ADVANCES IN THE HYBRID FLOATING BRUSH SEAL NOZZLE JOINT LOCATIONS

Scott Lattime and J. Braun
B&C Engineering
Akron, Ohio

HYBRID FLOATING BRUSH SEAL

- **BACKGROUND**
  - **The Hybrid Floating Brush Seal**
  - **The Room Temperature Test Rig**
  - **Brush Seal Design**

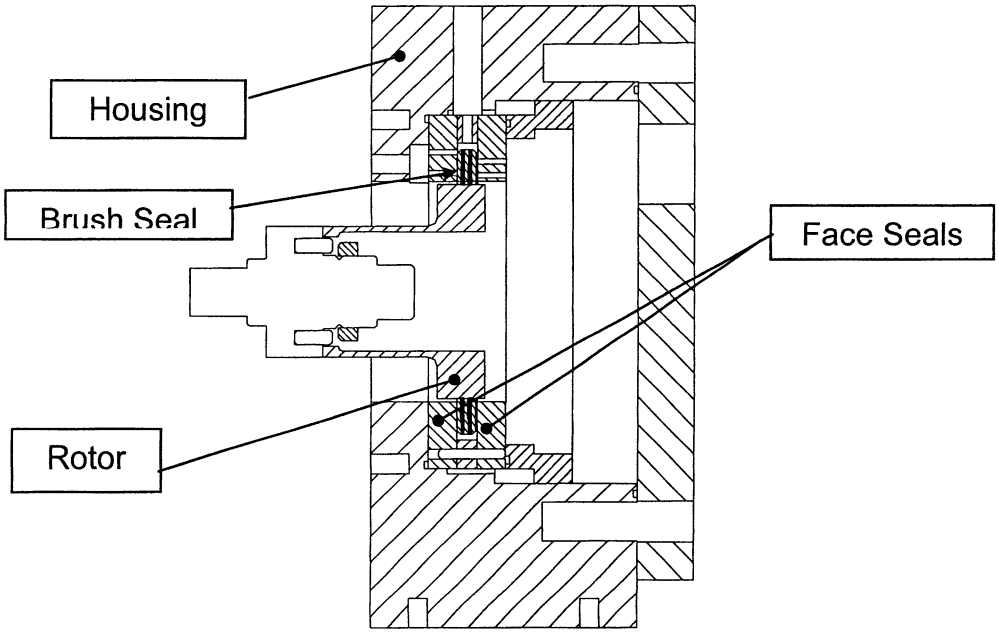
- **SUMMARY**
  - **Problems**
  - **Solutions**
  - **Achievements**

- **EXPERIMENTAL RESULTS**
  - **Leakage**
  - **Film Thickness**

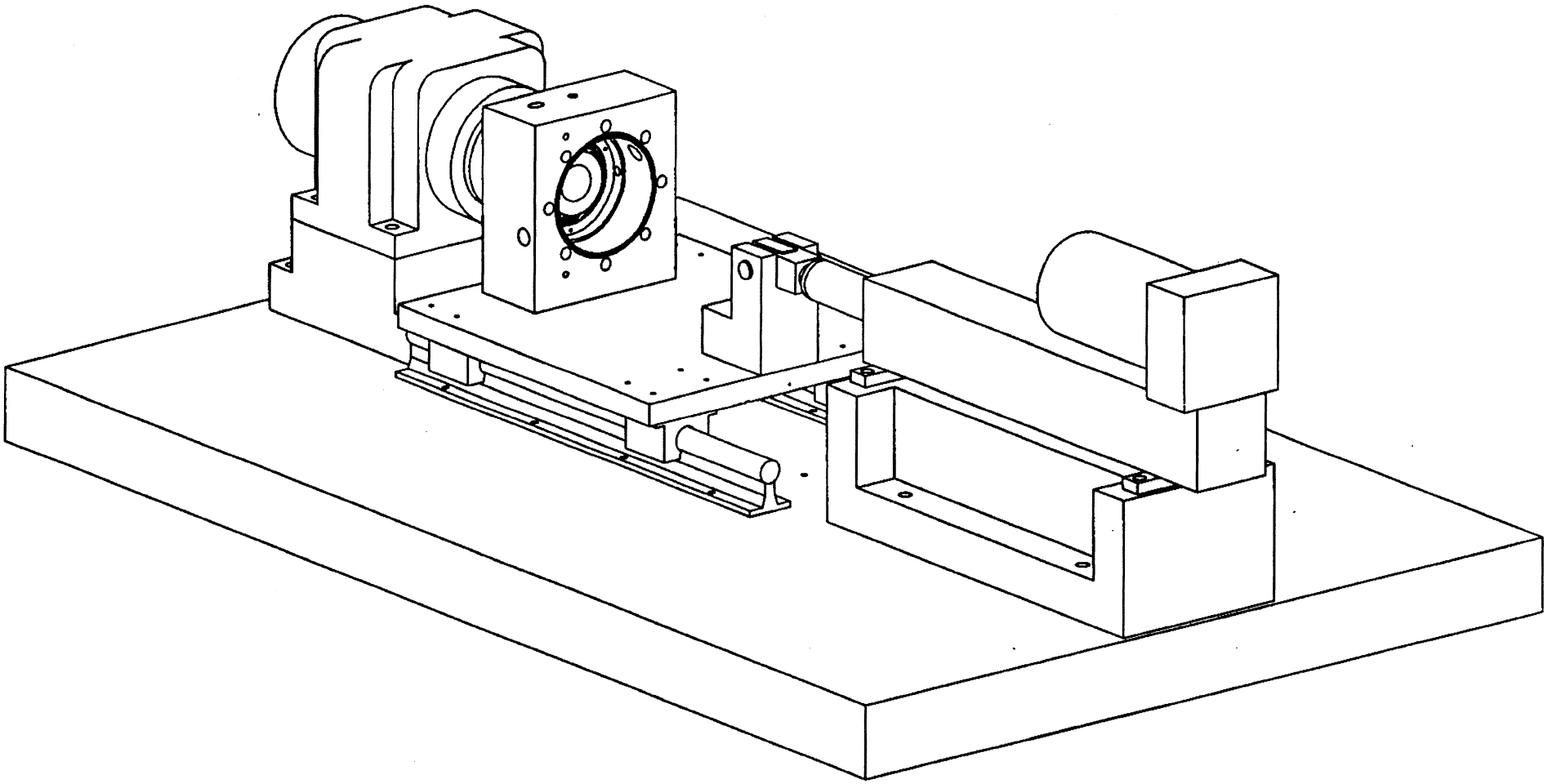
- **DIRECTION OF WORK**
  - **Goals**
  - **Tasks**

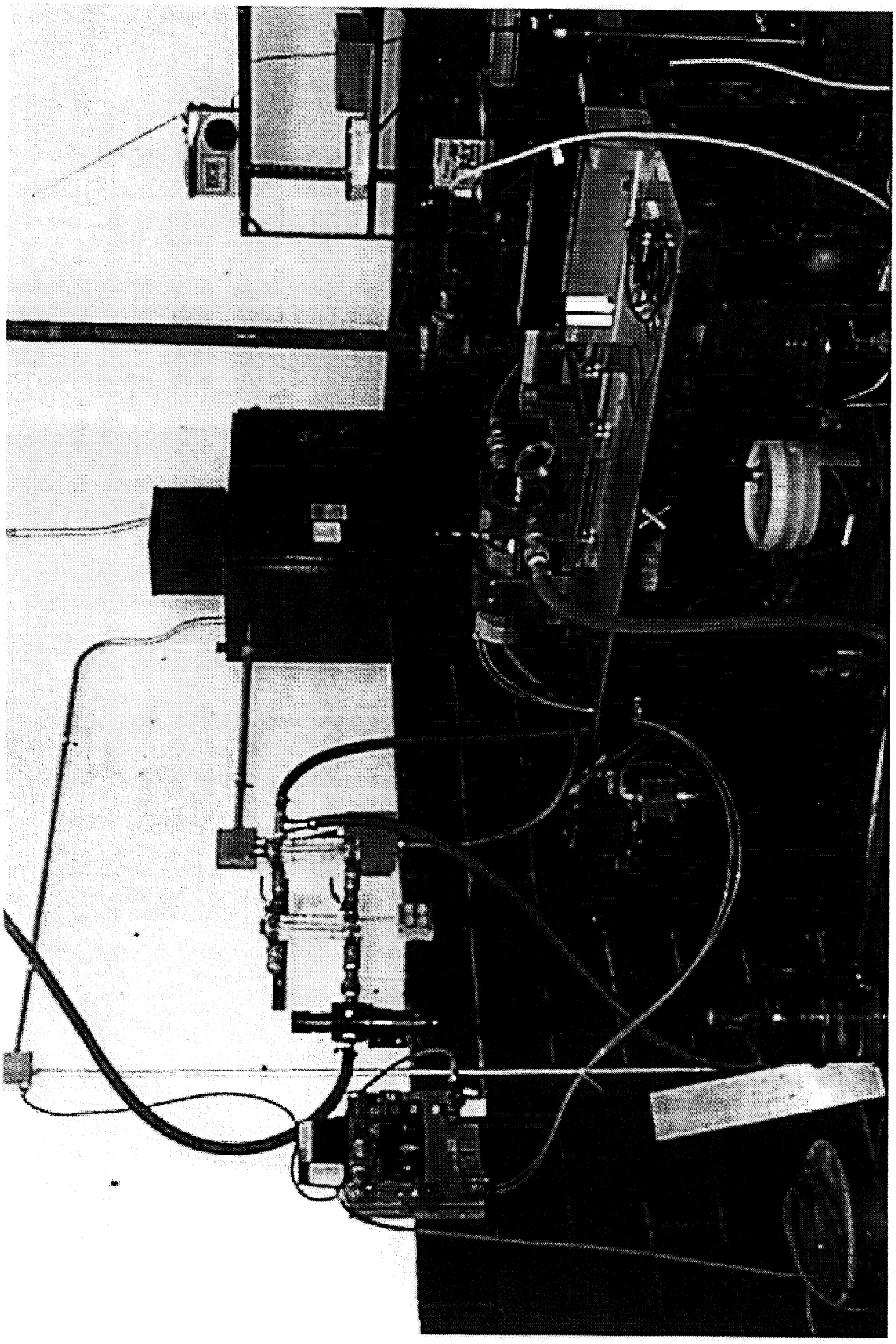
Background

The Hybrid Floating Brush Seal (HFBS)

