INTRODUCTION TO
FERROFLUIDIC SEALING
TECHNOLOGY

NIPPON FERROFLUIDICS CORP.

TOKYO, JAPAN

INTRODUCING OURSELVES

Soon after the development of ferrofluids at NASA in 1969, we at FERROFLUIDICS CORPORATION succeeded in commercializing this unique liquid in a rotary vacuum seal for the first time in the world. Since that time, we have been enjoying a worldwide reputation as the sole specialist of ferrofluids and related products. We have acquired many patents and unsurpassed expertise in this field.

In the area of exclusion sealing (our Exclusion Seal,which is known as EX-SEAL for its excellent exclusion of contaminants), we have sold over 2.5 billion of these seals for computer hard disk drives and other machine parts. Domestic manufacturing started in December, 1982 at NFC. We thank our customers deeply for this achievement of which we are proud and we pledge continued service and our finest efforts in developing new products, such as very thin seals, to meet the requirements of high capacity small hard disk drive spindles, either fixed or rotation shaft types.

This brochure is a complement to the EXCLUSION SEAL Handbook we published in November, 1984, so that our customers may better acquaint themselves with the properties of ferrofluids and the performance of our EX-SEALs.

January 1989

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WHAT ARE FERROFLUIDS?

A ferrofluid is a stable colloidal suspension of sub-domain magnetic particles in a liquid carrier(Figure 1). The particles, which have an average size of about 100A', are coated with a stabilizing dispersing agent which prevents particle agglomeration even when a strong magnetic field gradient is applied to the ferrofluid. In the absence of an external magnetic field, the magnetic moments of individual particles are randomly distributed and the fluid has no net magnetization.

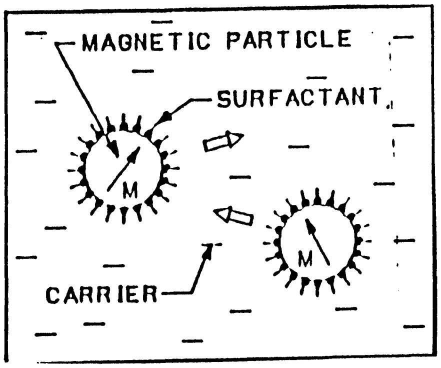
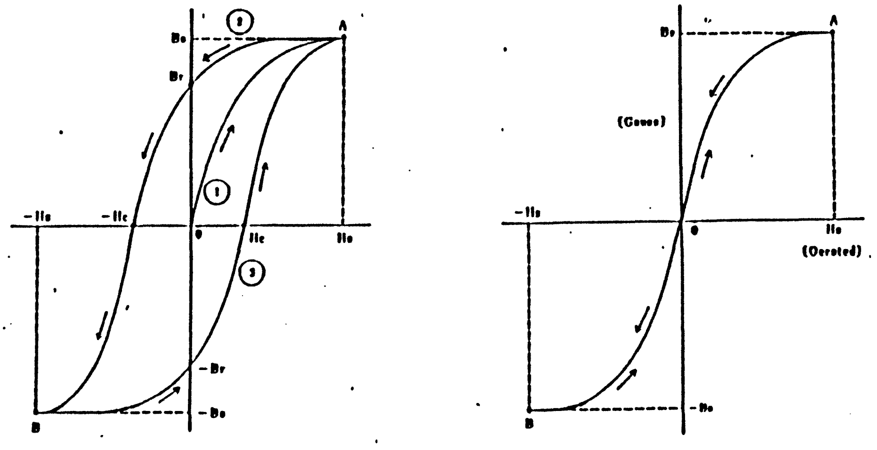


Figure 1. COMPONENTS OF A FERROFLUID

Magnetically, a ferrofluid is perfectly soft. This is illustrated in Figure 2.



Solid Magnetic Material   Ferrofluid

Figure 2. HYSTERESIS CURVES

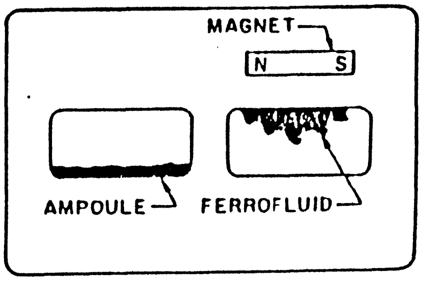
Changes in the magnetization (M) of a ferromagnetic solid as shown on the left lag behind changes in the applied magnetic field(H). This shows up in the form of a hystersis loop in a graph of M versus H.

When a magnetic field is applied to a ferrofluid, the magnetic moments of the particles orient along the field lines almost instantly. Thus, the magnetization (M) of the ferrofluid responds immediately to changes in the applied magnetic field(H), as shown on the right in Figure 2. When the applied field is removed, the moments randomize quickly. Ferrofluids belong to a class of materials defined as superparamagnetic.

The saturation magnetization of a ferrofluid is determined by the nature of the suspended magnetic material and by the volumetric loading of this material. The greater the quantity of magnetic material in suspension, the higher the saturation magnetizaiton of the fluid.

Ferrofluids are also characterized by their viscosity, which can be varied in a controlled manner from less than 5 centipoise to well over 25,000 centipoise @ 27'C depending primarily on the nature of the carrier. Similar to nearly all other materials,the viscosity decreases as the temperature increases. Ferrofluids generally exhibit Newtonian behavior.

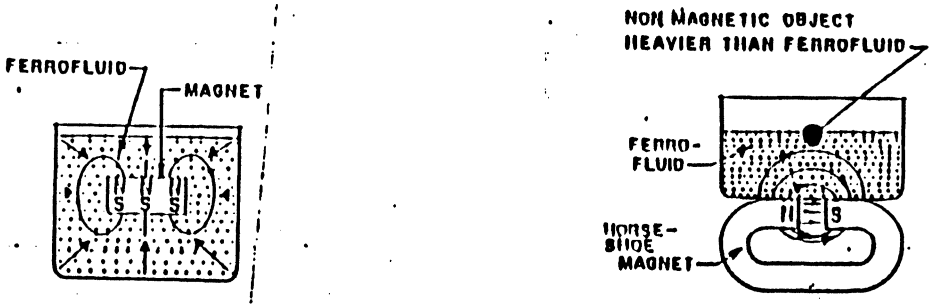
The chemical, mechanical, and physical properties of a ferrofluid correspond very closely to those of the carrier liquid. For example, all commercial ferrofluids utilizing organic carrier liquids have good lubrication and thermal properties. Ferrofluids are strongly affected by an applied magnetic field. In a uniform magnetic field, the particles in a ferrofluid experience only torque and align with the field. In a gradient field, however, the particles experience a force such that the fluid itself responds as a homogeneous magnetic liquid which moves to the region of highest field. Thus, ferrofluids can be precisely positioned and controlled by an external magnetic field. The forces which hold the ferrofluid in place are proportional to the gradient of the external field and the magnetization value of the fluid(Figure 3).



Ferrofluid Attracted and Held by a Magnetic Field

Figure 3. FERROFLUID ATTRACTED TO A MAGNETIC FIELD

Forces generated in the ferrofluid when it is in a magnetic field tend to expel nonmagnetic materials out of the ferrofluid. The expelling force is a function of both the saturation magnetizaiton of the fluid and the strength of the applied magnetic field(Figure 4).



Levitation of a Magnet   Levitation of a Nonmagnetic Object

Figure 4.

Ferrofluids, and products based on ferrofluids, are used in many industrial and consumer applications. These products,as well as many emerging applications, are constantly being refined and improved in our laboratories. Nippon Ferrofluidics Corporation is continuously seeking new areas of application for ferrofluids and welcomes suggestions.

Since the physico-chemical properties of a ferrofluid are mostly dictated by the carrier from which it is synthesized, the fluids are named after the carrier, e.g. water based ferrofluid and synthetic ester based ferrofluid, etc.

Table 1 presents typical applications of ferrofluids.

Table 1. Carriers for and Applications of FERROFLUIDS

Ferrofluid Type	Applications	Examples/Industries
Water	Observation of magnetic domains	Inspection of magnetic tapes and disks
Fluorocarbon	Reactive gas Radiation Environments	Semiconductor Industry, Nuclear Industry
Synthetic Ester	Seals, dampers, Heat transfer	EX-SEAL, fluid film bearings dampers, speakers, process seals
Synthetic Hydrocarbon	Sealing, damping and heat transfer	

Currently, we manufacture several different types of ferrofluids, which we classify by their function as follows:

(1) for vacuum environments	VSG Series
(2) for disk drives	CSG Series
(3) for inertia dampers:	CDG Series
(4) for loud speakers:	APG Series
(5) for magnetic domain observation:	EMG Series
(6) for fluid film bearings:	FFB Series
(7) for electrical grounding:	CFF Series

Physico-Chemical Properties of Ferrofluid

1. Saturation Magnetization of Ferrofluid:

The maximum magnetic moment per unit volume of a ferrofluid is called the saturation magnetization, and is given in Gauss. The magnetization curve for ferrofluid(CSG 26) is shown in M01075Z.

The force needed to hold a ferrofluid in a given position is proportional to the gradient of the magnetic field and the value of the magnetization of the fluid, *i*.e.

$$Fm = M/4\pi \cdot \nabla H$$

where Fm is the holding force density, M, the magnetization, and ∇H, the gradient of the externally applied magnetic field.

2. Rate of Evaporation

For an EX-SEAL to function satisfactorily as a hermetic seal, it is necessary that ferrofluid be present in the radial gap between the pole pieces and the shaft in a precise quantity. The lifetime of an EX-SEAL is determined by the evaporation rate of the carrier.

During the course of seal life, the viscosity of the ferrofluid increases as a result of evaporation which ultimately leads to a paste line material in the gap. However, the fluid will continue to perform until it becomes completely coagulated.

The evaporation rate of a ferrofluid changes with temperature, as well as with time. For example, if seal life is calculated by the rate of evaporation of a ferrofluid which was to be determined directly in the disk drive service temperature range of 0～65°C, the calculated seal life shows more short value than an actual seal life, and what would be found then would be an inordinately high rate of evaporation, since such a measurement would entail only low molecular components present in the fluid in the amount of 2 or 3 %.

This means that determining of the lifetime of an EX-SEAL is possible only after the low molecular components have evaporated away, because the high molecular components that are left behind determine the lifetime in essence.

