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The University of Tennessee
Department of Mechanical and Aerospace Engineering

THEORETICAL AND EXPERIMENTAL STUDIES OF VISCO-TYPE SHAFT SEALS

First Semi-annual Progress Report
April 15, 1964 - October 15, 1964

by

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National Aeronautics and Space Administration
under
Research Grant NsG-587

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Knoxville, Tennessee

ABSTRACT

This report, the first of a series, outlines the progress made on an analytical and experimental investigation of the visco-type shaft seal. This research is being conducted under Research Grant NsG-587 sponsored by The National Aeronautics and Space Administration.

The visco seal has had limited study in the United States and a more extensive study abroad. A critical review of all available data led to the identification of specific areas which require analytical and/or experimental study.

The design of an experimental test facility, which is presently being constructed, is described.

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I. INTRODUCTION

An investigation embracing the theory and performance of the visco-type shaft seal under laminar and turbulent conditions was started on April 15, 1964 at The University of Tennessee in the Department of Mechanical and Aerospace Engineering. The investigation is being conducted for The National Aeronautics and Space Administration under Research Grant NsG-587, and this report presents the progress of the investigation for the period - April 15, 1964 through October 15, 1964.

The initial proposal submitted to NASA included three phases of work (1). Briefly these areas of investigation were:

I. Survey and critical review of international literature on dynamic sealing.

II. Theoretical and experimental study of the buffered bushing seal.

III. Theoretical and experimental study of the visco seal.

At the request of NASA the initial proposal was modified to delete the work on the buffered bushing seal and to expand the effort on the visco seal (2). Several months after the proposal was submitted to NASA, personnel of the General Electric Advanced Technology Laboratories published an extensive two-volume bibliography on seals (3, 4). The reports, one dealing with unclassified abstracts provided by ASTIA and the other treating the open literature, cover both static and dynamic seals and are quite complete and carefully prepared. In view of the high calibre and completeness of the bibliographies cited, it appeared that further work on Phase I of the proposal was an unnecessary duplication of effort. Mr. Robert L. Johnson and Mr. Joseph Maltz of NASA were in accord with this view and it was decided to limit the effort outlined in Phase I to a continuing critical review of the literature relative to the visco seal.

II. OBJECTICES

Following the modifications outlined in the previous section, the general objective of this program became the theoretical and experimental study of the visco seal under laminar and turbulent conditions. The specific tasks include:

1. Experimental verification of the optimum seal geometry suggested by existing laminar visco seal theories.
2. Development of a turbulent theory of visco seal performance.
3. Determination of the optimum seal geometry for turbulent conditions.
4. Experimental evaluation of the sealing coefficients and dissipation function under turbulent conditions.
5. Theoretical and experimental evaluation of the effect of eccentricity on the sealing coefficient and dissipation function under laminar and turbulent conditions.
6. Study of the cause of "seal break" and its effect on visco seal performance.
7. Investigation of the ability of the visco seal to sustain radial hydrodynamic loads and to generate self-aligning forces.
8. Investigation of the effect of cyclic pressure changes on visco seal performance.
9. Evaluation of visco seal performance when non-Newtonian fluids are employed as the sealant.
10. Study of the visco seal performance, under both laminar and turbulent conditions, when the sealant fluid contains both the liquid and vapor phases.

11. Investigation of visco seal performance when operated at ambient pressures below the vapor pressure of the sealant.
12. Determination of the effect of thread shape on visco seal performance.

III. ACTIVITIES

During the period covered by this report the research effort has been principally directed toward:

1. Critical analysis and evaluation of previously published data on the visco seal and related devices.
2. Analytical study with primary emphasis being given to the development of a turbulent theory of the visco seal.
3. Experiment designs and programmed calculation of visco seal performance based on an accepted laminar visco seal theory.
4. Design and construction of experimental facilities.

Analysis

A survey and review of the technical literature dealing with the visco seal and visco pump has been prepared by the author (5). Since this report considered technical literature published through December 1961 only, additional analysis of the literature was made to include recent work. The status of visco seal studies may be briefly summarized as follows:

1. The visco seal has been analyzed by several investigators and a number of relations have been presented for predicting the sealing performance under laminar conditions (5). The investigations have ranged from purely empirical efforts to sophisticated analysis with experimental verification. However, the various equations representing sealing performance have been remarkably similar and can be characterized by the equation,

$$\Lambda = \frac{6\mu UL}{pc^2}, \tag{1}$$

where Λ is defined as the sealing coefficient. While Λ is usually indicated to be a function of the visco seal geometry, the various investigators have presented considerably different estimates of the nature of the equation,

$$\Lambda = f(\alpha, \beta, \gamma). \quad \text{Refer to Figure 1} \tag{2}$$

Thus, there is not good agreement as to the optimum geometry for a visco seal under laminar conditions.

