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To the Graduate Council:

I am submitting herewith a thesis written by George Mitchell Kiber entitled "An Experimental Investigation of a Radial Face Seal." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

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AN EXPERIMENTAL INVESTIGATION OF A RADIAL FACE SEAL

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee

George Mitchell Kiber

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ABSTRACT

An experimental method has been developed which will allow a complete description of the interface fluid film of a radial face seal. The equipment necessary for the monitoring of the vertical load, torque, temperature, supply pressure, interface pressure, interface clearance, and rotational speed has been integrated into a workable facility. The procedures needed for the operation of this equipment have been derived and are presented in this work.

The initial check-out of the facility has been completed for a particular design of a radial face seal. Tests have been conducted using Gulfspin 38 oil over a supply pressure range of 16.5 - 87 psig (1.14×10^5 - 6.0×10^5 N/m^2), an interface clearance range of 2925 - 4146 μin. (74 - 105 μ), and at rotational speeds of 490 - 1030 rpm.

The experimental results have been compared with the values predicted by a numerical analysis program. The numerical analysis was based on variable fluid properties. The experimental vertical loads were consistently below the predicted values with the differences decreasing at higher supply pressures. The interface pressures measured in the experiments reveal a trend toward pressure generation within the seal at higher supply pressures, lower interface clearances, and increased rotational speed. The experimentally determined temperatures were found to compare favorably with the predicted results. The torque values, obtained experimentally, did not compare favorably with the predicted results.

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CHAPTER I

PREVIOUS RADIAL FACE SEAL INVESTIGATIONS

The radial face seal has been the subject of many experimental investigations in recent years. All of these studies have been limited in the sense that suitable means of measuring the numerous parameters such as interface pressure, interface clearance, vertical load, torque, and temperature which were needed to completely describe the situation were not available. There has been a great deal of work in establishing that hydrodynamic lubrication conditions usually prevail in the sealing region.

The first extensive study of the radial face seal was made by Denny (1) in 1960. His research was concerned primarily with the film thickness and pressure generation measurements in the interface region of the seal. The annular rotating face was made of mild steel and had an outer diameter of 3.5 in. (8.9 cm) and an inner diameter of 2.24 in. (5.7 cm). Film thickness was measured by a capacitance method in which two segments of the stationary ring were insulated from the rest of the ring. Each segment then served as one plate of the condenser. The other plate of the condenser was formed by the rest of the stationary ring and the rotating ring after these portions were grounded. The output signal was calibrated by placing known capacitances in the circuit and converting the magnitude of the capacitance into a voltage signal. The face separation was then calculated from the dimensions of the

segments by using the proper dielectric constant for the fluid which was used in the tests.

Denny made an attempt to measure the pressure distribution in the interface region. An alternative stationary face was fitted with pressure tappings and thermocouples. The pressure taps were approximately 0.020 in. (0.5 mm) in diameter and were connected to mercury manometers. The thermocouples were mounted at different radii and lapped flush with the carbon ring surface. The pressure readings obtained varied over a wide range and many types of pressure distributions were recorded. Pressures in substantial excess of the applied pressures were frequently recorded. Because of the nonrepeatability of the readings, the measurements of the local pressures were abandoned and only the average pressure readings were recorded.

A load was applied to the seal faces using a lever and weight arrangement. In this way, the seal load was controlled as were the sealed pressure and the rotating speed. The measured quantities included leakage, friction, and film thickness (the friction was measured by a torque arm mounted on the stationary piece). Since an alternative stationary piece without capacitance segments was used to measure the temperatures, no simultaneous readings of film clearance and temperatures were obtained.

A variety of fluids were used in the investigation ranging from Castrol D 140 oil with a viscosity of 1800 cp (1.8 N sec/m^2) at 20°C to Acetone with a viscosity of 0.33 cp (3.3 x 10^{-4} N sec/m^2) at 20°C and sealed pressures of 0 - 25 psig (1.72 N/m^2). The measured face separation ranged from 20 μin.(0.5 μ) to 100 μin.(2.54 μ) while the

seal rotational speeds were from 550 to 3000 rpm. The investigation confirmed the existence of a fluid film in the interface region and that pressure was generated by the rotation of the seals but did not define the exact mechanism which produced this generation. The film thickness measurements revealed a periodic variation in amplitude at twice the rotational frequency of the shaft. These variations were 180° out of phase. The clearance transducers were 180° apart also.

Summers-Smith (2) investigations of commercial face seals were aimed primarily at conformation of the existence of a fluid film between the two surfaces of the seals. Friction and wear measurements were the main interest in this study. The test rig was designed in such a way that the rotating face (which was attached to a vertical spindle) supported the stationary face. The stationary piece closed the annular opening between a cylindrical vessel and the rotating piece. This vessel and stationary piece combination were free to move vertically but were prevented from rotating by a calibrated spring which supplied friction force data. A lever system at the base of the vessel assembly allowed the contact force between the two faces to be reduced. It was thus possible to study the effect of load independently of the pressure in the sealed liquid. Most of the tests in this study were for inward flow, using the vessel as a pressurized reservoir for the sealing liquid. An attempt was made to measure the temperature at the interface by placing a thermocouple in a drilled hole in the stationary face. However, in these tests no attempt was made to measure the precise conditions at the sealing faces.

The fluid used the most in these tests was water at a maximum pressure of 50 psig (3.44 N/m^2). The results were presented in the form

of a duty parameter which was a function of the load on the seal face, the face width, the fluid's viscosity, and the sliding speed of the faces. The data reveal a definite minimum value of this parameter which corresponds to hydrodynamic lubrication.

An explanation of the existence of an interface film was also the primary objective of the work done by Ishiwata and Hirabayshi (3). The apparatus was similar to that used by Summers-Smith in that the torque measurements were recorded from a calibrated spring device on the oil chamber. The temperature of the face surface was measured by a thermocouple embedded in a 0.078 in. (2 mm) diameter hole in this surface. The tests were run on relatively small seals. The maximum outside diameter of any seal used in this investigation was 1.42 in. (3.6 cm). The load on the seal was varied by using a system of pulleys and weights. The waviness and roughness of the test surfaces were measured by an interference-microscope and an optional flat using sodium light. The surfaces were checked many times in these experiments in an effort to evaluate the performance of the seal versus the seal face characteristics. The lubricant used in most of the tests was MS 30 motor oil with a viscosity of 328 cp (0.33 N sec/m^2).

Batch and Iny (4) were the first to measure the dynamic pressures within the interface film. The method required fitting 0.157 in. (4 mm) diameter piezo-electric type dynamic pressure probes into the 0.393 in. (10 mm) wide stationary seal (stainless steel) behind a thin diaphragm machined in the seal. The probe output was directly proportional to the applied pressure and the probes were statically calibrated. However, the steady component of the pressure in the

interface region was not readable from these probes. The gap between the seal faces was measured by using a capacitance method similar to that used by Denny. Three insulated probes were inserted in the stationary face 30° ahead of the pressure probes. The stationary face was then lapped so that the probes were flush with the seal face. After being grounded, the rotating face then served as the common second plate of the condenser. The electronics of the system were such that by setting the gap between the faces and observing the capacitance required to retune the system, a direct calibration of capacitance as a function of separation was obtained. The face temperature was evaluated by extrapolation from the temperature data given by four thermocouples installed on the stationary seal at 0.015 in. (0.38 mm) intervals in the axial direction. The fluid temperature was assumed to be equal to the face temperature and the fluid temperature was also assumed constant across the gap. No measurement of the frictional torque was made due to the construction of the test rig.

Batch and Iny found that both the film pressure and the film clearance had fluctuating components. The magnitudes of these variations were 10-240 psig (6.9×10^4 - 1.65×10^6 N/m^2) and 10 μin. (0.25 μ). The variations had frequencies at the shaft rotational frequency and at twice this value. The reasons for this were presented as being due to a steady component of film thickness which varied cyclically at the shaft rotational frequency and a component whose amplitude was dependent on speed and load.

The lubrication mechanism and the kind of lubrication taking place between the faces of the seal were the principle interest of Pape (5). His experimental apparatus consisted of a vertical spindle which was driven by a variable speed motor. The spindle was placed through a housing which contained the stationary face. The rotating face was then attached to the end of the spindle. Load was applied to the faces by varying the pressure in a pneumatic cylinder which was attached to the housing assembly. A strain gage torque arm was used to measure the torque. Axial holes were drilled into the stationary piece near the face for thermocouples. The temperature of the fluid in the film was found from the measured values by extrapolation curves which were obtained earlier in the procedure.

Again a capacitance method was employed to measure the clearances between the two faces of the seal. The probes were equally spaced along the circumference and were located just outside the face sealing area. Changes in the clearance produced changes in the probe's capacitance which in turn affected the electronic circuit of the system. This method, however, was found to be susceptible to drift produced by temperature and even the drift of the capacitance meter itself. Consequently, no accurate measurements of the film clearance were obtained.

The only pressure data were in the form of a physical parameter which Pape called the load ratio. This was the ratio of the average face pressure and the sealing fluid pressure. This load ratio was varied by adjusting the pneumatic cylinder pressure which loaded the stationary face independent of the supply pressure.

Pape observed film thickness fluctuations at twice the shaft speed frequency in all of the tests. Although two fluctuations were observed for each shaft revolution, the signals reproduced only once per revolution. The macroroughness or waviness of the rotating seal was presented as the only feasible source of these types of signals. The data were obtained for various oils. The seal geometry was defined by the case-hardened steel rotating face which had an outer diameter of 3.14 in. (8.0 cm) and an inner diameter of 1.57 in. (4.0 cm).

The mechanism by which a film of lubricating fluid forms between the faces of a face seal was the objective of Stanghan-Batch (6). The rotating face was mounted on a shaft which was mounted in precision tapered roller bearings. The stationary face was flexibly mounted on a pneumatic piston. The piston was used to apply the load to the seal. The stationary face contained pressure, clearance, and temperature transducers. The pressure measurements were obtained by mounting quartz crystal piezo-electric transducers behind diaphragms which had been machined in the stationary piece. These diaphragms were approximately 0.216 in. (5.5 mm) in diameter and between 0.015 in. (0.4 mm) and 0.023 in. (0.6 mm) thick. A capacitance method was used for the clearance measurements. Thermocouples were embedded 0.010 in. (0.25 mm) from the seal face to approximate the fluid temperature. This investigation also provided for surface profile measurements of the rotating face. The majority of tests in the investigation were conducted using two oils with viscosities of 4 cS (4×10^{-6} m^2/sec) and 30 cS (3×10^{-5} m^2/sec) at 40°C. The carbon rotating face had an

outer diameter of 2.75 in. (7 cm) and an inner diameter of 1.96 in. (5 cm).

After an initial run-in period during which the film thickness and pressure traces were changing, both measurements developed a frequency twice that of the shaft rotational frequency. The amplitude of the pressure fluctuations was observed to increase in proportion to the applied load. The pressure increased as the film thickness decreased and vice-versa. The film thickness fluctuations were concluded to be due to the waviness of the rotating seal face.

In all the previous work the seals have been artifically loaded. The results of these investigations appear to be satisfactory; however, no complete experimental investigation has been undertaken which satisfies the needs of the various aspects of face seal applications. The radial face seal is the subject of experimental work now being conducted by the Mechanical and Aerospace Engineering Department of The University of Tennessee. It is the purpose of this thesis to investigate the feasibility of measuring the interface pressure, interface clearance, vertical load, torque, and temperature of a radial face seal.

CHAPTER II

EXPERIMENTAL TEST RIG AND INSTRUMENTATION DESCRIPTION

The overall purpose of this thesis is the integration of the test rig and instrumentation to obtain a complete description of the behavior of radial face seals over a range of operating conditions. The seal mounting, drive mechanism, and oil supply are considered the test rig while the signal conditioning devices, amplifiers, and oscillograph make up the instrumentation console. The entire test apparatus is located in the dynamic sealing laboratory of the Mechanical and Aerospace Engineering Department of The University of Tennessee.

Test Seal

The stationary seal face used in these tests is the result of previous work in this area. The stationary seal, Figure 1, was constructed by the method outlined by Ghorashi (7). The test seal is formed by cementing a stainless steel foil piece 0.005 in. (0.127 mm) thick over a stainless steel disk. Photographs of the actual seal are also given in the work by Ghorashi. The Roman numerals refer to clearance probe holes while the Arabic numerals refer to pressure probe stations. After the final lapping process the seal was checked with an optical flat and was found to be slightly convex, being high by roughly 17 μin.(0.432 μ) in the center. The details concerning the pressure probes and clearance measuring probes will be discussed

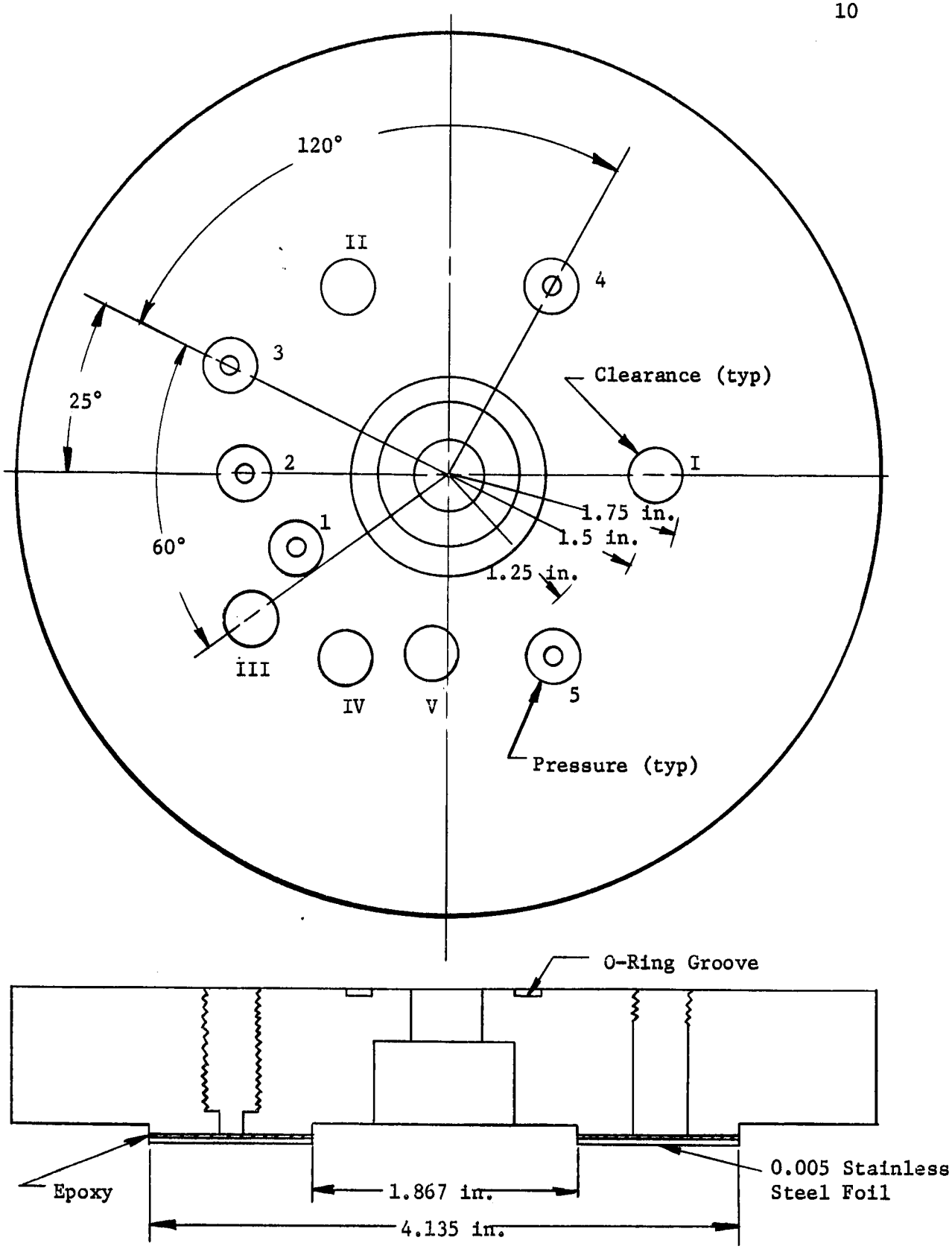


Figure 1. Stationary Seal.

later in this chapter. The basic consideration in the fabrication of the stationary seal has been to attempt to measure the parameters under investigation without disturbing the flow through the interface region.

The rotating seal face was mounted to the air spindle on the test rig. The dimensions of the rotating piece shown in Figure 2 define the seal geometry of this investigation. This piece was made of stainless steel. The face was lapped and checked with an optical flat. The face was found to be convex in the center by approximately 44 μin.(1.1 μ). A high spot was also noticed in the annular face.

Test Rig

The test rig, Figure 3, has been designed so as to permit a wide range of face seal operating conditions. The basic design of this rig has been presented in technical reports ME 71-T57-13 and ME 71-T57-14 of the Mechanical and Aerospace Engineering Department of The University of Tennessee (8 and 9). The stationary seal is mounted on a vertical support column centered in three vertical adjustment columns. These three columns provide the range of seal tilt and determine the spacing between the rotating and stationary seal faces. The stationary support column also provides for horizontal misalignment of the two seal faces. The stationary seal face is attached to the center support column by an instrumented section, Figure 4. This section is fitted with two complete strain gage bridge circuits; one for vertical load measurements and one for torque load measurements. The vertical bridge consists of foil gages and the torque bridge consists of piezo-electric

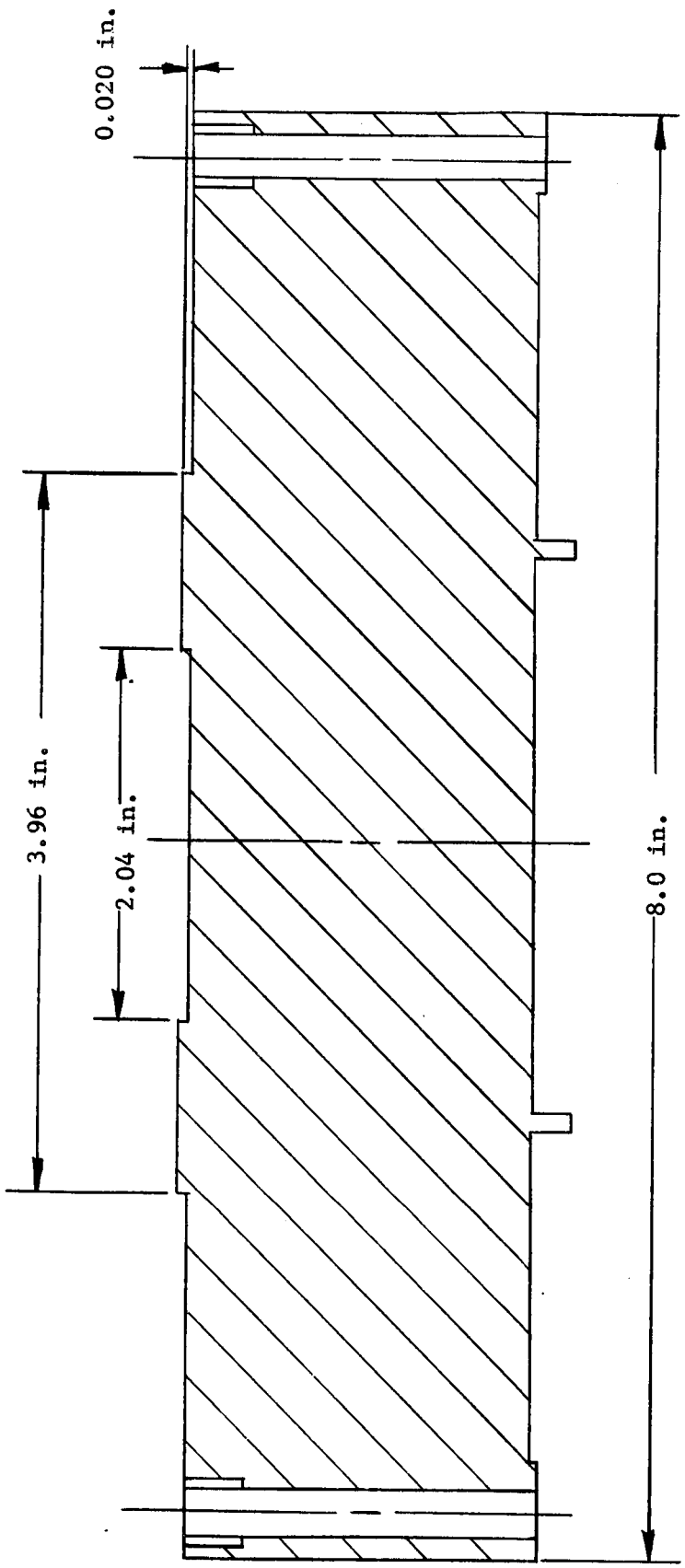


Figure 2. Rotating Seal.

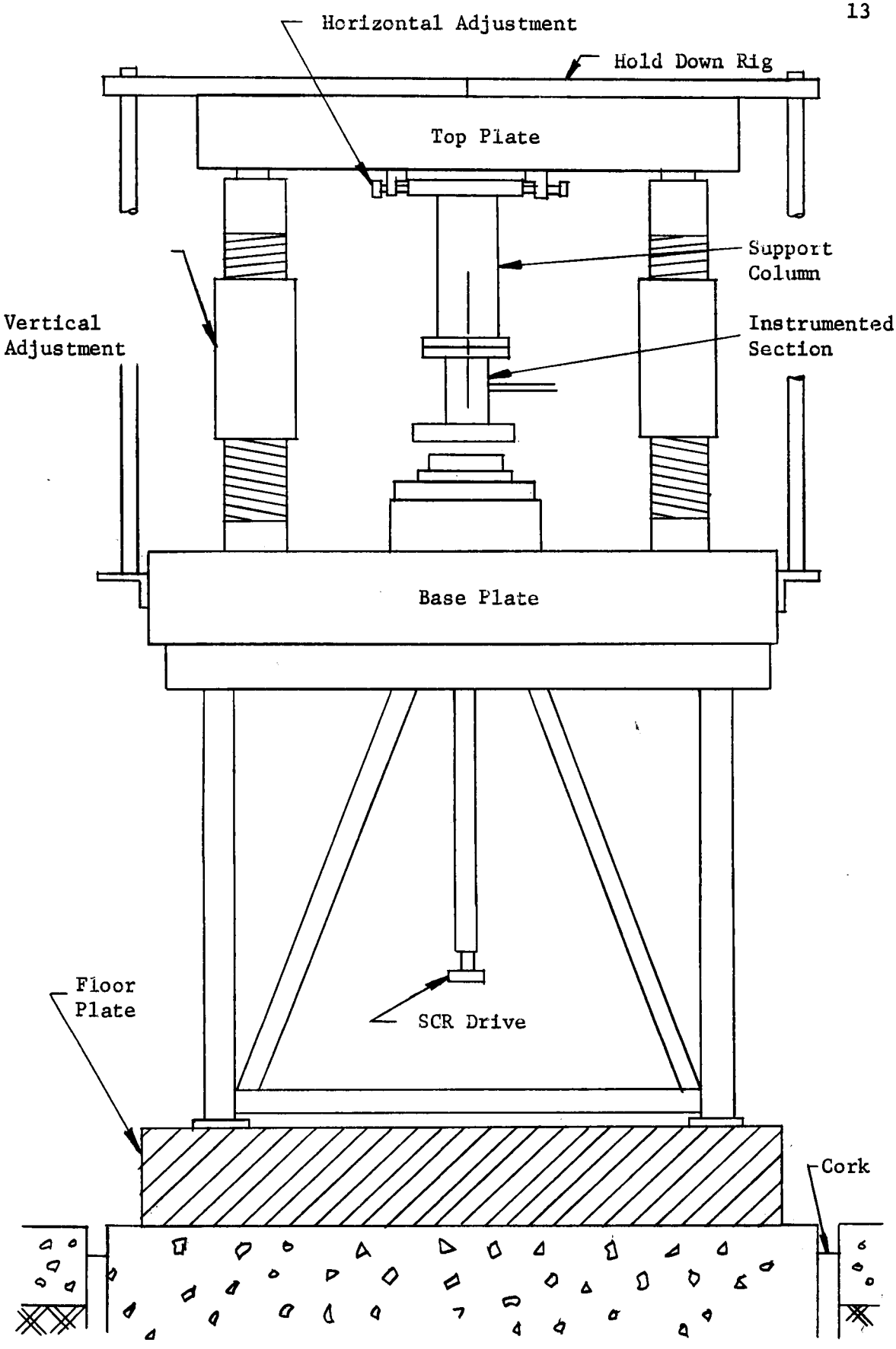


Figure 3. Test Rig.