The evaporation rates of oil based ferrofliuds are so small at service temperatures that they can not be measured accurately. The general procedure is to measure evaporation rates at elevated temperatures by using a microbalance and extrapolating the data to low temperatures by using the equation:

$$\varepsilon(T) = \varepsilon,.\exp(\beta/T)$$

Where β(T) is the rate of evaporation at temperature T'(K), and β, and ε are constants.

3. Viscosity

The viscosity of a ferrofluid is inversely related to temperature and is expressed in centipoise(cp). The rise in the temperature of the seal and the power consumption or torque are considered as the effects of viscosity. The dependence of viscosity on temperature is given by

$$\text{ferrofluid } \eta(T)=\eta(0)e\ \alpha/T$$

where $\eta(T)$=viscosity at temperature T
$\eta(0)$and α=constants, T=temperature, in ('K)

4. Stability of Ferrofluid

A ferrofluid owes its stability primarily to the smallness of the magnetic particles suspended in the carrier. That is to say, as mentioned earlier, the mean diameter of the magnetic particles we use is about 100 A'(0.01 μm), which is small enough to be carried by random thermal motion and not be allowed to make a straight descent. Also, the surfactant that covers the particle surfaces works effectively to prevent them from agglomerating into larger particles. Namely, each surfactant molecule has a 'head', which attaches itself to the particle, as well as a 'tail' , which has affinity with the carrier. The surfactant constituting molecules form an energy barrier preventing coalescence of particles. In addition to the stability of ferrofluids in a gravitational field, the fluids should also be stable in the magnetic field gradients that exist in an EX-SEAL.

Suffice it to say, we at FERROFLUIDICS are fully capable of selecting an appropriate ferrofluid and designing a seal structure to meet performance requirements; in short, we are proud of our ability to optimize design for any given set of specifications.

Properties of ferrofluids for disk drive application are summarized in Tables 2 and 3.

Table 2. Physical Properties of Ferrofluids

Type	CGS 26	CSG 26A	CSG 25A	CSG 24A	CSG 33	CFF 100A
Base Oil	HC(*1)	HC(*1)	HC(*1)	HC(*1)	Ester	Ester
Saturation (2) magnetization	200	200	250	300	300	250
Viscosity (3)	200	75	100	120	175	130
*Evaporation Rate (4)	3.8	3.8	3.8	3.8	3.8	3.8
Density (5)	1.06	1.06	1.12	1.195	1.23	1.15
Electrical Resistivity(6)	～109	～109	～109	～109	～109	～108

(1)Synthetic hydrocarbon; (2)Gauss; (3)cP, at 27'C; (4)in 10-9 g/cm2 · s, at 80'C; (5)g/cm3; (6)Ω · cm, at 50'C

* Evaporation rate is measured for low molecular components present in ferrofluid for the purpose of ferrofluid inspection, and is not related to actual seal life. -see 'Rate of Evaporation' on page 5.-

Table 3. Physico-Chemical Properties of Ferrofluids

Type	CSG 26	CSG 20A	CSG 33	CFF 100A
Fire Point('C)	262	262	265	265
Flash Point('C)	235	235	235	232
Pour point('C)	-51	-54	-30	-40

THE EXCLUSION SEAL (EX-SEAL)

The working principle of our Exclusion Seal, known as EX-SEAL, is illustrated in Fig. 6.

Mechanically, an EXSEAL consists of a permanent magnet, a pair of pole pieces (one attached to the N pole and the other to the S pole of the magnet) and a ferrofluid as a sealant. A closed magnetic circuit is formed between the EX-SEAL and the shaft of the spindle (which has to be magnetically permeable). The pole pieces concentrate magnetic flux in the radial gap between the pole piece inner diameter and the shaft, and the ferrofluid which is added to the radial gap constitutes a 'liquid O-ring' seal.

The Basic constructon of an EXSEAL is shown in Fig. 5, while Fig. 6 presents the actual magnetic flux distribution obtained by finite element computer modelling.

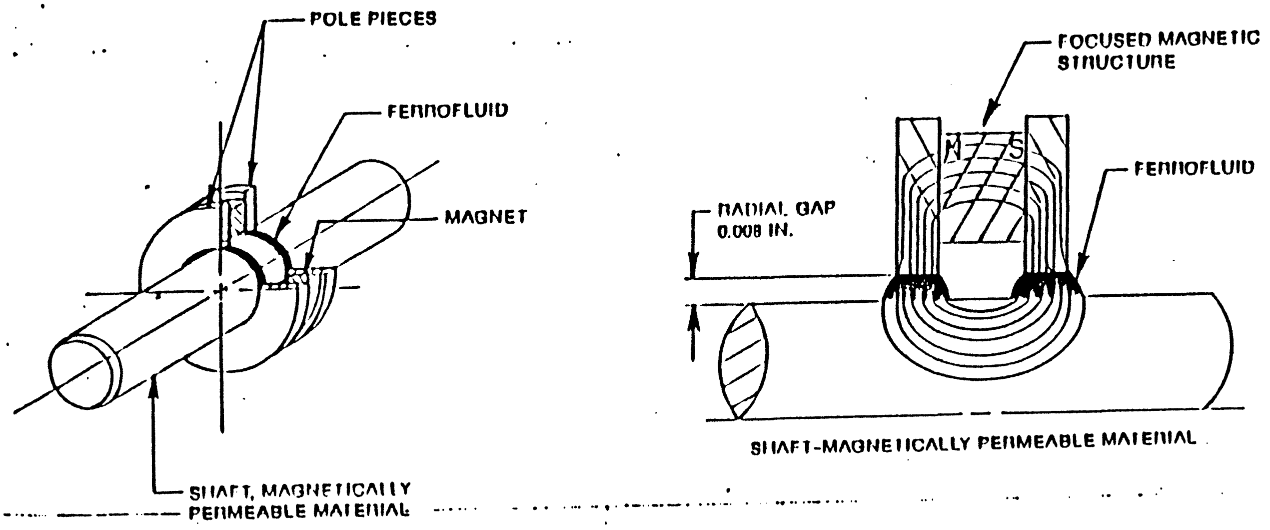


Fig. 5. Basic Construction of EXSEAL

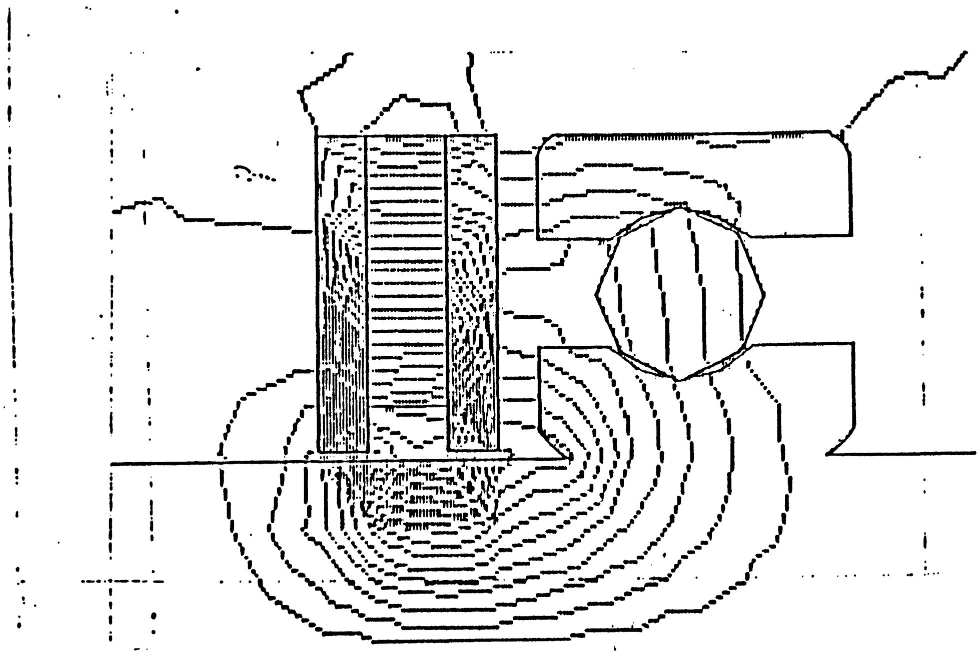


Fig. 6. Magnetic flux distribution of a two pole EX-SEAL

Service Lifetime of an EX-SEAL

As mentioned earlier, the service lifetime is defined as that period of time in which an EX-SEAL loses its sealing capacity due to the evaporation of the base oil. This means that the lifetime of an EX-SEAL is determined essentially by the evaporation rate of the base oil.

Theoretically, the lifetime of an EX-SEAL (τ) may be expressed in terms of ($m,$) the mass of the evaporative component present in the fluid used in the seal,(A) the exposed area of ferrofluid and ε, the rate of evaporation of the fluid. Namely,

$$\tau = m,/A \cdot \varepsilon .$$

For practical purposes, however, the above relationship should be expressed in more conventional parameters, such as the diameter of the shaft, the radial gap, the pole piece width, and the percentage composition of the evaporative component of the ferrofluid used. We have placed these design parameters in a correction factor to deal with various influences that an EX-SEAL is subjected to in actual service, as well as by another factor that covers the ferrofluid.

Namely,

$$\tau = K1 \cdot K2 \cdot \rho \cdot Lt/\varepsilon(T),$$

where τ : estimated service lifetime,

K1 : correction factor involving the size of EX-SEAL whether the seal is 'thin', or 'thick' seal, whether the seal is single or double pole filled and eccentricity etc.

K2 : correction factor involving the type of ferrofliud e.g. molecular weight distribution, evaporative constituents, viscosity and amount etc.

ρ : Density of ferrofluid,

Lt : thickness of the pole piece, and

$\varepsilon(T)$: evaporation rate of ferrofluid at the service temperature T.

It is very difficult to obtain the values of Correction factors K1 and K2, and thus some uncertainty is built into the calculations of seal lifetimes. Some measure of seal lifetimes can be gained by performing actual accelerated tests at elevated temperatures, but extrapolation to service temperature may introduce an error. However, our calculations do predict several years of seal life. This is supported by our accumulated field experience of over 10 years in the disk drive industry where our EX-Seals last over 5 years. Seal failures resulting from fluid evaporative processes have not yet been observed.

Concern regarding decrease of seal pressure capacity due to loss of ferrofluid by evaporation is natural, but groundless. Actually it has been shown that the pressure capacity is maintained approximately constant up to the very end of lifetime.