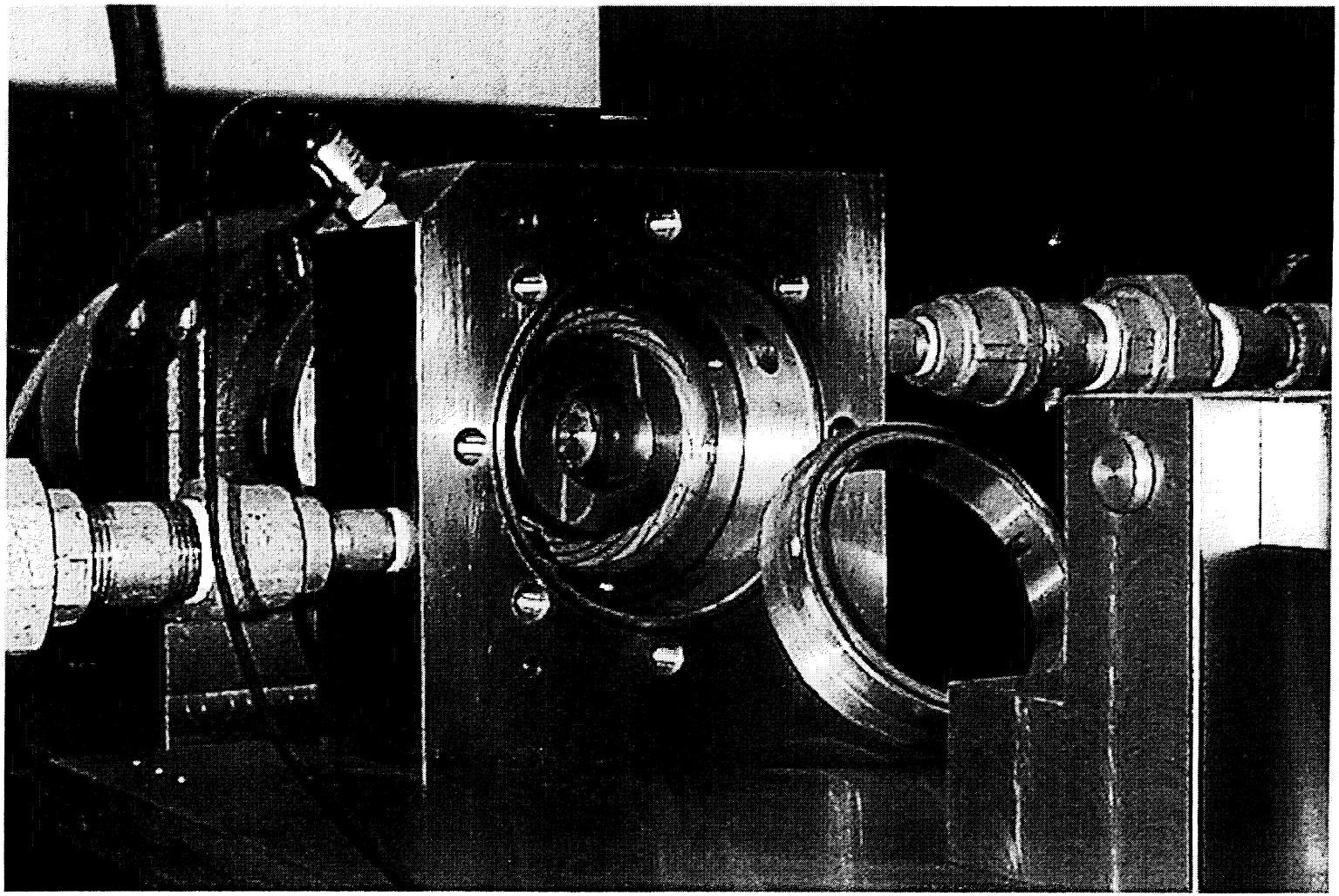


Room Temperature Test Rig (RTTR)

