ME69-T57-4

NASA CR 106257

NGR-43-001-003

THE UNIVERSITY OF TENNESSEE

DEPARTMENT OF MECHANICAL
AND AEROSPACE ENGINEERING

OBSERVATIONS ON A VISCOSEAL IN A TRANSPARENT HOUSING THE PREVENTION OF LEAKAGE AND BREAKDOWN

by
R. J. G. Boon

A Translation by
J. P. B. Vreeburg

March 1969
Knoxville, Tennessee 37916

ME 69-T57-4

OBSERVATIONS ON A VISCOSEAL IN A TRANSPARENT HOUSING-THE PREVENTION OF LEAKAGE AND BREAKDOWN

by

R. J. G. BOON

A Master's Thesis, June 1968
Chemische Werktuigen
TECHNISCHE HOGESCHOOL
Delft, The Netherlands

Translated by

J. P. B. Vreeburg

Fluid Sealing Research Laboratory
Mechanical and Aerospace Engineering Department
University of Tennessee

March 1969

Knoxville, Tennessee 37916

Table of Contents | Page

Abstract

A solution is sought for the leakage and break down phenomena as encountered by many researchers by means of visual observations on a viscoshaft seal in a transparent housing.

Our observations are compared with the phenomena mentioned in the literature.

An effort is made, notwithstanding gas inclusion, to prevent leakage in viscoshaft seals.

We tried to reduce gas inclusion by changing the surface energy of the seal.

The influence of the geometry of the seal on gas inclusion and leakage has been studied.

The influence of gas inclusion on the value of the sealing parameter has been looked into.

The measurements of the double V.S.S. in the Lab. of Chem. Equip. have been checked because it could be expected that gas inclusion had affected the measured values.

Conclusions

Our observations with regard to the gas inclusion mechanism check with those of Stair, Hale and Ludwig.

Leakage may be prevented by the installation on the shaft of bushings that have a small radial clearance and by the installation of a recirculation system for enclosed gas.

A teflon coating on the V.S.S. does not influence the severity of gas inclusion.

Viscoshaft seals with a large helix angle, multiple groove, land widths that are not too small and large groove depths, do not occasion gas inclusion.

Due to gas inclusion, the value of the sealing parameter decreases. This drop increases with the number of revolutions. We found a maximum drop of 34 percent.

The duplicate measurements on the V.S.S. test apparatus in the Lab. for Chem. Equip. were in very close agreement with earlier measurements.

References

1. E. F. Boon and S. E. Tal, "Hydrodynamische Dichtung fur rotierende Wellen" Chem. Ing. Technik, vol. 31 no. 3, January 31, 1959.

2. J. G. Pape and W. J. Vrakking, "Visco Seal-Pressure Generation and Friction Loss Under Turbulent Conditions"; Trans. ASLE, 11 (1968), 310 - 320.

3. W. J. Vrakking, "Visco Afdichting, theorie en experiment bij turbulente stromingscondities," Rapport Chemische Werktuigen, July, 1967.

4. W. Frossel, "Untersuchung von Gewindewellendichtungen," Konstruktion, 18 Heft 4, 152 (1966).

5. Husenblas and K. H. Switala, "Versuche an Oldichtgewinden bei hoheren Wellenumfangsgeschwindigkeiten," Konstruktion 14 Heft 5, 197 (1962).

6. J. M. McGrew and J. D. McHugh, "Analysis and Test of the Screw Seal in Laminar and Turbulent Operation," Journal of Basic Engineering, March 153 (1965).

7. A. E. King, "Screw Type Shaft Seals for Potassium Lubricated Generators," Supplement to I.E.E.E. Transactions on Aerospace, June (1965).

8. W. K. Stair and R. H. Hale, "The Turbulent Visco-Seal-Theory and Experiment," Third International Conference on Fluid Sealing, Cambridge England, April (1967) paper H 2.

9. J. M. McGrew and A. J. Orsino, "Non Contacting Dynamic Seals for Space Power Alternators Bearing and Seal Design in Nuclear Power Machinery," ASME, Edited by R. A. Burton, New York (1967).

10. L. P. Ludwig, T. N. Strom and G. P. Allen, "Gas Ingestion and Sealing Capacity of Helical Groove Fluid Filmseal (visco seal) using Sodium and Water as Sealed Fluids," NASA Report TN-3348, March 1966, Washington, D. C.

11. D. van der Meulen, "Onderzoek aan een visco-afdichting," 5e jaars rapport nr. 2-67, Lab. for Chem. Equip., Delft University of

List of symbols

c	clearance between land and housing
C_E	effective friction coefficient
d	shaft diameter (m)
h	groove depth = height of land (m)
l	active length of the visco shaft (m)
M	moment (Nm)
N	number of revolutions per minute
P	pressure (N/m^2)
Re	Reynolds number connected with the groove = $\beta Uc/\nu$
Re_1	Reynolds number over the land = Uc/ν
t	tangent of the helix angle
U	circumferential velocity $\omega d/2$ (m/sec)
a	groove width (m)
b	land width (m)
α	helix angle (degrees)
β	$(h + c)/c$
γ	$a/(a + b)$
η	dynamic viscosity ($Nsec/m^2$)
ν	kinematic viscosity (m^2/sec)
ψ	sealing parameter
ρ	density (kg/m^3)
ω	angular velocity, $2\pi N/60$ = (1/sec)

1. Introduction

The most important requirements for a shaft seal are: little wear and a leakage that is as small as possible. Stuffing boxes, mechanical seals, O-rings and labyrinth seals do all exhibit some leakage. During the last years, the visco shaft seal, in the following abbreviated as V. S. S., has become more prominent. This seal is contactless so that the wear is small and a long period of operation assured, moreover theoretically the leakage is very small.

The V. S. S. resembles a screwpump with zero capacity. The screw profile may be placed in either the shaft or the housing.

Only in the last few years have calculations of the operation of V. S. S.'s been performed. This seal develops, in the space between shaft and housing, an axial pressure gradient which can be expressed in a sealing parameter ψ .

In 1959, Boon and Tal (1) published their derivation for this parameter under laminar flow conditions for which is dependent only on the geometry of the seal under consideration;

$$\psi = \frac{Pc^2}{\eta \omega dl}, \text{ with } \psi = \frac{3t\gamma (1-\gamma)(\beta-1)(\beta^3-1)}{(1+t^2) \beta^3 + t^2\gamma (1-\gamma)(\beta^3-1)^2} \qquad 1$$

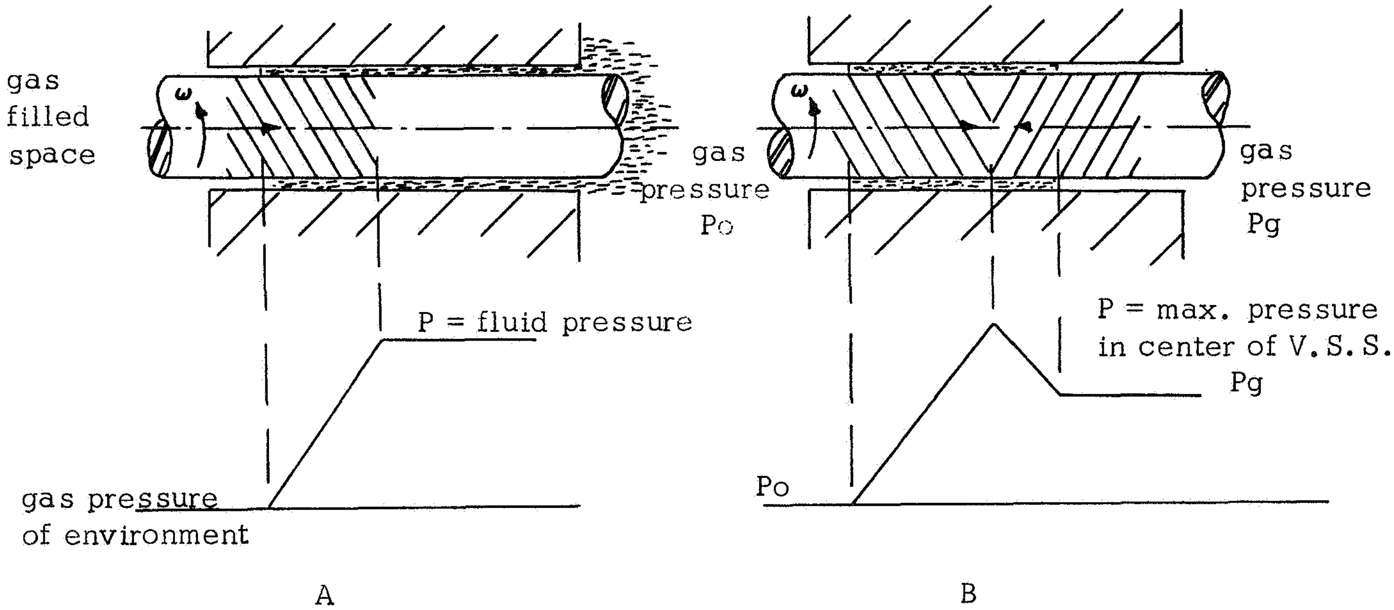
For turbulent flow conditions ψ also appears to be dependent on the Reynolds number. Pape and Vrakking (2) computed the sealing parameter for this case.

In the last few years, many investigators, also in the Lab. for Chem. Equip., compared the theory with experiments. In general a good agreement has been found (e.g. see 3).

With the given formulae, the machine designer can determine a design. In general, the shaft diameter, angular velocity and pressure sealed against will be the given quantities.

The minimal radial clearance between shaft and housing, c, is restricted by manufacturing feasability. The sealing pressure has to be realized with the geometry of the screw profile, the length of the shaft and the viscosity of the sealing liquid.

The V. S. S. can, for example, be used in the following cases:



A. <u>The single V. S. S.</u>

This one may be used as a seal between a gas and a liquid-filled space. The outwardly escaping liquid is pumped back by the screw.

B. <u>The double V. S. S.</u>

This one may be used as a seal between two gas-filled spaces. Using the sealing liquid, the seal generates a pressure at the center of the shaft. As long as the difference in pressure between the gases is smaller than the maximal pressure generated by the shaft, no leakage will occur.

Especially this last case offers interesting possibilities for applications. During pumping or compression of poisonous, flammable or explosive gases, hence in general with substances that are not to be in contact with the outside air, the neglectable leak is a great advantage. This leak is possible by diffusion of the gases that are to be sealed through the sealing liquid.

Indeed, at low circumferential velocities, visco shaft seals give excellent performance. However, at higher velocities, several investigators report a strong leakage of the V.S.S. and a decrease or ceasing of the pressure generation, indicated by "break down." Due to these phenomena the V.S.S. cannot longer be used as a seal.

To get an impression of the leak and break down phenomena, a literature survey has been carried out. Only those data that are connected to the failure of the V.S.S. are quoted.

2.1 Literature Survey

Frossel (4) investigated double V.S.S.'s. At high circumferential velocities there was a decrease in sealing pressure for all seals considered. Through a sight glass in the housing, he observed that this was accompanied by foam generation in the sealing liquid. The intensity of this phenomenon increased at still higher velocities and finally resulted in a complete ceasing of the pressure generation. He postulates that the foam diminishes the pressure generation in the seal due to its very low viscosity.

Hausenblas (5) investigated double V.S.S.'s with a grooved housing. He reports: at high circumferential velocities, the sealing pressure decreases and finally ceases to exist. He supposed that an air cushion had been formed around the smooth shaft due to the centrifugal force. Hereby, the oil in the grooves was not set in motion hence no pressure could be generated. The oil, supplied in the center of the seal, leaks towards the low pressure ends if there is a small pressure difference. The departing oil contains gas bubbles.

McGrew and McHugh (6), using a simple V.S.S. in vertical position, found that a sealed pressurized vessel filled with liquid showed a decrease in pressure at higher seal velocities. Furthermore, they observed that this phenomenon was accompanied by oil leakage from the lower end of the shaft (which was exposed to ambient atmosphere). They postulated that the Re number alone could not give a satisfactory explanation because leakage appeared in the laminar, turbulent and transition regimes. They supposed that the Weber number = $U^2 c\rho/\sigma$ influenced the leakage of liquid especially because it contains the surface tension. However they do not exclude other influences.

King (7) used a vertical double V.S.S. in which sealing liquid was recirculated at the upper end of the system. He found a so called "secondary leak" by which liquid leaks down out of the oil/air interface. This leak depends on the number of revolutions and the clearance, c, and does also appear when there is no pressure gradient. He supposes that the characteristic numbers of Weber, Froude and Reynolds are influential. During experiments with liquid Potassium as the liquid and Argon as the gas, he observed that gas was pumped into the liquid through the seal.

Stair and Hale (8) tested a simple V.S.S. that rotated in a horizontal position. The strong decrease of the sealing parameter at high Re number for a shallow grooved seal was attributed to enclosed gas. This partially fills the grooves resulting in a decrease of their active depths. Extra barriers with small radial clearances at the shaft ends give a slightly better performance. The following conclusions are made:

--The Reynolds number for which gas inclusion appears is dependent on the geometry of the V.S.S.

--Also in the turbulent regime a stable ψ may appear.

--At high Re number, the pressure generation along the shaft fluctuates. In this case they distinguish three situations:

1. Originally there are small pressure variations followed by a strong decrease in pressure. Hereafter the seal may generate a constant sealing pressure also at high Re numbers.

2. There are slow pressure fluctuations accompanied by a greater wetted length. At higher velocities, amplitude and frequency increase. A pulsating leakage of liquid appears when the necessary wetted length is greater than the real length.
3. Fast pressure fluctuations with increasing amplitude and pulsating leakage of liquid. This appears especially at the sealing of a small vessel filled with liquid.

Finally is summarized that gas inclusion is opposed by large values of β and γ and small values of α.

The investigations of McGrew and Orsino (9) indicated that the stability of the interface was not improved by a small helix angle. The shaft of the double V. S. S. was grooved. During testing under atmospheric pressure no observable oil leakage appeared; after imposing a small pressure difference the low pressure end leaked. Gas inclusion was suggested as a possible cause.

Ludwig (10) investigated a V. S. S. in a transparent housing. He observed that leakage of liquid and breakdown as described by McGrew and McHugh can be caused by gas inclusion in a closed vessel. Using a seal with a grooved shaft, he found that over a Re_g of 2300 gas inclusion always appeared.

When the housing was grooved, he found gas inclusion in a low Re region. Over $Re_g = 8400$ there was no more gas inclusion, however, he found that gas was still ingested at the immediate oil-gas interface.

Furthermore he observed that due to gas inclusion the sealing parameter ψ decreases; leakage of oil did not take place. Also, with his visual observations he is able to give a good explanation for the pulsating leak and seal break down as observed by Stair and Hale.

van der Meulen (11) made observations on the double V. S. S. of the Lab. for Chem. Equip. Sealing two gas filled spaces between which there was a pressure difference, he found the onset of leakage at low pressures. This phenomenon is transposed in a strongly fluctuating leak at a constant sealing pressure. At a pressure difference of 30% of the sealing pressure, the pressure build-up ceased after a few minutes. After that there was a strongly changing gas transport through the seal from the high pressure end to the low pressure end. This leak increases with the pressure difference. These phenomena are attributed to gas inclusion from the oil-air interface. He supposes that the important factors are: the geometry of the V. S. S., the circumferential velocity, the surface tension, and the viscosity of the sealing liquid.

2.2 Synopsis of the observations of the investigators mentioned in the literature

For a B. S. S. with a grooved shaft, the sealing pressure decreases for high circumferential velocities. In this situation there often is a leakage of oil. The pressure generation has to be maintained by a continuous supply of new sealing fluid in the center of the double V. S. S. It is clear that without this supply an open connection between the gas filled spaces will develop. Because the leaked oil contains gas bubbles or is in the form of foam, it may be assumed that by means of this foam a connection between the two gas-filled spaces is established. It has been observed that gas inclusion may be the cause of the leak and that the sealing parameter decreases due to the formation of foam in the sealing liquid. Even a complete drop of the pressure generation may be caused by this.

One investigator found that gas inclusion did not appear anymore for a seal with a grooved housing at high Re numbers. Neither with a grooved shaft, nor a grooved housing did leakage of sealing fluid from the seal take place.

3. Purpose of this investigation

The purpose of this investigation is the prevention of leak and break down of viscoshaft seals (V. S. S.).

4. Method of investigation

In order to attain the aforementioned purpose we decided upon a visual investigation of the phenomena in a V. S. S. From the literature survey it became clear that gas ingestion causes leaks and break down. It is expected that there will always be gas inclusion at very high circumferential velocities (high numbers of revolutions). Therefore we investigate if, notwithstanding gas inclusion and maintaining the shaft geometry, leak and break down may be prevented by changes in construction.

Also we investigate if by changing the geometry of the V. S. S. the gas inclusion diminishes whereby the goal may be attained also.

Besides these visual observations we checked the influence on the sealing parameter by foam formation in the sealing fluid. Indeed, break down may be caused also by a decrease of the sealing parameter.

5. Description of the apparatus. See Fig. 1

The essential part of the construction is a glass tube that has an inner diameter which, within very close tolerances, is the same over its entire length. In this tube the visco shafts may turn vertically in bearings. The principle of a visco shaft is indicated in Fig. 2 and a summary of the geometries of the investigated shafts is listed in Table 1. A motor powers the visco shaft by means of a V-belt. With the use of a number of pulleys eleven different numbers of revolutions can be obtained. Table 3 indicates the possibilities and also the Re_1 numbers that can be obtained with the sealing fluids used. The fluids and their physical properties are summarized in Table 2. The radial clearance between the lands of the shafts and the glass tube is 0.10 mm for all cases. Sealing fluid may be supplied from a reservoir at the side or through the opening at the upper end of the shaft formed by the upper bearing. With the single V.S.S., the turn direction of the shaft is such that there is a pressure generation towards the lower end. The pressure can be read from the manometer. The double V.S.S. generates the highest pressure in the middle of the seal. With the use of the mounting in Fig. 3, a pressure difference can be imposed over the seal. To this end the mountings depicted in Fig. 1 and Fig. 3 are connected at the points b. For a certain imposed pressure difference we can measure an eventual gas leak with the U-tube. Then the valve a will be closed when the system has been pressurized. A displacement of the liquid level in the U-tube corresponds then to a certain leakage. Using a stroboscopic illumination of the revolving visco shaft permits visual observations of the motionless picture.

6. General remarks with regard to the research

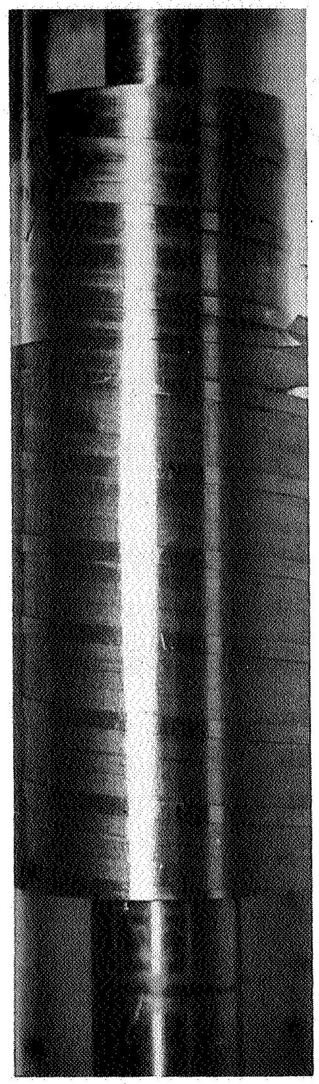
Already during the first experiments we confirmed suppositions of other investigators, that the cause of leakage and break down is gas inclusion in the sealing fluid. See pictures 37-21 and 37-25. Before examining the results of this experiment closer, the following remarks are made.

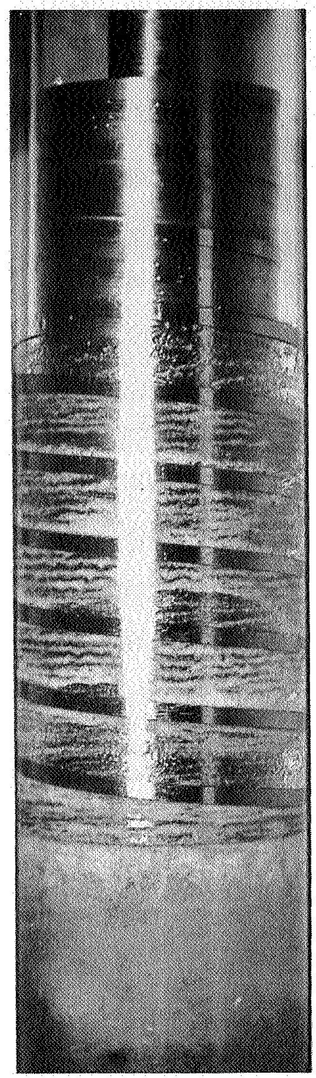
6.1 Definition of the Reynolds number

For the computation of the sealing parameter one has to use a laminar or turbulent flow theory. It appears that the border between these two regions can be indicated clearly with the Reynolds number $Re_1 = Uc/\nu$. This Re number is thus related to the clearance between the lands and the housing (c in Fig. 2). It appears from this investigation that this number Re_1 is not significant with regard to gas inclusion. Because the groove depth is influential on the gas inclusion, it is better to relate the Reynolds number to the groove depth. $Re_g = Re_1 . \beta$. Because this definition was not suitable as a criteria for gas inclusion ocurred, we used the definition of Re_1. In this way it is easier to compare the results with results from the literature.

6.2 Reproducibility of visual observations

It appeared several times that, under the same conditions, different experiments yielded different pictures. This could be observed especially





37-21

N = 1802 rpm

Re_1 = 151

37-25

N = 2590 rpm

Re_1 = 362

The cause of leak and breakdown appeared to be gas inclusion in the sealing fluid

(Shaft no. 2 single grooved)

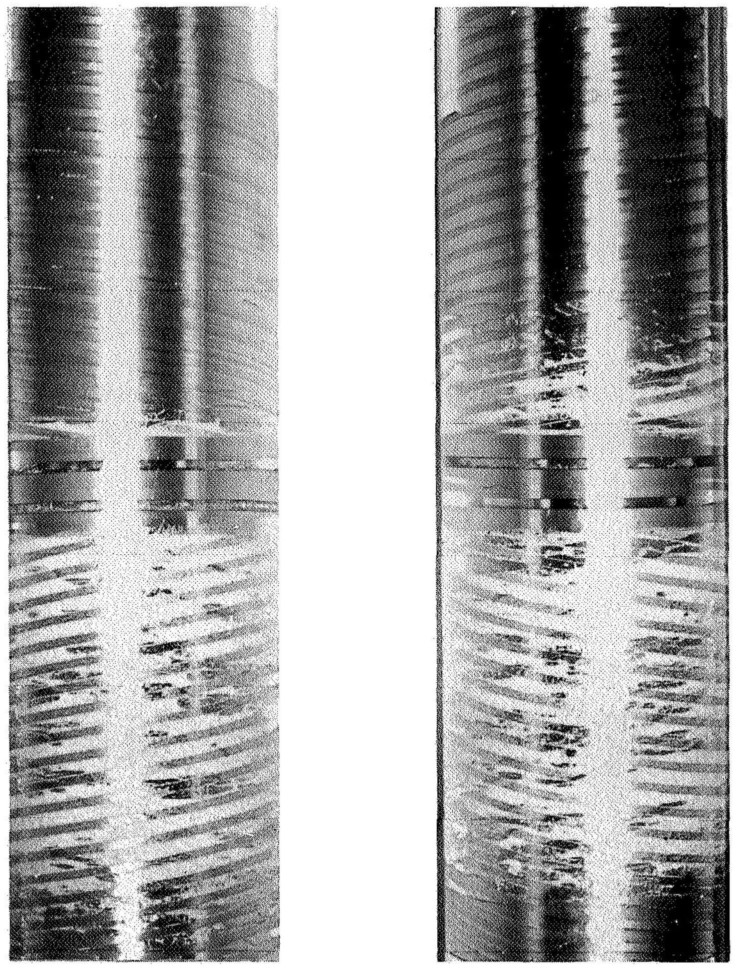
with the double V. S. S. It even happened that the picture changed during one experiment. The photographs 36-9 and 36-11 exemplify this. Without regularity these pictures changed into each other via many transitions. With the double V. S. S.'s it appeared that generally the gas inclusion at the lower end of the shaft was less prominent than at the upper end. However, this is no rule, pictures 33-12 and 37-17, show that under the same conditions sometimes gas inclusion does occur and sometimes not. The pictures are not reproducible satisfactorily.

6.3 Non-exact indication of numbers of revolution and Reynolds numbers

In connection with the earlier mentioned nonreproducibility of pictures, it is clear that no number of revolution of Reynolds number can be indicated for which a certain phenomenon occurs or not. However we often can still give some indication. "At low Reynolds" implies that a certain phenomenon has been observed mainly in that region. The chance that during many experiments, it will not be observed in that region is small just like the chance that it will be observed for high Reynolds numbers. Sometimes an exact indication is possible and this will be indicated clearly.

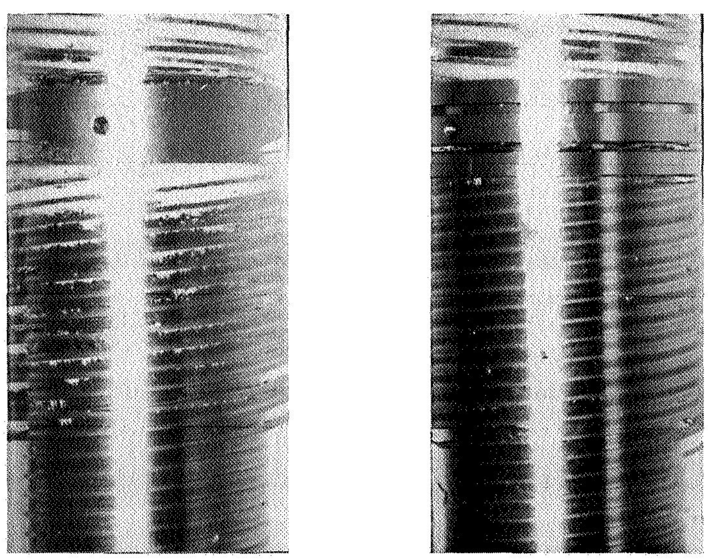
6.4 The influence of the viscosity of the sealing fluid on gas inclusion

In the beginning of this investigation it became apparent that the sealing fluids no.'s 1 and 2 (Table 2) did not cause gas ingestion or gas inclusion. A sealing fluid with a lower viscosity than those of the no.'s 1 and 2 did exhibit gas inclusion in the same seal. Also based on the results of other investigators (lit. survey) it is expected that, for sufficiently high circumferential velocities, gas inclusion will also occur with highly viscous sealing fluids. This is why the influence of the viscosity has not been investigated and we did only use fluid no. 3 to study the gas inclusion phenomenon. It is clearly indicated when other fluids have been used in the seal.



36-9 36-11

Different pictures of gas inclusion for equal Re-numbers. The pictures can not be reproduced satisfactorily. During the same test run these pictures may change into each other.



33-12 37-17

Different picture at the lower end of the shaft. Often there is no gas inclusion on the lower end of the shaft but sometimes there is under the same conditions. Irreproducible situation.

6.5 Leak due to loss of sealing fluid

It appeared from the literature survey that by mentioning leak one means a loss of fluid possibly mixed with gas bubbles. The cause of this fluid leak is attributed to gas inclusion which gives rise to an unstable interface.

In our investigation such oil leakage was observed at some double V.S.S.'s. Due to this downward leaking, the sealing fluid disappears from the seal; if no new supply occurs this will result in a decrease and finally a complete drop in the pressure generation. This then results in a gas leak through the seal.

The observed oil leakage (picture 36-6), which was always accompanied by gas ingestion, is primarily seen as a loss of sealing fluid. A vertically positioned seal appears to be necessary for this loss to occur. Leak due to gas inclusion and leak due to loss of sealing fluid were observed as two particular phenomena.

6.6 The defining of the conceptions: gas ingestion; gas inclusion and leak[1)]

In the course of this investigation it appeared to be useful to depart from general nomenclature and to use more refined definitions.

A. Gas ingestion

Gas ingestion is defined as an instability at the interface between sealing fluid and gas by which a zone occurs containing foam and/or bubbles. (See picture 38-40).

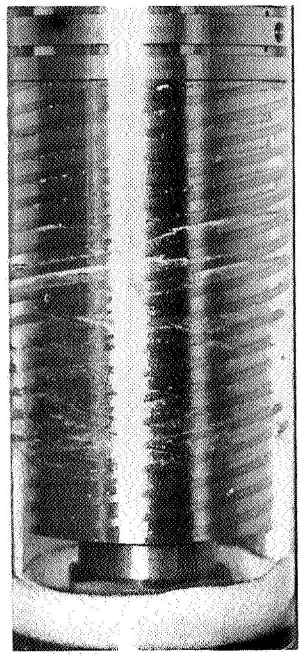
B. Gas inclusion

This phenomenon means that a quantity of gas in the form of an emulsion, form or bubbles fills the active length of the seal for some distance from the high pressure end. Almost always gas inclusion occurs by transport of the gas trapped by gas ingestion. (Pictures 44-39 and 44-40). The phenomenon may appear also by inclusion of a quantity of gas without the occurrence of gas ingestion (picture 36-13).

C. Leak

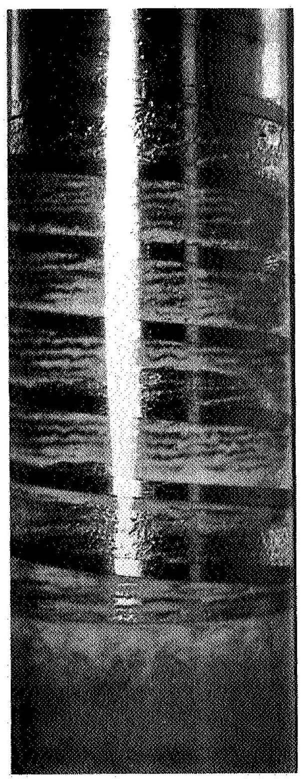
This means for the single V. S. S. that axial transport of gas occurs from

1) Translator's note: In current literature, gas ingestion is usually used for both gas ingestion and gas inclusion as defined by this author.