2. The sealing performance under turbulent conditions has been studied to a limited extent. A theory, based on turbulent lubrication theory, has been suggested but data are too meager to permit a meaningful correlation (6, 7). The optimum geometry for turbulent operation has not been investigated.

3. The power loss in a visco seal with the attendant heat dissipation problem has been acknowledged by many investigators to be an important consideration. However, power loss data have resulted from only two investigations (6, 10). In these two studies the design of the test units resulted in extraneous friction losses being present in the torque measuring procedure which reduced the precision of the data. The power loss or frictional dissipation may be expressed as

$$q = \frac{\pi\mu U^2 DL}{c}\phi, \tag{3}$$

where ϕ is the dissipation coefficient and, as was the case with Λ, is dependent upon the seal geometry. From an analysis patterned after that of Boon and Tal (8) it can be shown that

$$\Phi = \phi' + \phi'', \qquad (4)$$

where ϕ' represents the loss due to Couette flow and ϕ'' represents the loss due to Poisseuille flow.

$$\phi' = f(\beta, \gamma), \qquad (5)$$

and

$$\phi'' = f(\alpha, \beta, \gamma). \qquad (6)$$

It has been suggested that ϕ'', due to Poisseuille flow, is small and could be neglected (6). A programmed computation over a wide range of α, β, and γ indicates that ϕ''/ϕ' varies from a negligible value of 0.5% to a rather significant value of 67% and should not be neglected.

4. The effect of seal eccentricity has not been considered in any of the reported investigations. The assumption made in the development of sealing performance equations is that the seal operates concentrically. Eccentricity is frequently cited as a possible reason for the deviations found between theory and experiment. Reported deviations range from 15% to 50%. McGrew and McHugh included an eccentricity correction factor in their equation for the sealing coefficient (6). The assumption was made that the flow varies with eccentricity in a visco pump in the same way that flow in a plane annulus varies with eccentricity. Thus,

$$Q_{\epsilon} = Q_o(1 + 1.5\,\epsilon^2). \qquad (7)$$

However, the eccentriticy was not measured and the proposed correction was not subjected to experimental verification.

5. Only two experimental studies, those of Frossel (7) and Asanuma (9), have included sufficient tests to observe the effect of geometry on seal performance. In these two studies eccentricity and power loss measurements were not made and sufficient data are not available to verify the prediction of optimum geometry for a visco seal.

6. An important but somewhat isolated observation of a seal break was reported by McGrew and McHugh (6). The term "seal break" is utilized to describe a minute leak condition which was reported to have occurred in laminar and turbulent flow. The cause of the seal break is not known but it is believed to depend, at least in part, upon surface tension of the sealing fluid. No other investigators have reported this phenomena which could be an important limitation for seals used in systems having fixed and limited inventories of sealant fluid.

Following the review, problems requiring analytical and/or experimental study were identified and specific tasks were established as shown in the previous section.

An analysis of the laminar visco seal has been completed and programmed for machine computation. The analysis follows closely the work of Boon and Tal (8) which is considered to be the most rigorous and complete study presently available. The performance parameters Λ and Φ have been computed for 2300 different seal geometries. Geometries considered are in the following ranges of variables:

$\alpha = 5° - 20°$, $\beta = 2 - 19$, $\gamma = 0.1 - 0.8$

An analysis of the turbulent visco seal has been started. In this analysis, as is true for all studies of turbulent flow, some factors must be determined from a number of precise experiments. Fractional factorial experiment designs are presently being studied in order to minimize the number of visco seal test specimens required.

Design of Test Equipment

The major effort during this period has been devoted to the design and construction of an experimental test facility. The specifications for the visco seal experimental ranges were selected as follows:

Reynolds Number	50 - 16,000 approximately
Diameter	1.25 inches
Length	0 - 4 inches
Speed	300 - 30,000 rpm
Viscosity	0.65 - 10 centistokes (silicone fluids)
β	2 - 19
α	5° - 20°
γ	0.1 - 0.8

While these specifications are arbitrary, the selection permits an experimental map covering the areas of immediate and future interest.

