EXPERIMENTAL EVALUATION OF EFFECTIVE FRICTION COEFFICIENT FOR LIQUID RING SEALS

by

David W. Dorton

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APPROVED:

Dr. R. Gordon Kirk

Dr. Felix J. Pierce

Dr. John Moore

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David W. Dorton

Dr. R. Gordon Kirk, Chairman

Mechanical Engineering

(ABSTRACT)

Rotor dynamic analysis of liquid ring seals depends upon the correct specification of seal dynamic stiffness and damping characteristics. These are in turn dependent upon several parameters, including the friction holding force between the sealing face and the mating retaining ring. Designers currently assume a value for effective friction coefficient in order to utilize methods for prediction of response and stability. This thesis presents the results of testing on twelve actual seal rings of varying configuration at pressures of 689, 1378, 2068, and 2757 kPa in a static seal test rig to experimentally determine values of effective friction coefficient. The results are presented in graphical form as average effective friction coefficient versus eccentricity ratio for forward and backward motion of the rings.

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I would like to thank all of the people who have supported me through my educational endeavors. The are so many people who have helped make me the person that I am today; I can only mention those who come to my immediate thought.

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David W. Dorton

Blacksburg, Va.

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Nomenclature

B = exponent for pressure influence on viscosity, cm^2/N

c = radial clearance, cm

D_i = seal inside lip diameter, cm

D_o = seal outside lip diameter, cm

D_S = seal bore diameter, cm

$\vec{F}_N$ = axial thrust load, N

F_s = spring force, N

F_x, F_y = external seal ring loading, N

F_μ = friction load, N

g = acceleration due to gravity = 981 cm/sec^2

h = film thickness, cm

M_S = seal mass, kg

P_o = drain pressure, N/cm^2

P_s = suction pressure, N/cm^2

ΔP = pressure drop, N/cm^2

R = shaft radius, cm

Re_z = axial Reynolds' number = $\frac{2Vc}{\nu}$, dim

Re_θ = circumferential Reynolds' number = $\frac{R\omega c}{\nu}$, dim

V = axial velocity, cm/sec

X,Y = seal relative displacement, cm

β = seal lapped face loading factor, dim

ϵ = eccentricity ratio, dim

μ = oil viscosity, N-sec/cm^2

μ_f = coefficient of friction, dim

υ = kinematic viscosity, cm^2/sec

ω = rotor speed, sec^{-1}

Subscripts

i = inner seal

o = outer seal

R = rotor

S = seal

x = in x direction

y = in y direction

z = in axial direction

SI/English Engineering Equivalents:

Note: The data for this research was measured in English Engineering Units and then converted to SI Units to conform to the current policies for thesis writing. The following is a list of the equivalent converted measurements.

689 kPa	= 100 psi
725 kPa	= 105 psi
1378 kPa	= 200 psi
2068 kPa	= 300 psi
2757 kPa	= 400 psi
7600 kPa	= 1100 psi
52 °C	= 125 °F

Chapter 1

INTRODUCTION

Prediction of turbomachinery response and stability is an essential element of turbomachinery design and for improving the operation of existing equipment. Typical rotor analysis includes modeling of the rotor, consideration of bearing characteristics, and incorporation of the influence of the support structure. For turbomachinery that require floating ring oil seals, additional items of concern are how to correctly model these seals and the determination of their influence on response and stability. It has been noted [1] that "some of the major potential sources of destabilizing forces (in turbomachinery) are the seals in the machinery that have been responsible for the advances in ... efficiency."

Analysis of liquid ring seals depends upon the correct specification of seal dynamic stiffness and damping. These characteristics are functions of several parameters including the effective coefficient of friction between the sealing surfaces. The actual friction coefficient in operating machinery is not known. In order to utilize current methods for prediction of response and stability, designers assume a value of effective friction coefficient between 0.10 and 0.15. This range corresponds to typical dynamic friction factors for steel on steel. "The proper evaluation of the frictional force magnitude, direction, and sense for given dynamic conditions must be made to calculate the stick-slip motion of the ring seal"[2]. This thesis presents the results of testing on actual seal rings to experimentally determine values of effective friction coefficients for liquid ring seals under operating conditions. It is hoped that the results of this research will allow the turbomachinery designer to better evaluate radial loads on liquid ring seals for prediction of seal performance.

Chapter 2

BACKGROUND

This chapter describes the general operation of liquid ring seals and provides a brief discussion of the analysis of the seal rings as it pertains to the determination of effective friction coefficient from forces on the rings.

2.1 Application and Operation

Liquid ring seals are used in many industrial pump and compressor applications where a positive control of the process gas is required with minimal leakage of the sealing liquid into the process gas. A typical arrangement consists of one inner seal ring and one, or more, outer seal rings stacked axially on a turbomachine shaft. Springs are used to aid in assembly and initial pressurization of the seal. The seal is created by forcing a liquid, generally oil, through the clearance between the ring bore and the shaft. Figure 1 shows a cross section of a typical double breakdown oil seal with one inner and two outer seal rings. The oil seal pressure is maintained at suction (P_s) plus an increment

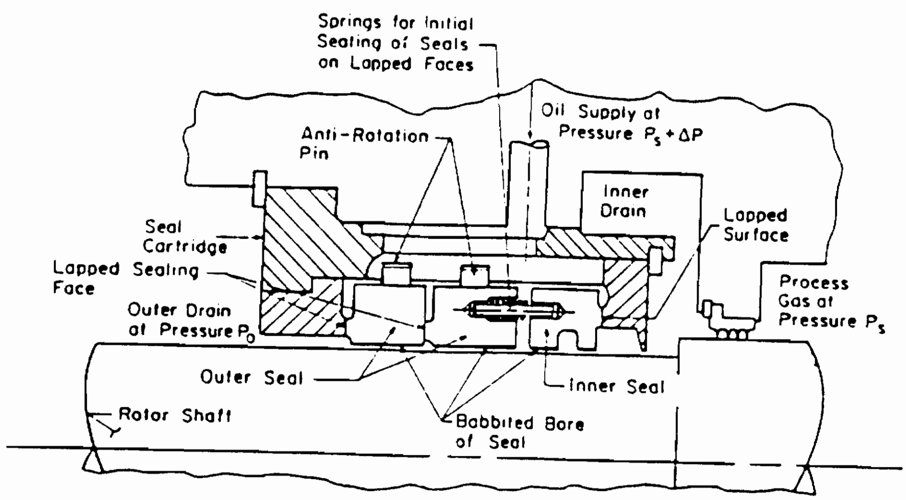


Figure 1: Cross Section of Multi-ring Oil Seal

ΔP which is typically generated by overhead oil supply tanks. The inner seal thus has a drop ΔP, whereas the outer seal has a drop from $P_s + \Delta P$ to the outer drain pressure, P_o [3]. The rings are floating bearing elements and generate full hydrodynamic fluid film reaction when they lock up against the mating retaining plate. Rotation of the outer rings is generally prevented by an anti-rotation pin. The loading on the ring due to the pin is much smaller in magnitude compared to other forces and is usually neglected for analysis purposes.

2.2 Analysis

It has been shown in the literature [3,4,5] that seal dynamic stiffness and damping can be calculated if the operating eccentricity, average film temperature, and pressure distribution are known. More recent analysis considers the influence of temperature gradients on the seal dynamic characteristics [6]. An assumed value for effective friction coefficient is used for this analysis, because the actual friction coefficient is not known. Improved calculations require experimentally determined values of friction coefficient.

As shown by Kirk [5], the friction holding force is related to the axial load on a ring by means of a force balance. Figures 2 and 3 show the forces on the inner and outer seal rings considered in this analysis, which is repeated here:

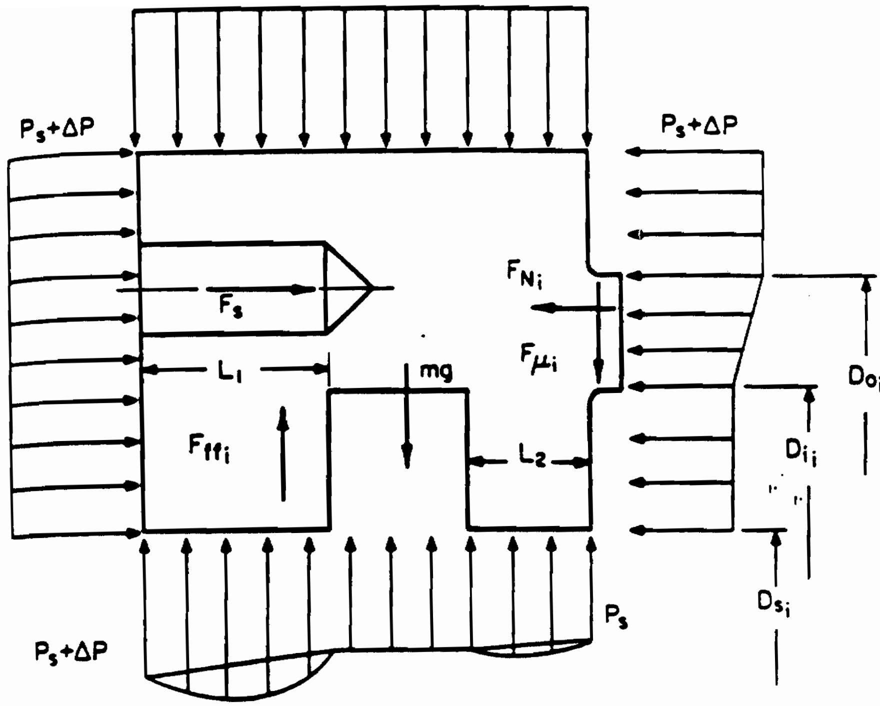


Figure 2: Forces on Inner Seal Ring

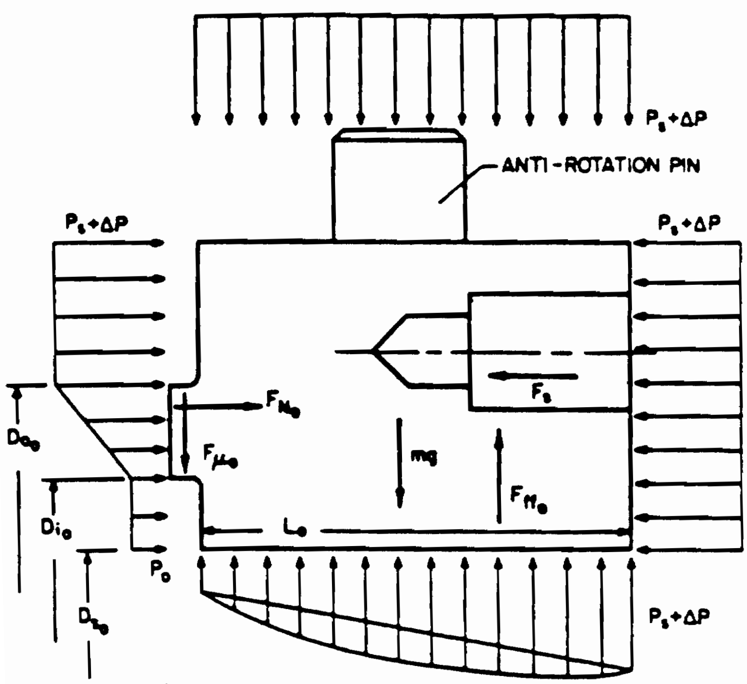


Figure 3: Forces on Outer Seal Ring

The pressure drop per outer seal ring is typically on the order of 130-260 N/cm^2 with the incremental pressure ΔP adjusted to be approximately 4.8 N/cm^2. Neglecting entrance effects on the axial flow, the global Reynolds number typically indicates no turbulence corrections are required. For a 260 N/cm^2 drop across a typical seal element, the Reynolds numbers for axial and circumferential flows are:

$$Re_z = \frac{2Vc}{\nu} = 144.3 \tag{1}$$

$$Re_\theta = \frac{Rc\omega}{\nu} = 524.6 \tag{2}$$

The method of solution lends itself to local correction on viscosity for turbulence effects when required. The correction may be incorporated into the solution in terms of a modified local viscosity. The local Reynolds number is expressed as

$$Re_L = \frac{\rho Rh\omega}{\mu} \tag{3}$$

The modified local viscosity may then be expressed as

$$\mu_{eff} = j\mu = 0.0139\, Re^{0.657}\mu \tag{4}$$

with the restriction that $j \geq 1.0$.

The influence of high pressure on the viscosity of the oil must also be accounted for when the pressures are in excess of 345 N/cm^2. Fuller [7] expresses this factor by the following equation:

$$\mu_{eff}\big|_p = \mu_{eff} e^{Bp} \tag{5}$$

For light turbine oil, the value of B is given as 1.37×10^{-4} in^2/lb. This value of B gives a 1.07 correction factor for a pressure drop of 345 N/cm^2 (500 psi).

Considering the inner seal and referring to Figure 2, the force balance can be expressed in terms of the seal geometry and the oil supply pressure level. The relatively small pressure drop across the inner seal produces a low normal loading on that seal ring in the axial direction. A linear pressure gradient $\frac{\partial P}{\partial r}$ is usually assumed across the seal lip interface. The inner seal ring axial thrust load equation, including the spring load, may be expressed as follows:

$$F_{N_i} = F_s + \frac{\pi}{4}(D_{o_i}^2 - D_{i_i}^2)\,\Delta P\,\beta_{F_i} + \frac{\pi}{4}(D_{i_i}^2 - D_{s_i}^2)\,\Delta P \tag{6}$$

The parameter β_F is a function of the condition of the lapped sealing surface. The calculation of β_F for an assumed linear pressure drop across the lapped face is given in the Appendix. The axial thrust load is multiplied by the appropriate coefficient of friction which yields the resisting friction force.

$$F_{\mu_i} = \mu_i F_{N_i} \tag{7}$$

The coefficient of friction is a function of surface finish, pressure loading, and the boundary lubrication conditions at the lapped seal lip-retainer interface. The resultant external seal radial loading is the vector sum of the friction load, which acts in a direction opposite that of the seal velocity, and the inner seal weight. This is expressed as:

$$F_{x_i} = \vec{F}_{\mu_i} \bullet \vec{\eta}_{x_i} \tag{8}$$

$$F_{y_i} = \vec{F}_{\mu_i} \bullet \vec{\eta}_{y_i} - M_{s_i} g \tag{9}$$

where

$$(\vec{\eta}_x, \vec{\eta}_y) = \left(\frac{-\dot{X}}{\sqrt{\dot{X}^2 + \dot{Y}^2}} , \frac{-\dot{Y}}{\sqrt{\dot{X}^2 + \dot{Y}^2}} \right) \tag{10}$$

A similar analysis can be performed for the outer seal ring. The pressure drop across this ring is large which gives rise to a high normal loading. The mating surfaces of the seal ring and the retaining ring are finely lapped surfaces which are assumed to give a nearly perfect seal. The pressure between the seal ring lip and the stationary retaining ring is assumed to be linear based on current knowledge of seal dynamic forces. The actual pressure is not known due to the thermal and mechanical distortion of the end plate at design conditions. A factor β_{F_o} , ranging from 0 to 1.0 is therefore specified for a particular design. A force balance yields (see Fig. 3).

$$F_{N_o} = F_s + \{\frac{\pi}{4}(D_{o_o}^2 - D_{i_o}^2)\,\beta_{F_o} + \frac{\pi}{4}(D_{i_o}^2 - D_{s_o}^2)\}(P_S + \Delta P - P_o) \qquad (11)$$

The outer seal ring axial thrust load is multiplied by the coefficient of friction which yields the resisting friction force. The resultant external outer seal loading is expressed in component form as follows:

$$F_{x_o} = \vec{F}_{\mu_o} \bullet \vec{\eta}_{x_o} \qquad (12)$$

$$F_{y_o} = \vec{F}_{\mu_o} \bullet \vec{\eta}_{y_o} - M_{s_o} g \qquad (13)$$

See Appendix E for a sample calculation for the test rig used in this research.

Chapter 3

TEST FACILITY

The apparatus and instrumentation used in the experiments for this thesis are described. Photographs of the actual facility accompany the description. At the end of this chapter is a discussion of the results of initial testing with the apparatus and how it affected the experiments used for this thesis.

3.1 Oil Console and Test Rig

The facility at Virginia Polytechnic Institute and State University that was used for the research presented in this thesis consists of an industrial high pressure lube-seal oil console, a static seal test rig, twelve outer seal rings, and the instrumentation necessary to measure the parameters of interest. The lube-seal oil console supplies oil to the test rig at pressures from 725 kPa to 7600 kPa. With the exception that the shaft is non-rotating, the static seal test rig models a centrifugal compressor and was designed from actual compressor drawings to conform to industrial specifications on roundness, runout, and perpendicularity. The rig was designed with a non-rotating shaft in order to eliminate the added complexity of shaft dynamics so that proper operation of the test rig could be verified. Once confidence is gained in the results obtained from the static rig, shaft dynamics can be incorporated for future research. Oil is supplied to the rig by means of a single line. One through-flow line and one by-pass line allow adjustment of rig pressure. Figure 4 shows the test rig with the lube seal oil console in the background. Figure 5 shows the rig with the shaft/end cap removed. Just inside the rig's inner wall is a cylinder with several flow holes to provide an even distribution of the supplied oil. This cylinder can be seen in Figure 6, which shows a top view of the rig with the end cap removed. At the bottom of the rig is the retaining ring that the seal rings mate against during test. A 70.231 mm diameter hole in the center of the retaining ring allows the shaft, which is an integral part of the end cap, to pass through. The rings seal against a raised lapped surface which borders the hole. The rings remain in contact with this surface throughout motion around the clearance circle. The diametral clearance between the shaft and seal ring bores is four mils. Four rods are positioned at ninety degree intervals on the rig's circumference, just above the retaining ring. The rods are threaded through the wall of the rig to allow the seal rings to be "pushed" across the clearance circle during test. Load cells (Omega model # LCG-1K) positioned at the end of the rods measure the force required to move the ring to a given position. Figure 7 shows a seal ring mounted between the push rods inside the rig with load cells in place.