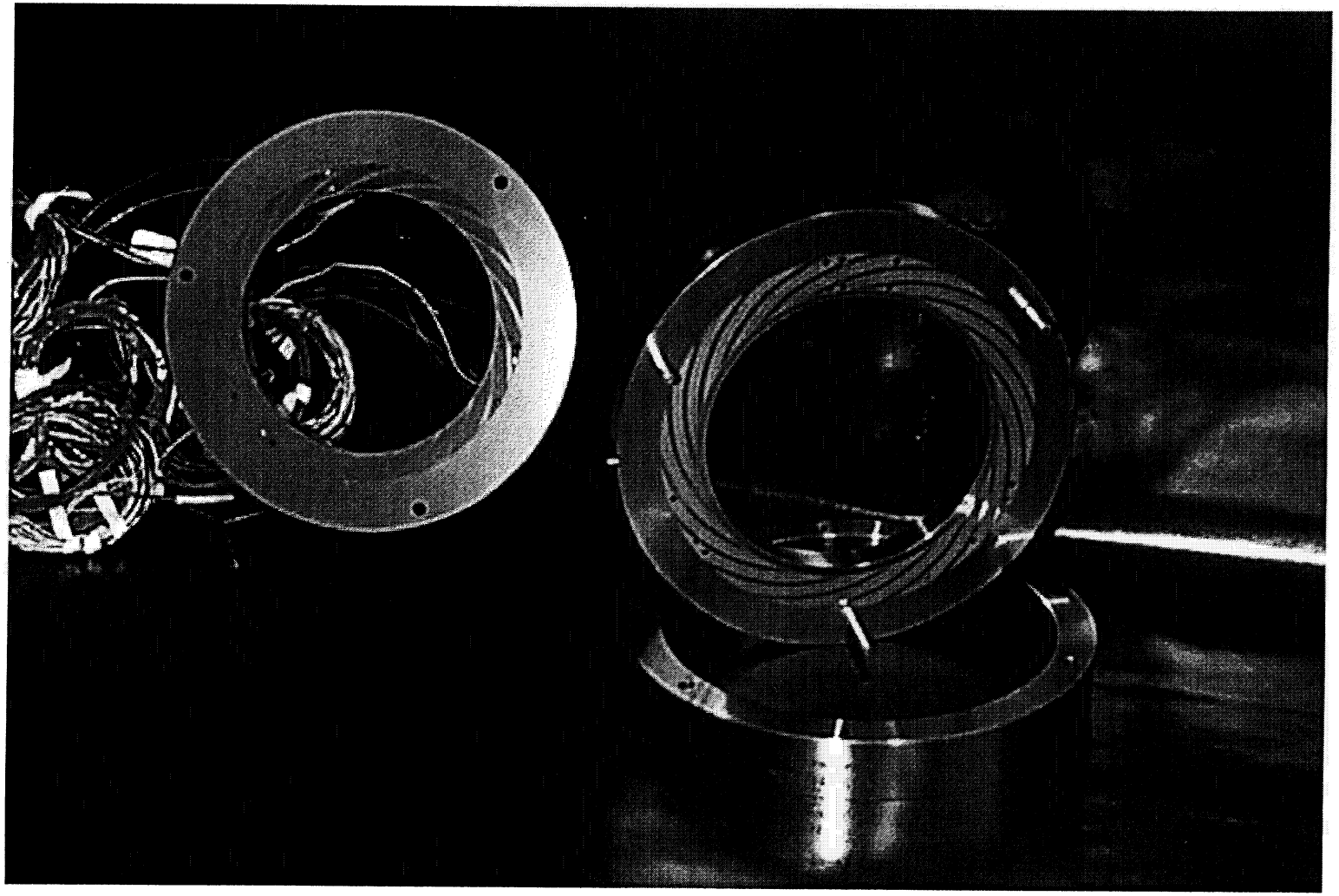




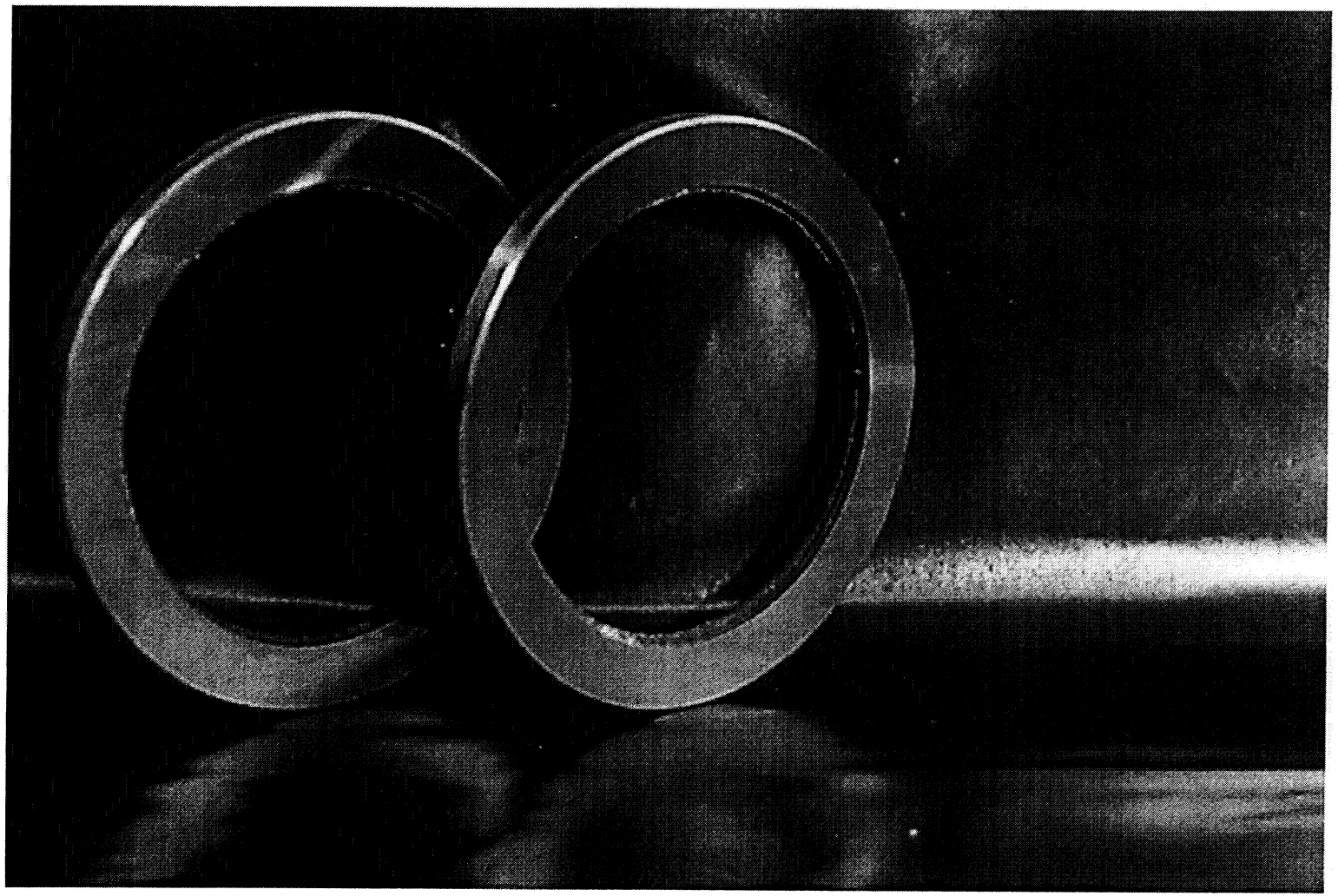
Housing



Face Seals



Brush Seals



Brush Seal Design

- The design of a brush seal for the HFBS is significantly different from that of a "standard" brush seal.

- In standard, stationary brush seals, the design focuses largely on tribo-pairing the materials of the brush and the moving rotor to reduce the wear at the interface of the two components.

- In the HFBS, the brush seal is being driven by the rotor. The design is therefore concerned with keeping the bristles from lifting off the shaft, due to centrifugal forces, to eliminate relative velocities between the two components.

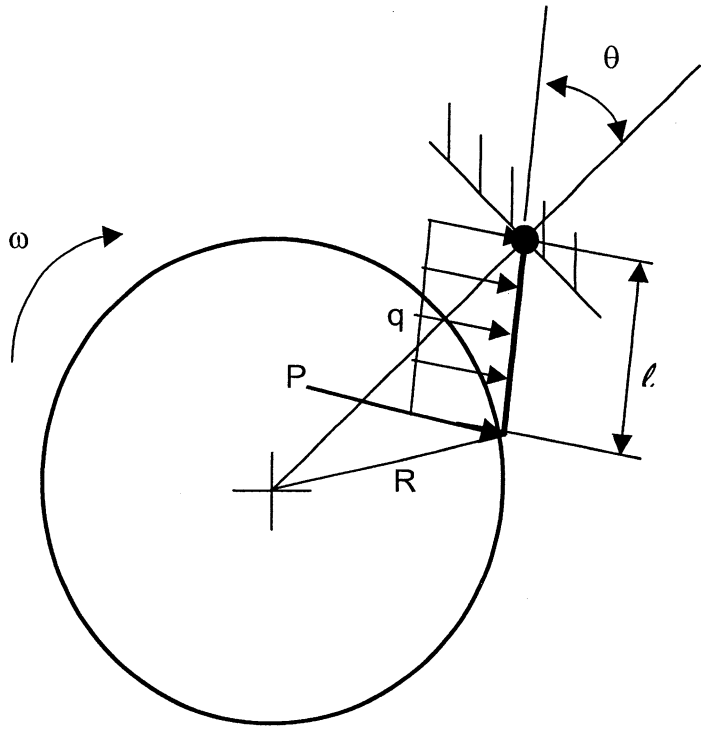
- This centripetal phenomenon was studied both analytically and experimentally.

BRISTLE DEFLECTION DUE TO CENTRIFUGAL LOAD

Consider the forces acting on a single bristle of length ℓ, diameter d, under a pre-load P, lay angle θ, and a rotational speed ω.

The pre-load is the force applied by the rotor onto the bristle, as the O.D. of the rotor pushes the end of the bristle outward radially from its center.

The deflection, δ_p, due to pre-load, P, is given by:



$$\delta_P = \frac{Pl^3}{3EI} \quad \text{where} \quad I = \frac{\pi d^4}{64}$$

$$\delta_w = \frac{ql^4}{8EI} \quad \text{where} \quad q = \frac{w\sin\theta}{l}$$