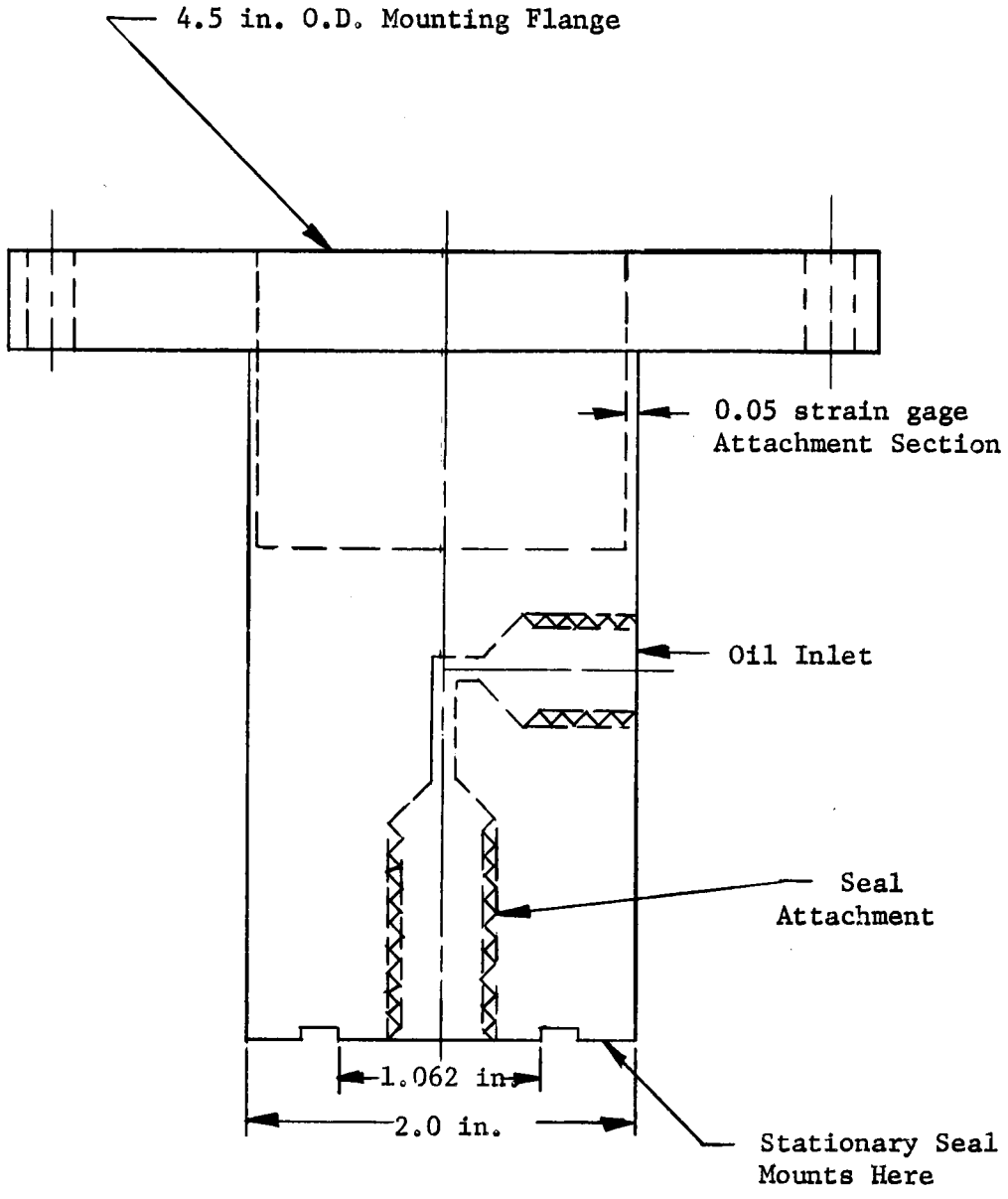


Figure 4. Load Measuring Instrumented Section.

gages. The manner by which these bridges are installed and pertinent information is shown on Figure 5.

The rotating seal face is mounted to an air spindle which provides the necessary flat rotating surface. This spindle is driven by an SCR Drive System which provides the variable rpm capacity needed for full face seal operating condition investigations. The seal pressurization system consists of a pressurized stainless steel oil reservoir. This reservoir contains approximately one gallon of fluid. The fluid used in all the tests conducted in this investigation was Gulfspin 38 with a viscosity of 0.3294×10^{-5} reyn (0.0226 N sec/m^2) at 25°C. The oil is filtered and the inlet supply pressure is monitored just as the fluid enters the instrumented section. The hold-down apparatus is to prevent any vertical movement of the stationary piece due to loads which might be in excess of the weight of the top plate.

Instrumentation

The instrumentation consists of the various signal conditioning devices, amplifiers, and recording equipment. The transducer signals for the interface pressure measurements and for the clearance between the seal faces are conditioned externally and serve as voltage inputs to the recording system.

Interface Pressure

The method of measuring the interface pressure is the result of previous work by Ghorashi (7). The pressure measurement is based on the change in capacitance between the diaphragm and a stationary probe mounted in the hole. The pressure causes the diaphragm to deflect

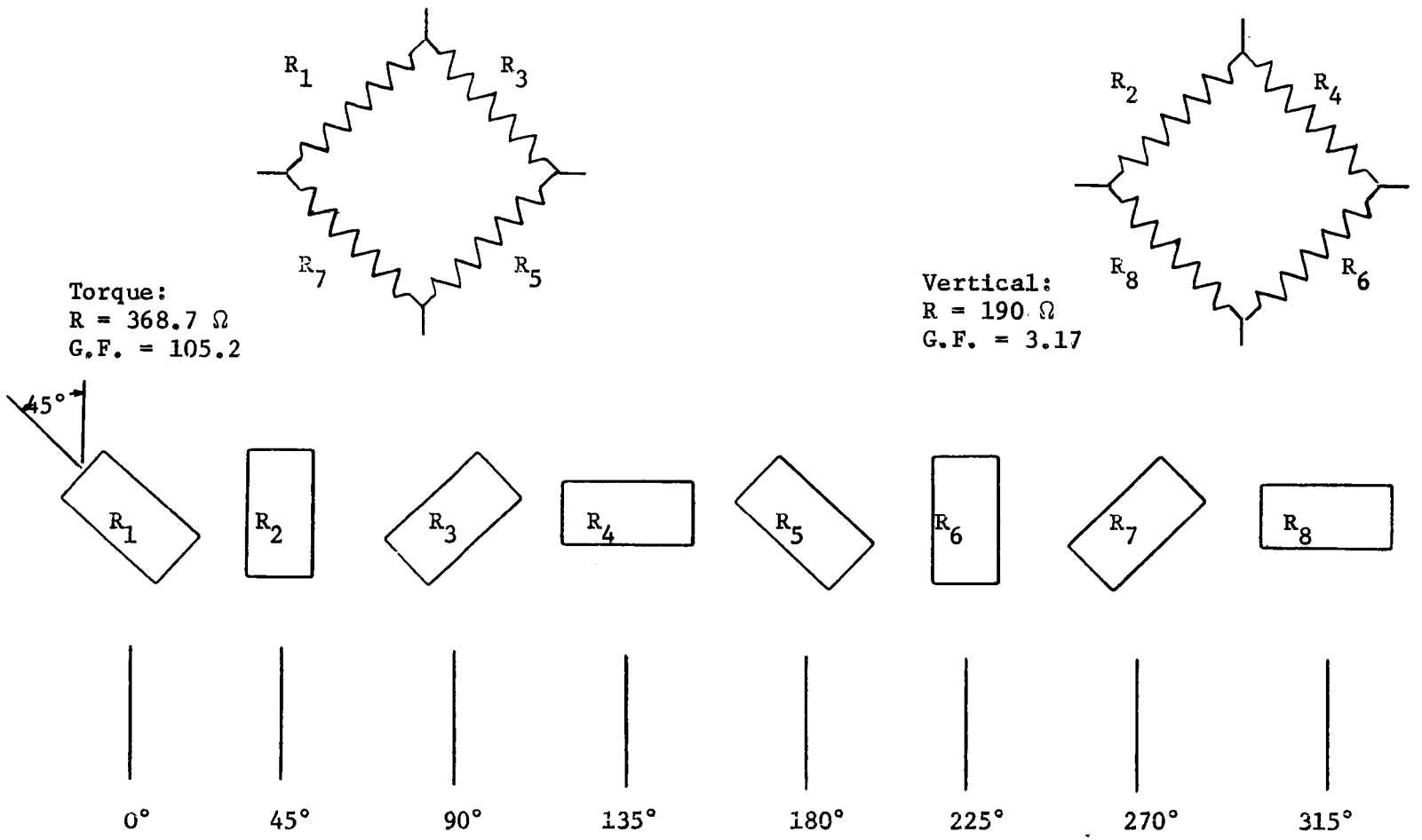


Figure 5. Vertical Load and Torque Bridge Circuits.

toward the stationary probe which causes the change in capacitance. This change was measured by Lion-type Twin-T bridge (10). The bridge is a C-line proximity probe. The transducer circuit was modified slightly so that a flexible connection would exist between the proximity sensor pickup and the associated electronics in the transducer itself. The driver unit for the probe was a C-line driver and readout type 202. This driver supplied the signal output voltage which was fed into the instrumentation console.

Interface Clearance

The clearance measurements in the interface region of the seal is the result of work done by Duncan (11). The system utilizes a nonpenetrating inductance probe mounted in the stationary seal and cemented to the diaphragm. The probe and its associated electronic equipment provide a voltage output which becomes the direct input of the galvanometers in the oscillograph. The probe consists of four coils; two drive coils and two pickup coils centered in the drive coils. The drive coils produce a magnetic field which induces eddy currents in the seal face. The eddy currents set up a magnetic field which opposes the magnetic field of the drive coil. The magnitude of the eddy current field is a function of the distance between the seal faces. The pickup coils sense an induced voltage that is proportional to the total magnetic field which is provided by a vector difference between the drive coil field and the eddy current field. The pickup coils are wound in opposite directions in order that the voltage which appears at the probe output is the difference between the voltage induced in each pickup coil. This produces a differential output signal from the

probe. The electronic system converts this amplitude modulated voltage sine wave from the probe into a DC voltage level which is a linear function of the clearance between the seal faces. Each probe has a null network which sets zero output at any distance.

Instrumentation Console

The instrumentation console, Figure 6, contains the strain gage conditioning units, amplifiers, and oscillograph which allow the recording of the different parameters under investigation. A typical path of a signal from the transducer to galvanometer is illustrated by Figure 7. A brief summary of unit name, abbreviation, purpose, etc. is located in Table I.

All strain gage transducers supply the input to the Accudata 105 units. These units provide gage excitation, balance, and calibration. One unit provides 12 volt DC power for every other strain gage unit located in its particular rack. This power is provided by the appropriate pins (12+, 24-) of the connector located at the rear of the units. The A-105 units also have a provision for internal bridge completion if a full external bridge is not contained in the transducer. This provision allows for one to three arms of the strain gage bridge to be completed inside the unit.

The bridge excitation voltage is set by the excitation control located on the front of the A-105 units. The excitation is variable from 3.5 to 11.5 volts for 350 ohm gages and from 1.5 to 5.0 volts for 120 ohm gages. The output jacks below this control allow the exact excitation voltage to be determined. The balance control provides a balance condition at no load. Calibration (plus and minus) is provided

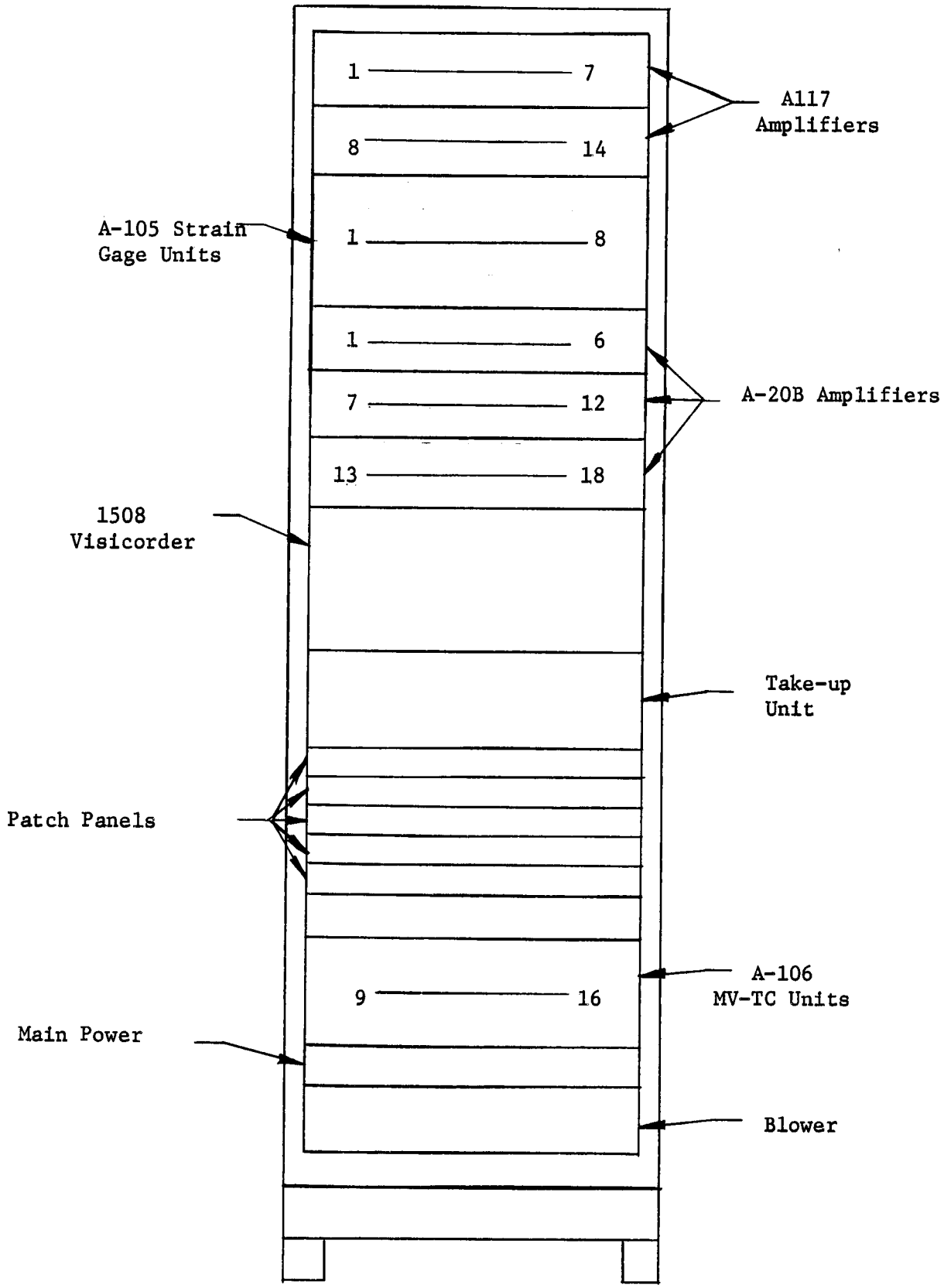


Figure 6. Instrumentation Console.

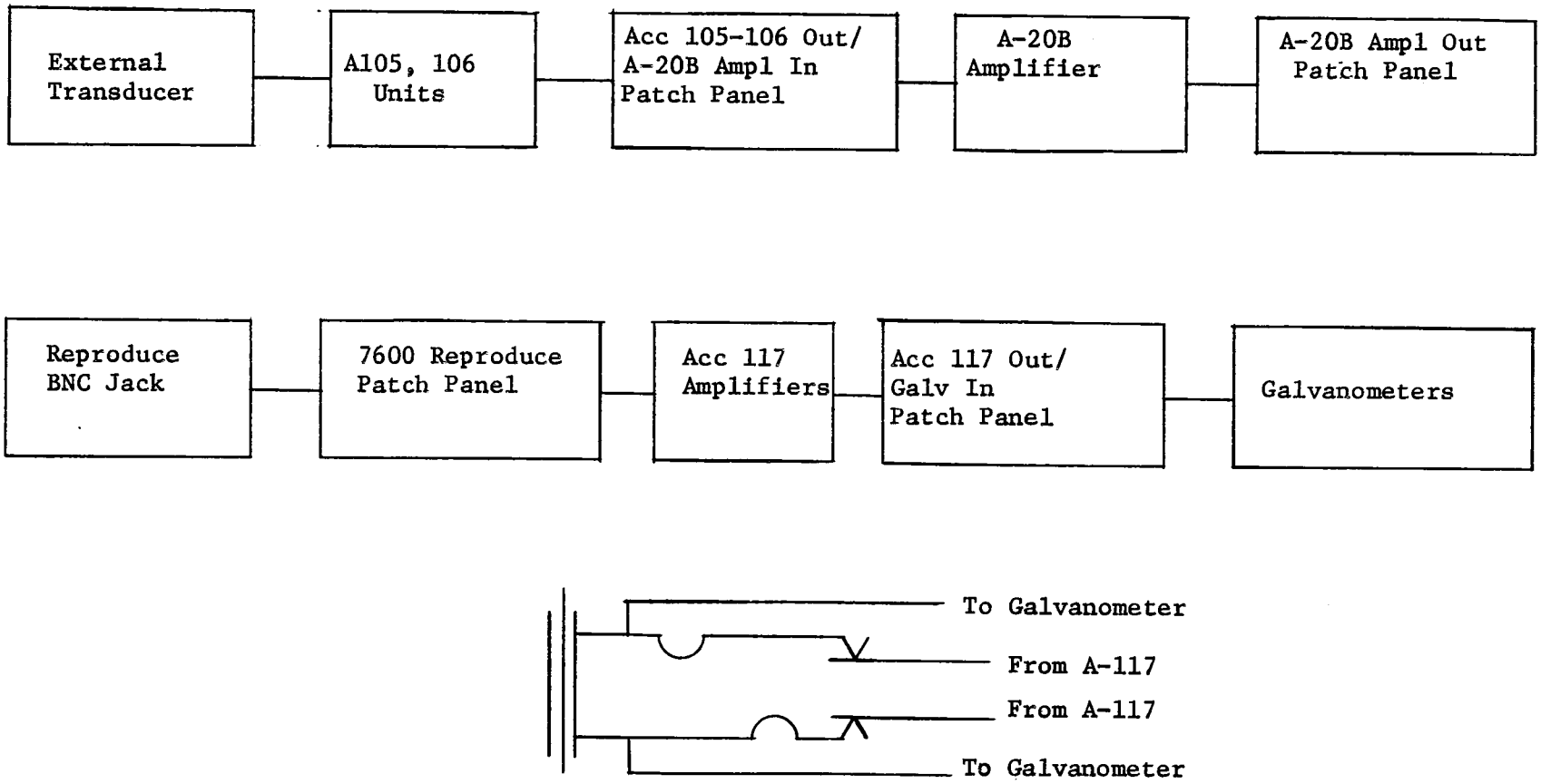


Figure 7. Signal Path.

TABLE I

INSTRUMENTATION OUTLINE

Unit Name	Abbreviation	Purpose
Accudata 105	A-105	Strain gage signal conditioner
Accudata 106	A-106	Millivolt input or thermocouple input
Accudata 117	A-117	Low gain amplifiers
A20B	A-20B	High gain amplifiers

by two internal calibration resistors R7 and R8. These resistors are attached via spring loaded terminals which allow variable calibration values of the bridge output. The selection of these resistors will be discussed at greater detail in the next chapter. The output switch provides for reverse, short, or normal output of the conditioned gage signal.

The external input to the A-105 unit is through the upper signal input panel located at the rear of the console. This panel accepts a five pin connector (Honeywell P/N 16750103-026); four pins for the external bridge (if full) and the fifth for shielding the input leads. The signal arrives at the rear of the A-105 unit through a seven pin connector J1.

The A-106 units require inputs in the millivolt range such as thermocouples, etc. Each of these units receive 120 volt AC line power from the rack position it occupies through pins 1 and 13 of connector P1 on the rear of the unit. Input to the units is through connector RT1 at the lower portion of the rear of the unit. The A-106 units have an internal mode switch which determines the operation of the unit. For millivolt inputs the switch is set to MV while for thermocouple inputs the switch is set to TC. If this switch is set to TC and if the thermocouple leads are attached to the appropriate terminals of RT1, a reference junction of 32°F is provided for the thermocouple. This is accomplished by an internal bridge network. The unit uses a compensation resistor board assembly to provide this reference. However, different types of thermocouples require the corresponding resistor board assembly; these boards are not interchangable for

different thermocouple types. If different thermocouple types are desired, the appropriate board must be used and an internal potentiometer TC ZERO (R5) must be set to specifications as outlined in the A-106 technical manual (12). When the unit is in the millivolt mode of operation, the compensation circuit is not used by the unit.

The front panel controls of the A-106 unit provide fine and coarse suppression, attenuation, calibration, and signal output modifications. The suppression allows an expanded scale of operation. The coarse control allows a suppression from -40 to +50 millivolts in 10 millivolt steps while the fine control provides variation between each fixed step. The manufacturer suggests that no negative suppression be used for a thermocouple input. It is further suggested that if any amplification of the signal is needed that the attenuation control be set to OUT. This investigation does require signal amplification. The calibration switch provides a $\pm$ 1.0 millivolt calibration signal for the output of the unit. As on the A-105 unit, the output control allows the reverse, short, or normal operation of the unit.

Although the A-106 units supply a reference junction internally in the thermocouple input mode, use of an external junction (ice bath) allows the measurement of temperature by thermocouples. In this procedure the unit is operated in the millivolt range with the output in millivolts. The A-106 units provide for three operating conditions which are:

A. Millivolt input - Millivolt record

B. Thermocouple input - Millivolt record

C. Thermocouple input - Record in degrees

Each method of operating requires different procedures to set up. These are listed in the A-106 technical manual. The method and procedure used in this test will be explained in Chapter III.

The A-20B amplifiers located beneath the A-105 units supply the needed signal amplification to drive the high frequency, fluid-damped galvanometers used in the oscillograph. The particular units for this facility are A20B-34G. These units provide fixed gain steps of 0, 10, 20, 50, 100, 200, 500, and 1000. Concentric with the fixed step control is a range control which provides a X.01 or a X1 scale control over the fixed step control. These amplifiers also have OFFSET and GAIN ADJ screwdriver adjustments for zero signal input adjustments and variable gain from X1 to X2.5 of the fixed setting, respectively. These amplifiers require about a 45-minute warm-up period to stabilize. The output of the A-20B unit is internally limited to 70 milliamps to provide galvanometer protection. Each A-20B amplifier position in the rack is wired in series with the appropriate position for the A-105 and A-106 units.

The A-117 units are low gain amplifiers whose main purpose is amplification of signals received from a separate tape recording system or some signal which requires minimum amplification. These units feature fixed gain steps of .01, .02, .1, .2, .5, 1, 2, 5, and 10 with a concentric control which varies the fixed gain over a range of X1 to X2.5. A zero screwdriver adjustment allows for any mechanical zero shift of the galvanometer due to a zero input signal. Figure 7, page 20, shows the two ways in which a signal can be fed through the A-117 units. A signal may be connected to the reproduce BNC jacks

located in the lower portion of the rear of the console or by patch plug into the 7600 REPRODUCE patch panel on the front of the console.

The patch panels on the console require further explanation at this point. The patch panel labeled ACC 117 OUT/GALV IN is represented by the typical installation presented on Figure 7, page 20. When a patch plug is not in this jack, the output of the A-117 channels becomes the input of the corresponding galvanometer channels. If, however, a patch plug is inserted into the jack, the input of the galvanometer is that originating at the plug itself. The plug physically breaks the contact between the arms of the jack as illustrated (Figure 7). This is true also for the ACC 105-106 OUT/A20B AMPL IN patch panel and for the 7600 REPRODUCE patch panel. The A20B AMPL OUT patch panel is different in the respect that these jacks provide a signal output which becomes the input of some recording device, usually a galvanometer of the recording oscillograph. If no patch plug is in these jacks, the conditioned and amplified signal cannot be recorded by any means. Placing a plug in these jacks picks up the signal from the A-20B amplifiers and feeds this signal to whatever unit the other plug end of the patch cord is connected. The 7600 RECORD patch panel is similar in that a plug provides a signal to the record BNC jacks on the lower rear portion of the console.

All parameters measured during the tests were recorded by the 1508 Visicorder oscillograph. This oscillograph contains the galvanometers which have been mentioned previously. This instrument utilizes light sensitive paper to record the signals produced by the signal conditioning devices. A signal from the transducer is converted

to a voltage which causes the mirror in the galvanometer to deflect. These mirrors supply the light beam to the paper which develops at room lighting to produce a trace on the paper. The trace deflection then gives an indication of the magnitude of the transducer signal.

The power control for the oscillograph has a MAIN position and LAMP position as well as the OFF setting. In the MAIN position, power is provided to the galvanometer magnet banks. This provides a constant operating temperature for these banks. The light source for the mirrors is turned on by placing the power control to LAMP. (When the unit is to be shut down, the control should be placed in the MAIN position for approximately 15 minutes before turning to off.) The other controls provide for a gridline intensity adjustment, a galvanometer trace intensity adjustment, and a time system. The time system provides for a line to be placed across the paper for each time increment as set by the control. The oscillograph paper speed is controlled by the push-buttons which provide a set range of paper speeds from 0.15-120 in./sec (0.38 - 305 cm/sec). The OPERATE bar turns the paper feed on and off.

A take-up unit below the oscillograph allows the paper to be stored as it is emitted by the oscillograph. This unit has a latensifier which makes the paper develop at a much faster rate than it would if exposed to room light only. A momentary take-up button allows a length of paper to be examined (while the oscillograph is not feeding) and rerolled back on the take-up spool.