The most serious limitation of currently available data is the absence of precise measurements of the power loss and the seal eccentricity. The decision was made to design and construct, if the design proved to be economically feasible, a test stand which would provide for precise determination of these important factors. The basic design concept is shown on Drawing No. VS-5-50. The use of flow-control valve compensation of hydrostatic bearings which support the test sleeve allows the eccentricity to be adjusted and permits the sleeve torque to be measured with a minimum of extraneous frictional effects. The eccentricity can be adjusted without disassembly of the test sleeve and screw. The preliminary design study indicated the design concept to be technically feasible and the cost to be reasonable.

The schematic arrangement of the test facility is shown on Drawing No. VS-1A. The film stiffness of the hydrostatic bearings has been computed to be 9.42×10^6 lb_f/in. in the radial direction. The torque measuring system makes use of bonded wire strain gages and has been designed to indicate torque values as low as 3.25×10^{-3} in-lb_f. The eccentricity of the seal is measured and monitored by four inductance probes which indicate x and y components of the film thickness.

The experimental facility is made up of three basic groups of components which are: (a) the visco seal test stand, (b) the hydraulic system, and (c) the instrument and control systems. The flow diagram of the complete system is shown on Drawing No. VS-5-51.

The status of the experimental facility is as follows:

1. The hydraulic system is 90% complete.
2. The visco seal test stand is 25% complete.
3. Water, air and electric service connections have been installed in test area and checked.
4. All major system components and instruments are on hand or are due to be received by October 31, 1964.

Activity Level

The personnel active in the visco seal research are as follows:

W. K. Stair, Director

April 15 - June 14	1/4 time
June 15 - Sept. 14	Full time
Sept. 15 - June 14	1/4 time

C. F. Bowman, Graduate Assistant

June 15 - Sept. 14	1/2 time
Sept. 15 - June 14	1/3 time

R. H. Hale, Graduate Assistant

June 15 - Sept. 14	1/2 time
Sept 15 - June 14	1/3 time

The level indicated above is scheduled for the remainder of the academic year through June 14, 1965. However, an additional graduate assistant is being actively sought.

IV. PROPOSED SCHEDULE

During the period October 16, 1964 - April 15, 1965 the following tasks are scheduled to be completed:

1. Complete fabrication and assembly of hydraulic system and visco seal test stand.
2. Make operation check of complete facility.
3. Conduct performance test and/or calibrate:
    a. Torque measuring system.
    b. Eccentricity control and measuring system.
    c. Temperature, pressure, and speed instrumentation.
4. Obtain viscosity-temperature data for test fluids other than water.
5. Prepare test spindles No. 1 through No. 10.

6. Conduct reproducibility test series using test spindle No. 1 ($\beta = 3.86, \gamma = 0.625, \alpha = 14.5°$).

7. Start the test series, using test spindles No. 2 through No. 10, to produce data required for items 1, 3, 4, 5 and 6 listed in Section II.

8. Prepare report on the laminar visco seal.

While not scheduled for completion during the next reporting period, effort will continue on items 2, 6, 9, and 10 listed in Section II.

NOMENCLATURE

a	axial length across load, inches
b	axial length across groove, inches
c	radial clearance, inches
D	major screw diameter, inches
h	screw thread depth, inches
L	length of seal, inches
p	pressure rise across seal, lbf/in^2
q	power loss or frictional dissipation, in-lb_f/sec
Q	flow, in^3/sec
V	surface velocity, in/sec
x,y,z	coordinates
α	screw thread helix angle, degrees
β	(h+c)/c, dimensionless
γ	b/(a+b), dimensionless
ϵ	eccentricity ratio, dimensionless
Λ	sealing coefficient, dimensionless
ϕ	dissipation function, dimensionless
μ	absolute viscosity, lb_f-sec/in^2
η, ξ	coordinates

REFERENCES CITED

1. Stair, W. K., "Fundamental Study of Clearance Type Dynamic Seals," A research proposal, The University of Tennessee, February 1963.

2. Letter communication, W. K. Stair to W. A. Greene, of NASA, December 27, 1963.

3. George, R. L., R. C. Elwell, "Bibliography of ASTIA Literature on Seals," The General Electric Advanced Technology Laboratories, Report No. 63GL101, July 2, 1963.

