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Preliminary Experimental Results for a Cryogenic Brush Seal Configuration

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AIAA/SAE/ASME/ASEE
29th Joint Propulsion Conference and Exhibit
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June 1993

Page 2, line 4: Replace the phrase "The sets of seals were placed at each end..."
Page 5, line 11: Replace the phrase "A five-brush set was placed at each end..."
with
"Data in table I were run with 1 brush set and 1 Laby seal"

Page 2, line 11, coating details change: Bond Coat 0.002–0.003 in. AMC 763 NiCrAly
Ceramic Coat 0.008–0.010 in. ZrO_2-$7Y_2O_3$
Surface Finish 9 to 16 R_A

Page 4, Equation (7) should be

$$\frac{b\varepsilon^3 Dp}{\rho} = 1.75(1-\varepsilon)$$

Page 7, Table 1: Test 046, Mass flow rate should be 0.26

PRELIMINARY EXPERIMENTAL RESULTS FOR A CRYOGENIC BRUSH SEAL CONFIGURATION

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SUMMARY

Preliminary fluid nitrogen flow data are reported for a five-brush, ceramic-coated-rub-runner brush seal system, where the brushes and the rub runner were placed at each end of a centrally pressurized multifunction tester ("back-to-back" set of brushes) and tested at rotor speeds of 0, 10, 18, and 22.5 krpm. The testing times were >3100 s at 10 krpm, >1500 s at 18 krpm, and >3900 s at 22.5 krpm. After testing, both the brushes and the ceramic-coated rub runner appeared pristine. The coating withstood both the thermomechanical and dynamic loadings with minor wear track scarring. The bristle tips showed some indication of material shearing (smearing) wear.

The Ergun porous flow equation was applied to the brush seal data. The Ergun relation, which required heuristic information to characterize the coefficients, fit the gaseous data but was in poor agreement with the fluid results. The brush seal exit conditions were two phase. Two-phase, choked-flow design charts were applied but required one data point at each rotor speed to define the ($C_f A$ × Constant) flow and area coefficients. Reasonable agreement between prediction and data was found, as expected, but such methods are not to be construed as two-phase-flow brush seal analyses.

INTRODUCTION

Brush seal systems consist of a brush (or set of brushes) and its associated rub runner interface. Although several research and development reports have focused on characterizing brush seal leakage (refs. 1 to 11) and a few on dynamics (e.g., ref. 12), only two address the critical issues of interface tribology (refs. 13 and 14). Further, there is a dearth of information on brush seal life. For cryogenic turbomachines of the space shuttle main engine (SSME) class, run times are short, but both the operating conditions and the fluid environment are hostile (e.g., surface speeds to 300 m/s (1000 ft/s), pressures to 55 MPa (8000 psi), temperatures from 20 K (36 °R), and nonequilibrium fluid mixtures). Herein we provide some preliminary test results for cryogenic nitrogen flowing through a brush seal system consisting of an assembly of five brushes configured with an yttria-stabilized-zirconia (ZrO_2-$6Y_2O_3$)-coated rub runner.

SYMBOLS

A	flow area
a,b	Ergun constants
C_f	flow coefficient
D_p	particle diameter

G mass flux, ρu

L length

P pressure

u velocity

V specific volume

$\dot{V}$ volumetric flow rate

$\dot{W}$ mass flow rate

ρ density

ε porosity

μ viscosity

Subscripts:

eff effective

exp experiment

max maximum flow condition (choking)

0 stagnation or reference

APPARATUS

The multifunction tester is shown in figure 1. Although the design and operational details remain proprietary to Rocketdyne, the figure shows the location of the five-brush, ceramic-coated-rub-runner brush seal system. The sets of seals were placed at each end to provide thrust balancing. Instrumentation included pressures and temperatures upstream and downstream of the seal sets, and some dynamic information on these seals was taken as the tester underwent forced excitation at 0.025-mm (0.001-in.) radius orbits. The dynamics associated with those data are not reported herein, but the leakage information is noted.