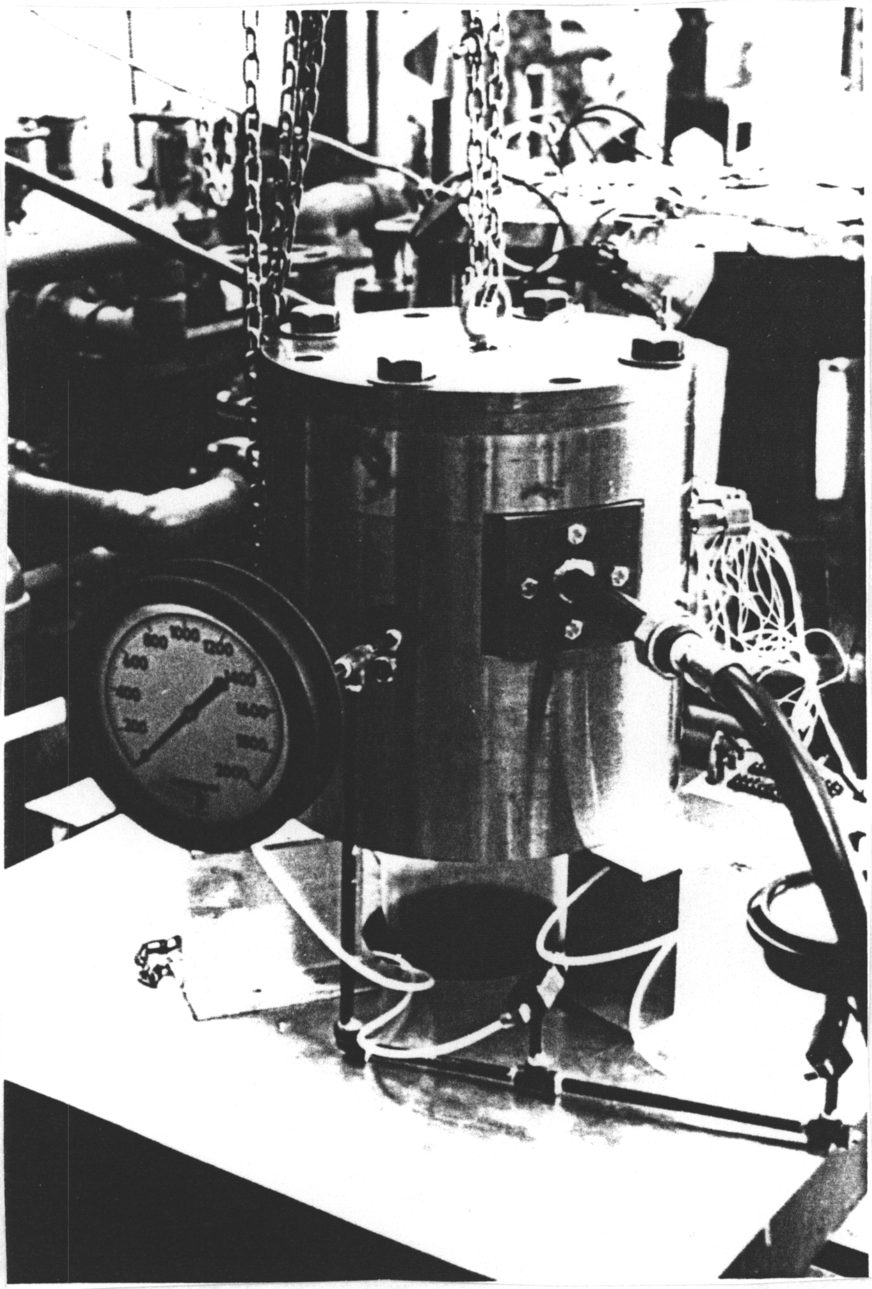


Figure 4: Static Seal Test Rig and Oil Console

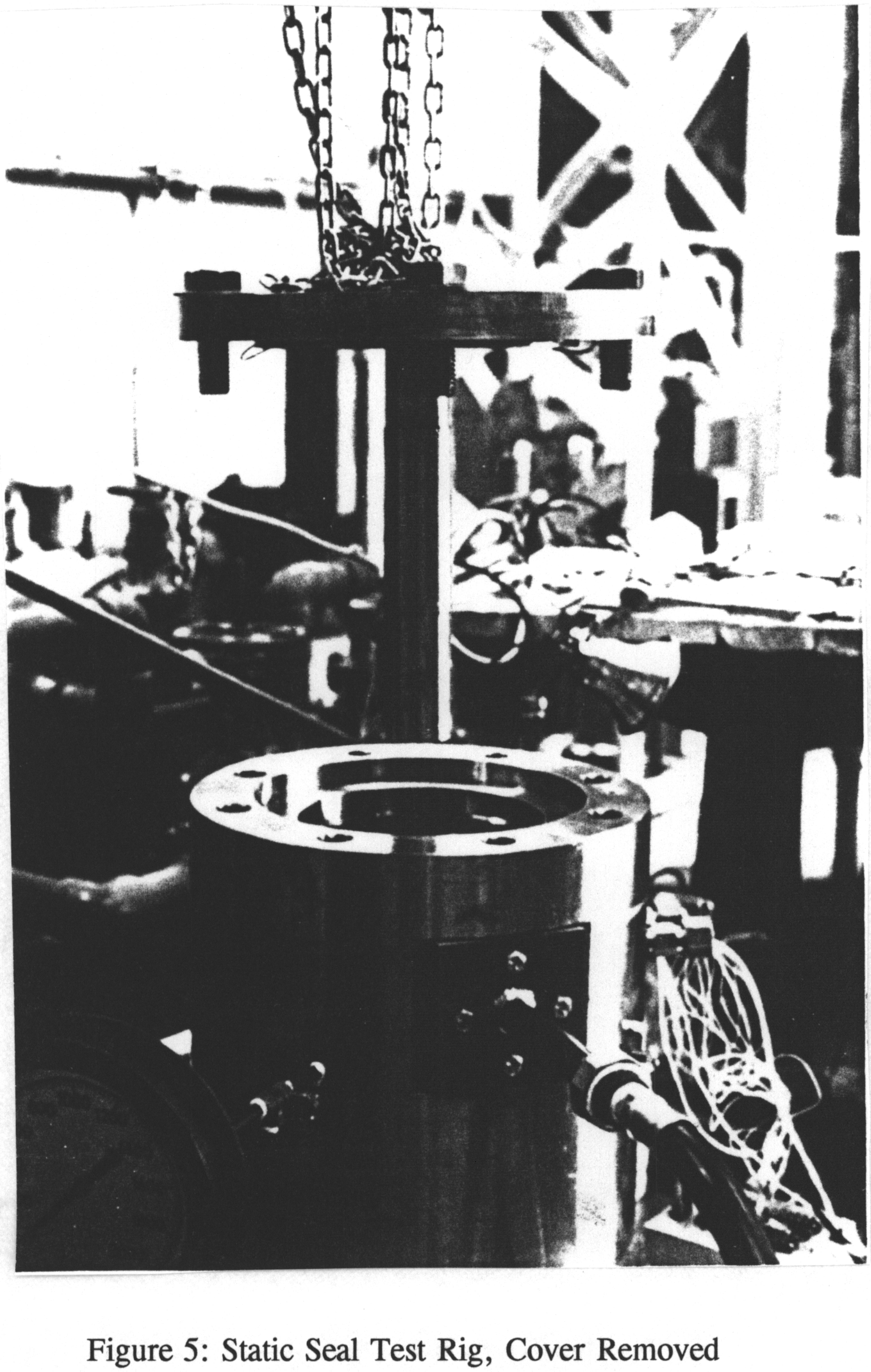


Figure 5: Static Seal Test Rig, Cover Removed

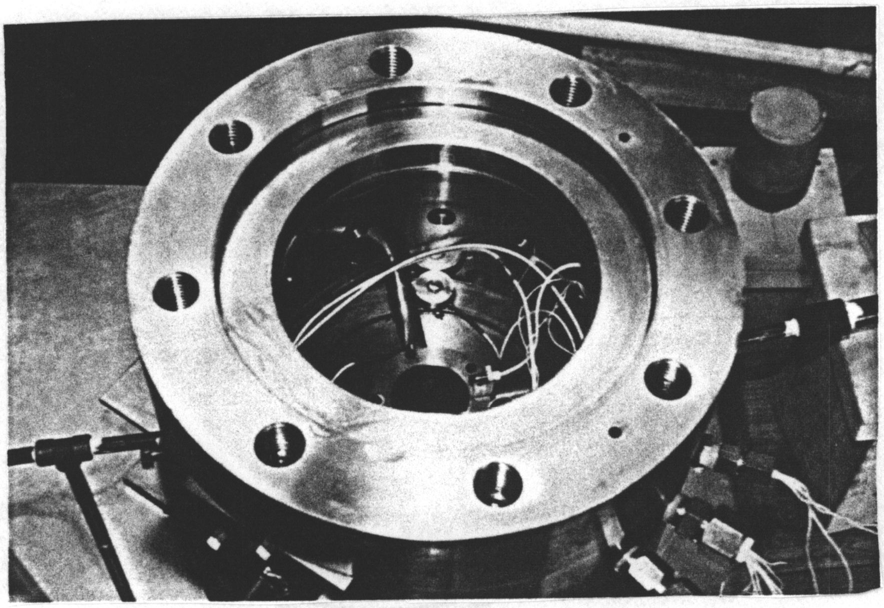


Figure 6: Static Seal Test Rig with Cover Removed, Top View

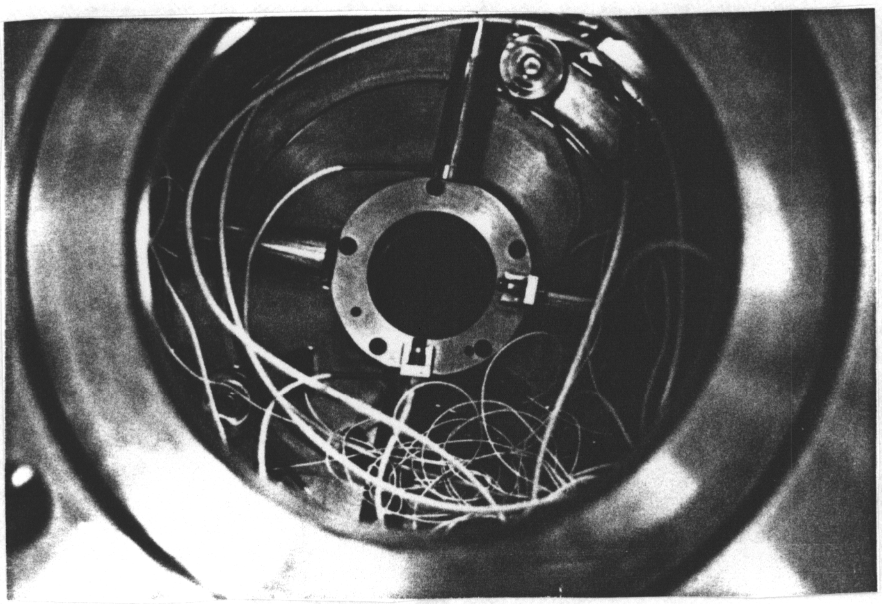


Figure 7: Seal Ring Mounted in Test Rig

3.2 Seal Rings

The seal rings were also made to industrial specifications and were further modified to accommodate the instrumentation required for this research. Twelve outer rings of varying configuration were tested. Table 1 lists the seal rings and indicates the sealing face width and groove configuration for each ring. Tapped holes were added to the seal rings to allow mounting of pressure probes and non-contact displacement probes. The two non-contact displacement probes (Bently-Nevada) are mounted ninety degrees apart on the top of the seal ring, opposite the sealing face. They measure the ring to shaft relative displacement in two directions, defined here as "X" and "Y". Twelve pressure probes (Kulite model # XT-140-500 A) are mounted through the ring wall. The probes are positioned in groups of three, at ninety degree intervals around the ring circumference. In each group, the first probe is located at one quarter of the axial length along the ring. The second probe is located at half of the axial length and the third probe is located at three quarters of the axial length. Within each group, the probes are offset by 18 degrees to allow clearance for the spotface (see Figures 7 and 8). This arrangement allows measurement of pressure in both the axial and circumferential directions. Figure 8 shows a seal ring with a wide sealing face width and no circumferential grooves. The tapped holes for mounting the pressure probes are visible on the sides of the ring. Figure 9 shows a seal ring with a narrow sealing face width and two circumferential grooves.

TABLE 1:
Details of Ring Seal Geometry

Ring No.	Sealing Face OD_F (mm)	Groove Configuration			
		Square		Round	No. Grooves
		Deep (mm)	Wide (mm)	Radius (mm)	
1	80.82				0
2	84.35				0
3	78.00			0.787	1
4	78.00	3.175	1.575		1
5	80.82	1.270	3.175		1
6	80.82	1.270	1.575		1
7	80.82	3.175	1.575		1
8	84.35		1.575		1
9	84.35		1.575		1
10	84.35		1.575		1
11	78.00	3.175	1.575		2*
12	78.00		0.787		2*

Overall dimensions of rings (mm):
ID = 70.05 -0.0, +0.0254
OD = 111.125 -0.102, +0.0
L = 30.15 +0.0, -0.102
Tolerance on sealing face OD_F = +0.0, -0.127

*The two grooves are spaced equally over the width of the ring

Figure 8: Seal Ring with No Circumferential Grooves

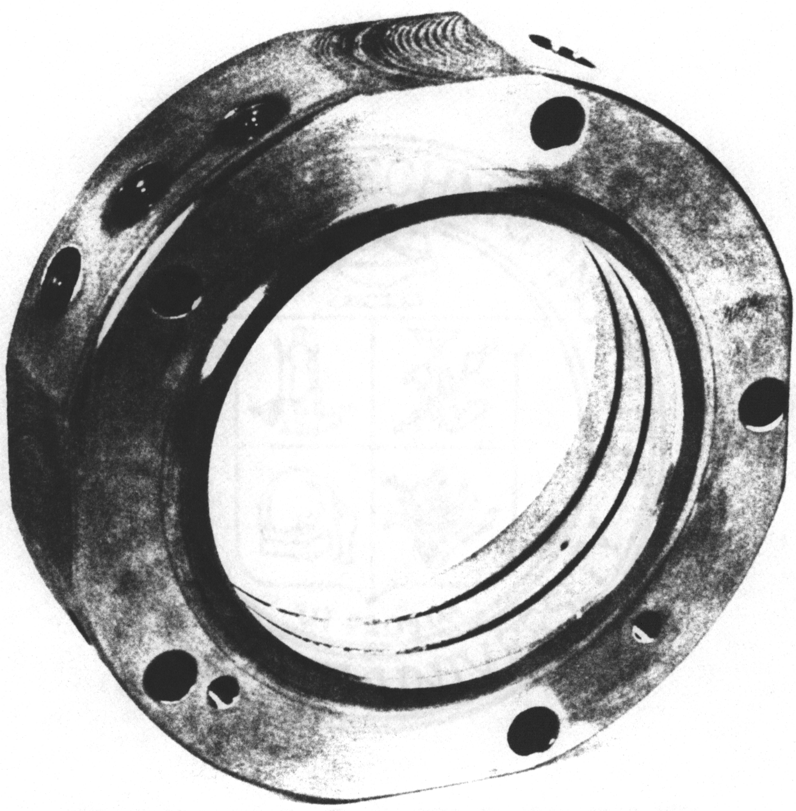


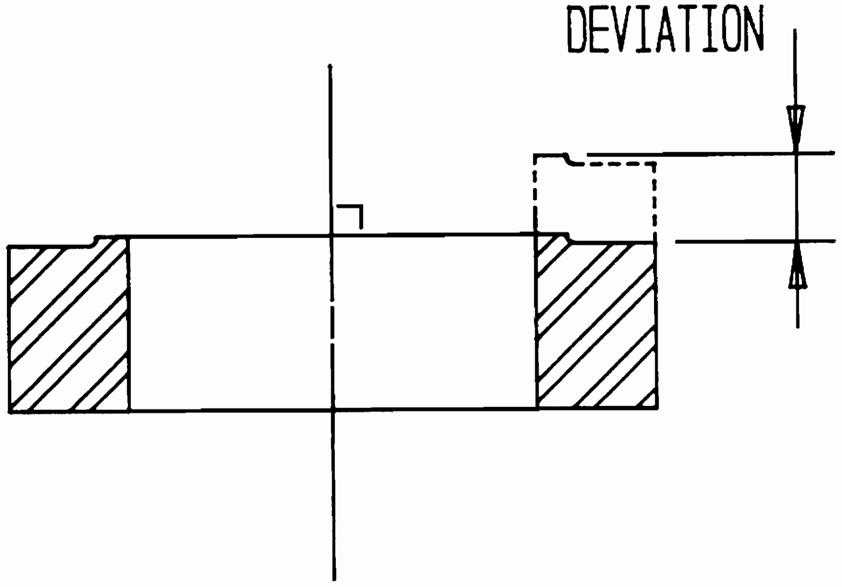
Figure 9: Seal Ring with Two Circumferential Grooves

3.3 Initial Testing

Initial testing with the rig [8,9] indicated that the radial forces on the ring were not symmetric, even though the rig was manufactured to standard turbomachinerytolerances. These unsymmetric forces may be due to minor shaft slope or ring bore-to-sealing face non-perpendicularity. Conventional analysis of these rings neglects the influence of these parameters because of their small length to diameter ratio, which is less than 0.5. A worst case shaft slope of 0.3 mm/m was confirmed by measuring the float clearance variation as a function of shaft clocking relative to the ring. The bore-to-sealing face non-perpendicularity of each ring was measured on a three-axis inspection machine. The maximum deviation from perfect perpendicularity for each ring is given in Table 2. In an effort to minimize the effects of shaft slope and to ensure repeatable testing conditions, results for all twelve rings at 516.7 kPa and different cover angular positions were compared. The end cover was then doweled in a position that showed the least influence of shaft slope in the X-direction for a majority of the rings. Testing of the rings therefore involves measurement of the radial forces in the X-direction only.

TABLE 2:
Ring Bore-to-Sealing Face Non-perpendicularity

RING NUMBER	NON-PERPENDICULARITY (mils)
1	-0.3
2	0.7
3	0.0
4	-0.4
5	0.3
6	0.3
7	-0.6
8	-0.5
9	0.4
10	-0.2
11	-0.2
12	-0.6



Chapter 4

PROCEDURE

This chapter describes the procedure used to take data with the test apparatus described in Chapter 3. The types of measurements that were taken are discussed as well as how they were used to determine effective friction coefficients.

4.1 Set-up

Once a ring had been fitted with pressure probes and the non-contact displacement probes, it was placed on the retaining ring inside the test rig. The rig has the capacity to incorporate spring preload, however, it was found that the ring will seal under its own weight in the vertical position and thus no preload was used for these experiments. The shaft and end cap were lowered into position, the end cap was doweled, and the cap bolts were tightened. The rig was then pressurized to 689 kPa with oil from the lube-seal oil console. The oil was forced through the clearance between the shaft and the seal ring bore to a reservoir at atmospheric pressure. Once the oil in the rig reached 52 °C testing was begun. A solenoid valve was used to control the flow of cooling water and maintain the oil at this temperature. Measurements were taken to locate the centered and extreme eccentric positions of the ring relative to the shaft. The positions of the ring that correspond to $\pm$ 0.25, $\pm$ 0.50, and $\pm$ 0.75 eccentricity ratios were then determined.

4.2 Data Acquisition

During test, the ring was moved with the push rods to positions that correspond to the various ratios of eccentricity. One pass consisted of motion from one extreme eccentric position to the opposite extreme eccentric position and back again. The force required to move the ring was recorded at $\pm$ 0.25, $\pm$ 0.50, $\pm$ 0.75 eccentricity ratio and at the centered position for each pass. Three passes per a given pressure were recorded to produce the radial load data for each ring. Pressure data was taken at each eccentricity ratio by moving the ring to the required position with the push rods and recording the readings from the various probes. The test procedure was repeated at pressures of 1378, 2068, and 2757 kPa.

4.3 Calculation of Effective Friction Coefficient

Given the seal geometry and the pressure inside the rig, the axial load on a ring can be calculated by the force balance given by Eq. 11. A computer code by Kirk and Reedy [10] that incorporates this force balance was used to evaluate the axial load for each case of sealing face width and pressure tested. Table 3 gives the results of these calculations. Values of effective friction coefficient were calculated from the radial load data by dividing the radial force required to move a ring by the calculated axial load on the ring.

TABLE 3:
Calculated Axial Loads

Sealing Face Width	PRESSURE (kPa)			
	689	1378	2068	2757
(mm)	AXIAL LOAD (N)			
3.175 (narrow)	373.1	735.5	1097.7	1459.9
4.760 (medium)	492.2	973.9	1455.2	1936.6
6.350 (wide)	647.0	1283.5	1919.7	2555.9

Chapter 5

RESULTS

This chapter presents the results of the testing done for this research. The friction coefficient results are presented in graphical form as well as tabulated in the appendix. The pressure data was not complete, but is included in the appendix in tabular form. Plots of pressure averages through the seal rings at zero eccentricity ratio are given.

5.1 Friction Coefficient Results

Figures 10 through 25, located at the end of this chapter, present the results of this research. The figures are plots of effective friction coefficient versus eccentricity ratio, for "forward" and "backward" motion of the rings, at pressures of 689, 1378, 2068, and 2757 kPa. Forward motion is defined as motion of the ring such that the displacement sensor, mounted on the ring, is moving toward the shaft. Backward motion is that in which the displacement sensor is moving away from the shaft. The test results show characteristics that are apparent for each ring regardless of configuration or pressure. The most noticeable characteristic is that there is some force required to center the rings, and once centered, there is an increasing force required to further decenter the rings. The most important part of the results for each ring appears to be the values of effective friction coefficient from a high eccentricity ratio to the centered position for each direction of motion. Since the friction coefficient in the direction of decreasing eccentricity is generally lower than in the direction of increasing eccentricity, a symmetrical external force on a ring would move the ring toward the centered position. The results also indicate a tendency for the rings to exhibit a lower effective friction coefficient in one direction. As stated earlier, this tendency may be due to the non-perpendicularity of the ring bore or to minor shaft slope inherent in the rig itself. Figures 26 and 27 illustrate how minor shaft slope or bore-to-sealing face non-perpendicularity can influence the radial loads on a ring. Figure 26 shows a sketch of the ideal situation of a perfectly centered ring with no shaft slope or non-perpendicularity. In this arrangement the pressures around the ring should be symmetric and thus the ring would see an equal resistance to motion in all directions. Figure 27, however, shows a situation where shaft slope or ring non-perpendicularity is present (exaggerated for clarity). Side A of the ring has more surface area exposed to high pressure. The radial pressure force on this side would facilitate motion in the direction of the arrow, while motion in the opposite direction would be more difficult. This unsymmetrical pressure force will be called the bias force in this thesis.

Since ring 3 has been determined to have perfect perpendicularity (with regard to the inspection machine) the results indicate that the shaft slope is in a direction that facilitates forward motion of the rings. If the effects of non-perpendicularity do not cancel the effects of shaft slope, some bias force will be apparent in the results, indicating the direction of motion that the combined influence favors. This thesis defines the magnitude of this bias force as the difference between forward and backward friction coefficients at zero eccentricity ratio.

Figure 10 shows the results for rings 1,2, and 3 at 689 kPa. These results are presented together to provide some comparison of the effects of different ring configuration. Rings 1,2, and 3 have medium, wide, and narrow sealing face widths, respectively. Rings 1 and 2 have no circumferential grooves, while ring 3 has one circumferential groove. This figure shows that ring 3 has the lowest friction coefficients of the three for forward motion of the ring and for backward motion greater than approximately 0.2 eccentricity ratio.

Figure 11 presents the results for rings 4,11, and 12, all of which have narrow sealing face widths, at 689 kPa. Also note that rings 11 and 12 are the only rings with two circumferential grooves. The results for rings with medium sealing face widths at 689 kPa are given in Figure 12. Rings 5 and 6 are similar in all respects; each has one circumferential groove and a maximum non-perpendicularity of 0.3 mils. As shown in Figure 12 these rings exhibit similar friction coefficient trends. Ring 5, however, shows a lower effective friction coefficient over most of the forward motion, whereas ring 6 shows a lower coefficient over backward motion. This is an example of how the non-perpendicularity has a directional influence on friction coefficient. Even though rings 5 and 6 have the same non-perpendicularity, the directions of the non-perpendicularities are not known. Figure 12 indicates that the non-perpendicularity of ring 5 is in a direction that promotes forward motion of the ring, whereas ring 6 has a non-perpendicularity in a direction that promotes backward motion.

Figure 13 presents the results for rings with wide sealing face widths at 689 kPa. The results for individual rings at 1378, 2068, and 2757 kPa are given in Figures 14 through 25. Tables 4 through 50, in Appendix B show the averaged friction coefficients that were used to create Figures 10 through 25. These tables also show the maximum and minimum friction coefficients from the tests as well as the standard deviations at each eccentricity.

5.2 Pressure Data

Some problems were encountered with the pressure probes during test that could not be resolved in time to be included in this thesis. The data that was obtained with the probes available is given in Appendix C. Included in this appendix is a diagram indicating the circumferential and axial location of the probes. Figures 28 through 35 show plots of averaged pressure data at zero eccentricity ratio for some of the rings.

These figures indicate substantial pressure losses at both the entrance and exit sides of the seal rings.

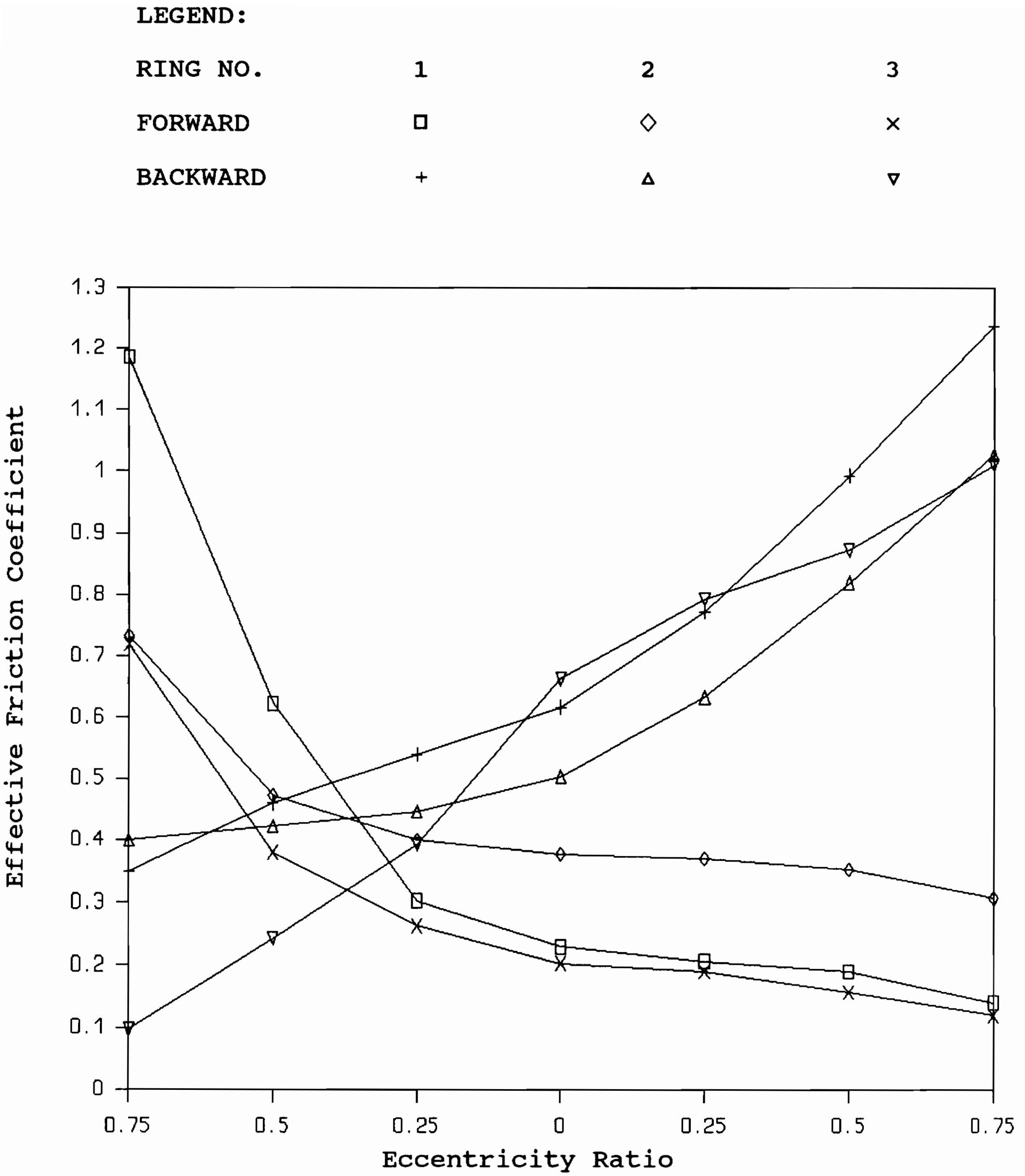


Figure 10: Average Effective Friction Coefficients for Rings 1, 2, and 3 at 689.48 kPa.

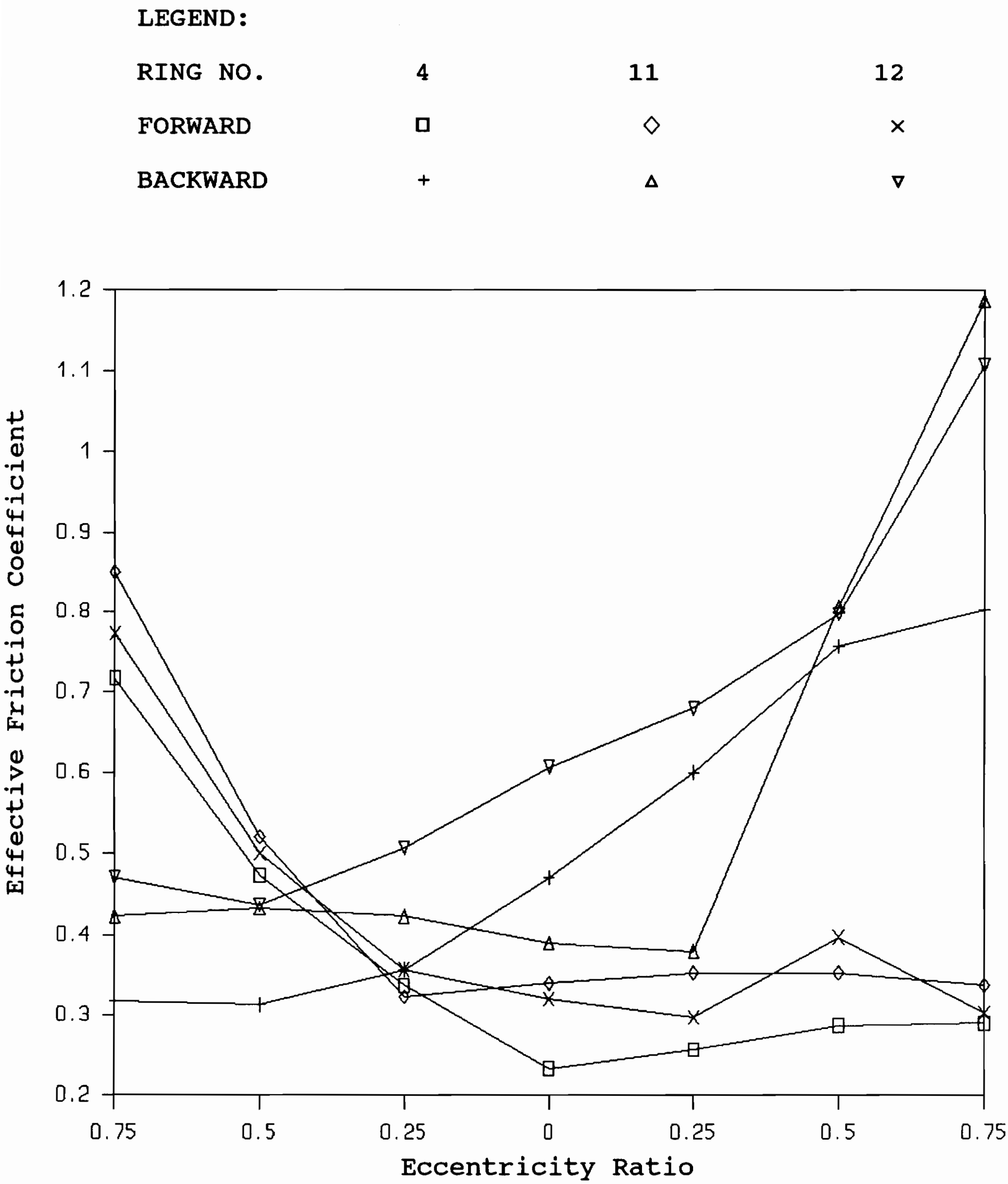


Figure 11: Average Effective Friction Coefficients for Rings with Narrow Sealing Face Widths at 689 kPa.