Power to every rack of the console is applied by the MAIN POWER module (Figure 6, page 19). Each amplifier rack also has its own separate power switch which places that rack in operational mode.

CHAPTER III

CALIBRATION PROCEDURES

The acquisition of data in the form of pressure, temperature, and clearance measurements in the seal interface region and the torque and vertical load on the seal required prior calibration of the transducers which would be used to obtain these measurements. The calibration of these devices became a governing concern in that the reduced data could be expected to be only as good as the calibration of the various transducers.

Interface Pressure

Although the stationary seal had provisions for seal interface pressure measurements at five locations, only two pressure locations could be used during any test. The problem arose as to which two points to use; however, condition of the diaphragm in these areas reduced the problem considerably. Ghorashi (7) found the output of the pressure measuring system was determined by the amount of space between the stationary probe and the diaphragm and the physical condition of the diaphragm itself. Since this study was to have a maximum fluid supply pressure of 100 psig (6.89×10^5 N/m^2), the probes used would be required to have an acceptable signal output over this range of pressures.

An attempt was made to investigate the possibility of using each pressure location to obtain data. The procedure involved placing a

5.0 in. O.D. O-Ring on the rotating seal face (it was not rotated during the calibration) and lowering the stationary face down to this O-Ring to form a sealed cavity between the two seal faces. This cavity was then pressurized with nitrogen in order to observe the response of the probes due to the applied pressure. For interpretation purposes, a goal of 4.0 inches of trace deflection was to represent 100 psig. The stationary probe was carefully lowered in the insulator until it just touched the diaphragm as indicated by an ohm meter deflection which had been placed across the probe and diaphragm. Excessive tightening of the probe would ruin the diaphragm in that it would cause a permanent depression in the stationary seal surface. Once the continuity was established, the stationary probe was backed out in rough increments of one quarter of a turn. The leads to the sending unit were then connected.

The sending unit of the probe contained a variable capacitor which allowed some adjustment in the system. If the meter on the drive unit would not zero on the scale used, this capacitor was adjusted to provide a zero meter reading. The output of the driver was used as the direct input of an A-20B amplifier. The amplified signal was then fed to a M1650 galvanometer in the oscillograph. As the pressure was applied (gage pressure of the supply system), the trace of the galvanometer deflected across the paper. The pressure measurement probe and driver were found to have some inherent noise as evidenced by the width of the trace. This resulted in a trade-off between the amplifier gain and the probe sensitivity as determined by the space between the stationary probe and the diaphragm. If the

space was too small, the diaphragm would touch the probe at higher seal pressures which destroyed the probe output. This in turn required adding more space between the probe and the diaphragm and readjustment of the variable capacitor.

Pressure locations 3 and 4 were found to be unsuitable. The stationary probe touched the sides of the recessed hole near the diaphragm before it reached the range of space needed between the diaphragm and the probe. Location 2 was found to give unsatisfactory results as it exhibited signs of a damaged diaphragm in this area. Location 5 was found to be physically acceptable but the trace width was too great (indicating noise in the system) to allow a very exact measurement. Location 1 was found to be very good in its response. Any possibility of equipment malfunction causing the wide trace was eliminated by changing probes, sending units, and drivers. The calibrating curves for locations 1 and 5 appear on Figures 8 and 9, respectively. The gain of the A-20B amplifiers was not changed after obtaining these curves.

Temperature

The diaphragm temperature was monitored by iron-constantan thermocouples which had been cemented to the diaphragm. These thermocouples were routed through the center of the clearance probes. The thermocouple leads were shielded and became the direct inputs for two of the A-106 units. Of the three types of input-record methods available with these units, the Thermocouple Input-Millivolt Record procedure was used. This required the use of a thermocouple conversion

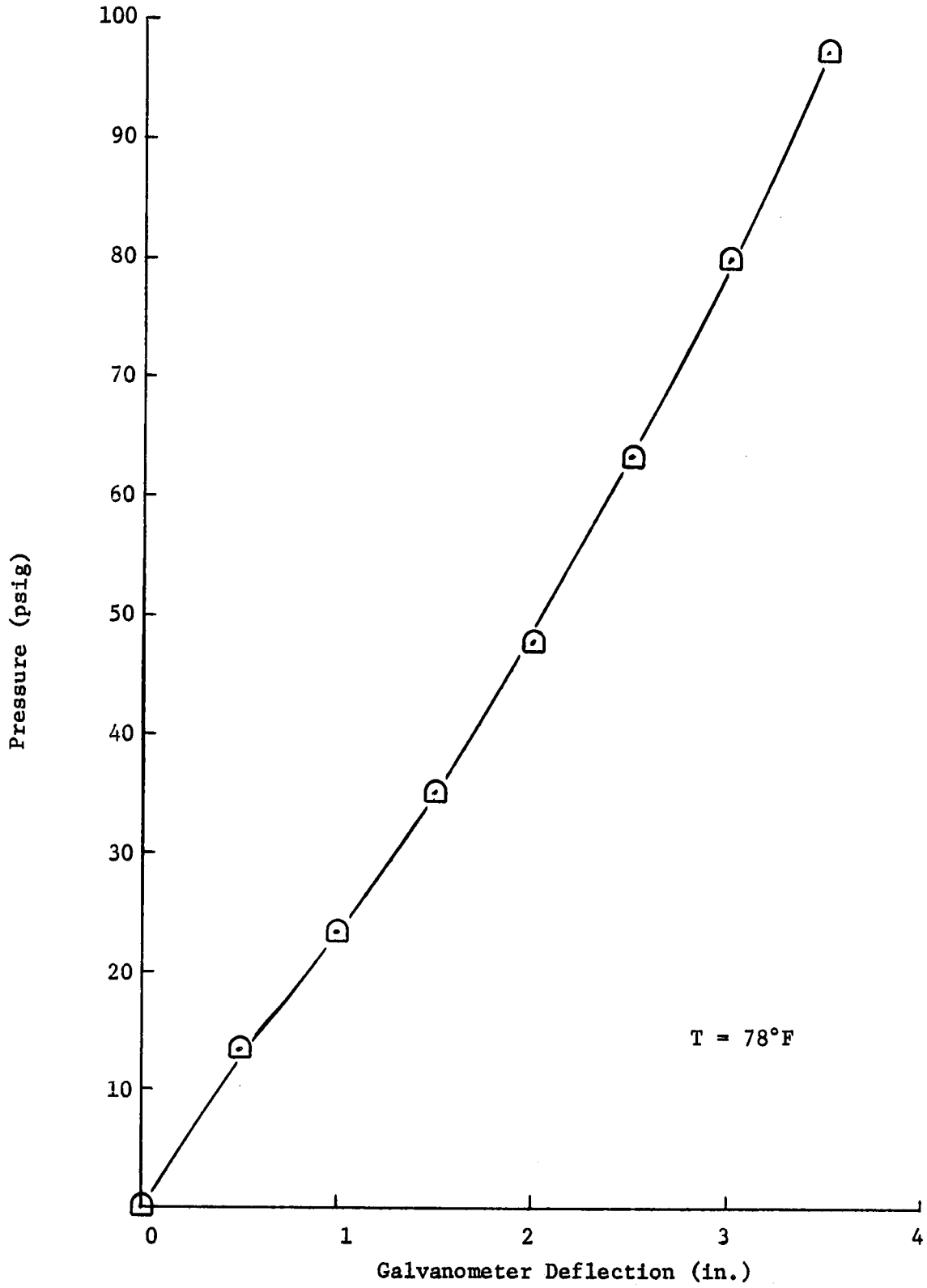


Figure 8. Pressure Probe 1 Calibration.

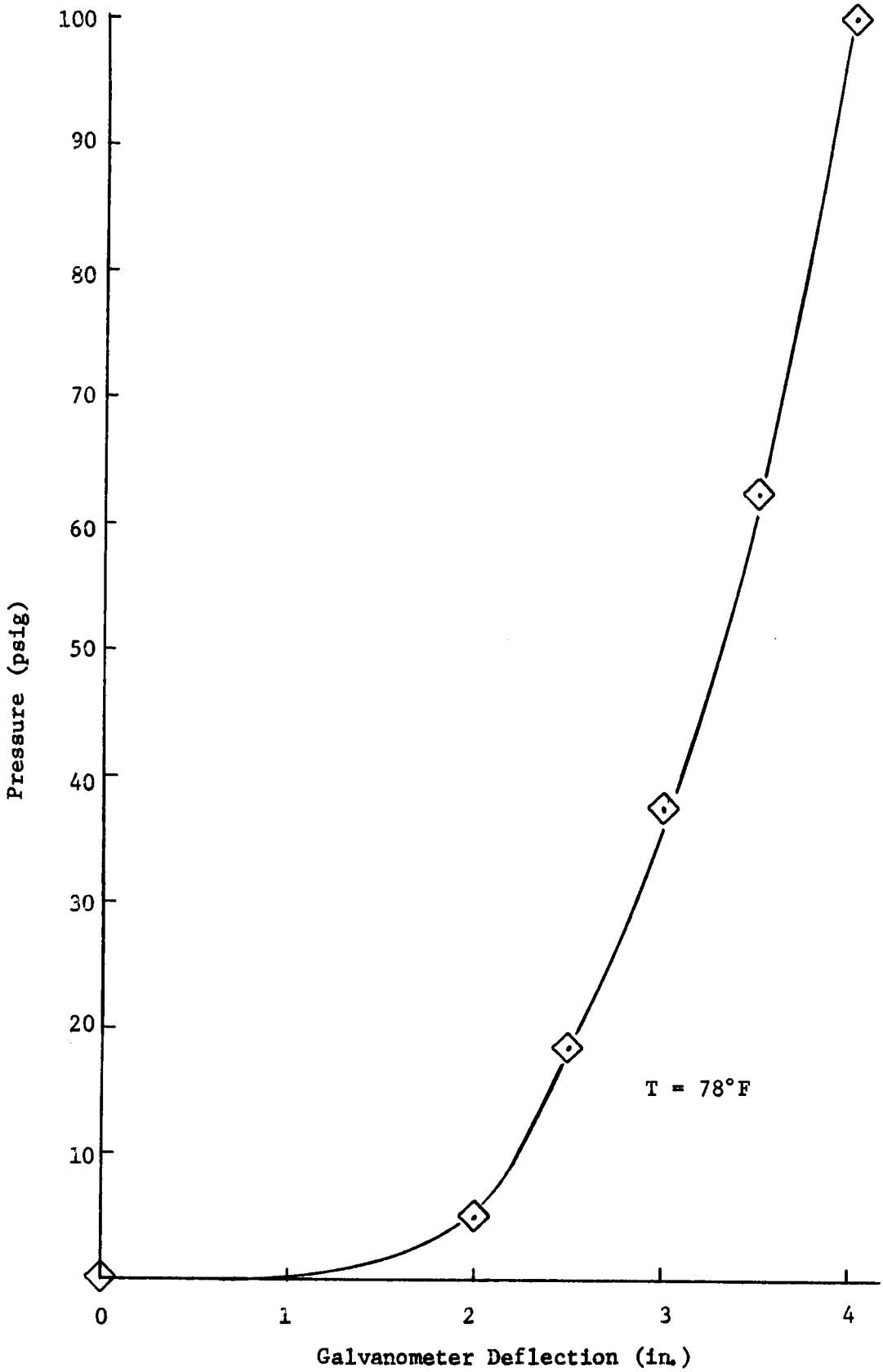


Figure 9. Pressure Probe 5 Calibration.

table to interpret the results of the tests. The internal mode switch was set to TC and the front controls of the A-106 units were set as follows:

STEP SUPPRESSION	+0
FINE SUPPRESSION	OUT
CALIBRATION	0
ATTENUATION	OUT
OUTPUT	SHORT

The particular galvanometer to be used to record the outputs of these units was then set at a convenient mechanical zero position. (This represents the zero output position.)

The next step in the procedure involved balancing the amplifier which would be used to amplify the A-106 output in order to drive the galvanometer. For the particular type of thermocouple used in these experiments, a generated EMF of 1.0 millivolt represented about 68°F (20°C) so for ease of interpreting the data the amplifier was balanced to produce 1.0 in. M1650 galvanometer deflection for an input of 1.0 millivolt. A Leeds and Northrup model 8686 Millivolt Potentiometer was used to supply the 1.0 millivolt input. The potentiometer leads were placed into the appropriate ACC 105-106 OUT/A20B AMPL IN patch panel. The corresponding A20B AMPL OUT patch panel position was then connected via patch cord to the galvanometer to be used to record the temperature. The following steps were then followed.

1. The OFFSET and GAIN ADJ controls were placed in the most counterclockwise position.

2. The gain control was set at the desired fixed position.
3. The potentiometer was set for zero EMF output.
4. The OFFSET screwdriver control was adjusted to place the galvanometer at its mechanical zero position.
5. The potentiometer was set to provide a 1 millivolt EMF output.
6. The GAIN ADJ control was then adjusted so that the galvanometer deflection due to the 1 millivolt input was exactly 1.0 in.
7. Steps 3 through 6 were then repeated until no interaction was determined.
8. The potentiometer was then unplugged from the patch panel.

After the amplifier was balanced, the OUTPUT control of the A-106 unit was switched to the NORM or REV position. The deflection of the galvanometer then represented the millivolt reading corresponding to the actual thermocouple temperature. If it had been desired to suppress any portion of the output signal, the procedure would have to had been modified slightly. [See A-106 technical manual (12) page 3-4.] It should be pointed out here that each control unit position in the console corresponds with the same A-20B amplifier position as shown by Figure 7, page 20.

Vertical Load and Torque

The instrumented section, Figure 4, page 14, was used to measure the vertical load and torque exerted on the stationary seal. Figure 10 shows the apparatus which was used to calibrate this section.

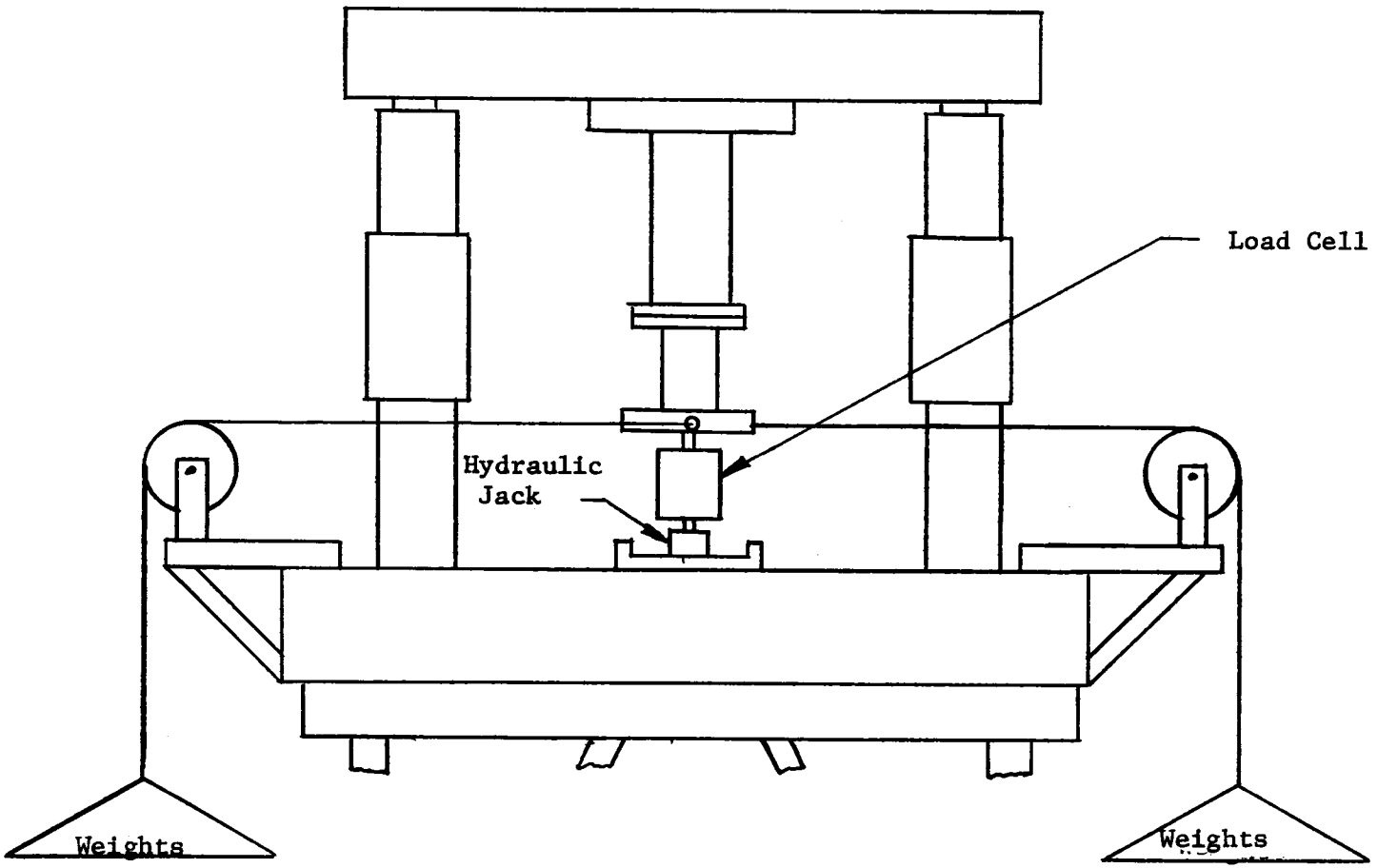


Figure 10. Vertical Load and Torque Calibration Rig.

The vertical load was applied through a steel ball by a hydraulic jack. It was measured by a Baldwin SR-4 load cell which was connected to an Automation Industries model P-350 strain indicator. This particular load cell was known to have an output of 2 μin./in. strain for every 1.0 lbf vertical load at a gage factor of 2.025. Every attempt was made to apply the load in a vertical plane. The torque was applied by weights, routed over "frictionless" pulleys. The moment arm for each identical weight attaching apparatus was 3.0 inches. The actual applied torque was then the amount of weight on one side multiplied by a moment arm of 6.0 inches.

The instrumented section was calibrated for numerous combinations of applied vertical load and applied torque. Also the section was calibrated by two methods. In the first calibration, the vertical load and torque bridge circuits were connected to Vishay Instruments model P-350A strain indicators. These indicators were the same type as used to measure the applied vertical load. The applied vertical load ranged from 0 to 2000 lbf (0 - 8.896×10^3 N) while the applied torque ranged from 0 to 606 in.-lbf (0 - 68 Nm). The gage factors of the vertical load and torque strain indicators were set at 4.05 and 2.025, respectively, during the calibration. These values had been used in a prior calibration procedure. The procedure involved setting the load cell indicator to the indicated strain which represented a known vertical load and applying pressure to the hydraulic jack until the indicator balanced. The vertical load and torque strain indicators were then balanced and the strain reading recorded. This procedure was repeated throughout the series of tests.

The data from the calibration procedure described above were used to verify the data obtained using the A-105 strain gage units and the associated recording equipment in the instrumentation console. The A-105 technical manual listed equations for the calculation of the calibration resistors R6 and R7 and the galvanometer deflection corresponding to these resistor values. The two equations of interest in this analysis are listed below.

$$Rcal = \frac{Ra}{(Na)(F)\frac{\Delta L}{L}} \tag{1}$$

$$Rcal = \frac{E\ Ra}{4\ Igd(Ra + Rg)} \tag{2}$$

where

Rcal = calibration resistor value

Ra = resistance of one arm of bridge

Na = number of active arms

F = actual gage factor of the strain gage

$\frac{\Delta L}{L}$ = strain (length change per unit length of bridge gage arm)

E = excitation voltage

Ig = galvanometer current

d = number inches of galvanometer deflection.

These equations were found to disregard any amplification needed to drive the galvanometer. The following modified equations were then derived:

$$Rcal = \frac{Ra}{F(\frac{\Delta L}{L})} \tag{3}$$

$$Rcal = \frac{E\ Ra}{4M} \tag{4}$$

where M represents a parameter to be used in balancing the A-20B amplifier for each A-105 output.

The previous calibration procedure had determined the maximum values of strain incurred due to the applied loads; but these values were obtained at gage factors different from the actual values of the respective bridge circuits. The definition of the gage factor was used to remedy this situation.

$$F = \frac{\frac{\Delta Ra}{Ra}}{\frac{\Delta L}{L}} \tag{5}$$

where

$\frac{\Delta Ra}{Ra}$ = resistance change per ohm of gage arm resistance.

The quantity $\Delta Ra/Ra$ represents a quantity which is the result of a physical load. For the same load conditions, this quantity remains unchanged regardless of the value of F or $\Delta L/L$. Consequently, there exists a direct relationship between the strain observed at any gage factor and the strain obtained at the correct gage factor.

$$F \frac{\Delta L}{L} \text{]indicated} = \frac{\Delta Ra}{Ra} = F \frac{\Delta L}{L}\text{] actual} \tag{6}$$

The actual maximum values of strain for the vertical load and torque were then found from this relationship.

Due to linearity considerations, the maximum galvanometer deflection was limited in these tests to 4.0 inches. The actual maximum strain could have been set to represent this value; however, for ease of data reduction the maximum strain was rounded off slightly. A galvanometer deflection of 4.0 inches was to represent a strain of 600 μin./in.(1.0 in. represented 150 μin./in.)for the vertical load.

A galvanometer deflection of 4.0 inches was to represent a strain of 500 μin./in. (1.0 in. represented 125 μin./in.) for the torque. These values were then inserted into Equation 3 to determine the respective Rcal values. Since there were provisions for two calibration resistors, one value was found which corresponded to a 1.0 in. galvanometer deflection and another value to correspond to a 4.0 in. galvanometer deflection for both the vertical load and the torque. The actual values of the resistances used in this investigation are presented in Appendix A.

After the appropriate values of calibration resistances had been determined, the resistors themselves had to be inserted in the A-105 units between the spring loaded terminals (R6 and R7). A precision resistor as near as possible to the calculated values was found by using an impedance bridge. The actual resistance as determined by the impedance bridge was then used in Equations 3 and 4 to determine the actual values of $\Delta L/L$ and M. The determined Rcal resistances were then inserted into Equation 4 to arrive at a value for M.

The quantity M was directly related to the excitation voltage E once Equation 3 had been solved. For a fixed excitation voltage, M represented the input to the A-20B amplifier in order to produce a galvanometer deflection corresponding to a particular calibration resistor value. The amplifiers were then balanced in a procedure similar to that used in the thermocouple measurements (p. 34) except for the values of the EMF output of the potentiometer. These values were given by the appropriate value of M.

Once the calibration resistors had been determined and the amplifiers balanced, the A-105 unit controls were ready to be set.

The initial control settings were:

CAL	0
OUTPUT	SHORT
EXCITATION	Full counterclockwise.

The galvanometer was set to the desired zero position. The OUTPUT switch was set to NORM (or REV) and the Balance control was adjusted for zero output (the galvanometer zero position). The CAL switch was then set to +1 and the EXCITATION was adjusted to provide the trace deflection which corresponded with the value of the calibration resistor. (The +1 and -1 CAL position places R7 in the bridge circuit while +2 and -2 places R6 in the circuit.) The value of the excitation voltage was monitored at the excitation jacks by a digital voltmeter. This value should have been the value used in Equation 4 but a slight variation was noticed. The deviation between the theoretical excitation voltage used in Equation 4 and the actual excitation voltage observed at the CAL positions was used in the correlation of the data obtained from both methods.

Each load condition produced a deflection in the traces of the vertical load and the torque. This trace deflection was converted to a load reading by Equation 7.

$$\text{LOAD} = [\frac{E_T}{E_A}]K\delta \tag{7}$$

where

E_T = theoretical excitation voltage used in Equation 4

E_A = actual excitation voltage required to produce a given deflection

K = calibration constant corresponding to deflection produced by E_A

δ = trace deflection.

This procedure produced typical calibration curves for vertical load versus vertical strain, Figure 11; torque versus torque strain, Figure 12; and vertical load versus torque strain, Figure 13.

The slope of the curve in Figure 11 was used to relate strain (which the transducer measured) to the vertical load which produced the strain. This was also done for the torque from Figure 12. Figure 13 shows the influence of the vertical load on the torque. At an applied torque of 0.0 in.-lbf, the transducer indicated a nonzero torque due to the applied vertical load. This fact dictated the manner in which the experiments were conducted and the manner by which the torque data were interpreted. The details of how this information was used is presented in Chapter IV.

Supply Pressure

The oil supply pressure was to be measured by a Precision Measurement Company model 150 pressure transducer. This transducer consisted of a 120 Ω strain gage bonded to a 0.15 in. (3.8 mm) diameter diaphragm. The transducer was epoxied into a machined stainless steel pipe plug. Approximately 0.002 in. (50 μ) of the diaphragm protruded from the surface of the plug which had been ground flat before installation of the transducer. The plug assembly was then lapped in order to produce a smooth, even surface across the face of the plug.