BRUSH SEAL SYSTEM

The rub runner (fig. 2) was fabricated from stainless steel and dimensioned to permit 0.127-mm (0.005-in.) radial interference fit with the brush and the rotating rub runner. The rub runner was plasma sprayed with 0.051- to 0.076-mm (0.002- to 0.003-in.) metallic bond coat (MCrAlY) followed by a dense plasma-sprayed ceramic coat, 0.127- to 0.152-mm (0.005- to 0.006-in.) yttria-stabilized (6 percent) zirconia (ZrO_2-$6Y_2O_3$). The surface was ground to a 25-rms finish by using a diamond compound. During the final lapping operations a dust-free work environment was required to achieve the tolerances and the surface finish.

Pressurized fluid entered at the center of the multifunction tester and flowed through a set of brush seals at each end (back to back) to mitigate the thrust balance problem. This back-to-back, five-brush seal system was designed to operate at pressures to 3.1 MPa (450 psia) and rotational speeds to 30 krpm at liquid hydrogen temperatures.

Each of the brushes (fig. 3) was of conventional Cross Mfg. construction with a bristle diameter of 0.071 mm (0.0028 in.) and a radial height of 7.1 mm (0.28 in.). The annealed Haynes 25 alloy wires were laid up at 40° to

45° to the interface and at a density of 98 per millimeter of circumference (2500 per inch of circumference). The backing plate and the pinch washer were made of Inconel with the fence height set at 0.25 mm (0.010 in.). (Maximum anticipated rotor displacement was 0.1 mm (0.004 in.).) The inside diameter of each brush was ground to provide a nominal 0.13-mm (0.005-in.) radial interference fit between the brush and the rub runner.

RESULTS AND ANALYSIS

Inspection of the brush sets and the rub runners after testing revealed little noticeable damage. The bristle tips attained the conventional shear flow characteristic at the interface, showing the trend to diamond-like bristle tips versus virgin elliptical tips, with small roughened and often hook-like appearance to the tips.

The rub runner interface coating of ZrO_2-$6Y_2O_3$ over MCrAlY withstood the rigors of both the thermo-mechanical shock and rotordynamic loadings without chipping, mudflat cracking, or crazing (fig. 2). The brush bristle tracks on the rotor appeared discolored, indicating heating, but the wear scars were minor in that they were less than 0.025 mm (0.001 in.). The exception, where the scar was nearly 0.025 mm (0.001 in.), can be seen as a circumferential scratch at each brush position (fig. 2).

Temperature and pressure measurements indicated the flow data to be two phase at the exit and beyond the capability of current brush seal analyses (table I). However, by assuming that the data can be represented as homogeneous two-phase choked flows through an equivalent nozzle, one can apply the generalized design charts developed by Simoneau and Hendricks (ref. 15, pp. 73 and 76) to estimate the leakage flow rates. These generalized charts (fig. 4) provide solutions to equations (1) and (2), the adiabatic frictionless equations for choked flow in an ideal nozzle:

$$G_{max}^2 = -\frac{2}{V_{max}} \int_{P_0}^{P_{max}} V\, dP \tag{1}$$

$$G_{max}^2 = \left[-\frac{dV}{dP}\bigg|_{max} \right]^{-1} \tag{2}$$

Flows through other than ideal configurations are related through the use of a flow coefficient, and the mass flows are then dependent on the effective flow area associated with that flow coefficient

$$\dot{W} = GA = C_f A G_{max} \times \text{Constant} \tag{3}$$

where G_{max} is in grams per square centimeter per second and the constant is a units conversion factor. In order to construct an equivalent nozzle, the $C_f A$ × Constant term must be assessed from one data point at each rotor speed. The point selected was the high-pressure-drop data point to ensure the existence of the two-phase conditions (table I). The resulting relation for these data only becomes

$$C_f A \times \text{Constant} = (0.085\ \text{krpm} + 1) \times 10^{-5} \tag{4}$$

These curves are superimposed on the data in figure 5, and it is not surprising that the agreement is reasonable as one is using data to find $C_f A$ × Constant. The relation cannot be construed as a two-phase flow analysis for brush seal systems without significant additional analytical and experimental work. Single-phase flows do not exhibit such a strong influence of rotor speed.