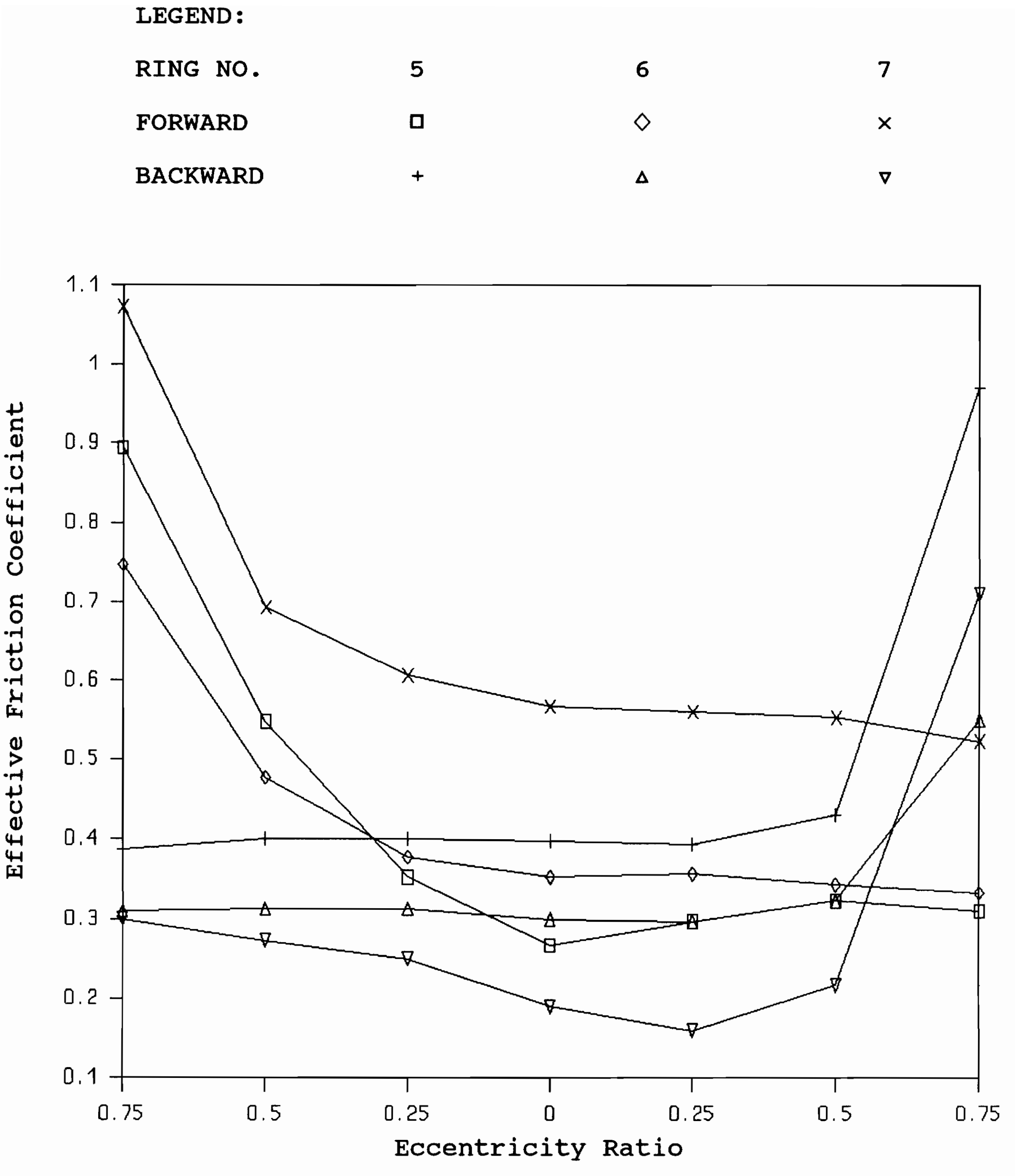


Figure 12: Average Effective Friction Coefficients for Rings with Medium Sealing Face Widths at 689 kPa.

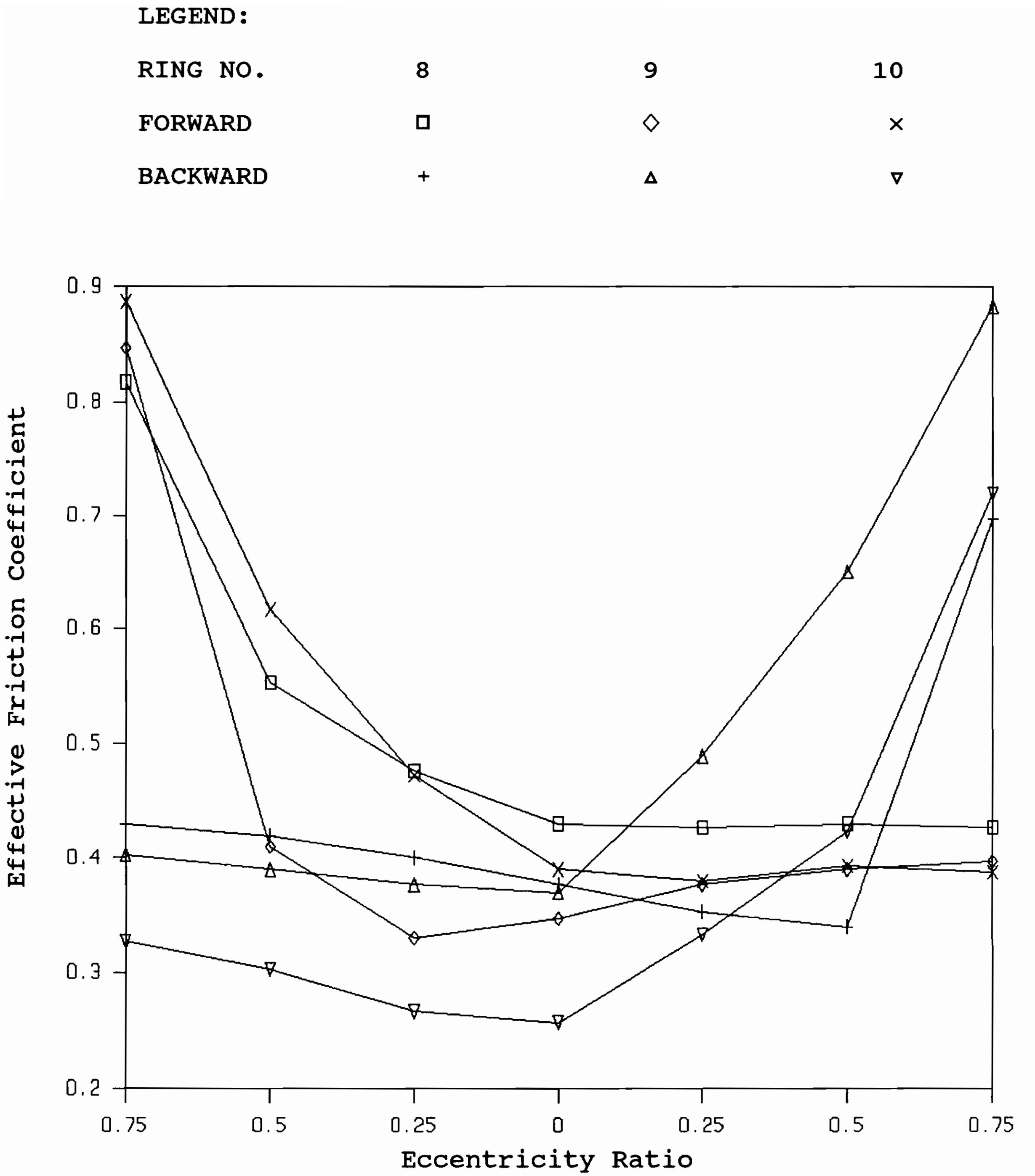


Figure 13: Average Effective Friction Coefficients for Rings with Wide Sealing Face Widths at 689 kPa.

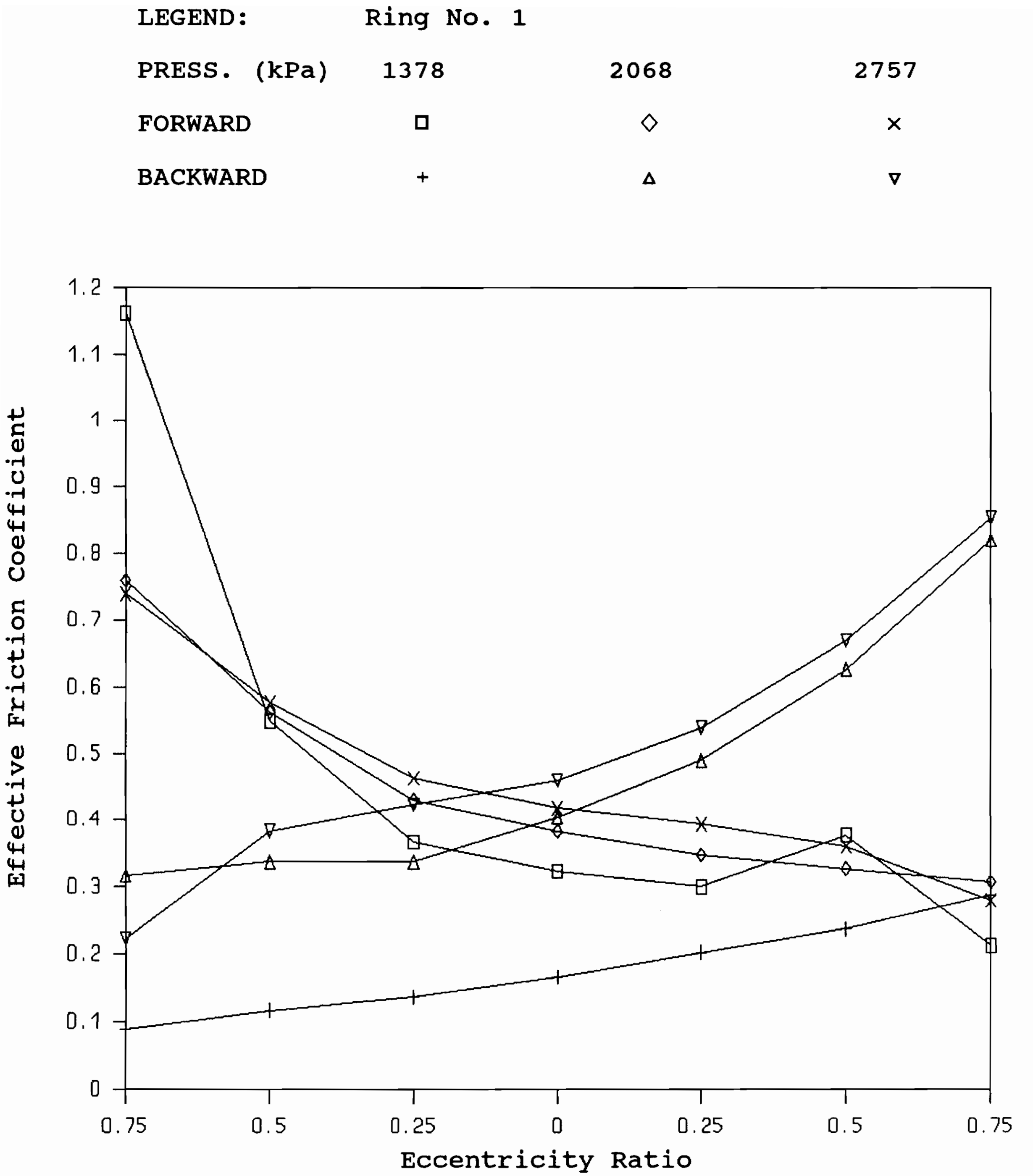


Figure 14: Average Effective Friction Coefficients for Ring 1 at 1378, 2068, and 2757 kPa.

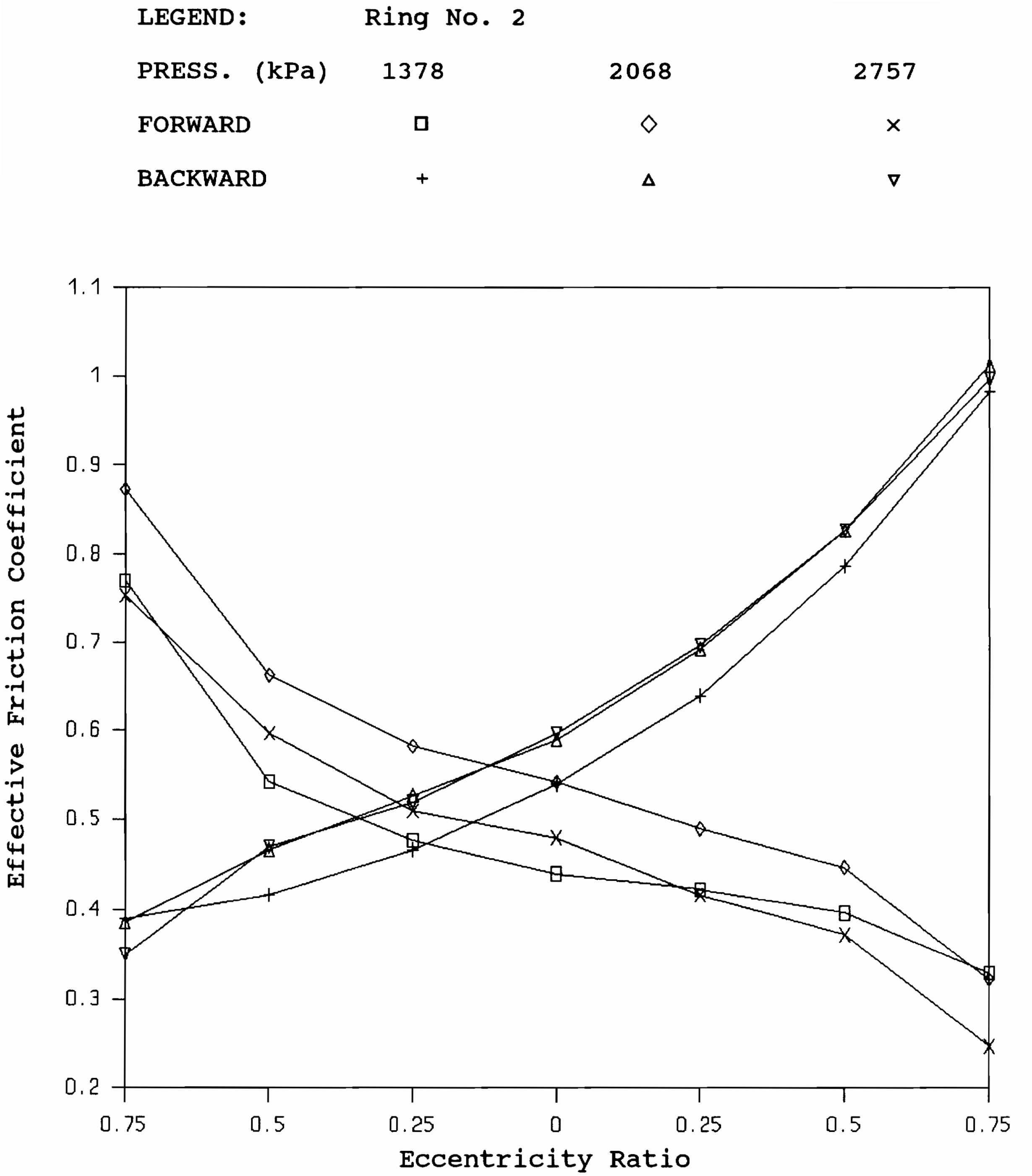


Figure 15: Average Effective Friction Coefficients for Ring 2 at 1378, 2068, and 2757 kPa.

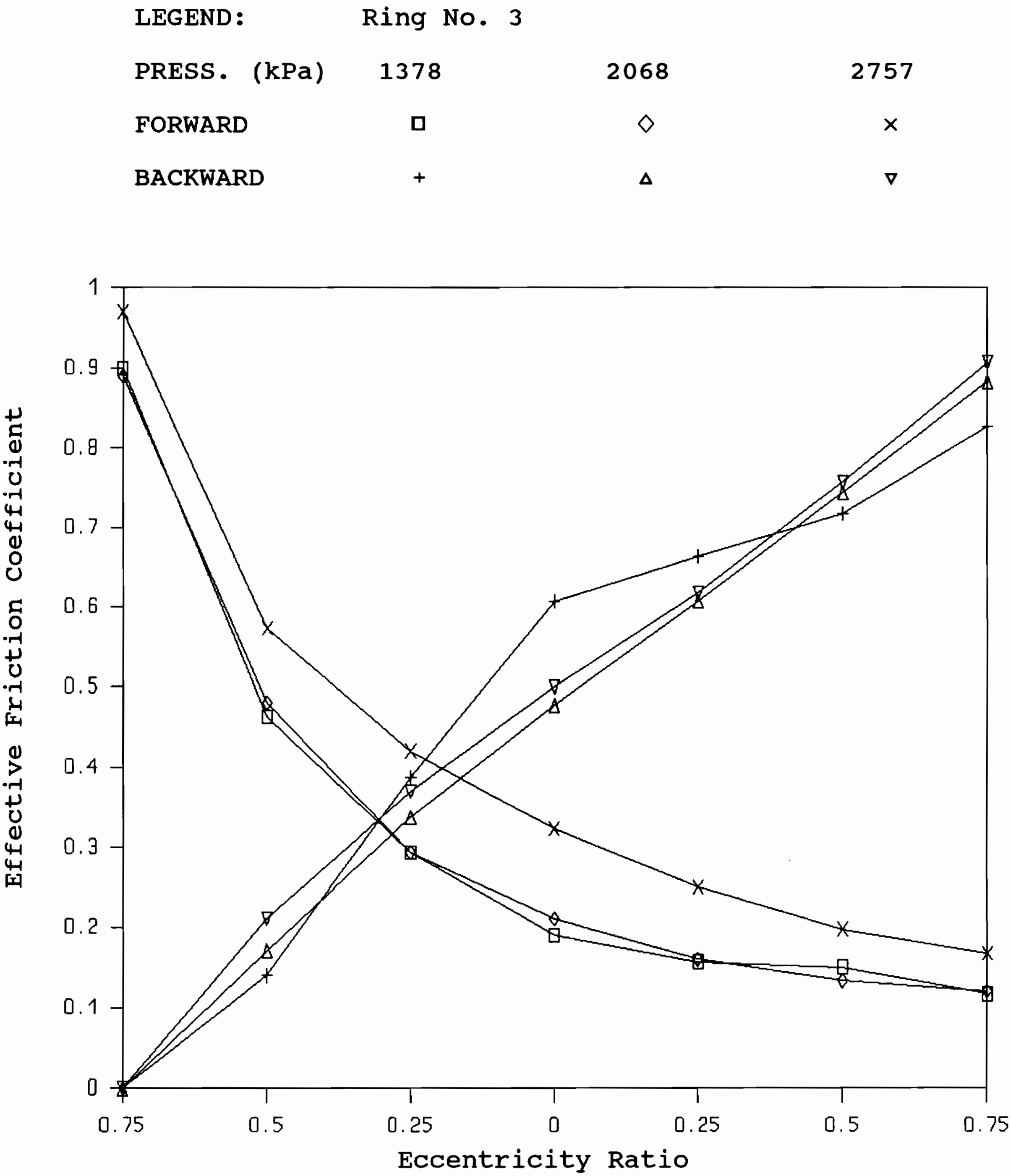


Figure 16: Average Effective Friction Coefficients for Ring 3 at 1378, 2068, and 2757 kPa.

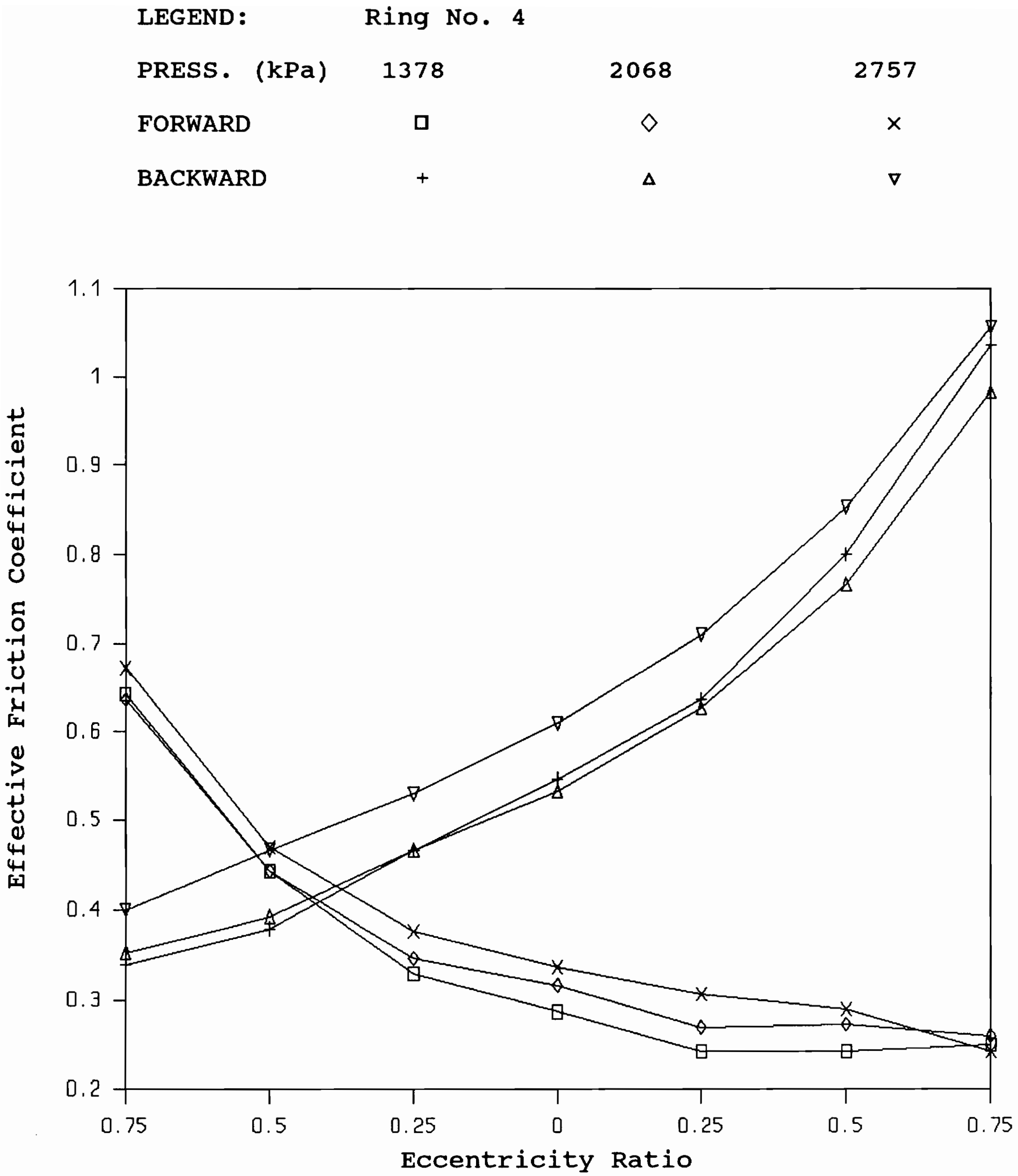


Figure 17: Average Effective Friction Coefficients for Ring 4 at 1378, 2068, and 2757 kPa.

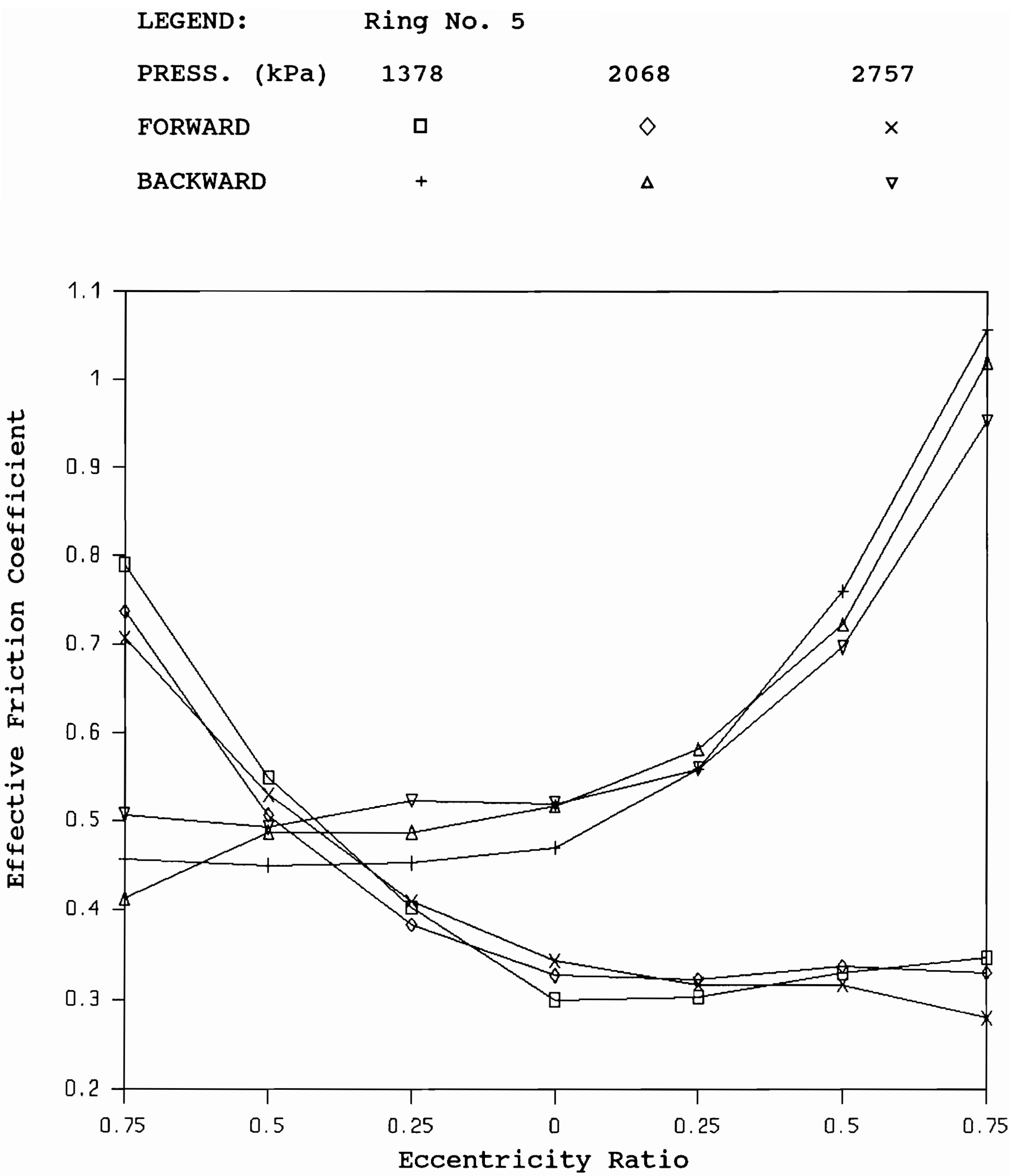


Figure 18: Average Effective Friction Coefficients for Ring 5 at 1378, 2068, and 2757 kPa.