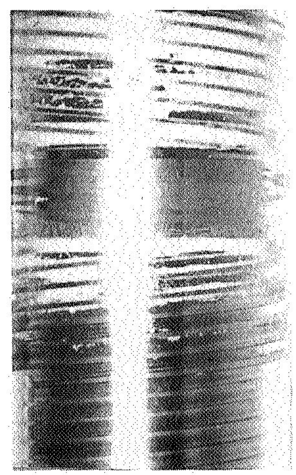
36-6

Observable leak of sealing fluid from the seal



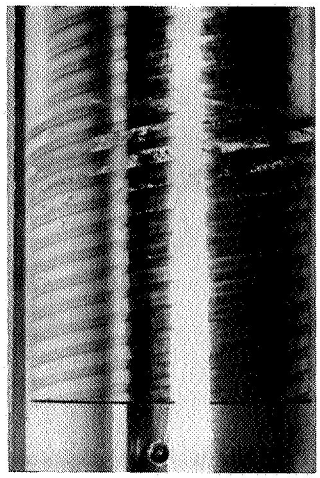
37-25

Single visco shaft gas ingestion gas inclusion and leak



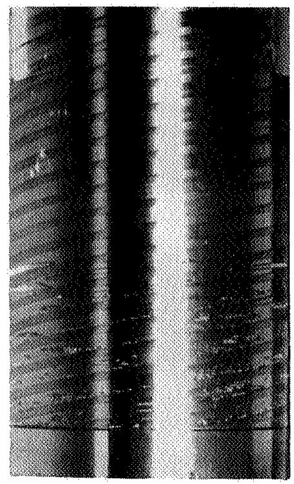
33-16

Double visco shaft gas ingestion, gas inclusion and (visible leak)



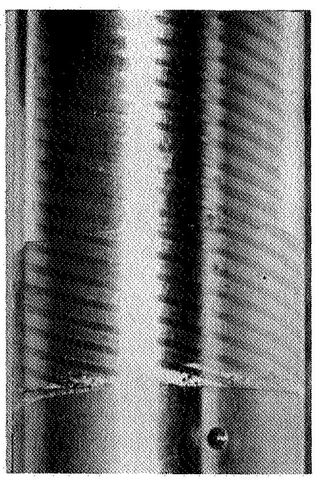
38-40

Gas inclusion

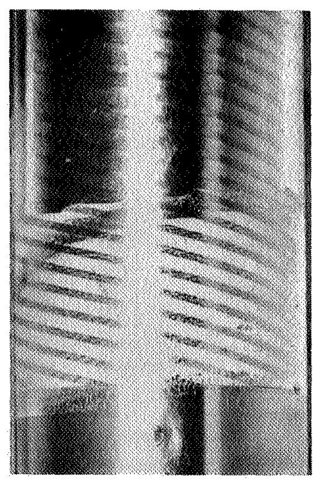


36-13

Gas inclusion without gas ingestion



44-39



44-40

Very little gas ingestion in 44-39 leads to gas inclusion and gas ingestion in 44-40 after 1 1/2 min.

the oil/gas interface to the space filled with fluid that has to be sealed (picture 37-25).

For the double V.S.S. axial transport of gas occurs through the seal from interface to interface. Due to the leak the sealing action of V.S.S. vanishes. Prior to leak we will have had gas ingestion and gas inclusion according to the aforementioned definitions.

For the double V.S.S. the leak always is visible because of the presence of gas in the central part of the seal (picture 33-16). This visible leak may also be an exchange. In the latter case an imposed pressure difference over the seal will not decrease; there is no measurable leak.

7. Observations, measurements and conclusions with regard to gas inclusion and leak of a single V.S.S., sealing against a chamber of constant volume

The shaft used in the seal is shaft no. 1 (Fig. 4) of which the round-machined shaft ends are due to changes of the original design.

7.1 The influence of the volume of the liquid on the observed phenomena

The sealed liquid-filled chamber is bordered on the lower side of the mounting by the system between the valves, See Fig. 1. Furthermore, the total volume is determined by the height of the liquid in the seal. This height can be determined accurately during the state of rest, however, the total oil volume does not appear to be fixed. This is caused by the quantity of gas in the system that is compressed during operation; hereby the wetted length decreases and therefore also the pressure generation.

The oil volume cannot be corrected during the operation, firstly because then the picture becomes distorted by gas inclusion and secondly because it is not feasible practically. No degassing channel has been installed because the variable quantity of gas primarily influences the observed picture. The latter turned out to be hard to reproduce during the entire investigation.

7.2 Observations with sealing fluid no. 1; Tellus 13

Although it is already mentioned that no gas inclusion occurs with this sealing liquid, some observations have still been made. This to obtain insight in the real conditions at a supposedly ideal seal.

For these observations, the special form of the oil/air interface was noticed (Fig. 7). The indicated interfaces are not characteristic for one particular number of revolutions. The situations overlap, they are not reproducable satisfactorily and during the observation they sometimes become merged.

In all cases there is a sharply defined interface of while the lines exhibit sharp corners. Three zones become apparent:

1st. The dry part of the seal.

2nd. A part where a thin oilfilm can be observed. It is supposed that this oil is hurled against the glass housing and does not have contact anymore with the rotating shaft.

3rd. The seal completely filled with oil.

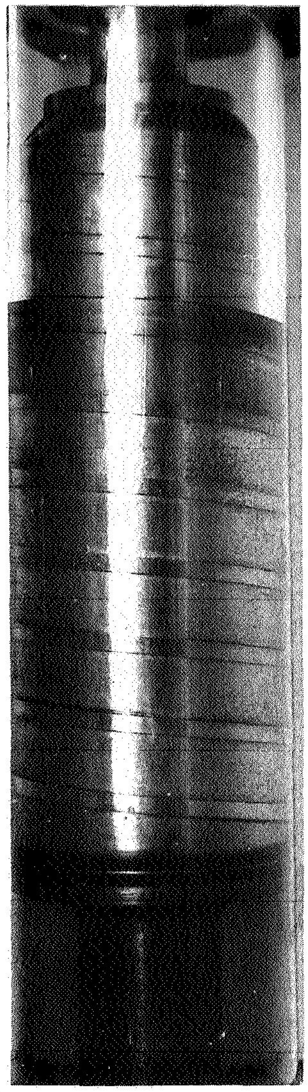
For numbers of revolutions larger than 1900 rpm bubble traces originate from the sharp interface. However these bubbles dissolve rapidly and do not give rise to gas inclusion.

7.3 Gas inclusion observations with sealing fluid no. 3

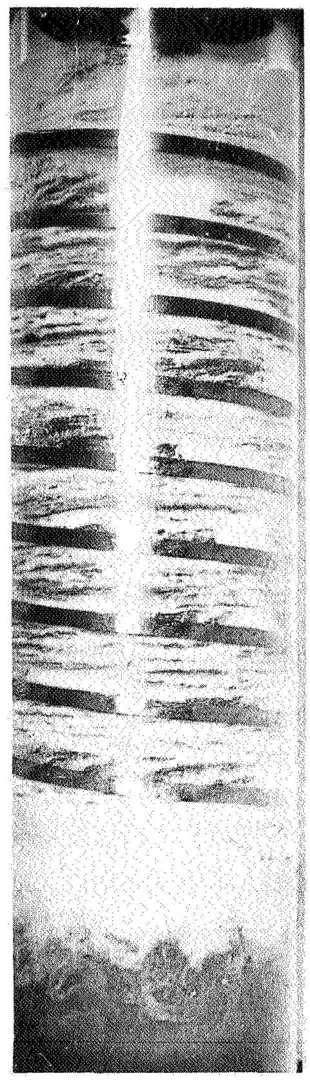
Except for the lowest possible number of revolutions, N = 1082 rpm, gas ingestion occurs at the interface. In all cases the level in the seal goes down strongly immediately after the start. The compressibility is caused by the air present in the closed chamber.

For N = 1082 rpm the stationary state is reached immediately after starting, pressure and level are constant (picture 8-7). For the highest number of revolutions possible, N = 4120 rpm, the stationary state is only reached after about 20 minutes (picture 8-33). The picture is reproducable in both cases just as the maximum pressure built up by the seal.

Between these mentioned extremes many observations are made. Exact reproducibility was not possible; see 7.1. It is observed that for a smaller volume of liquid to be sealed, the time necessary to attain a stationary condition increases. (Table 4). For three numbers of revolutions, N = 1522, 1910 and 3480 rpm, the progress of the gas inclusion is reported:



8-7
N = 1082 rpm
Re_1 = 151
Visco shaft seal
without gas ingestion
stationary immediately.



8-33
N = 4210 rpm
Re_1 = 575
V. S. S. with gas ingestion gas
inclusion and leak stationary
after 20 min.

Gas inclusion and leak for N = 1522 rpm; $Re_1 = 212$

The apparent volume of oil in the system in rest was 196 m.m. on the scale. Obviously there was still much air present in the system because the compressibility was high. Immediately after the start the level dropped back to 125 m.m. (picture 8-13).

The dependence of the measured sealing pressure as a function of time has been recorded graphically in Fig. 8. The difference in quantities of fluid is indicated as a difference in wetted shaft length (196 m.m. = 82%).

Air bubbles are ingested at the interface and transported to the space below the shaft. Hence leak occurs due to this axial transport of gas. Apparently the enclosed air supersedes the oil because the liquid level rises (picture 8-16). Concurrent with this rising, an increase in pressure generation takes place that corresponds with the theoretical value

$P = 0.026 \text{ kg/cm}^2$ per cm.

After some time no discernable rise of the level takes place; the fluid then wets the full active length of the seal. In this stationary state the intensity of the gas ingestion is decreased; the pressure build-up and apparently also the amount of enclosed gas are constant (picture 8-17).

It is possible that the round-finished shaft ends are the cause of the diminished gas ingestion.

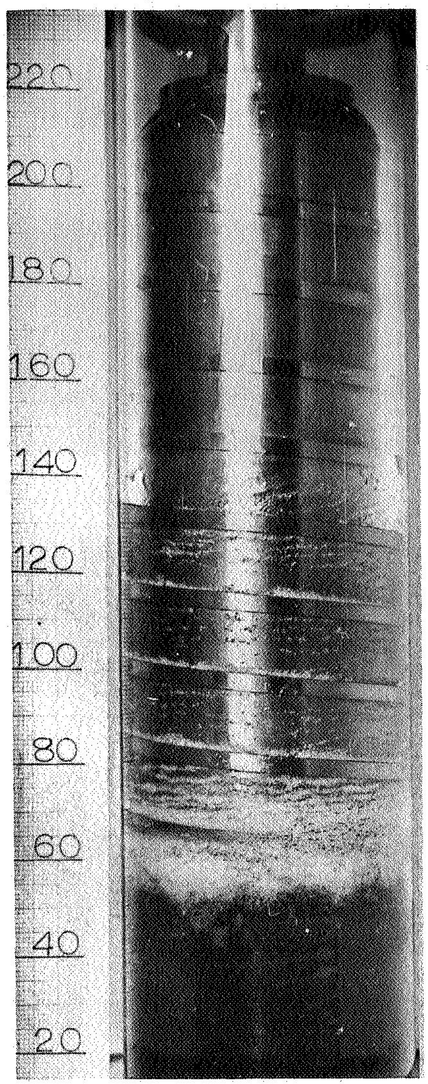
It is clear that bubbles are transported especially on the low pressure sides of the lands.

At an other experiment there was more oil in the system; the rest level was at 220 m.m. whereby the shaftlength is wetted for 100% (see Fig. 8). After the start the level goes down to 165 m.m.thereafter the level rises again until close to the shaft end. The phenomenon is stationary earlier than with a small oil volume.

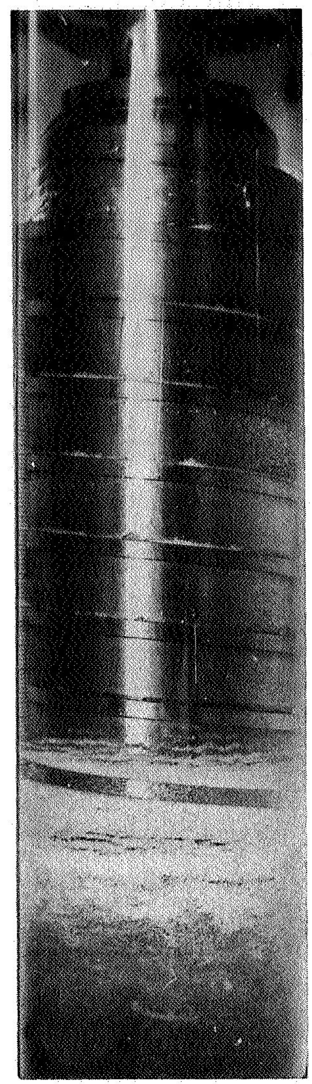
Gas inclusion and leak for N = 1910 rpm, $Re_1 = 267$

The pressure change for this case is recorded graphically in Fig. 9.

8-13



8-16



8-17

Gas inclusion and leak for N = 1522 rpm; Re_1 = 212; Fig. 8

4 sec. after starting gas ingestion and gas inclusion

35 sec. after starting, level rises because liquid below the V. S. S. is replaced by gas

7 1/2 min. after starting gas ingestion decreases when the level coincides with the machined shaft end. Stationary situation

Analogous to the former case, the level goes down immediately after the start whereby gas ingestion begins (picture 8-23). After about 4 minutes the enclosed air had superseded so much oil that the sealing fluid level rose over the active seal. After that the pressure remained constant (picture 8-27).

-----It is clear that for this case oil leakage would have started if the shaft were rotating in a horizontal position. Now this leakage is prevented by the system in the given vertical position.-----

When the full active length of the seal is wetted by the fluid the intensity of the ingestion diminishes strongly. The transport of gas to the space below the shaft decreases.

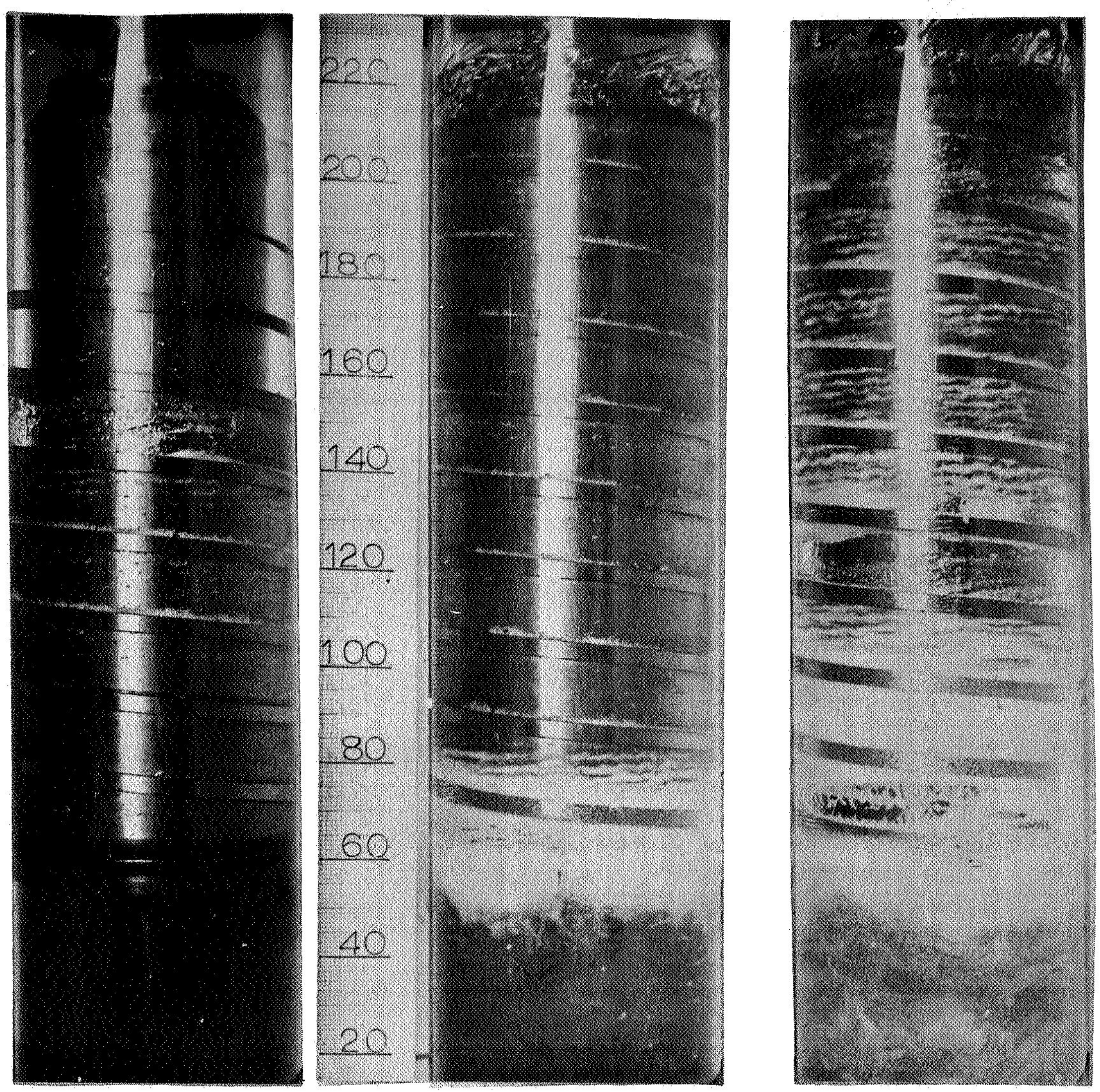
After about 8 minutes a large quantity escaped from the lower part (= high pressure end) in one bubble (picture 8-28). This so called gas front, did fill the whole seal with foam and gave rise to a sharp pressure drop (Fig. 9). Hereafter the pressure increased until again a gas front escaped. Apparently at the maximum pressure, there has to be a certain amount of air in the sealed space to cause "back leakage" of gas through the seal towards the low pressure end.

Gas inclusion and leak for N = 3480 rpm; $Re_1 = 486$

The dependence of the pressure on time is recorded graphically in Fig. 10. Immediately after the start the seal is already completely filled with foams (picture 8-31). Due to leakage of gas to the space below the shaft the level rises very strongly and after about 2 minutes reaches the upper end of the visco shaft ;(picture 8-33). This is accompanied with a small decrease in pressure after which small pressure fluctuations occur without disturbing the picture. This is the stationary state.

7.4 Determination of the rate of the gas leak

As became apparent from the previous observations the enclosed gas supersedes a quantity of liquid. The volume of the seal that may be filled



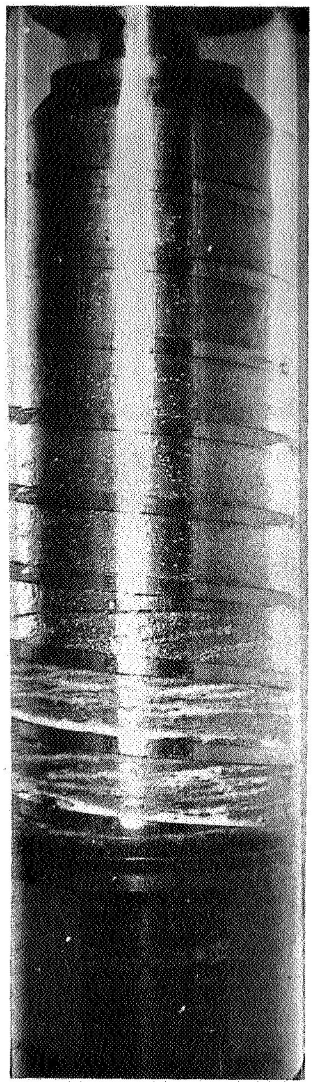
8-23 8-27 8-28

Gas inclusion and leak for N = 1910 rpm; Re_1 = 267; Fig. 9

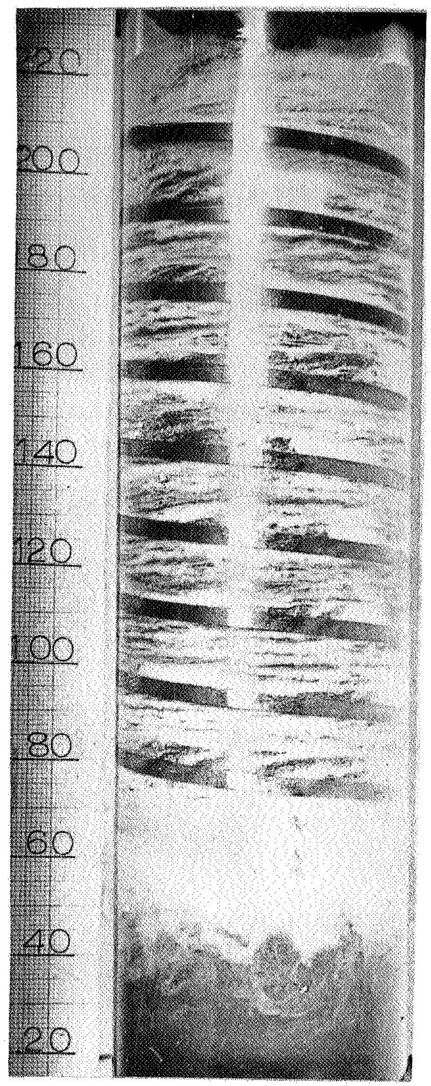
Gas ingestion

Enclosed air did supersede so much oil that the level rises over the seal. Gas ingestion diminishes but the transport does not.

Stationary case. Gas escapes upward in bubbles. Due to this strong pressure drop, later pressure increases again. After some time a <u>new gas front</u> appears.



8-31



8-33

Gas inclusion and leak for N = 3480 rpm; Re_1 = 486; Fig. 10.

Already after 2 sec. the seal is completely filled with foam

After 4 min. the level has risen due to gas inclusion and leak Stationary case with small pressure variations with liquid is simple to calculate. Per unit length we find: V = 0.09 ml/mm. According to formula (1) on page 1, l is proportional to $P/\psi \times N$. From this it follows that $dl/dt = dP/dt \cdot C_1/\psi N$ in which C_1 is a constant. The volume of liquid in the seal V, is proportional to the wetted length. Hence we can write $l \cong V$ and $dl/dt = dV/dt \times C_2$ in which C_2 is a constant. Combining both derivations we find:

$$\emptyset_v = dV/dt = \frac{dP/dt}{85.6 \times N\psi} \quad m^3/s \qquad (2)$$

The relation between the volume flow of the enclosed gas and the thereby displaced liquid is difficult to calculate. The gas ingestion is not constant and not reproducible, moreover the pressure of the enclosed gas changes, as more gas causes the wetted length to increase.

In the following manner an approximate value for the ingested gas flow has been obtained. The volume flow of the liquid $\emptyset_v$, when there is not yet gas in the chamber below the shaft. The pressure of the ingested gas is the pressure build up immediately after the start (Take a value within 10 sec.). For the calculation of the gradient dP/dt we use values within 30 sec. after start.

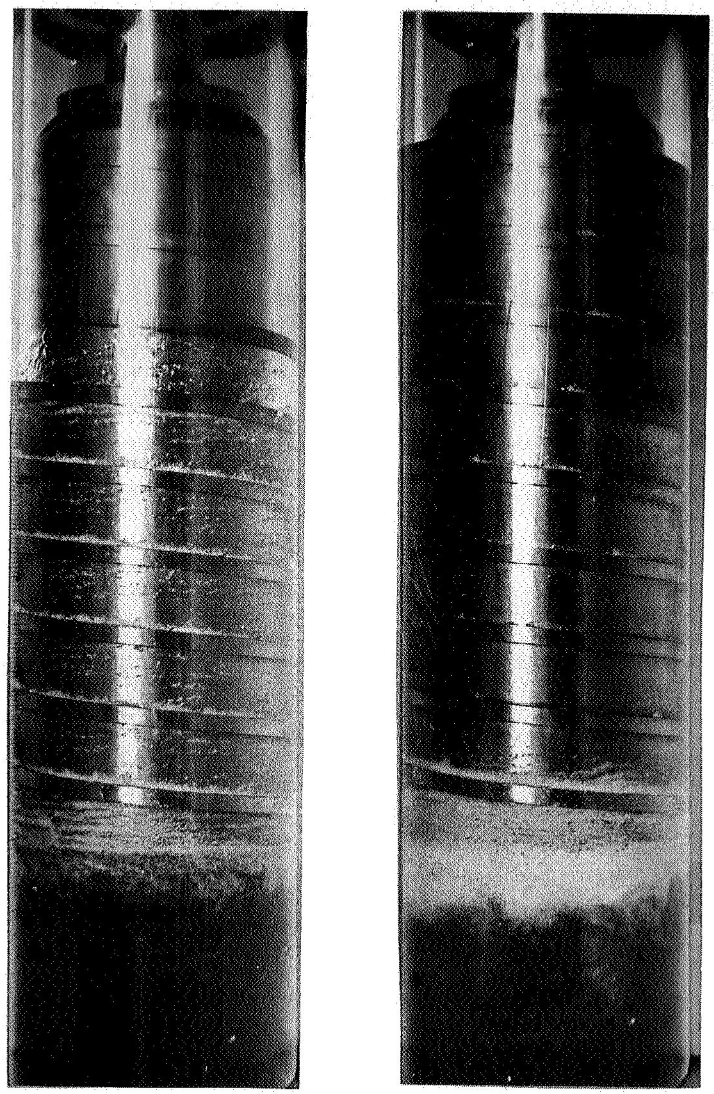
From graphs 8, 9 and 10 we find values for P and dP/dt. Formula (2) gives us $\emptyset_v$. We assume the mean temperature at 20° C and by setting P.V. = const. we reduce to gasflow equal to $\emptyset_v$ at pressure P to a gasflow $\emptyset_g$ at 1 atm. See Table 6.

Results: In Table 6 the results are summarized; the maximum quantity of ingested gas turns out to be $\emptyset_g$ = 8 ml/min (at P = 1 atm; T = 20° C). In general, the leak does increase with the number of revolutions.

7.5 Conclusions from the observations on viscoshaft seal no. 1

1. The phenomena observed with regard to the gas inclusion is in very accurate agreement with the experiments of Stair and Hale (8) and with the observations of Ludwig (10). Compare the summary of the literature survey in 2.1

2. For the lowest number of revolutions, N = 1082 rpm, there is a well defined oil/air interface whereby no gas ingestion occurs. For higher velocities there is no longer a well defined interface; gas ingestion does occur.
3. Gas ingestion may be prevented at high velocities by putting so much sealing fluid in the system that the level is far above the grooved part of the seal. The height of the level is restricted in our case by the construction of the apparatus. At a high level, the fluid may contact the upper bearing. Thereby foam will be formed that is transported axially through the seal (see also Fig 1.).
4. If the liquid level reaches the machined end of the shaft, decreased ingestion results. See pictures 8-20 and 8-21 and Fig. 4. This effect cannot be observed at high velocities where strong ingestion occurs.
5. For N = 1082 rpm whereby no gas ingestion occurs, it has been observed that a quantity of gas that was originally present in the space below the shaft does disappear slowly.
6. For the lower numbers of revolutions gas transport primarily takes place along the low pressure sides of the lands.
7. For numbers of revolutions higher than 1910 rpm pressure variations occur in the stationary state caused by the escape of enclosed quantities of gas. Hereby so called gas fronts are visible. The pressure fluctuations are maximal for N = 1910 rpm and decrease for increasing number of revolutions.
8. For numbers of revolutions <u>smaller than</u> 1910 rpm, it takes longer for a smaller volume of liquid to reach the stationary state than for a larger volume of liquid. See Table 4.
9. Due to the vertical mounting of our seal, fluid cannot possibly leak out of it. It has been observed that sealing fluid was transported beyond the active length of the seal at the escape of gas fronts and for high numbers of revolutions. For a shaft rotating in a horizontal position this could lead to leakage of oil. For the intermittantly escaping enclosed quantites



8-20 8-21

For low numbers of revolutions the gas ingestion decreases when the liquid level begins to coinside with the machined shaft end.

of gas (gas fronts) a pulsating leak occurs. This has been observed by Ludwig (10). If the fluid chamber to be sealed is large, then the gas will not accumulate at the high pressure end of the seal if it is rotating horizontally. The result is that gas is pumped continually in the liquid filled space. This is accompanied by a continuous leak of fluid.

10. An approximate calculation of the quantity of gas ingested is possible with the use of the slope dP/dt (Fig. 8, 9 and 10). An increase with the number of revolutions can be observed; the maximum quantity ingested was $\emptyset_g$ = ml/min. (for P = 1 atm; T = 20° C) (Table 6)

8. Observations and conclusions with regard to gas inclusion and leak of a single V. S. S. as a seal against a chamber of constant pressure.

For the observations described so far under 7, the space to be sealed was filled with a constant volume of liquid. After the start the pressure in the liquid increased until the pressure generated by the V. S. S. was reached.

In practice one will often be concerned with a seal against a chamber of constant pressure, for example pumps and compressors. The shaft seal must then at least be able to generate that pressure in order to prevent leakage.

With shaft no. 2 (see Fig. 5) a series of experiments is conducted; the sealing rings on the shaft had been removed.

Observations

The apparatus depicted in Fig. 3 was connected with the apparatus of Fig. 1 at the points b. After the start a pressure was introduced in the space below the shaft which was about 3/4 of the theoretical maximum sealing pressure.

For all numbers of revolutions larger than 1082 rpm gas inclusion and leak appeared. Thereby the fluid is superseded and the pressure is inclined to rise. A continuous correction with a regulating valve was necessary.

Except for the highest number of revolutions a steady state was attained within 5 minutes. Starting at N = 1382 rpm gas fronts are observed such as those observed under 7.3 where they start to appear at N = 1910 rpm. Concurrently with the gas fronts strong pressure fluctuations appear again; the maximumpressure is the imposed pressure. Data appear in table 5, shaft no. 2. For an increasing number of revolutions the pressure fluctuations decrease, and at N = 2590 rpm the pressure has become constant. In this situation large gas bubbles still escape upwards from the space below the shaft (gas fronts). For N = 4120 rpm the steady state is reached only after 15 minutes.

Conclusion

There is a sharp division between the number of revolutions N = 1082 rpm at which no ingestion appears and the seal does not leak and the number of revolutions N = 1382 rpm at which strong leakage occurs. The wetted length of the seal varies strongly due to the escape of gas fronts. Just as under 7.5 conclusion 9, gas escapes continually here also from the high pressure space below the seal through the latter to the low pressure end. If the chamber to be sealed is a flowing system, then the gas which leaks through the seal towards the high pressure space will be carried off. Gas fronts will not occur and the transport of gas through the seal takes place only in the direction of the pressure build-up. In this way the stream of liquid will be mixed with a stream of gas which, besides undesirable contamination, may have a detrimental effect on the pump capacity.

9. Prevention of leak of a simple V.S.S.

Since an insight in the leak phenomena is obtained from the observations of the single shaft no. 1 we can try to prevent leakage. One can:

a) Alow gas inclusion but prevent an axial transport of gas over the full length of the seal.

b) Try to prevent gas ingestion and gas inclusion.

Ad.a) A solution along these lines does not prevent gas inclusion. The question remains if the calculation method is still satisfactory as it does not take gas inclusion into account. An effort will be made to prevent leakage without changing the geometry.

Ad.b) After a solution has been found for a certain circumferential velocity, the chance always remains that gas inclusion and leak do appear again at higher numbers of revolutions. Therefore method a) is a more general solution for the prevention of leak. Method b) will be investigated by changing the surface energy of the shaft and by deepening the groove in the shaft. In the latter case the geometry does change.

9.1 Prevention of leakage by installing a gas barrier

It was supposed that leakage might be prevented by installing a barrier against the gas included. If it is placed at the high pressure end of the shaft (low end) the gas cannot penetrate the space containing the fluid to be sealed.

To realize this it is necessary to install a part that must be fitted in the housing with very close tolerances. As the theory indicates, it follows from the absence of net axial transport that the gas will not cross this smooth part of the shaft.

Because it was not feasible to construct a fitting bushing on the lower end of the existing shaft no. 1 a new shaft was machined with the same geometry as the first one having a closing ring at its ends (Fig. 5). The diameter of this closing ring is equal to the diameter taken over the lands; due to the tolerance on the radial clearance a larger diameter is not possible.

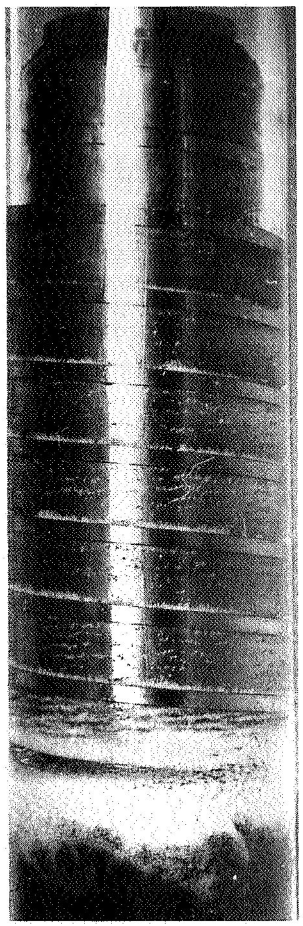
With a closing ring at its lower end this shaft is called no. 2-A.