$$= \frac{wl^3 \sin\theta}{8EI} \quad \text{where} \quad w = mr\omega^2,$$

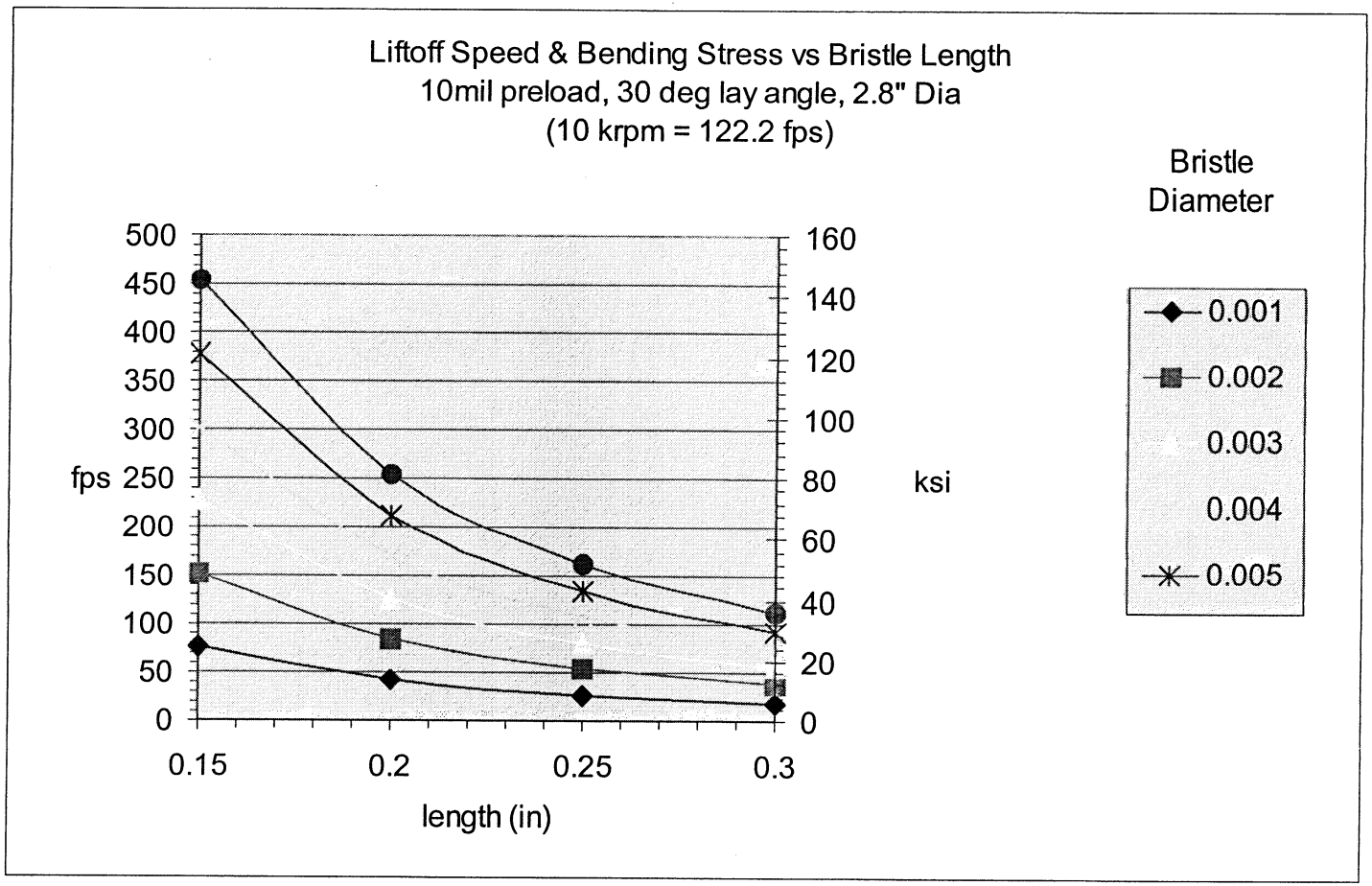
and m is the mass of the bristle

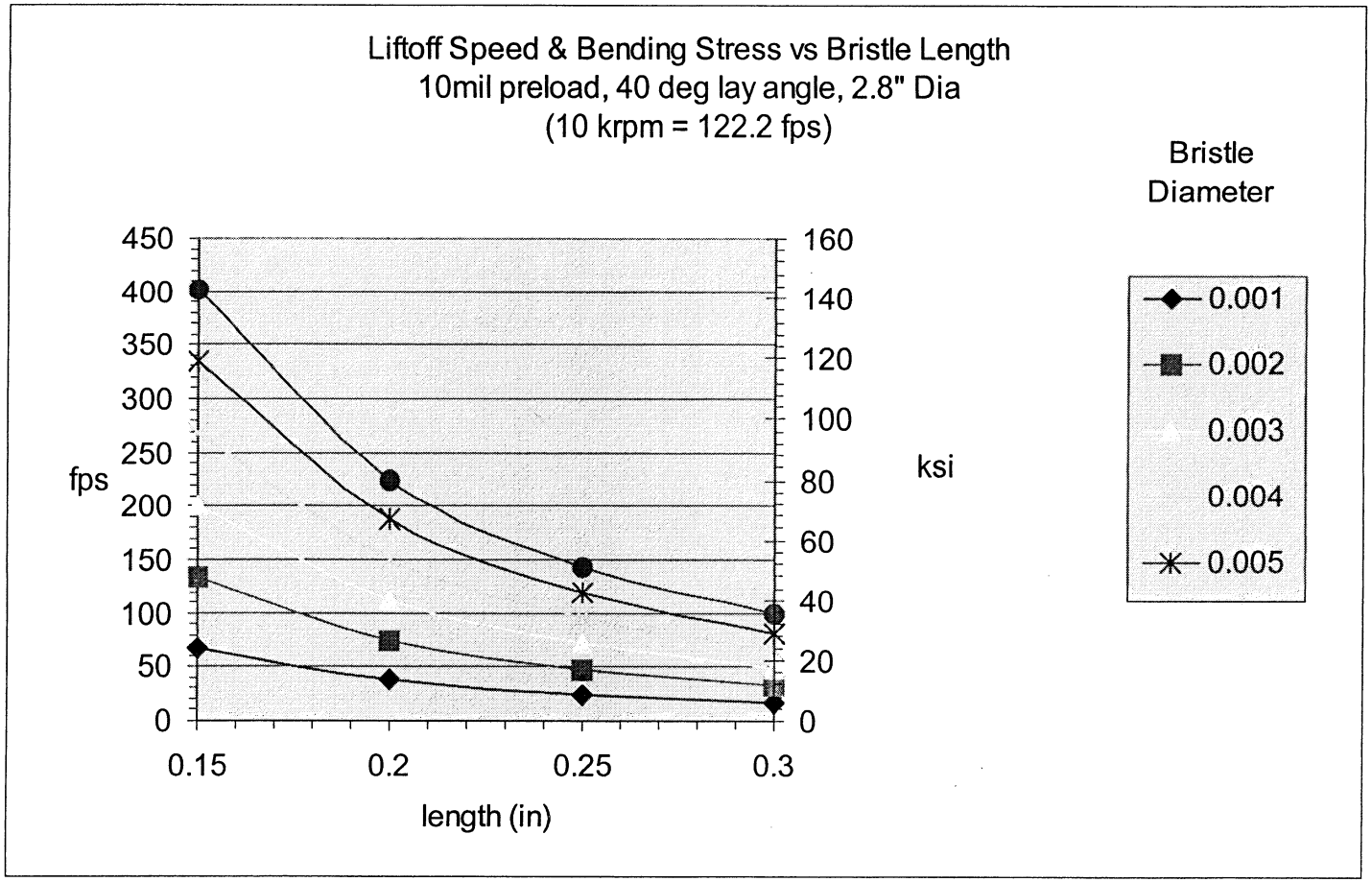
ANALYTICAL MODEL

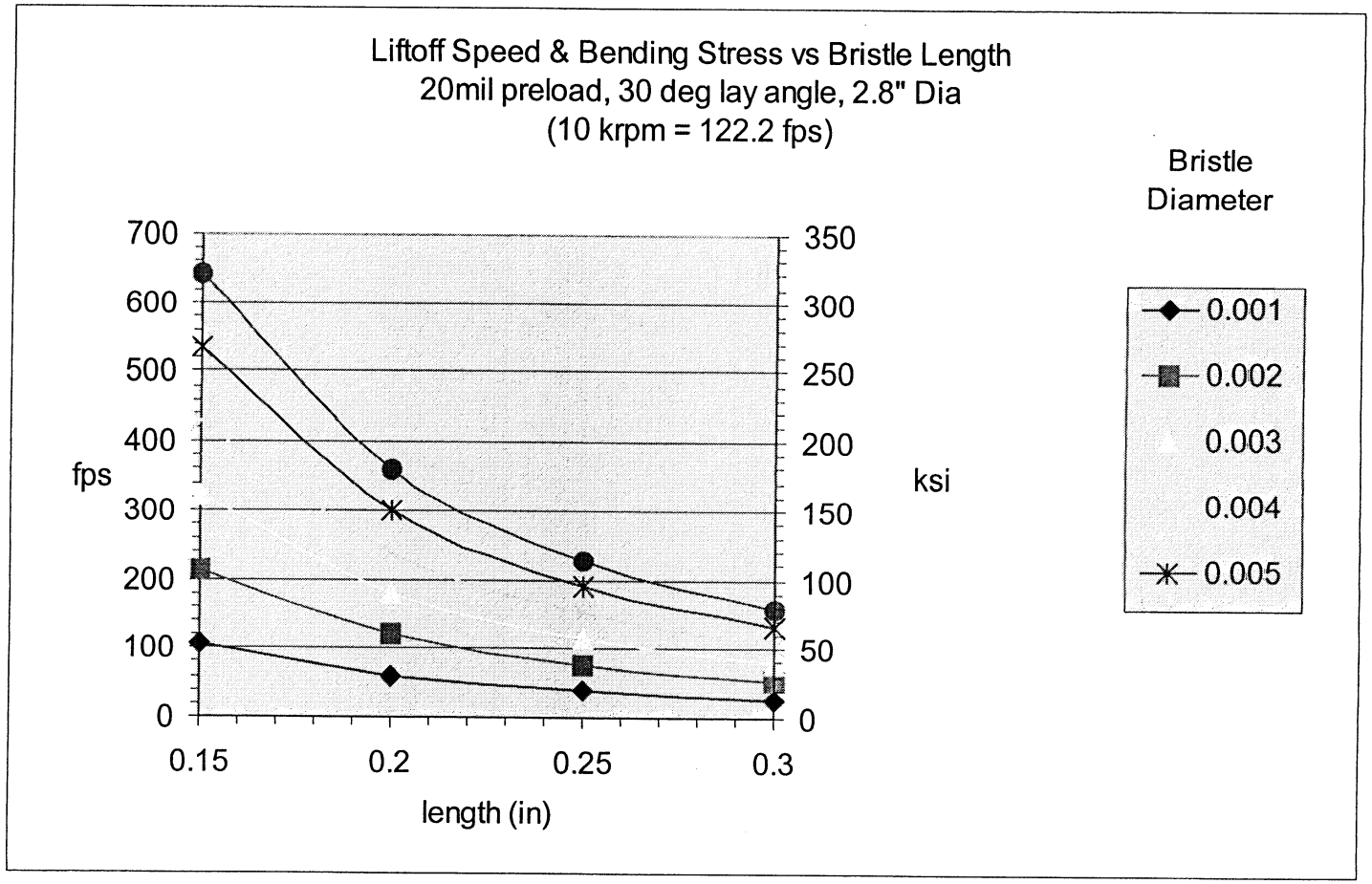
The design process of the brush seal involved parametric calculations using the geometric characteristics and material properties of the bristles. The calculations allowed the determination of the highest rotational speed at which the bristles would begin to lift off the rotor for a given bristle geometry.

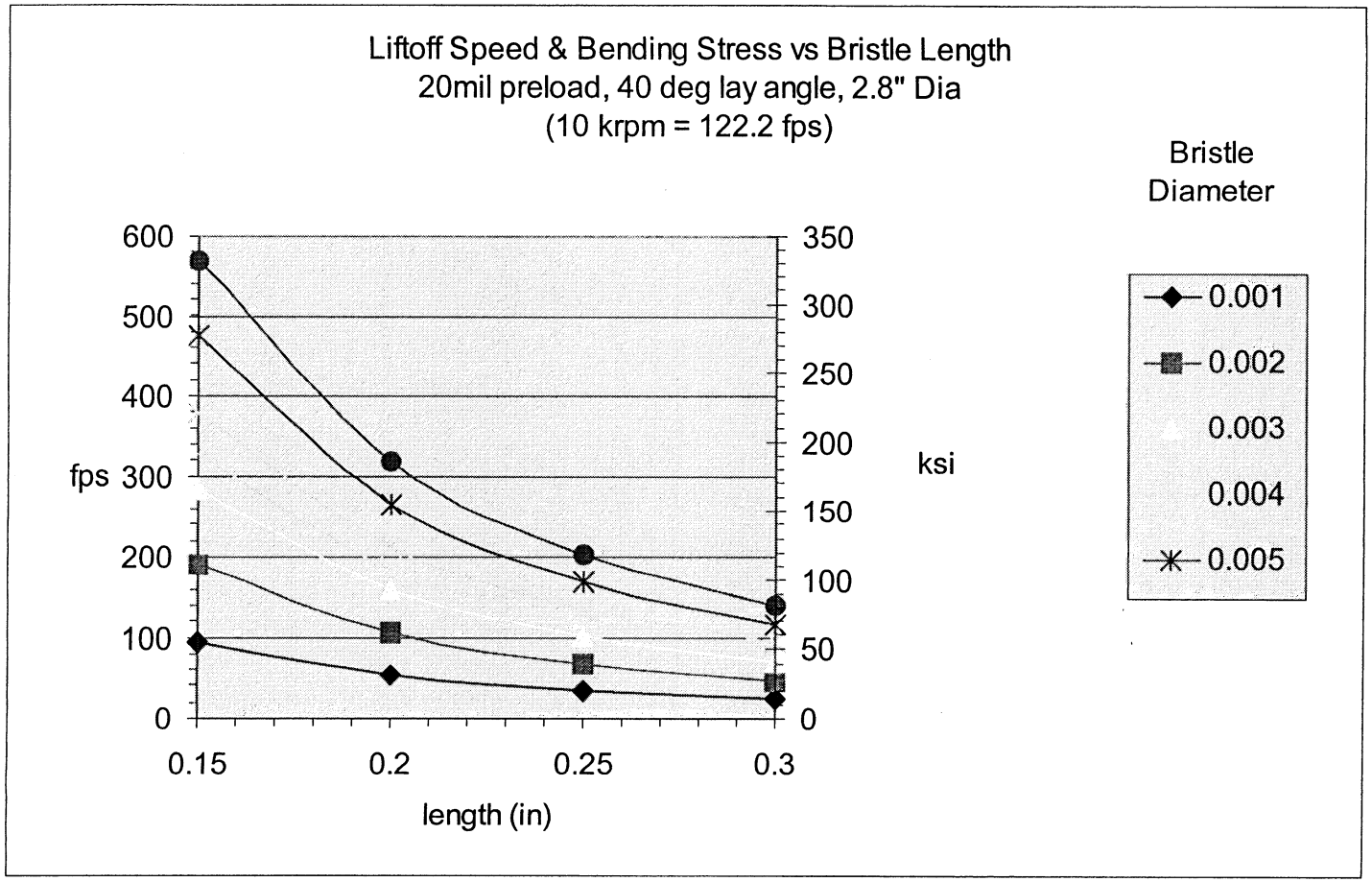
These properties included:

a) Free length of the bristles
b) Density and Elastic Modulus of the bristles
c) Diameter of the bristles
d) Lay angle of the bristles
e) Bristle pre-load
f) Bending stress of the bristles

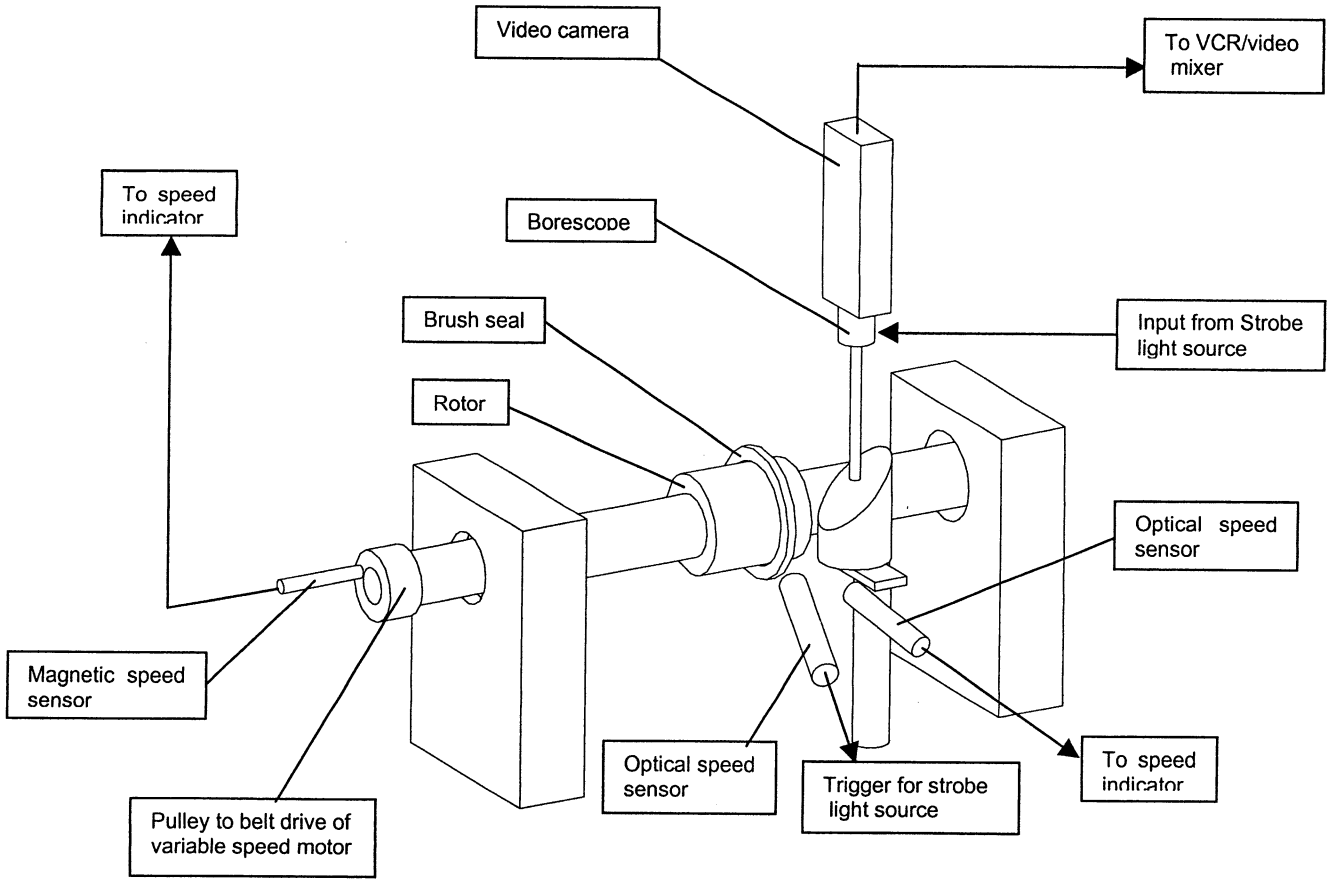

Liftoff Speed & Bending Stress vs Bristle Length
10mil preload, 30 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
Bristle Diameter
0.001
0.002
0.003
0.004
0.005
fps
ksi
500
450
400
350
300
250
200
150
100
50
0
160
140
120
100
80
60
40
20
0
0.15
0.2
0.25
0.3
length (in)

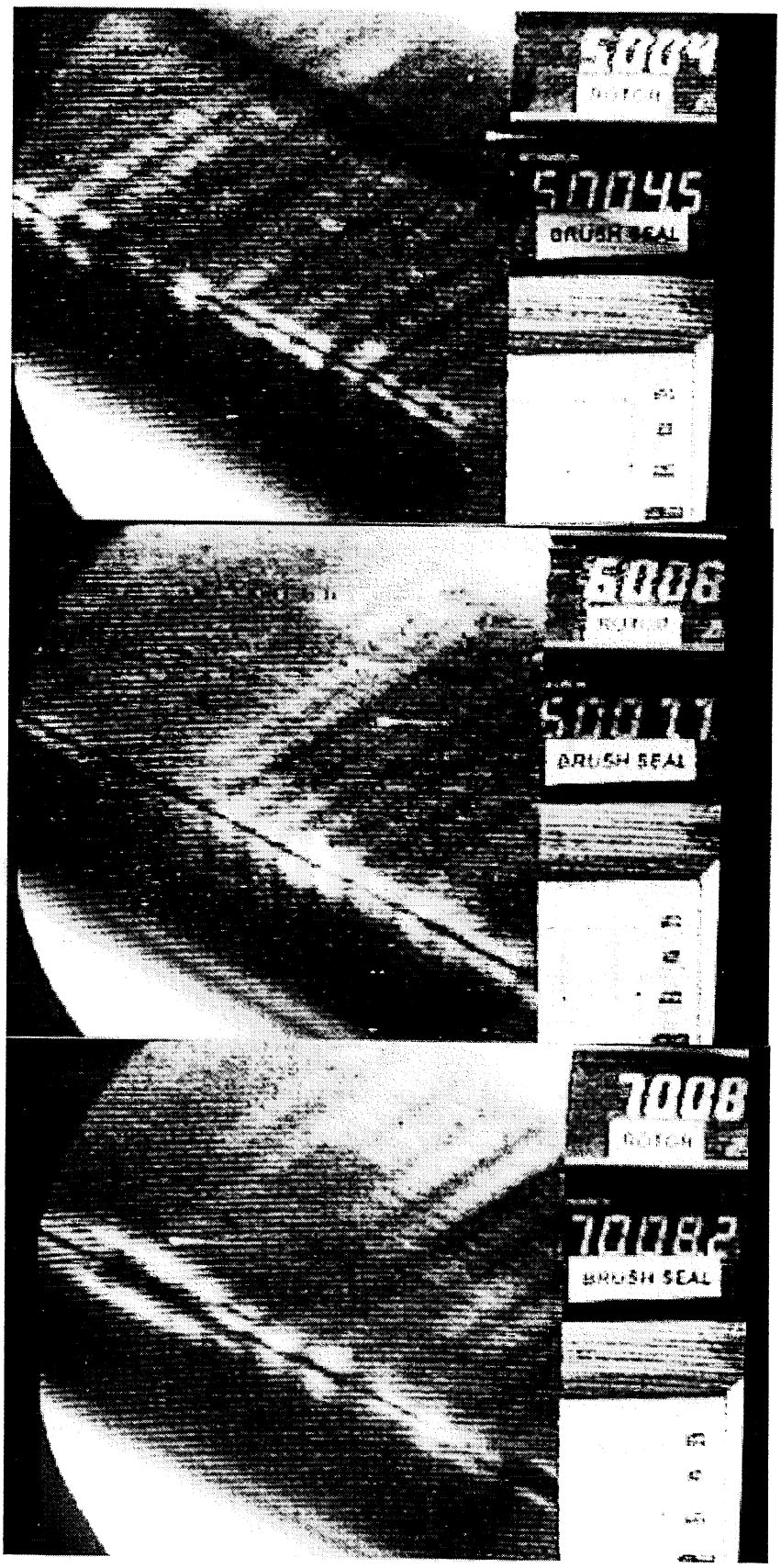

Liftoff Speed & Bending Stress vs Bristle Length
10mil preload, 40 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
fps
ksi
450
400
350
300
250
200
150
100
50
0
160
140
120
100
80
60
40
20
0
0.15
0.2
0.25
0.3
length (in)
Bristle Diameter
0.001
0.002
0.003
0.004
0.005