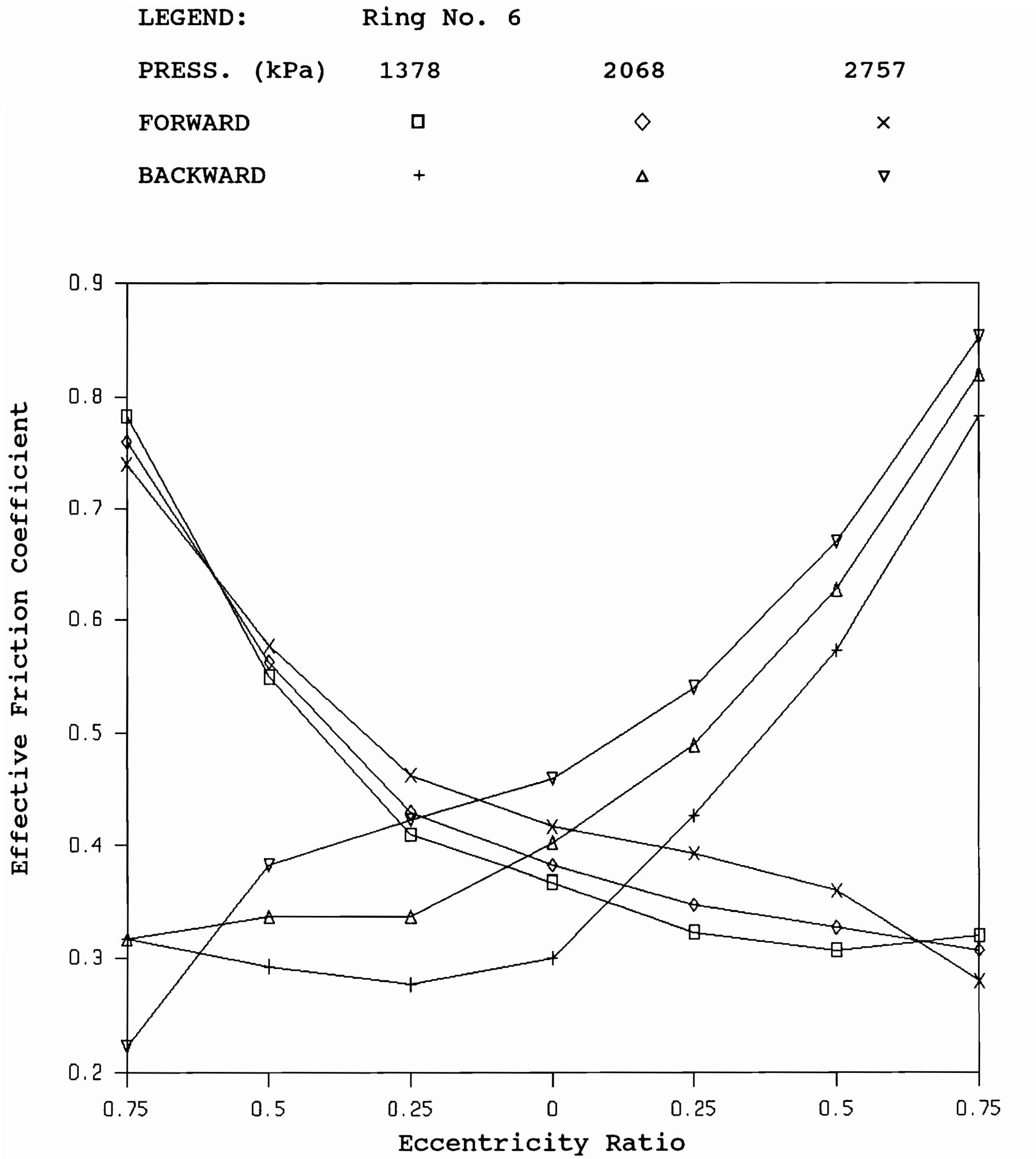


Figure 19: Average Effective Friction Coefficients for Ring 6 at 1378, 2068, and 2757 kPa.

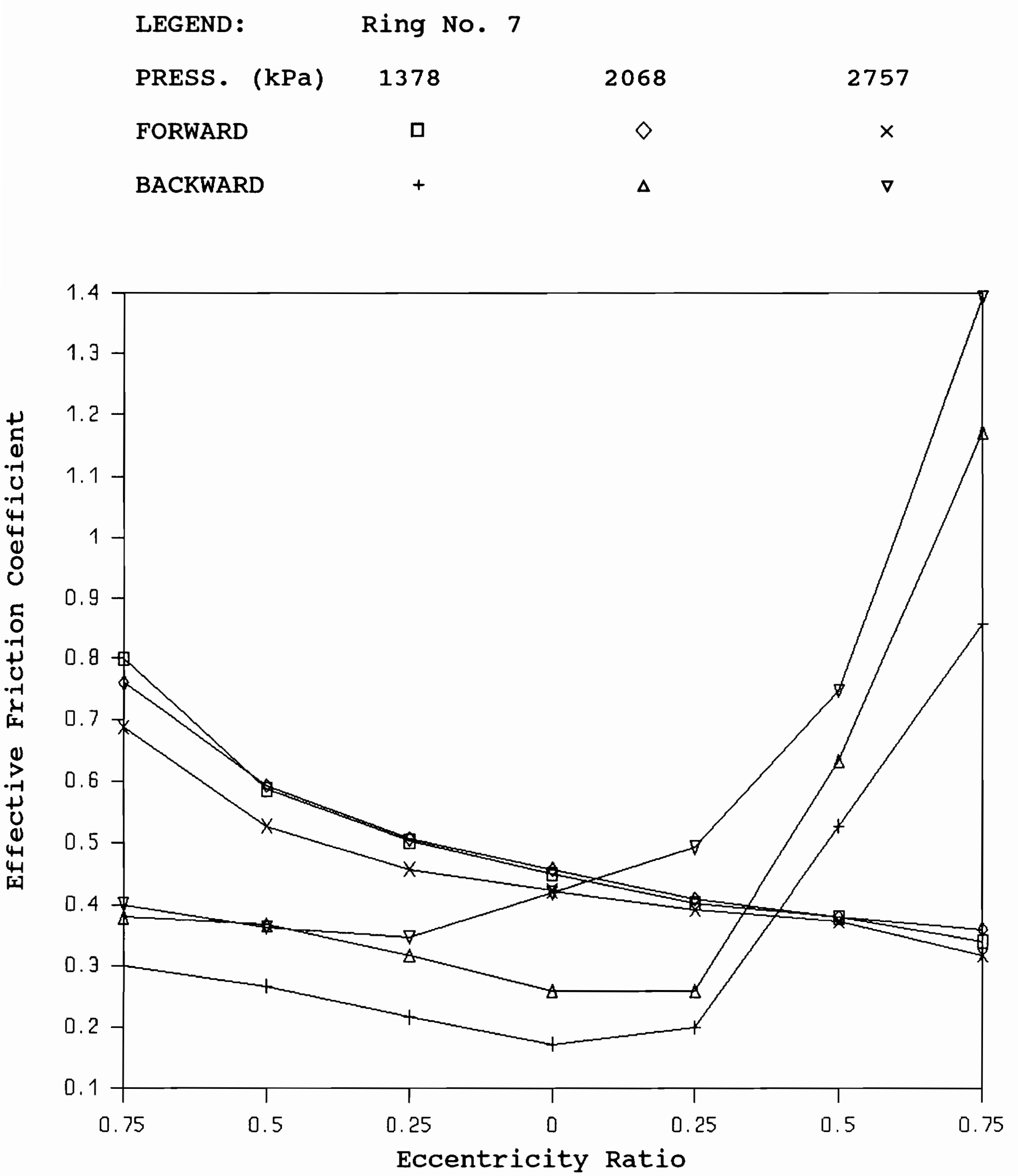


Figure 20: Average Effective Friction Coefficients for Ring 7 at 1378, 2068, and 2757 kPa.

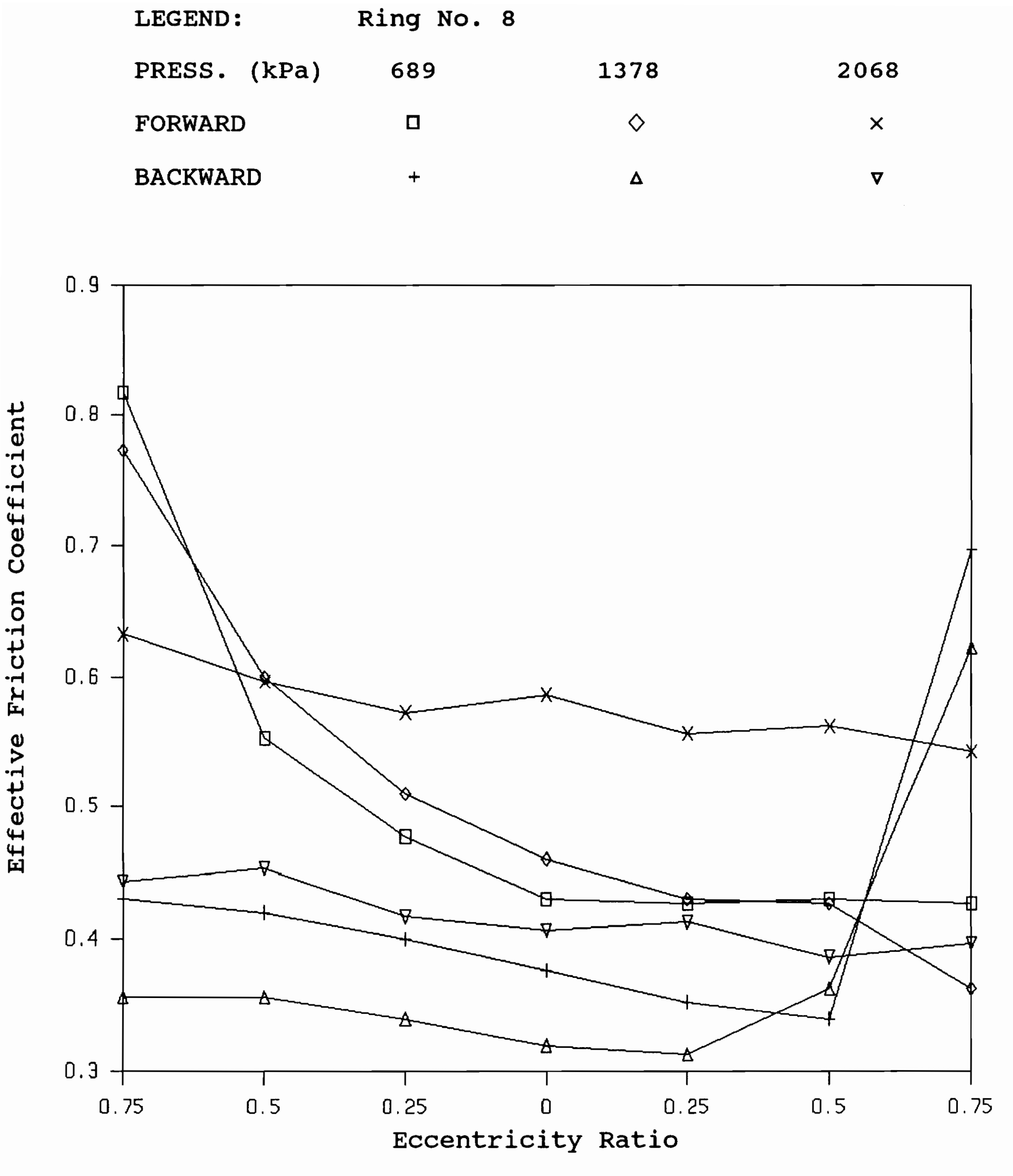


Figure 21: Average Effective Friction Coefficients for Ring 8 at 689, 1378, and 2068 kPa.

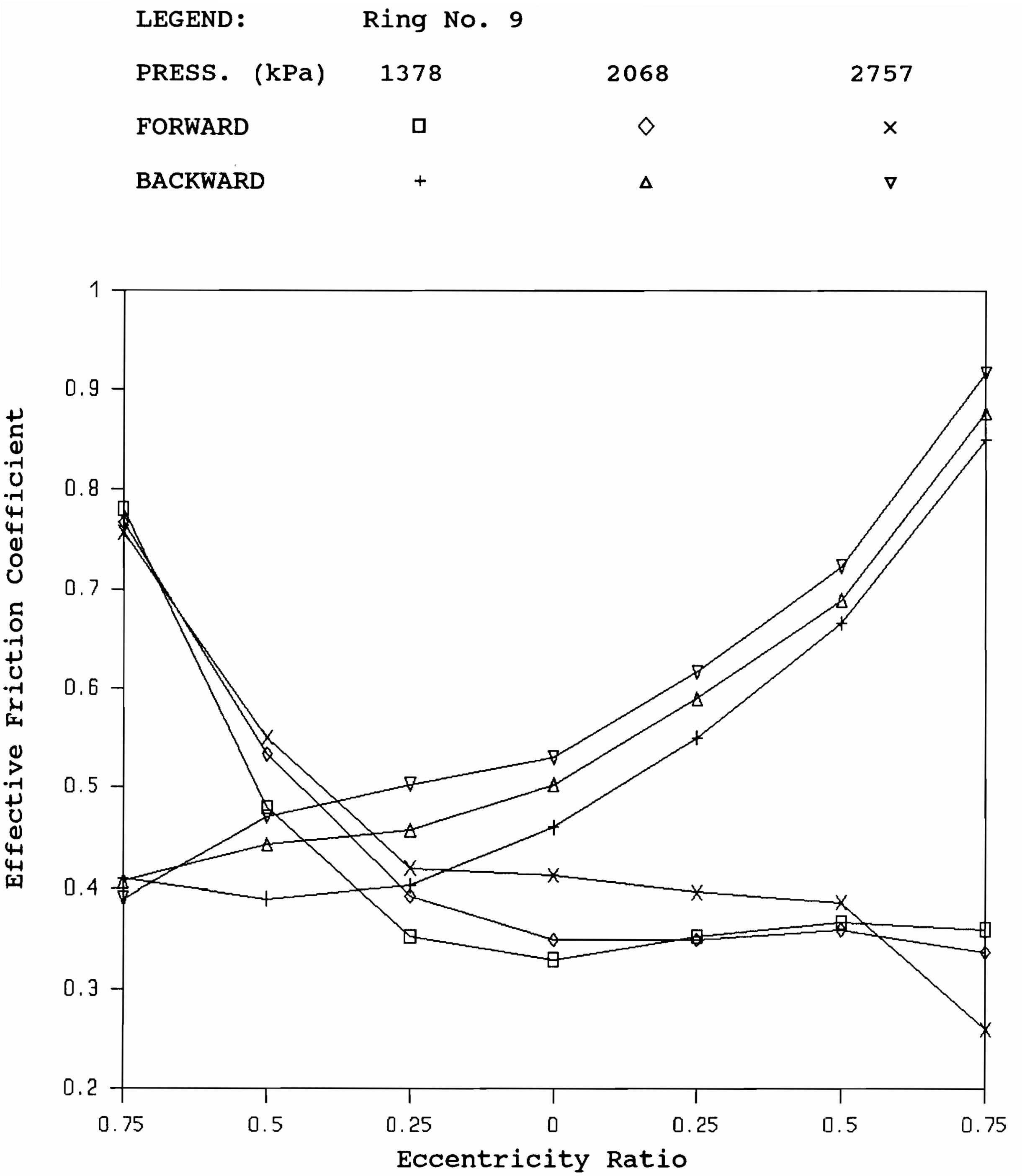


Figure 22: Average Effective Friction Coefficients for Ring 9 at 1378, 2068, and 2757 kPa.

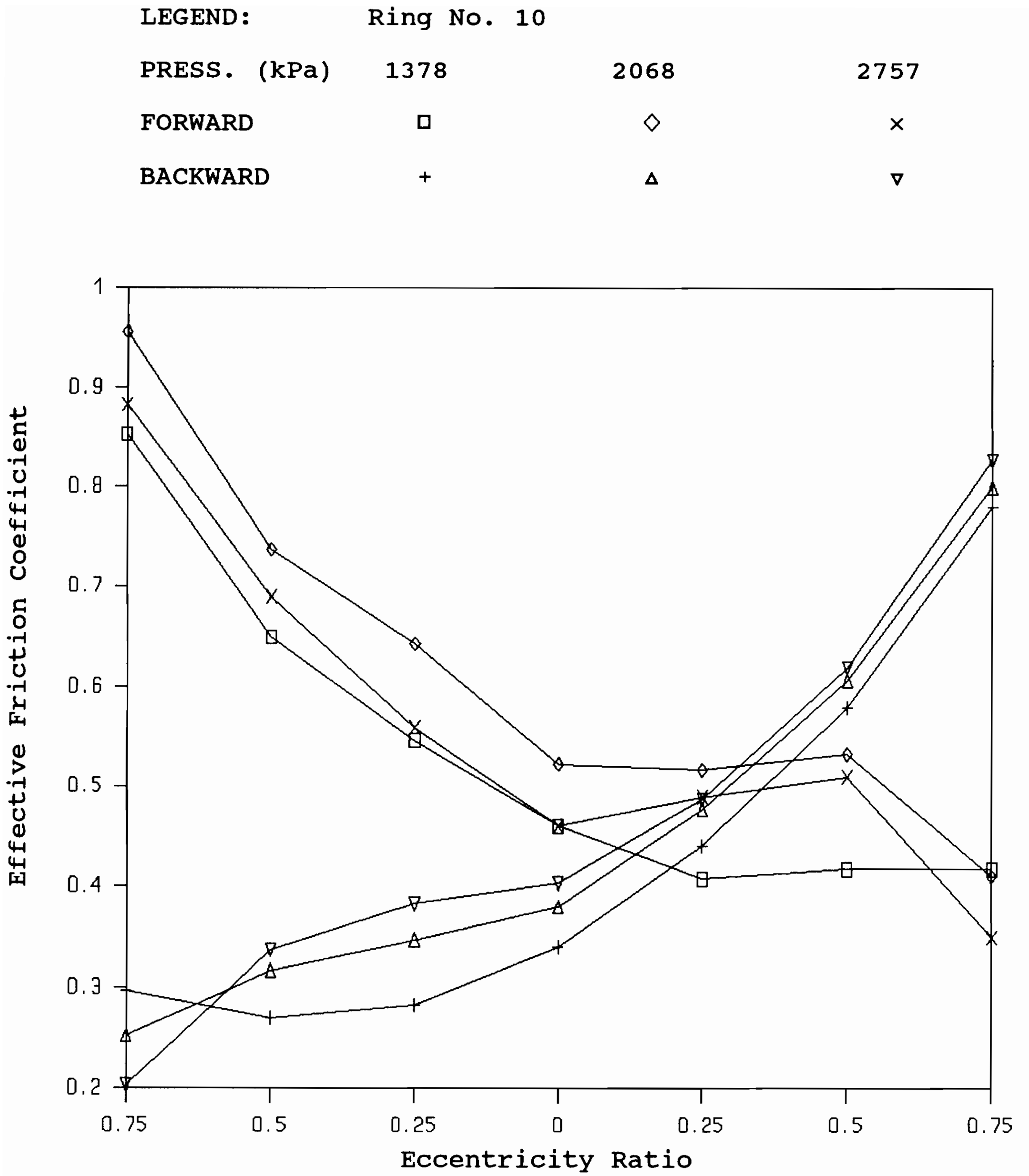


Figure 23: Average Effective Friction Coefficients for Ring 10 at 1378, 2068, and 2757 kPa.

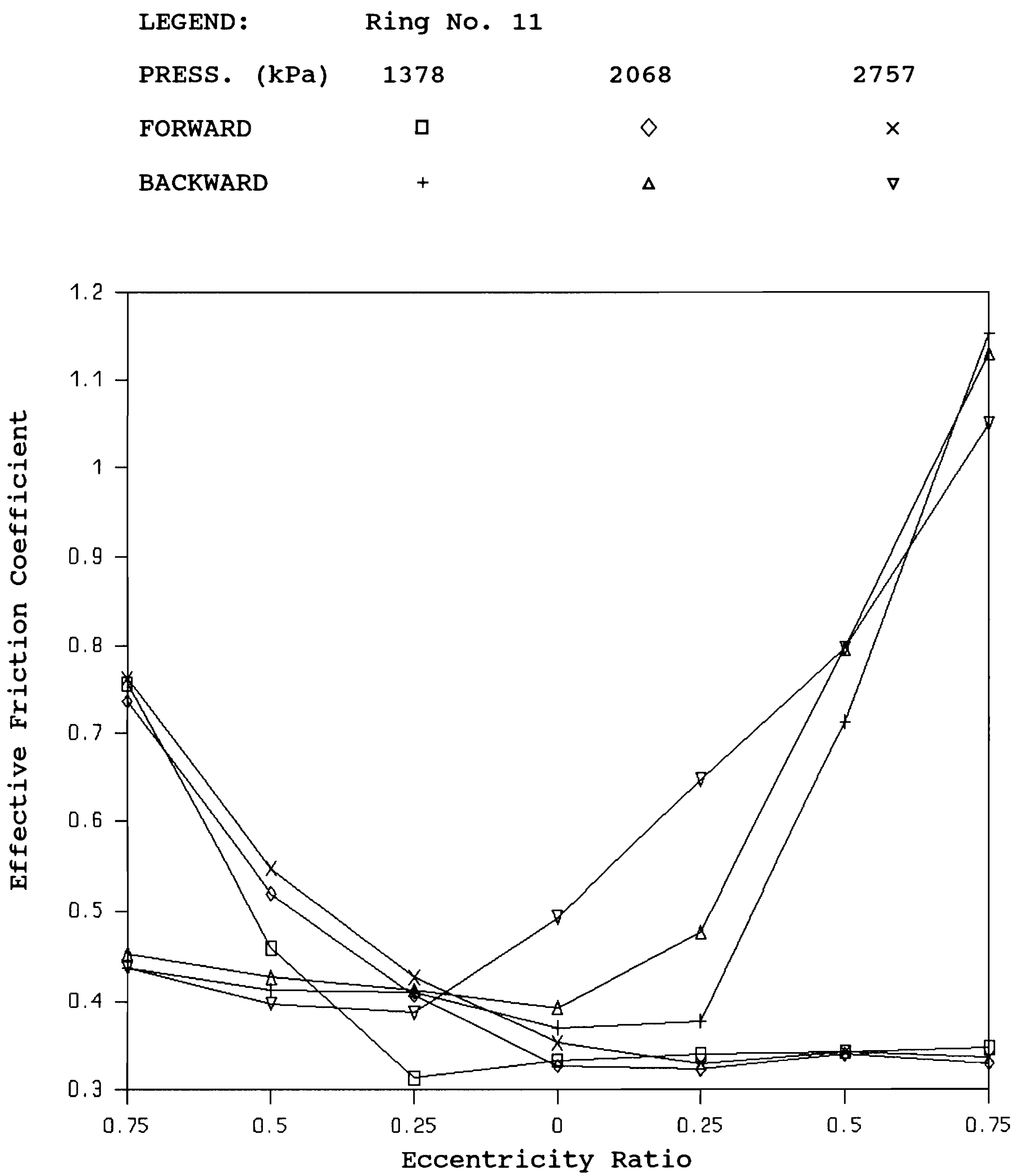


Figure 24: Average Effective Friction Coefficients for Ring 11 at 1378, 2068, and 2757 kPa.

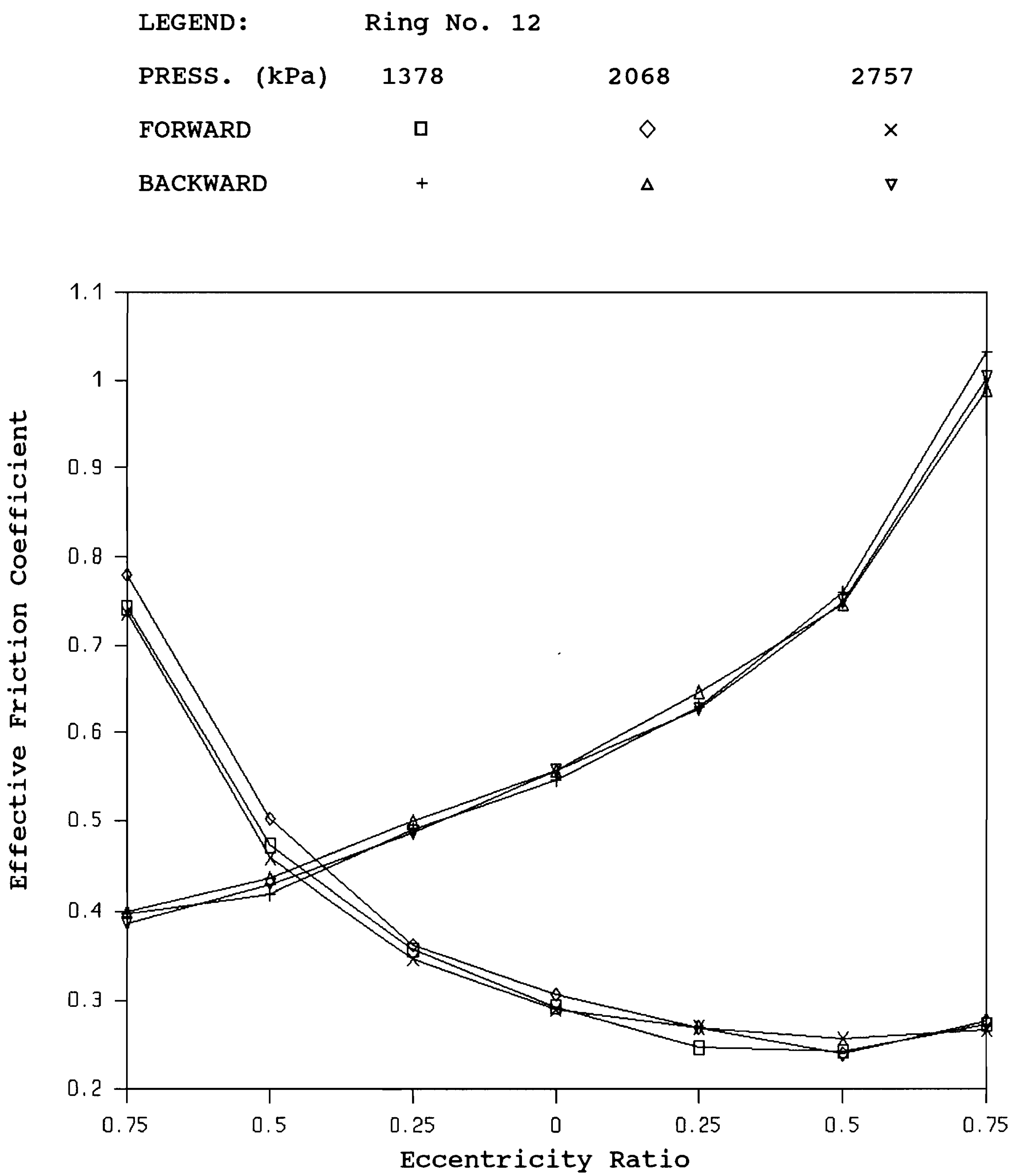


Figure 25: Average Effective Friction Coefficients for Ring 12 at 1378, 2068, and 2757 kPa.