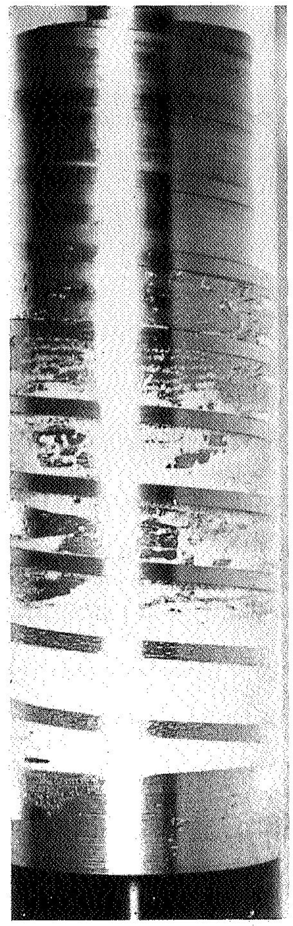
A. Observations

For the sealing with shafts nos. 1 and 2-A that have the same geometry, the initial gas ingestion is almost equal (pictures 8-8 and 9-28). The steady states differ (pictures 8-12 and 9-31).

-----At N = 1522 rpm, leakage of gas to the space below the shaft took place for shaft no. 1. At this same number of revolutions no or very little

8-12

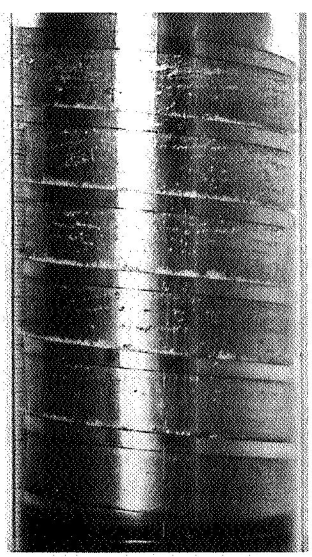


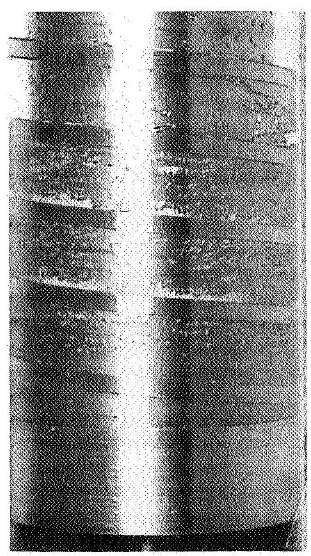


9-31

Comparison of the stationary states of shafts 1 and 2A; N = 1522 rpm. Shaft 1 gives rise to gas inclusion, shaft 2A gives gas inclusion but no leak.

8-8





9-28

Comparison of shafts nos. 1 and 2A; with and without closing ring. Pictures are made 3 sec. after starting; the initial gas ingestion is equal for both shafts.

leakage of gas took place across the closing ring of shaft no. 2A. In this case the ingested gas is accumulated in the seal and gives rise to intense formation of foam (picture 9-31). Gas fronts are observed from the upper part of the closing ring but this does not cause variations in the pressure. The steady state is attained faster for shaft 2-A than for shaft no. 1 possibly because almost no gas transport is necessary for the attainment of a steady state (see Table 4 at N = 1522 rpm).

It can be observed in picture 9-31 that gas is present over a large part of the closing ring, although on the average only at about 5 mm from the upper end. The penetration over a larger part coincides with the escape of a gas front. Apparently, the accumulated gas looks for an exit and in this case still finds it upward.

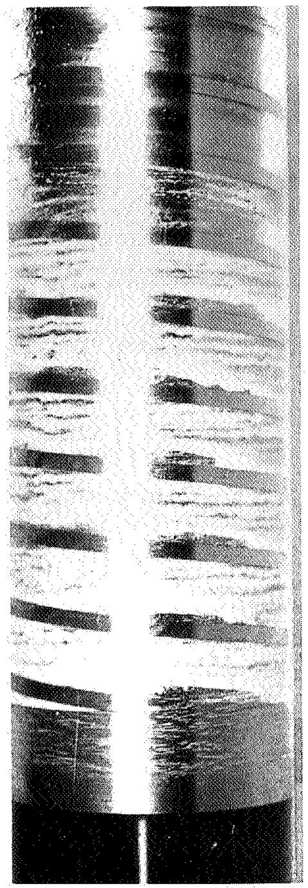
----- Starting with N = 1720 rpm leakage of gas takes place across the closing ring. This process is very slow but results finally in the formation of gas fronts from the space below the closing ring. Otherwise the picture is analogous to picture 9-31. When the fluid level rises so strongly due to the gas leak that it becomes situated above the active part of the seal, then no more gas ingestion occurs. A steady state arises for which there is a certain amount of gas below the closing ring.

----- For N = 2175 rpm sometimes a large quantity of gas accumulates under the closing ring although gas fronts do occur (picture 10-23).

----- For N = 4120 rpm a very dense foam develops immediately as for shaft no. 1.

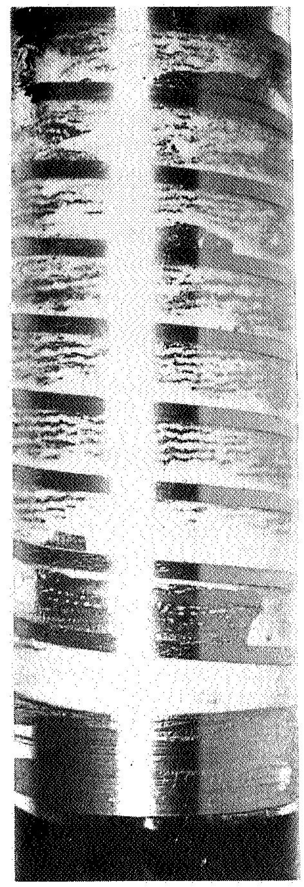
When a large volume of liquid was sealed <u>no</u> leak was observed. There was gas at 3/4 of the closing ring, but no leak was observed. This steady state was reached immediately after the start (picture 10-35).

For a smaller volume of liquid a leak did occur. Due to this process which went very slowly, the pressure build-up increased. After 34 min. the state was not yet steady. See Table 4.



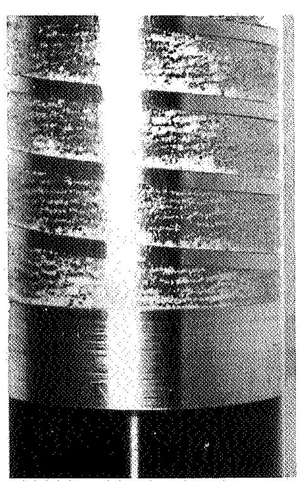
10-35

Shaft 2A; N = 4120 rpm. Gas appears on a large part of the closing ring but no leak occurs.

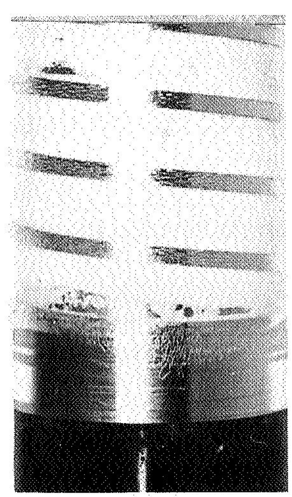


10-23

Shaft 2A; N = 2175 rpm. Sometimes much gas is accumulated in the space below the shaft, gas fronts are possible.



10-11



10-13

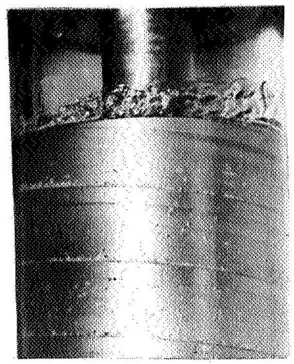
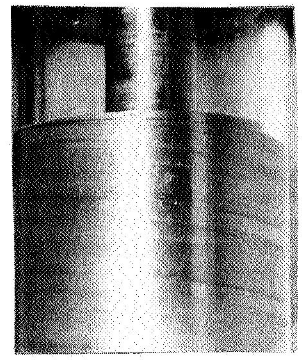
Transport across the closing ring for all numbers of revolutions occurs only in the pressure of a dense layer of foam above the closing ring.

B. <u>Conclusions</u>

1. Gas ingestion takes place with shaft 2-A as well as with shaft 1 for N larger than 1382 rpm.
2. If gas ingestion occurs there is more and denser foam on the shaft 2-A than with shaft no. 1. This is especially apparent for low numbers of revolutions.
3. Leak across the closing ring and escape of gas in fronts towards the low pressure end occurs first at N = 1720 rpm for shaft 2-A. However for shaft no. 1 leak occurred before that (at N = 1382 rpm) while gas fronts were observed firstly at N = 1910 rpm.
4. If leak occurs, then it takes considerably longer to reach the steady state for shaft 2-A than for shaft no. 1 (See Table 4).
5. Gas does only exist on the closing ring or is transported across it if a dense layer of foam having a width of at least 10 mm is present just above the closing ring (pictures 10-11 and 10-13).
6. The shaft 2-A exhibits edge effects. When the liquid level coincides with the upper edge of the seal increased gas ingestion occurs. This is easy to observe for N = 1082 rpm where <u>no</u> gas ingestion occurs when the liquid level is above or below the active length of the seal (pictures 38-11, 12 and 13).
7. It was observed at N = 1082 rpm that a small quantity of air in the space below the shaft disappeared in 15 minutes.
8. The situation is not reproducable for the lowest number of revolutions. Sometimes little gas ingestion occurs.

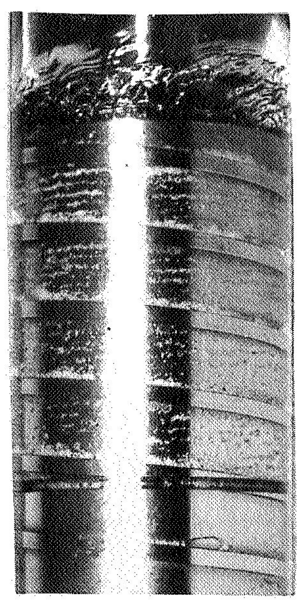
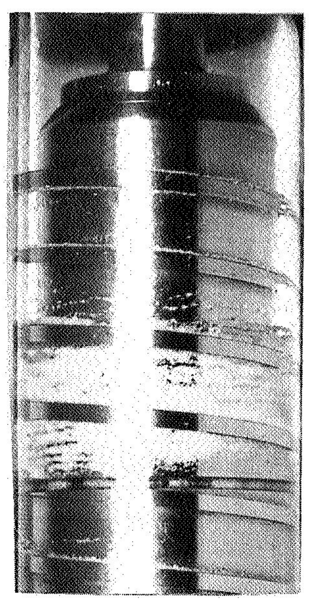
9.2 <u>Prevention of leakage by separating and returning the enclosed gas (Gas recirculation)</u>

The train of thought for this method was the following: The already ingested gas bubbles are not allowed to reach the lower end of the seal. After being separated from the sealing fluid the gas bubbles must be returned to the gas filled space. The gas will be pressed against the shaft

38-11 38-12 38-13

Edge effect of Shaft 2-A. When the fluid level coincides with the shaft end, increased gas ingestion occurs.

12-3 12-43

Shaft 1-D. If the upper recirculation channel ends in the liquid (picture 12-3) then less gas ingestion occurs as for a lower level whereby the channel ends in the gas.

due to its lower density and may disappear in it if an outlet is available. In order to accomplish this a number of changes were made in shaft no. 1 (Fig. 4); these will be indicated by adding a letter to the shaft number. At first we will try to eliminate the observed large gasflow at the upper sides of the lands.

Observations

----- See also Fig. 11. In visco shaft no. 1 a hole has been drilled along the axis. The upper end is closed again. Two radial channels, one in the center and one at the upper end, connect the shaft surface with the central cavity. Both channels begin directly below a land (Ø = 1 mm). For this shaft 1-A an oil gasflow from the upper channel was observable during operation. No decrease of the leakage flow was observed.

----- In the center of the shaft, just above a land, another radial channel was drilled in the same plane as the one drilled previously. For this shaft 1-B an observable decrease in the transport of gas occurred just beyond the point where the center channels were. The good recirculation of the gas was visible during an observation at N = 1382 rpm. In this case gas fronts escaped from the space below the shaft. Arriving at the center channels the gas disappeared in them while at the same time the foam intensity increased at the upper channel.

----- Around the shaft a groove was machined (depth 1 mm; width 2 mm) in the plane of the center channels. It was supposed that the gas pressed against the shaft could separate itself more easily from the oil in this groove to be subsequently returned. Also due to the cutting through the land and the absence of net axial transport no gas may cross the groove. Indeed, for this shaft 1-C a strong improvement is observed; however not yet sufficient.

----- Therefore the groove is deepened and brought to 4 mm. Both the radial channels are drilled to Ø = 1.5 in order to be able to carry off the probably large quantity of gas. This shaft 1-D shows a strong decrease of gas ingestion beyond the groove. Hereby both the time necessary for the complete wetting of the seal and time necessary to reach a stationary state increase. See also table 4 and compare with shaft 1. The necessary time increases with a factor from 5 to 10.

It appears as if the foam density above the groove is increased with respect to shaft 1 (pictures 12-43 and 8-19). When the seal is almost completely filled with liquid and if the upper channel ends in the liquid, the gas ingestion decreases again (pictures 12-3 and 12-43).

Gas fronts occur in larger intervals with shaft 1-D than with shaft 1. The ingestion at N=4120 rpm is analogous to shaft 1 (compare picture 12-3 with 8-33 at 7.3). However beyond the groove there is little gas transport. After about 15 minutes the first gas front escapes from the space below the shaft, it does not move farther than the groove and disappears (picture 12-5).

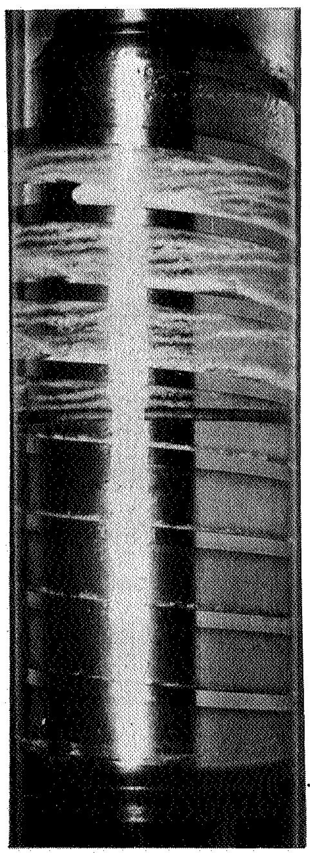
The castrahsport beyond the groove may be caused by a small decrease in pressure behind the inclining land. That is why the effect of machining away a part of the land was investigated. This yielded shaft 1-E Fig. 11.

This shaft did not give an observable leak under any circumstances if the liquid level was above the groove. The increasing improvement is recorded in the pictures 8-19, 12-41 and 13-22 at N = 1720 rpm.

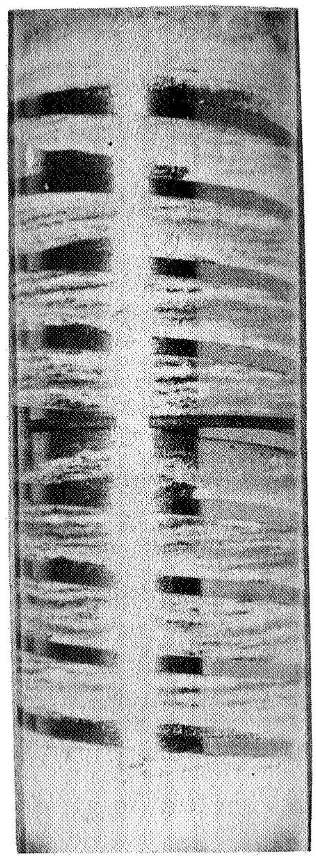
The shaft obtained a more or less "self stabilizing" mode of operation. If the level is too low originally intense gas inclusion and leak takes place, completely analogous to shaft 1 (picture 8-33 at 9.3). Due to the accompanying rise of the level, gas inclusion stops at a certain moment (pictures 13-24 and 26). In the stationary state there is then a certain amount of gas observed as a bubble around the shaft.

9.3 Synopsis of the results of 9.1 and 9.2

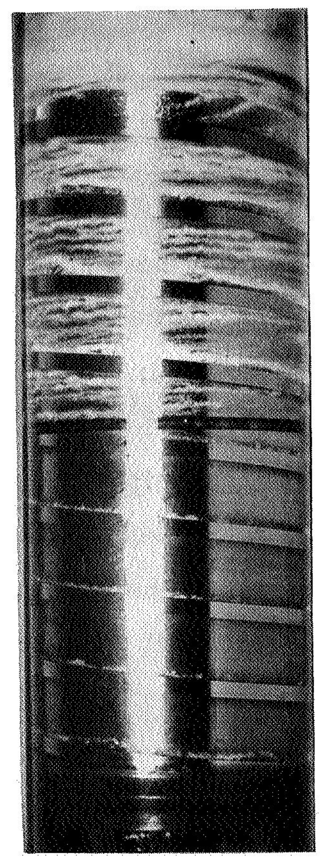
-----The solution of shaft 1-E is a complete solution. There occurs absolutely no leak through the seal. However by putting the groove around the center of the shaft the active length of the seal is cut in half.



12-8
Shaft 1-D

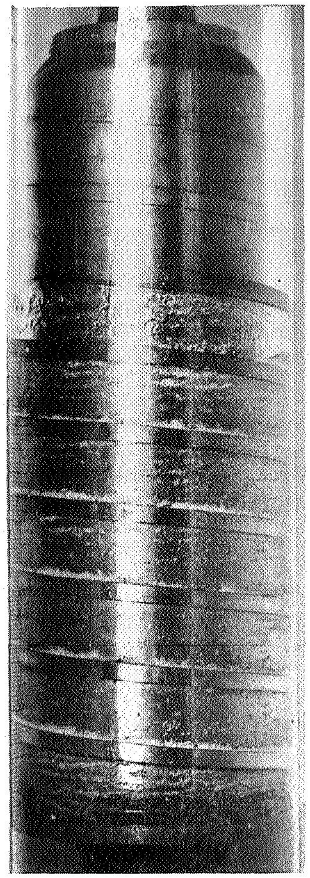


12-4
N = 4120 rpm

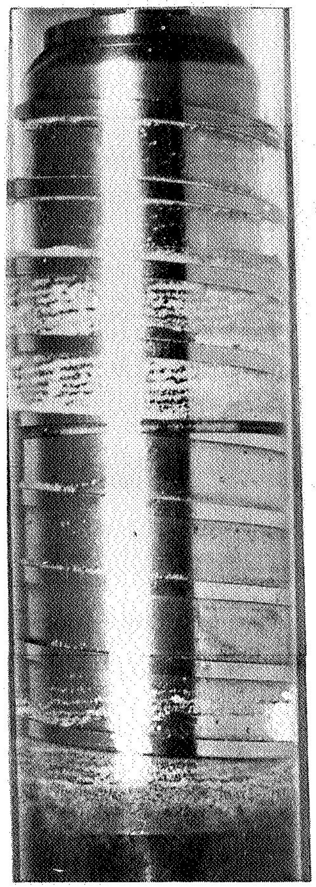


12-5
Re_1 = 575

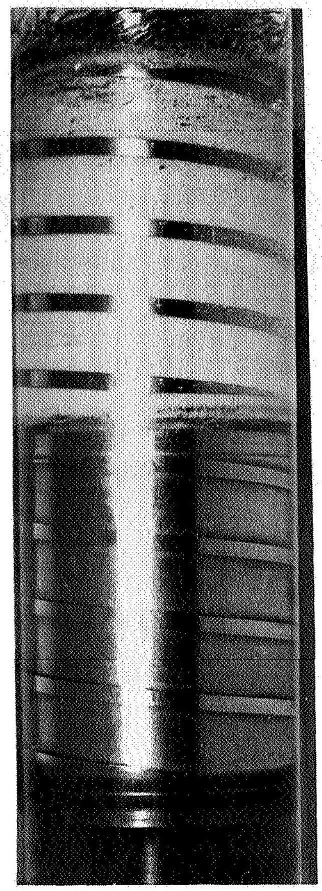
Just as with shaft 1 strong ingestion above the groove occurs immediately after starting (picture 12-8). The little ingestion below the groove leads after 15 min. to the escape of a gas front (12-4). Immediately thereafter the foam on the lower halve of the shaft disappears; below the shaft there is a clear "air bell" (picture 12-5) Gas ingestion and leak cause a new gas front to escape after about 1 1/2 min. whereby picture 12-4 appears again.



8-19
Shaft 1
N = 1720 rpm

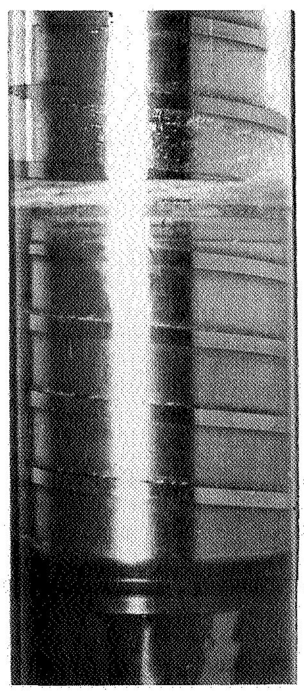


12-41
Shaft 1-D
$Re_1 = 240$

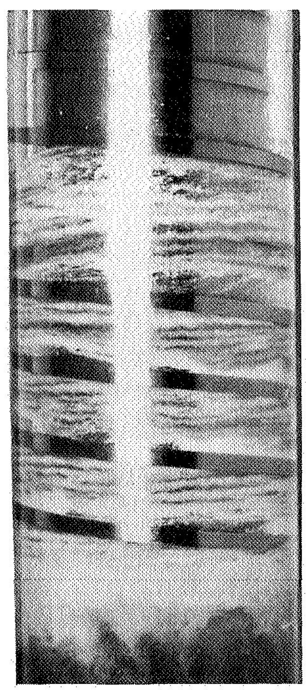


13-22
Shaft 1-E
internal recirculation system

Increasing improvement of the prevention of leak. 8-19 original shaft; 12-41 shaft with groove and recirculation system; 13-22, the land is machined away on both sides of the groove, no more leak occurs.



13-24



13-26

"Self stabilizing" operation of shaft 1-E. After initial gas inclusion (13-26) a stationary state without new inclusion occurs due to the rise of the level.

----- Shaft type 2-A only gave a delay of the leak, see Table 4; combined with the changes in construction of shaft 1 a solution ought to be gotten also.

----- For this reason shaft 2-C has been made, see Fig. 12. Here the groove is machined out of the upper part of the closing ring. Internal recirculation is possible. The shafts 2-C and 2-D that only differ in the position of the upper radial channel, also give a seal without any leakage.

9.4 Prevention of leakage by a part of the seal over which no axial transport is possible

For the aforementioned succesive changes of the shafts 1 and 2 it has not become certain if a groove without a possibility of internal recirculation can prevent leakage.

Theoretically no net axial transport occurs for the seal so that over smooth parts of the shaft or across the grooves no leak should be able to occur. In order to investigate this we closed the radial channels in the shafts 1 and 2; the shaft are indicate with 1-G and 2-E.

Observations

----- It was thought initially that these shafts also gave a complete solution for the prevention of leakage. Shaft 1-G satisfied best. Very sporadically gas bubbles were transported from the groove towards the lower end of the shaft. However they dissolve along the way. If we allow a little oil to flow away suddenly a net transport results and gas is clearly transported along the full length of the seal. This is contrary to the shaft with a possibility for recirculation because there no transport was observed after a sudden pressure drop. However the leak of shaft 1-G is of relative value because we found at all numbers of revolutions that the air present below the shaft disappears after some time. A slow diminishing of the oil volume does not yield an observable gas transport.

----- More leak appears for shaft 2-E. The phenomena are not reproducable. Here also it is observed that a small quantity of gas in the space under the shaft disappears for all numbers of revolutions. Especially when oil is drafted from the system gas is transported across the closing ring. Sometimes no leak occurs at low oil levels while for the same number of revolutions and high liquid levels in the seal leak does take place.

Conclusion:

For systems in which pressure variations occur we may observe gas inclusion and leak in the absence of an internal recirculation system. Shaft 1-G is best suited to remove the enclosed gas. It cannot be observed in what way the gas dissolves or how it is transported.

For shaft 2-E more ingestion occurrs and the disappearance of the enclosed gas progresses slower. Therefore we can say only that for both cases the gas inclusion and leak are only delayed.

9.5 Prevention of gas inclusion and leakage by changing the surface energy of the shaft

Till so far only constructive solutions have been discussed; this is a physical solution of the leak problem. The degree of wetting of a solid by a liquid depends on the surface energies. For a solid this can be varied by applying or having absorb foreign matter. The surface energy of a liquid can be changed by the addition of certain elements. One then may investigate if the wettability of the shaft surface influences gas inclusion and leak.

In general one may assume that a liquid with high surface energy does not spread over a solid with low energy. For wetting it is necessary that the surface energy of the fluid is lower than a certain critical surface tension of the solid.

The sealing fluid used, no. 3, does spread well on the shafts (material messing and steel). The surface energy of the liquid is about 30×10^{-3} N/m.

To induce a possible lesser spreading shaft no. 2 has been coated with a thin layer of Teflon. This material has a well known low critical surface tension of 18 x 10^{-3} N/m.

McGrew and Orsino (9) measured that for a V.S.S. coated with Teflon less leakage occurs. We cannot measure a leakage of liquid at a single V.S.S., however we can say on the basis of visual observations and the comparison of those if and how gas inclusion is affected.

----- During our investigation a Teflon coating did not appear to affect the intensity of gas inclusion. It is possible to obtain a slight decrease in the maximum attainable pressure generation; data concerning the pressure build-up of shaft no. 2 without coating were not available.-----

9.6 Prevention of gas inclusion and leakage by making the grooves of the seal deeper

The groove of shaft no. 2 has been deepened and brought to 0.90 mm. Therefore the geometry is changed; the shaft will from now on be indicated as shaft no. 9.

The groove may not be deepened too much because it can be derived theoretically that due to this process a strong decrease of the sealing parameter will occur after an initial increase (12). It is true that this investigation is primarily concerned with the prevention of leak and one will therefore be satisfied with a lower sealing parameter; however it is clear that a limit has to be imposed. Experience with double V.S.S.'s supplied the chosen groove depth.

Observations

The results are shown by the pictures. Internal recirculation is not possible. Compared with shaft no. 2 clearly less gas ingestion and gas inclusion occurs especially for the low numbers of revolutions. Only at the highest velocity (picture 41-10) a small leak occurred every once in a while. The visible quantities of gas in the space below the seal (pictures

41-12 and 41-13) did not get there because of leak; they were already there before the start.

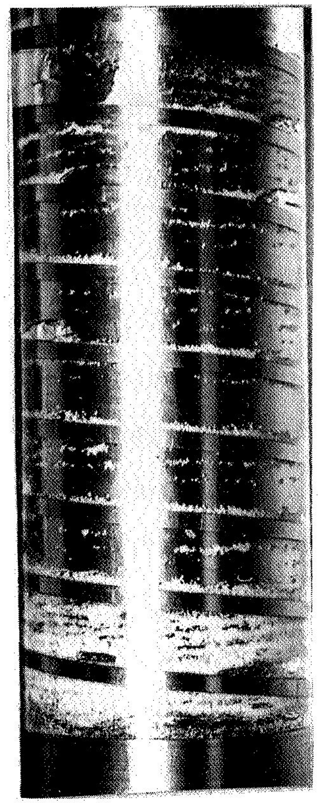
Conclusions

1. Deepening of the groove gives less gas ingestion and gas inclusion for the lower numbers of revolutions.
2. Leak does not appear except sporadically at the highest number of revolutions. For shaft no. 2 leak appeared for N = 1720 rpm.
3. For a strong decrease in pressure (due to letting off oil) leak does take place across the closing ring; this is analogous to shaft no. 2.
4. If gas has accumulated below the shaft, for example due to a pressure drop, then this gas dissolves and disappears. This phenomenon was also observed with the shafts 1 and 2 but the dissolution of the gas was not as fast. The elapsed time for this case is of the order of 5 min, for shafts 1 and 2 from 15 to 30 min. The time is dependent on the quantity of gas.
5. For two numbers of revolutions that is N = 1720 rpm and 1910 rpm, only gas ingestion occurs. Gas is hardly transported to the lower end of the seal. Hence there is no gas inclusion. See picture 41-12.
6. Contrary to shafts 1 and 2 gas ingestion and gas inclusion does occur for the lowest number of revolutions. This has been observed also with the shaft no. 8 to be discussed later, for which the geometry is equal to shaft no. 9 except for the number of grooves.

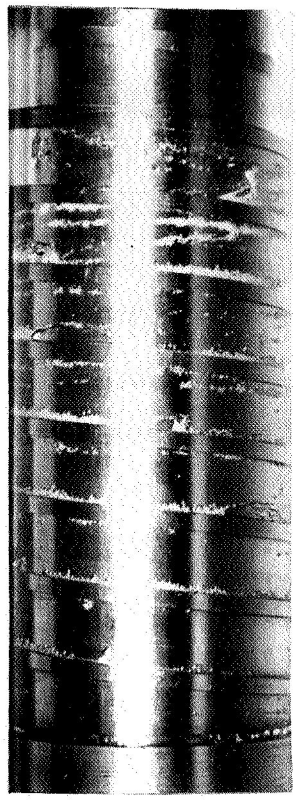
The effect of a further deepening of the groove will be investigated for the double V.S.S.'s.

10. Introduction to the investigation for the prevention of leakage and break down of double visco shaft seals

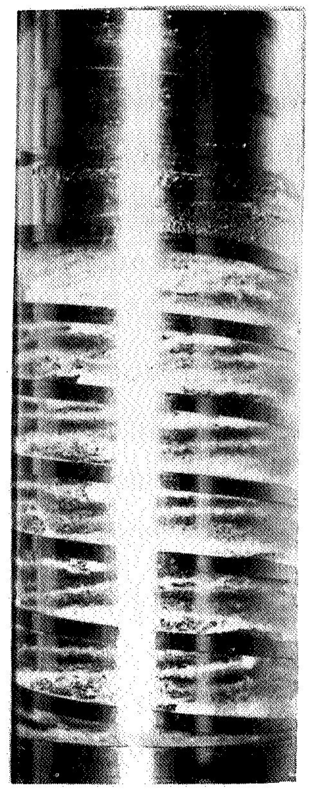
In the apparatus depicted in Fig. 1 the single visco shaft has been replaced by a double grooved shaft. It is drawn schematically in Fig. 13. The shaft consist of a steel core on which messing visco bushings can be



41-13
N = 1382 rpm



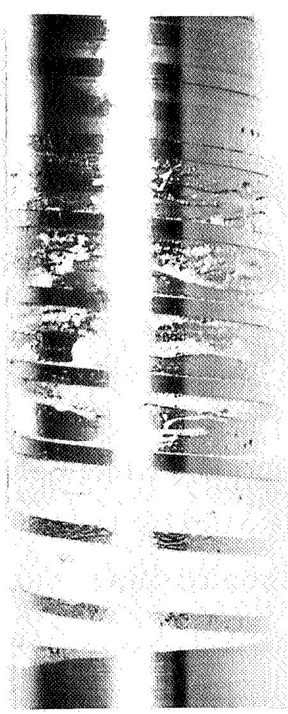
41-12
N = 1720 rpm



41-10
N = 4120 rpm

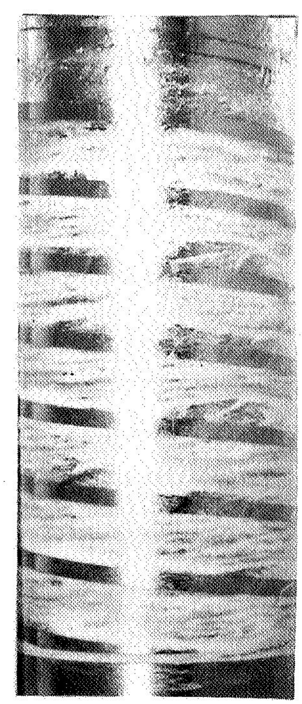
Effect of the deepening of the groove on the gas inclusion and leak. Above shaft no. 9, below shaft no. 2. Due to deepening the gas ingestion decreases and no leak occurs. For (41-12) only ingestion occurs and no leak or inclusion.