Liftoff Speed & Bending Stress vs Bristle Length
20mil preload, 30 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
fps
ksi
700
600
500
400
300
200
100
0
350
300
250
200
150
100
50
0
0.15
0.2
0.25
0.3
length (in)
Bristle Diameter
0.001
0.002
0.003
0.004
0.005


Liftoff Speed & Bending Stress vs Bristle Length
20mil preload, 40 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
Bristle Diameter
0.001
0.002
0.003
0.004
0.005
fps
ksi
600
500
400
300
200
100
0
350
300
250
200
150
100
50
0
0.15
0.2
0.25
0.3
length (in)

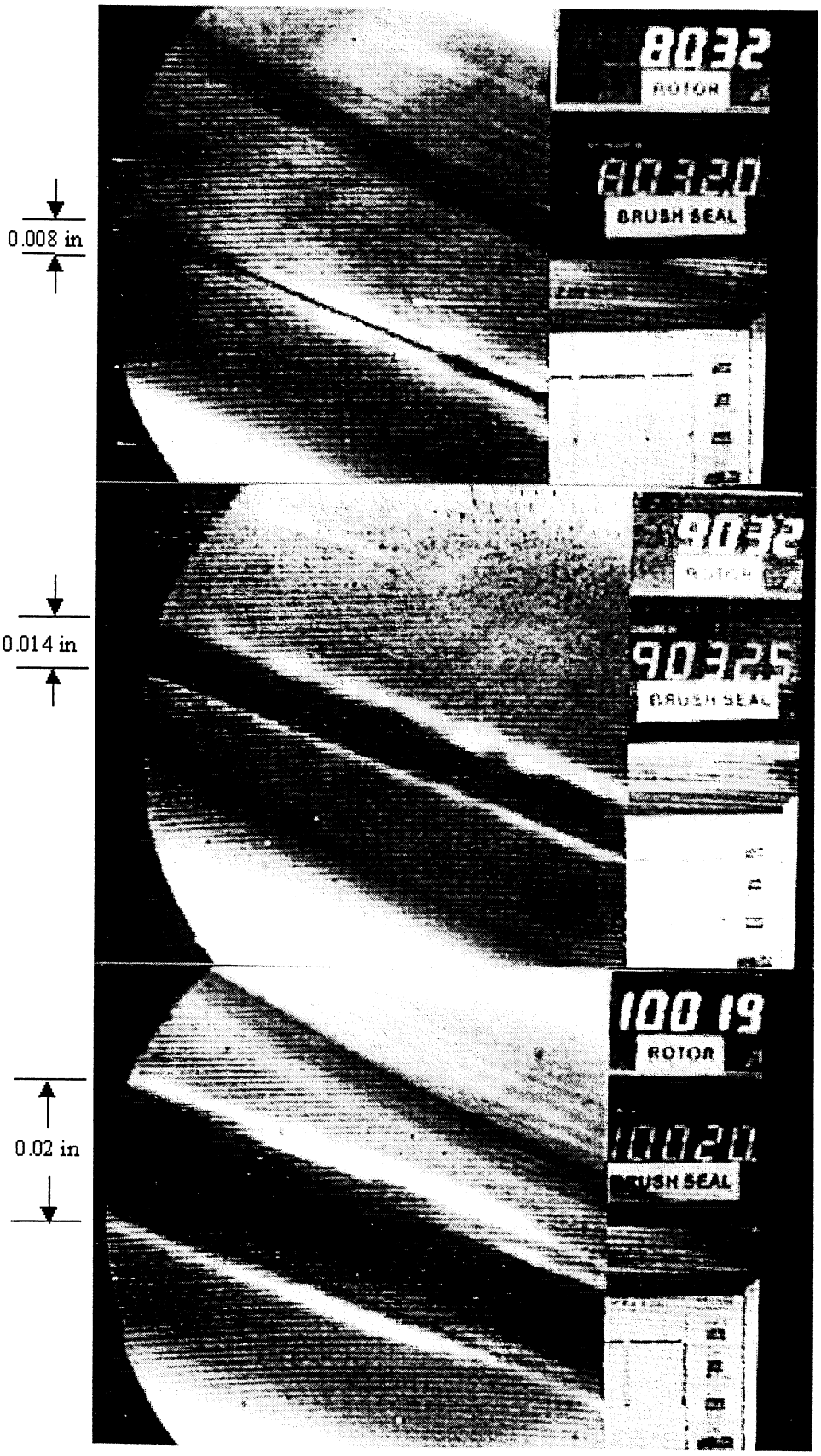
EXPERIMENTAL ANALYSIS





0.002 in

0.006 in


0.008 in
8032
ROTOR
80320
BRUSH SEAL
0.014 in
90325
0.02 in
100 19
ROTOR
100 20
BRUSH SEAL

95 16
ROTOR
BRUSH SEAL
10024
BRUSH SEAL
1 1038
ROTOR
BRUSH SEAL

SUMMARY

Problems

1. Face seal material. Due to thermal expansion considerations, the material chosen for the face seals (Inconel 909) was similar to the material used for the side plates of the brush seal (Hastelloy X). This material matching proved to be a detrimental in the start-up of this hybrid seal. In addition, the face seal manufacturer had a difficult time maintaining the flatness tolerance of the stators.

2. Brush seal design. Due to the manufacturer's concerns regarding bristle bending stress, conservative brush seal designs were approached to "get the ball rolling". Premature lifting of the bristles (well below the target speed, 40krpm) occurred with these initial designs due to a lack of bristle stiffness.

Solutions

1. Face seal material. Face seals were made of a material that the manufacturer was familiar with (Silicon Carbide). This material matches very well to the brush seal side plate material at room temperature. However, another material had to be chosen to meet the target temperature (900°F), while still keeping the hardness properties of Silicon Carbide. Silicon Nitride was recommended by the face seal manufacturer. It possesses the desired properties and will be tested in the High Temperature Test Rig (HTTR).

2. Brush seal design. Using beam deflection equations, a model was developed to predict bristle lift-off, stress, and the possibility of buckling due to centrifugal forces. This model was then used to develop bristle/rotor geometries that would allow the brush seal to reach its target speed while staying within allowable bending stress ranges.

Achievements

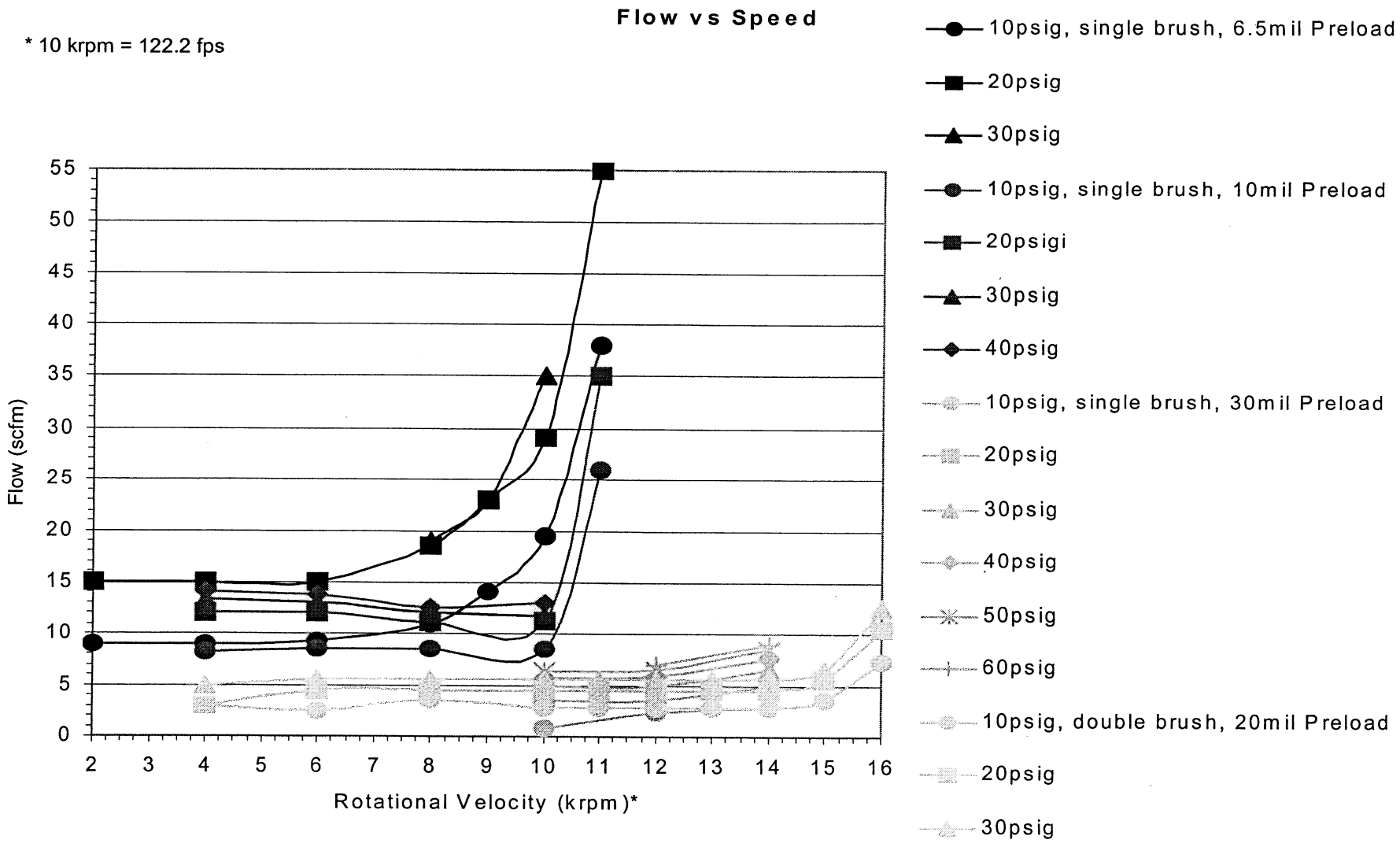
- The face and brush seal material matching problems were solved successfully.