The Ergun model (fig. 6) of single-phase flows in porous media (ref. 16) was applied in the same manner, but here it was required to determine suitable constants, a and b, such that the pressure drop may be expressed in terms of the equivalent two-phase bulk flow velocity

$$\Delta P = (au + bu^2)L \tag{5}$$

where for a packed bed of spheres the relations for a and b become (ref. 17)

$$a\varepsilon^3 D_p^2/\mu = 150(1 - \varepsilon)^2 \tag{6}$$

$$b\varepsilon^3 D_p = 1.75(1 - \varepsilon) \tag{7}$$

For the data herein the constants a and b were simply determined from the high-pressure-drop data point at each rotor speed. Calculating aL and bL, while using $\rho_0 = 0.0011$ g/cm^3, $\varepsilon = 0.7$, $\mu_0 = 0.19\times10^{-3}$ g/cm-s, $D_p = 0.005$ cm, and $L = 0.1$ cm gives

$$\frac{aL}{A_{eff}} = \frac{3000}{A_{eff}}\left(\frac{\mu}{\mu_0}\right) = 130\left(\frac{\mu}{\mu_0}\right) \text{ Pa} \tag{8}$$

$$\frac{bL}{A_{eff}} = \frac{7.85}{A_{eff}^2}\left(\frac{\rho}{\rho_0}\right) = 0.015\left(\frac{\rho}{\rho_0}\right) \text{ Pa} \tag{9}$$

where $V = (uA)_{eff} = u_0 A_{eff} = 23u_0$ from the data of Carlile et al. (ref. 18), and

$$\Delta P = 130\left(\frac{\mu}{\mu_0}\right)\dot{V} + 0.015\left(\frac{\rho}{\rho_0}\right)\dot{V}^2 \text{ Pa} \tag{10}$$

These equations are in good agreement with the air data of Carlile et al. (ref. 18). For the two-phase flow of liquid nitrogen with $\rho_0 = 0.809$ g/cm^3, $\mu_0 = 1.58\times10^{-3}$ g/cm-s, we will use mass flow rate $\dot{W}$ in grams per second and predict the pressure drop ΔP in megapascals.

$$\Delta P = 0.1035\,\dot{W}_0 + 9.9\times10^{-5}\,\dot{W}_0^2 \text{ MPa} \tag{11}$$

where $\dot{W}_0 = \dot{W}_{exp}/(0.085 \text{ krpm} + 1)$ g/s is the modified flow rate. Here agreement between prediction and data is poor at the low pressure drops.

Least squares curve fitting the 0-krpm data to the form

$$\Delta P = a\dot{W}_0 + b\dot{W}_0^2 \text{ MPa} \tag{12}$$

provides $a = -0.0145$ and $b = 0.00386$, where $\dot{W}_0$ is defined in equation (11). These coefficients differ considerably from those predicted from the Ergun relation and imply differences in modeling and flow regime. Much work remains to be done.

The results of using these constants on the remaining data illustrate an agreement typical of injecting heuristic results into a correlation. Again this is not a two-phase flow analysis of brush seals, and much analysis and experimental information are required to achieve a predictive technique.

SUMMARY OF RESULTS

Preliminary fluid nitrogen flow data were obtained for a five-brush, ceramic-coated-rub-runner brush seal system. A five-brush set was placed at each end of a centrally pressurized multifunction tester and run at 0, 10, 18, and 22.5 krpm. After testing, both the brushes and the rub runner appeared pristine with some indication of material shearing (smearing) of the bristle tips and minor wear tracking of the ceramic.

The thermal measurements indicated seal exit conditions to be two phase and beyond the predictive capability of current brush seal analyses. The two-phase flow design chart of Simoneau and Hendricks was applied to the data but required one data point at each rotor speed to define the $C_f A$ × Constant coefficients. The Ergun porous flow equation was also applied and required similar information to characterize the coefficients. Once these coefficients were determined, the agreement between prediction and data was good, but such methods are not to be construed as two-phase-flow brush seal analyses, and it will require much effort and experiment to achieve a two-phase-flow brush seal code.