9-32



9-35

19-8



mounted. One shaft seal should consist of at least a bushing with left-handed thread and a bushing with right-handed thread. The bushings must be mounted on the shaft such that during operation pressure will be generated towards the center of the shaft. The geometry that is obtained using the bushings, of the obtained seal is defined in table 1. Both bushings can be mounted separately. To this end a number of central bushings are available. Figure 14.

The double V. S. S. is suited to seal two gas filled spaces from each other. In our case these spaces are the space below the bottom bushing and the space above the top bushing. The latter has an open connection with the environmental air. Using the mounting in Fig. 3, the lower space can be pressurized as need may be.

The sealing fluid is supplied through the opening in the seal formed by the upper bearing when the shaft is not in operation.

For the investigation the following observations are of interest:

a) The degree of foaming in the seal. It appears that the sealing parameter is influenced by this and break down may occur. In another part of this investigation the influence of foaming on the sealing parameter will be investigated, now only the intensity of foaming will be established.

b) The observing and measuring of gas leakage and

c) The observation of an oil leak indicated by loss of sealing liquid.

Ad a) The non-reproducity of the foaming intensity and gas inclusion phenomenon has already been discussed in 6.2. Because the leak is dependent on the foaming intensity these phenomena are emphasized again here.

Ad c) This phenomenon including its consequences has been discussed already in 6.5.

10.1 The significance of the observed measured gas leak

The gas leak phenomenon has already been described in 6.6. For this phenomenon at the double V. S. S. a further explanation follows.

Gas leak, being an axial transport of enclosed gas through the seal, ought to te observable visually, if necessary with instruments. It is possible that leakage is observed although over the seal as a whole no net axial gas transport occurs. We then experience a leakage of gas in the form of an exchange process. Also if a pressure difference is imposed between the two spaces there may be leak only due to exchange. In that case no change in pressure occurs.

If during the above mentioned leakage process, the transport of gas in one direction is dominant then a net gas transport will occur through the seal. Dependent on the rate of the ensueing, exchange contamination of both gas-filled spaces with foreign gas will take place. This gas leak can be measured. If there is an enclosed quantity of gas at the bottom of the seal and there is mainly gas transport to the top of the seal, then the pressure in the space below the V. S. S. drops. Because the rig in Fig. 3, is now connected with the apparatus in Fig. 1, the level in the left leg of the U-tube rises if valve a is closed. This is called a positive leak.

If the direction of the net gas transport is opposite to the one in the former case, then the quantity of gas in the space below the shaft increases. The pressure rises and the level in the left leg of the U-tube drops. Now negative leak occurs.

The leak observations have always been made at imposed high pressure in the space below the shaft. Then, for a positive leak, a pressure drop will follow.

Together with a negative leak often a great loss of sealing fluid is observed. The fluid appears in the space below the shaft hence the gas volume decreases. If no gas transport occurs through the seal the decrease of the volume below the shaft will result in an increase of pressure there. This is also noted by the appearance of a negative leak.

Conclusion

An observed negative leak does not need to result from a leak in the seal. It may be caused by a loss of sealing fluid.

10.2 The appearance of leakage at the double V. S. S. in the Laboratorium for Chemical Equipment

Using visco bushings no. 3 a shaft was constructed similar to the one in the Lab. for Chem. Equip. The grooved parts of the shaft are in direct contact for this case (picture 38-37).

For gas inclusion leak will always appear. The gasses will contact in the middle of the seal (picture 38-38) whereby exchange occurs. Dependent on the circumstances we may also encounter positive or negative leak.

11. The prevention of leakage of a double V. S. S. by recirculating the ingested gas and/or the installation of a gas barrier

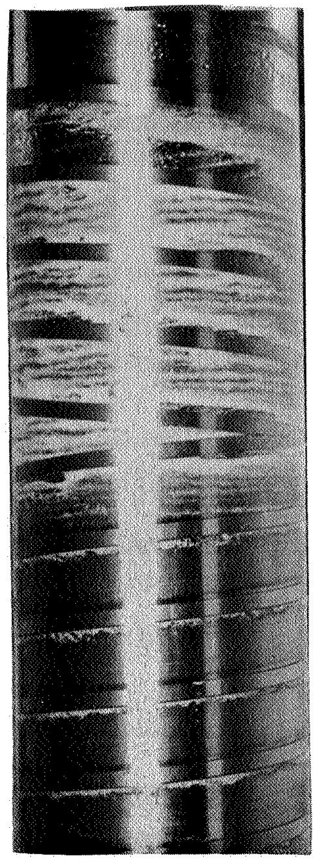
We may expect that the observed leakage phenomenon for the single V. S. S. will now occur from both ends of the seal. This is confirmed by the observations of 10.2.

We investigated if leak can be prevented in the same way as for the single V. S. S.

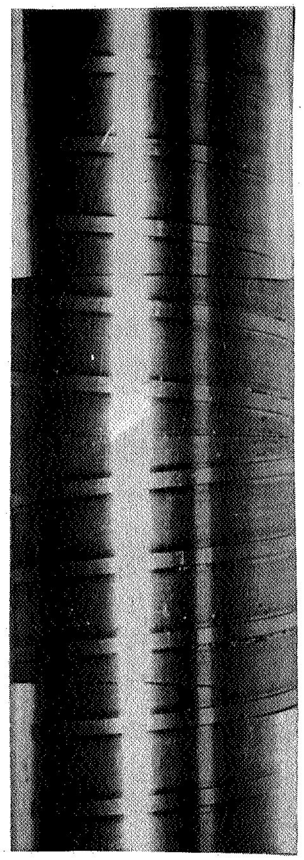
-----A gas barrier can be installed between the two halves of the seal using center bushings (Fig. 13 and 14).

-----In Fig. 6 is indicated how the recirculation system for the enclosed gas is installed in this double V. S. S.

The gas ingested at both halves of the seal must be recirculated to the space from which it was ingested. The presence of two separate recirculation channels is therefore necessary. In the grooves of center bushing B the enclosed gas is caught whereafter it can flow back through the internal channels (Fig. 6). To prevent leak through the clearance between bushing and shaft. In this way the recirculation channel is defined accurately;



38-38



38-37

Imitation of the V. S. S. in the Lab. for Chem. Instruments. The grooved parts of the shaft are next to each other. If gas inclusion occurs, at least exchange of gas will take place, this means leak.

the low pressure end is formed by the radial channel in the visco bushing.

11.1 The manipulation of the leak using the center bushing

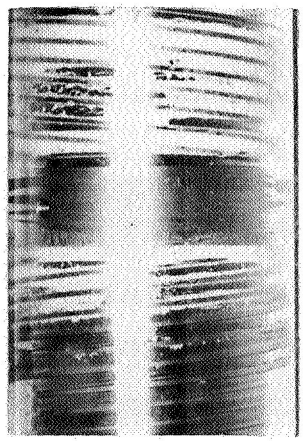
The center bushing A constitutes a gas barrier for both halves of the seal as investigated for the single V.S.S. at 9.1 and 9.4. Here also leak only occurs in the presence of a certain intensity of foaming (pictures 33-16 and 33-26). In this case center bushing A appears to be less able to prevent the leak than bushings D or C. For the last one there are two grooves next to the lands adjoining the visco bushings. This bushing appears to be able to prevent leakage in many cases; the larger volume of liquid that is then present in the center of the seal may be better able to absorb small pressure variations so that no axial transport of gas is possible. (Compare 32-32 with 36-10). In the remaining part of the investigation the influence of the center bushing will be investigated for each case. Also the resistance of the seal against sudden changes of the pressure difference between the gas-filled spaces will be investigated. It turns out that the least leakage occurs for a shaft with a center bushing C.

11.2 The prevention of leakage by separating and recirculating the enclosed gas

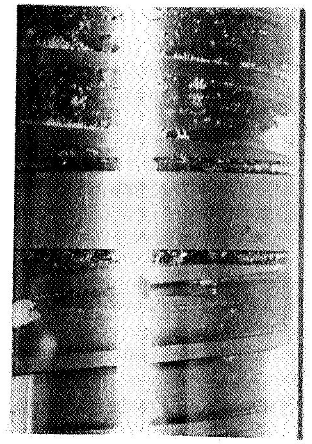
From the earlier discussion it appeared that center bushing C was the best solution for the prevention of leak. Therefore a second center bushing was made with the same geometry but with two radial channels (see Fig. 6 and Fig. 14). This is center bushing B. Via a groove in the shaft and radial channels in the visco bushings two recirculation systems are establishes.

Under no circumstances does leak appear now. Gas transport to the grooves in the bushing is clearly visible (picture 36-4).

If the capacity of the recirculation channels is too great then, besides gas, fluid will be pumped around also. This is visible on pictures 36-41 and 36-0. Although neither visible nor measurable leak was found, such a system does not appear to be reliable. The large quantities of gas that

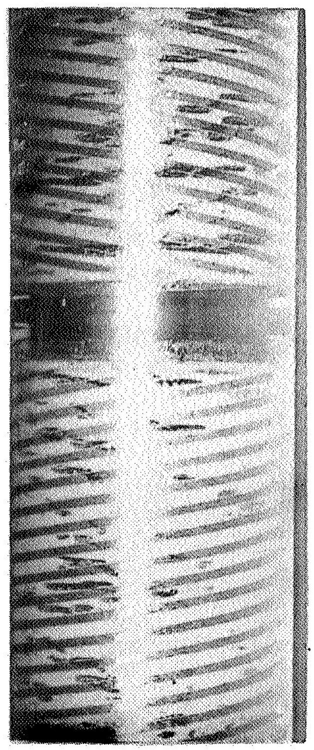


33-16

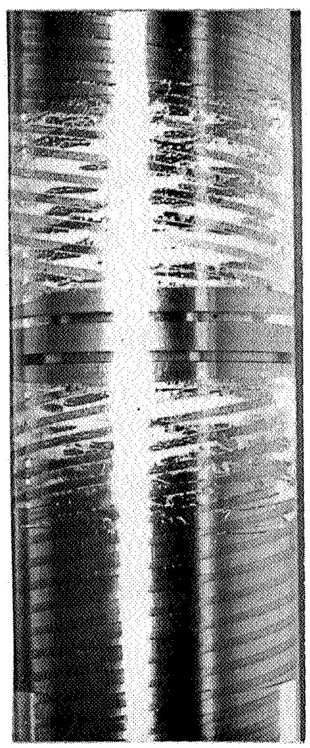


33-26

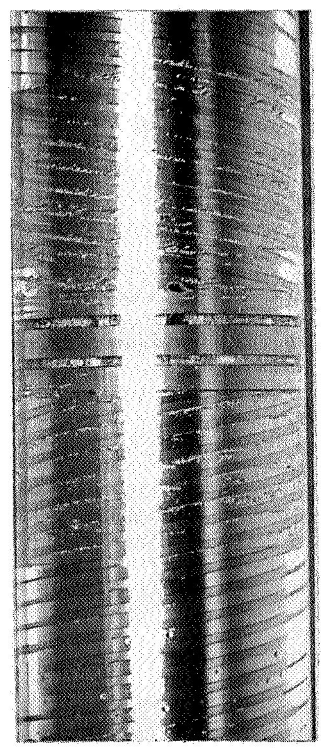
Double V. S. S., in all cases leak occurs only if there is a certain amount of foam in the center of the seal.



32-32

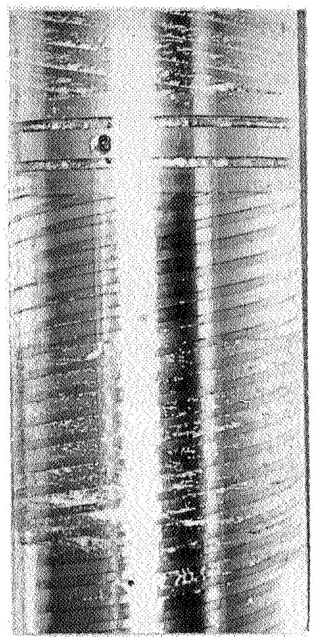


36-10

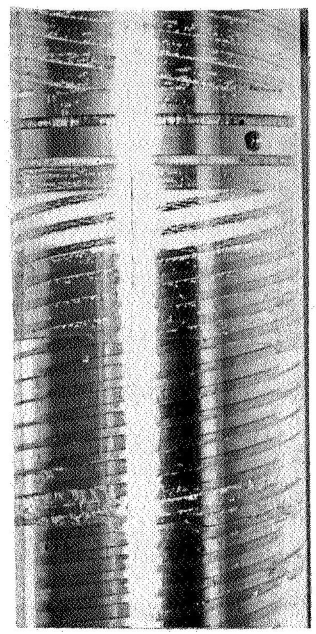


36-4

Possibilities for preventing leak using center bushing. Picture 32-32, center bushing A; leak due to exchange of gas. Picture 36-4, center bushing B; no leak but internal recirculation; transport of gas occurs via the grooves.



36-41



36-0

Due to the too great capacity of the recirculation channels, fluid is pumped around too. Because there is not enough fluid to fill the whole circuit there is intermittently a large quantity of gas in the center of the seal.

intermittently appear in the center of the seal need only to cover a short distance to cause leak.

In the ideal situation only gas is recirculated. An investigation as to which is the necessary diameter of the restriction channels will be conducted in the chapter about the manipulation of the sealing parameter by recirculation.

12. The influence of the geometry of the seal on the phenomena of gas ingestion and leak

Because now, as evidenced in the preceding chapter, one has a way to prevent the leak caused by gas inclusion, one may investigate how the geometry of the seal controls the leak. One will strive for a seal without any gas inclusion and gas ingestion because the cannot cause leak. However, by changing the geometry, the pressure generation through the seal and the dissipated energy change. A geometry optimized with respect to these two quantities will then have to be revised because of the prevention of leak.

The intensity of the gas ingestion and the gas inclusion is only observable visually in our experiment. A measure for the quantity of gas enclosed is the visible exchange of gas across the center bushing of the seal. Due to the many irreproducable pictures concerning the leak and foam formation we concentrated our observations on the intensity of foaming for a certain seal. Observations of leak and of loss of sealing fluid (6.5) will be considered independent of the intensity of the foaming.

----- Due to its character this must be a comparative investigation. On the basis of visual observations changes are made in the viscoseal geometry that decrease gas inclusion. ----- Table 7 shows the comparison possibilities. In all cases we used sealing fluid no. 3.

12.1 Observations on the double V.S.S. no. 3 (single groove)

The geometry of this seal is the same as those of the single seals nos. 1 and 2 (Table 1).

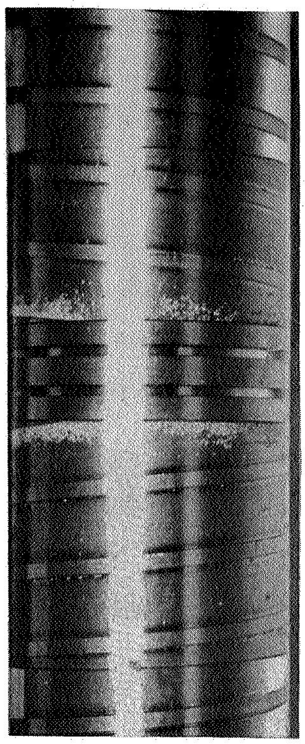
a) The intensity of foaming

The picture is strongly dependent on the number of revolutions. Compared with the analogous situation for the simple V.S.S. (pictures 9-36 and 37-14) less formation of foam does occur. Situations with more foam than shown in picture 37-14 do occur. For all low numbers of revolutions the picture of gas inclusion on the lower bushing is not the same as the one on the upper bushing. The gas inclusion on the upper bushing is divided over a large number of small bubbles; on the lower bushing the gas is concentrated in a few large air pockets (picture 37-14). As became also evident for the single V.S.S., gas inclusion can be prevented by a liquid level that is above the active part of the seal. For the double V.S.S. this condition could be obtained by pressurizing the space below the seal. In this way only the level at the upper side of the seal could be brought above the grooved part of the shaft. However it did not appear to be possible to reduce the gas inclusion by a high level in any case. Because the space above the shaft is equal for all double seals one does have a means to compare. It is supposed that the ingestion of gas, even for complete wetting of the active length, is a measure for the sensitivity to gas inclusion in general.

b) Observations of leak

For N = 1082 rpm, there hardly is ingestion or gas inclusion. Sometimes a little foam clings against the center bushing (picture 37-15). For the low numbers of revolutions no visible leak is observable. During a sudden pressure drop axial transport of gas occurs with all center bushings except bushing B.

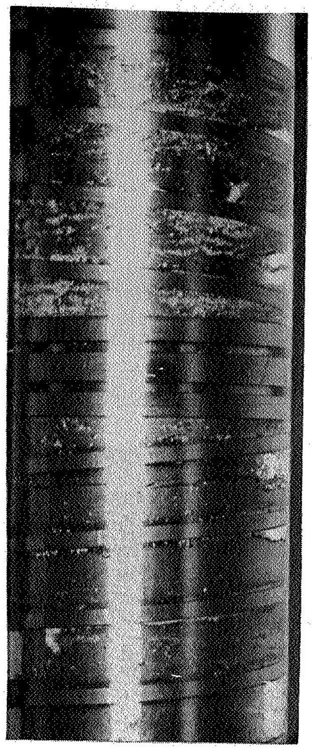
We can observe leakage across center bushing A up from N = 1720 rpm. A varying leak is measured using the U-tube rig. A positive leak of 20 ml/min; a small negative leak of 1 ml/min and no leak at all. This all for different experiments at N = 1720 rpm. Using center bushings B and C no leak is observed up from the above mentioned number of revolutions. However a



37-15

N = 1082 rpm

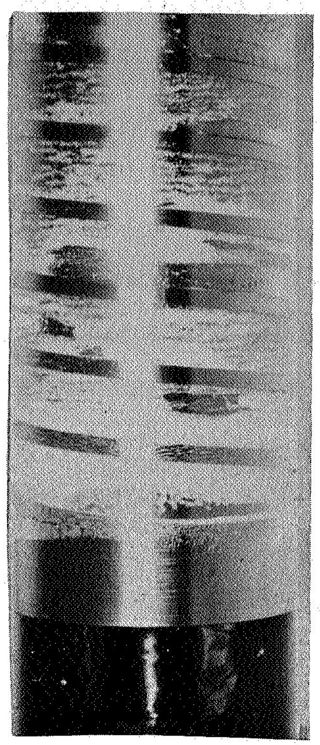
Stable interface without gas ingestion. Initially present gas is accumulated along the center bushing and does disappear very slowly or not at all.



37-14

N = 1720 rpm

Different inclusion picture on upper and lower bushing. The lower bushing contains less foam or bubbles at all low Re_1 numbers. The gas is concentrated in large air-pockets.



9-36

N = 1720 rpm

Single V. S. S. In this case foaming always occurs accompanied by gas fronts going up and eventual leak downwards.

negative leak is measured. This leak increases for higher numbers of revolutions and is imputed to the following phenomenon:

c) Loss of sealing fluid

For this seal the rapid loss of sealing fluid was striking. Due to this all fluid disappears from the seal in a short time because no fresh supply was possible. This phenomenon is accompanied by a strongly negative leak. The phenomenon could not be observed below N = 2270 rpm; for N = 4120 rpm and a pressure difference $\Delta p = 0.15\ kg/cm^2$ the following leak was observed:

time after start	negative gas leak
2 min.	0.39 ml
3 min.	4.52 ml
4 min.	shaft dry

In 7.4 we computed that the volume of the liquid in this seal was: V = 0.09 ml/mm. Therefore this double V.S.S. can contain about 16 ml at most. For an initially partially wetted seal, as was the case in the leak measurement mentioned above, a leak of 4.52 ml. can be explained as being due to loss of sealing fluid.

12.2 Observations on the double V.S.S. no. 5 (four grooves)

a) the intensity of foaming

For low numbers of revolutions there often is a dense and homogeneous foam along the center bushing. For N = 1082 rpm the gas ingestion is neglectable and an initially present dense foam disappears within 15 min. For other numbers of revolutions sometimes large quantities of gas escape from the center of the seal through the foam; these gas fronts we also encountered at the single V.S.S. (pictures 33-13 and 35-35). For high velocities the homogeneous dense foam is replaced by a less homogeneous gas inclusion picture. (Pictures 35-31 and 35-32). For a sufficiently high level of sealing fluid above the upper bushing gas ingestion can be prevented completely and the enclosed gas disappears from the bushing.

For low velocities, the foam is not always present initially; there is a little ingestion observable and foam is formed slowly from the center bushing towards the ends.

b) Observations of leak

Here the visible leak is strongly dependent on the type of center bushing and appears only if foam is present in the center of the seal as has already been noted in 11.1.

The difference between center bushings A and B is shown clearly by the pictures 33-13 and 35-35, and 33-9 and 35-21 respectively.

----- For center bushing A a clearly visible leak always occurs from N = 1382 rpm. Below this number of revolutions the center bushing is covered with foam over a large part but the two gas covered parts are not connected anywhere (picture analogous to 32-32).

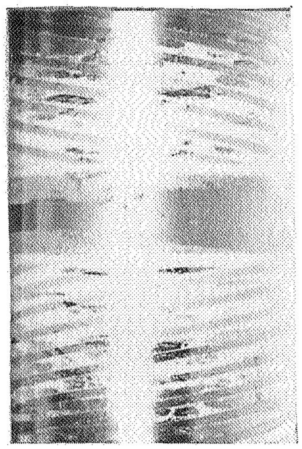
----- Less leakage occurs with bushings B, C and D, From N = 1910 rpm a visible leak is observable for bushing D; bushings B and C never show leaks. For bushing C both grooves do sometimes fill with gas but the center part still remains completely wetted.

----- If a sudden drop of the pressure difference between the two gas-filled spaces is imposed, bushings A, C and D show leakage. For bushing B, with internal recirculation; visually no leak occurs but photographs do show leakage. Picture 35-36 shows that transport of gas took place from the upper bushing to the lower groove.

----- Leak was not always measured for this seal; only negative leak accompanied by a strong loss of sealing fluid has been observed.

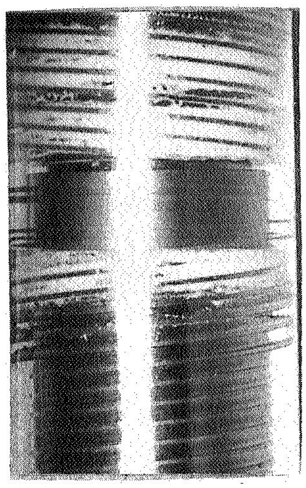
c) Loss of sealing fluid

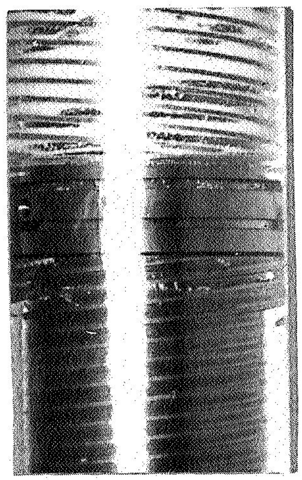
Up to N = 1720 rpm no leak was measurable for any center bushing at this seal; a small loss of sealing fluid is visible. For higher velocities

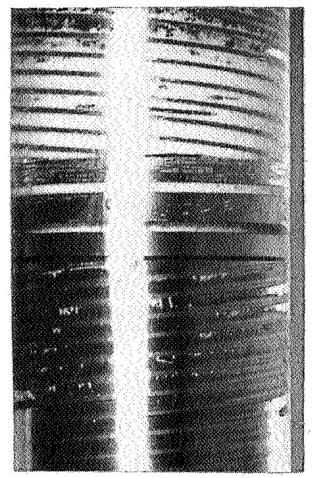


For N = 1382 rpm foam is present on the center bushing but no leak occurs.

32-33

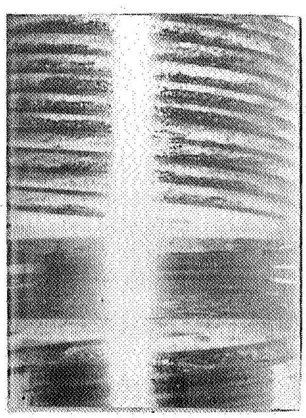


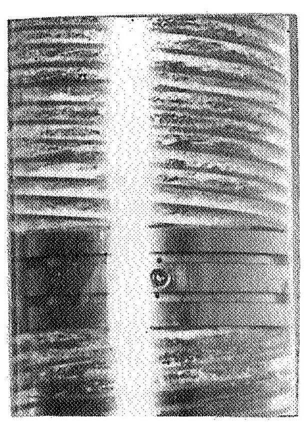


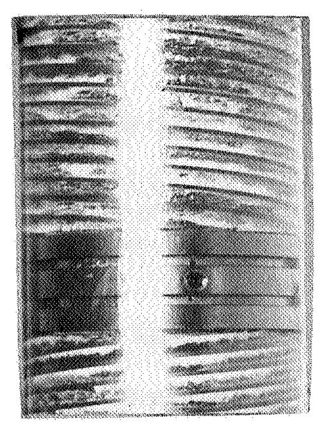


33-13 | 32-35 Internal recirculation | 35-36 $P = 0.130$ kg/cm^2

$Re_1 = 240$; bushing no. 5; Observations of leak. In the presence of foam center bushing A always gives leak. Center bushing B or C, with or without recirculation are able to prevent it. For a sudden pressure variation; it appears also if transport to the lower groove took place which would mean leak.







33-9 | 35-31 | 35-32

$Re_1 = 575$; bushing no. 5. With center bushing A there still is accumulation of foam in the grooves and therefore leak. For high Re_1 number, as in this case, no accumulation of foam takes place at center bushings B, C, and D and no leak occurs. They are well able to bar the gas also for a pressure drop of $P = 0.40$ kg/cm^2 (35-32).

at N = 4120 rpm a negative leak of max. 0.27 ml gas/min has been measured. A particularity was the very strong negative leak that occurred using bushing C. It was 1.35 ml/min, although no visible leak could be observed across the center of the seal.

12.3 Observations on the double V. S. S. no. 4 (three grooves)

a) The intensity of foaming

No generation of foam has been observed for these bushings at all low numbers of revolutions. Instead large air pockets can be observed now just as for shaft no. 3 (see 12.1).

For higher numbers of revolutions the air pockets disappear and gas inclusion occurs especially via the low pressure sides of the lands.

For a high fluid level gas ingestion can be prevented for every number of revolutions; then the already enclosed gas disappears.

b) Observations of leak

For every number of revolutions the seals with bushings B and C are leak proof; also after imposing a sudden drop of the pressure difference. Over N = 1720 rpm the use of center bushings A and D gives sporadically visible leak. For these cases a slightly fluctuating leak is measured, intermittently positive and negative from 0 to 0.0 ml gas. Experiments have been conducted also for which only negative leak was measured.

c) Loss of sealing fluid

For this seal this phenomenon has been investigated more accurately. With sealing fluid no. 1 whereby absolutely no gas ingestion occurs negative leak has been measured too, accompanied by a loss of sealing fluid downward. With the usual sealing fluid no. 3 already at the lowest number of revolutions a strong loss does occur together with a negative leak. In all cases the leak decreases if the lower bushing is not wetted anymore by the sealing fluid. Then by a small loss of fluid, the pressure generation still decreases some more and a complete reversal of leak from negative to positive occurs. However it often happens that the system is able to be in the unstable situation for a long time; the imposed pressure can be supported.

The observations are summarized in Table 8. We can check if the volume of the leaked fluid is the same as the volume of the measured gas leak.

This turns out to be the case for the first two experiments whereby no visible leak was observed. However in the last experiment visible leak occurs and the measured gas leak is smaller than was expected on the basis of loss of fluid. This indicates that gas leak towards the low pressure end of the seal took place.

12.4 Comparison of the double V.S.S.'s nos. 3, 4, and 5 that differ in the number of grooves and the landwidth

For the geometries see Tables 1 and 7.

a) Comparison of the bushings 3 and 5, that differ only in the number of grooves. Bushing 3 has one groove bushing 5 has four grooves. Therefore the geometry is equal but the groove and landwidth differ in an absolute sense. As we observed during the course of this investigation leak may easily appear if a dense layer of foam occurs. Bushing no. 5 causes leak (picture 33-15) although no leak can be observed for bushing 3 in the absence of foam. The leak at bushing 5 could be prevented easily by the use of a different center bushing, for example bushing B or C.

For both bushings 3 and 5 mainly negative leak was observed; for high velocities loss of sealing fluid occurred.

----- The gas ingestion seems to be less for the bushings with four grooves than for those with one; for the former foam occurs mainly due to accumulation. For the lower numbers of revolutions this can be observed well because the build-up of the foam layer requires some time.

----- The single grooved bushings are susceptible to gas ingestion because it was not possible to prevent gas inclusion by a high fluid level.

----- A disadvantage of the single grooved bushings seems to be the presence of air pockets on the shaft seal. Due to this large parts will not contribute to the pressure generation.

Conclusion

The effect of a diminished gas ingestion and a lower sensitivity to this phenomenon is lost for more grooves due to more intense foaming. Hereby leak occurs easily but is prevented by a right choice of the center bushing. For lower numbers of revolutions air pockets develop for the single grooved shaft; its effect on the stability is not known.

b) Comparison of the bushings 4 and 5 with a different number of grooves and unequal landwidth. Bushings 4 with a wide land do not exhibit the detrimental foaming effects of bushings 5 that have a narrow land. Compare pictures 32-40 and 33-15. Due to this visible leak for bushing 4 is much smaller. Just as bushing 5, bushing 4 is not sensitive to gas ingestion for a high level of the sealing fluid.

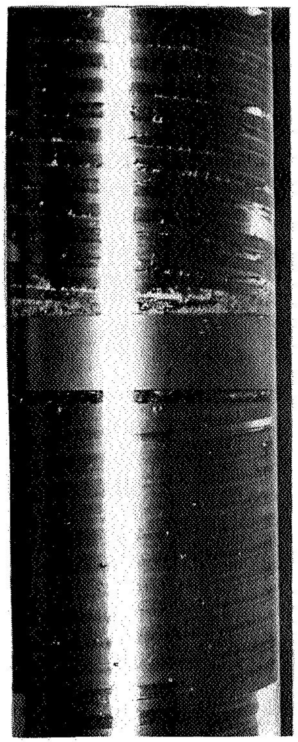
For a high number of revolutions there is gas inclusion for bushing no. 4 but the intensity is still less than for bushings nos. 3 and 5; compare pictures 35-1, 33-28 and 37-20. For bushing no. 4 the grooves are not completely filled with dense foam.

