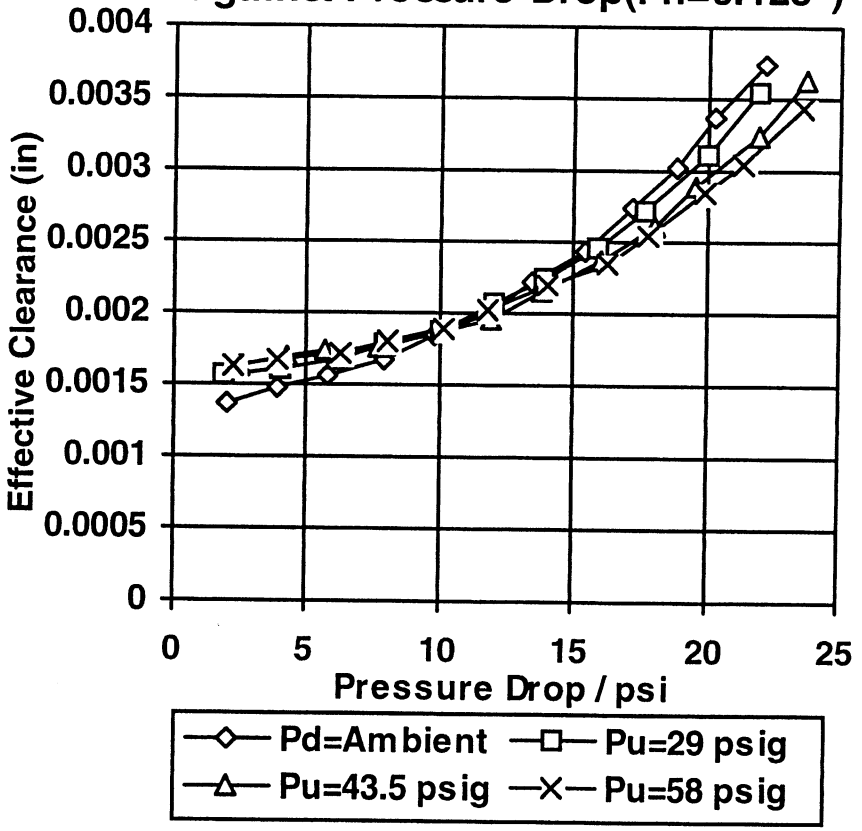


Fig. 2. Effective Clearance for Seal B against Pressure Drop(Fh=0.123")

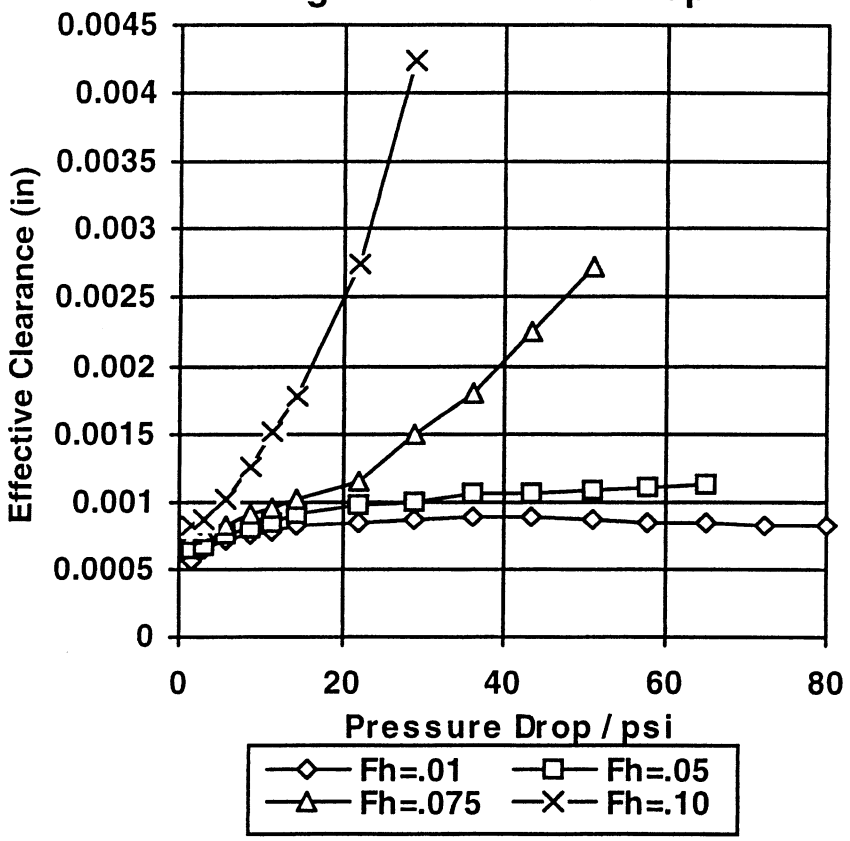


Every brush seal has a pressure drop capacity limit, on the seal B above this would be about 15 psi. This could represent a pressure ratio of 2 with ambient downstream conditions or only 1.15 with 100psia downstream, clearly two very different numbers.