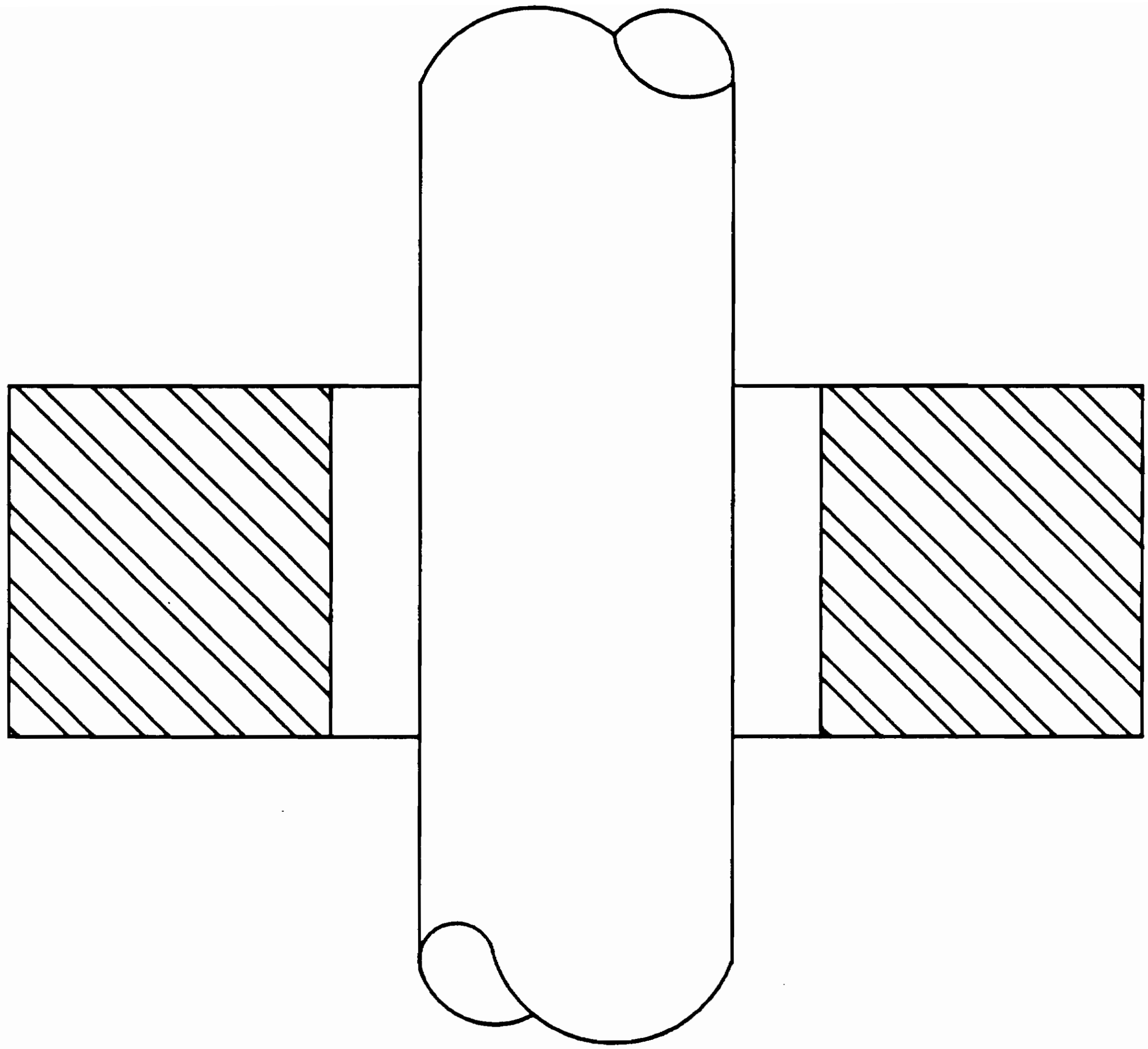


Figure 26: Ideal Seal Ring Orientation

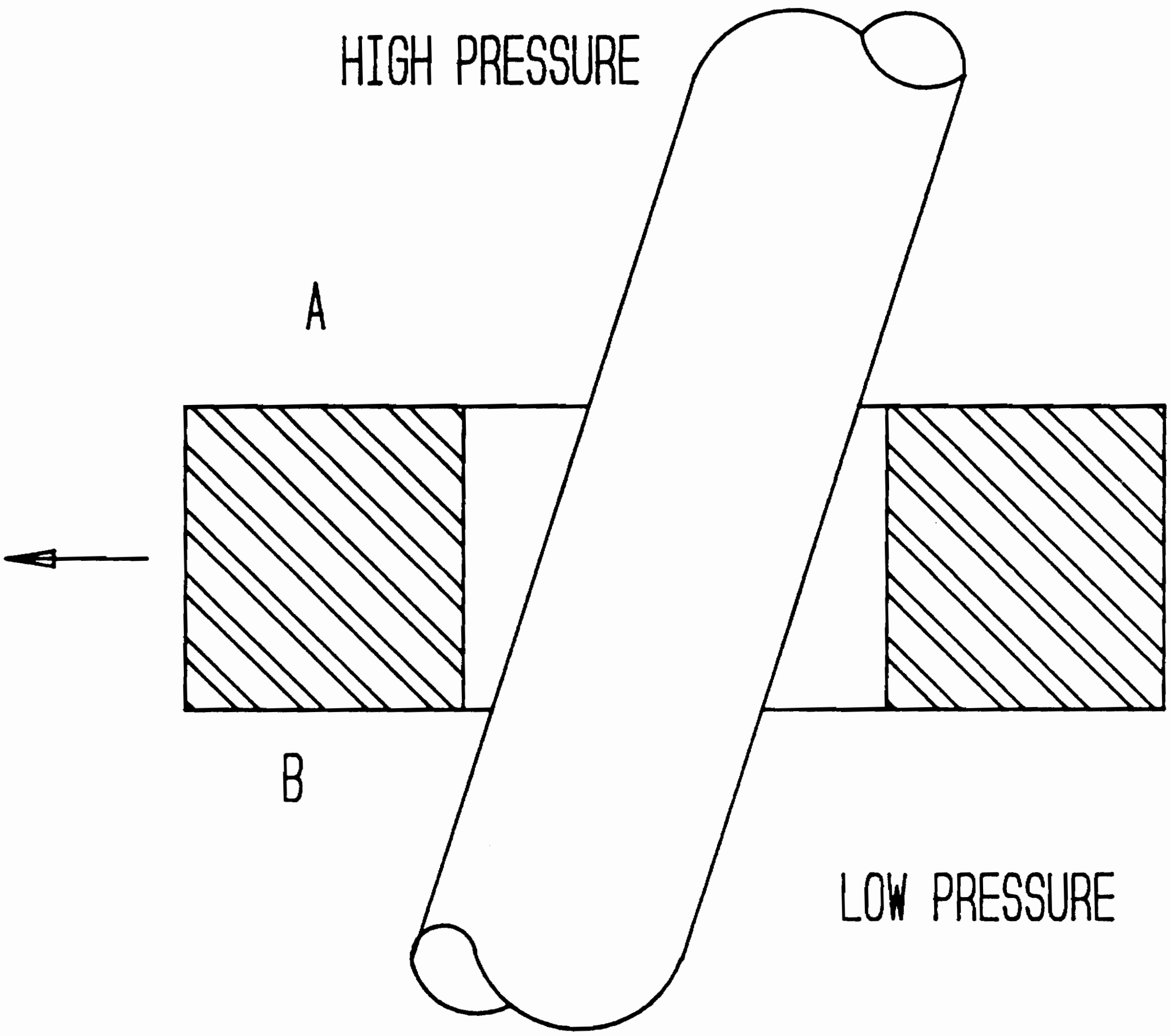


Figure 27: Seal Ring with Non-perpendicularity or Shaft Slope

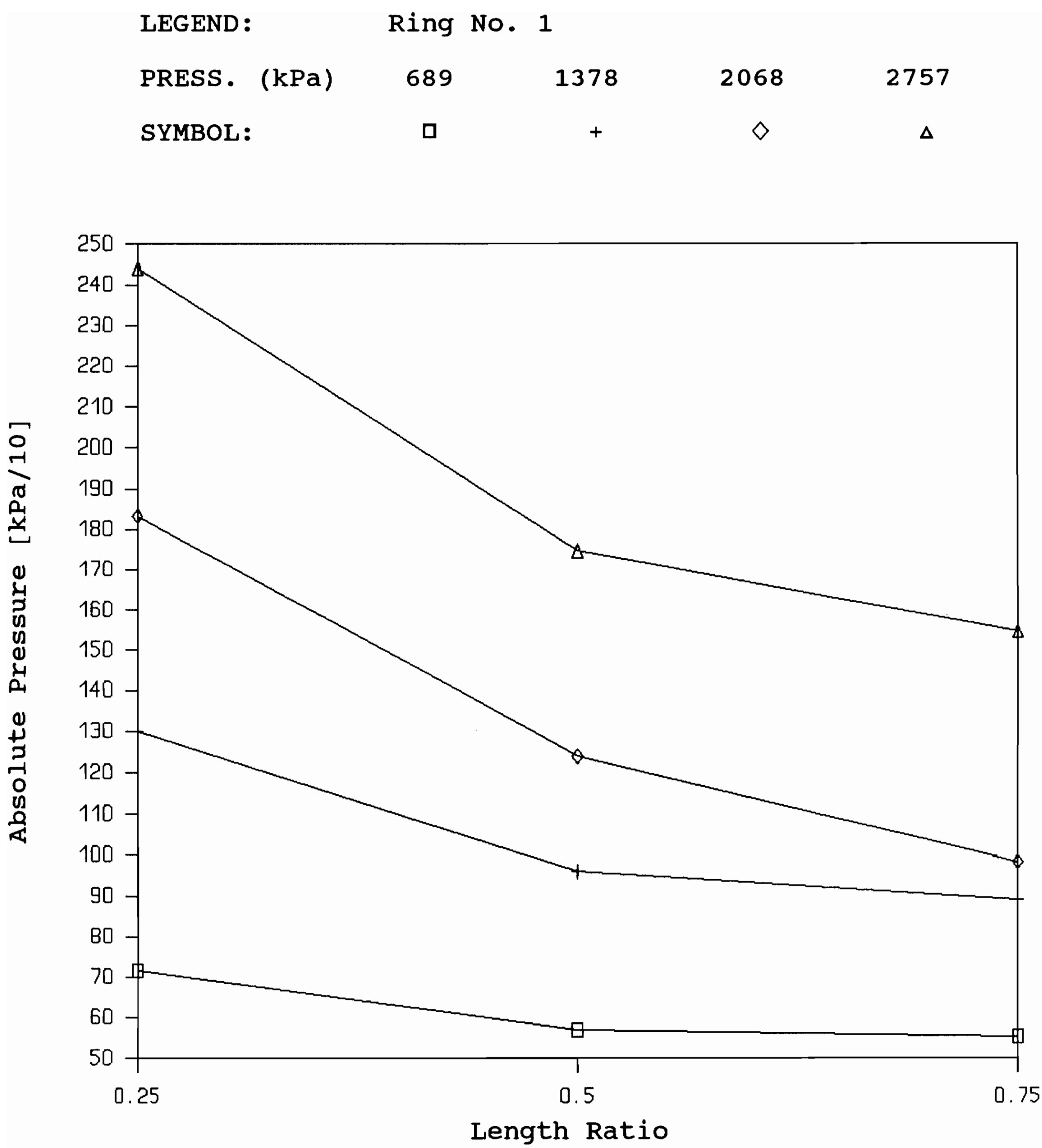


Figure 28: Pressure Data Averages for Ring 1 at Zero Eccentricity Ratio.

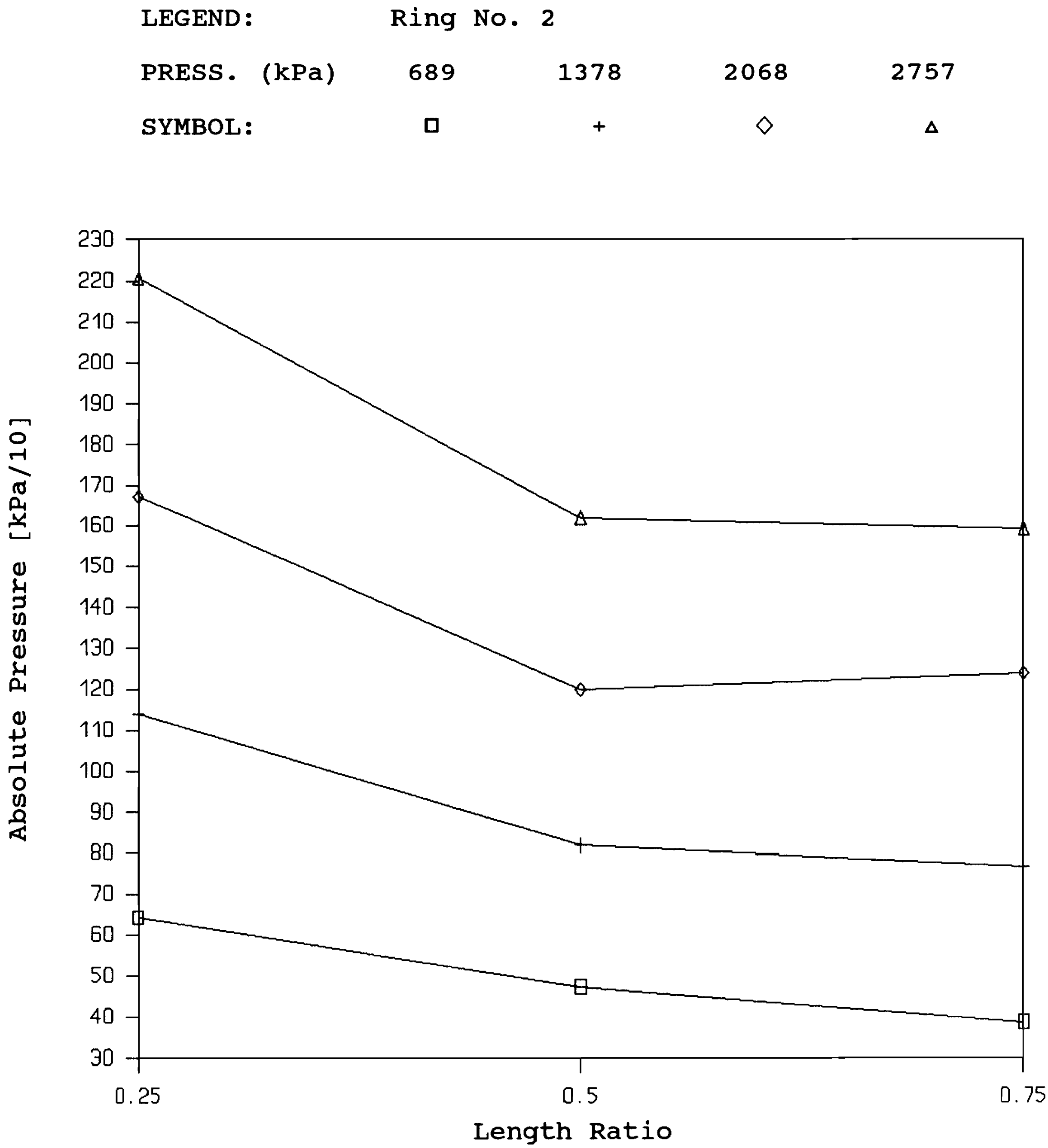


Figure 29: Pressure Data Averages for Ring 2 at Zero Eccentricity Ratio.

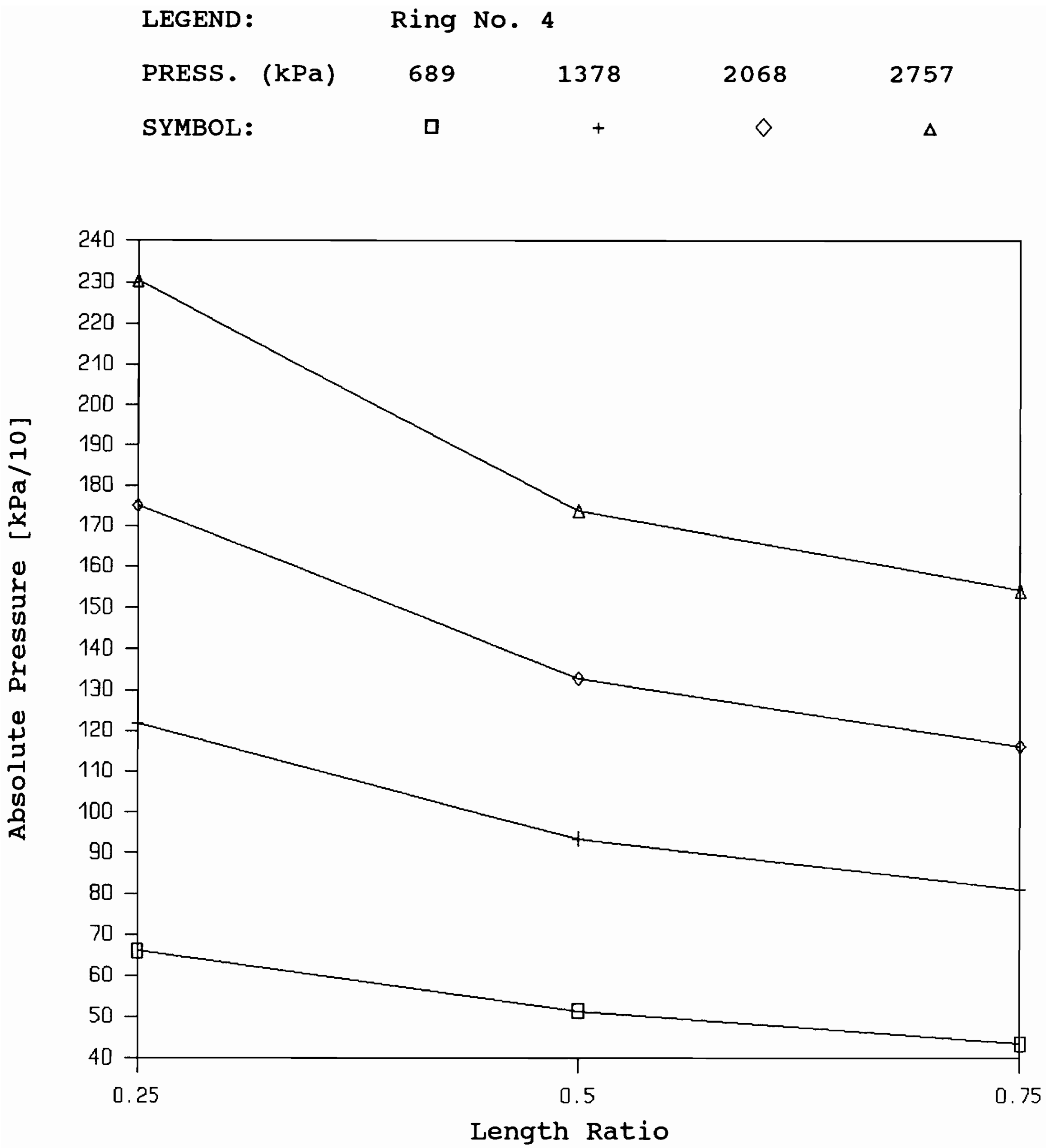


Figure 30: Pressure Data Averages for Ring 4 at Zero Eccentricity Ratio.

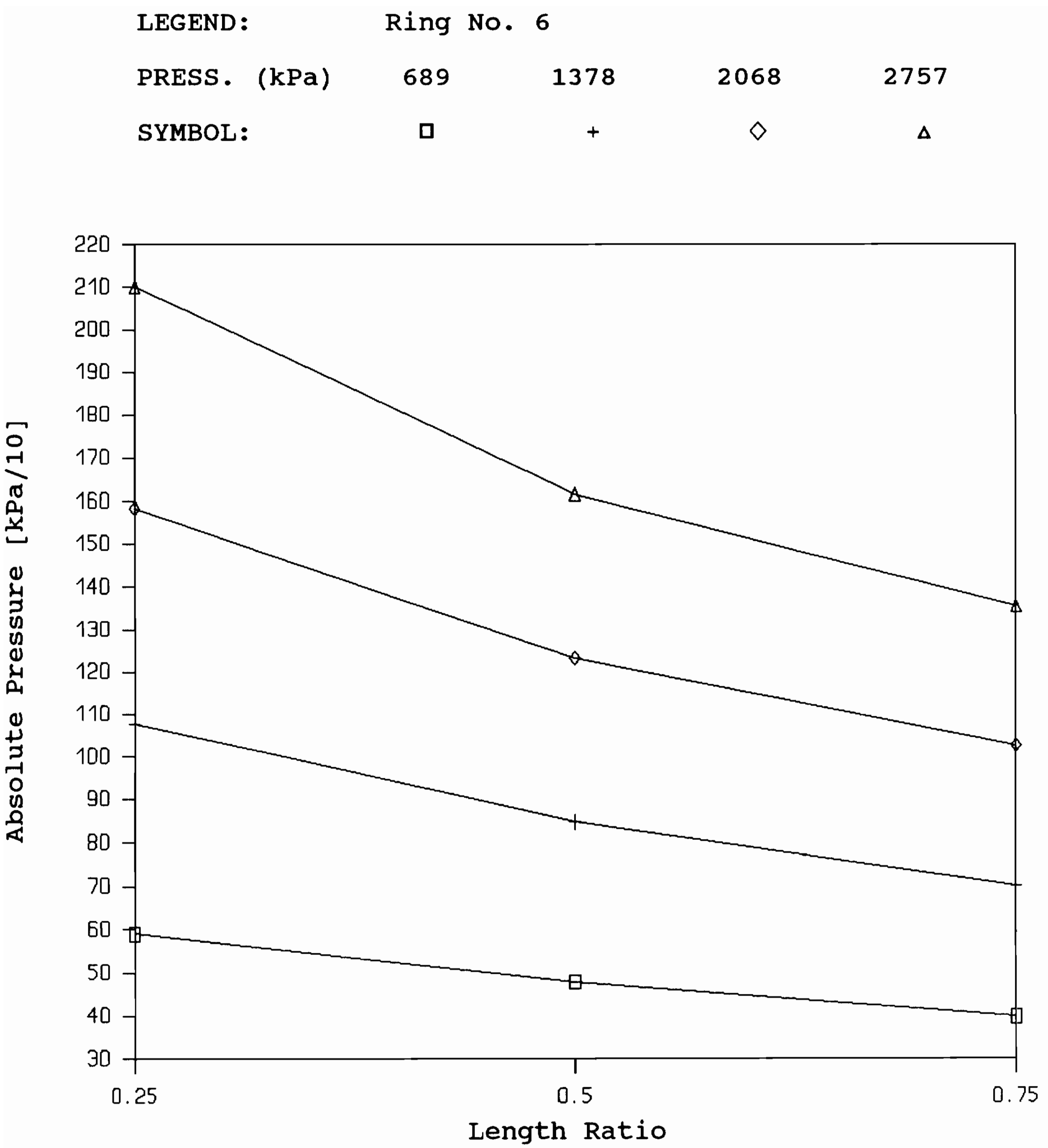


Figure 31: Pressure Data Averages for Ring 6 at Zero Eccentricity Ratio.

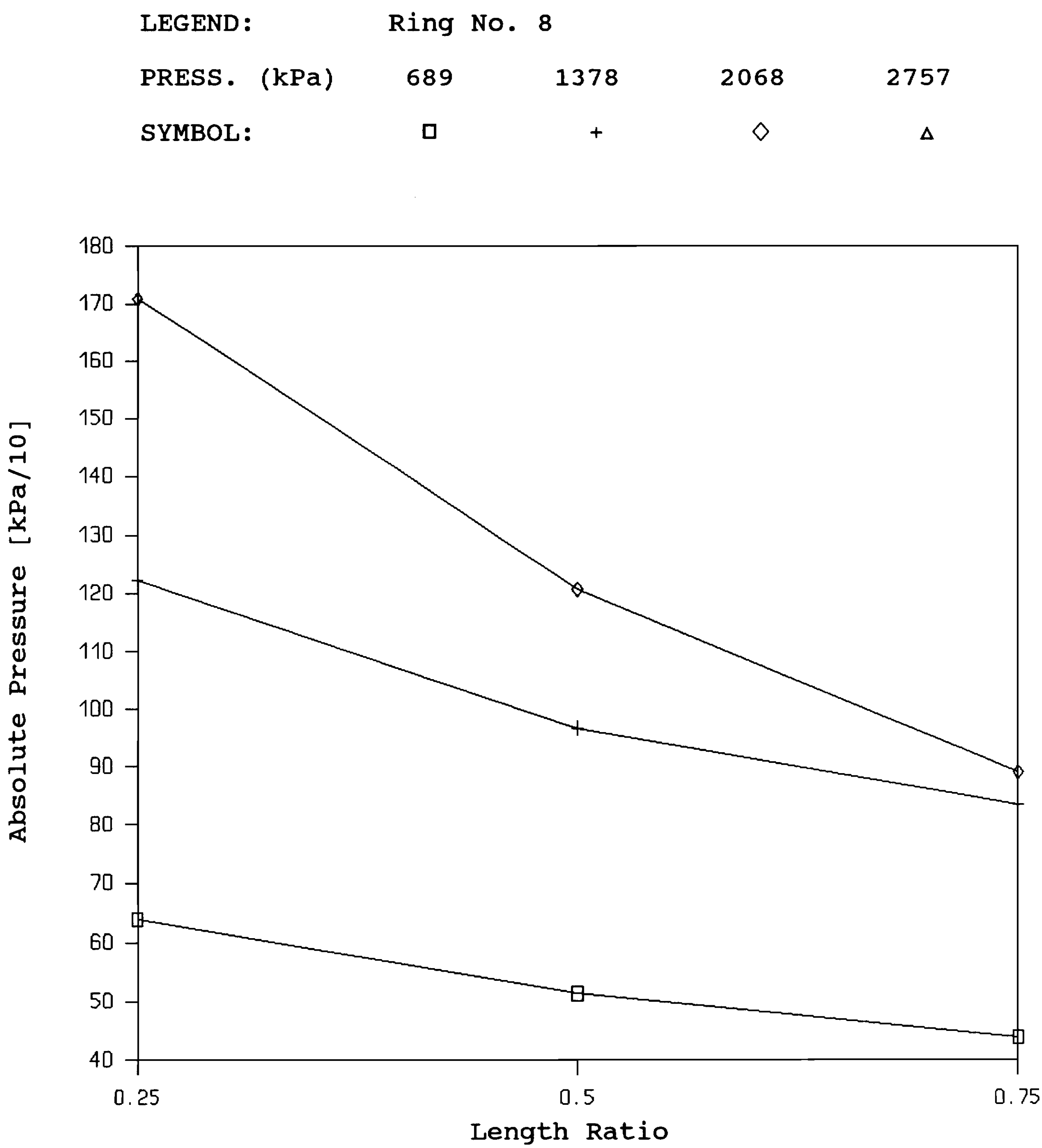


Figure 32: Pressure Data Averages for Ring 8 at Zero Eccentricity Ratio.