Conclusion

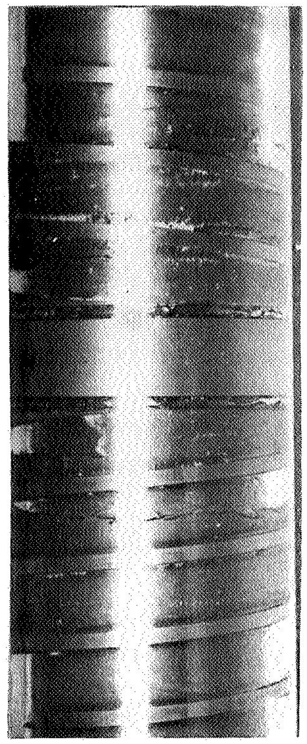
By increasing the land width the foam formation as observed for bushing 5 disappears. For the two bushings with more grooves the gas ingestion is less than for the single grooved. At a high number of revolutions the intensity of foaming is less for bushings no. 4 than for bushings nos. 3 and 5; on this basis we must choose: A multiple grooved bushing of which the land width may not be too small, decreases the intensity of the gas inclusion (bushing 4).

12.5 Comparison of the double V.S.S.'s nos. 4, 8, and 10 that differ in the depth of the groove

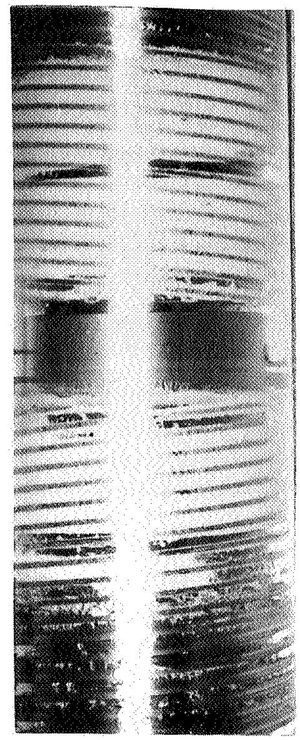
The bushing that was found most ideal in 12.4, the bushing no. 4 with



32-40
Bushing 4

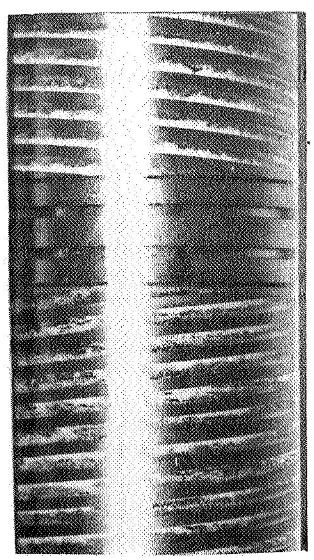


33-22
Bushing 3

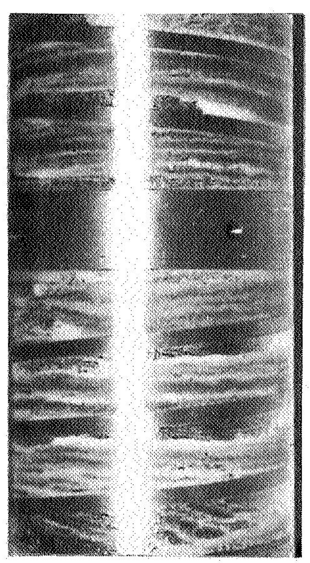


33-15 $Re_1 = 193$
Bushing 5

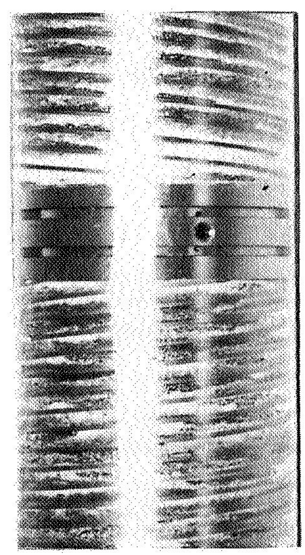
Comparison of bushings with one and four grooves with the same geometry (bushings 3 and 5) and of bushings with three and four grooves (nos. 4 and 5) that only differ in land width. The single grooved bushing no. 3 does not often exhibit foaming but air pockets occur on the lower bushing. Bushing no. 5 with 4 grooves always gives dense foaming for low Re numbers. This occurs due to accumulation because the actual ingestion is very little. The foam causes leak across the center bushing. Bushing no. 4 with 3 grooves almost almost never causes foaming. Air pockets do occur, there is no measurable leak and hardly any visible leak.



35-1



33-28



37-28

For $Re_1 = 575$ there is a more homogenous gas-liquid distribution on the shaft. The pictures can be reproduced well. Contrary to the foam at low Re number, This foam hardly penetrates on the center bushing or does not get there at all. There is no observable leak.

three grooves and wide lands, may be investigated further now with respect to changes in the geometry. To this end only a deepening of the grooves is considered and has been executed in two steps.

a) Comparison of the bushings 4 and 8; groove depths 0.60 and 0.97 mm.

On the basis of visual observations we cannot immediately decide if there is improvement or not. See pictures 35-43 and 41-1. Due to the deepening the sensitivity to gas ingestion increased strongly. For high fluid levels gas ingestion always occurs. Also if the level is on the grooved part of the shaft gas ingestion occurs for N = 1082 rpm however not on the lower bushing.

The nature of the gas inclusion is changed for low numbers of revolutions (pictures 35-43 and 41-1). The air pockets that filled the shallow grooves completely are replaced by smaller bubbles along the upper edges of the lands. This must be regarded as an improvement due to the better wetting of the shaft surface that results.

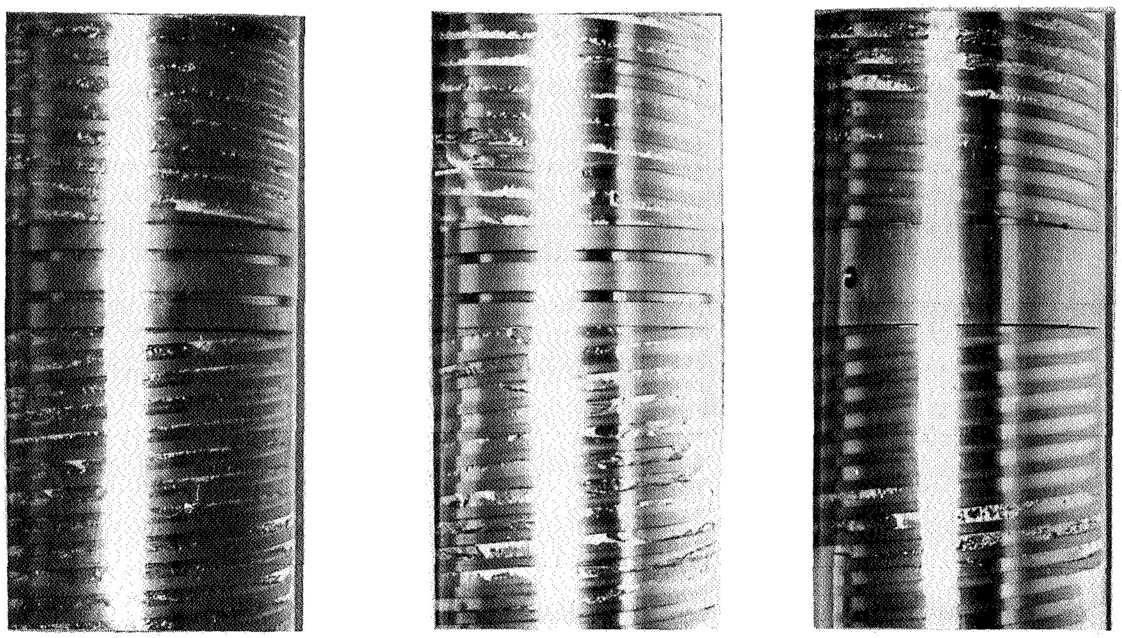
As far as leak is concerned, bushing 8 seems to have yielded an improvement. For N > 1522 rpm and use of center bushing A there even is no leak observable for a sudden pressure drop. This is a clear improvement with respect to bushing 4 where leak did occur already for center bushings A and D. The loss of sealing fluid is decreased for the deep-groove bushing and is only large for N = 4120 rpm.

----- In order for axial transport of gas to occur gas bubbles first must leave the groove against the centrifugal force. Only then can leak occur across the center bushing so that a deep groove appears to be favorable. Therefore we decided to deepen the groove even further.

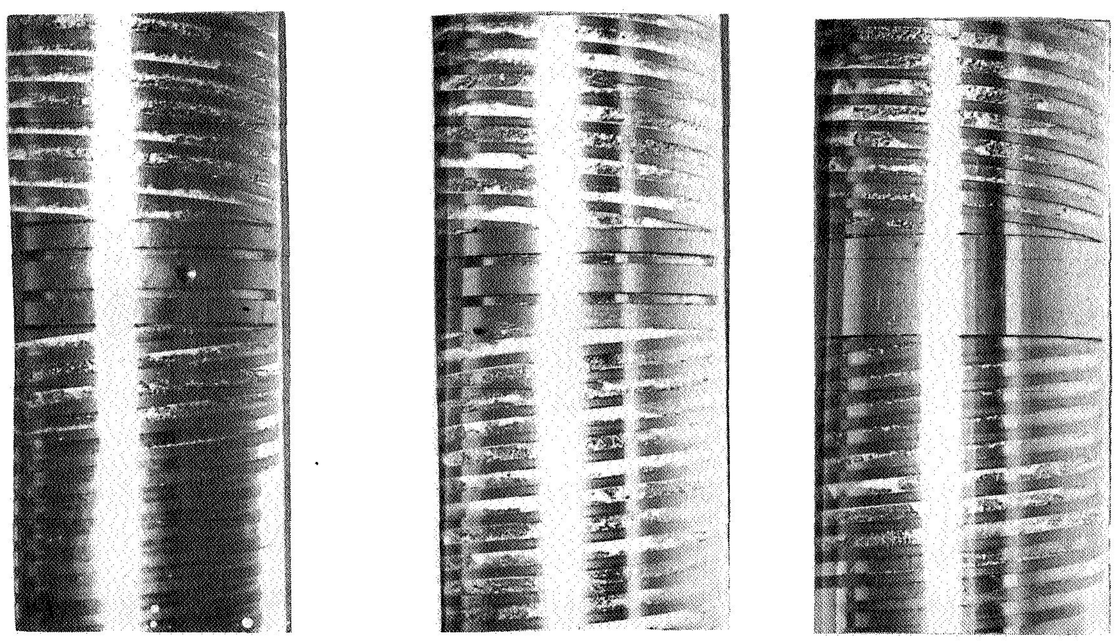
b) Comparison of bushing 10 with bushings 4 and 8.

Groove depth 1.5 mm.

----- For no number of revolutions does gas inclusion and leak appear. See pictures 44-35 and 44-33. Gas ingestion can still be observed at the interface; the center bushing does not contribute anymore to the prevention



$Re_1 =$ 357



$Re_1 =$ 575

35-43 and 35-2 Bushing no. 4 | 41-1 and 41-2 Bushing no. 8 | 44-35 and 44-33 Bushing no. 10

Bushings with three grooves. Deepening the grooves of bushing no. 4 finally results in bushing no. 10 which does not give any gas inclusion in the region considered. Even using tetra as sealing fluid (increasing Re_1) does not give enough gas inclusion to cause leak across the center bushing.

of leak. The width of the interface over which gas ingestion takes place increases with the number of revolutions.

For N = 4120 rpm also, there is still no gas inclusion and leak observable. Although it became apparent during the course of this investigation that the Re_1 number is no criterion for the occurance of gas inclusion and leak. bushing 10 is investigated also using a different sealing fluid so that a higher Re_1 number could be attained.

We used sealing fluid no. 4, (tetra chlorine carbon). The region of gas ingestion appears to be increased but there is still no transport of gas across the center bushing (picture 46-37).

For no number of revolutions has loss of sealing fluid or leak been observed.

Immediately after the start there often is gas present in the sealing fluid on the bushing. Sometimes a very small transport of bubbles is visible at a high number of revolutions (picture 44-33), however, this does not lead to the formation of foam or the occurance of leak. Within 2 minutes most of this gas has disappeared.

Conclusion

Using a deeper groove makes it possible to prevent gas inclusion and leak. Also no loss of sealing fluid occurs anymore, hence break down due to too little pressure generation in the seal does not occur.

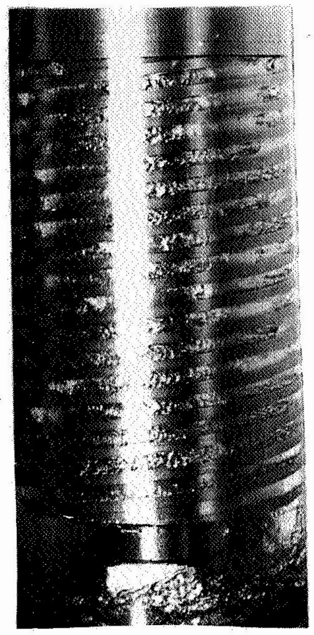
12.6 Observations on and comparison of the double V.S.S.'s nos. 6 and 7

With these bushings a start was made with the investigation of the influence of the helix angle on the gas inclusion. No comparison is possible using the shafts described so far because the groove depth (for bushing 6) has been decreased initially by one half.

Observations on shaft no. 6

a) The intensity of foaming

For N = 1082 rpm no gas ingestion occurs although initially present air may cause foaming. For higher velocities the ingestion is still very small



46-37

Bushing no. 10

$Re_1 = 1805$ (with tetra)

(pictures 36-39 and 36-5). After a short time however the picture may be changed because gas accumulates in the seal and causes intense foaming (picture 36-14). This foams extends to center bushings A and D, if those are used, but axial transport does not take place. The formation of foam is not a certainty; pictures 36-39 and 36-5 have been observed also with foam in the seal at the same number of revolutions.

Up from N = 2175 rpm, the foam on the bushings is replaced by gas ingestion or inclusion of bubbles (picture 36-5). Here it even appears that no gas reaches the center bushing anymore which would mean that only gas ingestion occurs.

For N = 4120 rpm gas inclusion and ingestion occurs (picture 36-7). This seems to be less than for bushing 4, compare with 35-2.

b) Observations of leak

For low numbers of revolutions visible leak occurs in the pressure of a dense layer of foam. The leakage decreases if there is very little sealing fluid in the seal.

For number of revolutions N = 2174 rpm no leak can be observed anymore; this apparently is due to the absence of foam.

In no case was leak observed using center bushing B and either a negative leak or no leak was measured.

c) Loss of sealing fluid

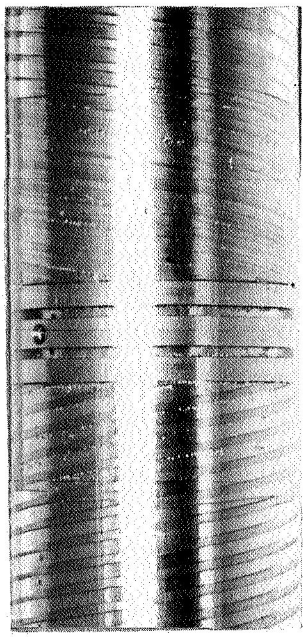
These bushings are characterized by a very strong loss of sealing fluid. When both bushings are wetted for 67% all sealing fluid has disappeared in 50 sec. for N = 3480 rpm and no pressure difference.

d) Observations while using center bushing E (Fig. 14)

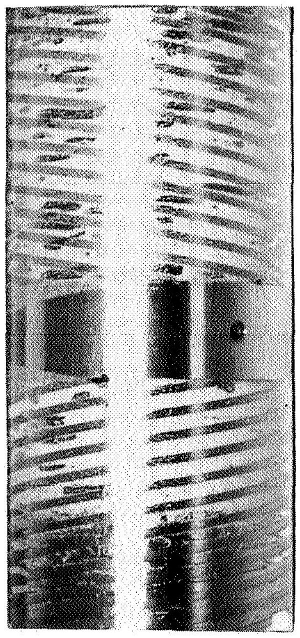
This center bushing was made to obtain an accurate imitation of the center part of the shaft of single V.S.S. no. 1, see Fig. 11. Contrary to the single V.S.S. this solution was not satisfactory here; for every number of revolutions leak was clearly present.

Conclusion

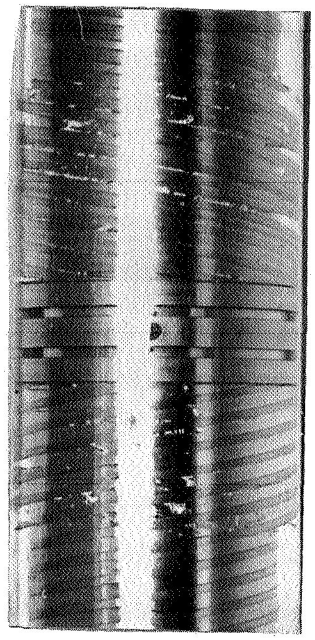
For a low number of revolutions these bushings cause an intense formation of foam due to which leak appears. For high numbers of revolutions the gas



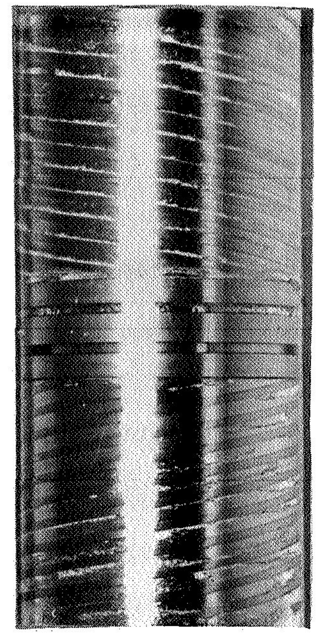
36-39
$Re_1 = 193$



36-14
$Re_1 = 240$



36-5
$Re_1 = 362$

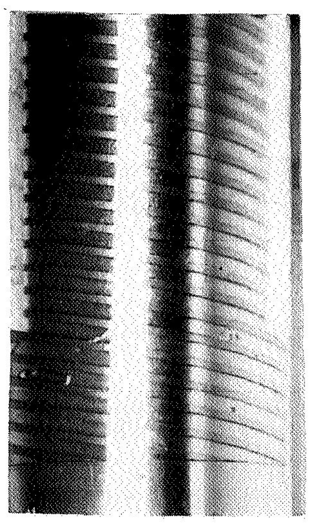


36-7
$Re_1 = 575$

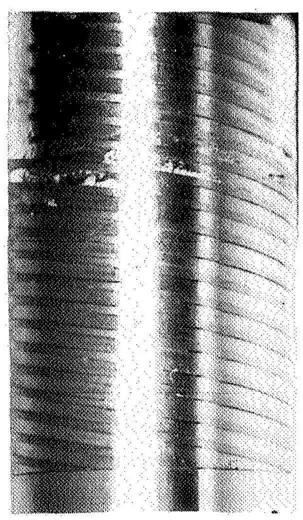
Bushing no. 6; 6 grooves $\beta = 3.94$ $t = 0.177$

At low Re often foaming occurs the gas inclusion increases for high Re

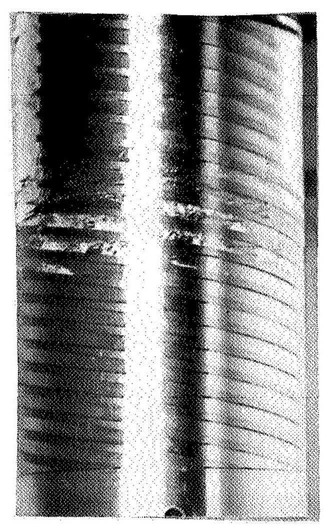
Deepening of the groove of bushing no. 6 yields a new bushing no. 7 that does not exhibit gas inclusion anywhere in the range considered up to $Re_1 = 575$.



38-0
$Re_1 = 193$



38-41
$Re_1 = 362$



38-40
$Re_1 = 575$

Bushing no. 7; 6 grooves; $\beta = 8.25$
$t = 0.177$

ingestion and gas inclusion are less than for bushings nos. 3, 4, and 5.

From intercomparison of the bushings with three grooves, it could have been concluded that a shallow groove promotes foaming and gas inclusion. The good result for the described bushings No. 6, high velocities should then be explained by the larger helix angle. If the different effects are cumulative, then it may be expected that by deepening the groove even less gas inclusion occurs.

Observations on shaft no. 7

Shaft no. 7 is obtained from shaft no. 6 by machining the grooves from a depth of 0.3 to a depth of 0.74 mm.

-----Shaft no. 7 in no case exhibits gas inclusion or leak; a little gas ingestion occurs. If we compare pictures 38-0, 38-41 and 38-40 of bushing no. 7 with the pictures of the bushings 8 and 10, then we see that bushing no. 7 shows the least ingestion.

Conclusion

For a larger helix angle a less deep groove is necessary to prevent gas inclusion and leak than for a geometry with a small helix angle.

12.7 Observations on and comparison of the double V. S. S.'s nos. 11, 13 and 15

On the basis of the results obtained so far it was expected that a seal with a still larger helix angle would not exhibit gas inclusion even for shallow grooves.

For a certain chosen large pitch (Table 1) and a land width that is not too small, the number of grooves was chosen to be 10. We started with the very shallow groove of 0.2 mm. This seal did not live up to the expectations expressed above.

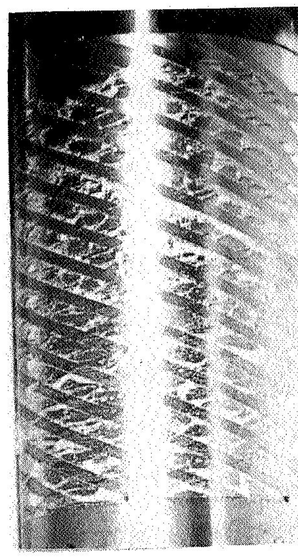
Observations

a) The intensity of foaming using shaft no. 11

In order to get an impression of the gas ingestion caused by this seal pictures 44-24, 44-27, 44-30, and 44-32 may be studied. True, they

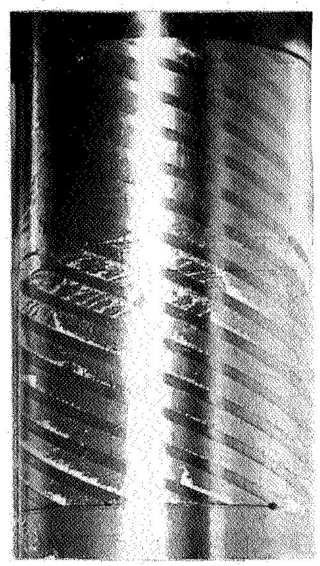
44-24

$Re_1 = 193$



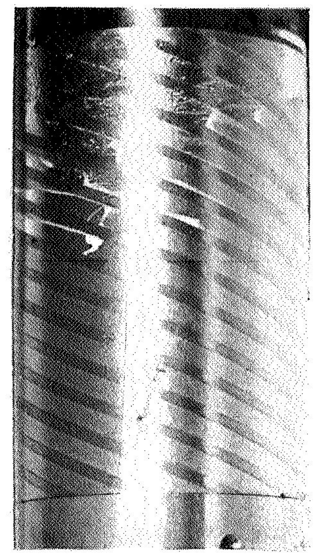
44-27

$Re_1 = 267$



44-30

$Re_1 = 362$



44-32

$Re_1 = 575$

Gas inclusion decreases for increasing number of revolutions for bushings nos. 11 and 12. After deepening the grooves, so that $\beta = 3.94$, the same phenomenon occurs; The Re_1 number whereby no gas reaches the center bushing anymore is reduced then from $Re_1 = 418$ to $Re_1 = 304$ (bushing 13) and to $Re_1 = 240$ for bushing 14.

depict a different shaft (no. 12) but a completely analogous picture was obtained for shaft no. 11.

For N = 1082 rpm absolutely no ingestion occurs. At the next number of revolutions, N = 1382 rpm, we could observe that the gas ingestion was very small but due to accumulation of gas there resulted a shaft fully covered with foam within 2 min. (picture 44-24).

For higher numbers of revolutions the intensity of foaming decreases and at N = 3000 rpm the gas is not ingested anymore up to the center-bushing (pictures 44-30 and 44-32).

A similar phenomenon was observed for shaft no. 6. For high numbers of revolutions a gas inclusion phenomenon remained present there whereas in this case it disappears completely. In order to investigate if the formation of foam is continued in a lower region of Re_1 numbers, we did some observation with sealing fluid no. 2.

Up to N = 1910 rpm no gas ingestion can be observed using this sealing fluid. After that the zone at the interface where ingestion takes place increases. For N = 2270 rpm there is ingestion across an interface down to 20 mm and this is about 30 mm for N = 4120 rpm.

Conclusion

During sealing with bushing no. 11 gas ingestion appears at $Re_1 = 64$. It increases and results in gas inclusion for $Re_1 = 193$. Hereafter this gas inclusion diminishes and for $Re_1 = 418$ only ingestion remains which decreases further towards $Re_1 = 575$.

----- By deepening the groove a different geometry appears, it is called bushing no. 13. Now the region of gas inclusion decreases down from the high Re_1 number. Already for N = 2185 rpm no more gas inclusion occurs.

----- By a still further deepening of the groove, shaft no. 15 appears. This seal is investigated using sealing fluids nos. 3 and 4. Nowhere in the investigated region from $Re_1 = 151$ to $Re_1 \doteq 1805$ did gas inclusion occur.

b) Observations of leak

Bushings nos. 11, 13, and 15 have not been made double. Only bushings with left handed thread are available. The other halve of the double V.S.S. in this investigation is formed by bushing no. 7 with right handed thread. This one did not show gas inclusion at any number of revolutions.

We now dispose of a system whereby gas inclusion occurs only from one of the oil/air interfaces. This interface is the upper interface because bushing no. 11 is there. Hence leak is only possible from the space ablve the seal to the space below the seal. Furthermore it is certain that an eventual measured leak is not due to loss of sealing fluid.

In the region where gas inclusion is observed we also always measured a negative leak. Hence from this leak values can be obtained for the transport of gas due to gas inclusion and leak. See the table below.

Measured negative leak in ml/min for $\Delta p = 0.1$ kg/cm^2.

N rpm	bushing 11	bushing 13	bushing 12	bushing 14
1082	0.0	0.0	0.0	0.0
1382	0.0	0.0	3.6	0.0
1522	5.3	8.5	-	0.0
1720	7.6	-	0.1	no inclusion
1910	15.1	0.1	0.0	"
2175	0.0	no inclusion	0.0	"
3000	no inclusion	"	no inclusion	"

Conclusion

The expectation that by increasing the helix angle a very shallow groove can oppose leakage has been born out only partially. Over N = 3000 rpm no gas inclusion appears for a shaft with a large pitch and a groove depth from 0.2 to 0.7 mm. Below this number of revolutions there is a comparatively small region where leak occurs due to gas inclusion. This region becomes smaller by deepening the groove. For a depth of 0.72 mm the region ceases to exist. The order of magnitude of the leak due to gas inclusion agrees with the measured leak for a single V.S.S. in 7.4

12.8 Observations on and comparison of the shafts nos. 12, 14, and 16

The only change of this bushing geometry with respect to the bushings in 12.7 is the larger helix angle.

a) The intensity of foaming

For bushing no. 12 there is a shaft fully covered with foam from the lowest number of revolutions N = 1082 rpm. The intensity of the inclusion decreases with the number of revolutions and for N = 3000 rpm there only is gas ingestion at the interface.

In a lower region of re_1 numbers, foam starts to appear at the interface for $Re_1 = 64$. An ingestion of very small gas bubbles is visible, they are transported over a long distance in the seal. Before they reach the center bushing, they are dissolved. The same phenomenon occurs for $Re_1 = 115$ where it is more clearly observable.

----- By deepening the groove the geometry of shaft no. 14 appears. The region of gas inclusion has become smaller and the intensity has decreased. For N > 1720 rpm only ingestion still occurs and this decreases with an increase of the number of revolutions.

----- If the groove is deepened further, shaft no. 16 appears. This one does not show gas inclusion anywhere in the investigated region from $Re_1 = 151$ to $Re_1 = 1805$.

b) Observations of leak

These are given in the preceding table. Here also the lower bushing of the shaft was bushing no. 7. Observable leak accompanies measurable leak.

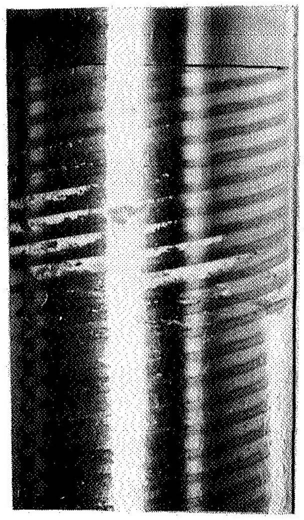
12.9 Comparison of the geometries of shaft seals with increasing helix angles

1) The bushings nos. 11 and 12.

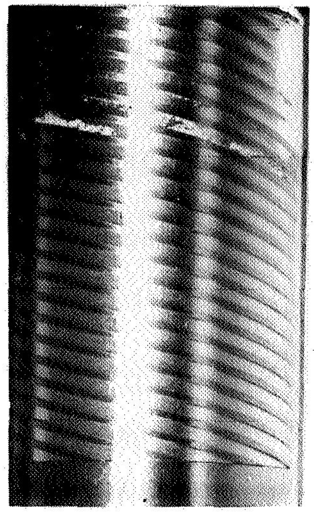
From the preceding table it becomes apparent that the region in which gas inclusion occurs becomes smaller if the helix angle is increased. The leak also decreases.

2) The bushings nos. 6, 13, and 14.

For shaft no. 6 gas inclusion occurs for all numbers of revolutions;



46-29
Bushing 7
t = 0.177

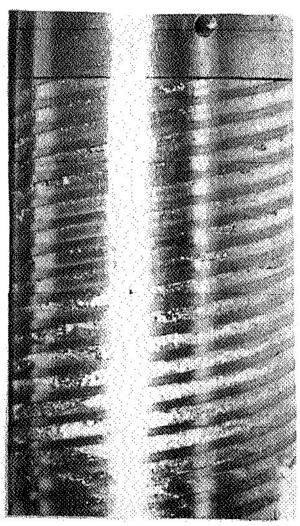


46-29
Bushing 15
t = 0.268

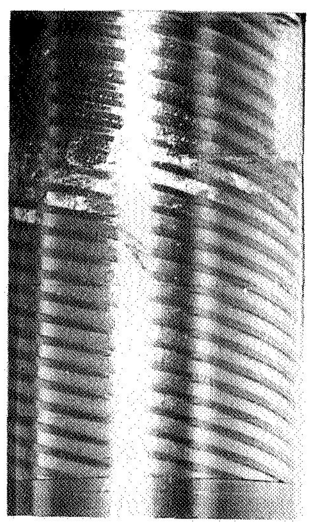
46-28
Bushing 16
t = 0451

Re_1 = 575 β = 8.05

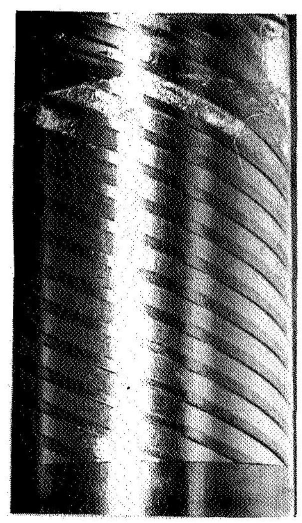
The increase of the helix angle form t = 0.177 to 0.268 to 0.431 has no influence anymore for this groove depth. Nowhere in the explored region from Re_1 = 151 to Re_1 = 575 does gas inclusion occur. At the oil-air interface ingestion occurs over at most 5 mm.



46-36
Bushing 7



46-36
Bushing 15



46-37
Bushing 16

Re_1 = 1805 Sealing fluid no. 4

β = 8.05

Also with this sealing fluid there is no gas ingestion anywhere in the explored region from Re_1 = 475 to Re_1 = 1805
The ingestion at the air-sealing fluid interface increased very slightly.

only for low velocities this causes leak. The small inclusion for high numbers of revolutions disappears for bushings nos. 13 and 14 if the pitch is increased. The region of gas inclusion at low numbers of revolutions in which gas is present as foam, decreases with increasing helix angle. The intensity of foaming diminishes too; for shaft no. 14 there is no visible leak anymore.