Because the density of magnetic particles in ferrofluid increases as the base oil evaporates, the saturation magnetization value of the fluid increases. At the end, when the interparticle distance has decreased under evaporated base oil, The fluid becomes so much like a paste that sealing is no longer possible and the pressure capacity then decreases rapidly.

Pressure Capacity of an EX-SEAL

1. Basic Considerations:

The pressure capacity of an EXSEAL, ΔP, is proportional to the product of H, the magnetic flux density in the sealing gap, Ms, the saturation magnetization of ferrofluid employed, and Nt, the number of sealing stages. Thus,

$$\Delta P \infty H \cdot Ms \cdot Nt,$$

A high enough magnetic flux density, together with a ferrofluid of a high enough saturation magnetization, is the primary requisite for attaining a high seal pressure capacity. However, it should be noted that even though the manufacturing of ferrofluids with a saturation magnetization of up to 600 Gauss is entirely feasible, such a fluid contains a high fraction of magnetic particles. This means that the lifetime of an EX-SEAL using this fluid would be reduced.

In computer hard disk spindles, where EX-SEALs are most commonly used, a negative pressure differential is created by the rotation of the disk. Although the magnitude of such a negative pressure differential depends on the size of the disk, it is generally taken to be 10 - 30 mmH20 for small drives, but a pressure capacity of 100 - 150 mmH20 during rotation is typically the specification. For large drives, such as 8 inches or more, the pressure capacity requirement is generally 200 ~ 400 mmH20.

In addition to these pressure capacity specificatons, our EXSEALs are capable of meeting the lifetime specification of five years or more. To meet these two requirements simultaneously, we at FERROFLUIDICS select a ferrofluid that has a saturation magnetization of 200 - 300 Gauss from many candidate ferrofluids. Furthermore, we ensure that the viscosity of ferrofluid is low enough so that the heat generation due to the viscous shear is minimized. The temperature rise of ferrofluid is thus reduced and the seal life is extended.

2. STATIC SEAL PRESSURE CAPACITY

The appended Data Sheet M00784Z illustrates the changes that take place in the pressure capacity of an EX-SEAL as the spindle undergoes a repetition of rotation (3,600 rpm) and stopping (or standing). It will be seen that the pressure capacity decreases to a certain level with time while in a stationary condition, but it regains its former level of pressure capability as soon as the rotation is resumed. This time-related decrease in the static pressure capacity of an EX-SEAL results from the properties of ferrofluid, as is explained in the following.

The phenomena discussed above takes place most conspicuously depending on the eccentricity between the EX-SEAL and shaft. The appended Data Sheet M00792Z illustrates the effects of eccentricity. The decrease in static pressure capacity with time is small when the eccentricity is also small.

That is to say, if the seal gap is not uniform, an additional gradient is created in the distribution of magnetic flux density in the air gap so that the ferrofluid in the gap is attracted to the region where the magnetic field has the highest value. Furthermore, there is also a segregation of magnetic particles. The time needed for this movement depends naturally on the magnitude of the additional magnetic field gradient and the viscosity of the fluid, but the fluid will assume ultimately a distribution in the gap. The pressure capacity of EX-SEAL in this case is determined by the largest gap.

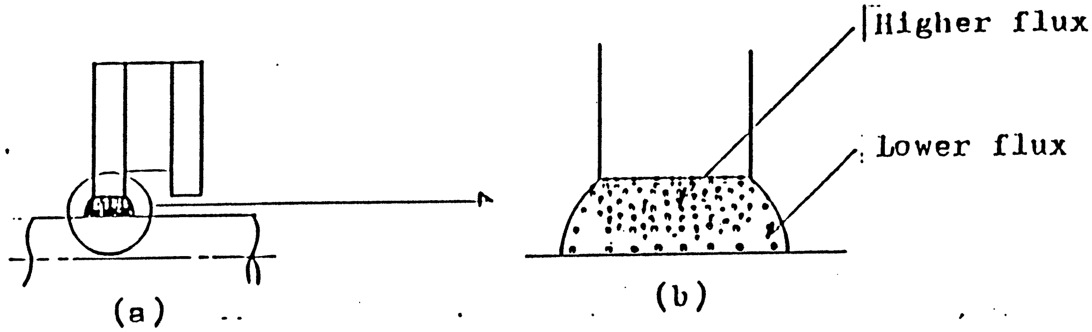


Fig. 7. Distribution of magnetic particles in a static seal

On the other hand, however, the time dependent decrease of static pressure capacity does take place even when the eccentricity is held to zero. This is due to movement of the magnetic particles, which, when left undisturbed in the fluid, collect from regions of low magnetic field to those of high magnetic field. As a consequence, the distribution of magnetic particles becomes uneven and results in a lower pressure capacity.

This situation is shown in Fig. 7, where (b) is a magnified view of the encircled part of (a), which depicts a ferrofluid in a sealing gap.

As soon as the spindle starts to rotate, however, the magnetic particles are mixed due to agitation in a homogeneous manner and the pressure capacity regains its full value as shown in Data Sheet M00784Z. Here, the mobility of particles is such that only one rotation of the spindle is often sufficient to restore the pressure capacity.

Since the sealing of disk cavity is required only when the spindle is rotating, as mentioned above, we specify only dynamic seal pressure capacity. However, the seal does has a sufficient pressure capacity even in the static case.

3. Method of Determining Pressure Capacity

Different testing methods can lead to different values of pressure capacity of an EX-SEAL. For this reason, we prefer to perform the test with an apparatus shown in appended Data Sheet M00785Z. Here, the spindle should be rotated at its rated speed; if rotation by motor cannot be achieved, the spindle should be rotated by hand immediately before testing.

The procedure for testing is as follows. Referring now to appended Data Sheet M00785Z:

1. Open the valve gradually as the rated rotational speed is reached and maintained, and let the pressure rise at a rate of about 2 mmH2O/s until the required positive pressure has been applied to the seal; then

2. Close the valve. The pressure drop should be no more than 5 mmH2O

Viscous Drag Torque of an EXSEAL

The drag torque that an EXSEAL exerts on a spindle shaft is due to the viscous nature of the ferrofluid. It is given by dividing the seal power loss with shaft speed, as;

$$T = P./N = D3 \cdot N \cdot \eta\, Lt/Lg$$

where
T : torque,
P : power loss,
D : shaft diameter,
N : shaft speed,
η : viscosity of ferrofluid,
Lg : radial gap, and
Lt : pole piece width.

The power loss due to the seal is very small. Table II shows calculated seal power losses for various shaft diameters at 3,600 rpm for a typical exclusion seal using CFF 100. The power loss also depends on temperature since the viscosity of ferrofluid is a function of temperature.

Designs of EX-SEAL

FERROFLUIDICS currently supplies three types of EXSEALs in production quantities. Their structures and features are presented below.

1. The double pole piece design

This design, which is illustrated in Fig. 8, is the most common and has also been discussed before(see Figures 6 and 7). One salient feature of this design is that, owing to the closed magnetic circuit formed by the two pole pieces and the shaft, a high magnetic flux density can be achieved in the radial gap. Therefore, not only a high holding force(Fm) is created to keep the ferrofluid in place, but also a high seal pressure capacity is obtained because of the double pole piece construction allowing the formation of two liquid O-rings.

TABLE II

Seal Power Consumption Using CFF 100

Shaft Diameter	Seal Power Consumption per pole	
	@ 10'C	@ 65'C
(mm)	(watts)	(watts)
5.7	0.024	0.002
7.0	0.045	0.004
9.5	0.115	0.011
12.0	0.230	0.023
12.7	0.273	0.027
19.0	0.921	0.092
30.5	3.768	0.318
35.5	6.000	0.600
45.7	12.720	1.272

Note: The seal power consumption for a two pole fill will be twice that of the above values.

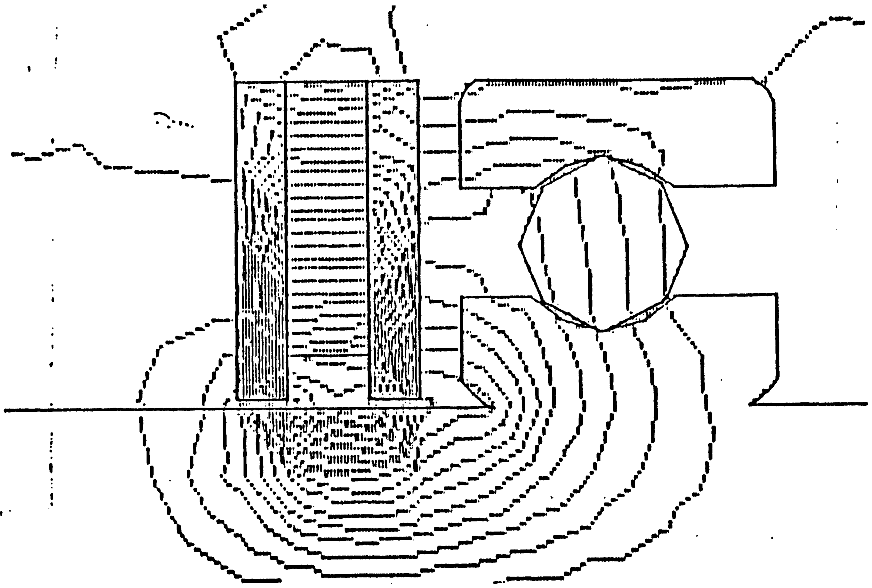


Fig. 8. Structure and magnetic flux distribution of Double Pole Piece EX-SEAL. On the right is shown a magnetically permeable ball bearing.

The total space required for a double pole EX-seal becomes rather large, because the same clearance must be provided between the lower pole piece and bearing as between the upper pole piece and either the drive hub or the shaft end. Although the clearance requirement between the upper and the lower pole pieces differs depending upon the seal design and the amount of ferrofluid used, a clearance of at least 0.75 mm must be maintained. (See 'EXCLUSION SEAL Handbook, Sept. '84 edition.)

The service life of a double pole filled seal is expected to be longer than the single pole filled seal. This is due to the fact that the inside fluid surfaces in a double pole fill evaporate into each other minimizing the carrier loss.

2. Uneven Pole Piece Design

In the double pole piece seal described above, if only one of the two pole pieces (usually the top pole piece) were to be charged with ferrofluid, the other, which is the bearing side pole piece, would merely be a pole to complete the magnetic circuit.