Brush Seal Testing: Fundamentals

2. Typical Brush Seal Characteristic

Fig 3. Effective Clearance for Seal A against Pressure Drop

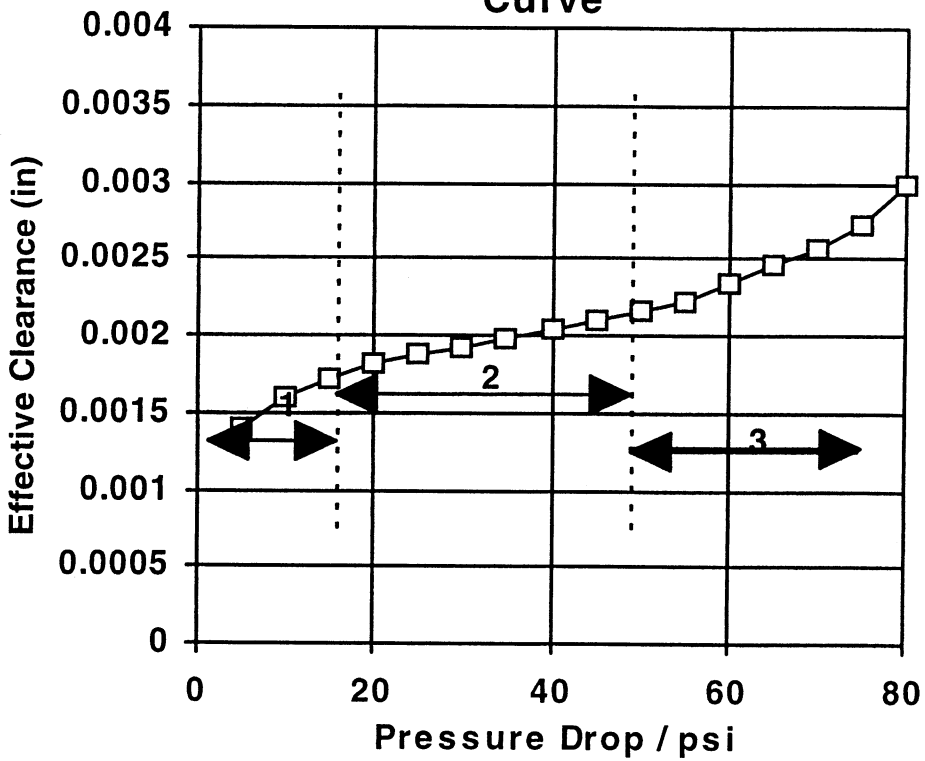


$$clearance_eff = \frac{q\sqrt{(T1 + 460)}}{P1.w.\mu}$$

μ the flow function is defined as follows:-

$$\mu = \sqrt{g.\gamma / R}.\sqrt{((2/(\gamma - 1)).PR^{-(\gamma+1)/\gamma}.(PR^{(\gamma-1)/\gamma} - 1))}$$

Fig. 4. Typical Characteristic Curve



A Typical Characteristics of a brush seal:

- Section 1 is usually from a pressure drop of 0 up to about 15 psi
- Section 2 is the area where most correctly designed seals function
- Section 3 is the area to be avoided when designing a brush seal

Brush Seal Testing: Fundamentals

3. Effect of Wire Size:

Fig 3. Effective Clearance for Seal A against Pressure Drop

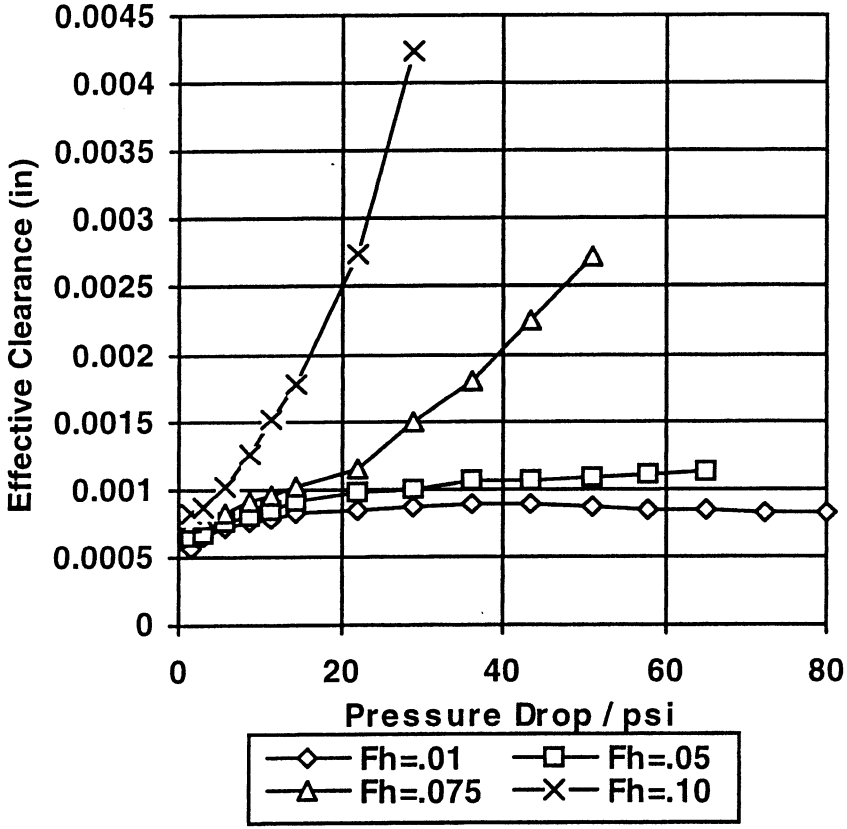
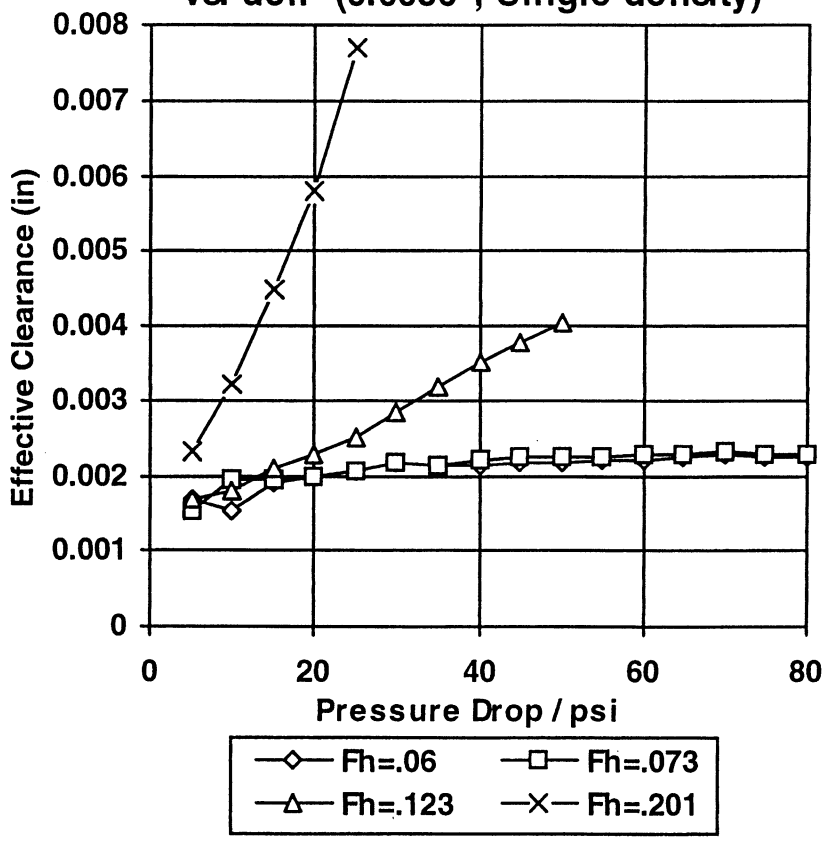


Fig7.Effective Clearance for Seal D vs. delP (0.0056", Single density)



Doubled Wire Thickness:

- **Holds large pressure load**
- **Leaks more, Generates more heat and Higher wear rate**