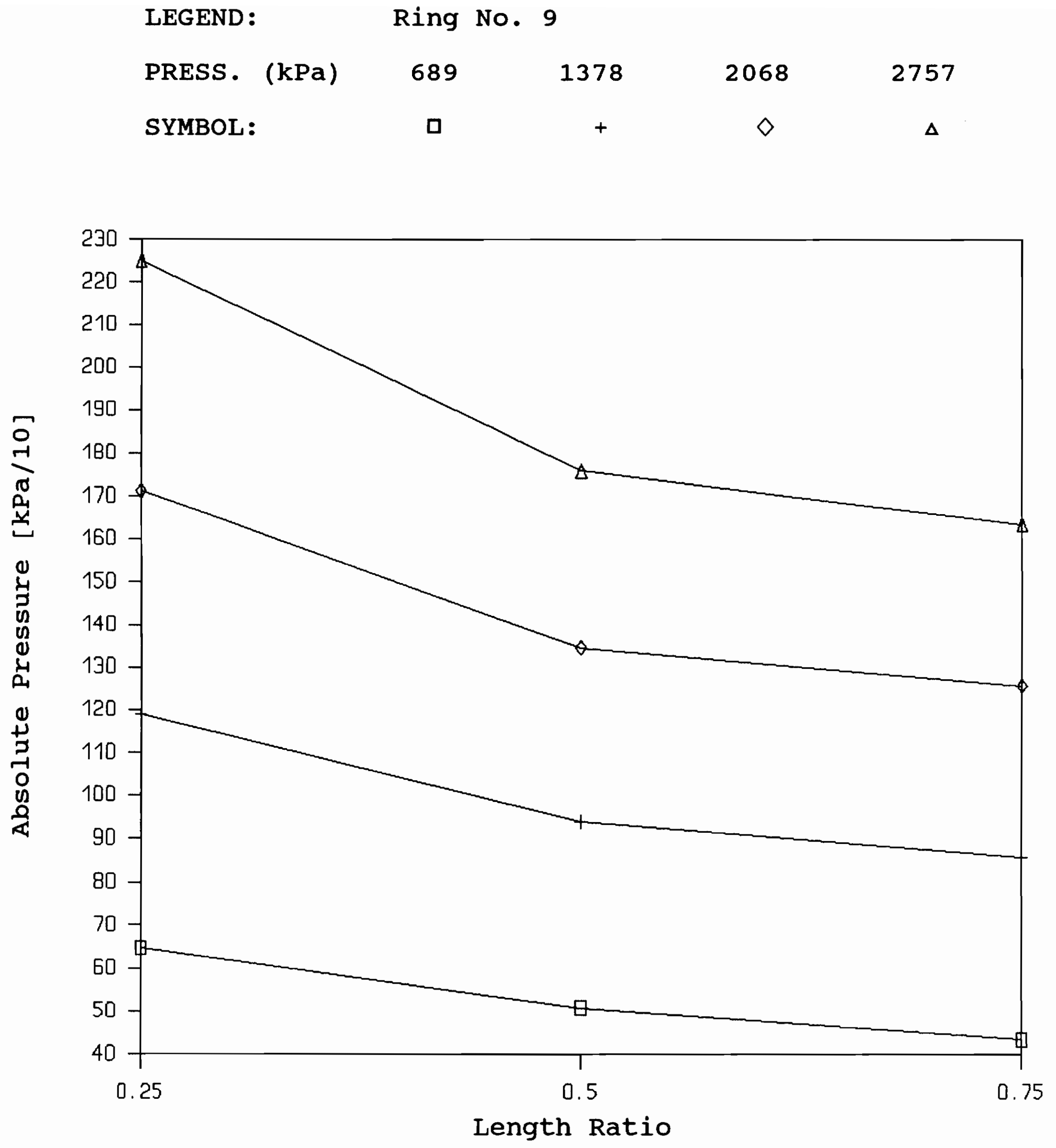


Figure 33: Pressure Data Averages for Ring 9 at Zero Eccentricity Ratio.

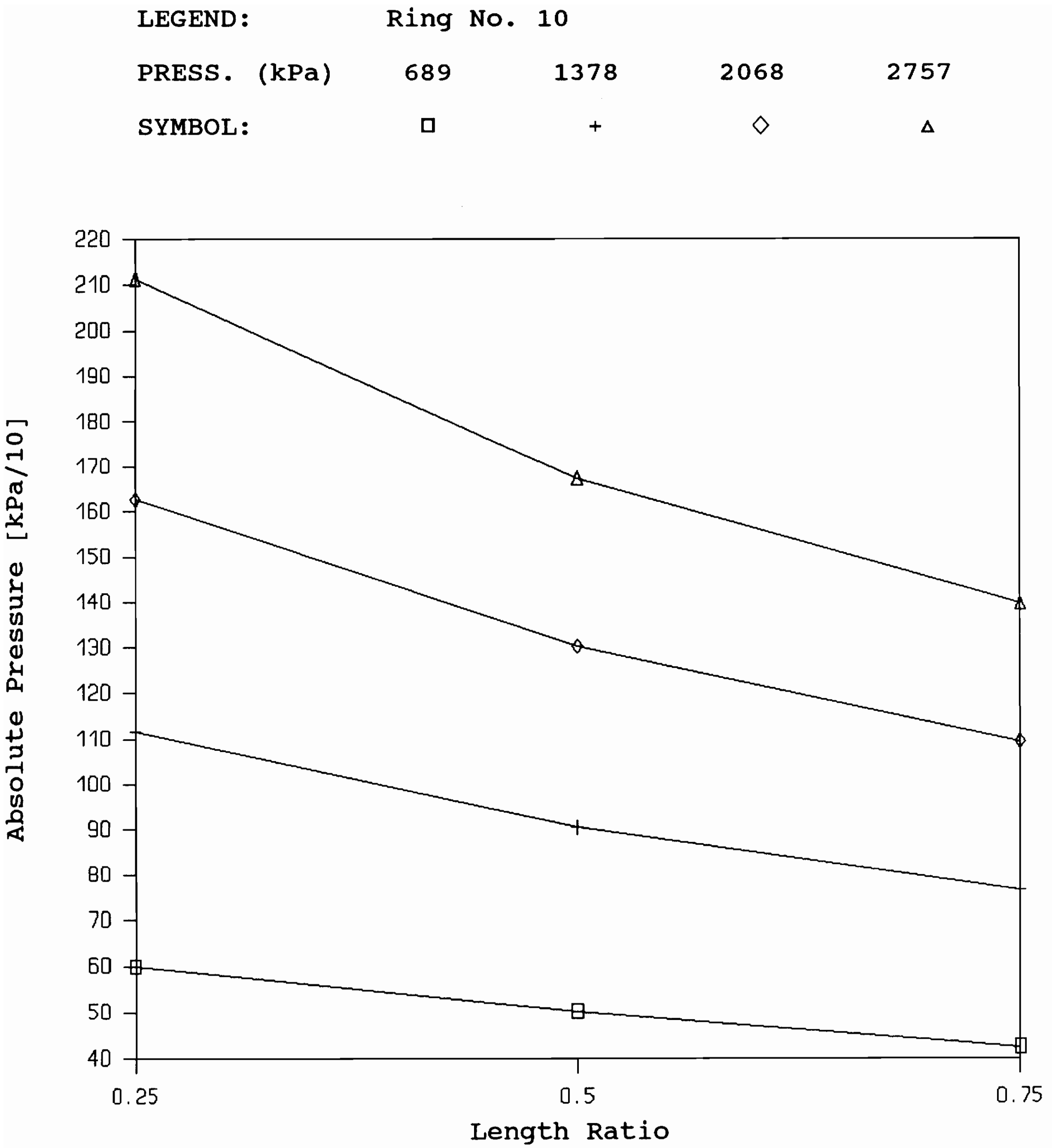


Figure 34: Pressure Data Averages for Ring 10 at Zero Eccentricity Ratio.

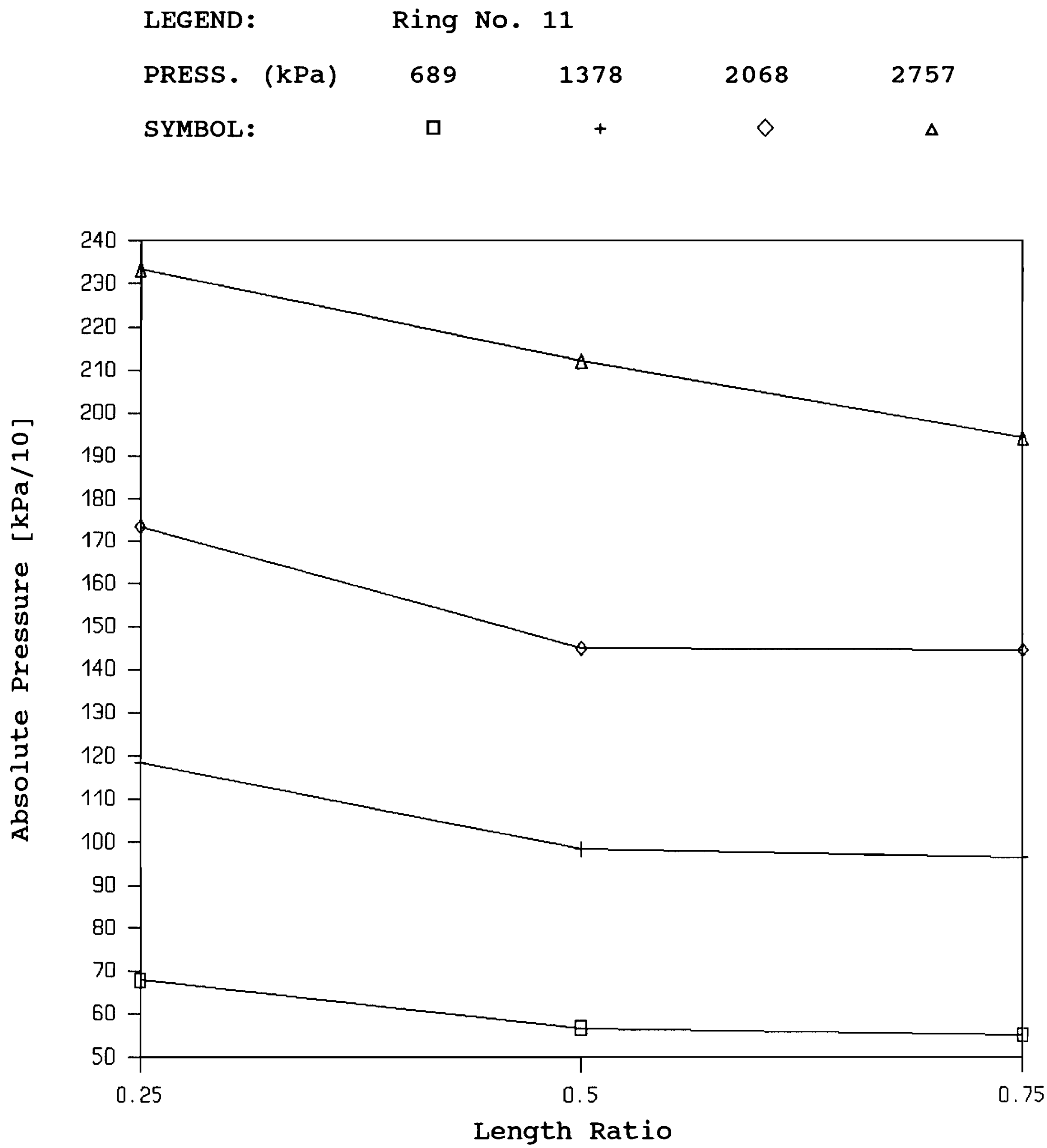


Figure 35: Pressure Data Averages for Ring 11 at Zero Eccentricity Ratio.

CONCLUSIONS

Based on the results of this research, the following conclusions have been made:

1) Minor shaft slope or seal ring bore-to-sealing face non-perpendicularity can have significant influence on shaft centering forces. Conventional analysis of these rings to determine dynamic characteristics neglects axial slope. The results indicate that these factors should be considered.

2) Experimental values from these tests indicate higher effective friction coefficients than is currently used in industry for design purposes.

3) It may be possible to optimize the centering capacity of a seal ring for use in turbomachinery with a sloped shaft due to gravity sag by incorporating bore-to-sealing face non-perpendicularity into the design of a ring to cancel the effects of shaft slope.

4) The results indicate a lower effective coefficient of friction when the seal ring is at high eccentricity and moving in a direction to center the ring, compared to a direction which further decenters the ring.

RECOMMENDATIONS

1) Further testing of the influence of seal ring bore-to-sealing face non-perpendicularity should be conducted to determine the possibility of optimizing a design considering shaft slope due to gravity sag.

2) A dynamic seal test rig is necessary to determine the effective friction coefficients under operating conditions including the shaft rotational effects.

3) Designers should consider higher friction coefficients than those currently used for analysis. Static test results indicate a predominance of effective friction coefficients in the range of 0.25 to 0.30 as lower limits for rings in the range of 0.50 to 0.75 eccentricity ratio, which is where many rings are predicted to operate.

4) Further testing on seal rings is needed to confirm that a circumferential groove added to a ring bore will reduce the effects of shaft slope or ring non-perpendicularity on radial centering forces.

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9. Kirk, R.G., and Dorton, D.W., "Test Results of Friction Holding Force in Floating Ring Seals," submitted for joint ASME/ASLE Tribology Conference, St. Louis, Mo., Oct. 13-16, 1991.

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APPENDIX A

Calculation of β_F

Calculation of β_F for Assumed Linear Lapped Face Pressure Profile

The factor β_F can be calculated for a linear pressure drop on the lapped face by integrating the profile pressure difference across the face width.

$$F_{pressure} = \int_{R_i}^{R_o} (P_s + \Delta P - P_o) \left[\frac{R_o - R}{R_o - R_i}\right] 2\pi R dR \qquad \text{(A-1)}$$

This results in the following expression,

$$F_{pressure} = \frac{\tilde{p} 2\pi}{\Delta R} \left[\frac{R_o^3 - R_o R_i^2}{2} - \frac{R_o^3 - R_i^3}{3}\right]$$

$$= \tilde{p}\frac{\pi}{4}(D_o^2 - D_i^2)\ \beta_F \qquad \text{(A-2)}$$

where

$$\tilde{p} = P_s + \Delta P - P_o \qquad \text{(A-3)}$$

$$\beta_F = \frac{1 - 3\overline{D}^2 + 2\overline{D}^3}{3(1 - \overline{D})(1 - \overline{D}^2)} \qquad \text{(A-4)}$$

and

$$\overline{D} = \frac{D_i}{D_o} \qquad \text{(A-5)}$$

For typical values of $\bar{D}$ the following results were obtained:

D_o	D_i	$\bar{D}$	β_F
(in)	(in)	(dim)	(dim)
6.5	6.0	0.923	0.492
7.0	6.0	0.857	0.487
5.0	4.0	0.800	0.481

These typical results give some assurance that using an average value of $\beta_F \sim 0.5$ is a good engineering approximation for a linear pressure drop on the lapped sealing face. The operating β_F can vary due to ring distortion or end plate distortion and increase or decrease the pressure loading for a given design. The actual β_F during operation is required for accurate seal operating eccentricity evaluation.

APPENDIX B

Friction Coefficient Data for Individual Rings

Table 4: Data for Ring 1 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	1.187	0.623	0.303	0.230	0.207	0.190	0.140
BACKWARD:	0.350	0.460	0.540	0.617	0.773	0.993	1.237
STANDARD DEVIATIONS:							
FORWARD:	0.031	0.034	0.012	0.000	0.005	0.008	0.000
BACKWARD:	0.016	0.014	0.008	0.009	0.021	0.031	0.025
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	1.230	0.670	0.550	0.630	0.800	1.020	1.270
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.330	0.450	0.290	0.230	0.200	0.180	0.140

The OVERALL MAXIMUM coefficient is: 1.270

The OVERALL MINIMUM coefficient is: 0.140

Table 5: Data for Ring 1 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	1.163	0.550	0.367	0.323	0.300	0.277	0.213
BACKWARD:	0.090	0.117	0.137	0.167	0.203	0.237	0.287
STANDARD DEVIATIONS:							
FORWARD:	0.012	0.062	0.012	0.024	0.028	0.026	0.017
BACKWARD:	0.016	0.025	0.025	0.025	0.029	0.025	0.039
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	1.180	0.620	0.380	0.340	0.320	0.300	0.340
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.070	0.090	0.110	0.140	0.170	0.210	0.190

The OVERALL MAXIMUM coefficient is: 1.180

The OVERALL MINIMUM coefficient is: 0.070

Table 6: Data for Ring 1 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	1.053	0.633	0.497	0.460	0.437	0.410	0.347
BACKWARD:	0.147	0.207	0.253	0.307	0.353	0.407	0.477
STANDARD DEVIATIONS:							
FORWARD:	0.246	0.041	0.026	0.041	0.049	0.041	0.041
BACKWARD:	0.009	0.045	0.054	0.046	0.033	0.012	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	1.270	0.680	0.520	0.510	0.500	0.460	0.480
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.140	0.170	0.210	0.260	0.310	0.360	0.300

The OVERALL MAXIMUM coefficient is: 1.270

The OVERALL MINIMUM coefficient is: 0.140

Table 7: Data for Ring 1 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.603	0.447	0.410	0.383	0.350	0.323	0.250
BACKWARD:	0.293	0.360	0.383	0.430	0.487	0.557	0.667
STANDARD DEVIATIONS:							
FORWARD:	0.172	0.151	0.170	0.175	0.163	0.147	0.099
BACKWARD:	0.076	0.065	0.068	0.016	0.026	0.048	0.063
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.730	0.660	0.650	0.630	0.580	0.600	0.730
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.190	0.270	0.270	0.240	0.220	0.200	0.170

The OVERALL MAXIMUM coefficient is: 0.730

The OVERALL MINIMUM coefficient is: 0.170

Table 8: Data for Ring 2 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.733	0.473	0.400	0.377	0.370	0.353	0.307
BACKWARD:	0.400	0.423	0.447	0.503	0.633	0.820	1.027
STANDARD DEVIATIONS:							
FORWARD:	0.021	0.063	0.029	0.026	0.024	0.021	0.031
BACKWARD:	0.008	0.009	0.005	0.029	0.021	0.008	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.760	0.560	0.450	0.540	0.660	0.830	1.030
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.390	0.410	0.360	0.340	0.340	0.330	0.280

The OVERALL MAXIMUM coefficient is: 1.030

The OVERALL MINIMUM coefficient is: 0.280

Table 9: Data for Ring 2 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.770	0.543	0.477	0.440	0.423	0.397	0.330
BACKWARD:	0.390	0.417	0.467	0.540	0.640	0.787	0.983
STANDARD DEVIATIONS:							
FORWARD:	0.028	0.057	0.025	0.029	0.041	0.034	0.022
BACKWARD:	0.008	0.012	0.012	0.014	0.022	0.021	0.021
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.810	0.610	0.510	0.560	0.660	0.810	1.010
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.380	0.400	0.450	0.400	0.370	0.350	0.300

The OVERALL MAXIMUM coefficient is: 1.010

The OVERALL MINIMUM coefficient is: 0.300

Table 10: Data for Ring 2 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.873	0.663	0.583	0.543	0.490	0.447	0.323
BACKWARD:	0.387	0.467	0.527	0.590	0.693	0.827	1.013
STANDARD DEVIATIONS:							
FORWARD:	0.045	0.060	0.033	0.025	0.024	0.029	0.058
BACKWARD:	0.009	0.005	0.012	0.016	0.017	0.017	0.012
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.930	0.720	0.620	0.610	0.710	0.850	1.030
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.380	0.460	0.510	0.510	0.460	0.410	0.260

The OVERALL MAXIMUM coefficient is: 1.030

The OVERALL MINIMUM coefficient is: 0.260

Table 11: Data for Ring 2 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.753	0.597	0.510	0.480	0.417	0.373	0.247
BACKWARD:	0.350	0.470	0.520	0.597	0.697	0.827	0.997
STANDARD DEVIATIONS:							
FORWARD:	0.017	0.012	0.022	0.022	0.019	0.031	0.025
BACKWARD:	0.033	0.014	0.008	0.005	0.009	0.012	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.770	0.610	0.530	0.600	0.710	0.840	1.000
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.310	0.460	0.480	0.450	0.390	0.330	0.220

The OVERALL MAXIMUM coefficient is: 1.000

The OVERALL MINIMUM coefficient is: 0.220

Table 12: Data for Ring 3 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.720	0.380	0.263	0.203	0.190	0.157	0.120
BACKWARD:	0.097	0.243	0.393	0.663	0.793	0.873	1.010
STANDARD DEVIATIONS:							
FORWARD:	0.024	0.022	0.009	0.019	0.008	0.026	0.008
BACKWARD:	0.012	0.005	0.012	0.005	0.005	0.009	0.014
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.750	0.410	0.410	0.670	0.800	0.880	1.030
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.080	0.240	0.250	0.190	0.180	0.120	0.110

The OVERALL MAXIMUM coefficient is: 1.030

The OVERALL MINIMUM coefficient is: 0.080

Table 13: Data for Ring 3 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.900	0.463	0.293	0.190	0.157	0.150	0.117
BACKWARD:	0.000	0.140	0.387	0.607	0.663	0.717	0.827
STANDARD DEVIATIONS:							
FORWARD:	0.037	0.017	0.009	0.008	0.005	0.014	0.034
BACKWARD:	0.000	0.008	0.045	0.009	0.012	0.019	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.940	0.480	0.450	0.620	0.680	0.730	0.830
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.000	0.130	0.280	0.180	0.150	0.130	0.070

The OVERALL MAXIMUM coefficient is: 0.940

The OVERALL MINIMUM coefficient is: 0.000

Table 14: Data for Ring 3 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.890	0.480	0.293	0.210	0.160	0.133	0.120
BACKWARD:	0.000	0.170	0.337	0.477	0.607	0.743	0.883
STANDARD DEVIATIONS:							
FORWARD:	0.029	0.000	0.045	0.057	0.029	0.005	0.014
BACKWARD:	0.000	0.000	0.005	0.009	0.009	0.005	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.930	0.480	0.340	0.490	0.620	0.750	0.890
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.000	0.170	0.230	0.130	0.120	0.130	0.110

The OVERALL MAXIMUM coefficient is: 0.930

The OVERALL MINIMUM coefficient is: 0.000

Table 15: Data for Ring 3 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.970	0.573	0.420	0.323	0.250	0.197	0.167
BACKWARD:	0.000	0.210	0.370	0.500	0.617	0.757	0.907
STANDARD DEVIATIONS:							
FORWARD:	0.029	0.005	0.014	0.017	0.014	0.012	0.012
BACKWARD:	0.000	0.014	0.000	0.014	0.005	0.009	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	1.010	0.580	0.430	0.510	0.620	0.770	0.910
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.000	0.190	0.370	0.300	0.230	0.180	0.150

The OVERALL MAXIMUM coefficient is: 1.010

The OVERALL MINIMUM coefficient is: 0.000

Table 16: Data for Ring 4 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.717	0.473	0.337	0.233	0.257	0.287	0.290
BACKWARD:	0.317	0.313	0.357	0.470	0.600	0.757	0.803
STANDARD DEVIATIONS:							
FORWARD:	0.012	0.009	0.019	0.017	0.005	0.012	0.014
BACKWARD:	0.005	0.005	0.021	0.014	0.016	0.005	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:	0.730	0.480	0.380	0.490	0.620	0.760	0.810
MINIMUM COEFF AT EACH ECCENTRICITY:	0.310	0.310	0.310	0.210	0.250	0.270	0.270

The OVERALL MAXIMUM coefficient is: 0.810

The OVERALL MINIMUM coefficient is: 0.210

Table 17: Data for Ring 4 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.643	0.443	0.330	0.287	0.243	0.243	0.250
BACKWARD:	0.340	0.380	0.467	0.547	0.637	0.800	1.037
STANDARD DEVIATIONS:							
FORWARD:	0.009	0.009	0.008	0.012	0.005	0.019	0.016
BACKWARD:	0.000	0.014	0.009	0.017	0.009	0.014	0.017
MAXIMUM COEFF AT EACH ECCENTRICITY:	0.650	0.450	0.480	0.570	0.650	0.820	1.060
MINIMUM COEFF AT EACH ECCENTRICITY:	0.340	0.370	0.320	0.270	0.240	0.230	0.230