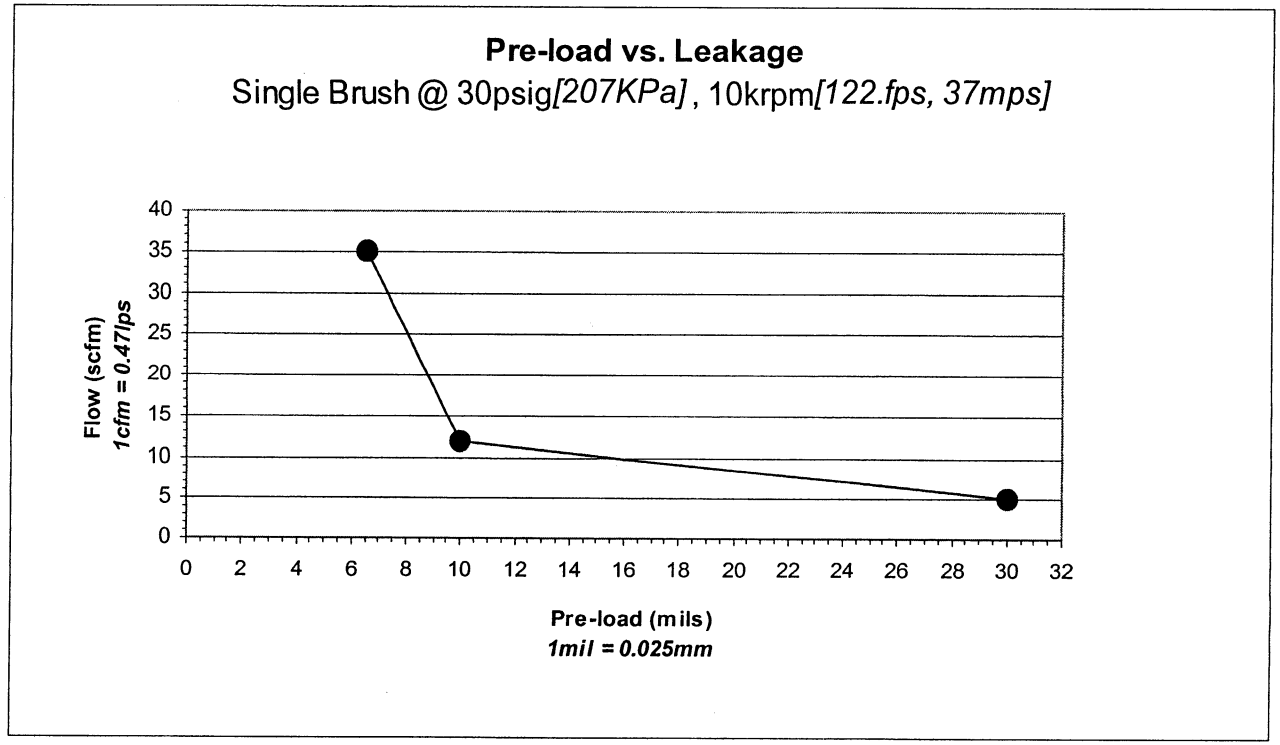
- The Hybrid Floating Brush Seal (HFBS) has proven feasibility for both low and high speed applications. Current testing of the HFBS has successfully run up to 16,000rpm at 40psi (double brush) and 1,800rpm at 100psi (single and double brush).

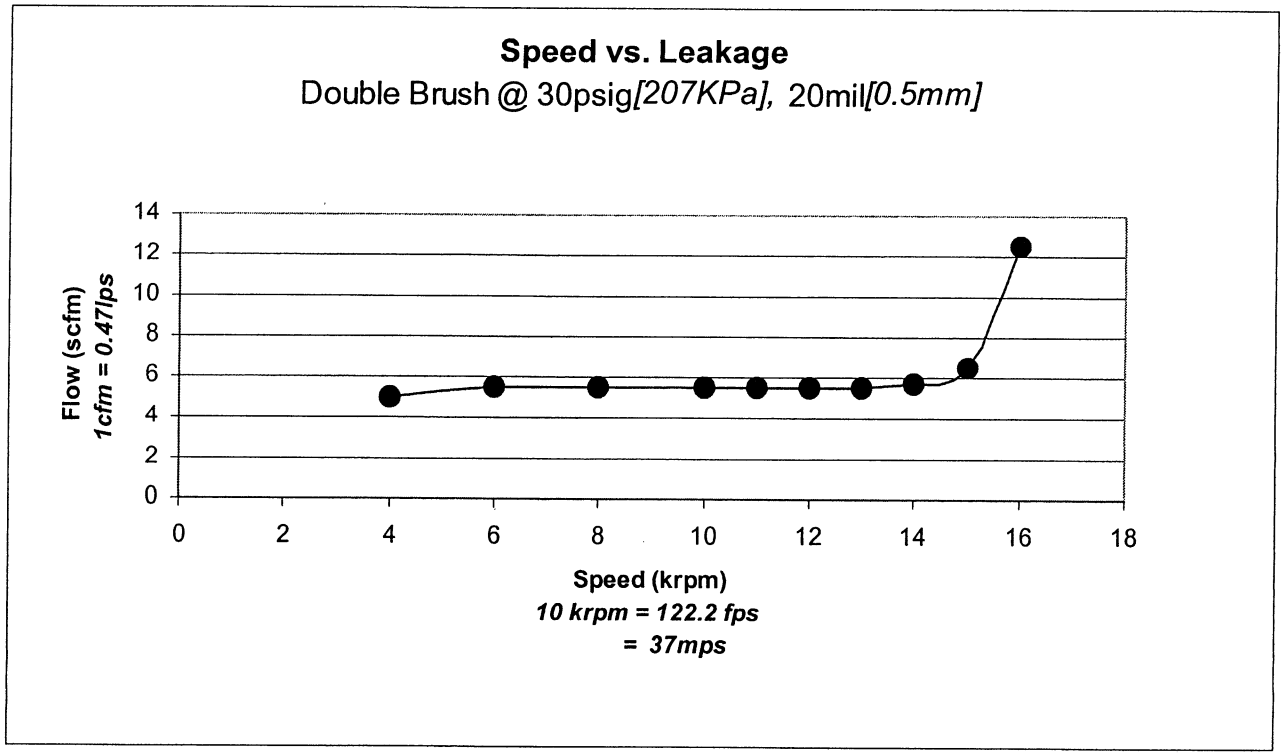
- New brush seal suppliers have been approached to fabricate the brush seals at a much lower cost than the current supplier. Companies show great interest in the HFBS concept and the chance for designing and testing new types of brushes for both high and low speed applications. A brush seal manufacturer will be a prominent component for success in phase III (commercialization).

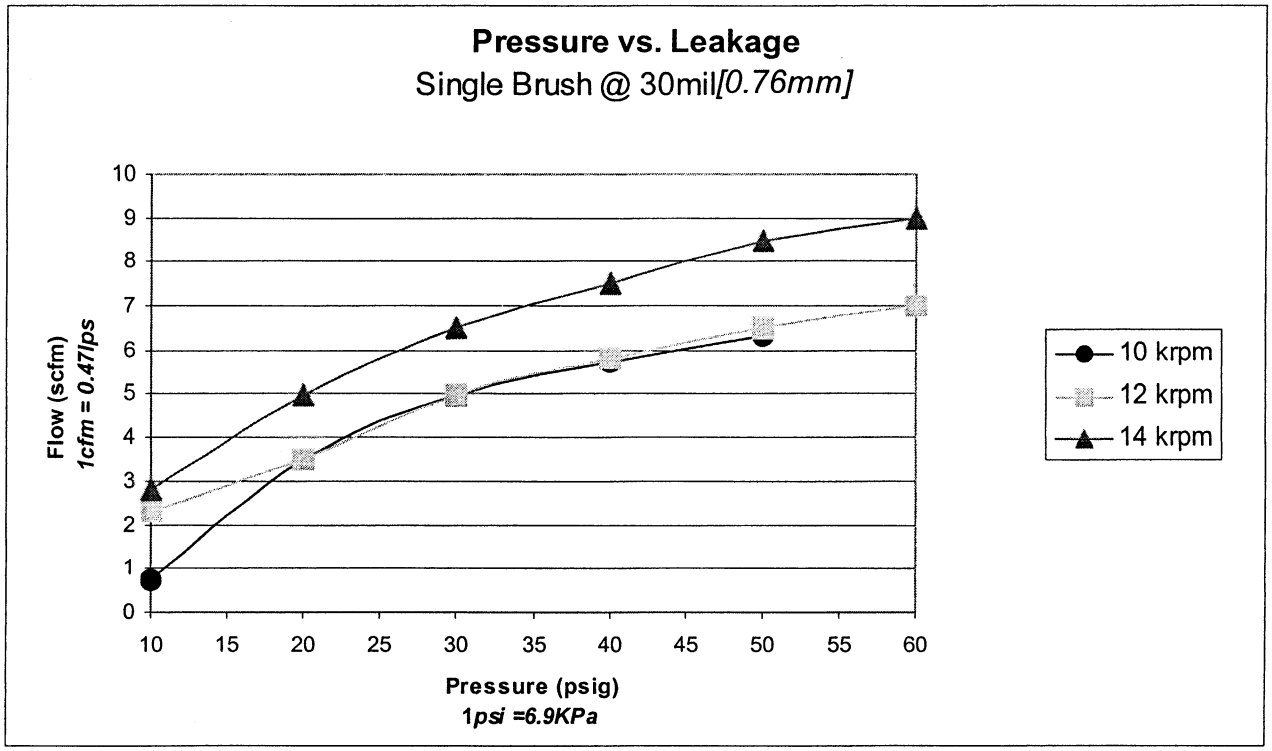
- BCEA has developed an analytical model that has been used for the new brush seal designs. The experiments planned for the near future are intended to validate the model and provide the desired types of brushes for the successful conclusion of the project.