Brush Seal Testing: Fundamentals

4. Effect of Wire Density:

Fig 5. Effective Clearance for Seal B vs. delP (0.004", Single Density)

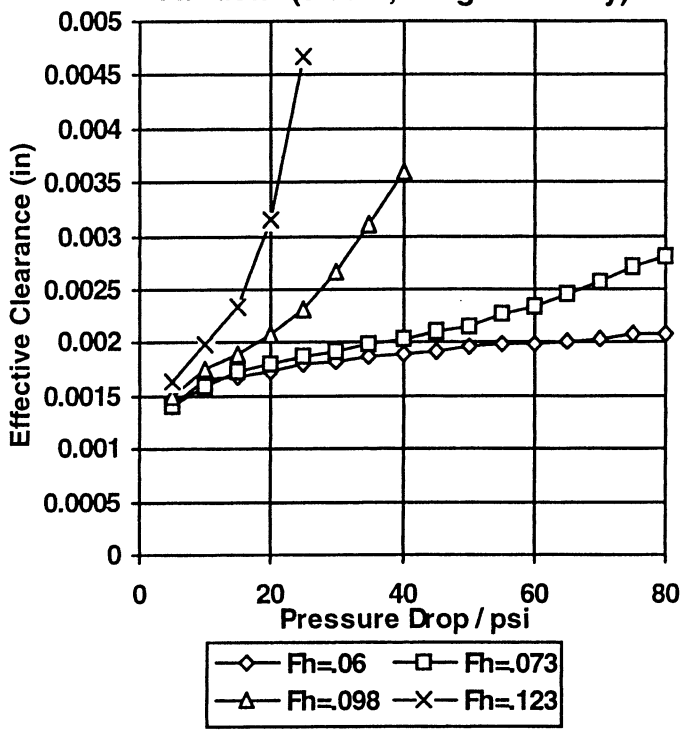
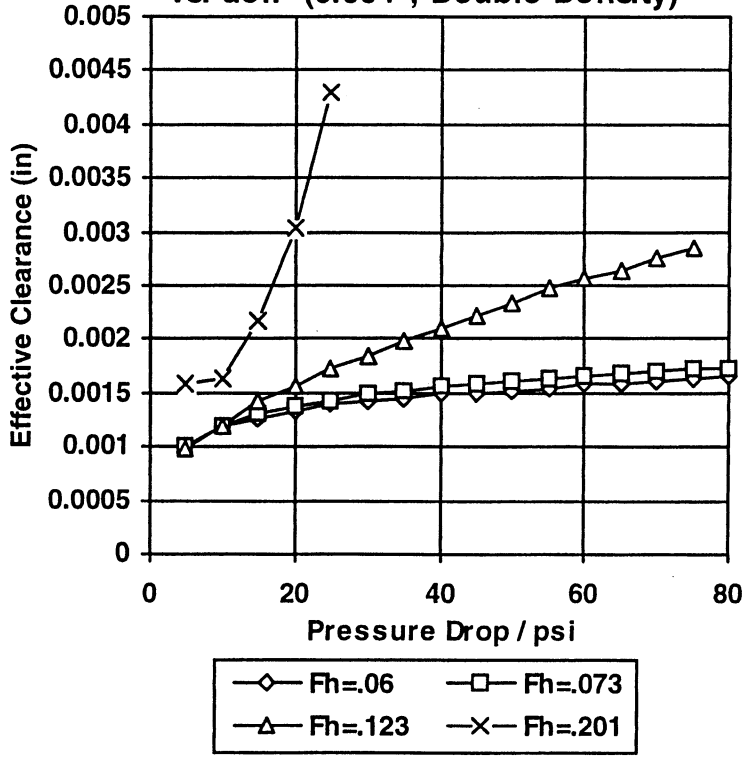


Fig 6. Effective Clearance for Seal C vs. delP (0.004", Double Density)

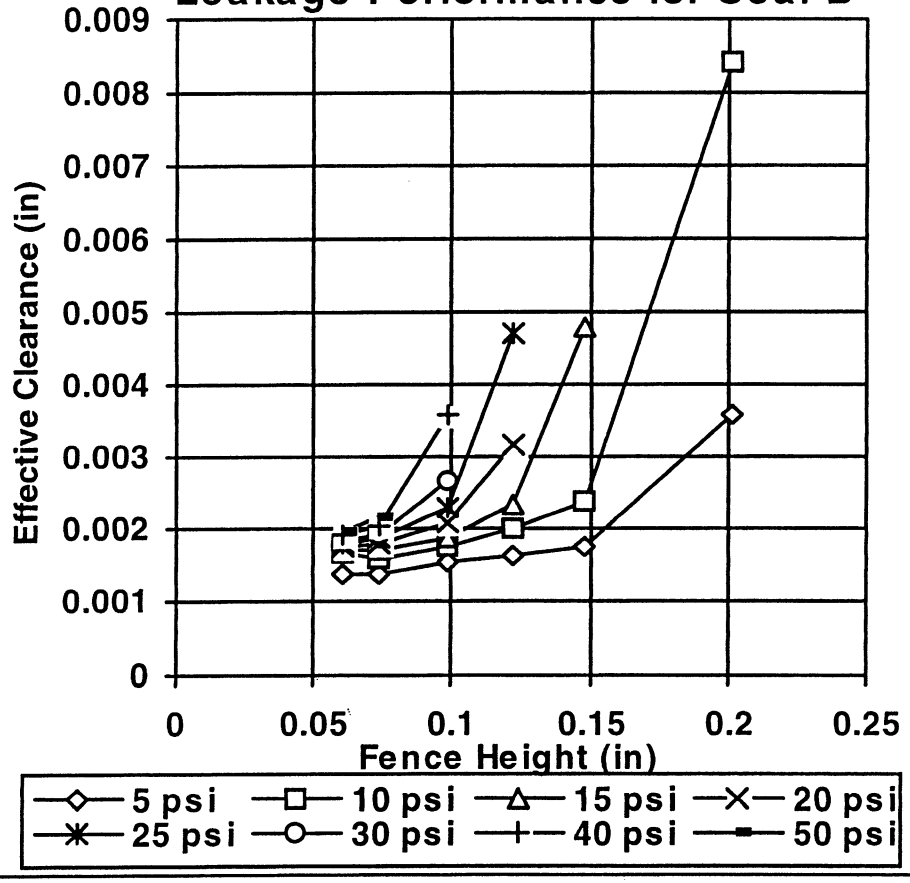


- Doubling the wire density had the effect of reducing the leakage by some 30% whilst also more than doubling the pressure capacity.
- Larger wires exhibited higher pressure capacities but higher leakages.