The OVERALL MAXIMUM coefficient is: 1.060

The OVERALL MINIMUM coefficient is: 0.230

Table 18: Data for Ring 4 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.637	0.443	0.347	0.317	0.270	0.273	0.260
BACKWARD:	0.353	0.393	0.467	0.533	0.627	0.767	0.983
STANDARD DEVIATIONS:							
FORWARD:	0.009	0.005	0.005	0.005	0.008	0.009	0.000
BACKWARD:	0.012	0.024	0.021	0.025	0.029	0.042	0.046
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.650	0.450	0.490	0.560	0.660	0.810	1.030
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.340	0.360	0.340	0.310	0.260	0.260	0.260

The OVERALL MAXIMUM coefficient is: 1.030

The OVERALL MINIMUM coefficient is: 0.260

Table 19: Data for Ring 4 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.673	0.470	0.377	0.337	0.307	0.290	0.243
BACKWARD:	0.400	0.467	0.530	0.610	0.710	0.853	1.057
STANDARD DEVIATIONS:							
FORWARD:	0.017	0.008	0.012	0.005	0.005	0.008	0.021
BACKWARD:	0.022	0.021	0.022	0.016	0.016	0.012	0.017
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.690	0.490	0.560	0.630	0.730	0.870	1.080
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.380	0.440	0.360	0.330	0.300	0.280	0.220

The OVERALL MAXIMUM coefficient is: 1.080

The OVERALL MINIMUM coefficient is: 0.220

Table 20: Data for Ring 5 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.893	0.547	0.353	0.267	0.297	0.323	0.310
BACKWARD:	0.387	0.400	0.400	0.397	0.393	0.430	0.970
STANDARD DEVIATIONS:							
FORWARD:	0.005	0.017	0.086	0.012	0.012	0.009	0.029
BACKWARD:	0.021	0.022	0.014	0.021	0.009	0.008	0.008
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.900	0.570	0.460	0.420	0.400	0.440	0.980
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.360	0.370	0.250	0.250	0.280	0.310	0.270

The OVERALL MAXIMUM coefficient is: 0.980

The OVERALL MINIMUM coefficient is: 0.250

Table 21: Data for Ring 5 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.790	0.550	0.403	0.300	0.303	0.330	0.347
BACKWARD:	0.457	0.450	0.453	0.470	0.560	0.760	1.057
STANDARD DEVIATIONS:							
FORWARD:	0.042	0.036	0.066	0.036	0.029	0.022	0.017
BACKWARD:	0.012	0.022	0.024	0.022	0.008	0.022	0.049
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.820	0.580	0.470	0.490	0.570	0.780	1.120
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.440	0.420	0.310	0.250	0.270	0.310	0.330

The OVERALL MAXIMUM coefficient is: 1.120

The OVERALL MINIMUM coefficient is: 0.250

Table 22: Data for Ring 5 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.737	0.507	0.383	0.327	0.323	0.337	0.330
BACKWARD:	0.413	0.487	0.487	0.517	0.583	0.723	1.020
STANDARD DEVIATIONS:							
FORWARD:	0.037	0.034	0.052	0.024	0.031	0.025	0.036
BACKWARD:	0.045	0.019	0.012	0.019	0.045	0.045	0.050
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.780	0.540	0.500	0.530	0.620	0.760	1.060
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.360	0.460	0.310	0.310	0.280	0.310	0.280

The OVERALL MAXIMUM coefficient is: 1.060

The OVERALL MINIMUM coefficient is: 0.280

Table 23: Data for Ring 5 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.707	0.530	0.410	0.343	0.317	0.317	0.280
BACKWARD:	0.507	0.493	0.523	0.520	0.560	0.697	0.953
STANDARD DEVIATIONS:							
FORWARD:	0.019	0.016	0.000	0.017	0.005	0.024	0.037
BACKWARD:	0.026	0.026	0.005	0.037	0.008	0.012	0.026
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.720	0.550	0.530	0.560	0.570	0.710	0.990
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.470	0.470	0.410	0.320	0.310	0.300	0.230

The OVERALL MAXIMUM coefficient is: 0.990

The OVERALL MINIMUM coefficient is: 0.230

Table 24: Data for Ring 6 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.747	0.477	0.377	0.353	0.357	0.343	0.333
BACKWARD:	0.310	0.313	0.313	0.300	0.297	0.323	0.550
STANDARD DEVIATIONS:							
FORWARD:	0.068	0.074	0.045	0.017	0.045	0.063	0.037
BACKWARD:	0.014	0.017	0.009	0.008	0.012	0.034	0.177
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.800	0.570	0.430	0.370	0.420	0.430	0.800
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.300	0.290	0.300	0.290	0.280	0.280	0.290

The OVERALL MAXIMUM coefficient is: 0.800

The OVERALL MINIMUM coefficient is: 0.280

Table 25: Data for Ring 6 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.783	0.550	0.410	0.367	0.323	0.307	0.320
BACKWARD:	0.317	0.293	0.277	0.300	0.427	0.573	0.783
STANDARD DEVIATIONS:							
FORWARD:	0.005	0.008	0.008	0.012	0.009	0.012	0.008
BACKWARD:	0.005	0.005	0.009	0.024	0.034	0.005	0.009
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.790	0.560	0.420	0.380	0.460	0.580	0.790
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.310	0.290	0.270	0.270	0.310	0.290	0.310

The OVERALL MAXIMUM coefficient is: 0.790

The OVERALL MINIMUM coefficient is: 0.270

Table 26: Data for Ring 6 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.760	0.563	0.430	0.383	0.347	0.327	0.307
BACKWARD:	0.317	0.337	0.337	0.403	0.490	0.627	0.820
STANDARD DEVIATIONS:							
FORWARD:	0.008	0.005	0.008	0.005	0.009	0.009	0.012
BACKWARD:	0.005	0.012	0.012	0.017	0.014	0.005	0.008
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.770	0.570	0.440	0.420	0.500	0.630	0.830
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.310	0.320	0.320	0.380	0.340	0.320	0.290

The OVERALL MAXIMUM coefficient is: 0.830

The OVERALL MINIMUM coefficient is: 0.290

Table 27: Data for Ring 6 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.740	0.577	0.463	0.417	0.393	0.360	0.280
BACKWARD:	0.223	0.383	0.423	0.460	0.540	0.670	0.853
STANDARD DEVIATIONS:							
FORWARD:	0.022	0.017	0.017	0.021	0.021	0.014	0.008
BACKWARD:	0.017	0.017	0.026	0.024	0.024	0.036	0.066
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.760	0.600	0.480	0.490	0.570	0.720	0.940
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.200	0.360	0.400	0.390	0.370	0.350	0.270

The OVERALL MAXIMUM coefficient is: 0.940

The OVERALL MINIMUM coefficient is: 0.200

Table 28: Data for Ring 7 at 689 kPa

		0.750	0.500	0.250	0.000	0.250	0.500	0.750
SEAL POSITIONS:		0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:								
	FORWARD:	1.073	0.693	0.607	0.567	0.560	0.553	0.523
	BACKWARD:	0.300	0.273	0.250	0.190	0.160	0.217	0.710
STANDARD DEVIATIONS:								
	FORWARD:	0.029	0.073	0.021	0.026	0.029	0.031	0.024
	BACKWARD:	0.008	0.017	0.016	0.000	0.000	0.082	0.008
MAXIMUM COEFF AT EACH ECCENTRICITY:								
		1.110	0.750	0.630	0.590	0.590	0.580	0.720
MINIMUM COEFF AT EACH ECCENTRICITY:								
		0.290	0.250	0.230	0.190	0.160	0.140	0.490

The OVERALL MAXIMUM coefficient is: 1.110

The OVERALL MINIMUM coefficient is: 0.140

Table 29: Data for Ring 7 at 1378 kPa

SEAL POSITIONS:		0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:								
	FORWARD:	0.800	0.587	0.503	0.450	0.403	0.380	0.340
	BACKWARD:	0.300	0.267	0.217	0.173	0.200	0.527	0.857
STANDARD DEVIATIONS:								
	FORWARD:	0.028	0.009	0.019	0.014	0.012	0.014	0.016
	BACKWARD:	0.008	0.012	0.009	0.017	0.042	0.005	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:								
		0.840	0.600	0.530	0.470	0.420	0.530	0.860
MINIMUM COEFF AT EACH ECCENTRICITY:								
		0.290	0.250	0.210	0.150	0.170	0.370	0.320

The OVERALL MAXIMUM coefficient is: 0.860

The OVERALL MINIMUM coefficient is: 0.150

Table 30: Data for Ring 7 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.760	0.593	0.507	0.457	0.410	0.380	0.360
BACKWARD:	0.380	0.367	0.317	0.260	0.260	0.633	1.173
STANDARD DEVIATIONS:							
FORWARD:	0.014	0.005	0.005	0.005	0.008	0.008	0.014
BACKWARD:	0.014	0.012	0.025	0.024	0.029	0.062	0.025
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.770	0.600	0.510	0.460	0.420	0.720	1.200
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.360	0.350	0.290	0.230	0.230	0.370	0.340

The OVERALL MAXIMUM coefficient is: 1.200

The OVERALL MINIMUM coefficient is: 0.230

Table 31: Data for Ring 7 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.687	0.527	0.457	0.423	0.393	0.373	0.317
BACKWARD:	0.400	0.363	0.347	0.420	0.493	0.747	1.393
STANDARD DEVIATIONS:							
FORWARD:	0.141	0.097	0.083	0.074	0.066	0.066	0.054
BACKWARD:	0.014	0.034	0.005	0.057	0.152	0.127	0.143
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.810	0.610	0.520	0.490	0.620	0.860	1.560
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.390	0.330	0.340	0.320	0.280	0.280	0.260

The OVERALL MAXIMUM coefficient is: 1.560

The OVERALL MINIMUM coefficient is: 0.260

Table 32: Data for Ring 8 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.817	0.553	0.477	0.430	0.427	0.430	0.427
BACKWARD:	0.430	0.420	0.400	0.377	0.353	0.340	0.697
STANDARD DEVIATIONS:							
FORWARD:	0.034	0.073	0.033	0.008	0.005	0.000	0.005
BACKWARD:	0.000	0.008	0.008	0.009	0.009	0.000	0.017
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.850	0.610	0.500	0.440	0.430	0.430	0.720
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.430	0.410	0.390	0.370	0.340	0.340	0.420

The OVERALL MAXIMUM coefficient is: 0.850

The OVERALL MINIMUM coefficient is: 0.340

Table 33: Data for Ring 8 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.773	0.600	0.510	0.460	0.430	0.427	0.363
BACKWARD:	0.357	0.357	0.340	0.320	0.313	0.363	0.623
STANDARD DEVIATIONS:							
FORWARD:	0.012	0.022	0.016	0.008	0.016	0.012	0.025
BACKWARD:	0.012	0.012	0.008	0.008	0.009	0.057	0.059
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.790	0.630	0.530	0.470	0.450	0.440	0.670
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.340	0.340	0.330	0.310	0.300	0.290	0.330

The OVERALL MAXIMUM coefficient is: 0.790

The OVERALL MINIMUM coefficient is: 0.290

Table 34: Data for Ring 8 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.633	0.597	0.573	0.587	0.557	0.563	0.543
BACKWARD:	0.443	0.453	0.417	0.407	0.413	0.387	0.397
STANDARD DEVIATIONS:							
FORWARD:	0.021	0.026	0.025	0.034	0.047	0.092	0.105
BACKWARD:	0.024	0.037	0.047	0.040	0.025	0.017	0.021
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.660	0.620	0.600	0.620	0.590	0.660	0.650
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.410	0.410	0.350	0.350	0.380	0.370	0.370

The OVERALL MAXIMUM coefficient is: 0.660

The OVERALL MINIMUM coefficient is: 0.350

NO DATA FOR RING 8 AT 2757 kPa

Table 35: Data for Ring 9 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.847	0.410	0.330	0.347	0.377	0.390	0.397
BACKWARD:	0.403	0.390	0.377	0.370	0.490	0.650	0.883
STANDARD DEVIATIONS:							
FORWARD:	0.017	0.016	0.022	0.019	0.021	0.022	0.034
BACKWARD:	0.009	0.008	0.009	0.008	0.014	0.008	0.021
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.870	0.430	0.390	0.380	0.500	0.660	0.910
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.390	0.380	0.300	0.320	0.350	0.360	0.350

The OVERALL MAXIMUM coefficient is: 0.910

The OVERALL MINIMUM coefficient is: 0.300

Table 36: Data for Ring 9 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.780	0.480	0.353	0.330	0.353	0.367	0.360
BACKWARD:	0.410	0.390	0.403	0.460	0.550	0.667	0.850
STANDARD DEVIATIONS:							
FORWARD:	0.050	0.128	0.049	0.022	0.005	0.005	0.000
BACKWARD:	0.016	0.024	0.031	0.036	0.014	0.024	0.028
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.820	0.580	0.430	0.490	0.560	0.700	0.890
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.390	0.300	0.290	0.310	0.350	0.360	0.360

The OVERALL MAXIMUM coefficient is: 0.890

The OVERALL MINIMUM coefficient is: 0.290

Table 37: Data for Ring 9 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.767	0.533	0.393	0.350	0.350	0.360	0.337
BACKWARD:	0.407	0.443	0.457	0.503	0.590	0.690	0.877
STANDARD DEVIATIONS:							
FORWARD:	0.009	0.012	0.012	0.014	0.014	0.028	0.019
BACKWARD:	0.012	0.009	0.009	0.017	0.016	0.016	0.026
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.780	0.550	0.470	0.520	0.610	0.710	0.900
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.390	0.430	0.380	0.340	0.330	0.320	0.310

The OVERALL MAXIMUM coefficient is: 0.900

The OVERALL MINIMUM coefficient is: 0.310

Table 38: Data for Ring 9 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.757	0.550	0.420	0.413	0.397	0.387	0.260
BACKWARD:	0.390	0.470	0.503	0.530	0.617	0.723	0.917
STANDARD DEVIATIONS:							
FORWARD:	0.009	0.008	0.014	0.012	0.009	0.005	0.024
BACKWARD:	0.029	0.014	0.009	0.016	0.029	0.024	0.042
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.770	0.560	0.510	0.550	0.650	0.740	0.960
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.360	0.460	0.400	0.400	0.390	0.380	0.230

The OVERALL MAXIMUM coefficient is: 0.960

The OVERALL MINIMUM coefficient is: 0.230

Table 39: Data for Ring 10 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.887	0.617	0.473	0.390	0.380	0.393	0.387
BACKWARD:	0.327	0.303	0.267	0.257	0.333	0.423	0.720
STANDARD DEVIATIONS:							
FORWARD:	0.037	0.033	0.066	0.000	0.008	0.012	0.026
BACKWARD:	0.012	0.039	0.041	0.048	0.068	0.172	0.008
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.930	0.640	0.520	0.390	0.400	0.550	0.730
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.310	0.250	0.220	0.190	0.240	0.180	0.350

The OVERALL MAXIMUM coefficient is: 0.930

The OVERALL MINIMUM coefficient is: 0.180

Table 40: Data for Ring 10 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.853	0.650	0.547	0.460	0.407	0.417	0.417
BACKWARD:	0.297	0.270	0.283	0.340	0.440	0.580	0.780
STANDARD DEVIATIONS:							
FORWARD:	0.040	0.036	0.031	0.054	0.017	0.012	0.005
BACKWARD:	0.005	0.000	0.017	0.008	0.008	0.016	0.014
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.910	0.700	0.590	0.520	0.450	0.600	0.800
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.290	0.270	0.260	0.330	0.390	0.400	0.410

The OVERALL MAXIMUM coefficient is: 0.910

The OVERALL MINIMUM coefficient is: 0.260

Table 41: Data for Ring 10 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.957	0.737	0.643	0.523	0.517	0.533	0.410
BACKWARD:	0.253	0.317	0.347	0.380	0.477	0.607	0.800
STANDARD DEVIATIONS:							
FORWARD:	0.009	0.021	0.029	0.009	0.026	0.021	0.086
BACKWARD:	0.012	0.012	0.005	0.000	0.005	0.012	0.022
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.970	0.760	0.680	0.530	0.540	0.620	0.830
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.240	0.300	0.340	0.380	0.470	0.510	0.290

The OVERALL MAXIMUM coefficient is: 0.970

The OVERALL MINIMUM coefficient is: 0.240

Table 42: Data for Ring 10 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.883	0.690	0.560	0.460	0.490	0.510	0.350
BACKWARD:	0.203	0.337	0.383	0.403	0.487	0.620	0.827
STANDARD DEVIATIONS:							
FORWARD:	0.031	0.014	0.022	0.028	0.024	0.022	0.000
BACKWARD:	0.021	0.009	0.009	0.012	0.005	0.008	0.017
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.910	0.710	0.580	0.480	0.520	0.630	0.850
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.180	0.330	0.370	0.390	0.460	0.490	0.350

The OVERALL MAXIMUM coefficient is: 0.910

The OVERALL MINIMUM coefficient is: 0.180

Table 43: Data for Ring 11 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.850	0.520	0.323	0.340	0.353	0.353	0.337
BACKWARD:	0.423	0.433	0.423	0.390	0.380	0.807	1.187
STANDARD DEVIATIONS:							
FORWARD:	0.022	0.042	0.019	0.022	0.021	0.021	0.025
BACKWARD:	0.009	0.005	0.005	0.000	0.000	0.039	0.025
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.870	0.550	0.430	0.390	0.380	0.860	1.220
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.410	0.430	0.310	0.320	0.330	0.330	0.310

The OVERALL MAXIMUM coefficient is: 1.220

The OVERALL MINIMUM coefficient is: 0.310

Table 44: Data for Ring 11 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.757	0.460	0.313	0.333	0.340	0.343	0.347
BACKWARD:	0.437	0.413	0.410	0.370	0.377	0.713	1.153
STANDARD DEVIATIONS:							
FORWARD:	0.033	0.106	0.012	0.005	0.000	0.005	0.009
BACKWARD:	0.012	0.005	0.016	0.016	0.012	0.130	0.012
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.800	0.540	0.430	0.390	0.390	0.810	1.170
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.420	0.310	0.300	0.330	0.340	0.340	0.340

The OVERALL MAXIMUM coefficient is: 1.170

The OVERALL MINIMUM coefficient is: 0.300

Table 45: Data for Ring 11 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.737	0.520	0.407	0.327	0.323	0.340	0.330
BACKWARD:	0.453	0.427	0.413	0.393	0.477	0.797	1.130
STANDARD DEVIATIONS:							
FORWARD:	0.012	0.014	0.005	0.024	0.017	0.014	0.014
BACKWARD:	0.005	0.017	0.012	0.012	0.061	0.025	0.028
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.750	0.530	0.430	0.410	0.550	0.830	1.150
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.450	0.410	0.400	0.310	0.300	0.320	0.320

The OVERALL MAXIMUM coefficient is: 1.150

The OVERALL MINIMUM coefficient is: 0.300

Table 46: Data for Ring 11 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.763	0.547	0.427	0.353	0.330	0.343	0.337
BACKWARD:	0.437	0.397	0.387	0.493	0.647	0.797	1.050
STANDARD DEVIATIONS:							
FORWARD:	0.024	0.021	0.021	0.041	0.022	0.017	0.019
BACKWARD:	0.009	0.021	0.009	0.019	0.021	0.041	0.100
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.780	0.570	0.450	0.520	0.670	0.850	1.140
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.430	0.370	0.380	0.300	0.300	0.320	0.310

The OVERALL MAXIMUM coefficient is: 1.140

The OVERALL MINIMUM coefficient is: 0.300

Table 47: Data for Ring 12 at 689 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.773	0.500	0.357	0.320	0.297	0.297	0.303
BACKWARD:	0.470	0.437	0.507	0.607	0.680	0.797	1.107
STANDARD DEVIATIONS:							
FORWARD:	0.042	0.051	0.104	0.037	0.040	0.038	0.019
BACKWARD:	0.014	0.005	0.068	0.021	0.037	0.021	0.040
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.830	0.550	0.560	0.630	0.720	0.820	1.140
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.450	0.430	0.210	0.270	0.240	0.270	0.290

The OVERALL MAXIMUM coefficient is: 1.140

The OVERALL MINIMUM coefficient is: 0.210

Table 48: Data for Ring 12 at 1378 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.743	0.473	0.357	0.293	0.247	0.243	0.273
BACKWARD:	0.397	0.420	0.490	0.547	0.630	0.760	1.033
STANDARD DEVIATIONS:							
FORWARD:	0.009	0.021	0.012	0.012	0.026	0.005	0.005
BACKWARD:	0.009	0.000	0.008	0.012	0.008	0.008	0.019
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.750	0.500	0.500	0.560	0.640	0.770	1.060
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.390	0.420	0.340	0.280	0.210	0.240	0.270

The OVERALL MAXIMUM coefficient is: 1.060

The OVERALL MINIMUM coefficient is: 0.210

Table 49: Data for Ring 12 at 2068 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.780	0.503	0.363	0.307	0.270	0.240	0.277
BACKWARD:	0.400	0.437	0.500	0.557	0.647	0.747	0.990
STANDARD DEVIATIONS:							
FORWARD:	0.029	0.009	0.012	0.009	0.008	0.008	0.012
BACKWARD:	0.008	0.012	0.008	0.021	0.009	0.012	0.008
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.810	0.510	0.510	0.580	0.660	0.760	1.000
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.390	0.420	0.350	0.300	0.260	0.230	0.260

The OVERALL MAXIMUM coefficient is: 1.000

The OVERALL MINIMUM coefficient is: 0.230

Table 50: Data for Ring 12 at 2757 kPa

SEAL POSITIONS:	0.750	0.500	0.250	0.000	0.250	0.500	0.750
FRICTION COEFFICIENT AVERAGES:							
FORWARD:	0.737	0.460	0.347	0.290	0.270	0.257	0.267
BACKWARD:	0.387	0.430	0.487	0.557	0.627	0.750	1.003
STANDARD DEVIATIONS:							
FORWARD:	0.017	0.008	0.009	0.000	0.000	0.012	0.021
BACKWARD:	0.025	0.008	0.005	0.009	0.005	0.000	0.005
MAXIMUM COEFF AT EACH ECCENTRICITY:							
	0.760	0.470	0.490	0.570	0.630	0.750	1.010
MINIMUM COEFF AT EACH ECCENTRICITY:							
	0.360	0.420	0.340	0.290	0.270	0.240	0.240

The OVERALL MAXIMUM coefficient is: 1.010

The OVERALL MINIMUM coefficient is: 0.240

APPENDIX C

Pressure Data for Individual Rings

Note: The pressures presented in the following tables are off by a factor of 2.26 due to incorrect voltage supplied to the probes which was dicovered after the creation of these tables. The correct pressure can be obtained by multiplying the given pressures by this factor.