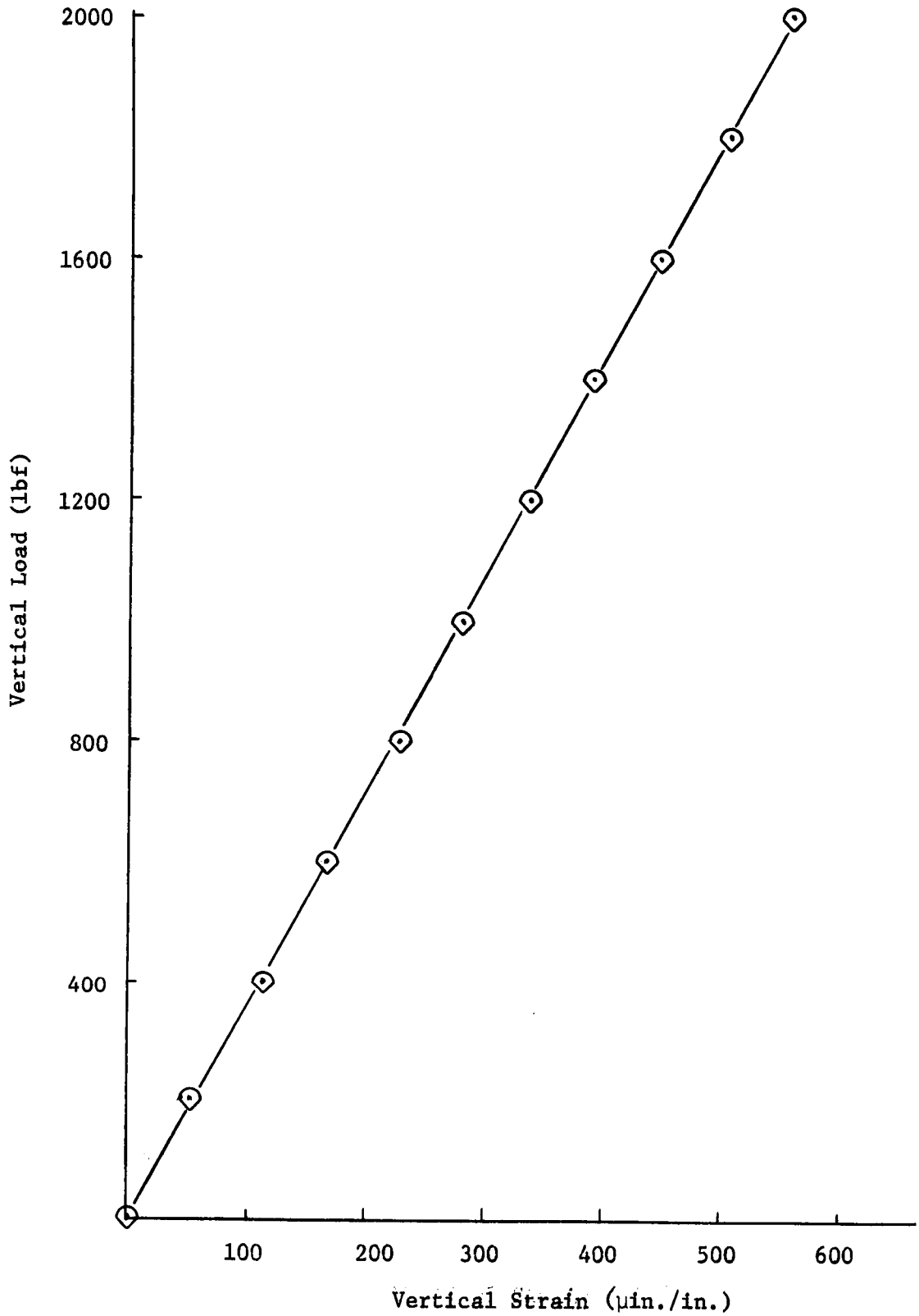


Figure 11. Vertical Load Calibration.

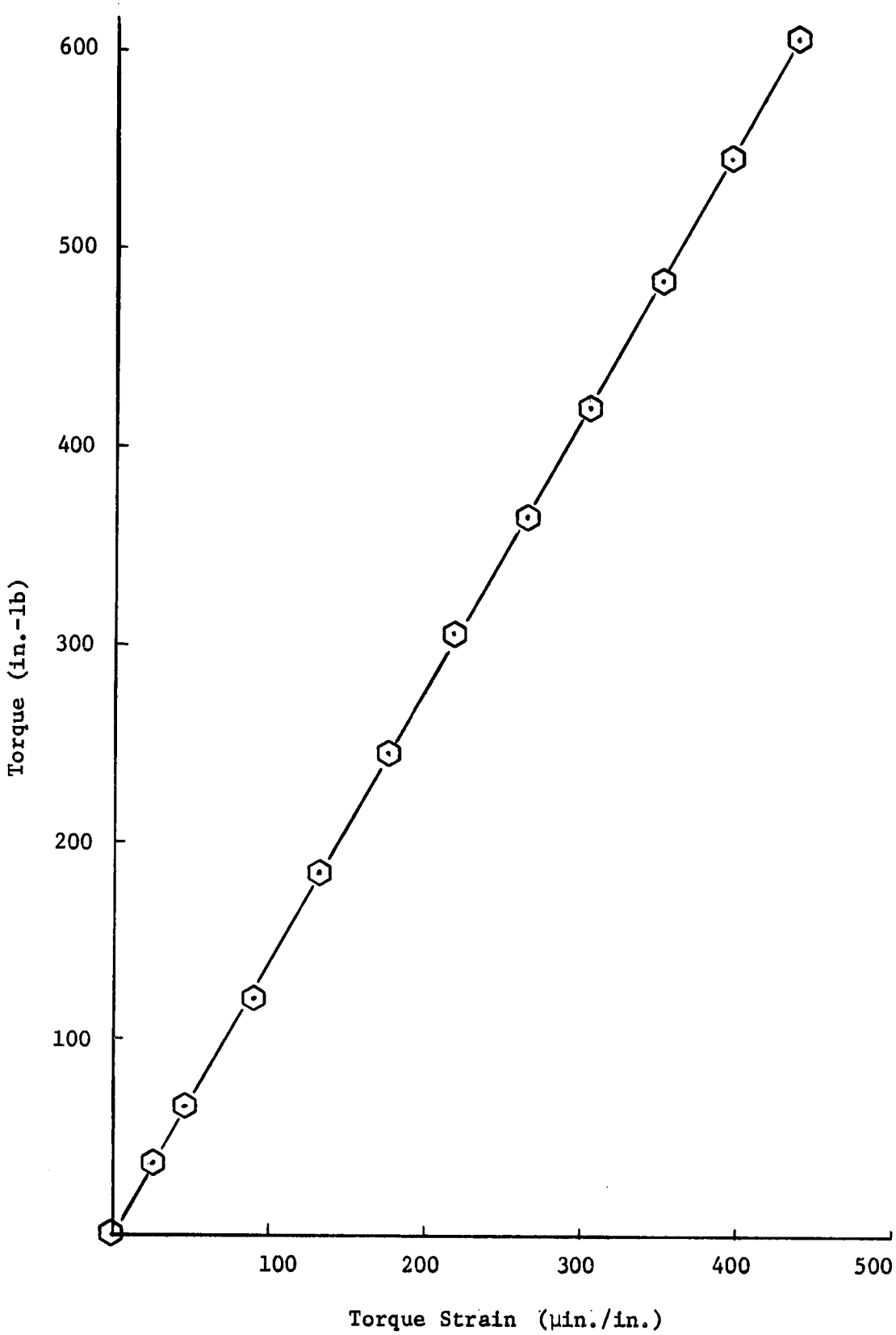


Figure 12. Torque Calibration.

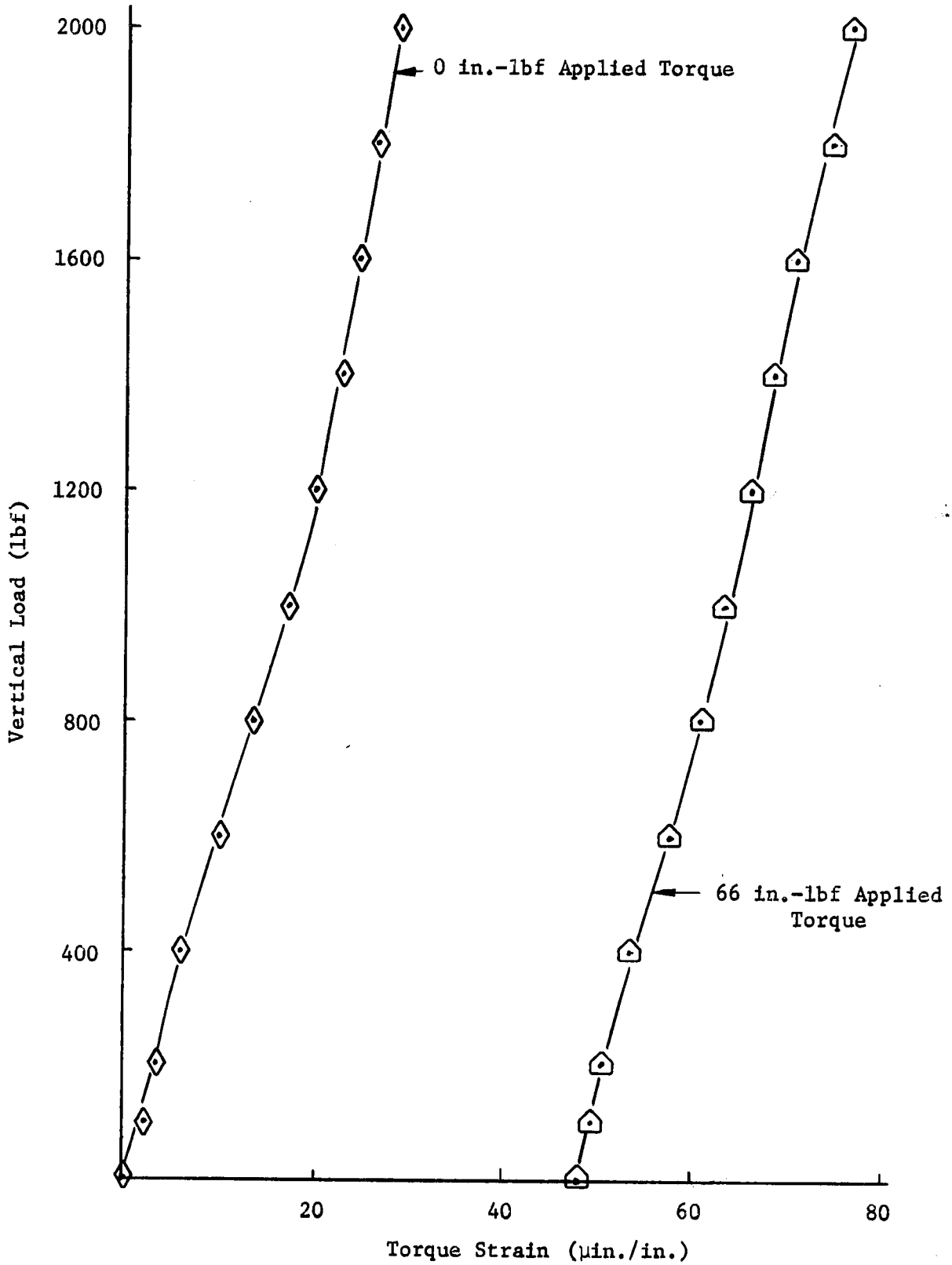


Figure 13. Vertical Load Influence on Torque.

The initial tests of this transducer involved connecting the transducer leads to a Vishay Instruments model P-350A strain indicator. The gage factor was 2.0. A static test facility, Figure 14, was used to observe the transducer output as a result of the applied pressure. There was also a provision for heating the chamber fluid to observe the effect of temperature on the transducer output. Figure 15 shows the probe output characteristics obtained from the static test facility.

The transducer contained one arm of a bridge circuit; therefore, the internal bridge completion provision of the A-105 units was utilized to form the complete strain gage bridge. Three 120Ω strain gages were connected to positions R1, R3, and R4 on the circuit board inside the A-105 unit. This particular configuration allowed the still to be determined calibration resistor to be directly across the transducer when switched into the circuit. The previous tests had yielded an approximate maximum strain output of 500 μin./in. corresponding to an applied pressure of 100 psig (6.89×10^5 N/m^2). A 4.0 in. trace deflection was to represent full scale as before. Equations 3 and 4 yielded the appropriate values for Rcal and M to give this deflection. The excitation voltage in Equation 4 was set at 4.0 volts as it was in the vertical load and torque calibrations. Only one calibration resistor corresponding to full scale deflection was used in this test.

Unlike the previous results for vertical load and torque calibrations, an excitation voltage of 4.0 volts produced the exact 4.0 in. trace deflection. However, as Figure 16 shows, an applied pressure of 100 psig did not produce exactly a 4.0 in. trace deflection. This

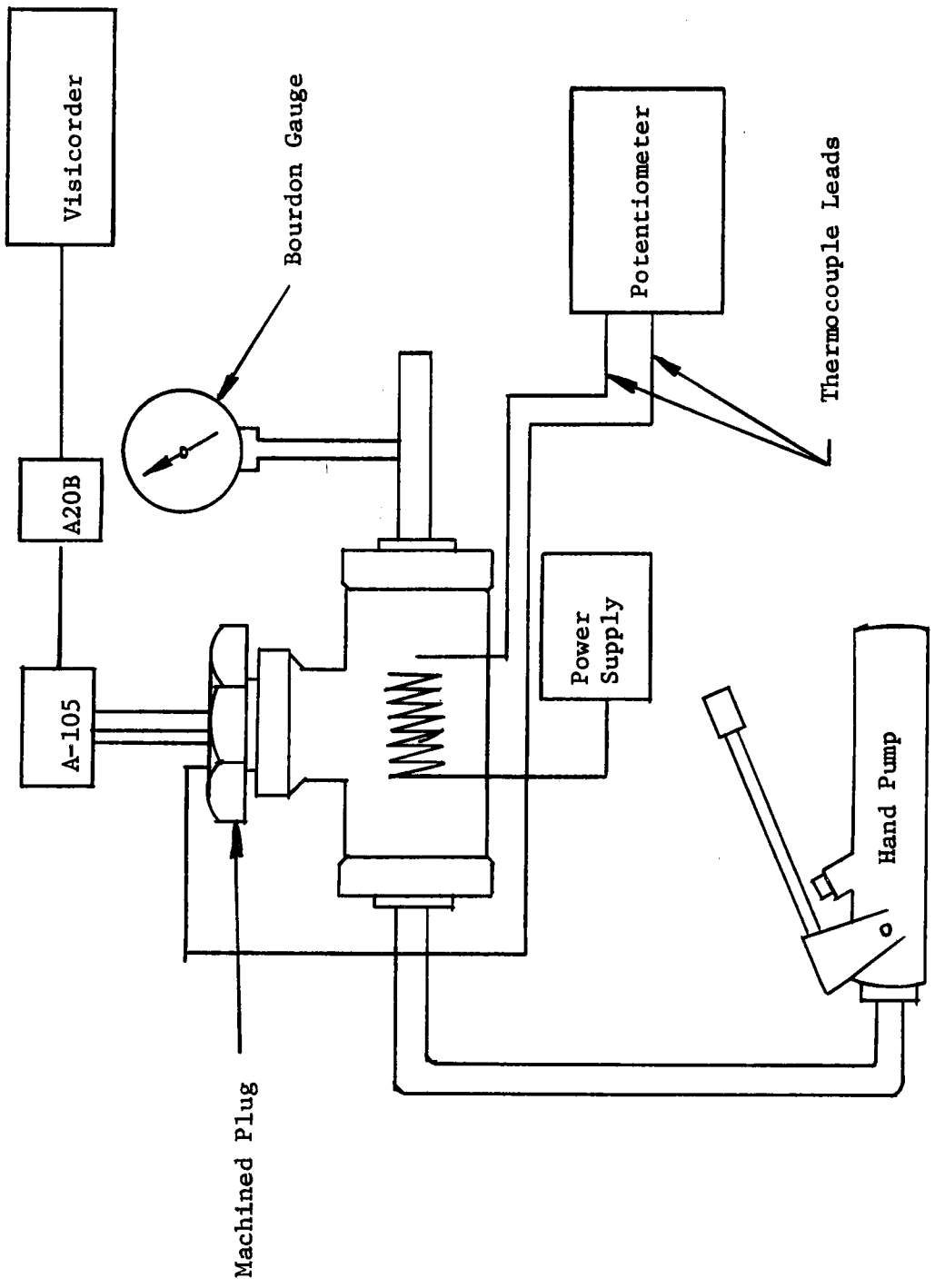


Figure 14. Static Pressure Transducer Calibration Rig.

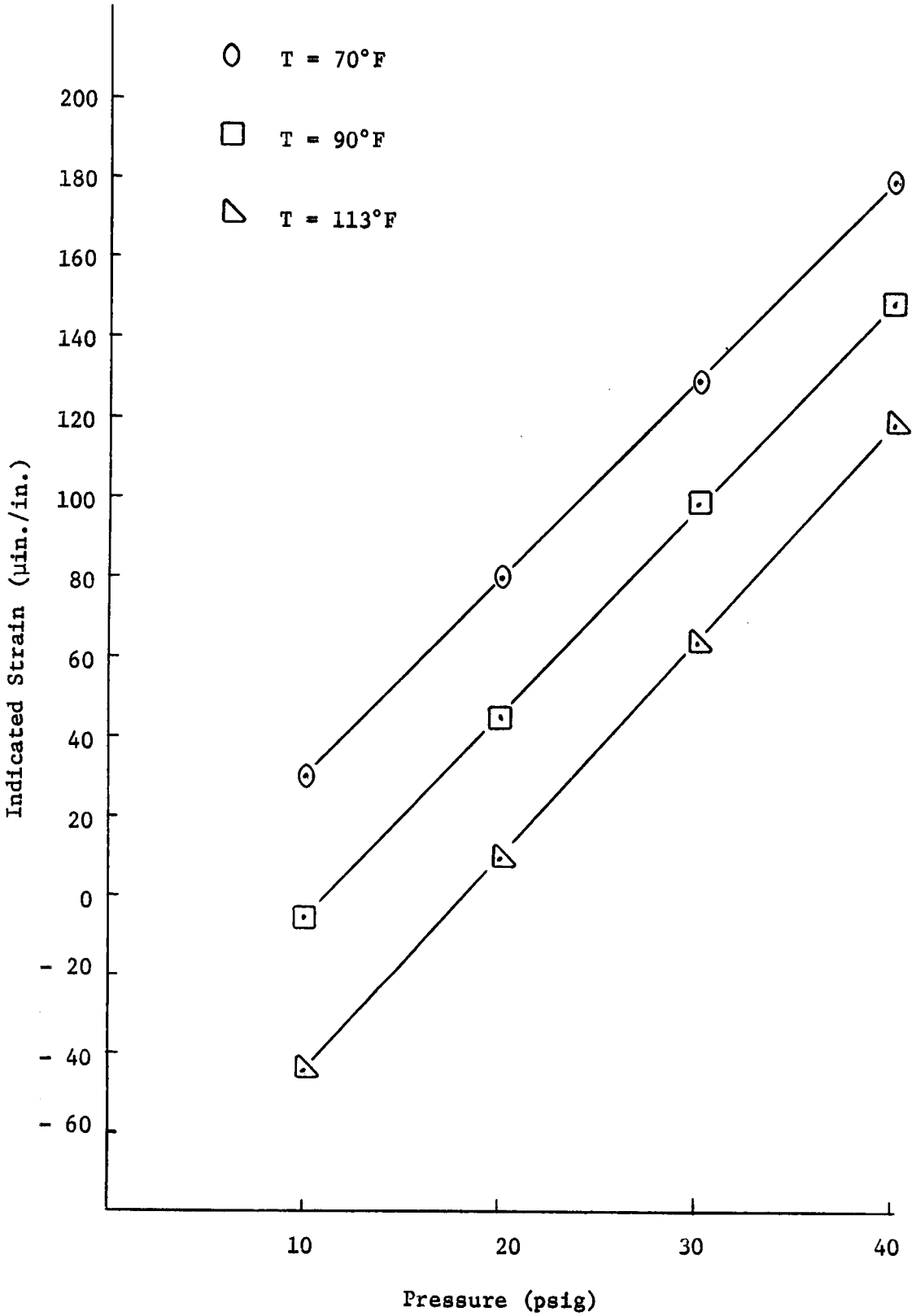


Figure 15. Supply Pressure Transducer Temperature Sensitivity,

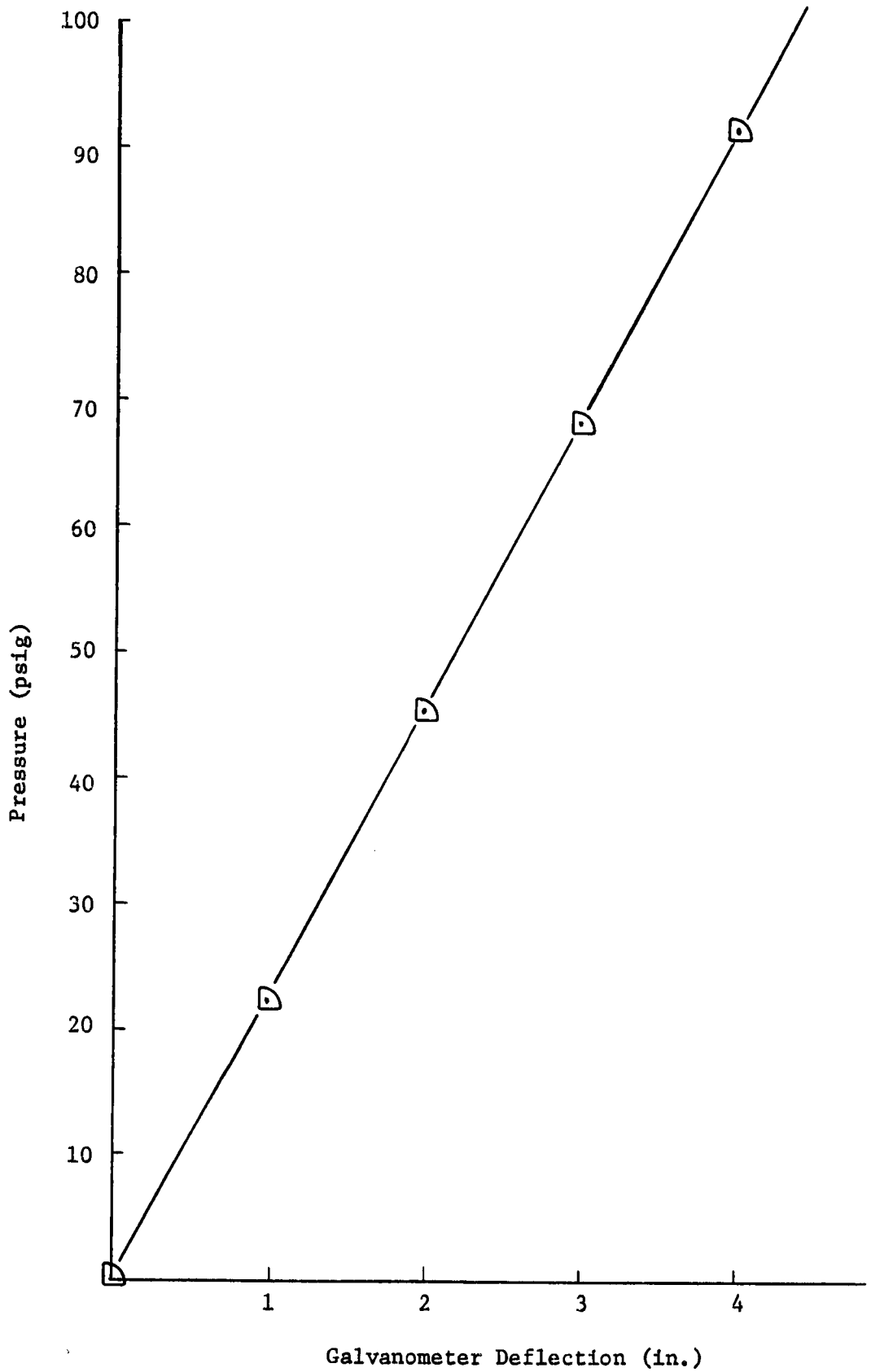


Figure 16. Supply Pressure Transducer Calibration.

was due to the approximation of the maximum strain found from the strain indicator. The exact pressure corresponding to a 4.0 in. trace deflection was found by a direct relationship between the desired output and the actual output.

$$\left[\frac{\text{deflection}}{\text{pressure}}\right]_{\text{desired}} = \left[\frac{\text{deflection}}{\text{pressure}}\right]_{\text{actual}}$$

In this manner it was found that 4.0 in. of deflection represented 92.165 psig and the actual sensitivity was 542.5 μin./in. for 100 psig. Figure 16 shows the calibration curve obtained from this work.

Clearance

The clearance probes were calibrated by placing the system in an operational mode and observing the system output as the stationary seal was raised and lowered. The particular range of interest was 0 - 5000 μin (0 - 127 μ). The system output was linear in this range as shown by Figure 17. The manner by which the output was converted to a trace deflection will be discussed in detail in the next chapter. It should be noted here that the clearance probes measure a localized clearance.