3) The bushings nos. 7, 15, and 16.

The photographs on the other page show these shafts with sealing fluids no. 3 and 4. Shaft no. 7 with the smallest helix angle still gives the most gas ingestion. There is no more gas inclusion and leak. These three bushings are completely leak proof in the investigated region. The depth over which gas ingestion occurs still decreases with lower numbers of revolutions and at N = 1082 rpm a completely stable interface is present.

13. The influence of foaming on the sealing parameter

We saw that, due to gas inclusion, a connection may open between the two gas-filled spaces to be sealed with a double V.S.S. However so far it has not been apparent that the visco-shaft seal using foam as the sealing medium would not be able to generate pressure.

The break down as noted by several investigators (lit. 5, 6, 8, 11) means that, for an imposed pressure difference between the gas-filled spaces, the fluid is blown out of the clearance between shaft and housing. The leakage flow is then the leak of gas through a narrow slit.

13.1 Theoretical values for the sealing parameter

In the laminar region formula (1) holds true. For turbulent flow conditions the sealing parameter ψ is dependent also on the Reynolds number besides on the geometry of the seal. Pape and Vrakking (lit. 2) found:

$$\psi = \frac{0.25t\gamma(1-\gamma)(\beta-1)(\beta^3 G_{ag} - G_{al})}{\beta^3 G_{al} G_{ag} + t^2\gamma(1-\gamma) G_{al} G_{tl} + \beta^3 t^2 (1-\gamma)^2 G_{al} G_{tg} + \gamma^2 \beta^3 t^2 G_{ag} G_{tl} + \beta^6 t^2 \gamma (1-\gamma) G_{ag} G_{tg}} \qquad [12]$$

For certain cases this formula can be simplified to:

$$\psi = \frac{0.25t\gamma(1-\gamma)(\beta-1)}{G_{t1} + \beta^3 t^2 \gamma(1-\gamma) G_{t2}} \qquad [26]$$

where:

$t \leq 0.268$ and $0.2 < \gamma < 0.8$

$\beta > 3.6$ $G = f\,(Re)$

For the computation of these parameters one assumes a homogeneous fluid in the seal. Hence one does not take gas inclusion into account.

13.2 The measurement of the sealing parameter

For this one uses the formula $\psi = Pc^2/\ \eta\,\omega\,dl$

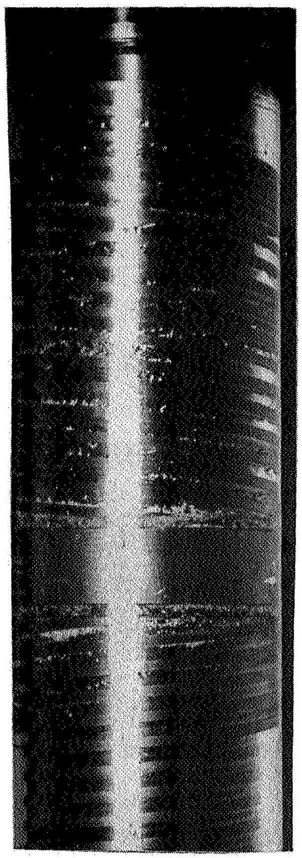
for a certain seal η, c, d and l are given quantities. If the pressure build-up is measured for a certain number of revolutions one can compute the sealing parameter.

In our case the pressure build-up can be determined accurately for a completely wetted shaft length l. It appears that the pressure build-up depends on the intensity of foaming in the seal. Therefore two parameters must be determined; the parameter without foam and the parameter with foam in the seal. This is done as follows via the determination of the maximum closing pressure:

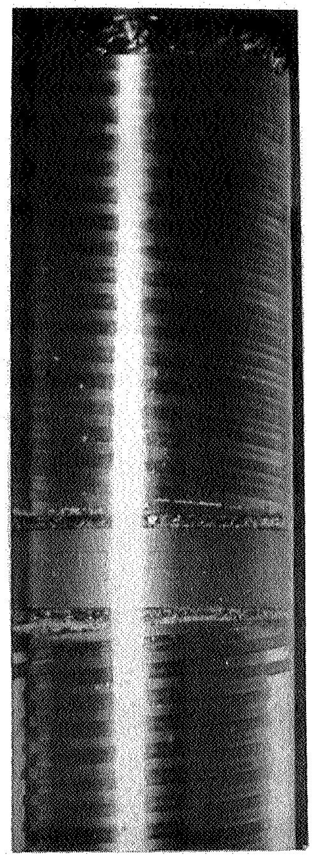
A) The closing pressure without foam in the seal

For single shafts this can be done by using a large quantity of sealing fluid so that the level is high above the grooved part. The pressure measured is the maximum pressure without gas ingestion.

For double shaft a pressure difference must be imposed over the seal by using air under pressure. For a large quantity of sealing fluid and increasing pressure there will be no more liquid in the lower part of the V.S.S. after a certain moment. If, at the same time, the level is far enough above the upper busing no gas inclusion will occur. If gas was present it will disappear



32-2



32-3

Determination of the sealing parameter without enclosed gas. Due to a pressure difference the wetted length of the lower bushing decreases and it increases on the upper bushing. For a sufficiently high level above the upper bushing no new ingestion is visible and the enclosed gas disappears. When the lower bushing is completely dry, the maximum closing pressure has been reached.

from the upper part of the seal within a short time. (pictures 32-2 and 32-3). The pressure measured in this way is the maximum closing pressure.

B) The closing pressure with enclosed gas in the seal

If gas inclusion occurs in a V.S.S. when the oil/air interface is on the grooved part of the shaft, then this will happen also if the level is only a short distance above the grooved end of the shaft. Compared with case A) the procedure is repeated only with less sealing fluid. With the so obtained maximum pressures the sealing parameters can be computed with foam as the sealing medium.

13.3 Inaccuracies due to temperature influences in the determination of the sealing parameter

It is not possible to measure or keep constant temperatures of the sealing system due to the simple construction of the apparatus. For high numbers of revolutions a clearly observable heat generation occurs. Even if we neglect the influence on the density then the influence of the temperature on the viscosity and via that one on the sealing parameter is an uncertain factor. We estimate the maximum temperature differences to be 20° C and from that it easily follows that the sealing parameter may change 25%.

The error due to temperature sensitivity can be reduced by conducting the experiments swiftly and by using fresh sealing fluid from a storage container each time. On the basis of this procedure a temperature of 20° C has been adopted for the determination of the sealing parameter.

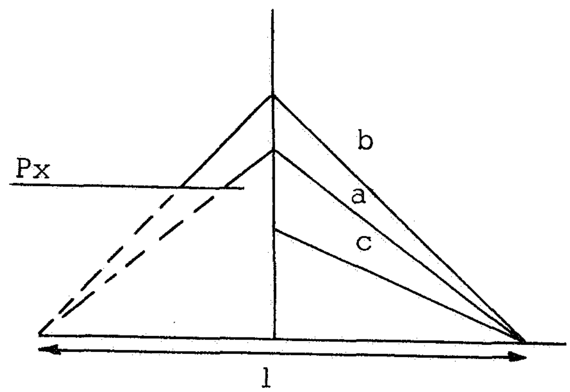
13.4 Results of measurements

For the seals with the shafts nos. 1, 2, 4, 5, and 6 the sealing parameters have been determined with and without foaming. In all cases the values of ψ with foam where lower than those without foam in the seal. See. Fig. 15 and 16. The values of the parameter with foam depend on the intensity of foaming and that is not reproducable. Consequently, the data points are spread out in a region below the curve that is measured without gas ingestion.

The drop of the sealing parameter due to foaming increases with the number of revolutions and a maximum drop of 34% of the value without gas ingestion has been observed.

13.5 Explanation of break down

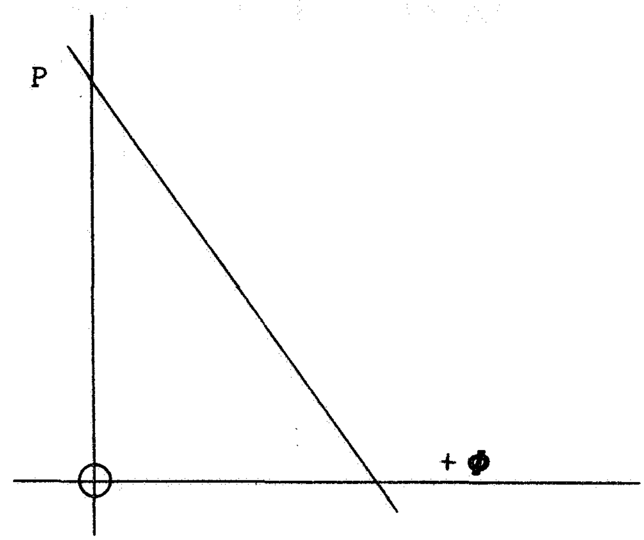
In the accompanying figure the behavior of the pressure along the length of the seal has been sketched. The pressure against which must be sealed is P_x. For a certain number of revolutions curve a represents the pressure build-up by the shaft. If for a higher number of revolutions no gas ingestion occurs then the maximum pressure build-up will continue to increase; the seal remains intact (curve b). However if gas ingestion occurs then leak may occur due to the drop of the maximum closing pressure if this pressure is lower then P_x (curve c).



----- In order to prevent break down the shaft therefore always has to be calculated for the "foam parameter." We may only ask ourselves how the sealing parameter is influenced by foaming at higher velocities than measured by us. In view of the strong decrease of 34% in a small velocity region, it does not seem to be unlikely that the sealing parameter approaches zero for higher velocities. Hereby break down would occur again. The opposing of leak will then be futile. One will have to find a solution that opposes the gas inclusion.

14. <u>The influence of the recirculation system on the sealing parameter</u>

For the V.S.S. a pump characteristic may be derived from a theoretical calculation. From this it follows that for a net axial transport of fluid towards the high pressure end of the V.S.S. a decrease of sealing pressure occurs (see figure). The center bushings A, C, and D did not appear to have any influence on the foam-free parameter. For bushing B there is dependence on the diameter of the recirculation channel. The channels in bushing B (see Fig. 14) have their diameter not changed contrary to the diameters of the channels in the visco shafts and the visco bushings.



The diameter for several bushings has been varied from Ø = 0.3 to Ø = 1.5 mm.

The table below shows the results.

Shaft No.	Ø recirculation channel in mm	ψ foamfree, reduction with respect to ψ without recirculation
2	1.5	37.6%
2	0.8	19.5%
3	0.6	0 %
4	0.6	0 %
5	0.3	0 %
6	1.0	22 %
7	0.6	0 %

The foamfree parameters with and without recirculation have been compared. The channels appeared large enough to dispose of the enclosed gas; in no situation did we observe that they were too small.

Therefore one has to take the channel diameter smaller than 0.6 mm in order to prevent unnecessary loss of pressure. The decrease of ψ due to a too large recirculation channel is given in Fig. 15 and 16.

15. Comparison of theoretical and practical values of the (foamfree) sealing parameter

Although it does not belong to the investigation, the results of the measurements are given in Fig. 15, 16, 17, and 18. Except for seal 2 a small decrease of the measured parameter occurs for all low Re_1 numbers. Thereafter the measured values increase faster for increasing Re_1 number than is predicted theoretically. The formulae used for the calculation are given in 13.1.

An explanation of the discrepancy between theory and practice possibly may be found in the fact that our measurements have been made just in the transition region between laminar and turbulent flow.

16. Check of the results of measurements on the double V.S.S. apparatus in the Lab. for Chemical Equipment

Earlier investigators concerned themselves mainly with the comparison of theory and practice for the parameters of the V.S.S. Vrakking (lit. 3) summarizes a large amount of data. He arrives at the conclusion that the theory checks very well with the experiments. At the end of this investigation concerning gas inclusion some doubt appeared as to the correctness of this conclusion. The following points played a role in this.

1) The geometry of the shaft investigated by Vrakking is accurately equal to the shafts nos. 1, 2, and 3 employed in this investigation.
2) The sealing fluid used, Tellus 11/Petrol 1:5, is also used by Vrakking.
3) Our possible numbers of revolutions are all in the range investigated by Vrakking.

4) Under the circumstances mentioned under 1), 2), and 3) we always observed gas inclusion and a lowering of the sealing parameter with respect to its value without gas inclusion.

On the basis of our observations we argue that Vrakking very probably also must have encountered gas inclusion. In view of the influence of this phenomenon on the sealing parameter it does not appear very likely to us that his values can agree with theoretical values.

Verification of the values measured by Vrakking

Picture 38-38 clearly shows that gas inclusion occurs for the shaft which is equal to the one investigated by Vrakking in the Lab. for Chem. Equip. except for its length. In order to measure the sealing parameter without foam an alteration has been made in the shaft in the Laboratory (picture 38-39). Two bushings of which the diameters are equal to the one taken over the lands have been installed at the ends. We assumed that these would form a sufficient barrier against gas to prevent inclusion. In the transparent mounting this indeed appeared to be the case (see picture 38-39). A necessary condition is that the seal between the lands and the shaft ends always has to be filled with sealing fluid. Therefore a small continuous flow of oil was supplied to the seal.

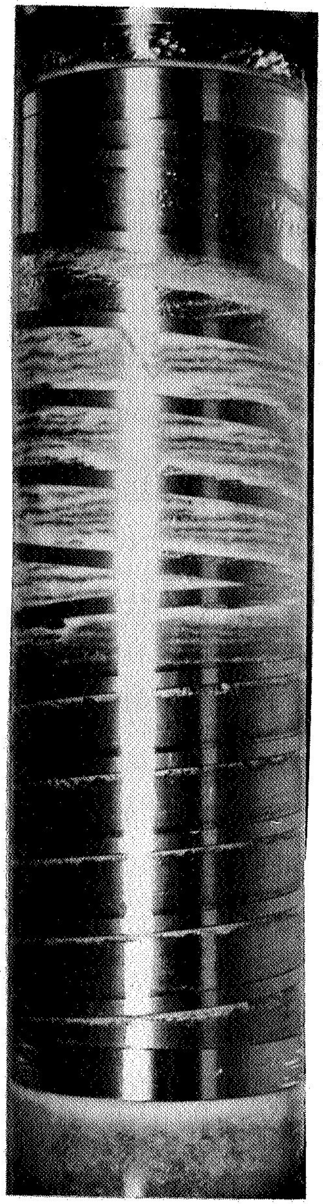
We verified that this flow of oil did not exert a measurable influence on the sealing parameters.

Results of measurements

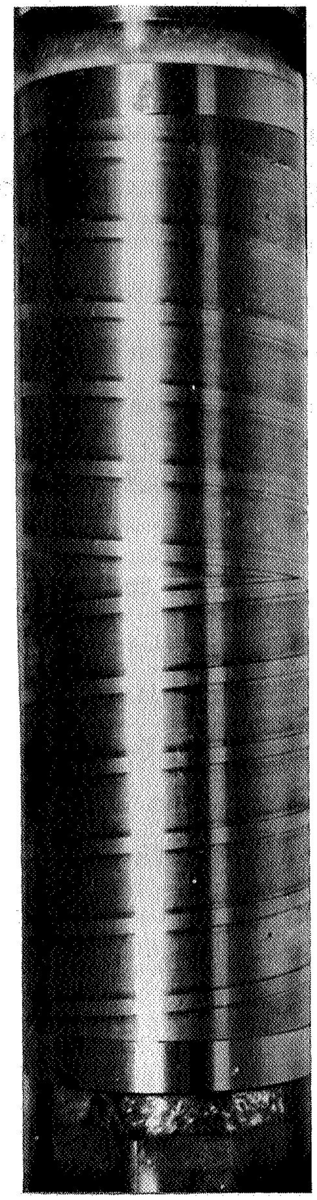
The whole range of Reynolds' numbers from $Re_1 = 125$ to $Re_1 = 4630$ has been remeasured. The maximum closing pressure in the center of the seal and the moment exerted on the visco shaft could be measured. For an accurate description of the apparatus we refer to, for example, lit. 3.

The values of the sealing parameter were computed using the formulae (1).

The value of C_E, the effective friction coefficient, has been computed



38-38



38-39

N = 4120 rpm shaft no. 3

If the levels are on the grooved part of the shaft gas inclusion certainly will occur (picture 38-38). This may be prevented by installing to end bushing that have a small radial clearance in the housing. There also must be so much sealing fluid that complete wetting of the shaft occurs. (38-39).

using the formula:

$$C_E = \frac{64\ M_{measured}}{\pi \rho \omega^2 d^4 l}$$

The results are plotted in Fig. 19 together with the data of Vrakking taken from lit. 3.

The values of the sealing parameter agree very closely with the values measured by Vrakking. The value of the effective friction coefficient shows a very slight increase at low Re_1 number as compared to the values measured by Vrakking. This can be explained as being due to the friction of the installed end bushings.

Conclusion

Apparently no gas inclusionoccurred for the earlier obtained values of the V.S.S. This can be explained by assuming that the system contained enough sealing fluid under all circumstances to maintain a liquid level above the grooved end of the seal.

Because the shaft is hanging in a cylinder with a sealed bottom, fluid loss is not possible downward. It appears reasonable that a cylinder filled with enough fluid does not cause inclusion on the shaft.

Table 1. Geometries of investigated viscoshafts

Shaft No.	l (m)	h $\times 10^4$ (m)	a $\times 10^3$ (m)	b $\times 10^3$ (m)	pitch $\times 10^3$ (m)	number of grooves	β	γ	t	ψ_{lam} $\times 10^3$
1	0.145	6.0	3.27	12.32	15.59	1	6.89	0.790	0.099	188
2	0.150	"	"	"	"	"	"	"	"	"
3	0.090	"	"	"	"	"	"	"	"	"
4	"	"	2.12	3.08	"	3	"	0.593	"	237
5	"	"	0.82	"	"	4	"	0.790	"	188
6	"	3.0	1.65	3.05	28.00	6	3.94	0.65	0.177	241
7	"	7.4	"	"	"	"	8.25	"	"	171
8	"	9.7	2.12	3.08	15.59	3	10.50	0.593	0.099	182
9	"	9.0	3.27	12.32	"	1	9.81	0.790	"	170
10	"	15.0	2.12	3.08	"	3	15.70	0.593	"	104
11	"	2.0	1.50	2.70	42.00	10	2.96	0.643	0.268	232
12	"	"	2.40	4.37	67.70	"	"	0.645	0.431	254
13	"	3.0	1.50	2.70	42.00	"	3.94	0.643	0.268	261
14	"	"	2.40	4.37	67.70	"	"	0.645	0.431	231
15	"	7.2	1.50	2.70	42.00	"	8.05	0.643	0.268	135
16	"	"	2.40	4.37	67.70	"	"	0.645	0.431	89

For all shafts: $d = 0.05$ m ; $c = 1.02 \times 10^{-4}$ m

Table 2. Sealing Fluids Used

No.	Sealing Fluid	$\rho_{20} \times 10^{-3}$ kg/m^3	$\eta_{20} \times 10^3$ $N \cdot s/m^2$
1	Tellus 13	0.865	18.50
2	Tellus 11	0.837	8.00
3	Tellus 11/Petrol. 1:5	0.790	1.53
4	Carbon Tetrachloride	1.595	0.97

$1\ N.s/m^2 = 10^3$ centipoise

Table 3. Possible numbers of revolutions and Reynolds numbers

Gear Combination	Revolutions per minute	Re_1 (20° C) for Sealing Fluid			
		No. 1	No. 2	No. 3	No. 4
60/180	1082	13	30	151	475
80/180	1382	17	38	193	605
80/160	1522	19	43	212	667
100/180	1720	21	48	240	755
100/160	1910	23	54	267	837
100/140	2175	27	61	304	950
120/160	2270	28	64	317	996
120/140	2590	32	73	362	1137
120/120	3000	37	84	418	1315
140/120	3480	43	97	486	1528
140/100	4120	51	115	575	1805

Table 4. Time in minutes necessary to reach a steady state

Revolutions per minute	Shaft No. and level of sealing fluid at rest								
	1 220 mm	1-F 195 mm	2-A 220 mm	2-A 195 mm	2 220 mm	2 195 mm	1-A 220 mm	1-B 220 mm	1-D 220 mm
1082	<1	<1	<1	<1	<1	<1			<1
1382	<1	16	<1	<1	<1	6	19	12	<1
1522	4	7	<1	<1			4		
1720	5	5	29	50		5		8-5	34
1910	9	9					5-9		
2175	6	6	10	55		5			36
2270	5	5							
2590	3	4	26			4			
3000							5		21
3480	4	4					2		
4120	16	16	1	>34					15

N = 1082 ; no gas ingestion

1382 < N < 1720 ; ingestion and gas inclusion; occasional leak

N > 1910 ; ingestion and leak

Table 5. Observed pressure variations for leaking viscoshafts

Revolu- tions per minute	P in kg/cm^2; rest level and duration of period.								
	1				2-A	2	1-A	1-B	2
	220 mm	t. sec.	195 mm	t sec.	195 mm				P. const.
1082									
1382						0.08		0.10	0.025 (25 s)
1522									
1720					0.125	0.07			0.025 (8 s)
1910	0.22	60	0.21	120			0.18		
2175	0.14		0.20	15	0.07	0.11			
2270	0.14	12	0.14						
2590	0.20		0.11			0.145			0.005 (t large)
3000	0.07						0.07		
3480	0.04		0.08				0.04		
4120	0.03		0.08	20					

Table 6. Calculated gas ingestion velocities

Revolutions per minute rpm	ΔP for t<10 sec. level = 220 mm	$\frac{dP}{dt}$	$\frac{dV_1}{dt}$ $\frac{ml}{sec.}$ x 10^2	ϕ_g ml/min P = 1 atm	ΔP for t<10 sec level = 196 mm	$\frac{dP}{dt}$	$\frac{dV_1}{dt}$ $\frac{ml}{sec.}$ x10^2	ϕ_g ml/min P= 1 atm
1082	0.24	small	-	-	0.14	small	-	-
1382	0.36	small	-	-	0.18	53	0.21	0.15
1522	0.39	20	0.69	0.57	0.18	116	4.00	2.83
1720	0.32	150	4.48	3.55	0.19	173	5.17	3.69
1910	0.34	133	3.88	3.12	0.20	186	4.88	3.50
2175	0.35	167	3.78	3.06	0.21	173	4.00	2.90
2270	0.44	167	3.60	3.11	0.21	167	3.59	2.61
2590	0.42	180	5.15	4.38	0.22	236	4.35	3.18
3000								
3480	0.40	734	9.46	7.95	0.25	667	8.60	6.44
4120	0.48	768	8.10	7.18	0.30	634	6.66	5.19

TABLE 7

COMPARISON POSSIBILITIES OF GEOMETRIES OF INVESTIGATED VISCO-SHAFTS

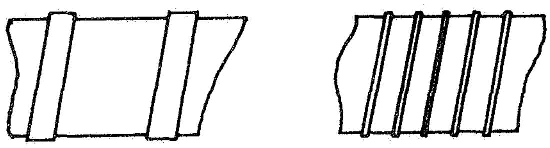
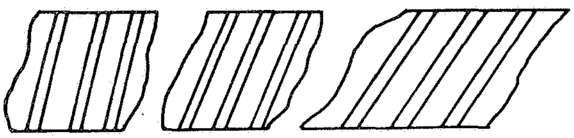
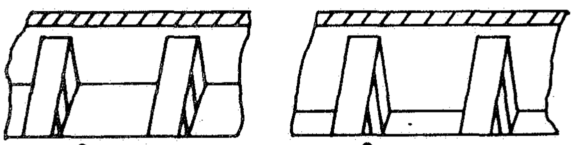
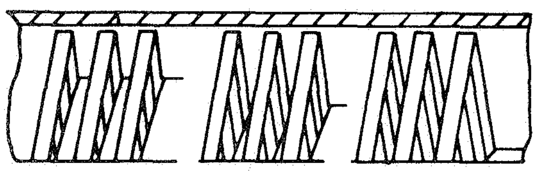
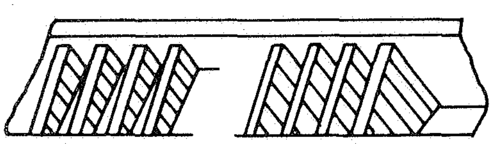
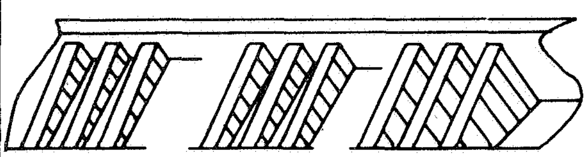
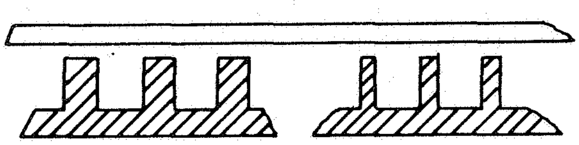
VARIABLE QUANTITY	COMPARISON BETWEEN SHAFT NOS.	NUMBER OF GROOVES	VALUE OF CONSTANT QUANTITIES OF THE GEOMETRY
NUMBER OF GROOVES  1 GROOVE 4 GROOVES	(1,2,3) & (5)	1;4	$\gamma=0.79$ $\beta=6.89$ $t=0.099$
HELIX ANGLE  $t=0.177$ $t=0.268$ $t=0.431$	(6) & (13) & (14) (7) & (15) & (16) (11) & (12)	6;10 10	$\gamma=0.65$ $\beta=3.94$ $\gamma=0.65$ $\beta=8.05$ $\gamma=0.65$ $\beta=2.96$
GROOVE DEPTH  $\beta=6.89$ $\beta=9.81$	(1,2,3) & (9)	1	$\gamma=0.79$ $t=0.099$
 $\beta=6.89$ $\beta=10.50$ $\beta=15.70$	(4) & (8) & (10)	3	$\gamma=0.593$ $t=0.099$
 $\beta=3.94$ $\beta=8.25$	(6) & (7)	6	$\gamma=0.65$ $t=0.117$
 $\beta=$ .96 $\beta=3.94$ $\beta=8.05$	(11) & (13) & (15) (12) & (14) & (16)	10 10	$\gamma=0.643$ $t=0.268$ $\gamma=0.645$ $t=0.431$
LAND WIDTH  $a=2.12$ (3g) $a=0.82$ (3g)	(4) & (5)	3;4	$\beta=6.89$ $t=0.099$ $\gamma=0.593$ $\gamma=0.79$

Table 8. Loss of Sealing fluid for Shaft No. 4

Volume of the shaft: about 0.07 ml/mm

time in minutes	measured leak, ml P = 1.7 kg/cm^2	measured leak, ml P = 1 kg/cm^2	% wetted shaft Upper	% wetted shaft Lower	Loss of Fluid ml	
0	0	0	67.9	17.8		Tellus 13
6	-0.17	-0.29	52.2	11.1		N=1522 rpm
10	-0.49	-0.83	60.1	6.7		no visible
15	-0.63	-1.07	59.0	3.9		leak.
26	-0.45	-0.77	56.8	0		
50	-0.80	-1.36	56.8	0	-1.81	
	P = 1.2 kg/cm^2					
0	0	0	100	11		Sealing fluid No. 3
6	-0.45	-0.54	96.6	6.7		N=1082 rpm
9	-0.63	-0.76	92.2	3.3		no visible leak.
18	-0.89	-1.07	89.0	0	-1.38	
	P = 1.4 kg/cm^2					
0	0	0	100	27.8		Sealing fluid No. 3
4	-0.36	-0.50	75.2	5.6		N=4120 rpm visible
6	-0.36	-0.50	66.7	0		leak.
12	-0.63	-0.88	66.7	0	-3.78	