4. George, R. L., R. C. Elwell, "Bibliography of Open Literature on Seals," The General Electric Advanced Technology Laboratories, Report No. 63GL102, July 2, 1963.

5. Stair, W. K., "The Visco Seal - A Survey," Report ME-5-62-2, The University of Tennessee, March 1962.

6. McGrew, J. M., J. D. McHugh, "Analysis and Test of the Screw Seal in Laminar and Turbulent Operation," The General Electric Advanced Technology Laboratories, Report No. 63GL66, May 3, 1963.

7. Frossel, W., "Hochtourige Schmierolpumpe," Konstrucktion, Vol. 12, No. 5, 1960, pp. 195-203.

8. Boon, E. F., S. E. Tal, "Hydrodynamische Dichtung fur rotierende Wellen," Chemie-Ing.-Technik., Vol. 31, No. 3, Jan. 31, 1959, pp. 202-212.

9. Asanuma, T., "Studies on the Sealing Action of Viscous Fluids," International Conference on Fluid Sealing, Paper A3, April 17-19, 1961, BHRA, Harlow, Essex, England, 26 pages.

10. Hughes, D. P., "Shaft Seal For High Gas Pressures," International Conference on Fluid Sealing, Paper C1, April 17-19, 1961, BHRA, Harlow, Essex, England, 14 pages.