The uneven pole piece design, shown in Fig. 10, has one pole piece thicker than the second pole piece. The pole piece closest to the bearing is usually thin and the pole piece on the hub side is usually thick.
The advantage of such a seal is that its axial length is smaller than the two pole standard seal. The uneven pole seal can be charged with ferrofluid either in a single or double pole fill mode. The service life of the seal is attributed to the fluid in the gap of the thicker pole piece, and is at least equal to the standard two pole seal.

3. Single Pole Piece Design

This type of EX-SEAL is a logical extension of an uneven pole piece design in which the second pole piece has been completely removed. Such a seal has a very small axial length. As illustrated in Fig. 11, the bearing side pole piece has been eliminated. Since the magnetic circuit in this case is partially open, the magnetic flux density in the sealing gap is lower than that of the conventional double pole piece design. However, the field is still high enough to retain the fluid in the gap against the centrifugal forces, shocK and vibrations and will provide a sufficient pressure capacity for the seal.

One concern may be the magnetic leakage flux that passes through the bearing and its possible effect on the bearing performance, but in our five-year history of supplying this type of EX-SEAL to our customers, there have been no complaints. The permanent magnets used inside the spindle motor usually produce larger magnetic fields at the bearing site than the EX-SEAL. Again the life of this type of seal is equivalent to the other two seals.

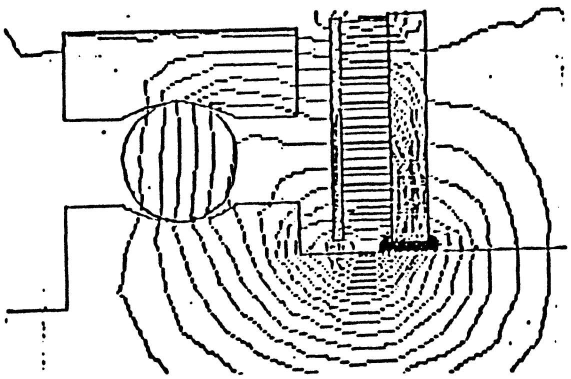


Fig. 9. Structure and magnetic flux distribution of Uneven Pole Piece EX-SEAL

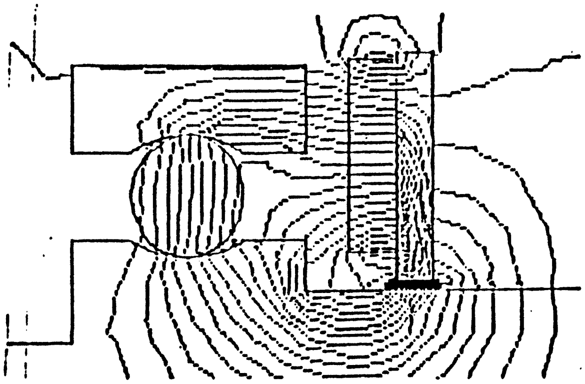


Fig. 10. Structure and magnetic flux distribution of Single Pole Piece EX-SEAL

Design Procedures of EX-SEAL

There are four important parameters in designing an EX-SEAL. They are:

1. size of the radial gap
2. magnetic flux density in the gap,
3. thickness of pole pieces, and
4. selection of permanent magnet.

Designing an EXSEAL begins by deciding which type of materials will be used for the permanent magnet and the pole pieces and their sizes. An SUS 400 series stainless steel is customarily used for the pole pieces for its corrosion resistance.

Once approximate dimensions (as may be dictated by the spindle specifications) are decided, the permeance of the magnetic circuit is calculated. From this value and by using the demagnetization curve, the magnetic induction of the permanent magnet can then be determined. Finally the air gap flux density is calculated as outlined below:

Permeance coefficient $Bm/Hm = Ag \cdot Lm \cdot F/2Lg \cdot Am \cdot f$, and

Air gap flux density $Hg = Bm \cdot Am/F \cdot Ag$,

where,

Bm: magnetic induction of the permanent magnet,

Hm: magnetizing force of the magnet,

Ag: area of radial gap

Lm: thickness of permanent magnet,

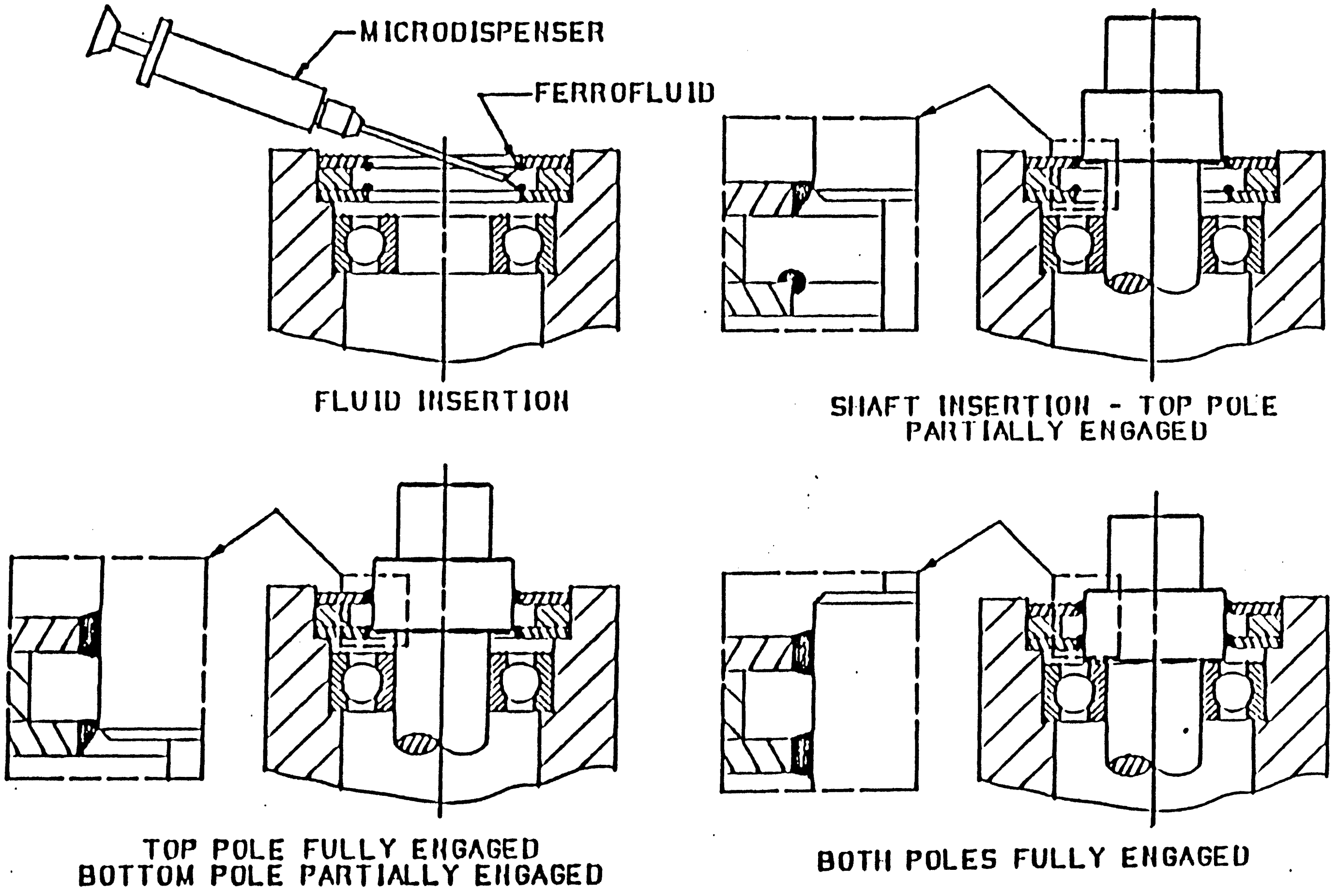
F : leakage factor

Lg: radial gap

Am: surface area of permanent magnet

f: reluctance factor, and

Hg: Air gap magnetic flux density



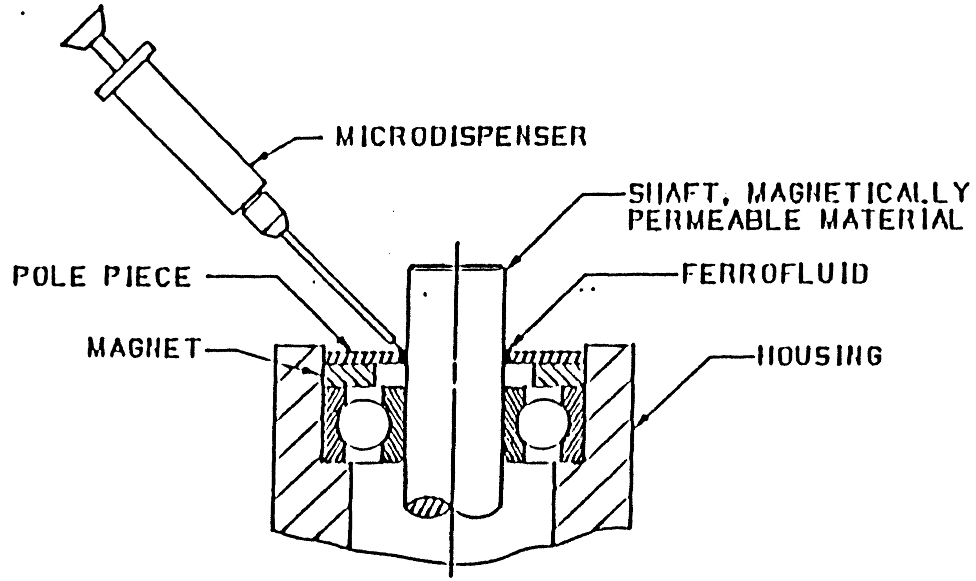
FLUID INSERTION

SHAFT INSERTION - TOP POLE PARTIALLY ENGAGED

TOP POLE FULLY ENGAGED
BOTTOM POLE PARTIALLY ENGAGED

BOTH POLES FULLY ENGAGED

Double Pole fill method



Single Pole fill method

Figure11: Illustration of two different types of fill methods

A careful examination is then made as to whether the magnetic flux density obtained is high enough to magnetize the fluid to its saturation magnetization and, at the same time, is within the range that it will not affect the collidal stability. Should the result be negative, reselection of the type of permanent magnet or of varions dimensions such as the radial gap, and pole piece widths will be made. The calculations are repeated until a satisfactory design is obtained.