Brush Seal Testing: Fundamentals

5. Effect of Fence Height

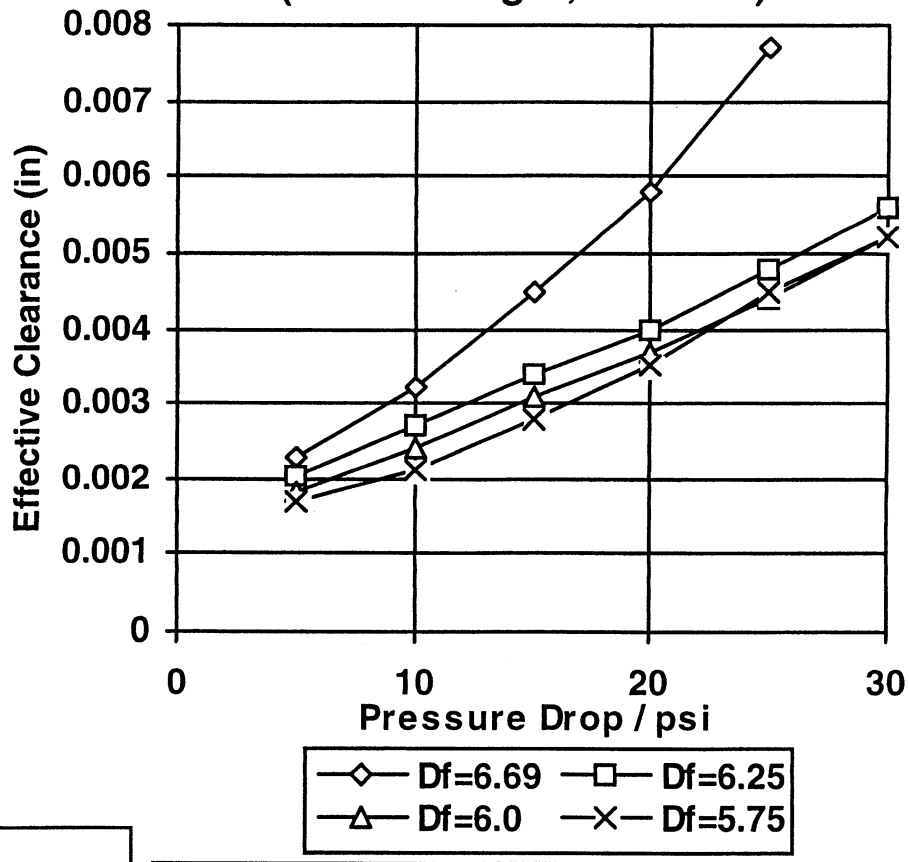
Fig 8. Effect of Fence Height on Leakage Performance for Seal B



The pressure capacity of any given seal can be increased and the leakage reduced by making the free bristle length shorter. This however can lead to other problems

6. Effect of Bristle Free Lenght

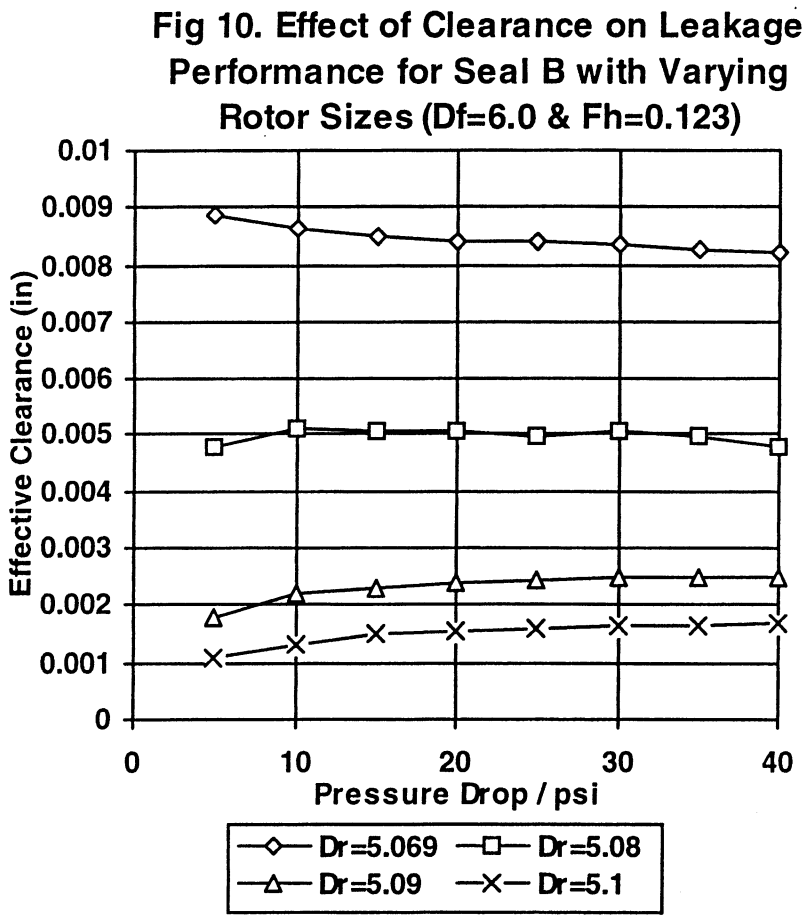
Fig 9. Effect of Front Plate Height on Leakage Performance for Seal D (Fence height, Fh=.201)



Decreasing the front plate bore and thus shortening the free bristle length has the effect of reducing the leakage.

Brush Seal Testing: Fundamentals

7. Effect of Clearance on Seal Performance



Performance Evaluation:

- Rotor Dia Dr=5.10", Seal ID=5.093",
  - Seal Eff Clea: 0.0015 - 0.0017"
- Rotor Dia Dr=5.08", Seal ID=5.093"
  - Seal Open Gap Clea: 0.0065",
  - Seal Eff Clea: 0.005" (from 0.0015")
    - Increase Eff Clea: 0.0035"
  - Seal Blow down: 0.003"
  - Gap Discharge Coeff: Cd=0.0035/0.0065=0.54
- Rotor Dia Dr=5.069", Seal ID=5.093"
  - Seal Open Gap Clea: 0.012",
  - Seal Eff Clea: 0.0085" (from 0.0015")
    - Increase Eff Clea: 0.007"
  - Seal Blow down: 0.005"
  - Gap Discharge Coeff: Cd=0.007/0.0012=0.58

Brush Seal Design Process for Turbine Applications

I. Establish Seal Operating Conditions

- Phigh, Plow, delP, Temperature, RPM
- Excursions; Thermal transient Radial & Axial motion
- Startup/Shutdown cycles, Local vibrations,
- Flows; Required cooling flows, Fluid (air/steam),
- Geometric Considerations: Assembly stackup tolerances, Seal housing elipticity,
- Materials; Rotor material for wear, Seal housing material and expansion coefficient