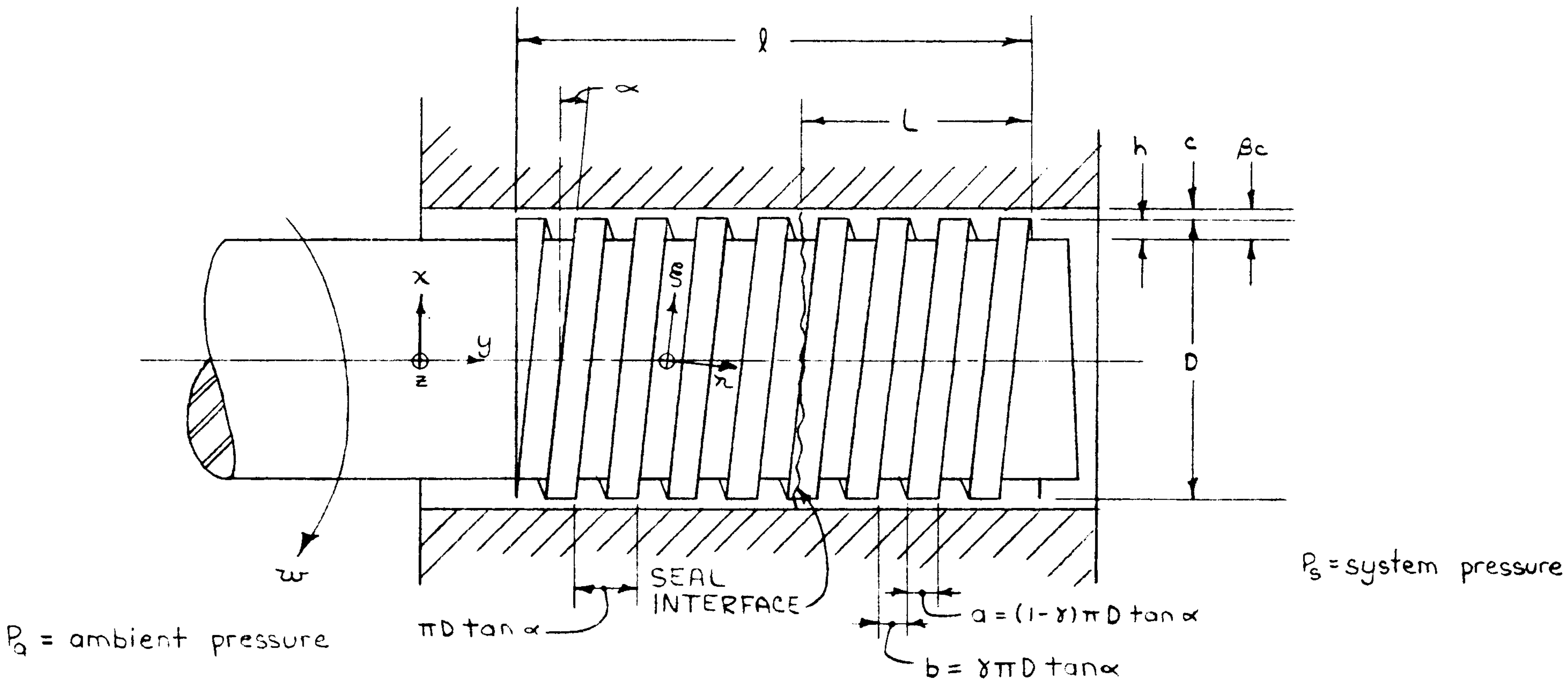
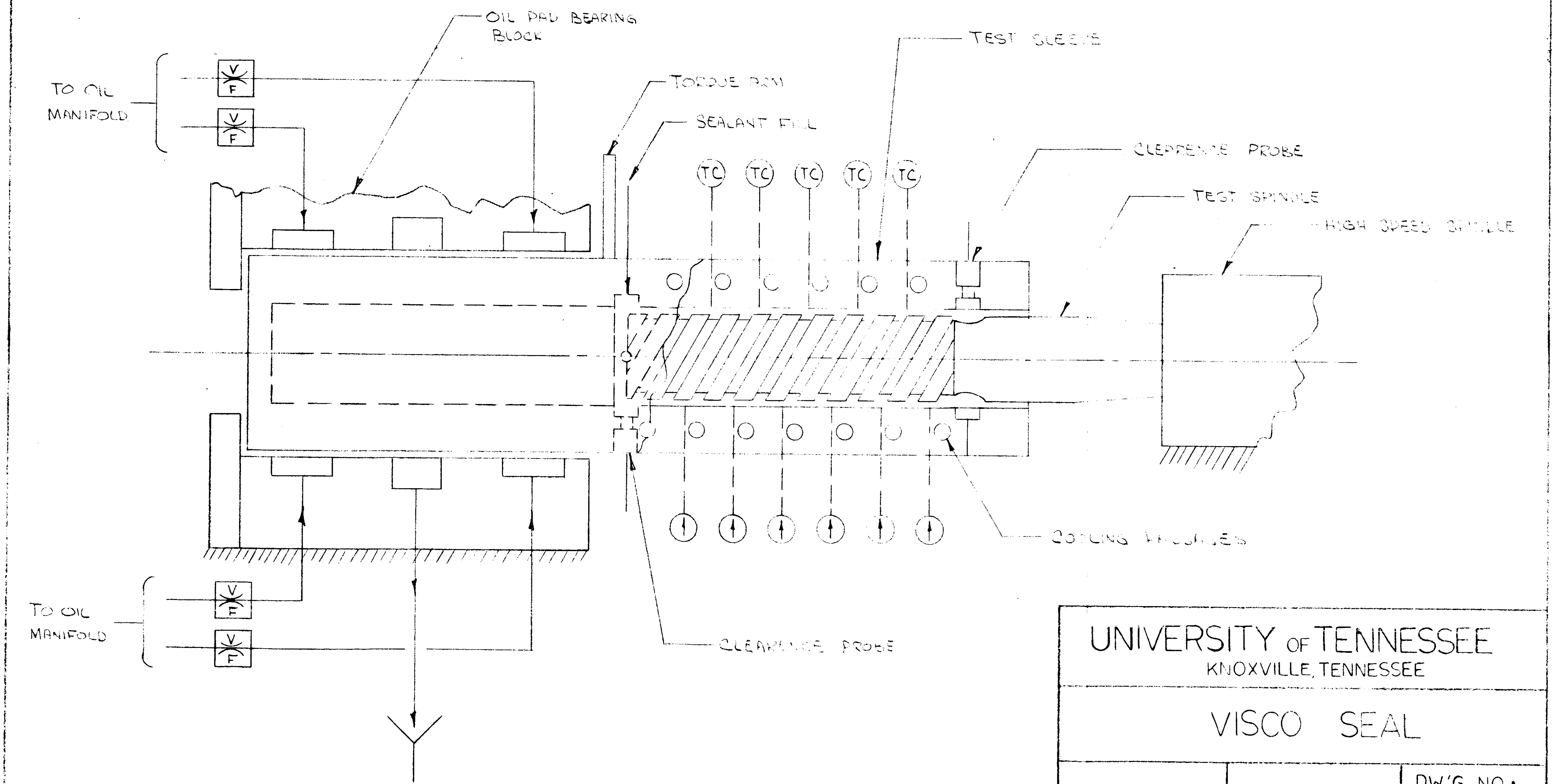