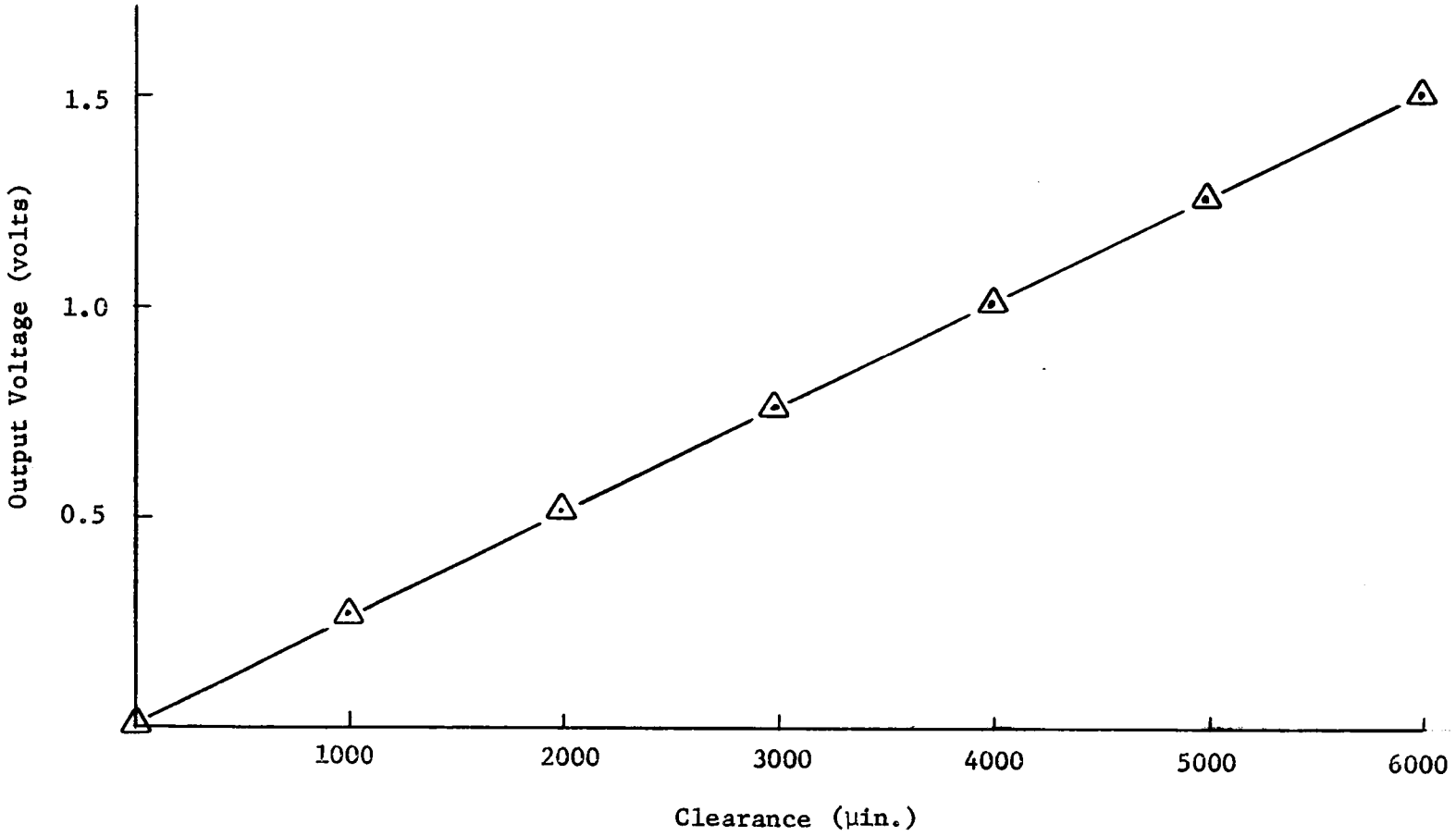


Figure 17. Clearance Probe I and II Calibration. Source: Figure V.9, p. 84, Duncan (11).

CHAPTER IV

EXPERIMENTAL TESTS AND DATA REDUCTION

The collection of data was limited by the physical condition of the stationary seal face. This seal had been fabricated by first drilling the holes for the pressure and clearance probes. The 0.005 in. (127 μ) thick stainless steel foil was then epoxied to the disk which then formed the diaphragm for these measurements. After lapping the foil surface of the stationary piece, the clearance probe assemblies were epoxied in the appropriate holes. The installed system was then checked and calibrated to insure the probes were still in a workable condition. The calibration of the pressure probes explained in Chapter III was then determined. After these processes were completed, all of the instrumentation which before had only been checked separately was integrated into a complete workable facility.

Before any tests were undertaken, the stationary surface was lowered to about 0.005 in. above the rotating seal face (still stationary). The gap between the two surfaces was then observed. The stationary face was observed to protrude slightly in certain areas of the face. Since these protrusions were clearly visible, they were considered to be of such magnitude that they would touch the rotating seal face in operation at low clearances. These depressions occurred

between the time the seal was lapped and the calibrations of the pressure and clearance probes. Based on these surface asperities, it was decided to limit testing to set clearances above 0.003 in. (76 μ).

Limiting the interface clearance to a minimum of 0.003 in. also meant short run times were mandatory. The oil supply reservoir did not have the needed fluid capacity to insure a constant supply of oil over a long period of time; particularly at high pressures and seal rpm. The short run time required following a precise procedure in obtaining the data.

When all the transducer signals were displayed at once on the oscillograph, certain peculiarities were observed. With every signal at zero load on the oscillograph except the pressure probes, the traces were very good. Connecting the pressure probes, particularly probe 5, caused a shift in the thermocouple outputs as well as making these traces excessively wide. The system was then checked for ground loops. After eliminating the ground loops, the effect on the thermocouples due to pressure probe 1 was eliminated; however, probe 5 still had an adverse effect on the thermocouples. For this reason probe 5 was disconnected leaving only one pressure measurement in the interface region. All transducer leads which were previously not shielded were shielded and connected to a common ground. The stationary seal had previously been connected to ground in order to form the circuit necessary for the operation of the pressure measuring system.

The initial check-out of the clearance probes after their installation in the stationary seal had revealed a characteristic of

the rotating portion of the seal. As the rotating seal was turned by hand through one revolution, the clearance probes produced a single sinusoidal wave for each probe. The waves were 120° out of phase; since the probes were mounted 120° apart, the rotating face was deduced to have a wavy surface instead of being flat. A convenient reference was chosen for the rotating face and this point was marked on the side of the rotating seal face. This point was used to index the rotating portion of the seal for all future tests.

Each testing period required a set-up procedure. The procedure involved setting the null networks to zero output at a seal interface clearance of approximately 1 in. The seal surfaces were cleaned at this point to remove all the oil from the surfaces. The supply line was disconnected during this nulling period. The stationary seal was then lowered to rest freely on the rotating seal face. The electronic system for the clearance probes was then adjusted to a zero output. A trace for the zero clearance position was then obtained on the recording paper for each probe. The stationary seal was then raised to the desired spacing by using the probe calibration data. The exact procedure for setting up the clearance measuring system is included in Appendix B. The hold-down straps were then adjusted to insure that the stationary seal would not move upward due to the pressure in the interface region. After this adjustment, a trace was obtained on the oscillograph. The read-out of the voltmeters for each system were recorded at both zero clearance and the adjusted clearance. A trace was also made for one complete hand

rotation of the rotating seal surface. The seal was set at the index mark after this revolution (it had started at the index mark also).

After obtaining the traces for clearance measurements, the next step in the initializing procedure involved obtaining calibration data for the strain gage circuits and the thermocouples. A galvanometer trace was obtained for each Rcal position and the exact excitation voltage was recorded at each position for every strain gage circuit. A trace was also made at the SHORT and NORM position, the CAL switch was activated to +1 MV and -1 MV and a trace was made at these positions. After these preliminary steps were completed, the test was ready to proceed.

The oscillograph was turned on to a slow speed and the oil supply pressure was set to the desired value. The seal was not rotating at this point. The condition of zero seal rpm necessarily meant zero applied torque. The supply pressure caused a vertical load to be imposed on the seal. As Figure 13, page 44, shows, an applied vertical load produced a torque output. The torque output due to the vertical load at zero rpm in effect became the zero torque condition. The SCR Drive System was then turned on and adjusted to provide the desired seal rotation as measured by a General Radio Company model 1531 Strobotac. When the desired rotation was obtained, the oscillograph paper speed was switched to 120 in./sec and a burst of data was obtained. The exact position of the rotating seal face relative to the stationary seal face was found by a magnetic pickup unit located over a set screw on the bottom of the

drive shaft. The magnetic pickup output was fed through the A-117 amplifiers directly to a M5000 galvanometer. Since the run time was restricted to short intervals, the drive system was turned off after the fast speed burst of data was taken. The paper speed was immediately reduced and the supply pressure reduced to zero. A typical set of data obtained in this manner appears on Figure 18. After the rotating seal had been indexed to the same position it had prior to the run, the strain gage and thermocouple outputs were put through the calibration steps once again to assure confidence in the signal outputs.

The interpretation of the data then simply involved determining the deflection of each trace from its own appropriate zero and multiplying this deflection by the corresponding calibration constant to determine the value of the measured parameter. The data were analyzed over one revolution of the seal by using the magnetic pickup to distinguish the individual revolutions. The paper length for one revolution was divided into eight sections corresponding to 45° increments of rotation. The deflections at each increment were analyzed to determine the nature of the behavior in the interface region.

In the data analysis it was determined that the clearance probes indicated an increase in the interface clearance as the supply pressure was increased. The vertical loads corresponding to these points of increased indicated clearances were significantly below the total weight (50% maximum) of the stationary seal mounting apparatus. The stationary seal mounting apparatus was analyzed

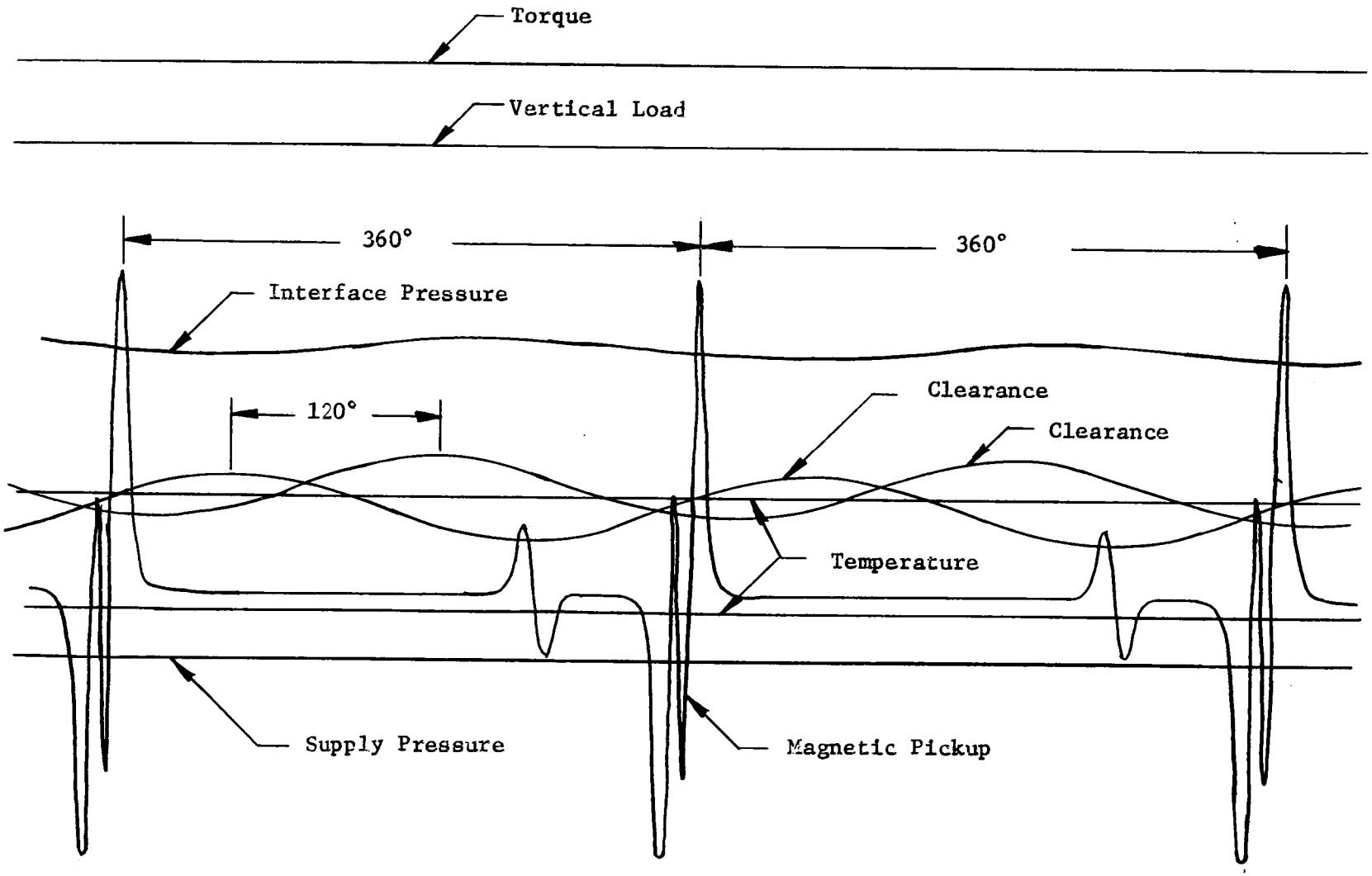


Figure 18. Typical Oscillograph Record (1030 rpm).

(Appendix C) to determine the deflection of the support members. The results showed that the indicated increase in the clearance between the seal faces was due to the deflection of the diaphragm. This observation was used in determining the interface clearance as will be explained later in this chapter.

The interface pressures as determined by the capacitance probe were inconsistent. In some cases the interface pressure was greater than the supply pressure. Denny (1) had observed similar effects when attempting to measure the local interface pressures but abandoned the attempt in favor of measuring the integrated pressure over the whole surface. Since the interface clearance was monitored at only two locations (Figure 1, page 10), it was decided that the stationary seal could be aligned in a wedge type fashion which would produce the increased pressures at the monitoring point. The nature of the clearance traces on Figure 18 support this observation.

One testing period usually consisted of numerous tests at various imposed conditions of supply pressure, seal rotational speed, and in some cases various clearances. The calibration steps for the strain gage networks and thermocouple outputs mentioned previously were undertaken at the beginning and end of each testing period. However, the rotary seal face was indexed, turned through one revolution, and indexed again before and after each individual test during a given period. The voltmeter for each probe was monitored and the volt reading corresponding to the index position of the rotary face was recorded in addition to recording the probe output during these steps on the oscillograph.

The actual clearance measured by each probe as determined by the output voltage and sensitivity was used to interpret the clearance data. This actual clearance was divided by the galvanometer deflection noted at that clearance to convert the trace deflections during the tests to clearance values. As mentioned earlier, the clearance probes were found to be sensitive to the interface pressures. Figures 19 and 20 show the typical probe outputs due to increased pressure. These figures were computed directly from the probe output voltage. For data interpretation purposes, the clearances and sensitivities observed at zero supply pressures were taken to represent the most correct values. It should be noted here that these values were obtained at the indexed position of the rotating seal. The data obtained for the one revolution condition were used to find a mean clearance indicated for each probe. The mean seal clearance was then found from the mean values for each probe. Although the values of clearance per inch of galvanometer deflection for each probe differed slightly from one test to the next, the final values for each probe are believed to be within 100 μin./in. of galvanometer deflection. For example, the sensitivities for Probe I and II throughout a test period ranged from 1657 to 1675 μin./in. galvanometer deflection and 1430 to 1470 μin./in. galvanometer deflection, respectively. In this particular case the sensitivities used to interpret the data were 1675 and 1440 μin./in. deflection, respectively.

In conjunction with this investigation a computer program has been developed by Swafford (13) which simulates the performance

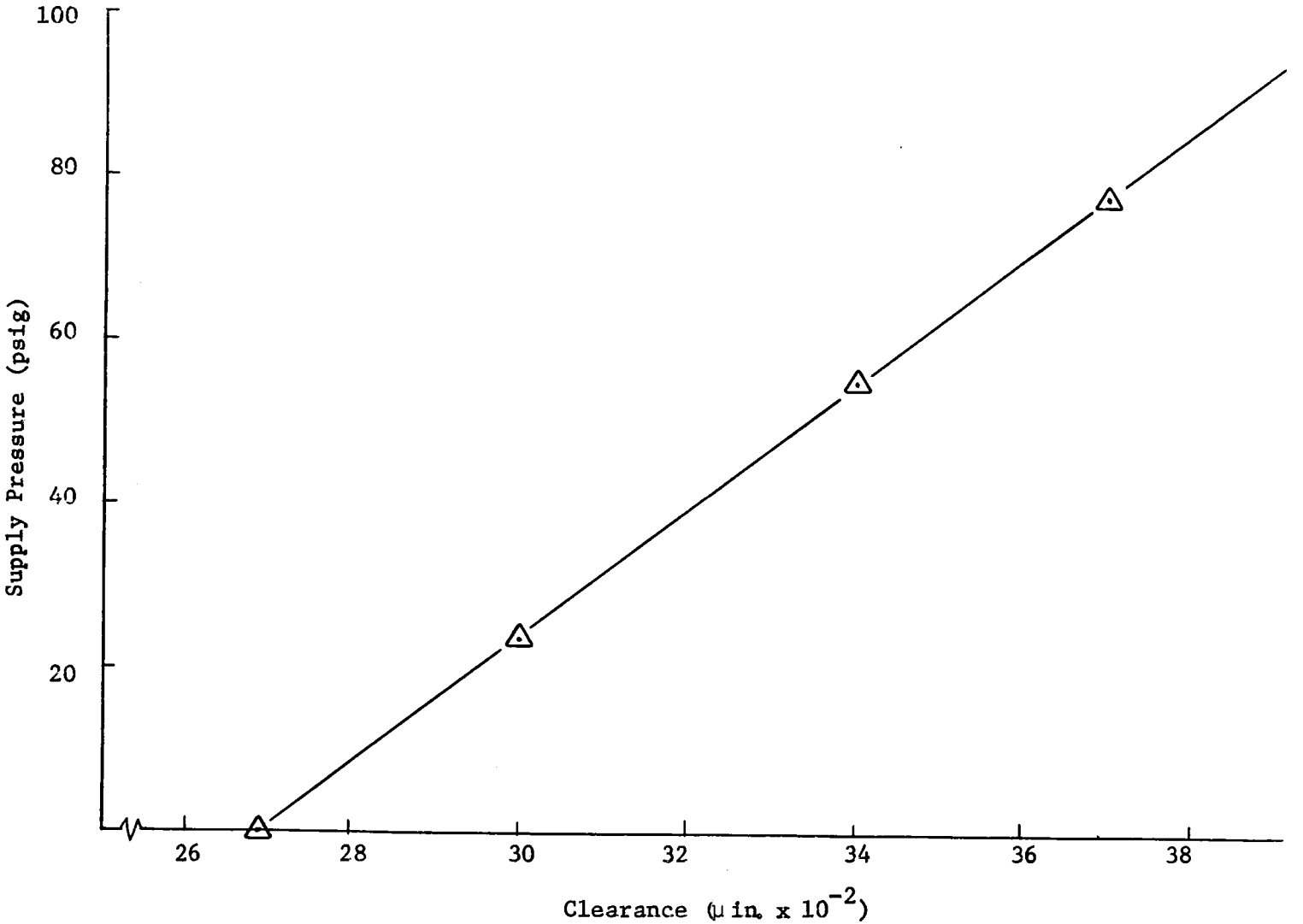


Figure 19. Clearance Probe I Sensitivity to Supply Pressure.

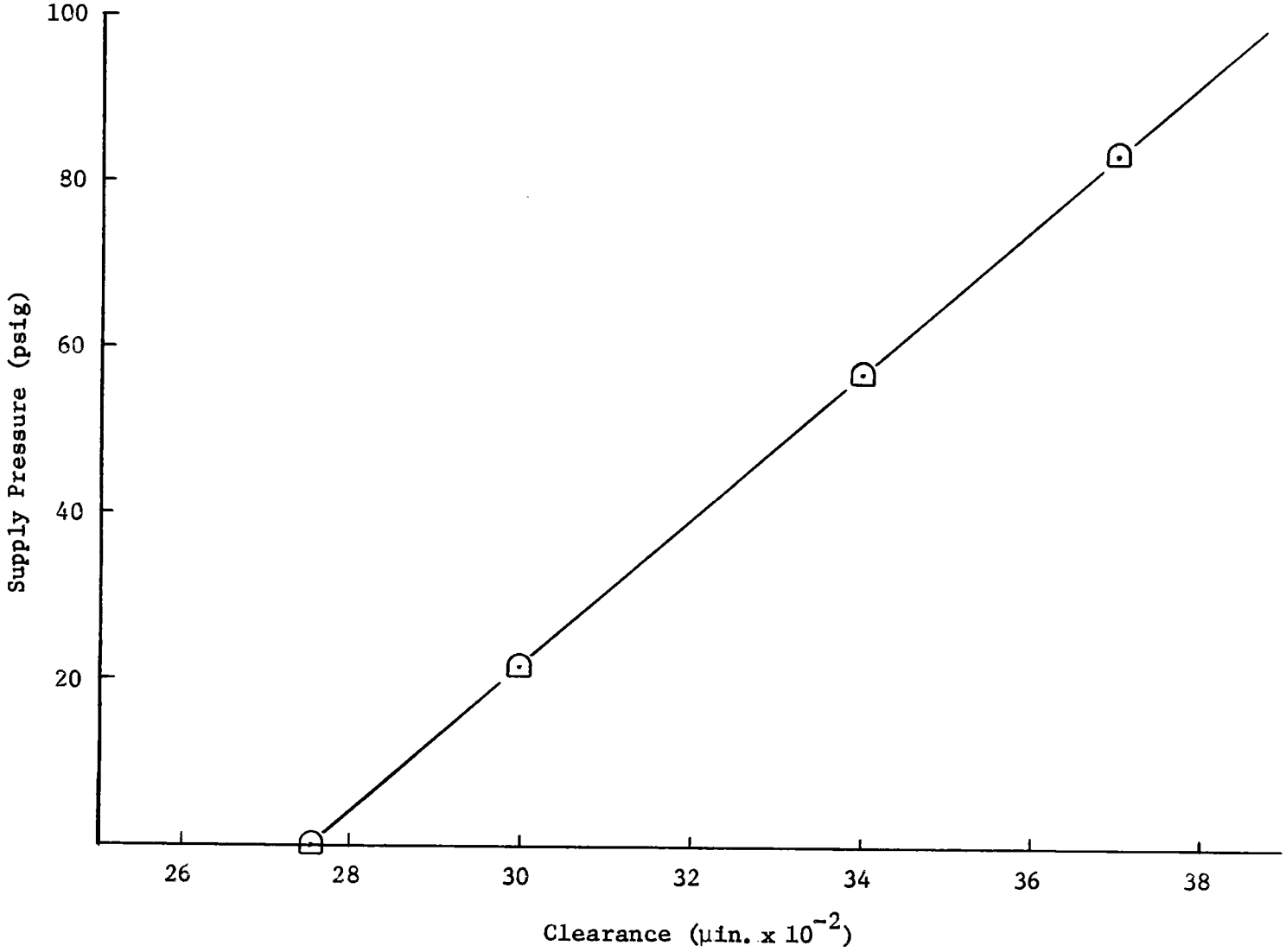


Figure 20. Clearance Probe II Sensitivity to Supply Pressure.

characteristics of a radial face seal. This program has been designed to analyze a seal of the same dimensions as was used in the experiments. The program was based on an analysis presented by Snapp (14) but this analysis has been modified slightly to allow for the variations of the oil properties with temperature. The program is based on the following assumptions:

1. Laminar flow conditions exist in the seal.
2. The liquid is Newtonian and incompressible.
3. The pressure is constant across the film thickness.
4. The velocity varies in both the radial direction and across the film.
5. The viscosity is a function of the oil temperature.
6. There is no circumferential variation of pressure.

The program allows inputs of interface clearance, inlet supply pressure, inlet oil temperature, and rotational speed. A general outline of the method used in the program appears in Appendix C.

The average supply pressure over one revolution of the seal was obtained from the high paper speed recordings on the oscillograph. The rotational speed was found from the Strobotac measurements. The average clearance was determined from the aforementioned procedure. The oil inlet temperature was measured from the calibration data at the start of each period of testing. (The reservoir was constantly being refilled with the same temperature oil.) Each of these parameters served as inputs to the computer program. In effect, some of the measured quantities were used to check the other quantities (such as vertical load, torque, temperature, etc.).

The interpreted data from all the experiments undertaken in this investigation are listed in tabular form in Table II. The values for the parameters are the averaged values over one revolution of the rotating face. Conditions 10 and 11 represent one test. A long strip of data was obtained at various paper speeds for this test. The two entries correspond to the first portion of the test and the last portion of the test. The data are compared with values predicted by Swafford's program in Figures 21-34 listed in the table. In the cases where more than one test was made at approximately the same supply pressure and the same clearance, an average value of this pressure was inserted into the program for a representative comparison. The exact measured rotational speed of the seal was used also. For clarity, only one curve for seal rotational speed has been presented in Figures 21 and 26. The computer predicted results are within 0.5 psig at seal rpms of 490 and 1010 for the respective supply pressures in these two figures.