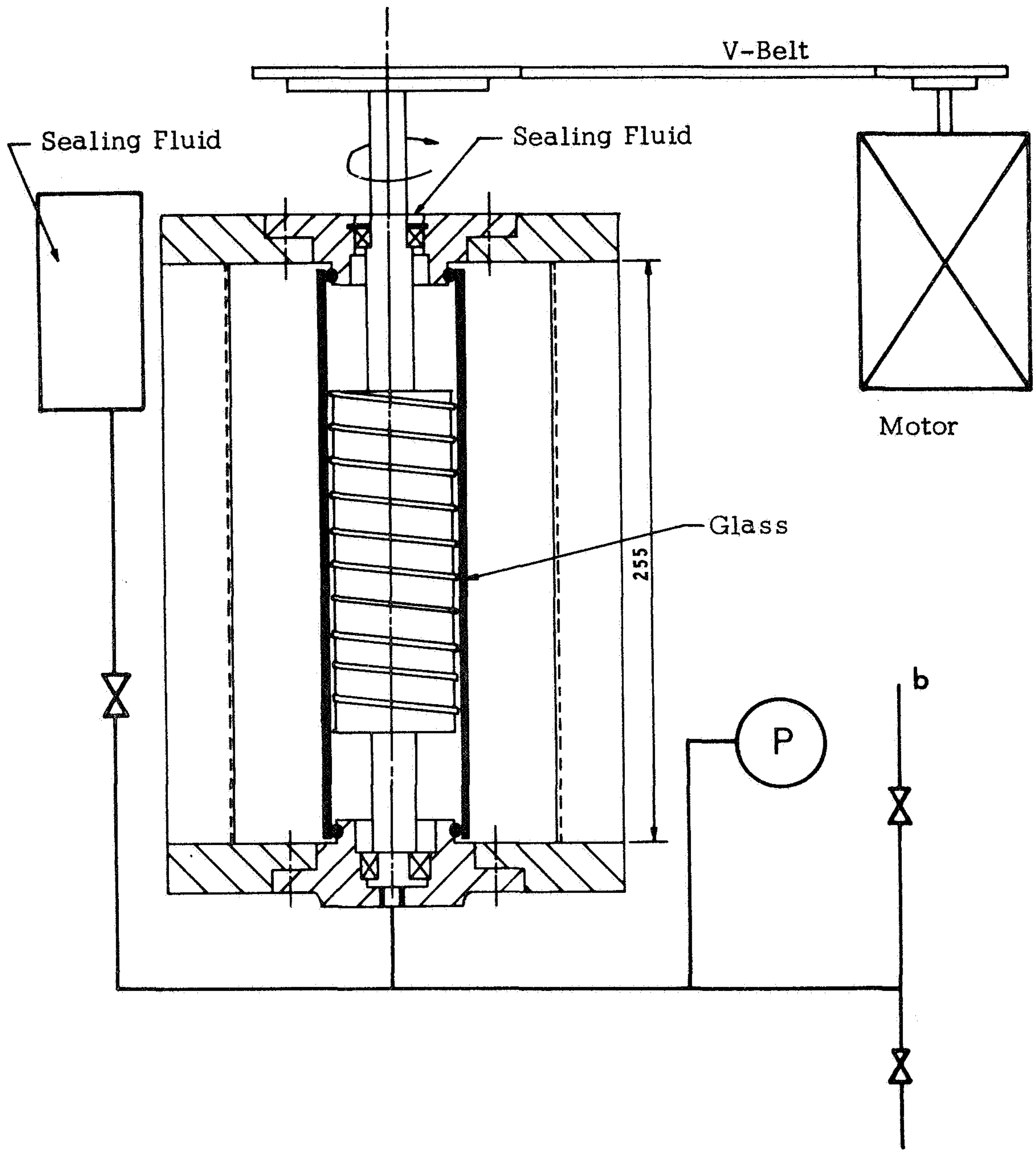


FIG. 1

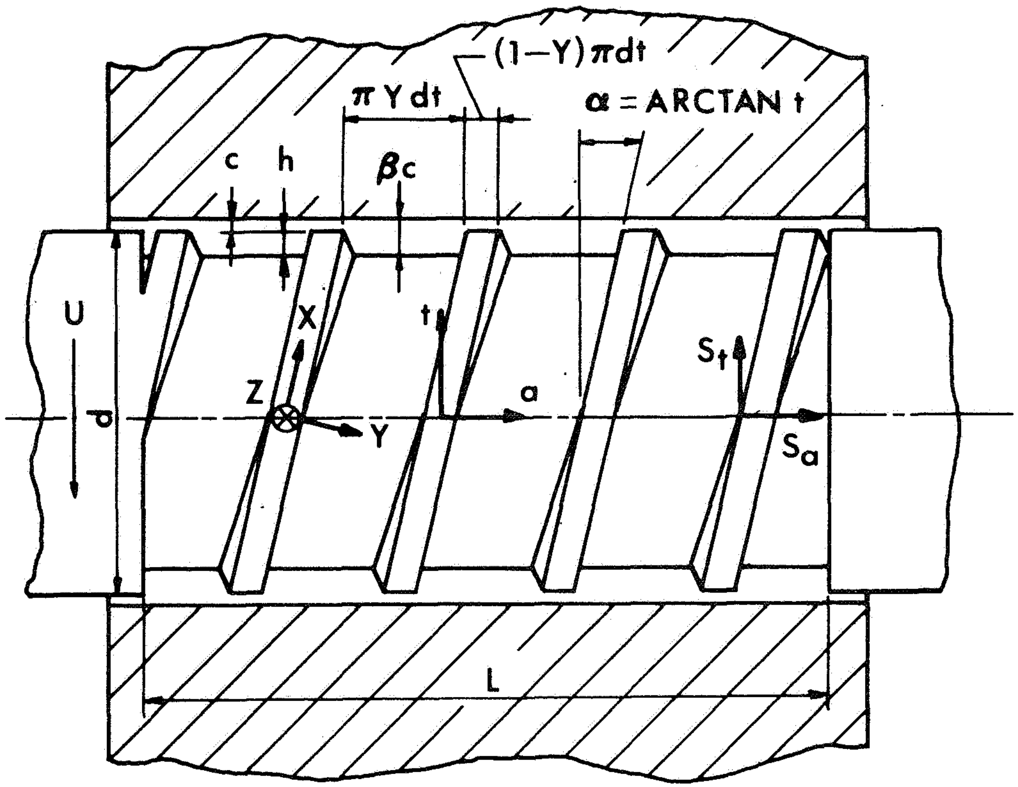

(1−Y)πdt
πYdt
α = ARCTAN t
c
h
βc
U
X
t
Z
a
St
d
Y
Sa
L

FIG. 2

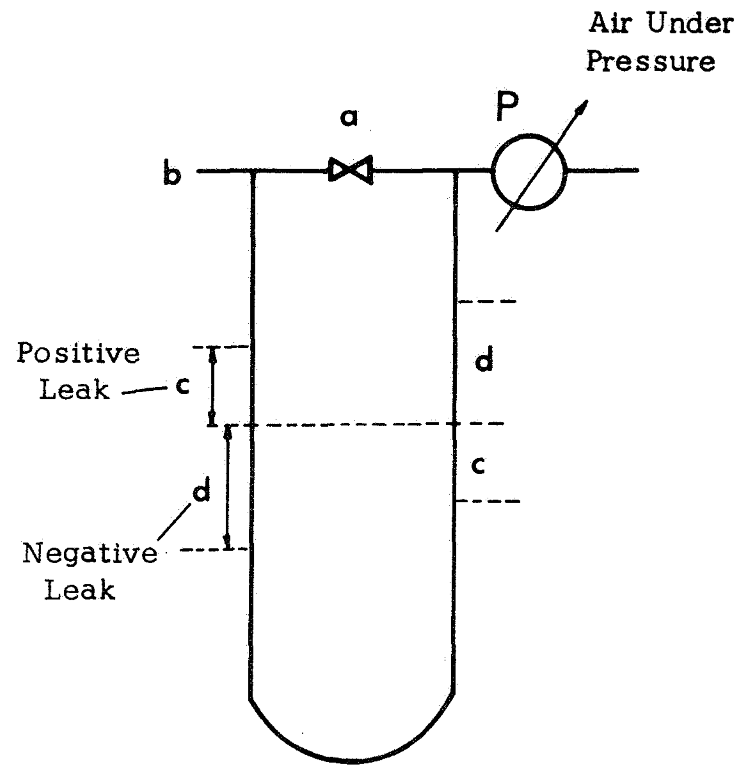

Air Under
Pressure
a
P
b
Positive
Leak
c
d
c
d
Negative
Leak

FIG. 3

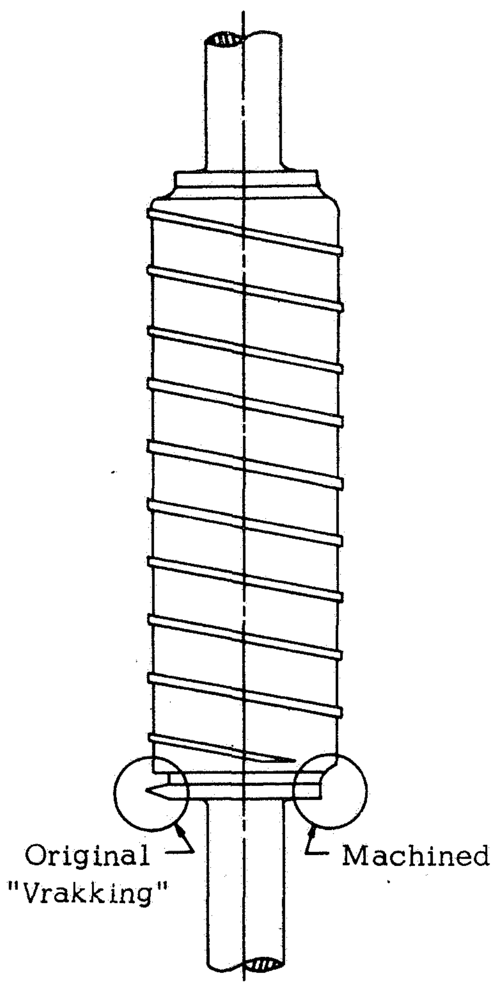


FIG. 4

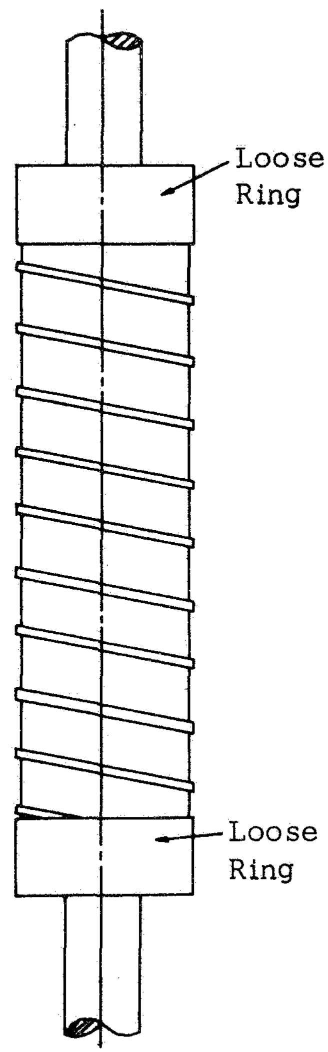


FIG. 5

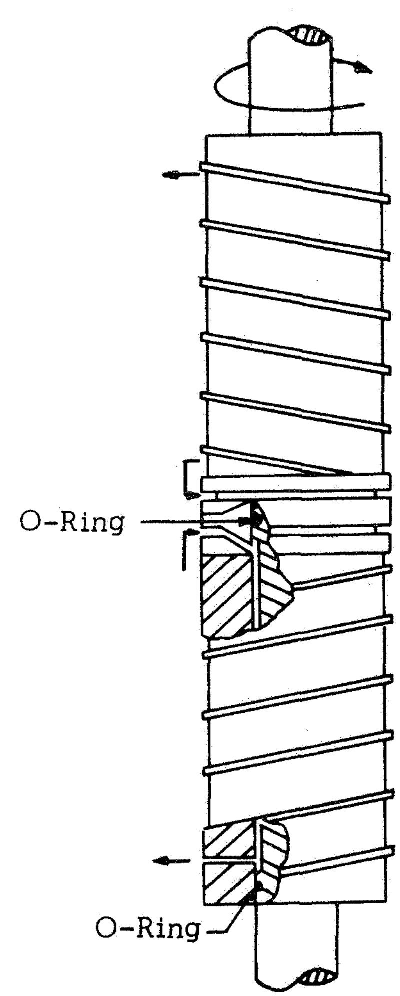
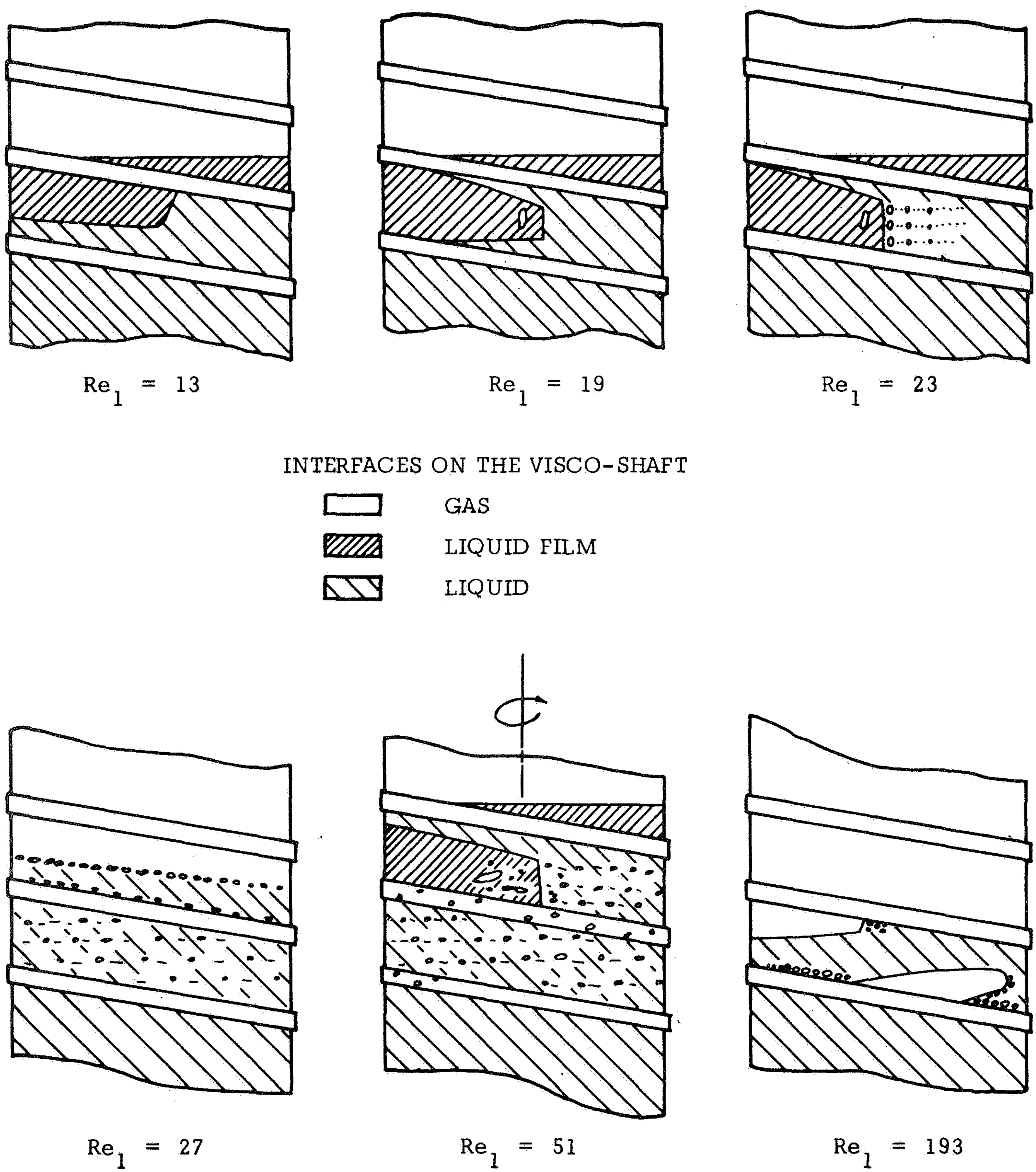


FIG. 6



SCALE 1:1

FIG. 7

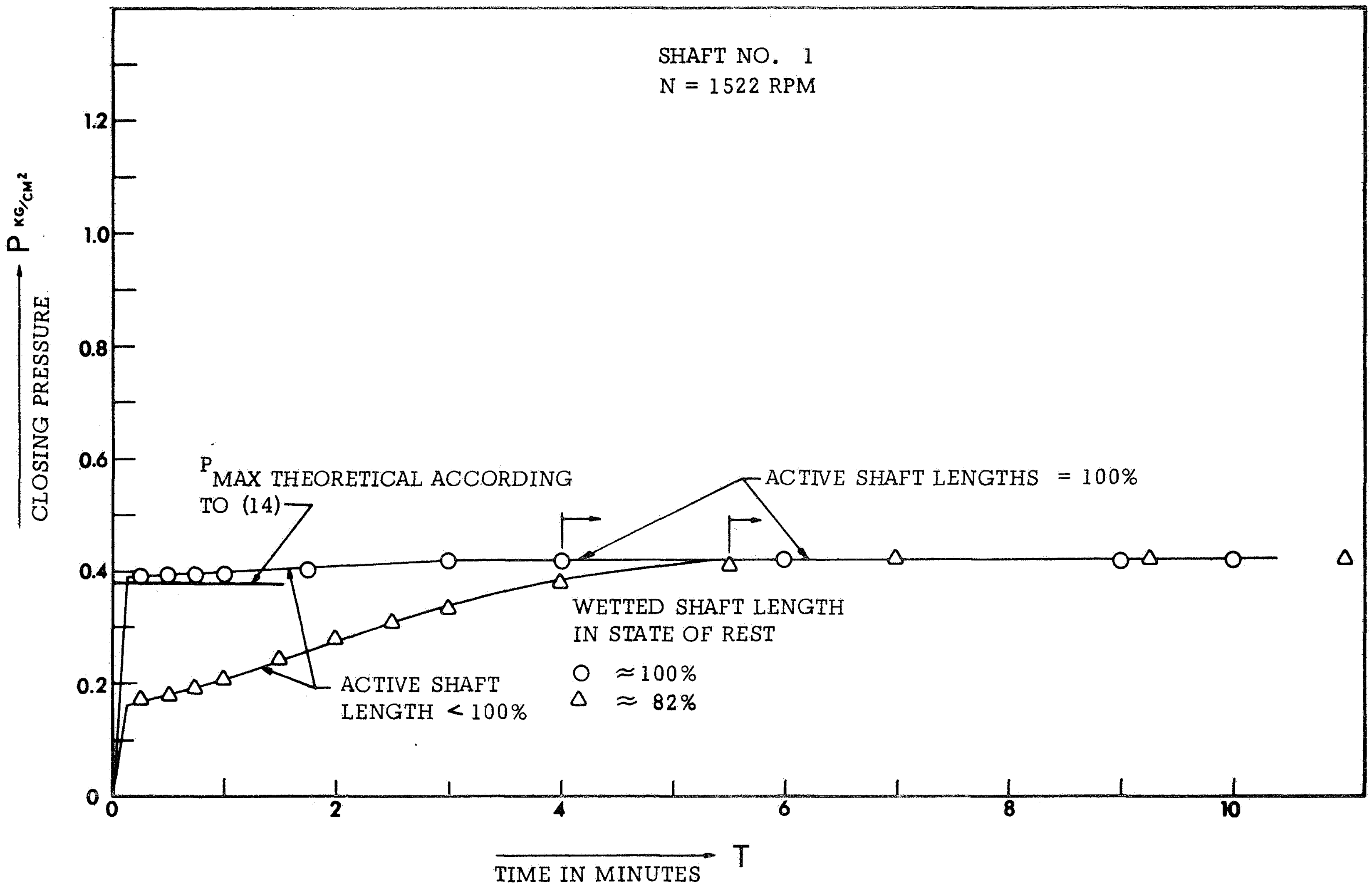

SHAFT NO. 1
N = 1522 RPM
P KG/CM²
CLOSING PRESSURE
1.2
1.0
0.8
0.6
0.4
0.2
0
P MAX THEORETICAL ACCORDING TO (14)
ACTIVE SHAFT LENGTHS = 100%
ACTIVE SHAFT LENGTH < 100%
WETTED SHAFT LENGTH IN STATE OF REST
○ ≈ 100%
△ ≈ 82%
0
2
4
6
8
10
TIME IN MINUTES
T

FIG. 8

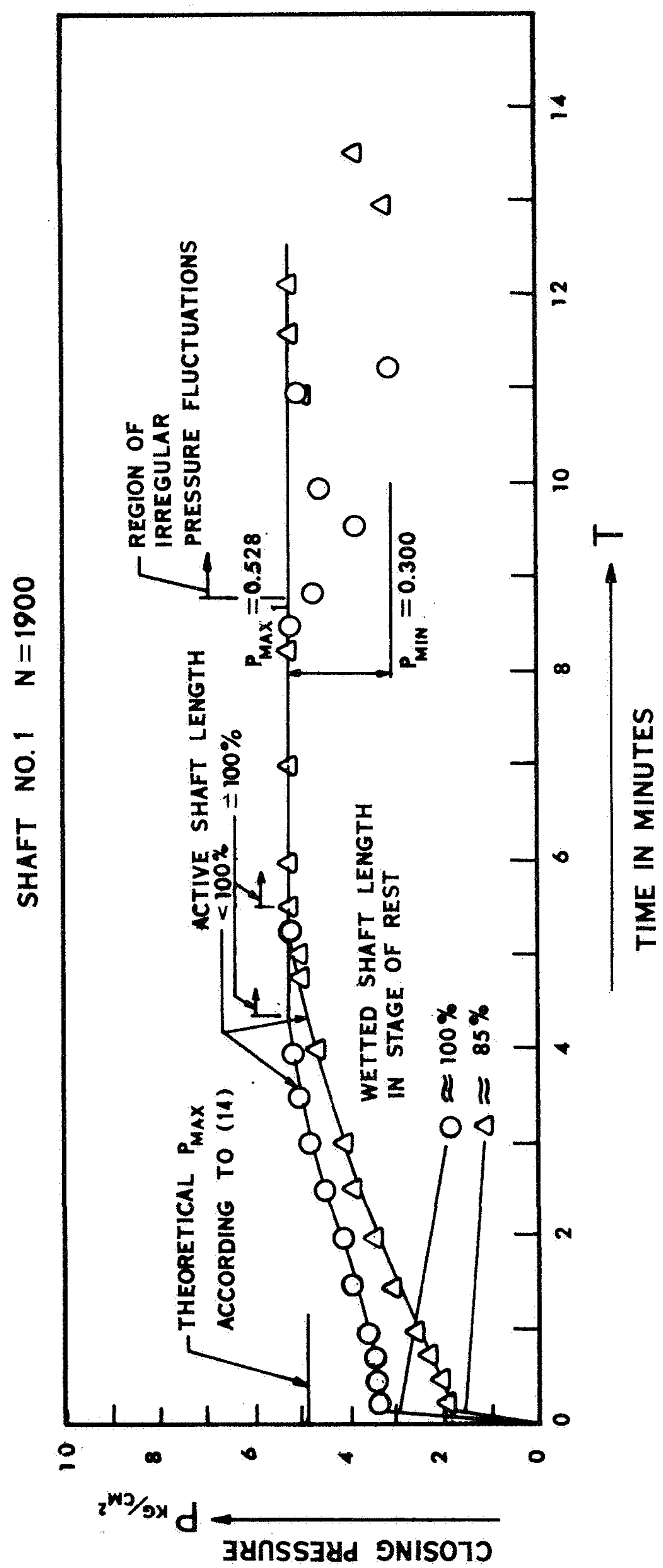
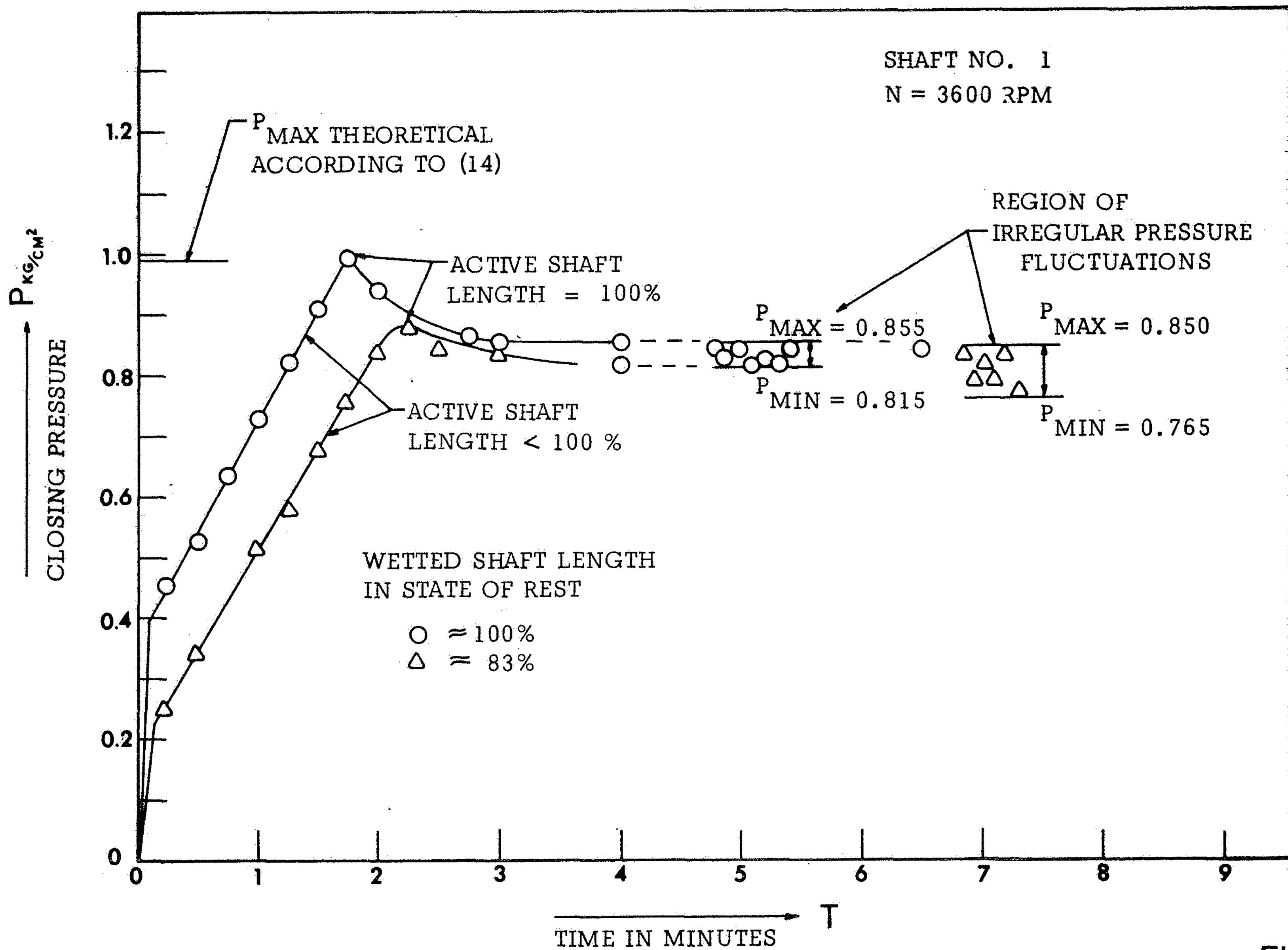
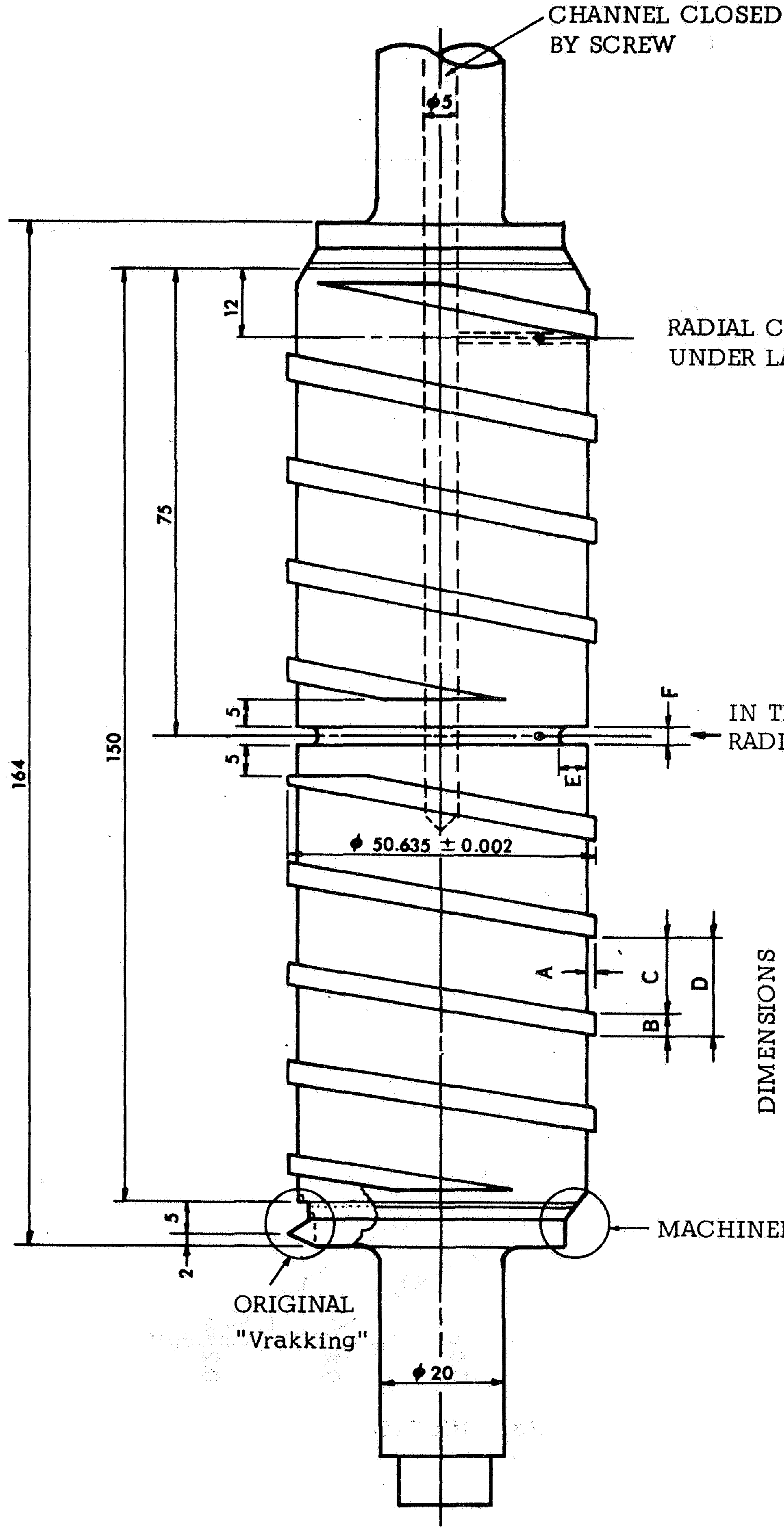

SHAFT NO. 1 N = 1900
CLOSING PRESSURE P KG/CM²
TIME IN MINUTES
T
THEORETICAL P MAX ACCORDING TO (14)
ACTIVE SHAFT LENGTH
< 100%
≐ 100%
WETTED SHAFT LENGTH IN STAGE OF REST
○ ≈ 100%
△ ≈ 85%
REGION OF IRREGULAR PRESSURE FLUCTUATIONS
P MAX ≐ 0.528
P MIN ≐ 0.300
0
2
4
6
8
10
12
14

FIG. 9



SHAFT NO. 1
N = 3600 RPM
P MAX THEORETICAL ACCORDING TO (14)
ACTIVE SHAFT LENGTH = 100%
ACTIVE SHAFT LENGTH < 100 %
REGION OF IRREGULAR PRESSURE FLUCTUATIONS
P MAX = 0.855
P MIN = 0.815
P MAX = 0.850
P MIN = 0.765
WETTED SHAFT LENGTH IN STATE OF REST
○ ≈ 100%
△ ≈ 83%
CLOSING PRESSURE
P KG/CM²
TIME IN MINUTES
T
0
0.2
0.4
0.6
0.8
1.0
1.2
1
2
3
4
5
6
7
8
9