Next, the magnetic holding force Fm is determined and compared with the centrifugal force Fc that acts on the fluid, and at the same time, selecton is made for the ferrofluid. The design standard at FERROFLUIDICS is that the magnetic holding ratio(the ratio of Fm as calculated from the mean magnetic flux density in seal gap to Fc) should be at least nine. Namely,

Magnetic holding force	Fm oc Ms · Hg/Lg,
Centrifugal force	Fc oc D · N2
Magnetic holding ratio	Fm/Fc $\geqq$ 9.

Should the magnetic holding ratio fail the requirement, selection of the ferrofluid or the design of the magnetic circuit is revised until desirable results are obtained. More recently, computer modelling of a magnetic field and its destribution in and around the air gap was performed to further support the basic design methodology described above.

Finally, calculations for the seal pressure capacity(see Chapter 'Pressure Capacity of an EXSEAL'), viscous drag torque losses (see Chapter 'Viscous drag of an EXSEAL'), and service lifetime(see Chapter 'Service lifetime of an EXSEAL') are performed to complete the design.

Rotating Seal Type EX-SEAL

Recently, the motor design has been changing from conventional outer rotor type to in-hub type in order to reduce spindle size and increase its storage capacity. A rotating EX-SEAL has been developed to meet such a demand.

That is to say, since the straight adaption of an EX-SEAL which is designed for service in an outer rotor type spindle motor to an in-hub type spindle motor would give rise to rotation of the seal itself, one may anticipate some difficulties. Therefore, the development of rotating EX-SEAL was done on a design concept that was very different from the traditional one.

In a rotating seal, the velocity distribution of the ferrofluid is reversed compared to that of rotating shaft type seals, namely, where the velocity of the fluid becomes zero at the pole piece inner diameter for a rotating shaft, it is at its maximum value at the same location for a rotating seal. Since the velocity of the fluid is increased going along with an inclination of velocity distribution, the ferrofluid in rotating seal which is given a rotating velocity, is effected by its maxmum centrifigual force.

On the other hand, size of fluid meniscus is on the increasing with an increasing amount of the fluid, and also,an increasing size of the meniscus lead to an increasing potaintial problem of fluid splash. Because, a ferrofluid in the seal is holded by lower magnetic field due to an incraesing size of fluid meniscus.

Furthermore, the gap eccentricity produces a magnetic field gradient within the gap, increasing the flux density where the gap is narrower. As the fluid tends to collect itself in a portion of the gap, a state of excessive ferrofluid exists at the narrow part of the gap leading to a large fluid maniscus and a splash. Thus rotating EX-SEALs are more sensitive to eccentricities compared with rotating shaft seals.

This means that the amount of ferrofluid to be added to the seal and the eccentricity in the seal gap are critical for a rotating (EX-SEAL) seal. Therefore, special attention is necessary with regards to:

1. the gap eccentricity, which should be held within specification after the EXSEAL has been installed on the spindle;

2. the ferrofluid is to be charged in the specified amount and in the way specified.

FERROFLUIDICS has already established optimum designs for the rotating (EXSEAL) seals. Also, a new type of extremely stable ferrofluids such as CSG 33 and CFF 100 for these types of applications have been developed. Furthermore, a 'thin seal', where the fluid maniscus is so low that no ferrofluid splash occurs resulting from small errors in eccentiricities and fluid quantity has also been developed.

SELECTION OF BEARING GREASE

The primary function of an EX-SEAL is to prevent the bearing grease mist from entering into the disk area. The EX-SEAL should be set at a certain distance away from the bearing to avoid any direct mixing of the ferrofluid and grease. The recent trend of miniaturizing spindle motors, however, calls for a closer distance between the EX-SEAL and bearing (and the anti-rust oil used on the bearing surfaces). Thus, the compatibility of ferrofluid with bearing grease becomes a matter of even greater importance.

We have examined this issue for CSG 26 and CSG 20A series ferrofluids with respect to popular brands of bearing greases for hard disk drive spindle motors. It has been ascertained that these ferrofluids are perfectly compatible with MARTEMPSRL, ISOFLEX DS18, ISOFLEX NBU15, BEACON 325, and WIDERANGE WR3. However, any combination of other ferrofluids with other brands of greases must be tested before the seal is used in the spindle.

It has been found in our compatibility studies that the saturation magnetizaton of the fluid may be lowered and its viscosity may be increased by some of these compatible greases if a large amount of grease is mixed with the ferrofluids. Since the reduction in saturation magnetization will lead to degradation of pressure capacity, the intrusion of bearing oil (and anti-rust oil etc.) into the ferrofluid should be minimized.

SELECTION OF SOLVENT

Such polar solvents as water, acetone, and alcohol can affect the quality of ferrofluid if present in excessive quantities. The solvents such as freon, toluene, and hexane of low polarization, on the other hand, can cause leakage of ferrofluid by mixing even though they do not react with the fluid chemically.

Therefore, sufficent care should be taken so as not to let either solvent come in contact with ferrofluid.(See 'EXCLUSION SEAL Handbook',Chapter 'Cares for Handling EXSEALs'.)

SELECTION OF ADHESIVE

Ultraviolet ray hardening epoxy resins and anaerobic adhesives are generally used to bond an EX-SEAL to the motor housing. Since they become perfectly inert to the ferrofluid when hardened completely, the ferrofluid should be added into the seal only after the adhesive has been fully cured. Because there are some adhesives, though very rare, that can degrade the fluid even after complete hardening, it is suggested that compatibility tests should be performed after selecting an adhesive.

EVAPORATION OF FERROMAGNETIC FLUID

Ferrofluid does not contaminate the disk area from its evaporation and will not lead to head crash.

The rate of evaporation of the base oil of a ferrofluid is of the order of 10-9 g/cm2 · s at the temperature of 80'C which amounts to vaporizing 0.0001 μgrm of material from each square centimeter area every second. It is simply inconceivable that material deposition of this level should present any influence on the disk.

Furthermore, only the base oil evaporates from the ferrofluid ; no magnetic particles can leave the fluid. Since the size of the evaporating material is about 40 A', which is very small compared with the flying height of the hard disk head(typically 400 A') this too cannot be taken seriously as a possible cause for head crashes.

APPLICATION OF ELEVATED TEMPERATURES TO FERROFLUIDS

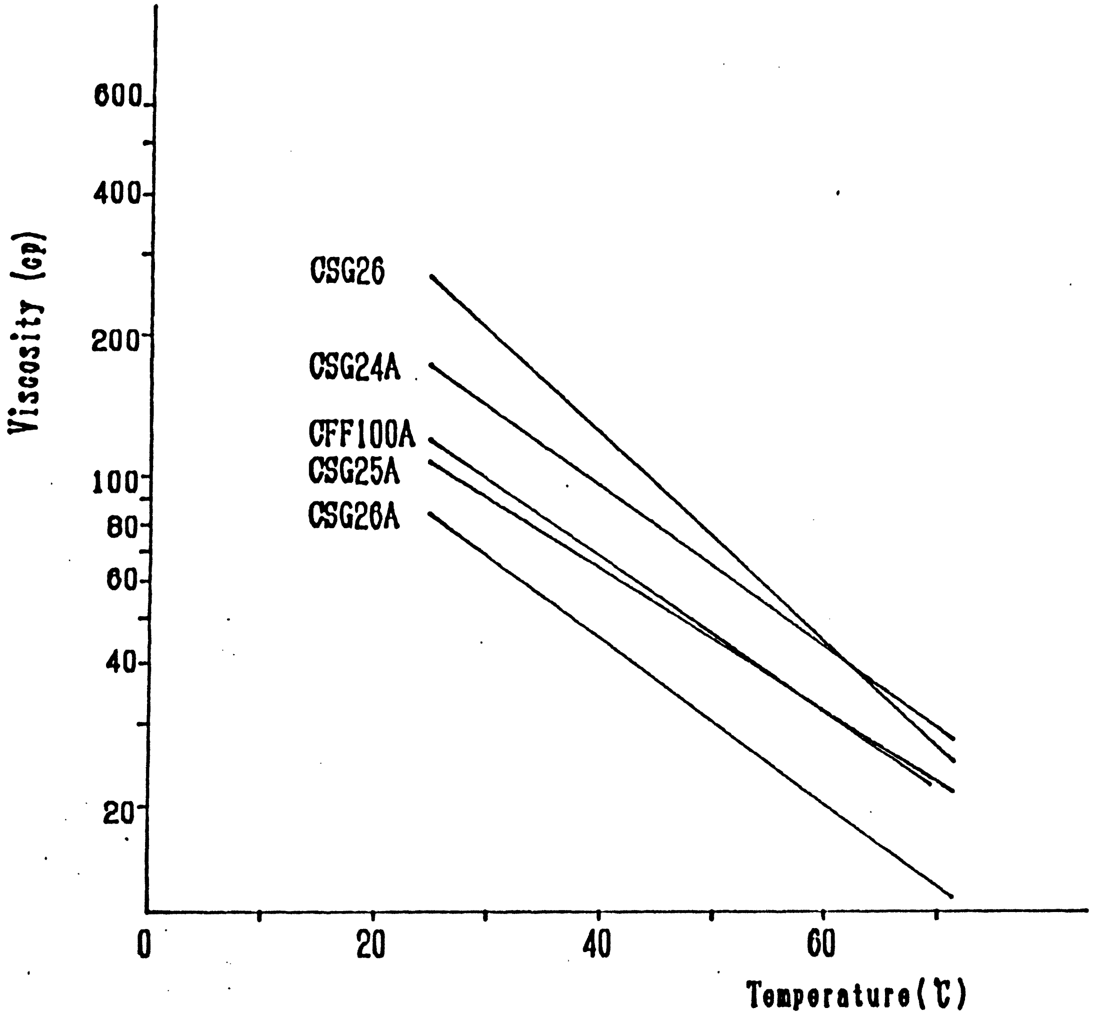
Exposing any oil based ferrofluid to elevated temperatures should be avoided as far as possible.

For all computer seal grade ferrofluids, in particular, application of elevated temperatures beyond the time periods specified below must not be carried out even for purposes of shrinkage fitting of hubs etc.