The interface pressure measurements from probe 1 reveal an interesting point when compared with the computer predictions. The experimental value at 16.5 psig (11.37×10^4 N/m^2) supply pressure is approximately 10% lower than the predicted value; however, as the supply pressure increases, the difference between the measured pressure and the predicted value increases to approximately 66% higher for the measured pressure at a supply pressure of 87 psig (59.98×10^4 N/m^2). This is illustrated in Figures 21, 24, 25, 26, 29, and 32.

TABLE II

EXPERIMENTAL DATA

Run	Supply Pressure (psig)	Rotational Speed (rpm)	Average Clearance (μin.)	Average Vertical Load (lbf)	Average Torque (in.-lbf)	Pressure Probe 1 (psig)	Figure
1	16.95	494	4146	90.3	1.76	11.4	21, 22, 23
2	15.9	1010	4146	91.5	1.76	10.35	21, 22, 23
3	17.84	486	3548	98.7	1.17	11.5	22, 23, 24
4	20.5	488	2925	103.8	1.61	13.6	25
5	39.0	1000	3548	215.3	2.54	30.3	26, 27, 28
6	40.2	492	3548	218.3	1.76	31.9	26, 27, 28
7	47.8	1030	2925	284	1.58	44	29, 30, 31
8	48.4	487	2925	285.5	1.27	47.5	29, 30, 31
9	49.36	488	2925	280.6	0.782	47.6	29, 30, 31
10	86.5	1030	2925	506	1.1	98.6	32, 33, 34
11	87.1	1030	2925	514.8	1.37	100.4	32, 33, 34

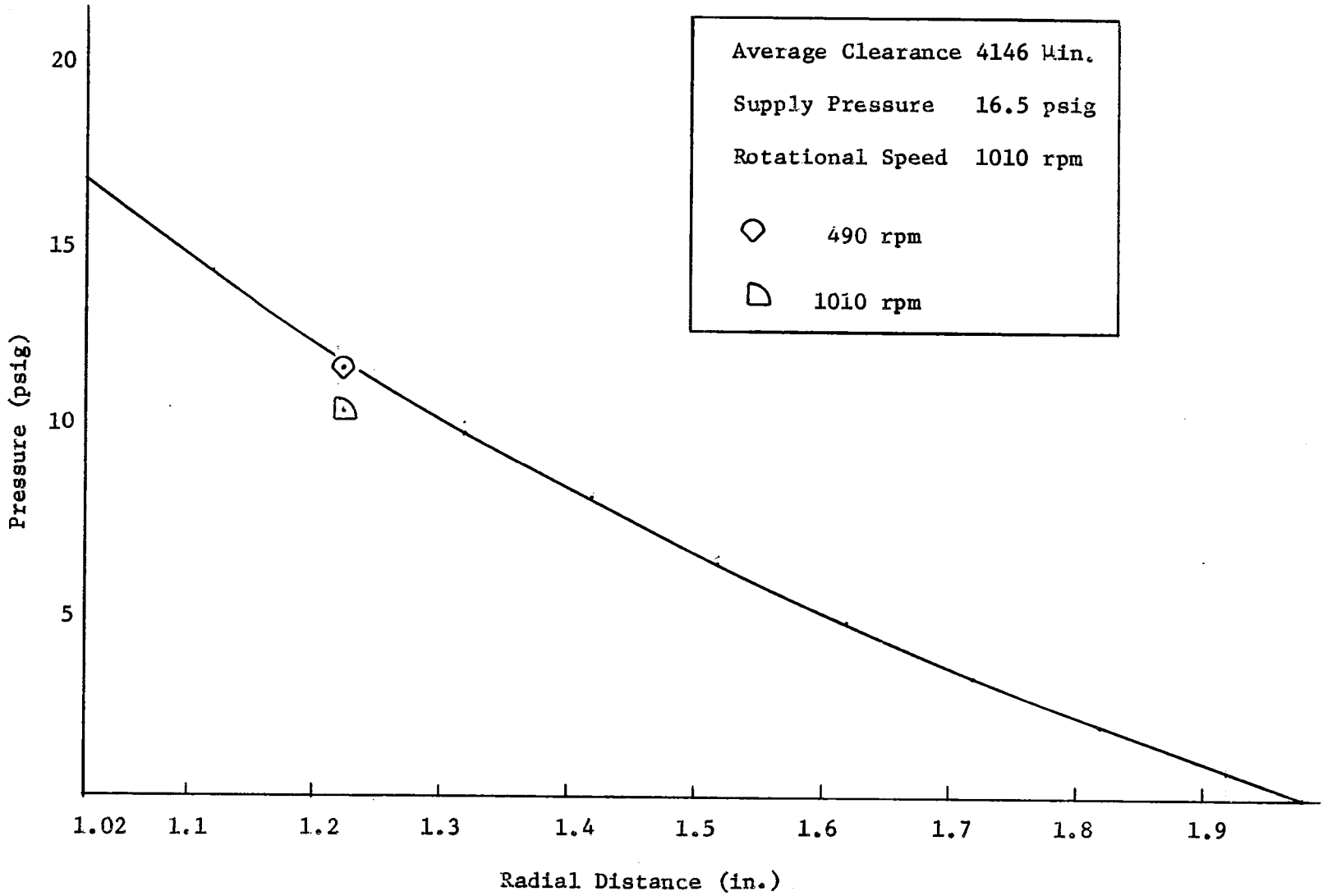


Figure 21. Interface Pressure vs Radial Distance (Runs 1, 2).

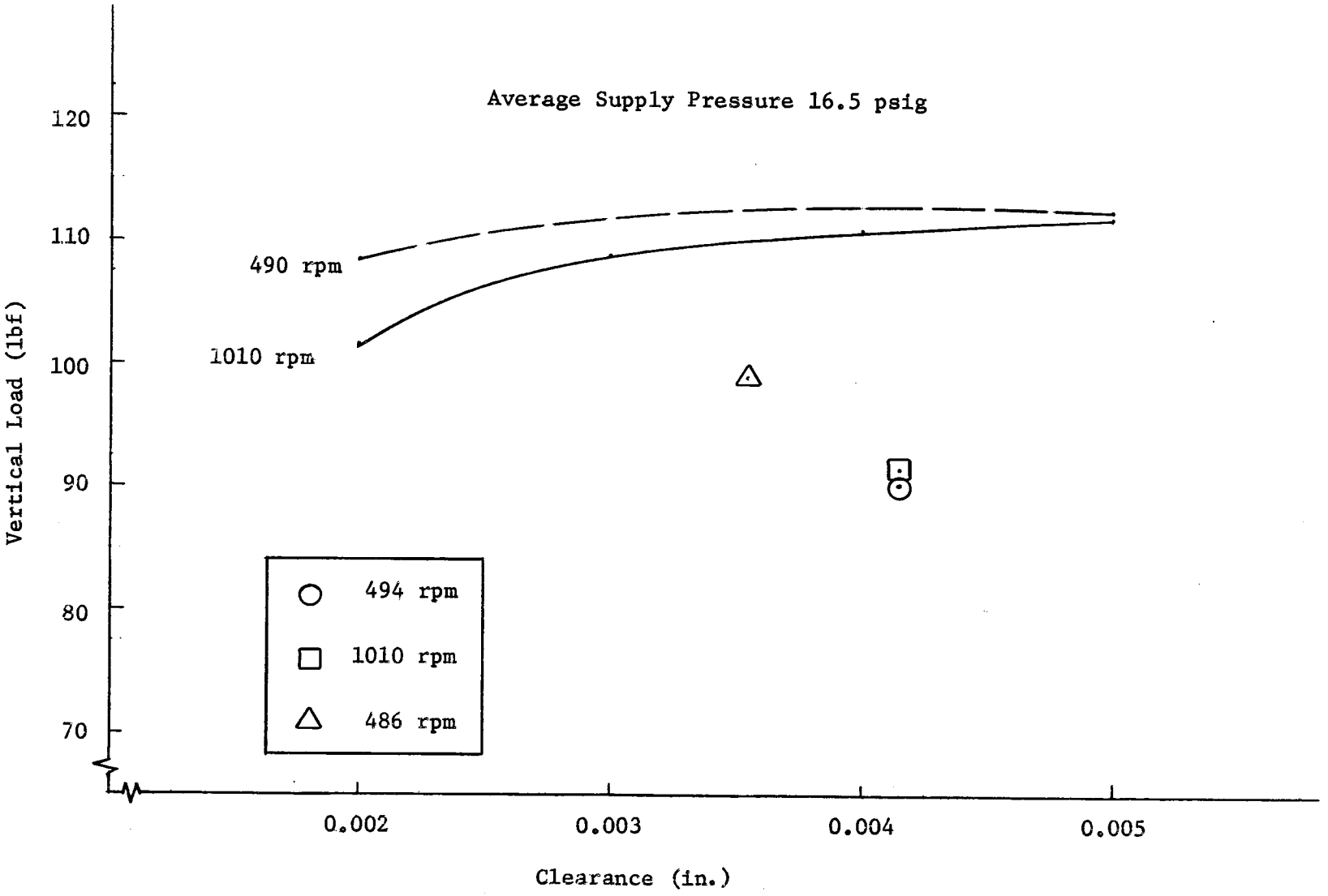


Figure 22. Seal Vertical Load vs Clearance (Runs 1, 2, 3).

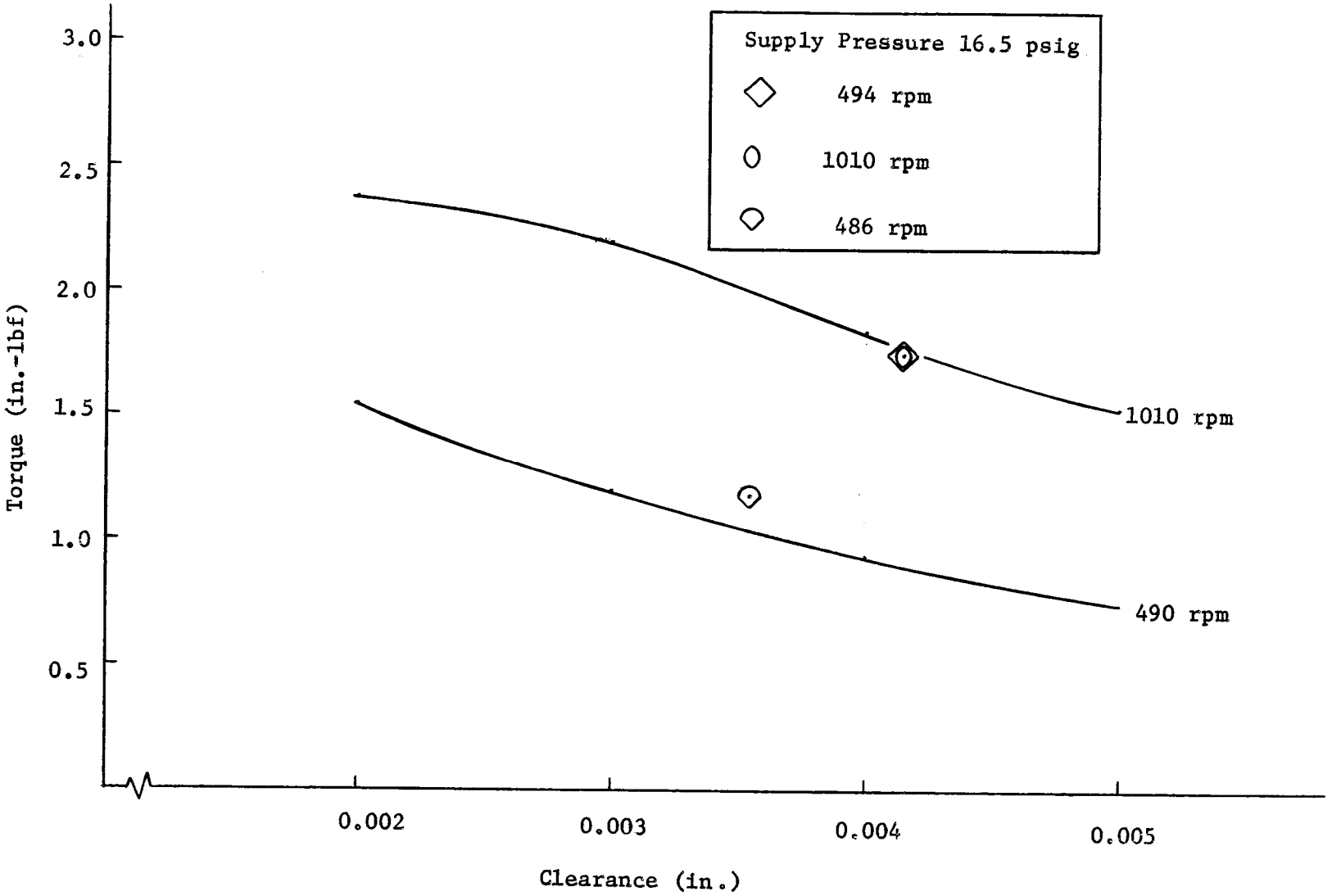


Figure 23. Seal Torque vs Clearance (Runs 1, 2, 3).

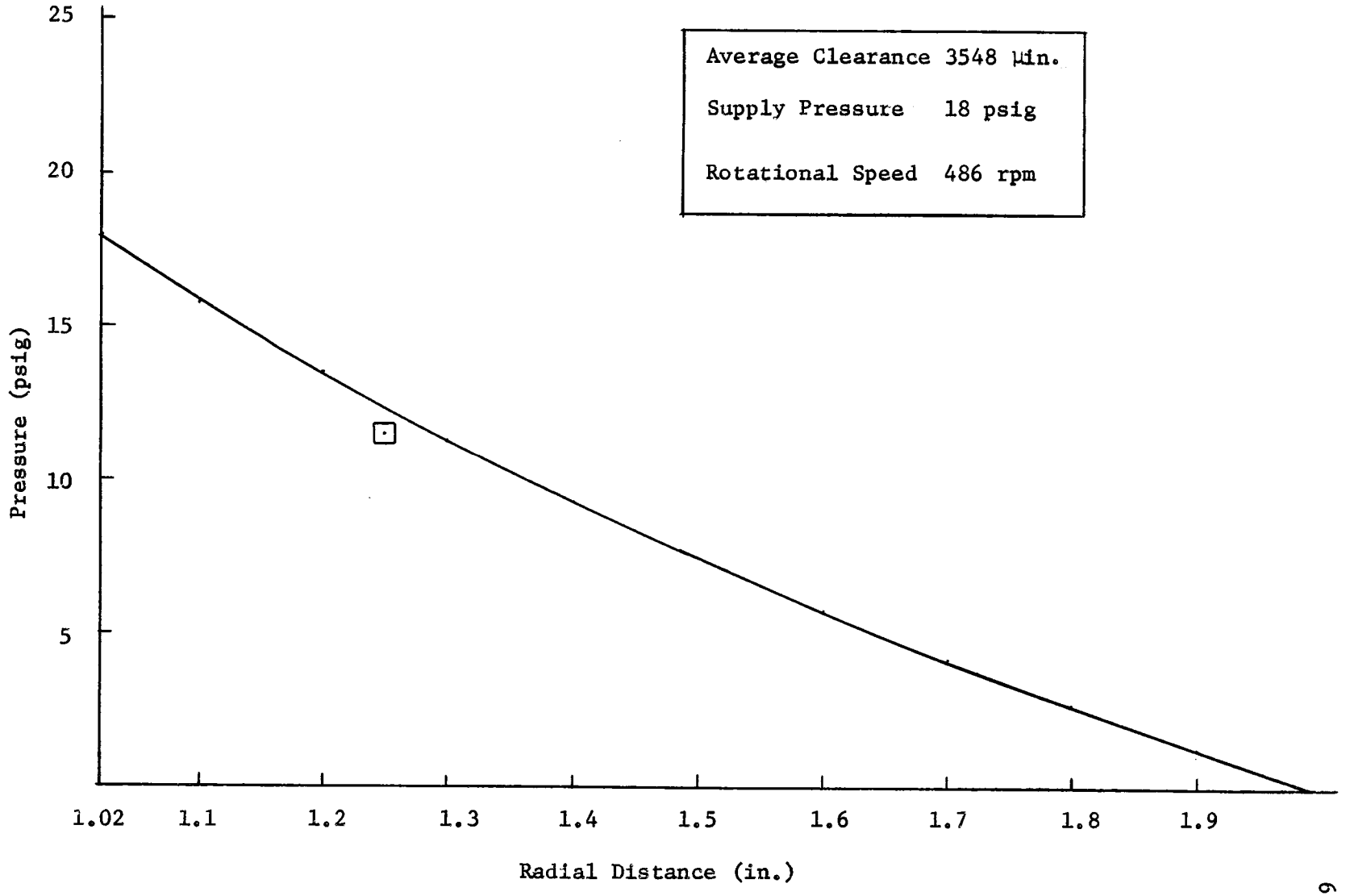


Figure 24. Interface Pressure vs Radial Distance (Run 3).

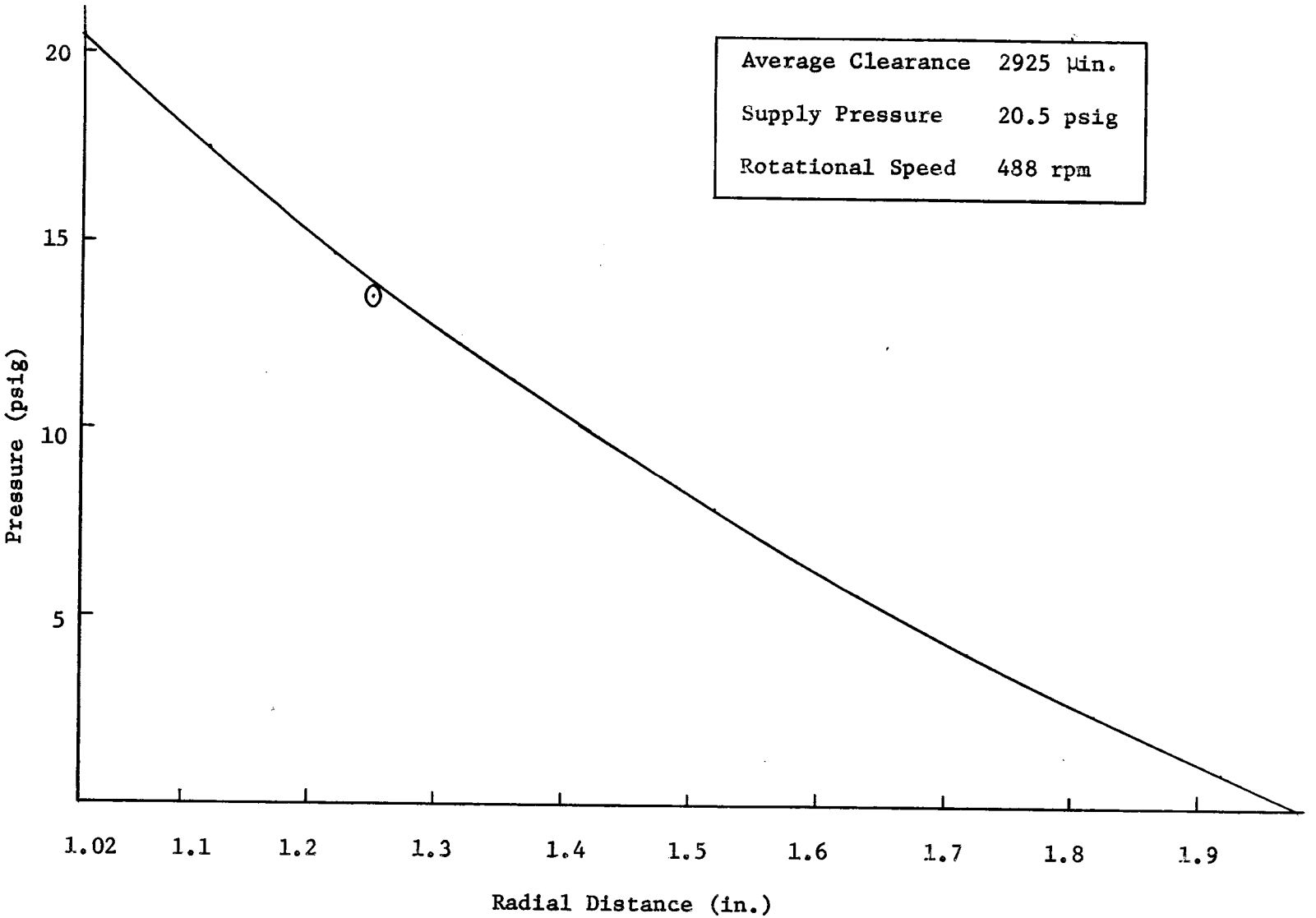


Figure 25. Interface Pressure vs Radial Distance (Run 4).

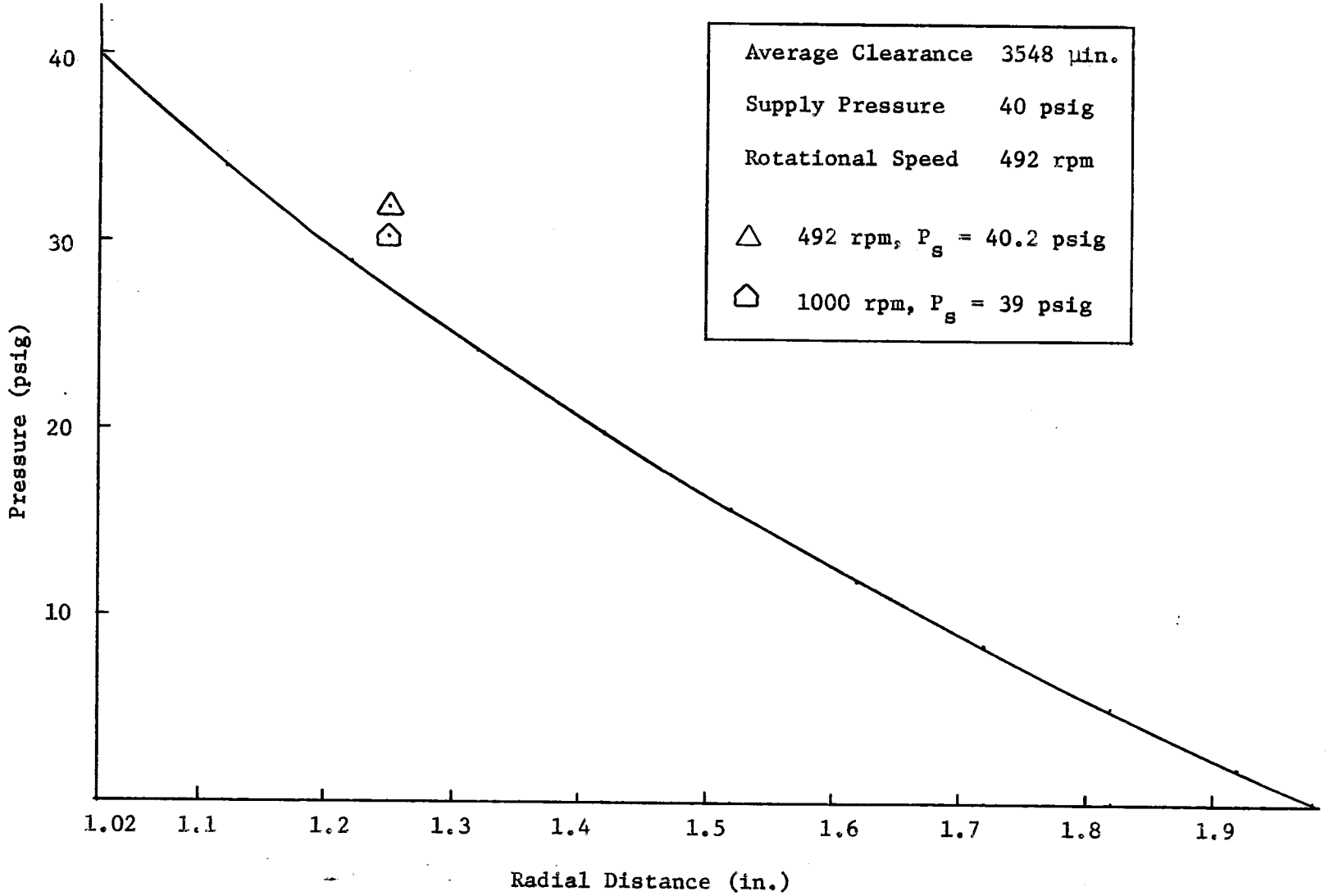


Figure 26. Interface Pressure vs Radial Distance (Runs 5, 6).