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TABLE I.—BRUSH SEAL TEST DATA (AS OF 10-13-92)

Test	Speed, krpm	Upstream pressure, psig	Upstream temperature, °F	Downstream pressure, psig	Downstream temperature, °F	Mass flow rate, lb/s	Absolute pressure ratio
043	0	492	−295	28	−296	0.067	0.085
	10	493	−294	43	−291	.115	.114
	18	495	−289	64	−284	.173	.155
	22.5	211	−282	39	−292	.106	.239
	22.5	496	−282	71	−282	.2	.168
044	0	36	−293	3.7	−311	.023	.365
	10	182	−295	26	−297	.075	.208
	22.5	182	−278	31	−295	.095	.233
045	10	148	−296	21	−300	.07	.220
	22.5	150	−270	22	−299	.083	.224
						.26	
046	0	462	−293	156	−290	.063	.358
048	10	149	−300	27	−298	.065	.256
	22.5	152	−271	31	−297	.085	.275
049	10	180	−294	33	−295	.068	.246
	22.5	216	−281	46	−291	.103	.264
050	10	181	−295	33	−295	.07	.245
	18	151	−281	36	−294	.091	.307
	18	181	−289	41	−291	.096	.285
	18	195	−288	44	−291	.097	.281
	22.5	202	−281	46	−290	.103	.281
051	0	197	−295	23	−300	.044	.179
	10	195	−294	27.5	−298	.067	.202
	18	196	−289	31.7	−296	.082	.221
	22.5	205	−289	34	−295	.089	.222
052	0	182	−296	19.8	−302	.049	.176
	10	182	−294	23.8	−300	.067	.197
	18	182	−287	26.4	−299	.079	.210
	22.5	182	−279	26.9	−299	.076	.212
053	0	149	−300	11.9	−307	.039	.164
	10	149	−297	15.8	−304	.058	.187
	18	150	−285	20.8	−301	.078	.216
	22.5	151	−271	18.9	−303	.073	.204

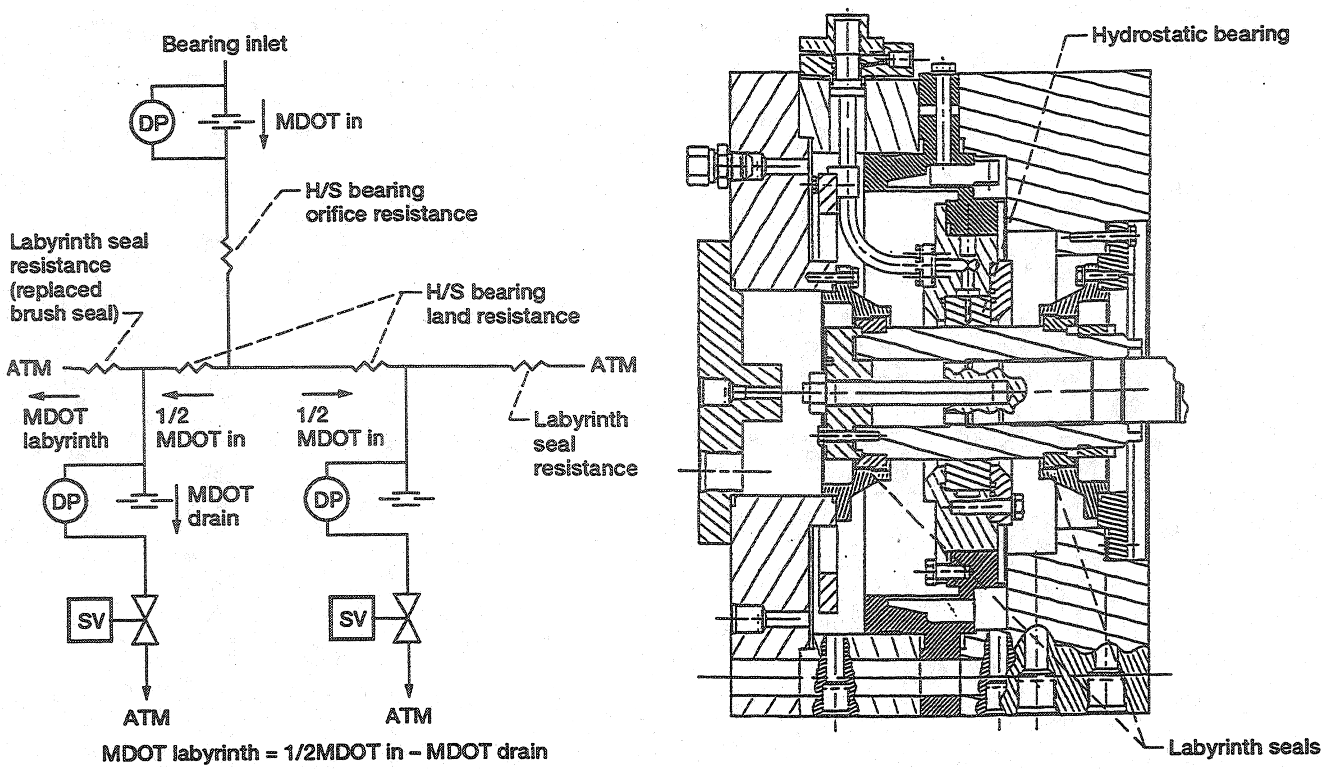
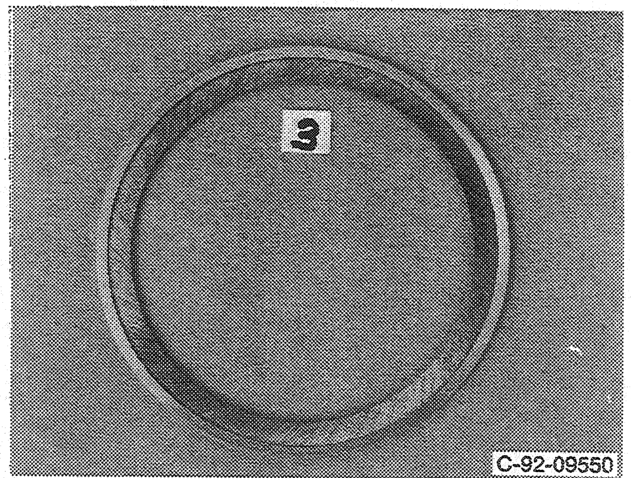
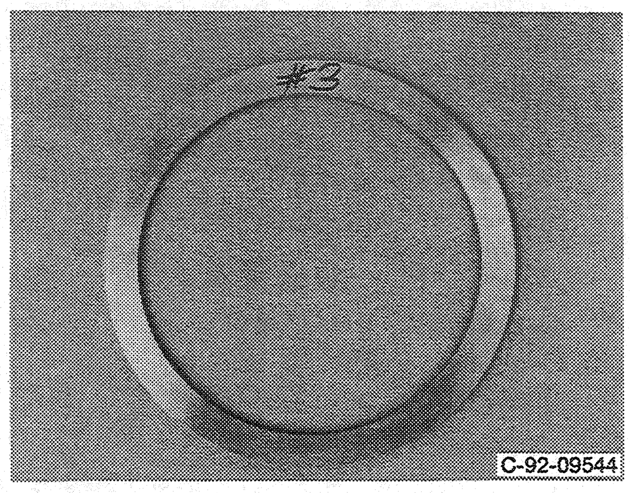