Temperature 'C	Allowed Time of Applicaton min
200	10
150	30
100	1,000

REVISIONS

LTR	ZONE	DESCRIPTION	DATE



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES UNLESS NOTED :
LESS THAN mm ±
OVER (INCLUDED) mm ±
ANGLES ±
RADII

FINISH :

MATERIAL :

mm
0 25
TRUE SCALE

PREPARED
CHECKED
ENGINEER
MFG
SCALE :
SHEET OF

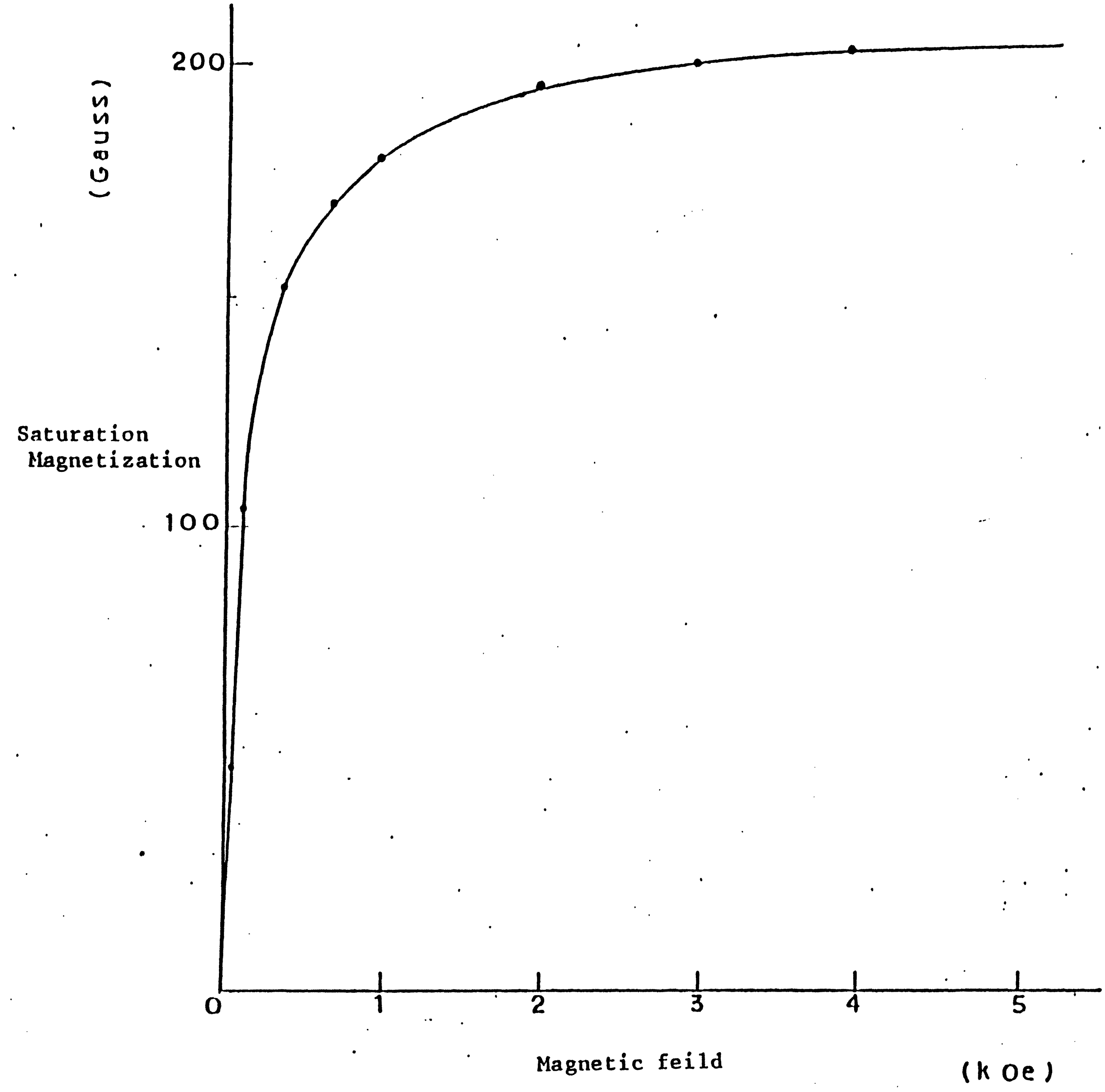
Ferrofluidics TOKYO JAPAN

Viscosity as a function of temperature for various ferrofluids

DRAWING NO. M00779

REV. Z

REVISIONS			
LTR	ZONE	DESCRIPTION	DATE



DWG. FERROFLUID CSG26 MAGNETIZATION CURVE

001	TRUE SCALE		**Ferrofluidics** TOKYO JAPAN
	PREPARED	秋 葉	'87-11-4
	CHECKED	向 後	'87-11-5
	ENGINEER		
	MFG		
	SCALE	NONE :	
	SHEET	1 OF 1	

SPECIFICATION

DRAWING NO.	REV.
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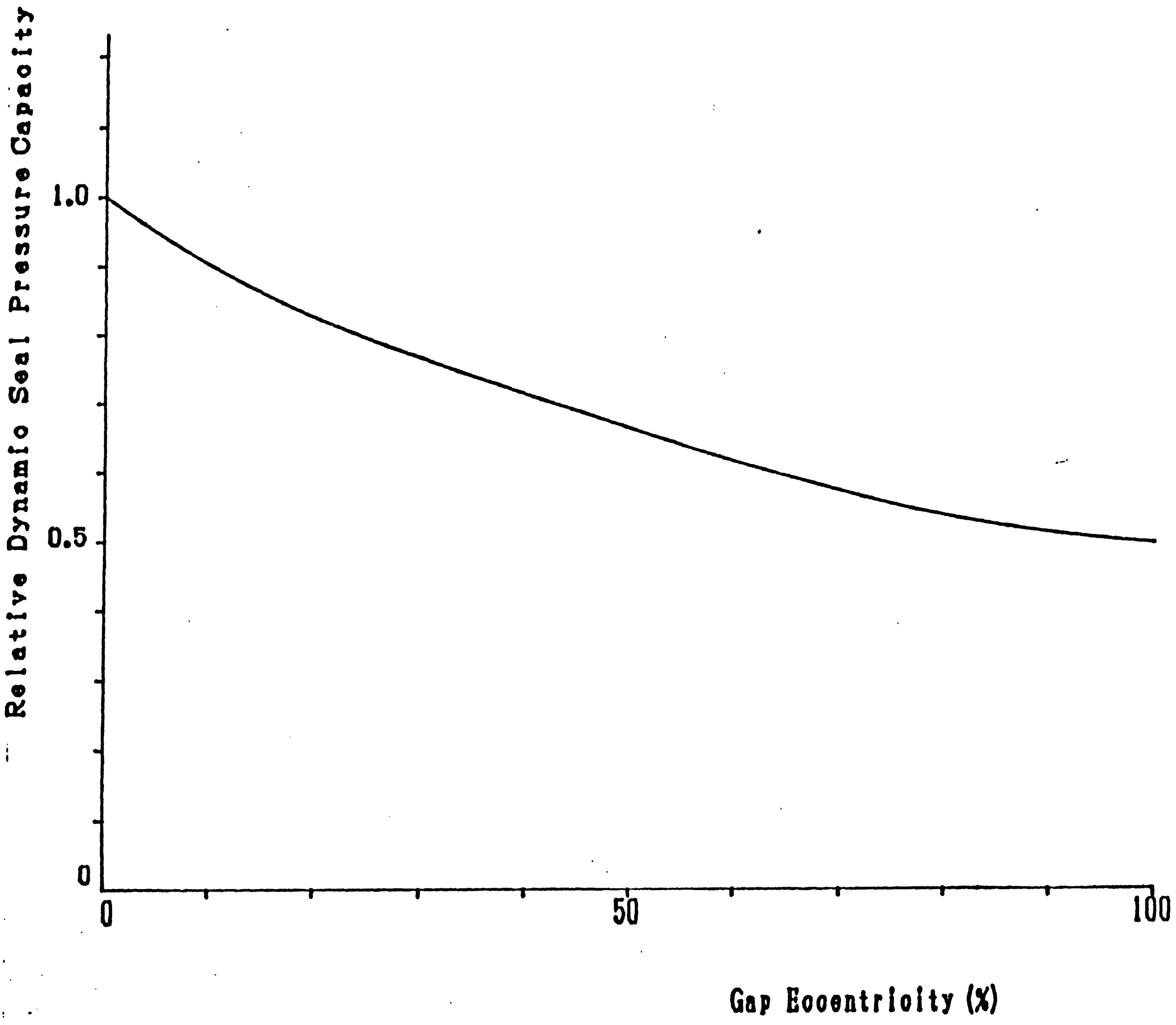
REVISIONS			
LTR	ZONE	DESCRIPTION	DATE



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS	mm 0 25 TRUE SCALE	**Ferrofluidics** TOKYO JAPAN	
TOLERANCES UNLESS NOTED : LESS THAN mm ± OVER (INCLUDED) mm ± ANGLES ± RADII	PREPARED CHECKED ENGINEER	Change in dynamic seal pressure capacity as a function of gap eccentricity	
FINISH :	MFG	DRAWING NO.	REV.
MATERIAL :	SCALE :	M00782	Z
	SHEET OF		