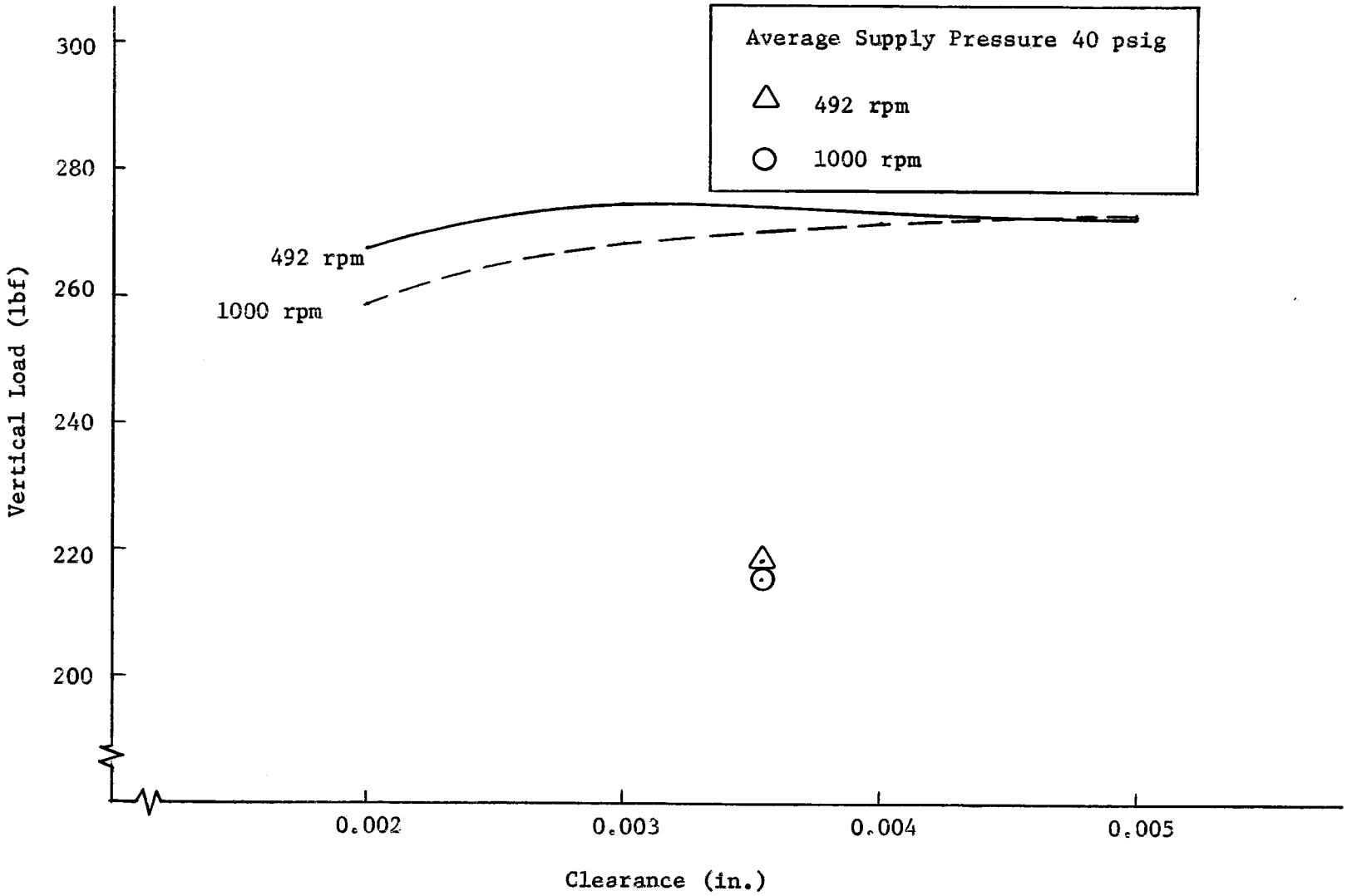


Figure 27. Seal Vertical Load vs Clearance (Runs 5, 6).

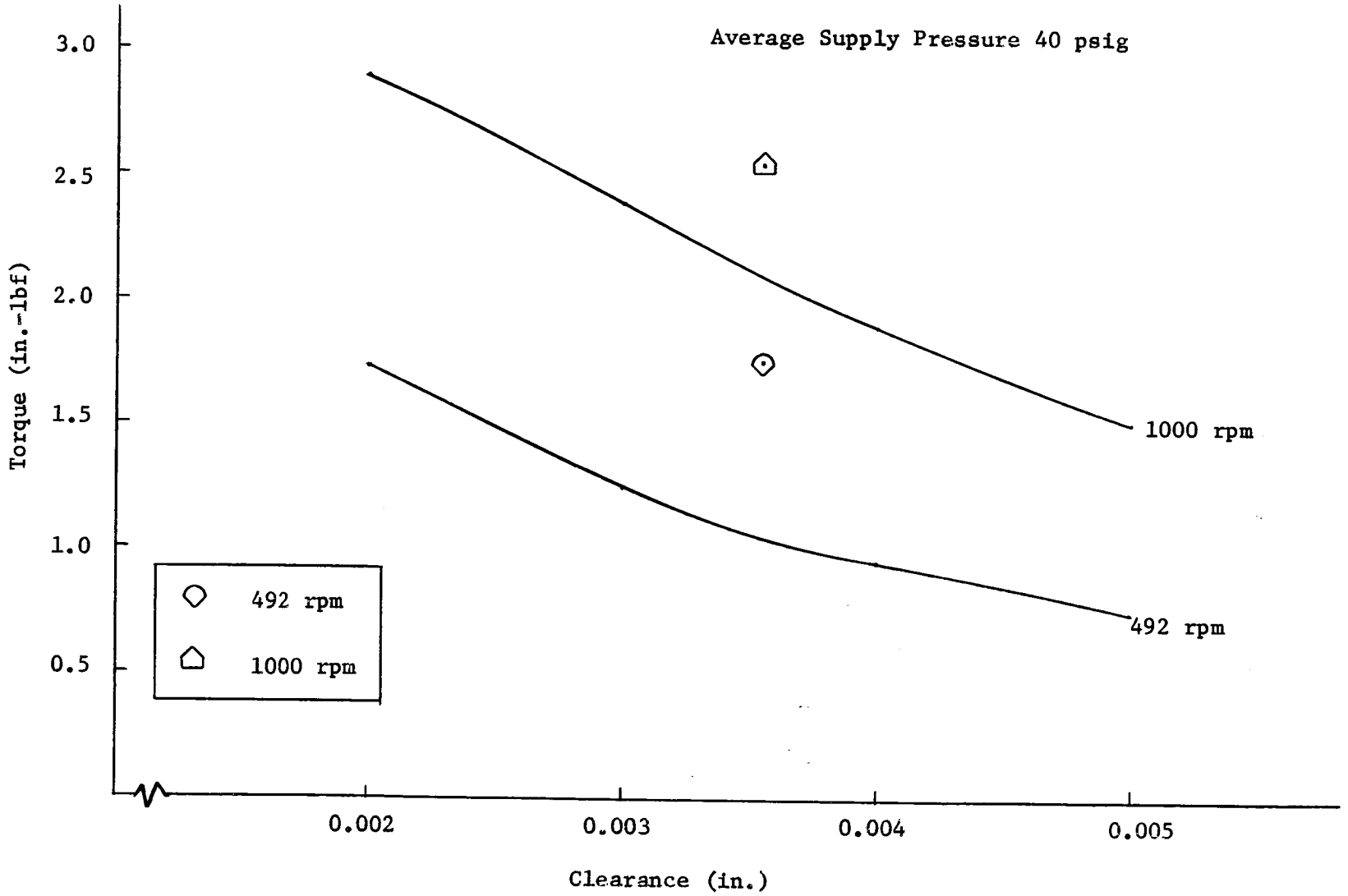


Figure 28. Seal Torque vs Clearance (Runs 5, 6).

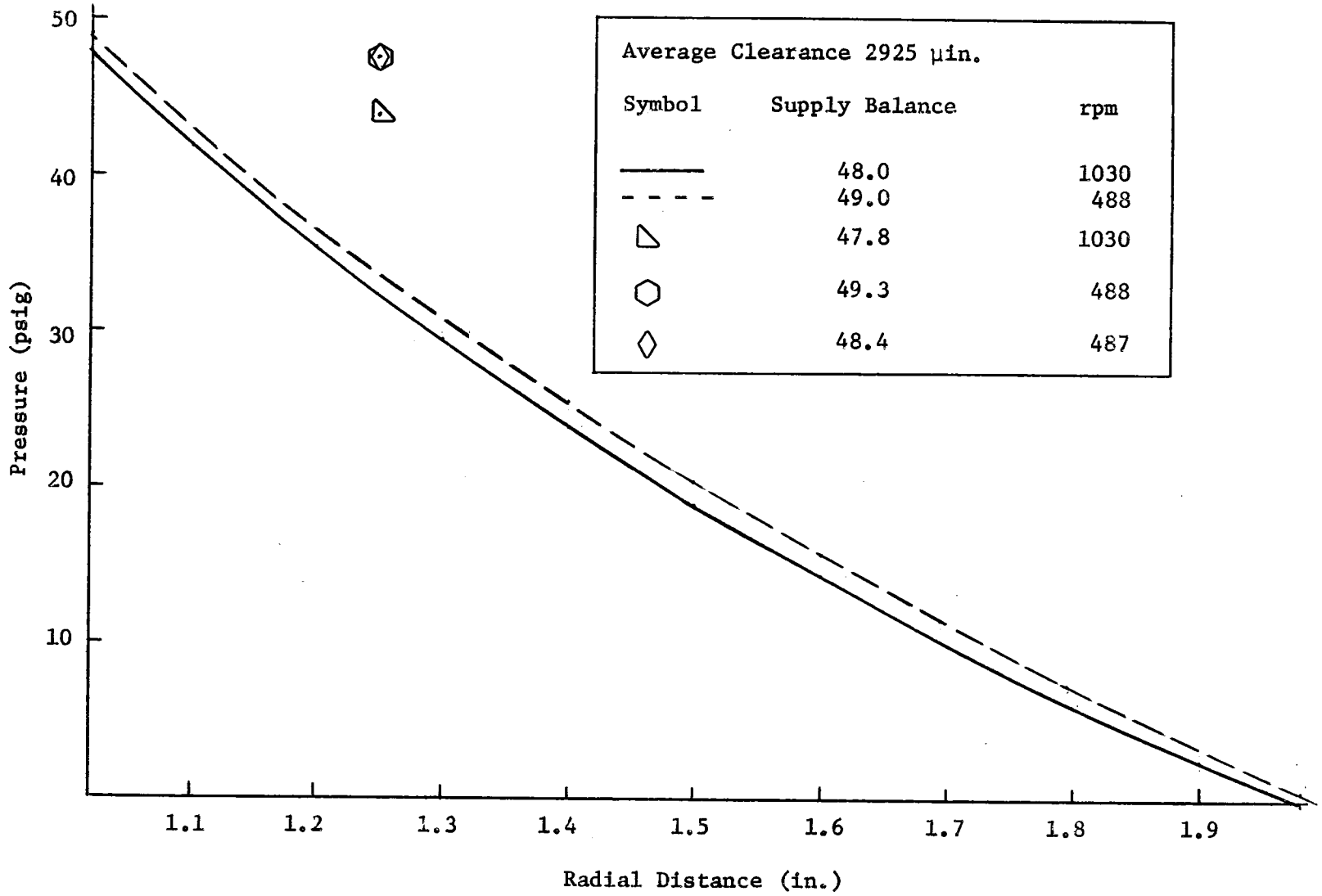


Figure 29. Interface Pressure vs Radial Distance (Runs 7, 8, 9).

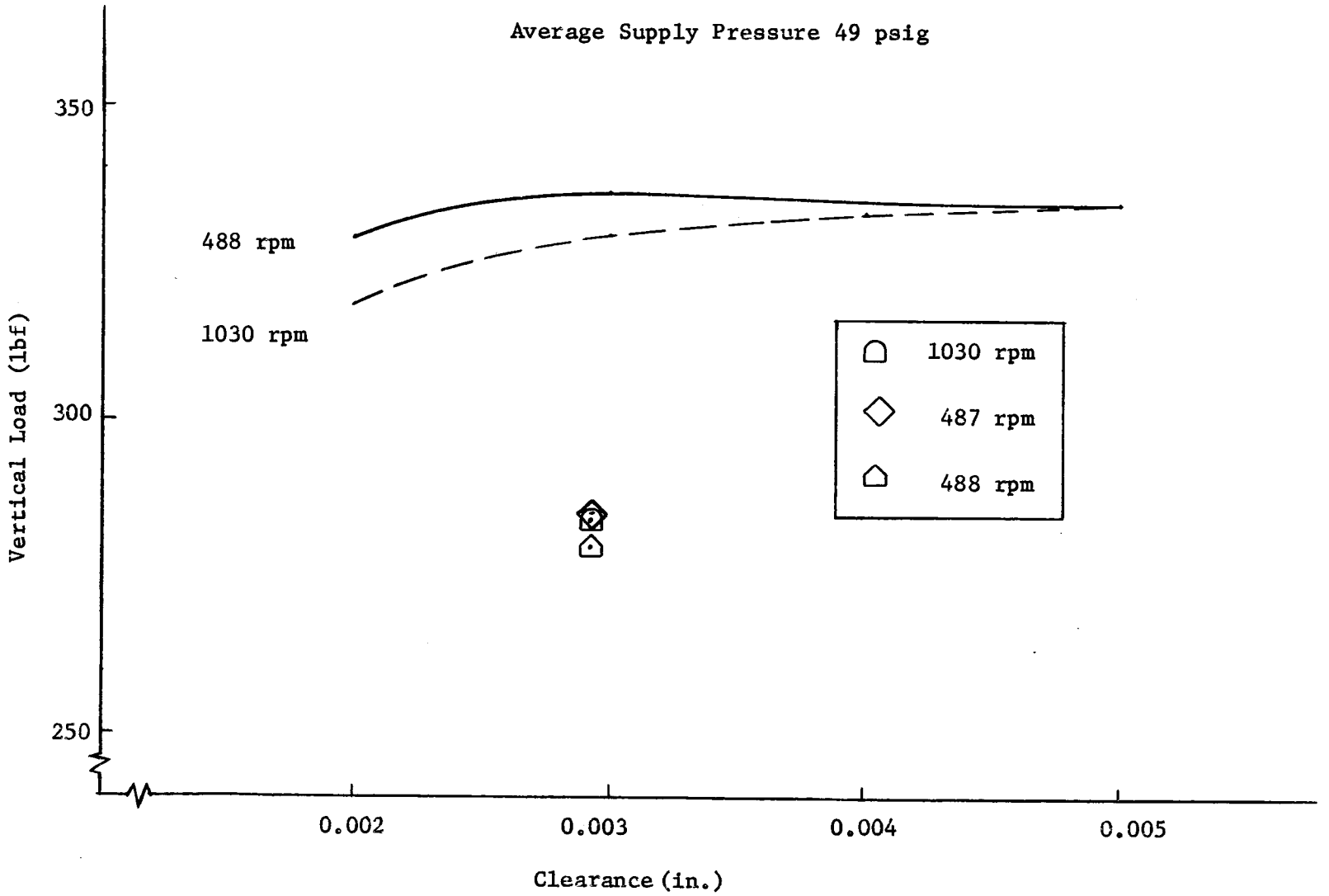


Figure 30. Seal Vertical Load vs Clearance (Runs 7, 8, 9).

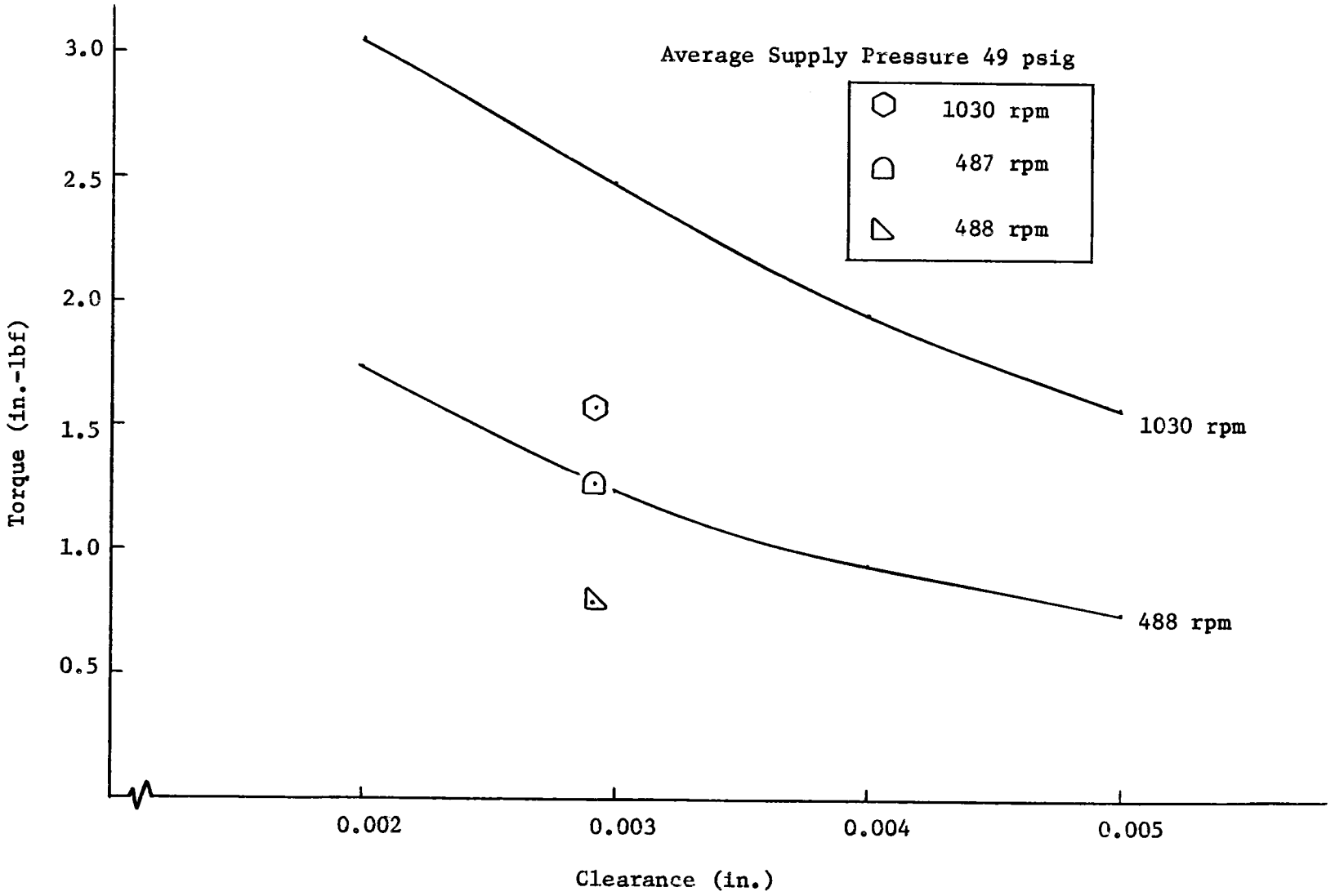


Figure 31. Seal Torque vs Clearance (Runs 7, 8, 9).

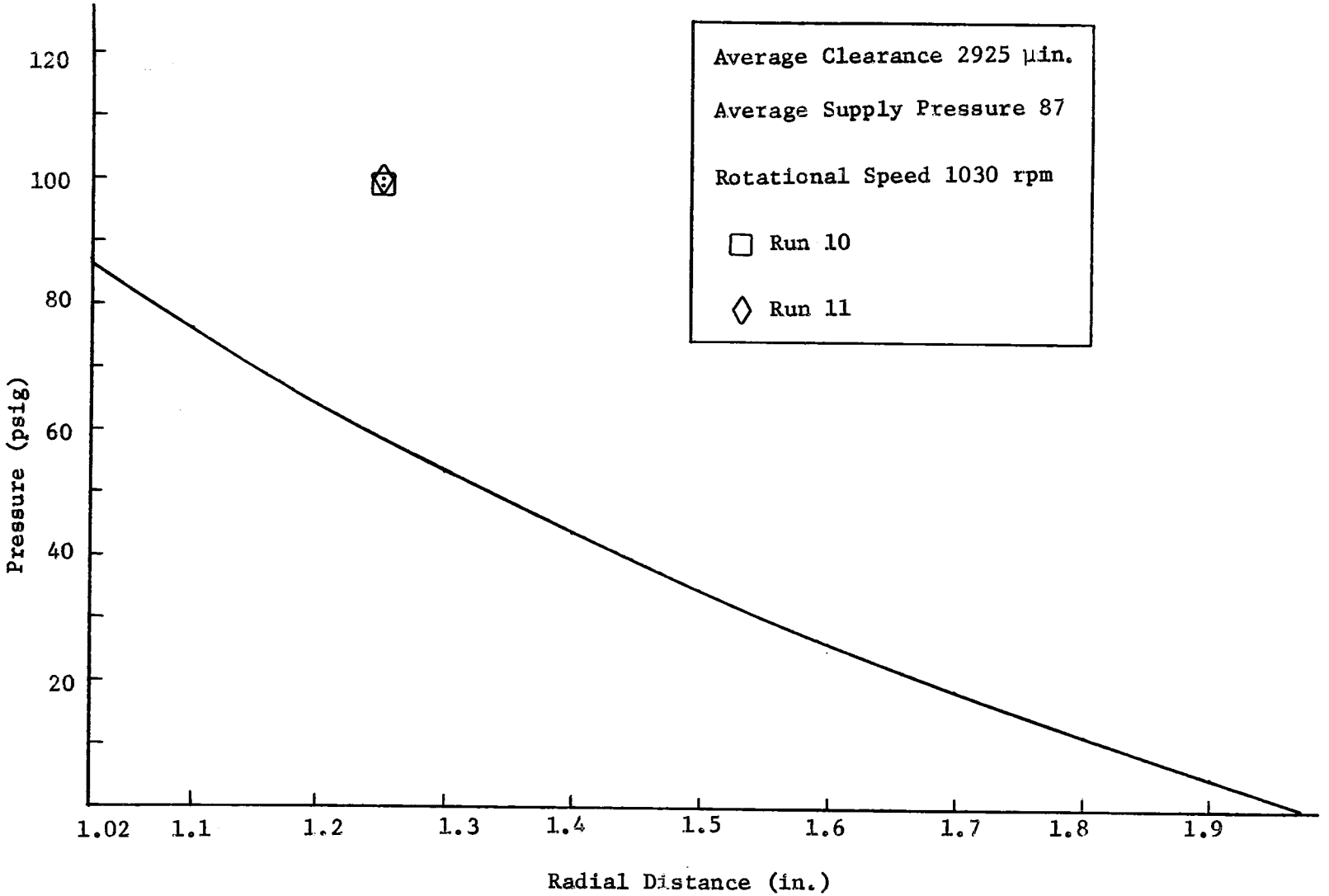


Figure 32. Interface Pressure vs Radial Distance (Runs 10, 11).

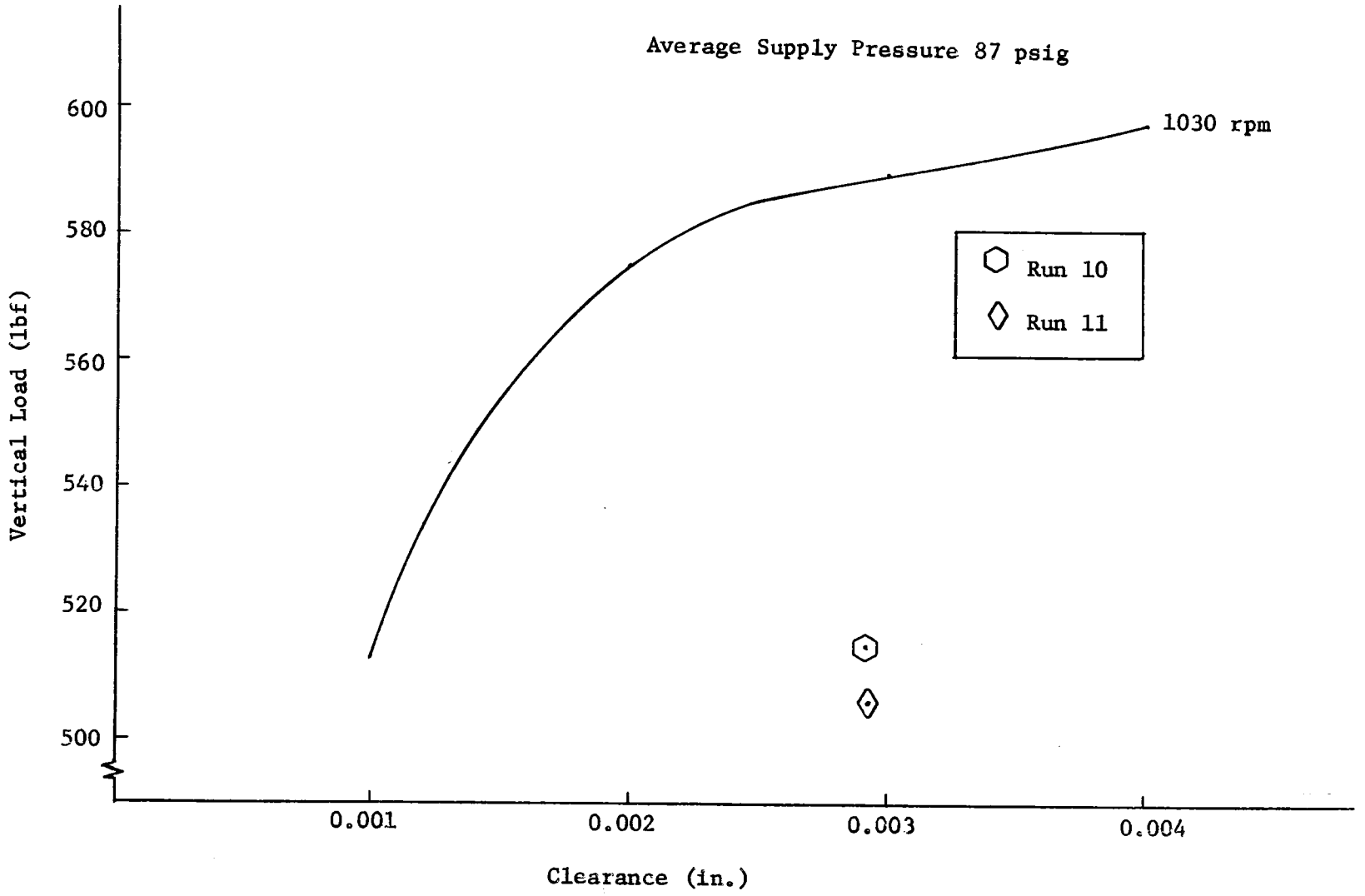


Figure 33. Seal Vertical Load vs Clearance (Runs 10, 11).