II. Develop Prototype Seal - Identify and Retire Risks

1. **Performance/Leakage/Hysterisis:** Static and Rotational seal tests on test rigs at CRD, Cross, EGT, RPI and YFT Analysis
   - Seal Design Parameters; # of Stages, Seal radial height, Bristle diameter, Seal fence height, Packing thickness, Assembly clearances, # of Segments
   - Anti-hysterisis features,
   - External cooling flow provisions,
   - Seal long term performance
2. **Wear:** Sliding wear tests, Rotating wear tests
   - Bristle material and diameter, Seal radial height,
   - Bristle tip pressure, Seal stiffness,
   - Seal life

3. Durability:

- Pressure tests w/ & w/o rotation; Seal geometry, fence height, Front & back plate geometry, # of seal stages, Bristle pack spacing, Seal axial location
- Bristle material evaluation for higher temperatures and rotor materials
- Bristle flutter, Primary seal flow impingement; CFD Analysis, FE Analysis

4. Turbine Cooling Flow YFT Analysis:

- Turbine section cooling requirements, current cooling circuit, flows w/Brush Seal,
- Performance improvements predictions

5. Effect on Rotor/Rotordynamics:

- Temp rise test, FE Analysis, Bristle tip pressure, Frictional rotor heating,
- Rotor dynamic stability analysis

6. Producibility/Assembly:

- Seal cross-sectional design, # of segments, End gap configuration,
- Assembly trials, Anti-rotation devices, Seal & housing materials
- Instrumentation

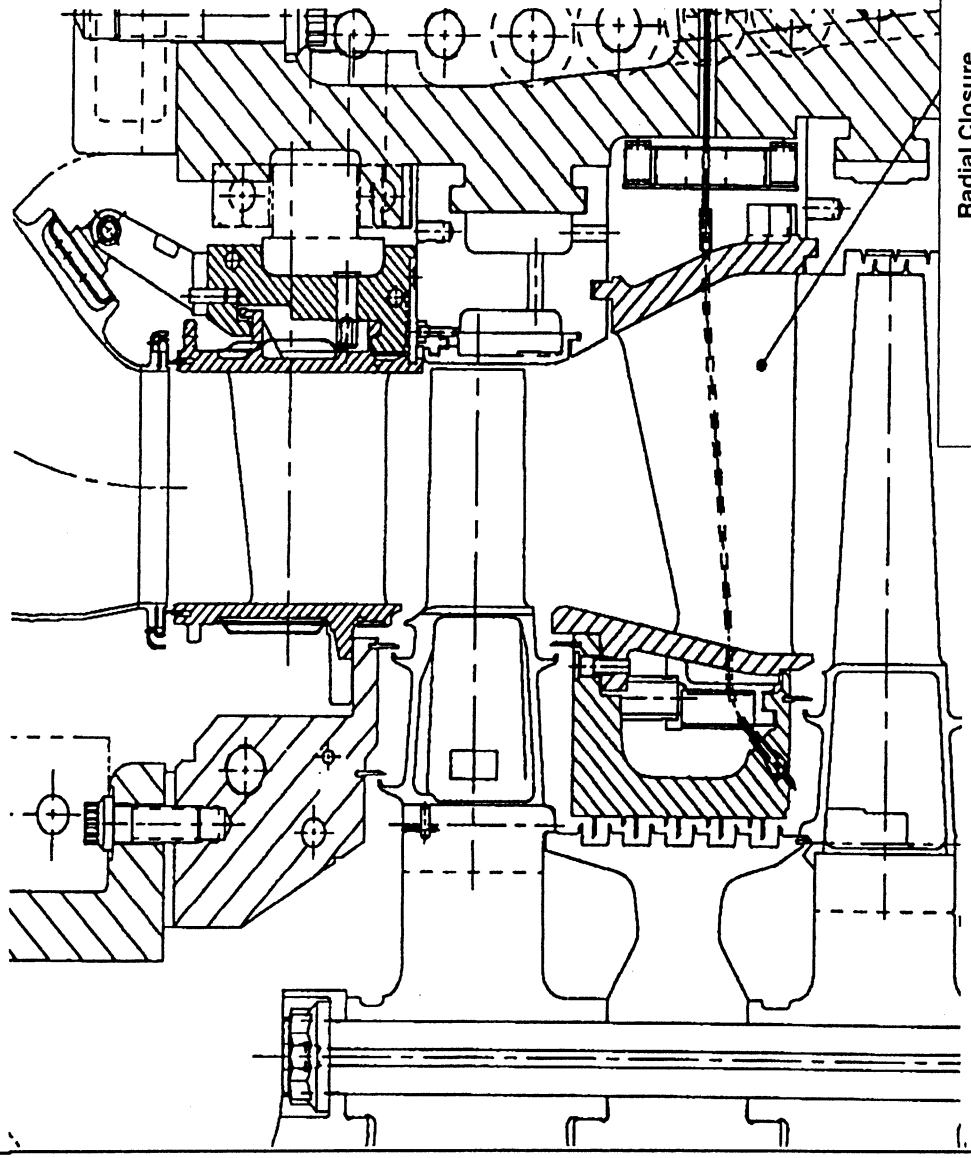
III. Establish Final Brush Seal Design:

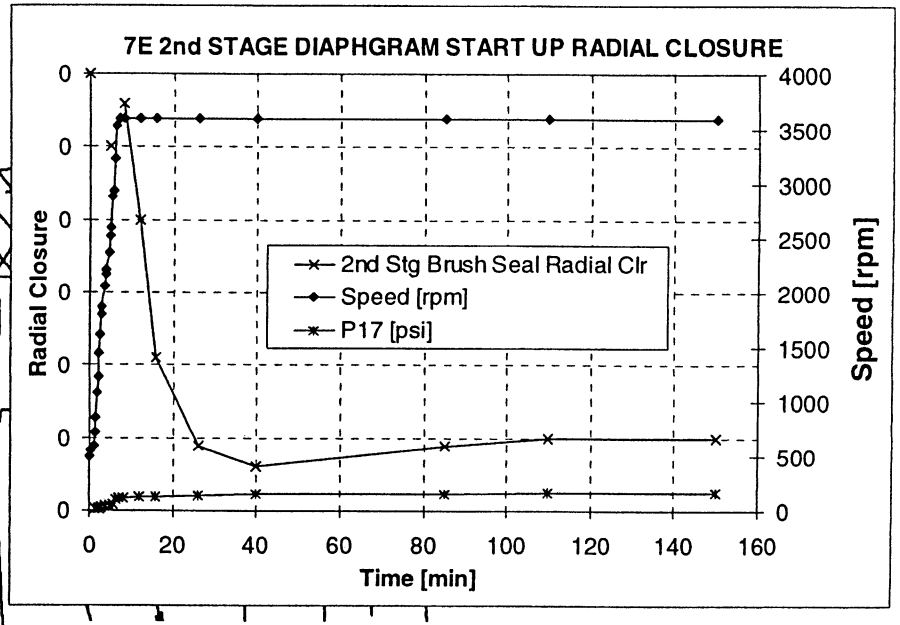
- Proof Test on a full scale production turbine
- Field Prototype Installations; Seal Installation, Field Instrumentation
- Field Testing; Performance testing, Seal performance degradation monitoring