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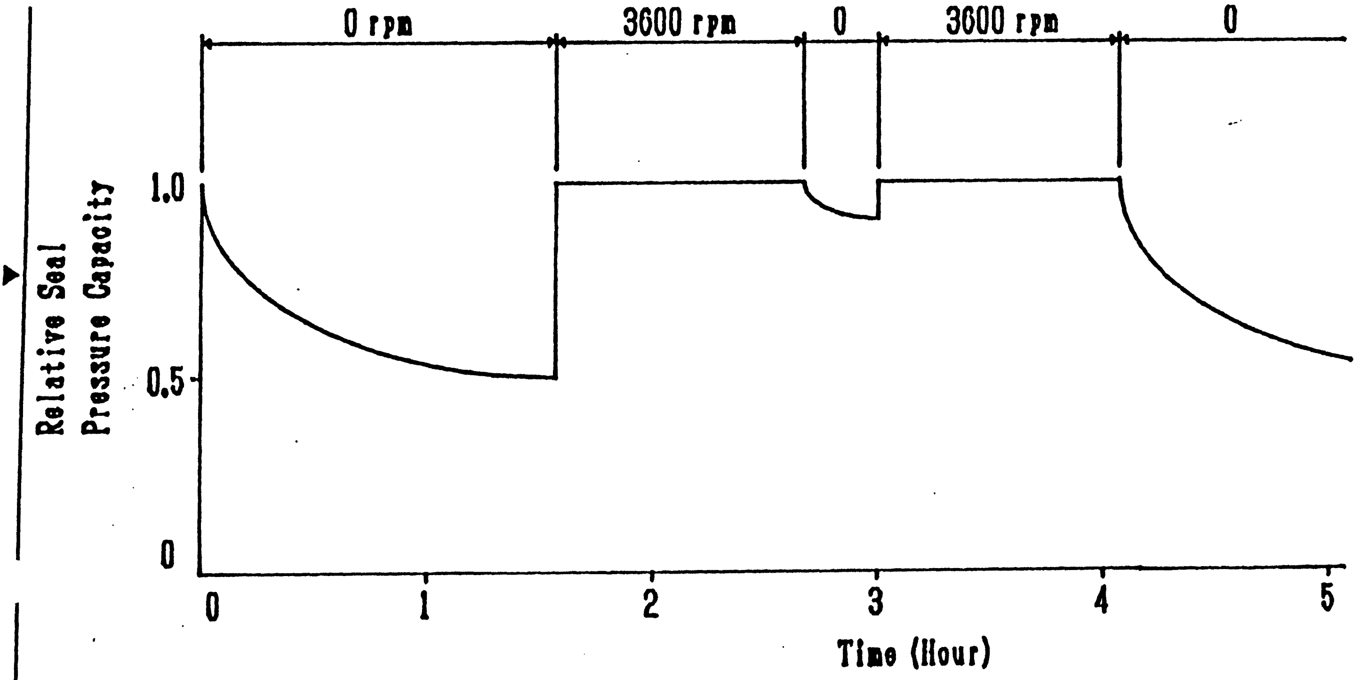
REVISIONS			
LTR	ZONE	DESCRIPTION	DATE



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES UNLESS NOTED :
LESS THAN mm ±
OVER (INCLUDED) mm ±
ANGLES ±
RADII

FINISH :

MATERIAL :

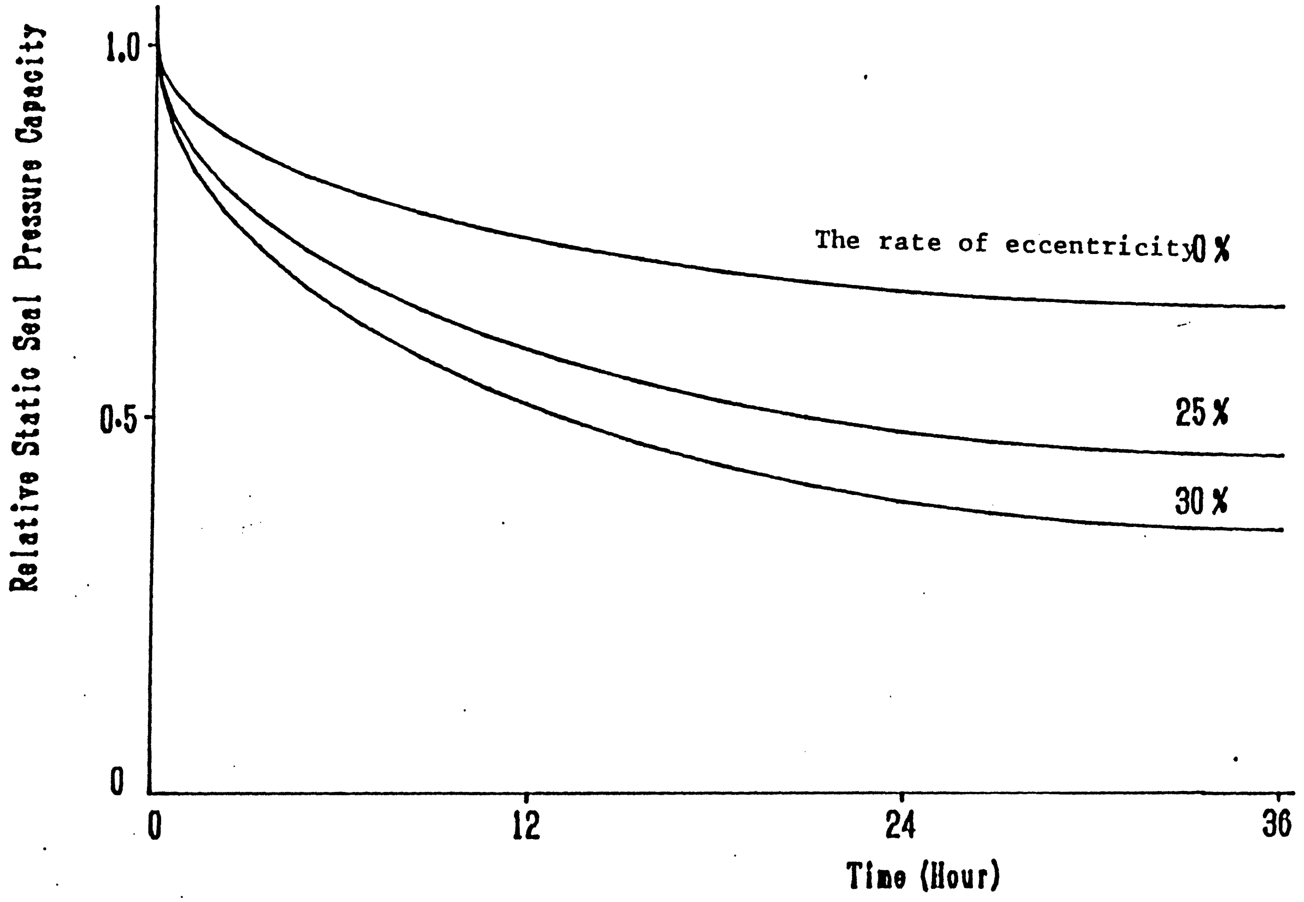
PREPARED
CHECKED
ENGINEER
MFG
SCALE :
SHEET OF

Ferrofluidics TOKYO JAPAN

An example of change in seal pressure capacity during start-and-stop operation of the spindle

DRAWING NO. M00784
REV. Z

REVISIONS			
LTR	ZONE	DESCRIPTION	DATE



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES UNLESS NOTED :
LESS THAN mm ±
OVER (INCLUDED) mm ±
ANGLES ±
RADII

FINISH :

MATERIAL :

PREPARED
CHECKED
ENGINEER
MFG
SCALE :
SHEET OF

Ferrofluidics TOKYO JAPAN

Decreasing static pressure capacity with time

DRAWING NO. M00792

REV. Z

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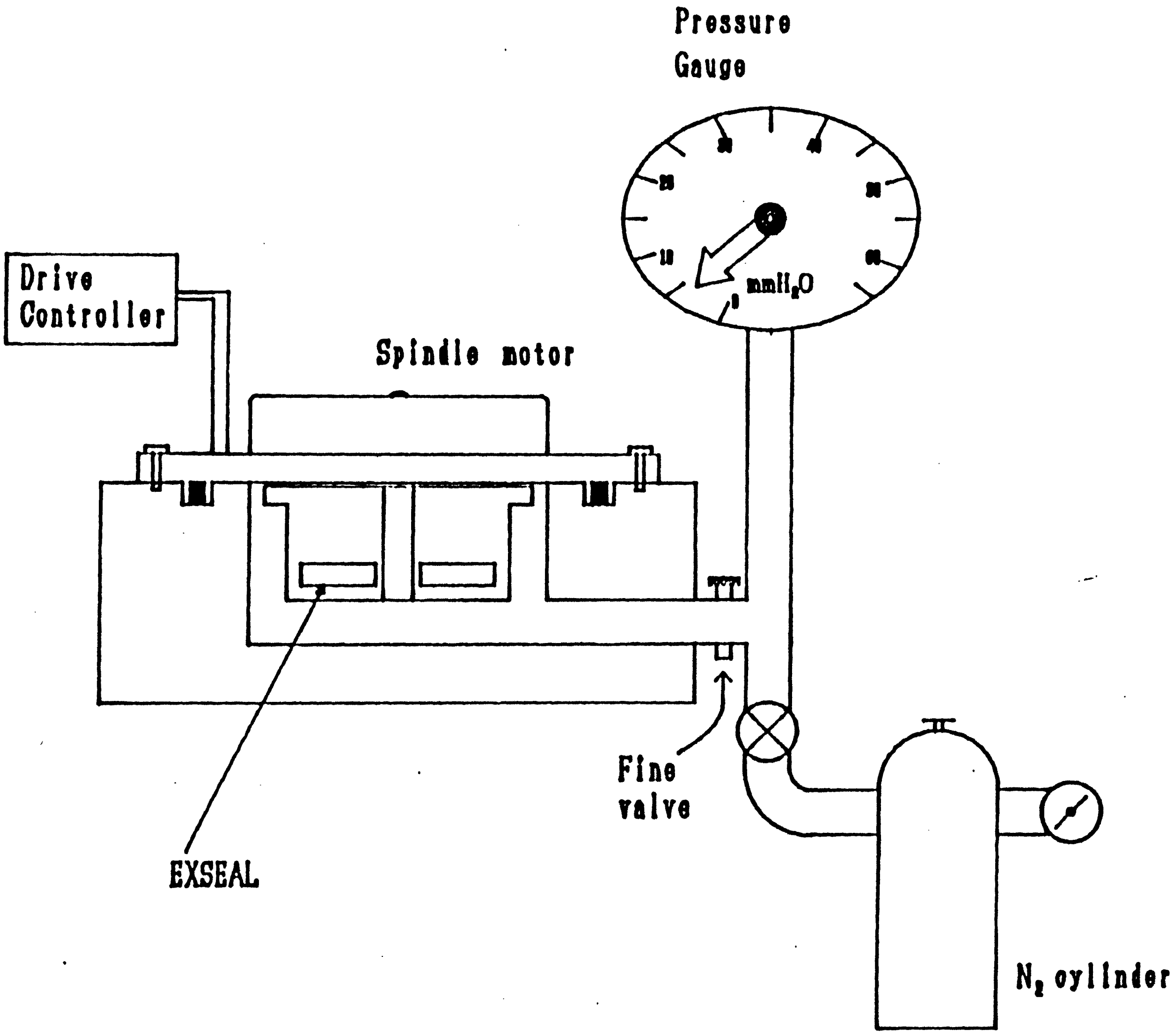
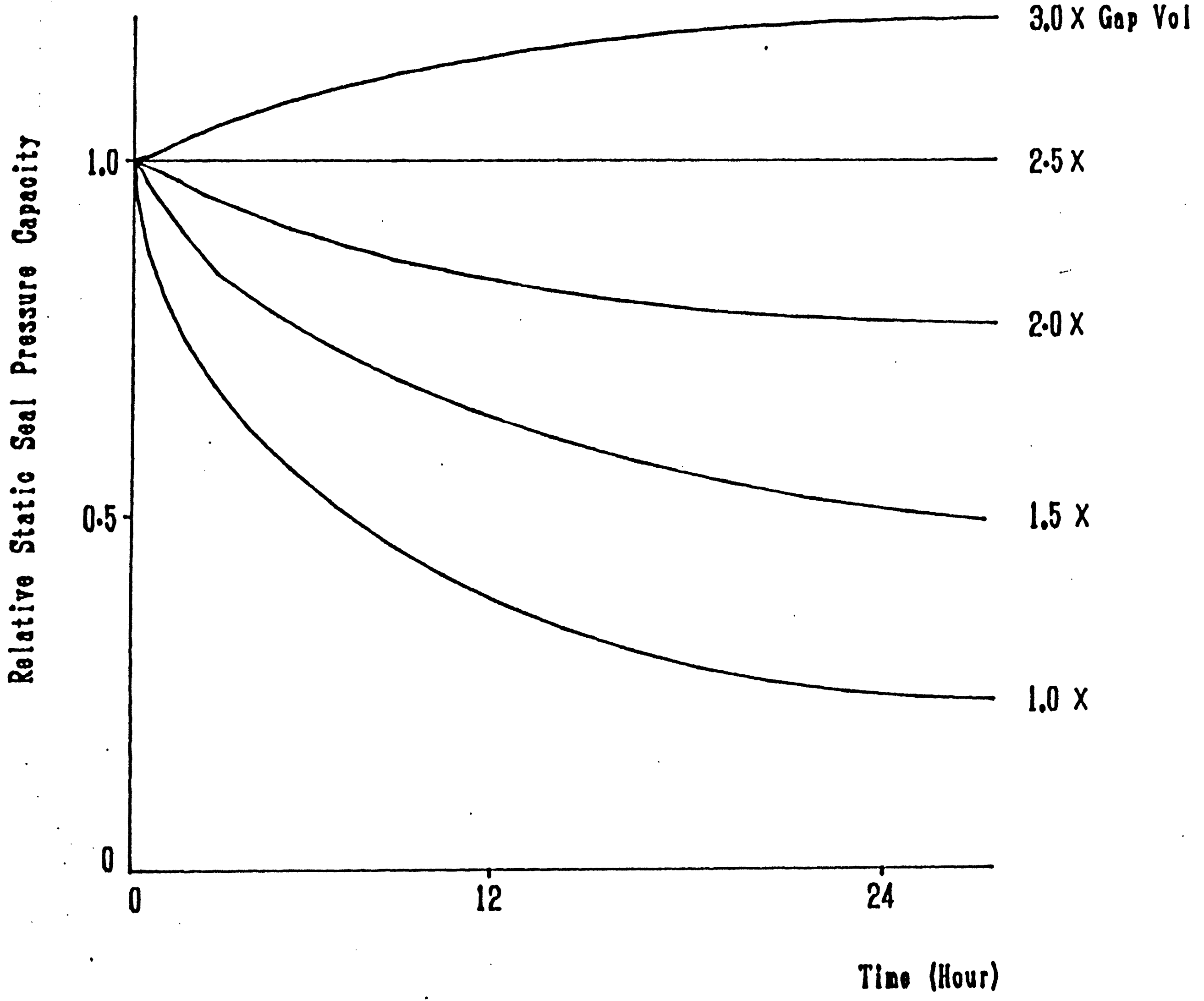