FIG. 1 - BASIC ELEMENTS OF A VISCO SEAL



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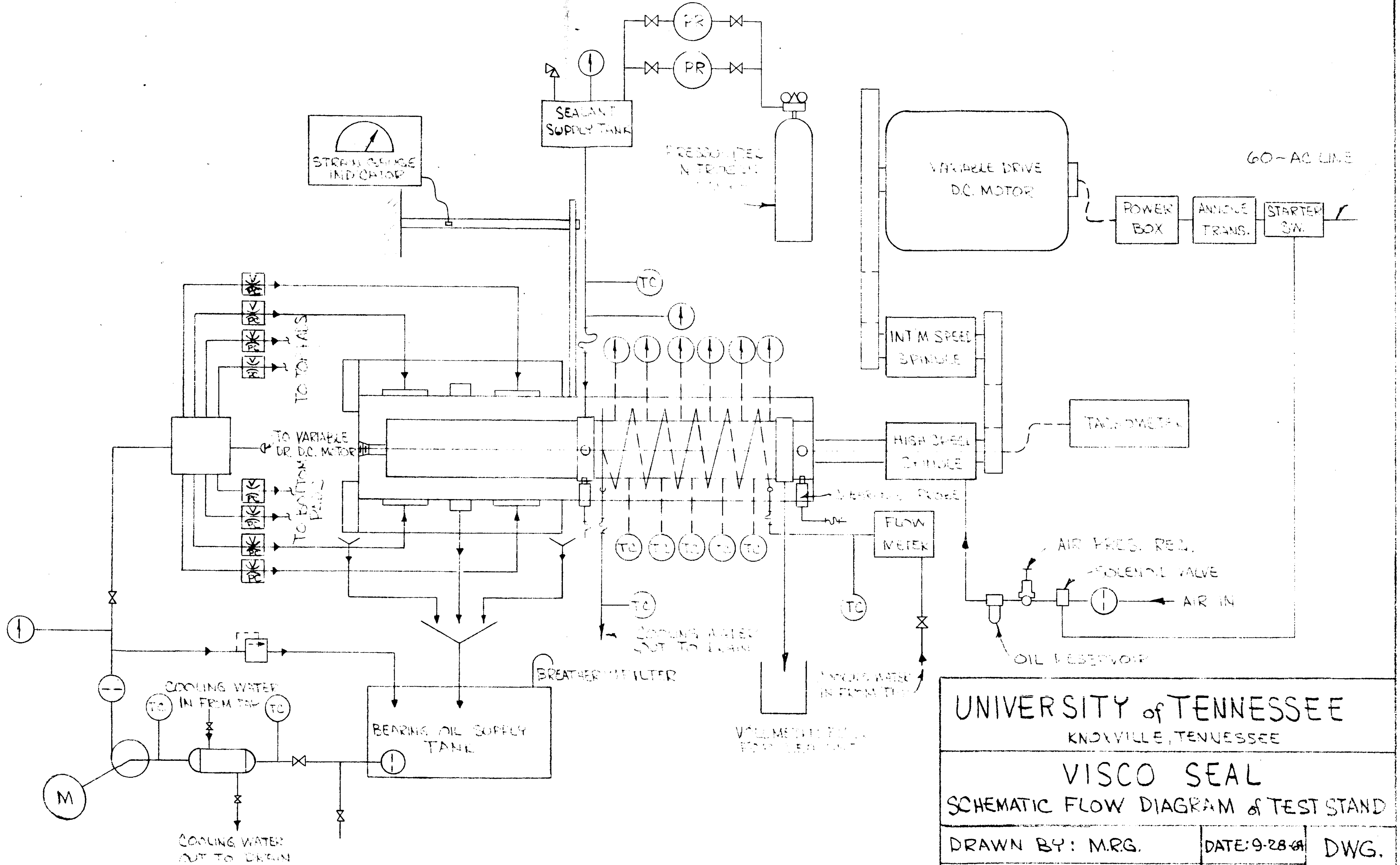
VISCO SEAL