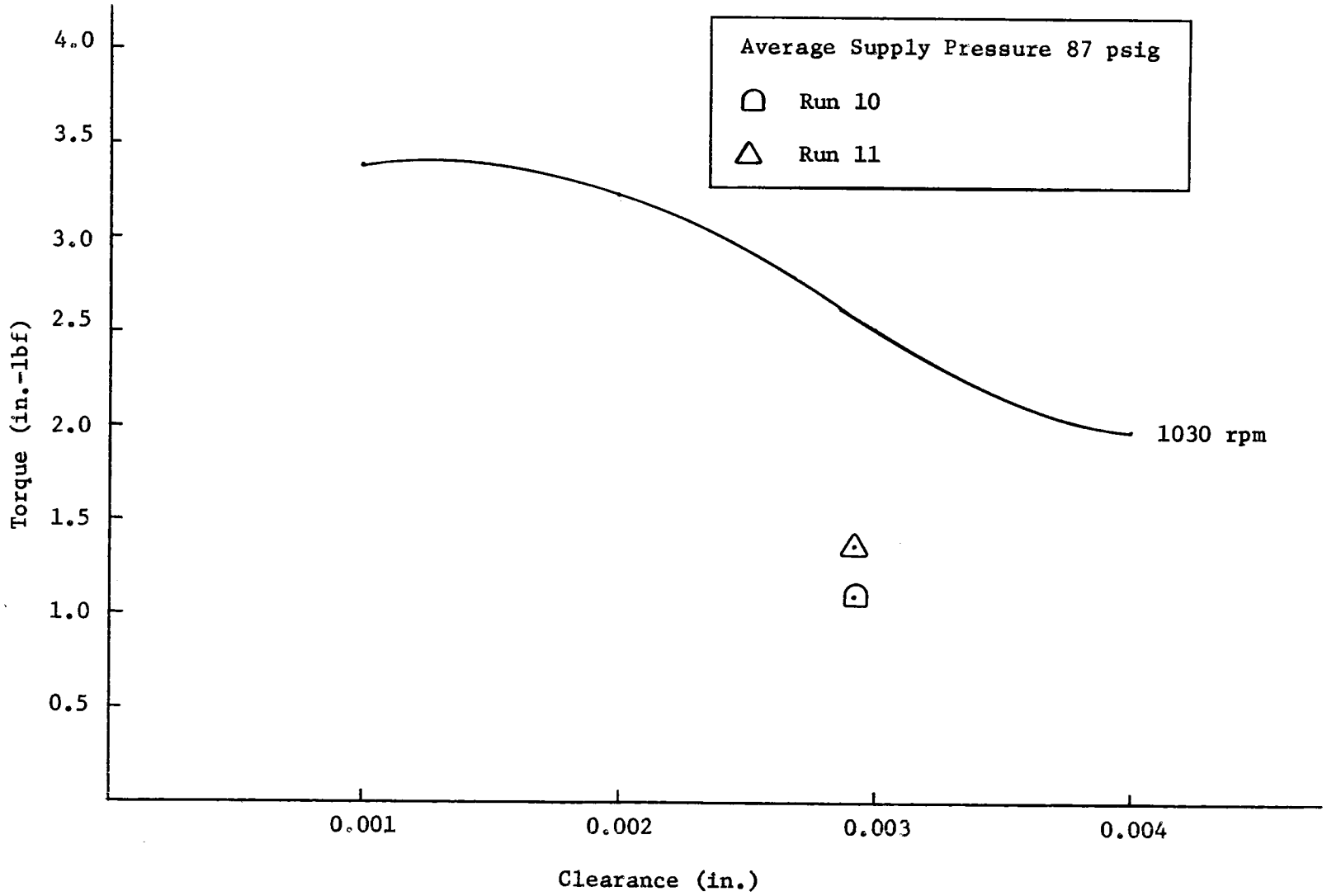


Figure 34. Seal Torque vs Clearance (Runs 10, 11).

The measured vertical load is consistently lower than the predicted results. As the supply pressure increases, the percentage difference decreases. For example, at a supply pressure of 16.5 psig the difference is roughly 25% but at a supply pressure of 87 psig the difference is only 13%. The torque measurements in this investigation are very inconsistent with the predicted results. The measured torque ranges from 88% higher than the predicted torque at a supply pressure of 16.5 psig to 50% lower than the predicted torque at a supply pressure of 87 psig. At two test conditions the torque values compare very well as shown by Figures 23 and 31, pages 66 and 74.

It is believed that the calibration constants caused the inconsistency in the comparison between the computer predicted values and the experimental values, especially for the vertical load and the torque. For the first tests in this investigation the calibration constants for the vertical load and the torque were 538 lbf/in. deflection and 176 in.-lbf/in. deflection, respectively. The galvanometer deflections were measured by a scale graduated in hundredths. As the representative data in Table II, page 63, shows, some of the measured torque values were 1.76 in.-lbf or less which corresponds to a total deflection of 0.01 in. The calibration constants for later runs were 547 lbf/in. deflection and 35.3 in.-lbf/in. deflection for the vertical load and the torque, respectively. This represented some improvement in the torque determination; however, an error in the scale reading of 0.01 in. still produced an error in the torque of 0.35 in.-lbf. When compared

to the data, these discrepancies could represent a significant portion of the measured values.

Extensive presentation of the temperature measurements obtained in this investigation has been omitted due to the consistency of the data. Figure 35 gives a typical indication of the temperature results. It should be pointed out that the computer predicted results are the actual fluid temperatures, but the measurements in this investigation were of the diaphragm temperature. For the small temperatures measured, the diaphragm temperature is representative of the actual fluid temperature as shown by Ghorashi (7).

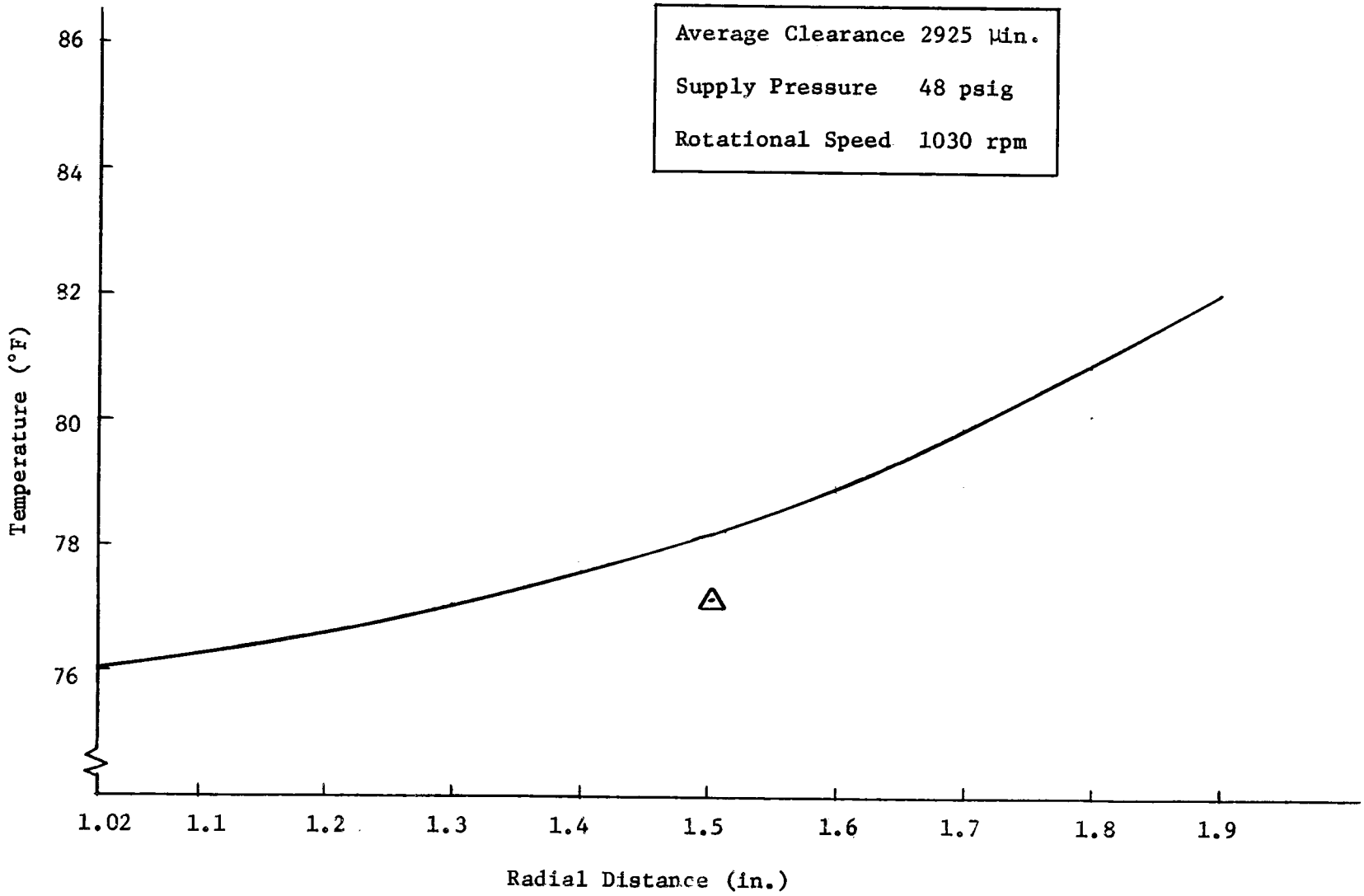


Figure 35. Temperature vs Radial Distance (Run 7).

CHAPTER V

CONCLUSIONS AND SUGGESTIONS

As mentioned in the previous chapter, these tests were limited to relatively large interface clearances. This was due to the surface of the stationary seal. The resulting small values of friction torque indicated (as was proven) correspondingly small changes in the fluid temperature. Consequently, any temperature effects on the measurement of interface pressure or clearance were neglected. Very little work has been done on the temperature effects of the clearance probes. This effect should be investigated further before any testing is done at smaller clearances. The clearance probes were found to be pressure sensitive indicating a larger clearance at increased supply pressures. Since the determined vertical loads were inadequate to cause any movement of the stationary support apparatus, the clearance was determined from the actual measured clearances before applying the pressure to the oil reservoir. If the pressure could have been monitored at the same radial location, the clearance data could have been corrected. The measurement of interfacial pressures by the capacitance method provided numerous problems and uncertainties in the correctness of the results. The fabrication of the diaphragm has overwhelming effects on the pressure measurements.

The transducer which was used to monitor the supply pressure provides an excellent means of acquiring better interface pressure data. A new stationary seal is in the fabrication process which will have the transducers imbedded in the surface like the pipe plug used in this investigation. This will allow a more accurate and extensive analysis of the pressures in the interface region.

The installation of the clearance probes should be revised also. Some work has already been done in this area by investigating the use of new bonding compounds. The new compound should be such that it allows little or no deflection of the diaphragm due to applied pressure. The epoxy used in this investigation allowed considerable deflection.

A new oil supply system has been designed to provide greater fluid capacity and to allow a measurement of the oil flow rate. This will increase the time of operation also. The new system will allow the reservoir to be refilled without shutting down the experiment.

It is suggested that the test rig be calibrated for low torque values (0-10 in.-lbf). This will provide increased accuracy in interpreting the torque data. An increased scale of operation will result in a calibration constant for torque of approximately 2 in.-lbf/in. deflection or less instead of the 35 in.-lbf/in. deflection used in the latter portion of this investigation. The vertical load scale can be increased simply by increasing the amplifier gain as was done for the torque.

The purpose of this investigation was to establish an experimental procedure to allow a complete description of radial face seal characteristics and to develop a working knowledge of the associated equipment involved in the experimental analysis. A procedure has been developed and if the suggestions presented in this chapter are implemented, an accurate experimental investigation of the radial face seal should be forthcoming.

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APPENDICES

APPENDIX A

CALIBRATION RESISTOR CALCULATIONS

The actual values of the calibration resistors for all the strain gage inputs for this investigation are given below. The Rc terms are actually Rc + Ra; however, in most cases the Ra has little significance.

Vertical Load

Maximum indicated strain = 575 μin./in.

Let 4 in. galvanometer deflection = 600 μin./in.

1 in. galvanometer deflection = 150 μin./in.

$$Rc = \frac{Ra}{F \frac{\Delta L}{L}}$$

$$Rc = \frac{E\ Ra}{4M}$$

For a 1.0 in. deflection:

$$Rc_1 = \frac{190}{(3.17)(150 \times 10^{-6})}$$

$$Rc_1 = 399.57\ K\Omega$$

Actual resistor value = 399.6 KΩ

$$399.6\ K\Omega = \frac{E(190)}{4M}$$

$$M = 0.11886 \times 10^{-3}\ E$$

Let E = 4.0 volts

M = 0.4754 mv

Balance amplifier so an input of 0.4754 mv produces a 1.0 in. deflection. For a 4.0 in. deflection:

$$Rc_2 = \frac{190}{(3.17)(600 \times 10^{-6})}$$

$$Rc_2 = 99.89\ K\Omega$$

Actual resistor value = 99.31 KΩ

$$(99.31 + 0.19)K\Omega = \frac{E(190)}{4M}$$

Let E = 4.0 volts

M = 1.909 mv

A 1.909 mv input to the amplifier should produce a 4.0 in. deflection.

Note: It is suggested that the full scale values be used to balance the amplifiers.

Torque

Maximum indicated strain = 469 μin./in.

Let 4 in. galvanometer deflection = 500 μin./in.

1 in. galvanometer deflection = 125 μin./in.

For a 1.0 in. deflection:

$$Rc_1 = \frac{378.8}{(105.6)(125 \times 10^{-6})}$$

$$Rc_1 = 28.696\ K\Omega$$

Actual resistor value = 27.93 KΩ

$$(27.93 + 0.378)K\Omega = \frac{E(378.8)}{4M}$$

$$M = 0.3345 \times 10^{-2} E$$

Let E = 4.0 volts

$$M = 13.38 \text{ mv (1.0 in. deflection)}$$

For a 4.0 in. deflection:

$$Rc_2 = \frac{378.8}{(105.6)(500 \times 10^{-6})}$$

$$Rc_2 = 7.174 \text{ K}\Omega$$

Actual resistor value = 6.782 KΩ

$$(6.782 + 0.378)K = \frac{E(378.8)}{4M}$$

$$M = 13.22 \times 10^{-3} E$$

$$M = 52.9 \text{ mv}$$

An input of 52.9 mv into the amplifier should produce a 4.0 in. galvanometer deflection.

For the latter tests in this investigation the gain on the torque amplifier was increased to increase the scale on the recording paper. If the gain is increased, the deflection caused by Rcal increases for the same bridge excitation. The value of strain which Rcal represents is not changed but only the strain per inch of galvanometer deflection is changed. The amplifier gain was increased such that Rc_1 gave a deflection of 5.0 in. instead of 1.0 in. Then 1.0 in. of galvanometer deflection represented 25 μin./in. instead of 125 μin./in. This was used in interpreting the data for the following tests:

Clearance	2925 μin.
Supply pressure	20.5, 48.0, 87
Rotational speed	487 and 1030 rpm

Supply Pressure

Maximum indicated strain = 500 μin./in.

Let 4.0 in. galvanometer deflection = 500 μin./in.

For a 4.0 in. deflection:

$$Rc_2 = \frac{120}{(2.0)(500 \times 10^{-6})} \qquad Rc_2 = 120\ K\Omega$$

Actual resistor value = 120.5 KΩ

$$120.5\ K = \frac{E(120)}{4M}$$

$$M = 0.2489 \times 10^{-3}\ E$$

Let E = 4.0 volts

$$M = 0.9958\ mv$$

An input of 0.9958 mv to the amplifier should cause a 4.0 in. deflection.

APPENDIX B

CLEARANCE PROBE OPERATING PROCEDURE

The procedure used for operation of the clearance probe systems is described as follows.

System Hook-up

1. Set power supply voltage to +15 volts, then turn supply off.
2. Connect ground (GND) to - on one supply and connect that - to the + on the other supply. (This forms a $\pm$ 15 volt supply.)
3. Connect the unused + of the power supply to the red jack (+ 15 volt input) on each system preamp and readout electronics.
4. Connect the GND used previously on the power supply to the black jack (GND input) on each system preamp and readout electronics.
5. Connect the - (- 15 volt) on the power supply to the yellow jack (- 15 volt input) on each system preamp and readout electronics.
6. Connect signal generator 600Ω output to the frequency counter input using coaxial cable.
7. Connect the signal generator 50Ω output to the null network DRIVE input with 50Ω coaxial cable (RG58).
8. Connect the 1 output of the null network to the 1 input of the probe and the 2 and 3 output of the null network to the 2 and 3 input of the probe using 50Ω coax (RG58).

9. Connect the probe output to the preamp input and the preamp output to the readout electronics input with 50Ω coax.

10. Connect the readout electronics slow output to the voltmeter and connect the GALV output to the data acquisition system (ACC 117 OUT/GALV IN patch panel).

System Turn-on

1. Turn the voltmeters on to the 20 VOLT scale.

2. Turn the oscilloscope power ON.

3. Initial scope settings:

VOLTS/DIV	to 50 m
COUPLING	to AC
VERT MODE	to ALT
TIME/DIV	to 5 μsec
COUPLING	to AC
SOURCE	to CH 1
HORIZ DISPLAY	to A (LOCK KNOBS)

4. Turn the Hewlett-Packard power supply (signal generator) for the probes on.

5. Turn the Hewlett-Packard frequency counter on.

6. Initial counter settings:

SENSITIVITY	to .1 V
GATE SELECTOR	to 1 sec

7. Turn signal generator OUTPUT ATTENUATOR to 1.0 volts.

8. Generator settings:

RANGE	to X10K

AMPLITUDE	to 0.5
FREQUENCY	to 98,574 $\pm$ 2-3 Hz.

System Nulling Procedure

1. Close the power switch to the SCR DRIVE System.
2. Set spindle air supply pressure to 150 psig.
3. Set index mark on rotating seal face.
4. Disconnect oil feed line to stationary seal.
5. Raise the stationary seal to "infinite" spacing ($\sim$1 in.).
6. Connect the scope to "fast output" on the system.
7. Check signal generator output for 98,574 Hz.
8. Adjust R_{adj} and C_{adj} on the null network for a flat line on the scope (flat as possible).
9. Repeat steps 6-8 for each system.
10. Disconnect scope from fast outputs.
11. Lower the stationary seal and unbolt from the support shaft; let it rest on the rotating face.
12. Check the signal generator output for 98,574 Hz.
13. Adjust ZERO on each system to provide a zero reading on the 2 VOLT scale of each voltmeter.
14. Reattach the stationary seal to the support column.
15. Connect the oil supply line to the stationary seal.

Distance Adjustment

1. Adjust the rig to the desired seal clearance by reading the voltmeter reading (sensitivity 0.22 mv/μin.).

2. Install the hold down rig.

3. Actual clearance obtained from voltmeters.

APPENDIX C

INSTRUMENTED SECTION DEFLECTION

The deflection of the instrumented section and the support column due to the vertical load on the stationary seal was analyzed to find what portion of the increased interface clearance was due to the actual deflection of the mounting apparatus and what portion was due to the deflection of the diaphragm under the clearance probes. The following load-deflection relationship was used in this investigation.

$$\delta = \frac{PL}{AE}$$

where

δ = deflection

P = applied load

L = length before loading

A = cross-sectional area

E = modulus of elasticity.

The 0.05 in. thick strain gage attachment section of the instrumented section was analyzed for the maximum load condition (515 lbf) as were the lower portion of this piece and the support column. The resulting deflections at this load were found to be:

Strain gage section	71 μin.
Lower portion	13.5 μin.

Support column	24 μin.
Horizontal Adj columns	11 μin.

Since these values represent about 10% of the indicated increase in the interface clearance, the deflection of the clearance probe diaphragm represented the major cause of the clearance discrepancies.

APPENDIX D

NUMERICAL ANALYSIS OUTLINE

The theoretical analysis of face seals presented by Snapp (14) form the basis of the modified numerical analysis by Swafford (13). An outline of Snapp's work is presented below for the reader's benefit.

The analysis by Snapp for parallel surfaces is based on the following assumptions:

1. Laminar flow conditions exist.
2. The liquid is Newtonian and incompressible.
3. The pressure is constant across the film thickness.
4. The velocity varies in both the radial direction and across the seal face.
5. The viscosity is constant circumferentially and across the seal face.
6. There is no pressure variation nor flow in the tangential or circumferential direction, or two dimensional flow exists.

By summing the pressure, shear, and centrifugal forces on an element of unit volume the governing equation was found to be:

$$\frac{dp}{dr} - \mu\frac{\partial^2 u}{\partial y^2} - \rho r\omega^2\left(\frac{y}{h}\right)^2 = 0. \qquad \text{(D-1)}$$

This equation was integrated and the boundary conditions applied to produce a velocity distribution across the film.

$$V = \frac{1}{2\mu}\frac{dp}{dr}(y^2 - hy) - \frac{\rho r\omega^2}{12\ \mu h^2}(y^4 - h^3 y) \qquad \text{(D-2)}$$

The leakage through the seal faces was expressed as:

$$Q = 2\pi r \int_0^h v\,dy \qquad \text{(D-3)}$$

Equations D-2 and D-3 were then combined and integrated to produce Equation D-4.

$$\frac{dp}{dr} = \frac{3\rho r\omega^2}{10} - \frac{6\ \mu Q}{\pi r h^3} \qquad \text{(D-4)}$$

Integrating between the limits of P_1 at R_1 and P_2 at R_2 produced:

$$P_2 - P_1 = \frac{3\rho\omega^2}{20}(R_2^2 - R_1^2) - \frac{6\ \mu Q}{\pi}\int_{R_1}^{R_2}\frac{dr}{rh^3} \qquad \text{(D-5)}$$

Equation D-5 provided an expression for the leakage as:

$$Q = \frac{-\pi h^3}{6\mu \ln\left(\frac{R_2}{R_1}\right)}\left[P_2 - P_1 - \frac{3\rho\omega^2}{20}(R_2^2 - R_1^2)\right] \qquad \text{(D-6)}$$

The pressure at any radial position follows as a general expression of Equation D-5.

$$p = P_1 - \frac{6\ \mu Q}{h^3\pi}\ln\left(\frac{r}{R_1}\right) + \frac{3\rho\omega^2}{20}(r^2 - R_1^2) \qquad \text{(D-7)}$$

The total load on the seal face was obtained by the following integration:

$$W = 2\pi\int_{R_1}^{R_2} pr\,dr \qquad \text{(D-8)}$$

The assumptions used in the analysis by Swafford (13) are the same as those used by Snapp (14) except for assumption 5. Equations D-1 through D-4 remained the same. In his analysis, Swafford solved Equation D-4 for incremental changes in radius, Δr, to produce:

$$P_{r + \Delta r} - P_r = \frac{3}{20} \omega^2 \rho (2r\Delta r + \Delta r^2) - \frac{6m\nu}{\pi h^3} \ln \left(\frac{r + \Delta r}{r}\right) \qquad (D\text{-}9)$$

Newton's law of viscous flow was then used to evaluate the force at any radial position.

$$dF = \mu 2\pi r \, dr \, \frac{V\omega}{h} \qquad (D\text{-}10)$$

where

$$V\omega = rw_s.$$

An expression for the seal moment was then found to be:

$$dM = \left(\frac{2\pi\omega\mu}{h}\right) r^3 dr \qquad (D\text{-}11)$$

Equations D-10 and D-11 then provided a means of determining the load and torque by integrating between the limits of r_1 to $r_1 + \Delta r$. The friction energy was expressed as:

$$E = M\omega \qquad (D\text{-}12)$$

Swafford assumed that no heat was conducted into the seal or that the oil absorbed all of the friction energy. A temperature rise was then predicted using:

$$\Delta T = \frac{E_f}{\dot{m} c_p J} \qquad (D\text{-}13)$$

This temperature rise from r_1 to $r_1 + \Delta r$ was used to evaluate the oil properties at $r_1 + \Delta r$. The continuity equation was then

used to provide a check on the Δr increment. If there was a significant difference between the mass flow rate at the outer edge of the increment and the starting point, the entire procedure was repeated with a smaller Δr increment. The conditions of 0 psig at the outer seal boundary was the governing factor in the program analysis.

VITA

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