Each Brush Seal Product Implementation Has Own Unique Features Requiring Specific Seal Design and System Considerations

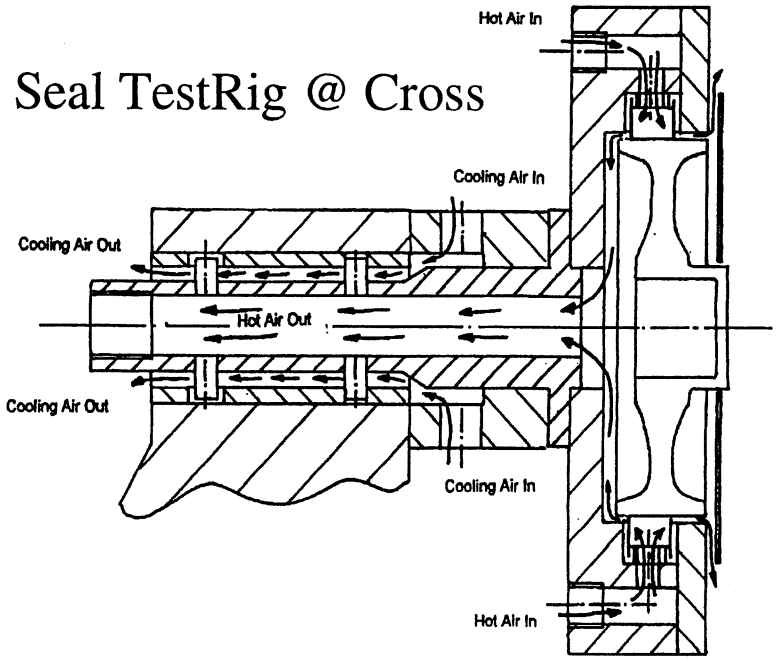
Brush Seal Application:

- Interstage Sealing

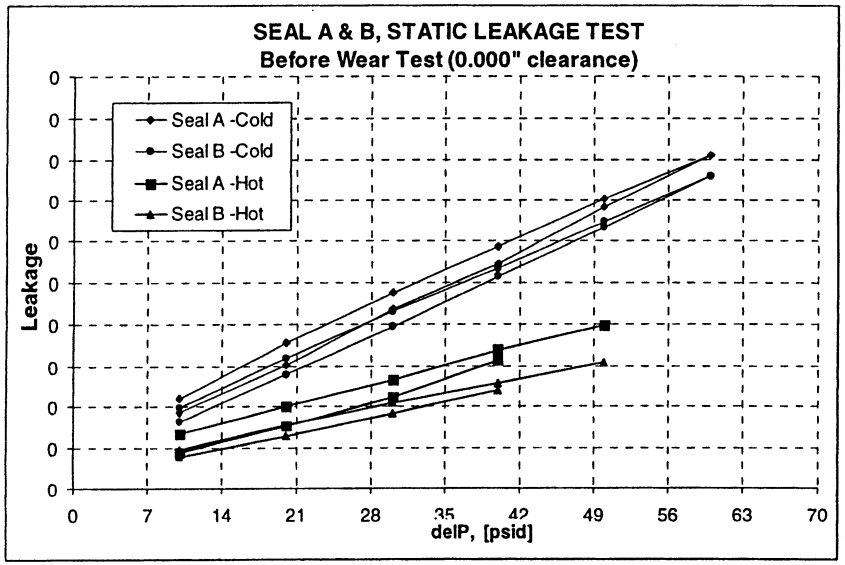


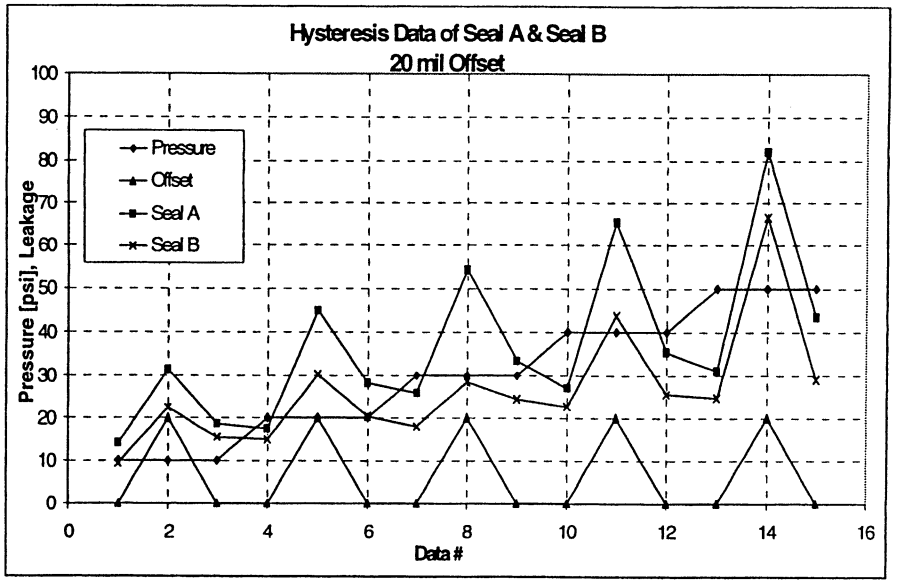


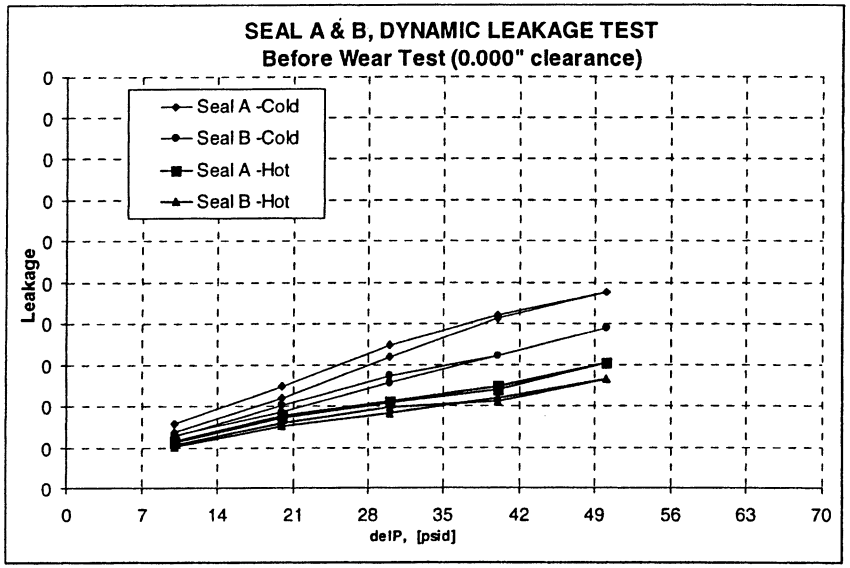
Seal TestRig @ Cross

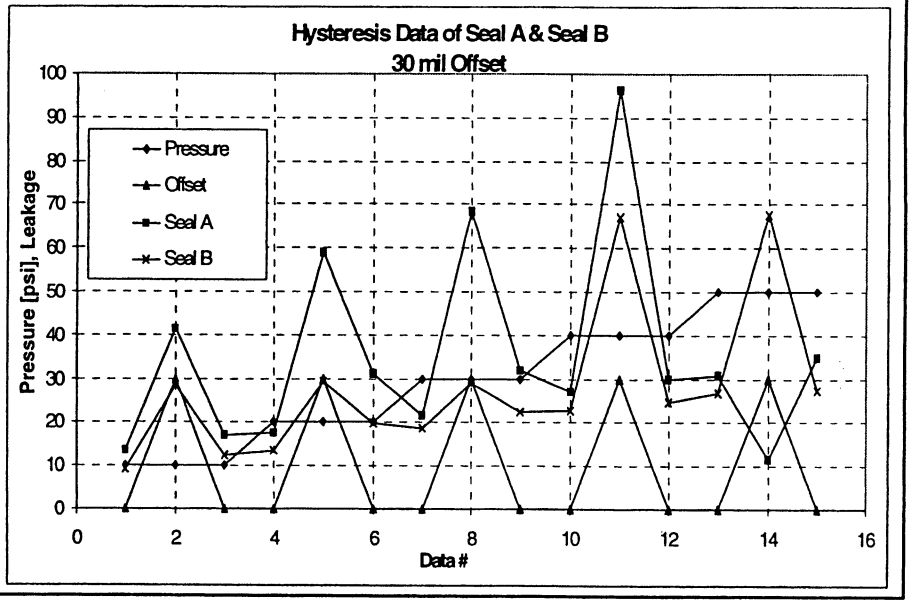


Intersatge Seals: Leakage and Hysterisis

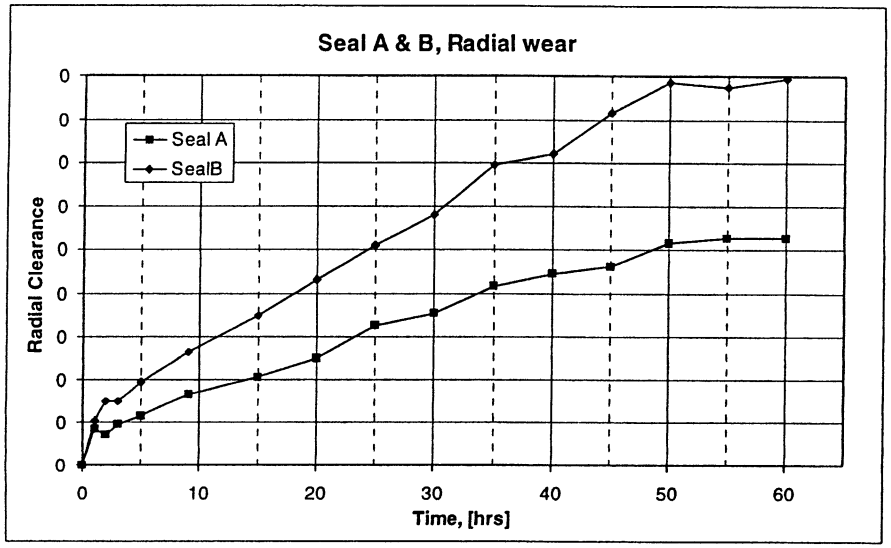


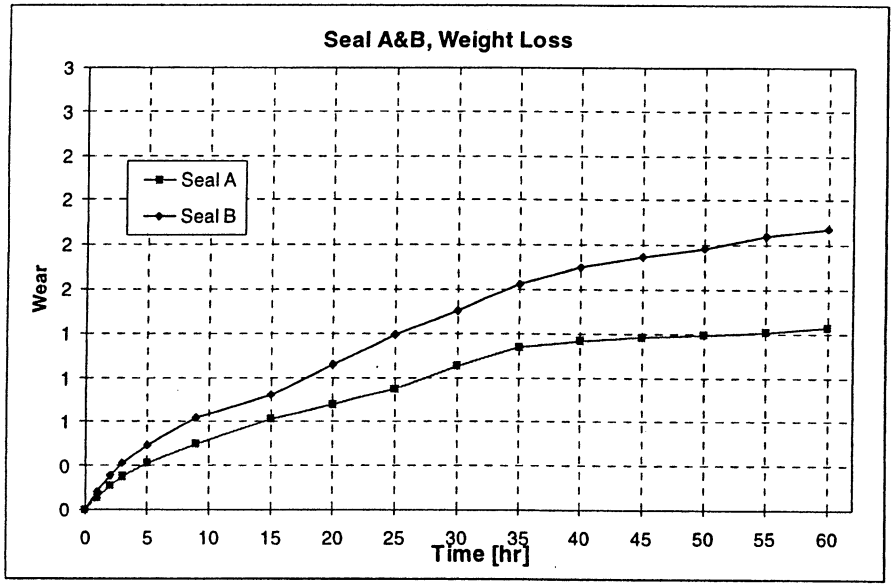


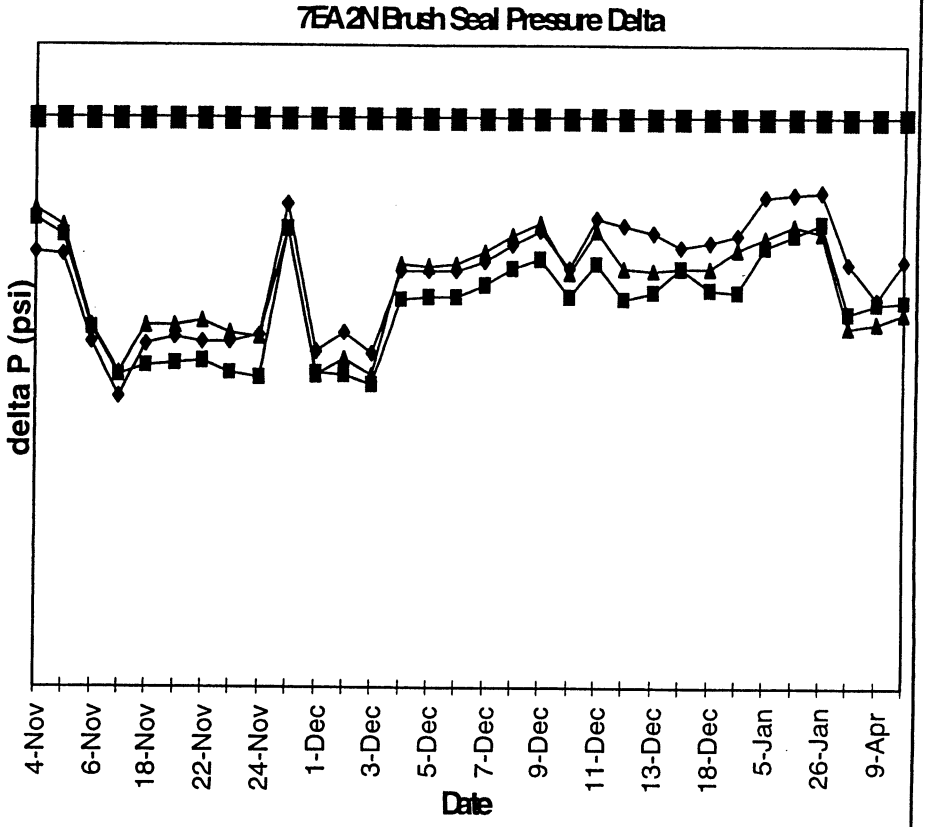




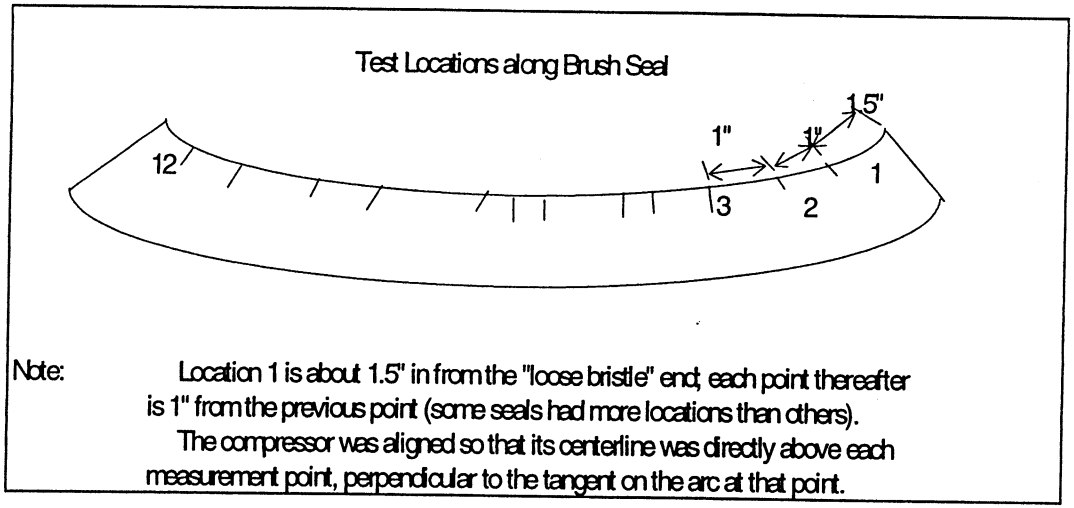
Intersatge Seals: Wear Test and Field Pressure Data







Brush Seal Stiffness Measurements



Note: Location 1 is about 1.5" in from the "loose bristle" end; each point thereafter is 1" from the previous point (some seals had more locations than others). The compressor was aligned so that its centerline was directly above each measurement point, perpendicular to the tangent on the arc at that point.

Location #	Seal from Vendor #1 **(psi/mil)** *Design Kbr=0.25 psi/mil*	Seal from Vendor #2 **Stiffness (psi/mil)** *Design Kbr=1.0 psi/mil*
1	0.42	2.87
2	0.65	6.18
3	0.67	5.38
4	0.89	5.77
5	0.48	3.64
6	0.56	2.42
7	0.52	7.00
8	0.65	4.50
9	0.71	5.13
10	0.60	5.21
11	0.34	4.96
Average	**0.59**	**4.82**

Advanced Seal Test Rigs at CRD

	"Shoebox" Rig	5.1" Rotary Rig	36"/50" Rotary Rig
Working Fluid	Air	Air or Steam	Air
Total Flow Rate (lbm/s)	2.0	1.5 Steam/2.0 Air	12