Figure 1.—Schematic and section view of multifunction tester. (Note: Some probes are not shown for clarity.)

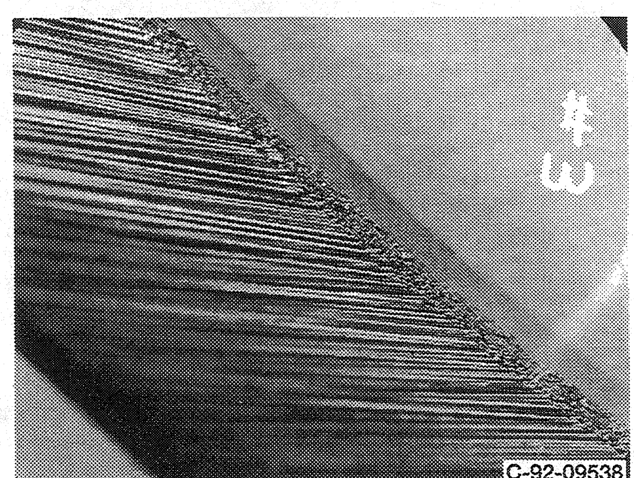
Figure 2.—Post-test photograph of rub runner illustrating wear tracks of five-brush configuration.



(a) Upstream side.

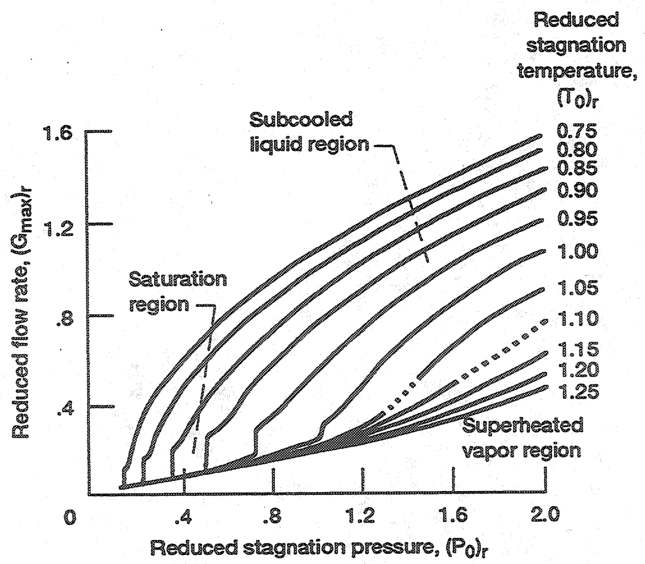


(b) Downstream side.

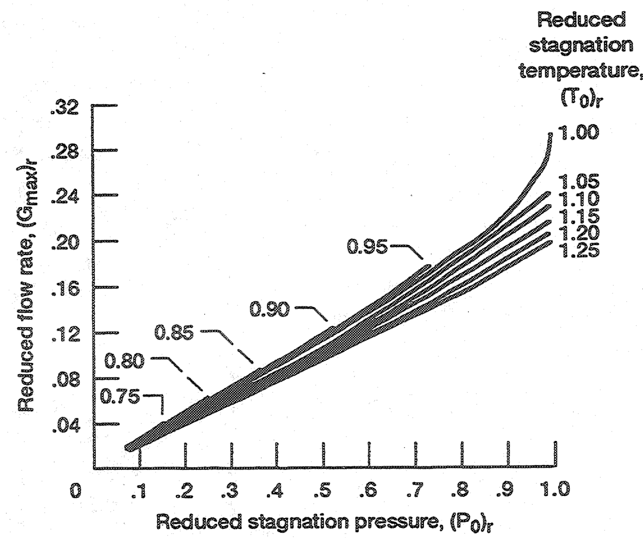


(c) Bristle interface.

Figure 3.—Photographs of a single brush typical of five-brush configuration.



(a) Reduced choked flow rates based on isentropic homogeneous equilibrium model.



(b) Reduced choked flow rates based on isentropic homogeneous equilibrium model (expanded scale of vapor side).

Figure 4.—Generalized design charts for two-phase choked nozzle flow. From ref. 16, p. 74.