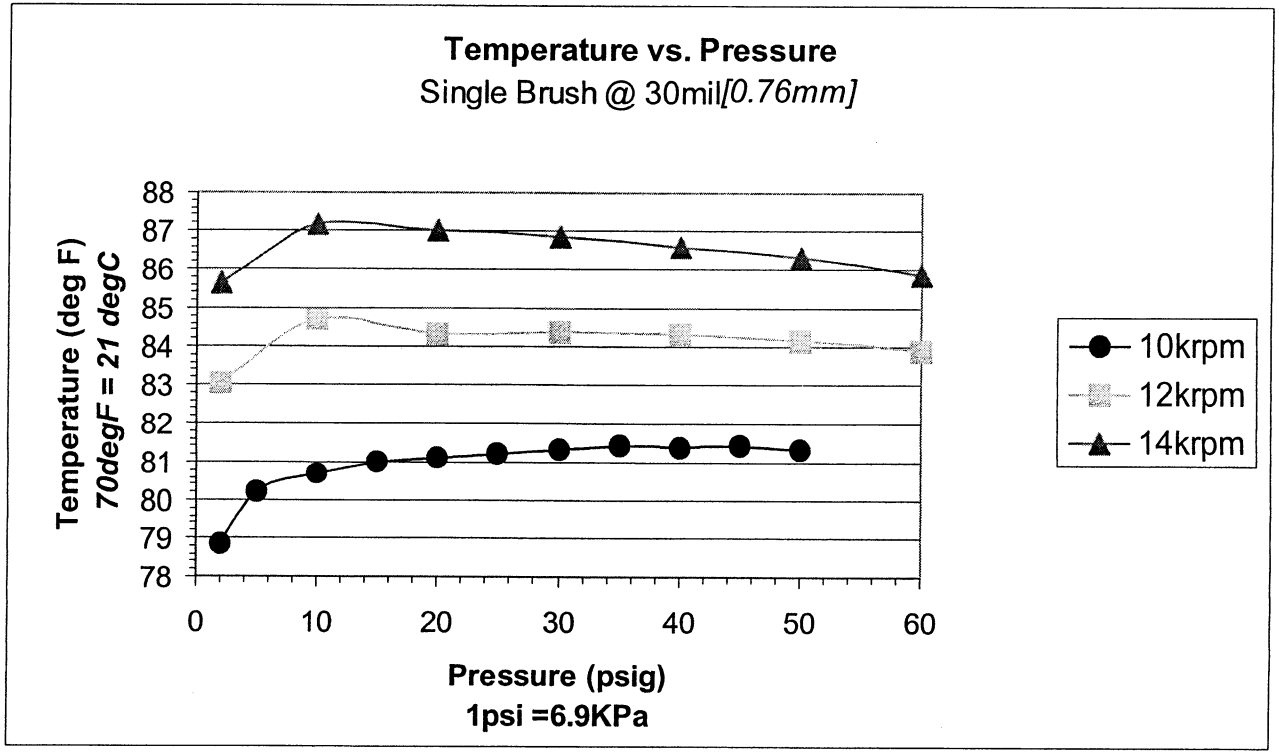
Experimental Results

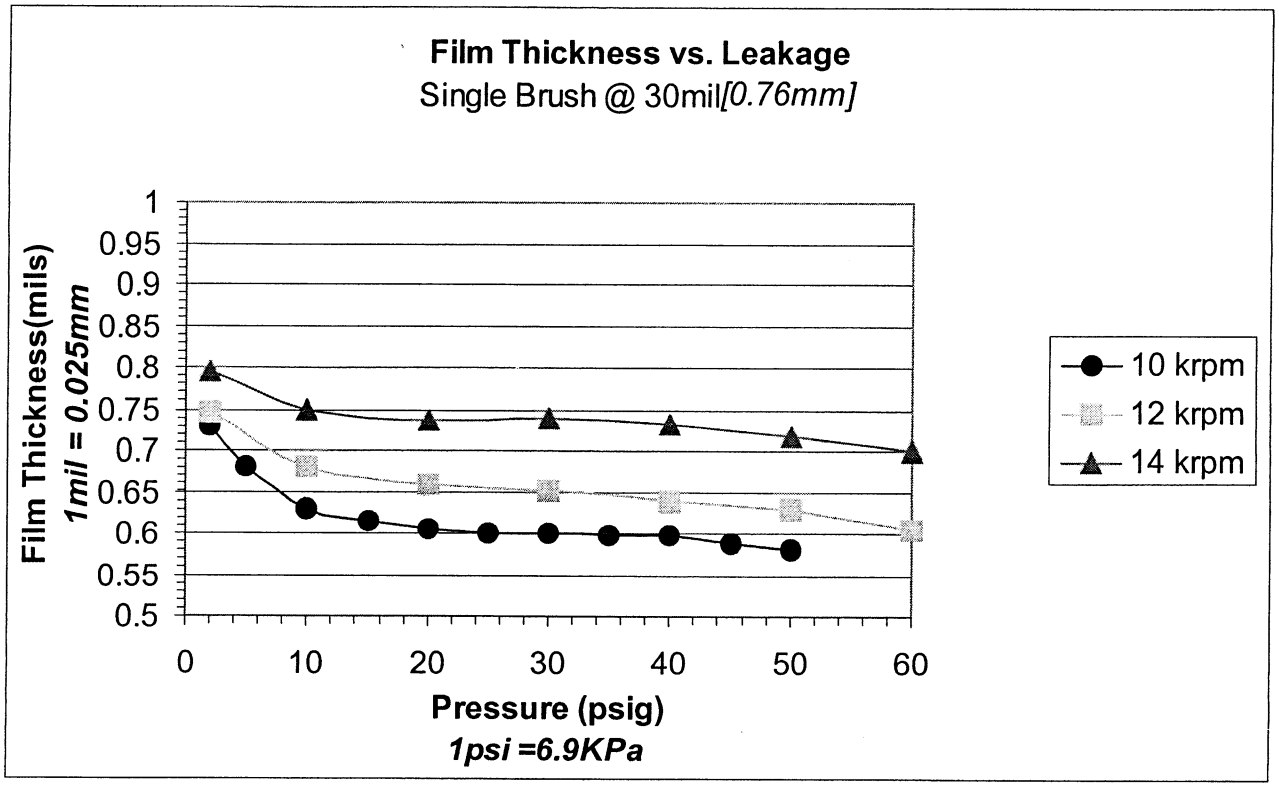



Pre-load vs. Leakage
Single Brush @ 30psig[207KPa], 10krpm[122.fps, 37mps]
Flow (scfm)
1cfm = 0.47lps
40
35
30
25
20
15
10
5
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Pre-load (mils)
1mil = 0.025mm


Speed vs. Leakage
Double Brush @ 30psig[207KPa], 20mil[0.5mm]
Flow (scfm)
1cfm = 0.47lps
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
Speed (krpm)
10 krpm = 122.2 fps
= 37mps


Pressure vs. Leakage
Single Brush @ 30mil[0.76mm]
Flow (scfm)
1cfm = 0.47lps
0
1
2
3
4
5
6
7
8
9
10
10
15
20
25
30
35
40
45
50
55
60
Pressure (psig)
1psi =6.9KPa
10 krpm
12 krpm
14 krpm


Temperature vs. Pressure
Single Brush @ 30mil[0.76mm]
Temperature (deg F)
70degF = 21 degC
88
87
86
85
84
83
82
81
80
79
78
0
10
20
30
40
50
60
Pressure (psig)
1psi =6.9KPa
10krpm
12krpm
14krpm


Film Thickness vs. Leakage
Single Brush @ 30mil[0.76mm]
Film Thickness(mils)
1mil = 0.025mm
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0
10
20
30
40
50
60
Pressure (psig)
1psi =6.9KPa
10 krpm
12 krpm
14 krpm

Direction of Work

Goals

- Design brush seal to run at speeds of 40krpm and beyond.
- Optimize seal performance for both high (turbine, jet engines) and low (compressors, pumps) speed applications.
- Obtain partners and support for commercialization of the HFBS in both high and low speed rotating machinery markets.

Tasks

- Study bristle lifting and leakage characteristics at speeds up to 40krpm and pressures up to 120psi.
- Examine the effects of bristle geometry: diameter, length, lay angle, and density.
- Comparison/ validation of bristle lift model to experimental results.
- Test effects of radial runout and rotor axial motion on seal performance.
- Evaluate start up conditions under pressure load and ramping up pressure and speed.
- Examine bristle hysteresis and possible permanent deformation
- After confidence is reached at room temperature, test seal performance up to 900°F.