Inlet Pressure (psig)	430	1200 Steam/450 Air	125
Exhaust Pressure (psig)	430	300	125
Temperature (°F)	1000*	750 Steam/1000 Air*	100
Speed (RPM)	N/A	36000	2400
Surface Speed (ft/s)	N/A	800	375
Axial Motion (in.)	N/A	+/- 0.75	N/A
Seal Configuration	12" max. linear strip (1 seal strip)	5.1" diameter brush, labyrinth, etc. (2 seals req'd)	36" dia. brush, aspirating, etc. (2 seals req'd)

Note: Temperature limits depend on test pressures. Limits given are ablsolute maximum.

5.1" Test Rig Capabilities

Leakage testing

Single stage brush seals tested up to 400 psid in air; up to 1200 psid possible in steam.

Wear testing

Long term seal and rotor wear testing under same conditions as leakage testing.

Seal hysteresis testing

360° Seal/Rotor interference can be applied/removed by moving entire rig housing relative to stepped rotor, with applied pressure.

Rotor heating evaluation

Rotor surface temperature measured using infrared fiber optic probe adjacent to brush seal; thermal imaging camera used to evaluate zero-pressure frictional heat generation.

Rotordynamic evaluation

Two Bentley-Nevada proximity probes per bearing for full rotor vibration evaluation (Rotor orbits, Vibration vs. Speed, Vibration vs. Time, Vibration Spectrum Analysis).