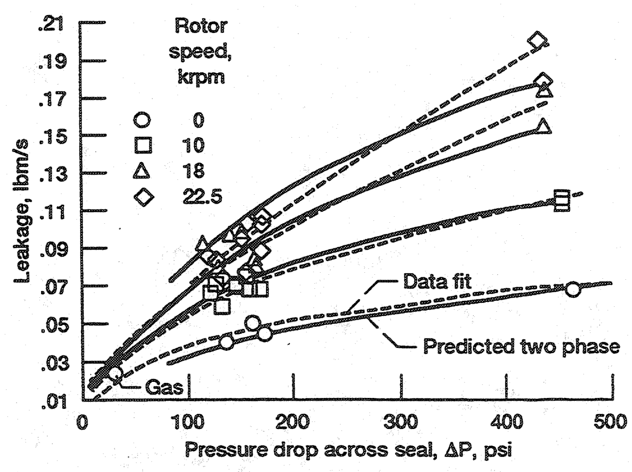


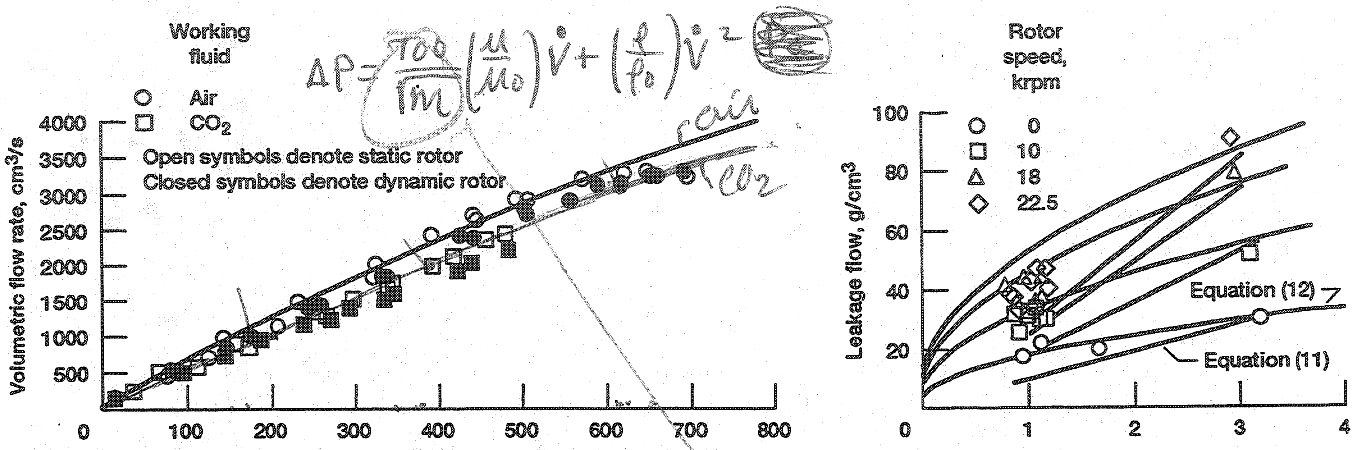
Figure 5.—Five-brush seal configuration leakage as a function of pressure for selected rotor speeds.

brushseal system gas flow data

Unclear how rotor speed effects ~~gas data~~

$\dot{V}$ in cm³/sec
ΔP in Pascals

$$\Delta P = \frac{700}{\sqrt{m}}\left(\frac{\mu}{\mu_0}\right)\dot{V} + \left(\frac{\rho}{\rho_0}\right)\dot{V}^2$$



(a) Air and carbon dioxide results, ref. 19.

(b) Fluid nitrogen results, table I.

Figure 6.—Ergun relationship showing equivalence to porous media flows and curve fit.

$$\frac{\mu_{CO_2}}{\mu_{air}} = \sqrt{\frac{44}{29}} = 1.23$$

$$a \propto \mu$$

$$\boxed{\frac{a_{CO_2}}{a_{air}} = 1.23}$$

$$\Delta P = \frac{700}{\sqrt{m}}\left(\frac{\mu}{\mu_0}\right)\dot{V} + .015\left(\frac{\rho}{\rho_0}\right)\dot{V}$$

$25\sqrt{m}$

$$\Delta P_{air} = 130\left(\frac{\mu}{\mu_0}\right)\dot{V} + 0.015\left(\frac{\rho}{\rho_0}\right)\dot{V}^2$$

$$\Delta P_{CO_2} = 160\left(\frac{\mu}{\mu_0}\right)\dot{V} + 0.015\left(\frac{\rho}{\rho_0}\right)\dot{V}^2$$

$\dot{V}$	~~[illegible]~~	
1000	160,000 + 15,000	175,000
2000	320,000 + 60,000	380
3000	480,000 + 135,000	615

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13. ABSTRACT ***(Maximum 200 words)***

Preliminary fluid nitrogen flow data are reported for a five-brush, ceramic-coated-rub-runner brush seal system, where the brushes and the rub runner were placed at each end of a centrally pressurized multifunction tester ("back-to-back" set of brushes) and tested at rotor speeds of 0, 10, 18, and 22.5 krpm. After testing, both the brushes and the ceramic-coated rub runner appeared pristine. The coating withstood both the thermomechanical and dynamic loadings with minor wear track scarring. The bristle tips showed some indication of material shearing (smearing) wear. The Ergun porous flow equation was applied to the brush seal data. The Ergun relation, which required heuristic information to characterize the coefficients, fit the gaseous data but was in poor agreement with the fluid results. The brush seal exit conditions were two phase. Two-phase, choked-flow design charts were applied but required one data point at each rotor speed to define the ($C_f A \times$ Constant) flow and area coefficients. Reasonable agreement between prediction and data was found, as expected, but such methods are not to be construed as two-phase-flow brush seal analyses.

14. SUBJECT TERMS

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