1. Rotate the moter・spindle system at its rated speed, and open the valve gradually to let the pressure rise at a rate of about 2 mmH_2O/s until the specified positive pressure has been applied to the seal ; then
2. Close the valve, and observe the gauge the pressure drop should be no more than 5 mmH_2O/s

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS	0 mm 25 TRUE SCALE	**Ferrofluidics** TOKYO JAPAN	
TOLERANCES UNLESS NOTED : LESS THAN mm ± OVER (INCLUDED) mm ± ANGLES ± RADII	PREPARED CHECKED ENGINEER	Experimental set up to measure seal integrity	
FINISH :	MFG	DRAWING NO.	REV.
MATERIAL :	SCALE : SHEET OF	M00785	Z

REVISIONS			
LTR	ZONE	DESCRIPTION	DATE



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS

TOLERANCES UNLESS NOTED :
LESS THAN mm ±
OVER (INCLUDED) mm ±
ANGLES ±
RADII

FINISH :

MATERIAL :

mm
0 25
TRUE SCALE

PREPARED		
CHECKED		
ENGINEER		
MFG		
SCALE	:	
SHEET	OF	

Ferrofluidics TOKYO JAPAN

Change in static seal pressure capacity with time for various fill quantities of ferrofluid

DRAWING NO. M00783 REV. Z

REVISIONS			
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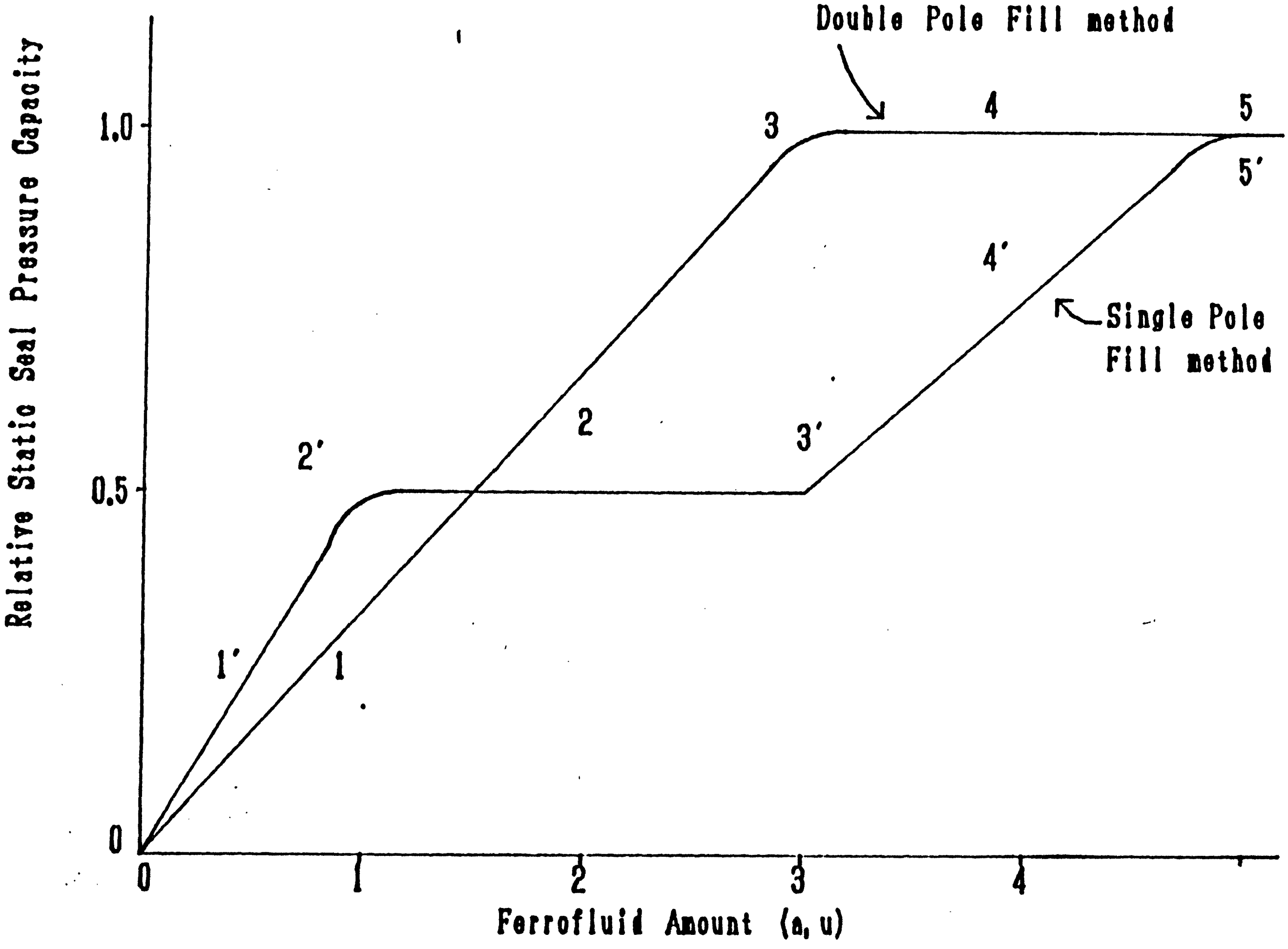
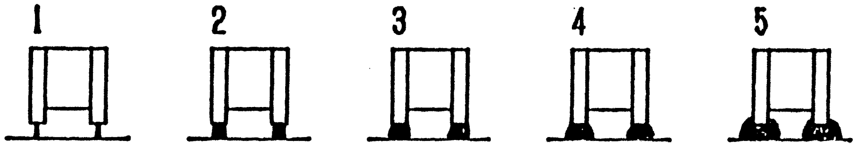
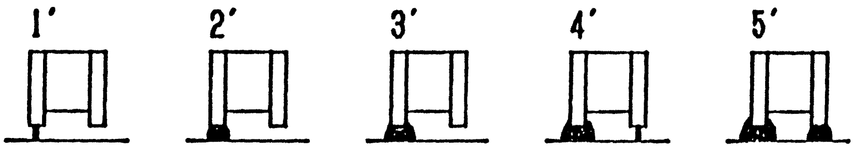


Double Pole Fill Method (S 2620)



Single Pole Fill Method (S 2610)



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS	TRUE SCALE	**Ferrofluidics**	TOKYO JAPAN
TOLERANCES UNLESS NOTED : LESS THAN mm ± OVER (INCLUDED) mm ± ANGLES ± RADII	PREPARED CHECKED ENGINEER	Static seal pressure capacity versus ferrofluid amount for two different fill methods	
FINISH :	MFG	DRAWING NO.	REV.
MATERIAL :	SCALE : SHEET OF	M 0 0 7 8 1	Z