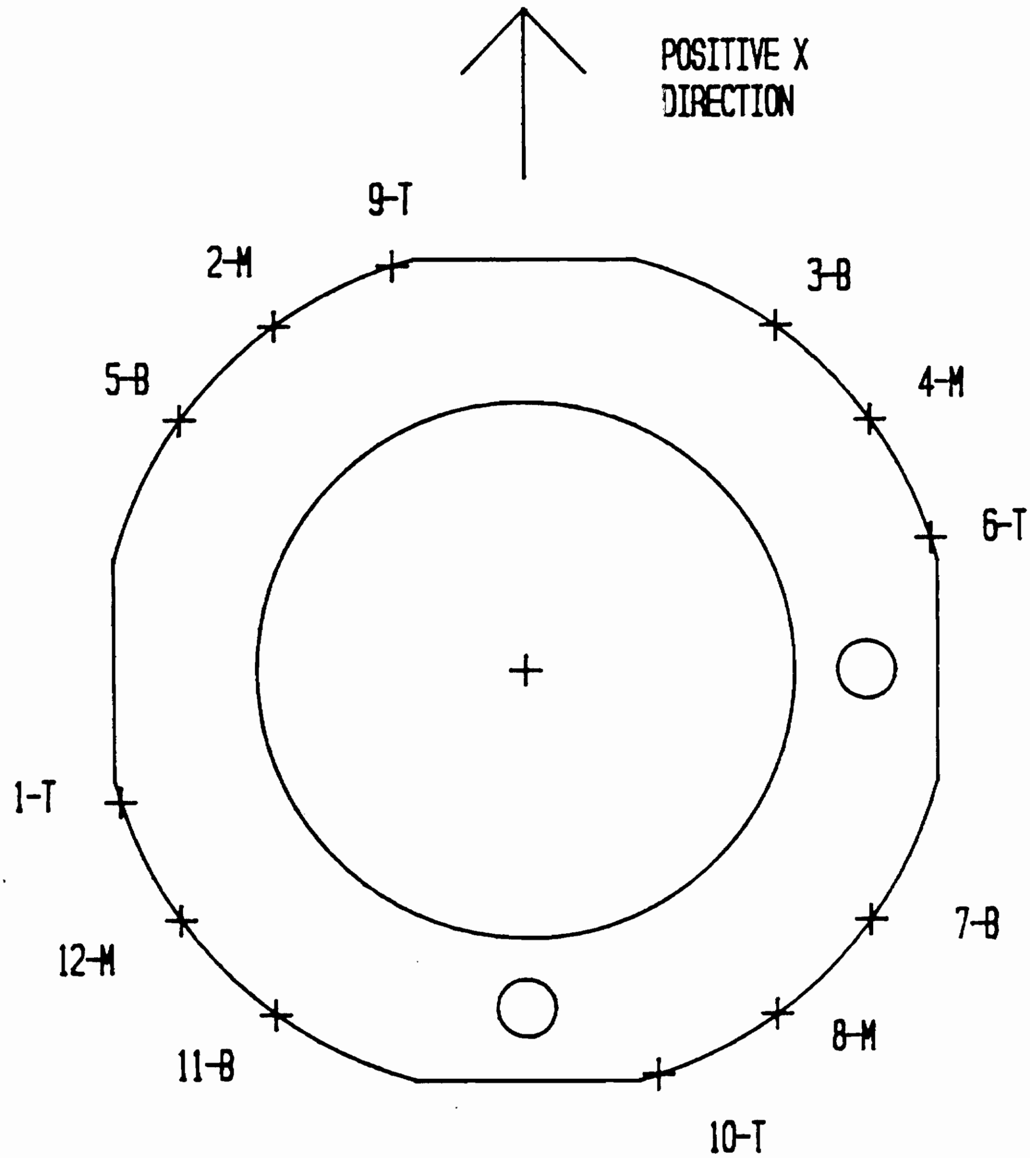

Figure 28: Diagram of Ring Indicating Pressure Probe Locations

Note: T = top ; M = middle ; B = bottom

Table 51:

Pressure Data (N/sq cm) for Ring #1 at 689 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	22.83	23.72	24.81	26.06	27.28	26.26	27.02
3	25.25	24.56	23.78	22.60	21.58	20.48	20.48
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	32.20	32.26	32.14	31.83	31.53	31.22	31.13
7	25.91	26.95	27.16	26.53	25.87	24.34	23.82
8	25.02	25.10	24.94	24.47	24.11	23.56	23.32
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	32.48	32.22	32.00	31.57	31.37	31.23	31.08
11	16.94	14.85	13.66	12.86	12.33	12.07	11.90
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 52:

Pressure Data (N/sq cm) for Ring #1 at 1378 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	37.44	38.89	39.98	40.87	41.80	42.75	44.30
3	44.39	42.31	39.94	37.33	34.92	33.90	34.56
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	58.59	58.74	58.50	57.89	57.04	56.43	56.34
7	41.96	43.81	42.94	41.47	39.70	38.34	37.36
8	45.31	45.58	44.99	44.13	43.06	42.35	41.84
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	58.21	57.81	57.49	57.01	56.10	55.64	55.22
11	30.13	26.29	23.44	21.68	20.49	19.66	19.29
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 53:

Pressure Data (N/sq cm) for Ring #1 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	48.79	48.99	49.06	49.38	50.28	51.20	52.52
3	57.16	52.26	47.45	44.67	43.49	44.39	48.67
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	83.34	82.52	81.28	80.55	80.64	81.13	82.04
7	49.38	46.94	44.22	42.34	40.99	40.32	40.11
8	65.68	64.22	62.13	60.36	59.06	58.23	57.44
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	86.24	85.07	83.45	81.68	80.69	80.20	79.29
11	42.83	34.14	30.26	28.67	27.58	26.95	26.62
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 54:

Pressure Data (N/sq cm) for Ring #1 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	68.12	68.75	71.12	73.17	75.81	78.05	83.20
3	86.12	78.70	73.39	67.27	63.03	61.40	62.62
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	112.02	111.77	111.14	109.50	107.95	107.07	106.88
7	72.43	73.37	71.87	69.61	67.55	66.09	65.54
8	84.12	84.27	83.17	81.48	79.98	78.99	78.76
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	108.98	108.69	107.81	106.53	104.90	103.99	103.68
11	59.87	50.75	42.63	38.55	36.36	35.34	34.41
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 55:

Pressure Data (N/sq cm) for Ring #2 at 689 kPa

	ECCENTRICITY RATIO						
probe	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	19.83	19.99	20.22	20.72	21.38	22.70	24.54
3	21.05	19.99	18.93	18.03	17.46	17.34	17.79
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	9.57	9.99	10.40	11.06	11.50	12.10	12.39
6	28.79	28.67	28.49	28.34	28.22	28.10	28.00
7	22.81	22.95	22.67	22.36	22.11	22.01	21.97
8	21.87	21.71	21.47	21.28	21.12	21.00	21.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	29.03	28.86	28.69	28.60	28.49	28.35	28.29
11	10.31	11.20	11.24	10.91	10.77	10.71	10.71
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 56:

Pressure Data (N/sq cm) for Ring #2 at 1378 kPa

	ECCENTRICITY RATIO						
probe	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	31.70	32.03	32.86	34.21	36.29	40.28	43.78
3	38.51	36.06	33.49	31.74	30.52	29.90	30.19
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	17.71	19.50	24.64	33.46	41.81	49.13	42.11
6	52.00	51.73	51.27	50.94	50.72	50.51	50.18
7	35.87	36.63	36.88	36.70	36.42	36.21	35.45
8	38.65	38.57	38.37	38.22	38.06	38.02	37.67
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	50.69	50.34	50.03	49.94	49.74	49.72	49.46
11	14.42	17.10	17.60	17.34	17.14	17.00	16.91
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 57:

Pressure Data (N/sq cm) for Ring #2 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	44.54	44.17	47.08	49.68	52.52	59.48	66.97
3	55.12	49.98	50.02	47.08	45.08	43.90	43.57
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	26.48	27.37	41.70	64.52	80.12	82.41	80.36
6	76.42	75.48	76.09	75.51	75.23	75.11	74.78
7	48.75	48.68	52.55	52.93	53.07	53.45	54.78
8	55.75	55.36	56.38	56.42	56.62	56.93	58.11
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	73.42	73.05	72.71	72.48	72.59	72.54	72.88
11	20.58	24.60	24.13	23.83	23.73	23.60	23.77
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 58:

Pressure Data (N/sq cm) for Ring #2 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	54.93	55.29	55.45	68.62	81.05	90.72	94.42
3	60.14	55.08	52.22	61.48	58.10	56.38	55.48
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	30.67	30.79	30.73	80.54	108.12	108.68	105.86
6	97.13	96.74	96.37	100.14	99.26	98.83	98.87
7	51.88	50.46	49.48	69.47	69.89	70.55	73.09
8	71.08	70.05	69.26	74.74	74.94	75.61	77.81
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	97.32	96.58	96.10	95.24	95.05	95.16	95.93
11	33.02	31.19	30.56	30.43	30.00	30.00	30.73
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 59:

Pressure Data (N/sq cm) for Ring #3 at 689 kPa

	ECCENTRICITY RATIO						
probe	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	21.94	22.47	22.53	22.30	21.71	20.95	20.12
3	23.05	23.13	22.68	21.74	20.36	18.89	17.58
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	10.55	11.20	11.86	12.69	13.22	12.13	10.67
6	26.67	27.00	27.00	26.79	26.42	26.00	25.54
7	23.26	24.45	24.79	24.62	23.99	23.19	22.22
8	23.36	23.99	23.99	23.56	22.85	21.91	20.92
9	24.99	25.40	25.45	25.17	24.76	24.25	23.61
10	27.69	28.03	28.03	27.69	27.29	26.87	26.41
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 60:

Pressure Data (N/sq cm) for Ring #3 at 1378 kPa

	ECCENTRICITY RATIO						
probe	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	36.68	37.41	37.84	39.29	38.47	36.78	34.77
3	41.08	40.84	40.31	40.47	38.27	35.29	32.27
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	20.36	21.31	22.47	25.94	28.47	25.41	21.58
6	48.05	48.38	48.54	48.75	50.24	49.24	47.90
7	39.49	41.65	42.52	42.97	43.63	41.86	39.38
8	41.88	42.87	43.14	43.06	43.65	41.72	39.20
9	46.24	46.73	46.88	47.01	48.42	47.24	45.57
10	49.09	49.52	49.55	49.57	50.91	49.92	48.49
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 61:

Pressure Data (N/sq cm) for Ring #3 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	51.53	52.95	53.84	53.67	52.45	49.78	47.01
3	58.99	58.54	57.89	55.85	52.87	48.14	44.51
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	31.06	33.08	35.78	40.36	42.05	37.18	31.80
6	69.25	70.22	70.92	70.92	70.04	68.19	66.52
7	57.25	60.59	62.09	62.26	61.01	57.84	54.60
8	60.44	62.13	62.76	62.37	60.71	57.21	54.02
9	67.18	68.38	68.97	69.05	68.15	66.08	64.31
10	70.51	71.57	71.91	71.74	70.77	68.55	66.73
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 62:

Pressure Data (N/sq cm) for Ring #3 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	69.28	70.00	70.86	70.83	69.21	65.78	61.39
3	80.53	77.68	76.21	73.56	69.48	63.60	57.77
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	43.24	45.59	49.18	56.20	55.66	49.13	41.64
6	93.98	94.19	94.73	95.01	94.31	92.37	89.27
7	76.40	80.16	81.73	81.90	80.23	76.30	71.21
8	82.34	83.45	83.92	83.29	81.28	76.98	71.71
9	91.58	92.25	92.76	92.86	92.27	89.91	86.63
10	95.05	95.76	95.90	95.59	94.82	92.28	88.75
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 63:

Pressure Data (N/sq cm) for Ring #4 at 689 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	23.16	23.22	23.06	22.56	21.94	21.31	20.78
3	23.34	22.81	21.91	20.56	19.17	18.07	17.58
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	13.58	14.09	14.74	14.59	13.79	13.08	12.60
6	28.98	28.95	28.82	28.58	28.34	28.06	27.79
7	22.98	23.33	23.33	22.67	21.83	21.10	20.61
8	23.99	23.95	23.68	23.05	22.30	21.51	20.92
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	30.54	30.34	30.17	29.94	29.60	29.29	28.98
11	14.22	13.99	13.82	13.42	12.99	12.60	12.33
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 64:

Pressure Data (N/sq cm) for Ring #4 at 1378 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	39.55	39.88	39.69	39.16	38.04	36.22	34.74
3	43.12	42.14	40.35	38.31	31.66	32.88	31.21
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	25.94	27.07	28.71	30.55	33.14	29.06	25.89
6	53.27	53.49	53.49	53.27	52.64	51.48	50.48
7	37.61	38.55	38.90	38.51	37.29	35.27	33.46
8	44.44	44.64	44.36	43.54	42.08	40.03	38.06
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	56.10	55.19	55.13	54.70	53.93	52.94	51.60
11	23.37	23.80	23.83	23.53	22.81	21.68	20.82
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 65:

Pressure Data (N/sq cm) for Ring #4 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	55.72	56.25	55.92	54.86	52.82	50.74	48.43
3	62.79	61.28	58.38	54.75	50.59	47.08	44.35
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	38.22	40.48	42.77	46.27	51.26	52.39	42.44
6	76.81	77.33	77.33	76.75	75.20	73.69	72.47
7	51.68	53.59	53.80	53.14	51.47	48.99	46.42
8	64.30	64.93	64.18	62.72	60.48	57.60	54.88
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	79.00	79.43	81.85	78.21	76.98	75.02	73.53
11	32.58	33.45	33.55	32.98	31.79	30.53	29.10
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 66:

Pressure Data (N/sq cm) for Ring #4 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	74.36	74.62	73.50	71.06	68.85	66.31	63.83
3	85.43	82.78	78.05	71.72	66.38	61.60	58.79
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	52.93	55.57	58.01	64.85	73.91	77.80	61.16
6	103.94	104.03	102.90	101.05	99.75	98.56	97.41
7	68.18	70.55	70.06	68.39	66.30	63.58	61.53
8	86.99	87.58	85.49	82.74	79.90	76.55	74.11
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	106.56	106.44	104.59	103.02	101.37	99.60	98.63
11	42.40	44.09	44.29	42.63	41.34	39.74	38.25
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 67:

Pressure Data (N/sq cm) for Ring #6 at 689 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	20.45	20.78	20.95	20.92	20.72	20.16	19.66
3	18.07	17.95	17.62	17.09	16.48	15.71	15.38
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	10.10	10.67	11.44	12.81	14.29	11.71	10.64
6	26.03	26.15	26.27	26.27	26.12	25.88	25.54
7	21.69	22.53	23.02	23.09	22.67	21.87	21.28
8	21.04	21.39	21.55	21.51	21.16	20.49	19.94
9	24.25	24.40	24.53	24.68	24.81	25.35	26.61
10	27.64	27.64	27.66	27.66	27.47	27.15	26.84
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 68:

Pressure Data (N/sq cm) for Ring #6 at 1378 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	34.41	34.90	35.23	35.36	34.80	34.01	32.82
3	32.56	32.03	31.25	30.27	28.88	27.78	26.89
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	19.08	19.94	21.25	24.28	28.26	28.71	21.58
6	46.74	47.08	47.41	47.56	46.96	46.50	45.86
7	36.28	37.61	38.51	38.79	38.06	36.91	35.31
8	38.57	39.12	39.56	39.75	38.69	37.70	36.40
9	44.75	45.14	45.65	46.08	46.06	47.37	51.06
10	48.75	48.89	49.23	49.26	48.46	47.89	47.29
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 69:

Pressure Data (N/sq cm) for Ring #6 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	49.42	50.01	50.64	50.61	49.85	48.59	47.31
3	47.49	46.06	45.04	43.57	41.82	40.02	39.25
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	28.89	30.61	33.20	37.48	42.94	42.47	32.96
6	68.86	69.37	69.86	70.01	69.56	68.52	67.85
7	52.16	54.08	55.12	55.26	54.36	52.62	51.19
8	57.40	58.23	58.63	58.55	57.60	55.79	54.29
9	66.69	67.49	68.00	68.56	69.20	71.18	75.82
10	71.26	71.77	71.88	71.88	71.43	70.06	69.15
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 70:

Pressure Data (N/sq cm) for Ring #6 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	64.66	65.38	65.75	65.75	64.99	63.37	62.81
3	61.89	59.97	58.01	56.01	54.02	52.02	51.49
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	39.11	41.16	45.02	52.69	56.61	52.96	44.99
6	91.12	91.73	92.52	92.61	91.97	90.91	90.30
7	68.39	70.10	71.39	71.39	70.41	69.23	69.57
8	76.55	77.10	77.85	77.38	76.08	74.42	73.64
9	88.99	89.58	90.94	91.63	92.32	96.58	101.60
10	94.08	94.22	95.13	94.90	93.79	92.68	60.37
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 71:

Pressure Data (N/sq cm) for Ring #8 at 689 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	21.34	21.84	22.20	22.47	22.50	22.50	22.47
3	18.44	18.52	18.48	18.36	18.11	18.03	18.20
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	11.71	12.39	13.37	14.68	15.19	15.19	14.65
6	26.70	27.09	27.37	27.55	27.55	27.52	27.55
7	23.05	24.24	25.07	25.39	25.45	25.45	25.39
8	21.83	22.42	22.93	23.13	23.17	23.13	23.09
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	28.49	28.69	29.00	29.09	29.09	28.95	28.89
11	14.78	14.59	14.72	14.88	15.02	15.81	15.51
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 72:

Pressure Data (N/sq cm) for Ring #8 at 1378 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	37.61	38.56	39.59	40.41	40.97	41.17	41.34
3	33.90	33.94	34.23	34.43	34.43	34.43	35.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	22.88	24.31	26.72	30.46	36.44	38.55	31.68
6	51.09	51.67	52.36	53.15	53.67	54.00	54.25
7	40.15	42.48	44.57	45.97	46.56	46.73	47.15
8	41.95	42.91	44.17	45.31	45.86	46.18	46.33
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	53.59	53.71	54.33	55.10	55.30	55.64	55.67
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 73:

Pressure Data (N/sq cm) for Ring #8 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	46.25	47.70	49.06	49.98	51.03	52.09	53.28
3	38.80	39.70	40.67	41.33	42.59	44.31	47.49
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	27.37	28.53	29.63	30.25	31.35	32.45	33.97
6	70.56	72.68	74.29	74.72	75.17	75.60	76.12
7	40.08	41.93	44.43	46.73	50.04	53.00	55.89
8	52.24	54.29	56.02	56.85	58.43	59.81	61.11
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	76.53	76.44	76.95	76.58	76.90	77.04	76.92
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

NO DATA FOR RING #8 AT 2757 kPa

Table 74:

Pressure Data (N/sq cm) for Ring #9 at 689 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	23.69	23.46	22.96	22.30	21.57	20.95	20.49
3	26.11	25.05	23.62	21.99	20.48	19.34	18.73
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	13.49	13.58	13.28	12.84	12.36	12.07	11.89
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	24.20	24.31	23.71	23.02	22.25	21.69	21.35
8	24.51	24.23	23.56	22.77	21.87	21.08	20.53
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	29.74	29.54	29.17	28.72	28.29	27.84	27.52
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 75:

Pressure Data (N/sq cm) for Ring #9 at 1378 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	40.38	40.44	40.18	39.26	37.94	36.26	34.74
3	48.59	47.32	45.53	42.92	39.82	36.64	34.56
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	26.27	26.95	28.41	29.78	30.22	28.23	27.28
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	39.87	41.37	41.96	41.19	39.77	37.89	36.53
8	45.27	45.23	44.91	43.85	42.16	40.11	38.30
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	53.71	53.45	53.22	52.62	51.71	50.63	49.49
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 76:

Pressure Data (N/sq cm) for Ring #9 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	57.83	51.23	57.10	55.39	53.81	51.43	50.67
3	71.97	69.76	66.66	62.18	58.38	53.44	50.43
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	39.85	41.40	43.06	46.90	51.35	51.15	45.71
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	56.34	58.88	59.09	57.91	56.48	54.25	55.12
8	66.78	66.90	65.76	63.83	61.93	58.86	58.03
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	77.92	77.87	76.95	75.81	74.82	72.94	72.45
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 77:

Pressure Data (N/sq cm) for Ring #9 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	74.59	74.39	73.60	71.69	69.31	66.67	64.36
3	95.06	91.10	86.98	81.19	75.43	70.05	64.79
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	52.78	54.56	56.32	61.93	70.08	68.77	59.14
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	71.73	74.94	74.97	74.00	72.01	69.78	69.47
8	87.54	87.27	86.05	84.04	80.96	77.62	75.01
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	101.54	101.20	100.49	99.63	97.75	95.39	93.54
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 78:

Pressure Data (N/sq cm) for Ring #10 at 689 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	20.22	20.95	21.57	21.84	21.81	21.51	21.01
3	16.97	17.34	17.67	17.71	17.50	17.26	17.09
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	10.16	10.88	11.65	12.21	12.07	11.65	11.09
6	6.35	6.29	6.29	6.32	6.32	6.44	6.50
7	23.68	25.11	26.08	26.50	26.40	25.94	25.32
8	20.84	21.75	22.46	22.73	22.69	22.26	21.67
9	24.14	24.63	24.99	25.17	25.20	25.12	25.73
10	27.09	27.49	27.78	27.89	27.86	27.58	27.27
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 79:

Pressure Data (N/sq cm) for Ring #10 at 1378 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	34.34	35.60	36.91	37.67	37.84	37.41	36.29
3	30.11	30.64	31.25	31.54	31.41	31.05	30.76
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	19.32	20.60	22.47	25.26	27.52	24.40	22.02
6	8.93	8.78	8.90	9.11	9.20	9.08	9.05
7	39.17	41.72	43.70	45.02	45.27	44.57	43.25
8	38.53	40.27	41.60	42.55	42.71	42.00	40.82
9	45.57	46.60	47.42	48.03	48.24	48.37	50.85
10	48.92	49.80	50.43	50.86	50.91	50.43	49.77
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 80:

Pressure Data (N/sq cm) for Ring #10 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	49.65	50.61	51.96	53.34	53.57	52.88	52.16
3	44.67	44.06	44.47	45.00	44.88	44.63	44.51
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	29.66	30.85	33.31	37.33	39.11	36.20	33.58
6	11.30	10.72	10.87	10.21	10.27	9.90	9.87
7	56.27	58.99	61.39	63.13	63.45	62.64	61.88
8	57.68	58.98	60.75	62.01	62.29	61.46	60.56
9	67.72	68.33	69.64	70.51	71.02	71.84	76.56
10	71.17	71.74	72.91	73.51	73.79	73.31	72.39
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 81:

Pressure Data (N/sq cm) for Ring #10 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	64.20	65.25	66.77	67.79	68.72	67.92	66.90
3	58.30	56.99	56.99	57.08	57.73	57.69	57.57
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	39.14	40.80	44.16	48.32	51.44	47.79	44.52
6	12.67	12.67	12.54	12.79	12.79	12.76	12.94
7	72.85	75.81	78.42	80.30	81.07	80.06	79.43
8	76.12	77.22	78.88	80.45	81.12	79.98	79.11
9	89.07	89.45	90.43	92.02	93.02	94.12	99.65
10	92.79	93.02	93.85	95.27	95.70	94.73	94.08
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 82:

Pressure Data (N/sq cm) for Ring #11 at 689 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	24.54	25.27	25.53	25.17	24.64	24.21	23.95
3	25.42	26.72	26.97	25.99	24.64	23.50	22.60
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	28.95	29.55	29.74	29.40	28.92	28.43	28.16
7	26.40	27.47	27.61	26.74	25.66	24.69	23.96
8	25.29	26.08	26.20	25.61	24.86	24.11	23.68
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	30.17	30.83	30.97	30.68	30.20	29.66	29.37
11	20.22	21.28	21.45	20.55	19.42	18.46	17.73
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 83:

Pressure Data (N/sq cm) for Ring #11 at 1378 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	40.02	41.57	42.29	41.37	40.31	39.26	38.43
3	44.31	47.16	48.26	46.14	43.41	40.72	38.51
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	50.91	52.15	52.52	51.73	50.72	49.72	48.81
7	42.10	44.43	45.20	43.35	40.99	38.79	37.05
8	44.60	46.21	46.65	45.43	43.77	42.24	40.97
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	52.25	53.51	53.76	53.08	52.02	51.00	50.06
11	35.57	37.89	38.75	36.79	34.47	32.22	30.36
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 84:

Pressure Data (N/sq cm) for Ring #11 at 2068 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	55.55	57.93	59.58	60.44	59.91	57.93	56.41
3	63.36	67.60	70.17	71.07	69.15	63.81	59.16
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	72.56	74.63	75.93	76.21	75.23	73.05	71.29
7	57.94	61.39	63.24	63.69	62.16	57.67	53.94
8	63.75	66.35	67.77	67.92	66.78	63.51	60.79
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	73.82	76.10	77.27	77.41	76.70	74.36	72.51
11	51.38	54.76	56.72	57.18	55.26	50.82	46.87
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

Table 85:

Pressure Data (N/sq cm) for Ring #11 at 2757 kPa

probe	ECCENTRICITY RATIO						
	0.75	0.50	0.25	0.00	0.25	0.50	0.75
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	75.02	77.69	79.21	80.56	80.66	78.51	76.24
3	87.51	92.85	95.30	96.28	93.87	86.08	79.43
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	99.23	101.30	102.02	102.72	102.18	99.41	96.31
7	77.93	82.42	83.89	84.27	82.15	75.74	70.51
8	87.19	90.38	91.17	91.56	90.38	85.77	81.71
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	100.34	102.94	103.39	103.91	103.68	100.52	97.35
11	71.30	75.44	77.20	77.53	75.05	68.45	62.91
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Zero pressure indicates no data available for probe

APPENDIX D

Instrumentation Calibrations

Table 86: Pressure Gauge Calibration

PRESSURE (psi)	GAUGE READS (psi)
50	45
100	98
150	150
200	200
250	251
300	301
350	352
400	404
450	455
475	481

Table 87: Pressure Probe Calibrations

Probe No.	1	2	3	4	5	6
Sensitivity (mV/psi)	0.214	0.209	0.169	0.186	0.232	0.227

Probe No.	7	8	9	10	11	12
Sensitivity (mV/psi)	0.198	0.175	0.269	0.242	0.208	0.197

Zero Pressure Output: < ± 5% of Full Scale

Table 88: Load Cell Calibration (+X Direction)

Serial No. 191003

LOAD (pounds)	READING (lb)	LOAD (pounds)	READING (lb)
10	10	450	428
20	20	500	474
30	30	550	520
40	40	600	566
50	50	650	612
100	98	700	658
150	146	750	704
200	194	800	750
250	241	850	796
300	289	900	842
350	335	950	889
400	381	993	928

Table 89: Load Cell Calibration (-X Direction)

Serial No. 191010

LOAD (pounds)	READING (lb)	LOAD (pounds)	READING (lb)
10	11	450	439
20	20	500	487
30	30	550	536
40	40	600	584
50	50	650	633
100	99	700	681
150	147	750	731
200	196	800	780
250	244	850	828
300	293	900	876
350	341	950	925
400	390	996	970

APPENDIX E

Sample Calculation of Reynolds' Number

Sample Calculation of Reynolds' Numbers for Test Rig:

Dimensions:

Shaft Diameter = 6.995 cm

Bore Diameter = 7.005 cm

Axial Length = 3.015 cm

Radial Clearance (c) = 0.005 cm

Absolute Viscosity (μ) = 1.548 x 10^{-6} N-s/cm^2

Kinematic Viscosity (ν) = 0.179 cm^2/s

$$Q = VA \quad ; \quad Q = \frac{\Delta P\, D_S\, c^3}{12\mu L} \quad ; \quad A = \frac{\pi}{4}(D_{bore}^2 - D_S)$$

Thus,

$$V = \frac{\Delta P D_S c^3}{3\mu L(D_{bore}^2 - D_S^2)} = \frac{(689\, kPa)(6.995\, cm)(0.005\, cm)^3}{3(1.548x10^{-}6\, \frac{N\text{-}s}{cm^2})(3.015\, cm)(7.005^2\, cm^2 - 6.995^2\, cm^2)}$$

$$V = 30.7\ \frac{cm}{s}$$

$$Re_z = \frac{2Vc}{\nu} = \frac{2(30.7\,\frac{cm}{s})(0.005\,cm)}{0.179\,\frac{cm^2}{s}} = 1.72$$

For N = 12,000 RPM,

$$\omega = 12{,}000 \times \frac{\pi}{30} = 1257\,\frac{rad}{s}$$

$$Re_\theta = \frac{Rc\omega}{\nu} = \frac{(\frac{7.005\,cm}{2})(0.005\,cm)(1257\,\frac{rad}{s})}{0.179\,\frac{cm^2}{s}} = 123$$

VITA

The author was born on January 9, 1967 in Alexandria, Virginia. He grew up in Woodbridge, Virginia and graduated from Potomac High School in 1985. That same year, the author began his studies at Virginia Tech, where he studied Mechanical Engineering. The author was a co-op student with IBM Corporation and graduated with his Bachelor of Science in Mechanical Engineering in 1990. He immediately began work on his Master's Degree as a research assistant under Dr. R. Gordon Kirk. He has currently accepted a position with Lord Corporation in Erie, Pennsylvania.