FIG. 10



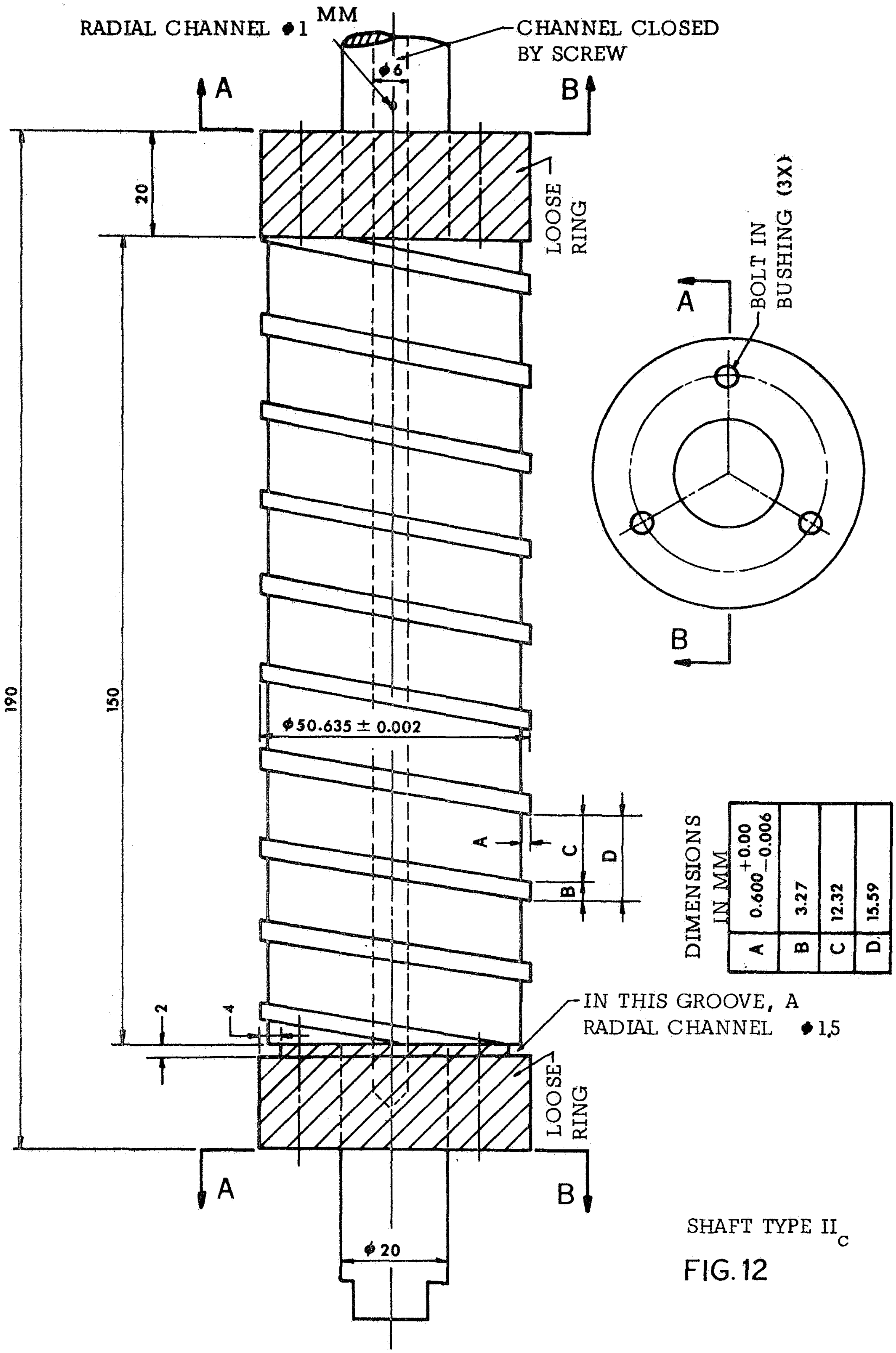
E	4.0
F	2.0

DIMENSIONS IN MM

A	$0.006^{+0.00}_{-0.006}$
B	3.27
C	12.32
D	15.59

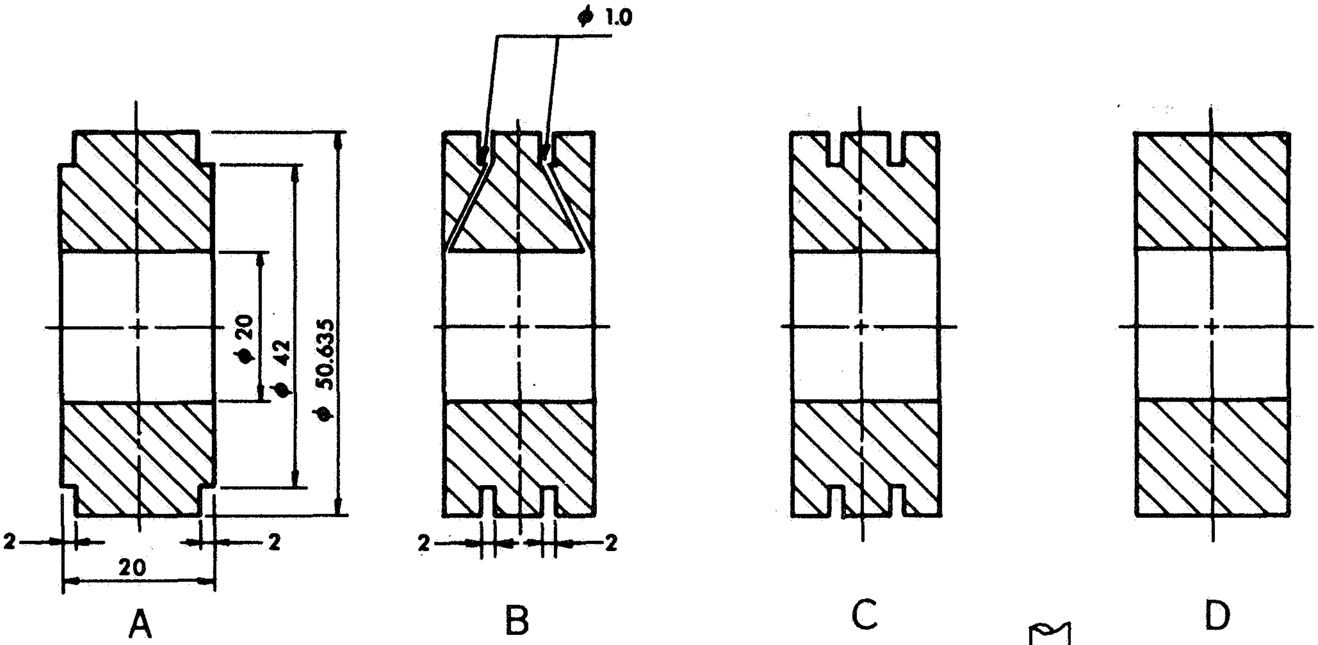
SHAFT TYPE I_E

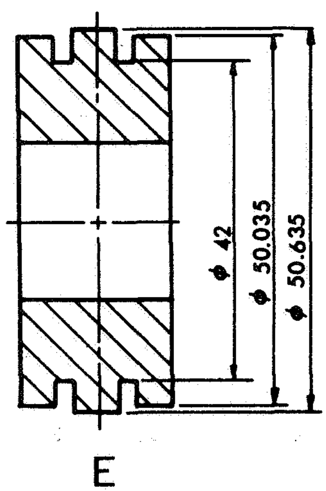
FIG.11

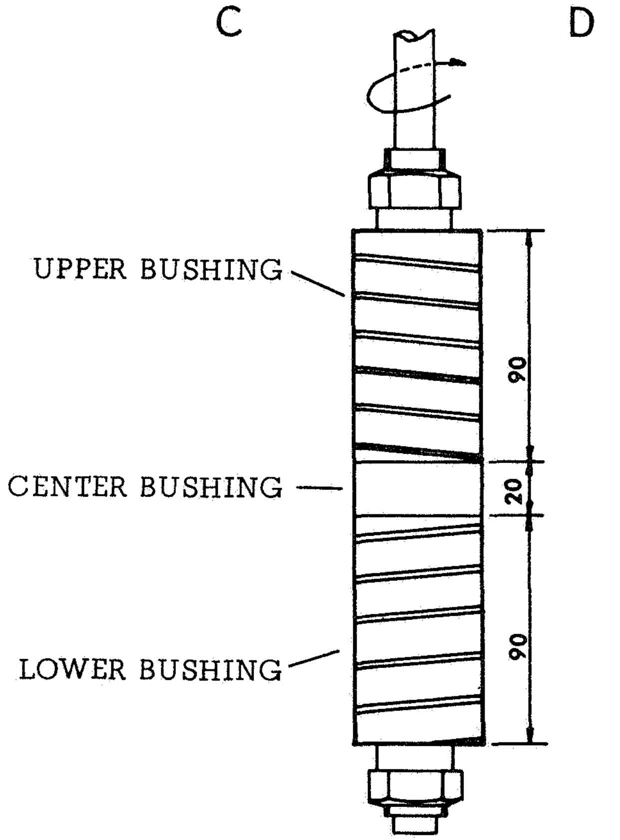


SHAFT TYPE II_C

FIG. 12







SCALE 1:1

CENTER BUSHINGS
OF VISCOSHAFT

FIG. 14

SCHEME OF DOUBLE
VISCOSHAFT

FIG. 13

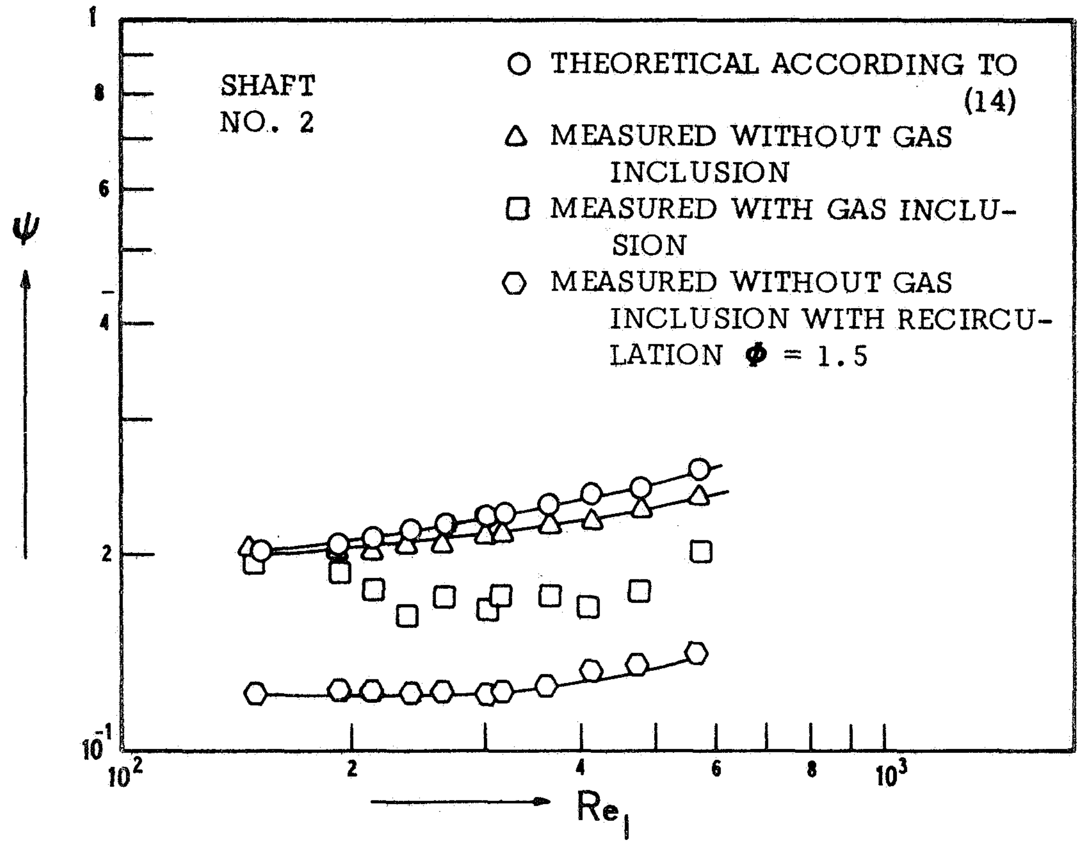

SHAFT NO. 2
THEORETICAL ACCORDING TO (14)
MEASURED WITHOUT GAS INCLUSION
MEASURED WITH GAS INCLUSION
MEASURED WITHOUT GAS INCLUSION WITH RECIRCULATION Φ = 1.5
ψ
Re_l
10^-1
10^2
10^3
2
4
6
8

FIG.15

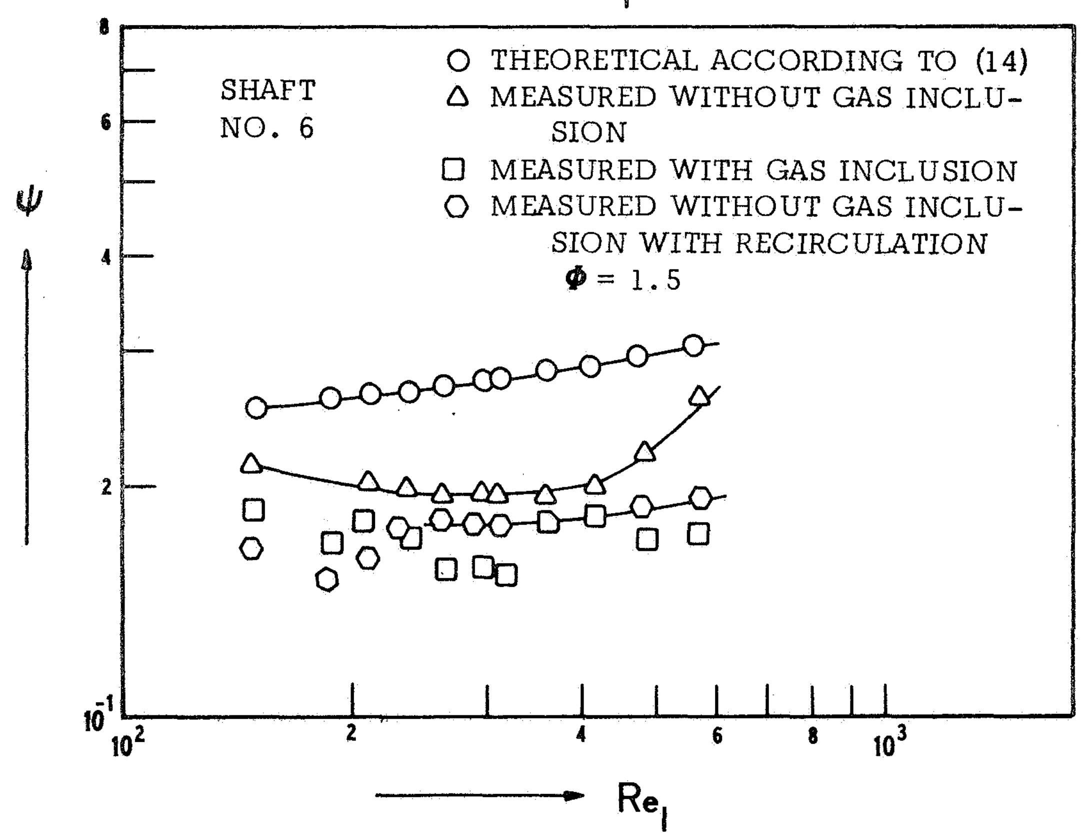

SHAFT NO. 6
THEORETICAL ACCORDING TO (14)
MEASURED WITHOUT GAS INCLUSION
MEASURED WITH GAS INCLUSION
MEASURED WITHOUT GAS INCLUSION WITH RECIRCULATION
Φ = 1.5
ψ
Re_l
10^-1
10^2
10^3
2
4
6
8

FIG.16

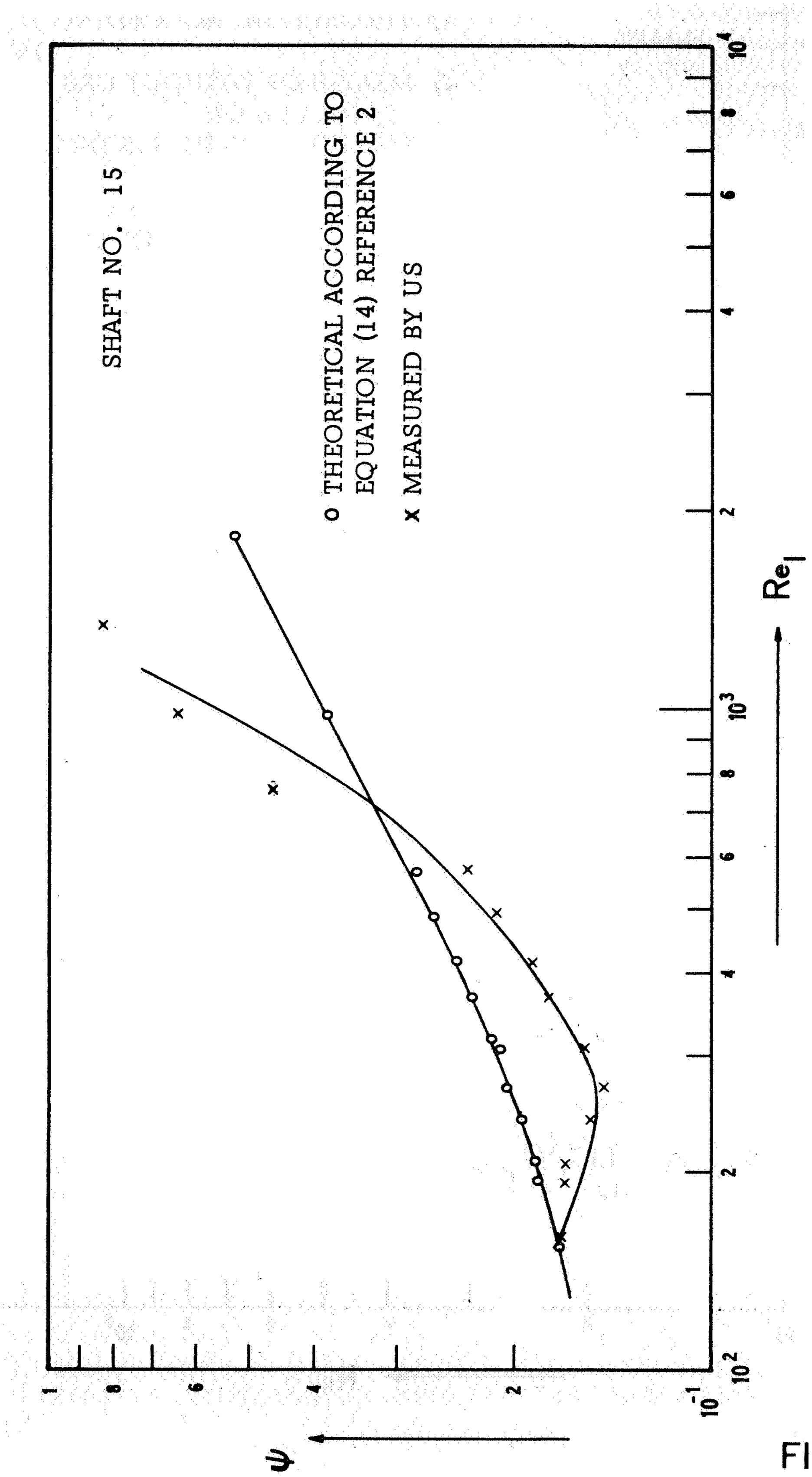

SHAFT NO. 15
o THEORETICAL ACCORDING TO EQUATION (14) REFERENCE 2
x MEASURED BY US
Re_l
ψ
10^{-1}
2
4
6
8
1
10^2
2
4
6
8
10^3
2
4
6
8
10^4

FIG. 17

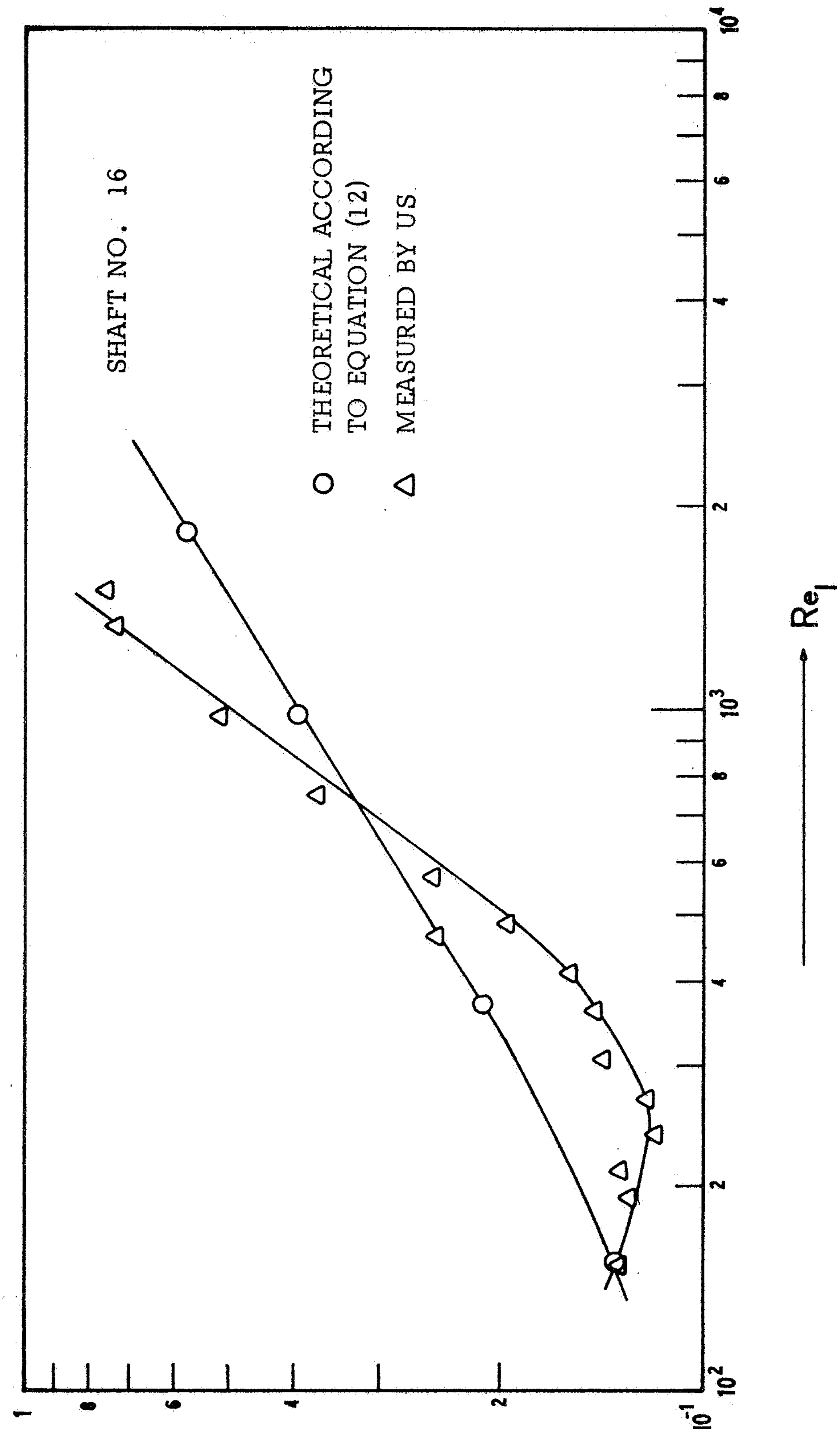
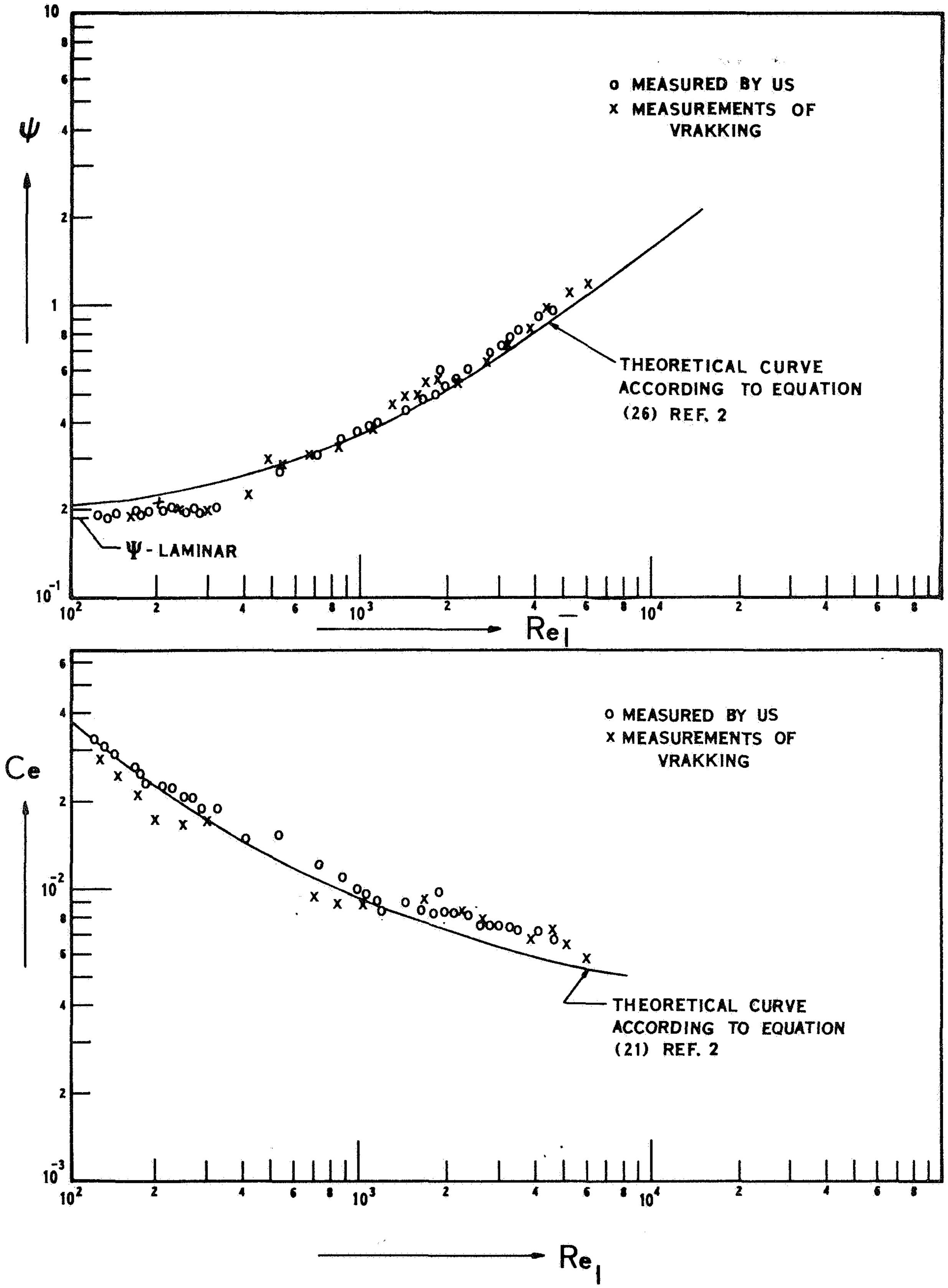

SHAFT NO. 16
○ THEORETICAL ACCORDING TO EQUATION (12)
△ MEASURED BY US
ψ
Re_l
10^{-1}
2
4
6
8
1
10^2
2
4
6
8
10^3
2
4
6
8
10^4

FIG. 18



o MEASURED BY US
x MEASUREMENTS OF VRAKKING
THEORETICAL CURVE ACCORDING TO EQUATION (26) REF. 2
Ψ - LAMINAR
Ψ
Re_l
o MEASURED BY US
x MEASUREMENTS OF VRAKKING
THEORETICAL CURVE ACCORDING TO EQUATION (21) REF. 2
Ce
Re_l

FIG. 19

DISTRIBUTION LIST

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22314

Mr. P. H. Broussard
NASA, R-ASTR-GC
Marshall Space Flight Center
Huntsville, Alabama 35812

Mr. John J. Gurtowski
Naval Air Systems Command
Code AIR 52032C - Dept. of the Navy
Washington, D. C. 20360

Mr. Robert L. Johnson
Chief, Lubrication Research Branch
NASA, Lewis Research Center
Cleveland, Ohio 44135

Mr. W. C. Karl
Office of Naval Research, Code 473
Department of the Navy
Washington, D. C. 20360

Mr. Lawrence P. Ludwig
Head, Seals Section
NASA, Lewis Research Center
Cleveland, Ohio 44135

Mr. Joseph Maltz
Materials Research Program
National Aeronautics & Space Adm.
Washington, D. C. 20546

Col. W. Metscher
Office of Director of Defense Research and Engineering
Room 3C128, Pentagon
Washington, D. C. 20301

Mr. E. R. Taylor
Reactor Engineering Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Mr. Marshall J. Armstrong, Jr.
U. S. Army Mobility Equipment Research and Development Center
Fort Belvoir, Virginia 22060

Mr. Richard N. Belt
U. S. Army Mobility Equipment Research and Development Center
Fort Belvoir, Virginia 22060

Mr. Floyd Lux
U. S. Tank Automotive Center
Propulsion Systems Laboratory, SMOTA-RCP.4
Warren, Michigan 48090

Mr. J. R. Crowder
Flight Mechanics & Fluid Systems Section (AIR 5303)
Naval Air Systems Command - Dept. of the Navy
Washington, D. C. 20360

Mr. Roy R. Peterson
Naval Ship Systems Command (Code 03413)
Department of the Navy
Washington, D. C. 20360

Dr. Earl Quandt
Naval Ship Research & Development Center
Annapolis Division
Annapolis, Maryland 21402

Mr. Alan Schrader
Naval Ship Research & Development Center
Annapolis Division
Annapolis, Maryland 21402

Mr. Lyman Carlyle Fisher
Naval Ordnance Laboratory
Department F (Code 510) - White Oak
Silver Spring, Maryland 20910

Mr. Stanley Doroff
Office of Naval Research (Code 438)
Department of the Navy
Washington, D. C. 20360

Mr. John W. Zmurk
Air Force Aero Propulsion Laboratory (APIP-1)
Wright-Patterson Air Force Base, Ohio 45433

Capt. Kenneth R. Hooks
Air Force Weapons Laboratory WLDC
Kirtland Air Force Base, New Mexico 87117

Dr. Joseph F. Masi
Air Force Office of Scientific Research, SREP
1400 Wilson Boulevard
Arlington, Virginia 22209

Mr. Frank J. Mollura
Rome Air Development Center, EMEAM
Griffiss Air Force Base, New York 13440

Mr. Gerald S. Leighton
SEPO - Division of Space Nuclear Systems
U. S. Atomic Energy Commission
Washington, D. C. 20545

Mr. C. E. Miller, Jr.
Division Reactor Development & Technology
U. S. Atomic Energy Commission
Washington, D. C. 20545

Bureau of Naval Personnel
Department of the Navy
Washington, D. C. 20370
Attn: Technical Library

Naval Air Systems Command
Department of the Navy
Washington, D. C. 20360
Attn: Technical Library Division, AIR-604

Naval Applied Science Laboratory
Flushing and Washington Avenues
Brooklyn, New York 11251
Attn: Technical Library, Code 222

U. S. Naval Oceanographic Office
Suitland, Maryland 20390
Attn: Library, Code 1640

U. S. Naval Postgraduate School
Monterey, California 93940
Attn: Library, Code 0212

DISTRIBUTION LIST (Cont'd)

Naval Ship Engineering Center
Philadelphia Division
Philadelphia, Pennsylvania 19112
Attn: Technical Library

Naval Ship Research & Development Center
Annapolis Division
Annapolis, Maryland 21402
Attn: Library, Code A214

Naval Ship Systems Command
Room 1532 Main Navy
Washington, D. C. 20360
Attn: Technical Library

U. S. Atomic Energy Commission
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60440
Attn: Library

National Bureau of Standards
Washington, D. C. 20025
Attn: Library

Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201
Attn: Library

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Attn: Library

Naval Undersea Warfare Center
3202 East Foothill Boulevard
Pasadena, California 91107
Attn: Technical Library

Navy Underwater Sound Laboratory
Fort Trumbull
New London, Connecticut 06320
Attn: Technical Library

U. S. Naval Weapons Laboratory
Dahlgren, Virginia 22448
Attn: Technical Library

The Franklin Institute
Benjamin Franklin Parkway at 20th Street
Philadelphia, Pennsylvania 19103
Attn: Library

Power Information Center
University City Science Institute
3401 Market Street, Room 2107
Philadelphia, Pennsylvania 19104

Aerojet-General Corporation
Von Karman Center
Azusa, California 91702
Attn: Library

Aerojet-General Nucleonics
San Ramon, California 94583
Attn: Library

University of Arizona
Department of Aerospace and
Mechanical Engineering
Tucson, Arizona 85721
Attn: Professor Kececioglu

AiResearch Manufacturing Company
9851 Sepulveda Boulevard
Los Angeles, California 90045
Attn: Library

AiResearch Manufacturing Company
402 South 36th Street
Phoenix, Arizona 85034
Attn: Library

General Electric Company
Flight Propulsion Division
Cincinnati, Ohio 45215
Attn: Library

General Electric Company
Mechanical Technology Laboratory
Research and Development Center
Schenectady, New York 12301
Attn: Library

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) University of Tennessee Knoxville, Tennessee William K. Stair, Mech. & Aerospace Engr. Dept.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP --

3. REPORT TITLE

Observations on a Viscoseal in a Transparent Housing - The Prevention of Leakage and Breakdown

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Interim (A Translation) - March 1969

5. AUTHOR(S) (First name, middle initial, last name)

R. J. G. Boon Translation by J. P. B. Vreeburg

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1969	102	11

8a. CONTRACT OR GRANT NO. NGR-43-001-003 and N00014-68-A-0144	9a. ORIGINATOR'S REPORT NUMBER(S) ME 69-T57-4
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) --
d.	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
--	--

13. ABSTRACT

A solution is sought for the leakage and break down phenomena as encountered by many researchers by means of visual observations on a viscoshaft seal in a transparent housing.

Our observations are compared with the phenomena mentioned in the literature.

An effort is made, notwithstanding gas inclusion, to prevent leakage in viscoshaft seals.

We tried to reduce gas inclusion by changing the surface energy of the seal.

The influence of the geometry of the seal on gas inclusion and leakage has been studied.

The influence of gas inclusion on the value of the sealing parameter has been looked into.

The measurements of the double V.S.S. in the Lab.of Chem. Instr. have been checked because it could be expected that gas inclusion had affected the measured values.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Viscoseal, Sealing, Gas Ingestion, Gas Inclusion, Seal Breakdown, Lubrication						