DRAWN BY: M.R.G.	DATE: 10-6-64	DW'G. NO.:
CHECKED BY: WKS	DATE: 10-9-64	VS-5-50



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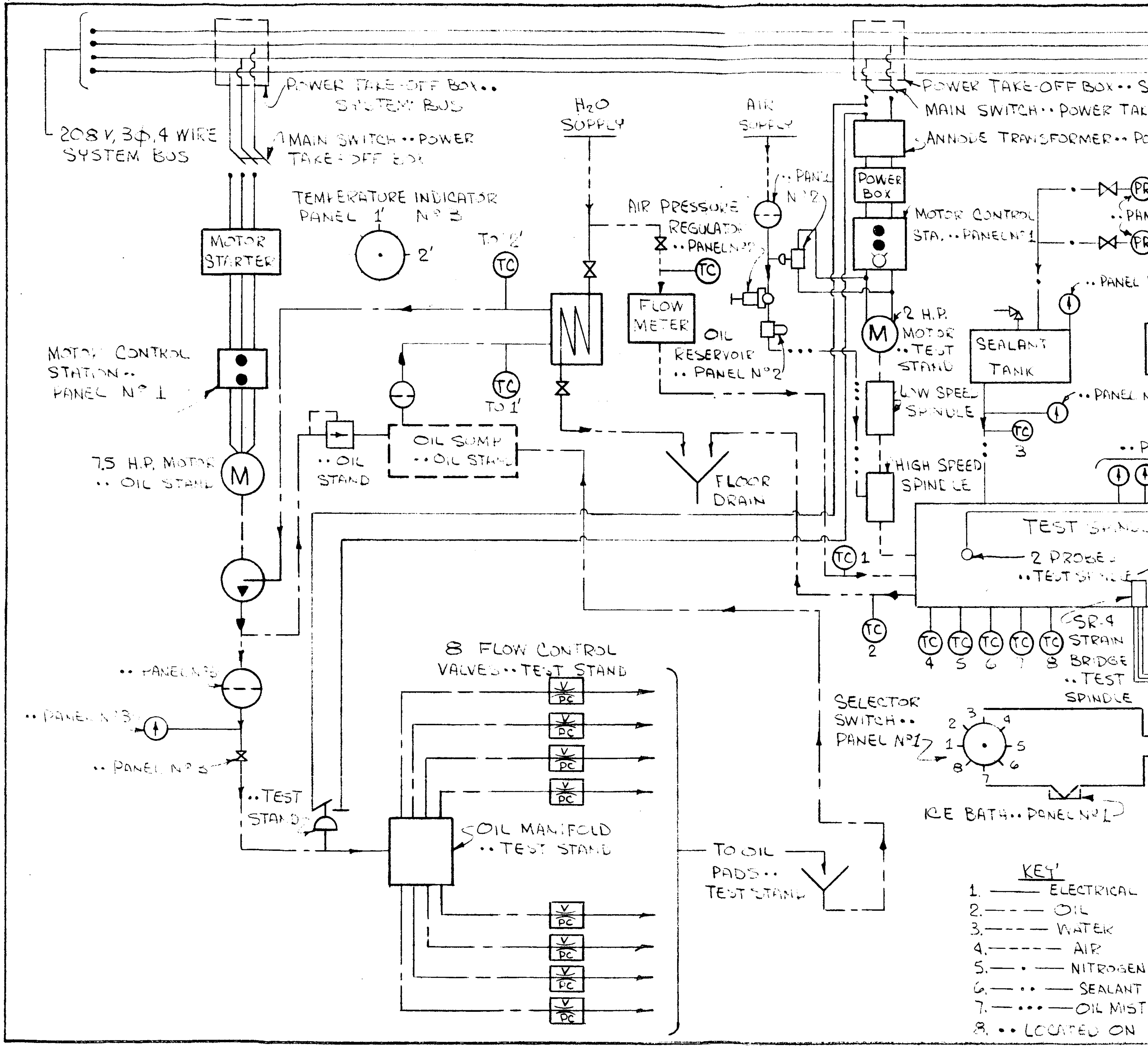
VISCO SEAL

SCHEMATIC FLOW DIAGRAM of TEST STAND

DRAWN BY: M.R.G.	DATE: 9-28-64	DWG.
CHECKED BY: W.K.S.	DATE: 10-1-64	No VS-1-A



KEY

1. ——— ELECTRICAL
2. — — — OIL
3. - - - - WATER
4. — — — AIR
5. — • — NITROGEN
6. — •• — SEALANT
7. — ••• — OIL MIST
8. •• LOCATED ON

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VISCO SEAL ASSEMBLY

FLOW DIAGRAM

DRAWN BY: M.R.G.	DATE: 10-6-64	DW'G. NO.:
CHECKED BY: WKS	DATE: 10-8-64	VS-5-51