

LUBRICANT DENSITY AND VISCOSITY
IN A ROLLING LINE CONTACT

by

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A thesis submitted for the degree of

DOCTOR OF PHILOSOPHY

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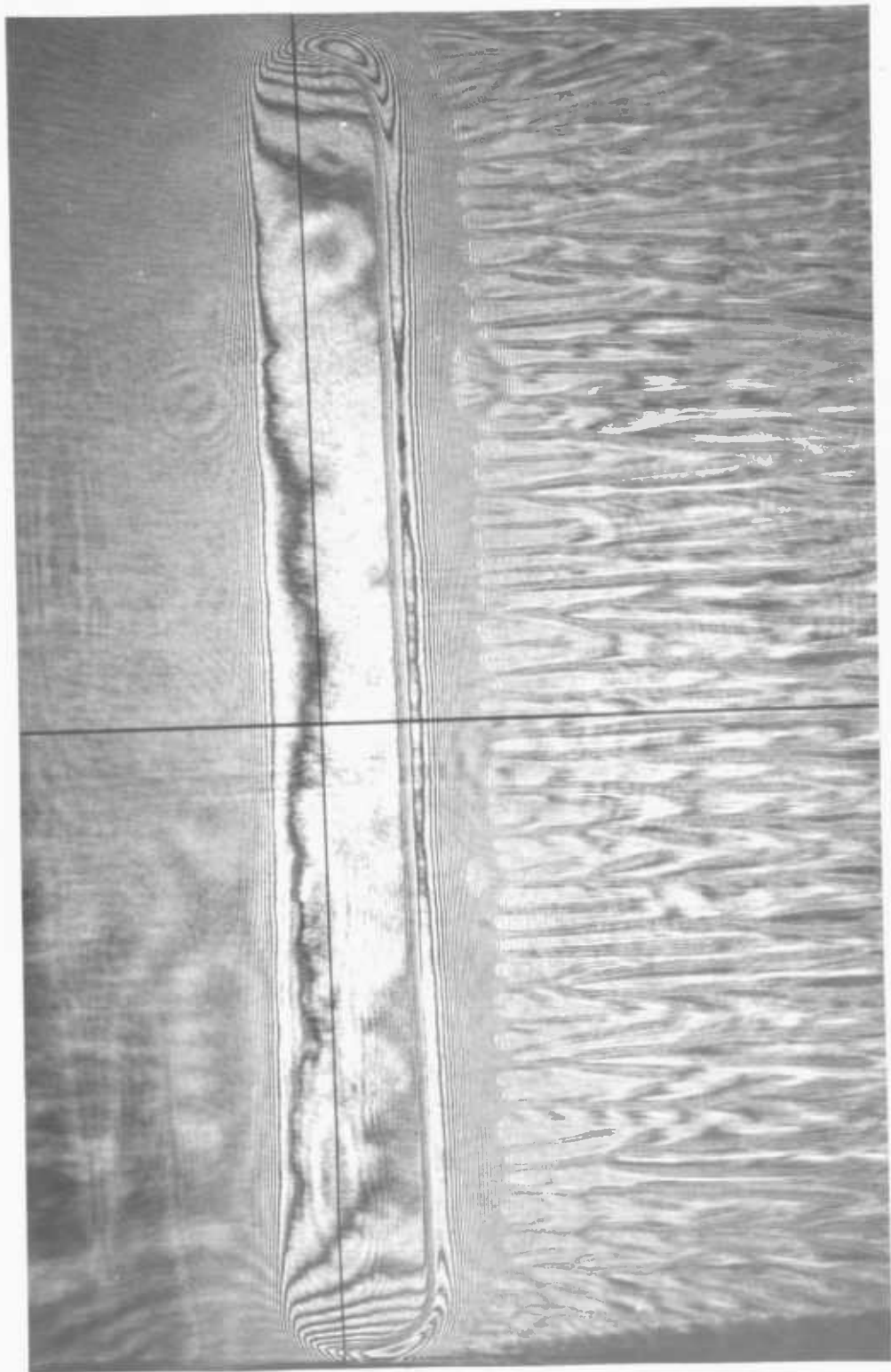
UNIVERSITY OF LONDON

and also for the

DIPLOMA OF IMPERIAL COLLEGE

1979

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Frontispiece

AN INTERFEROMETRIC PATTERN OF A ROLLING CONTACT
(Fluid 5P4E, Speed 0.325 m/S, Load 0.24 MN/m)

ABSTRACT

Measurements of the density and viscosity of oils in the inlet and high pressure zones of an elastohydrodynamic conjunction have been made. The work was carried out on a new line contact viscometer which uses a double interferometric system. The density and viscosity are found to be time dependent and correlate well with results from the impact viscometer. One oil shows that time related phenomena occur even in the region where there is evidence of solidification taking place. The low pressure viscosity follows the well known exponential pressure dependence and good agreement with other measurements is found. There is however a major disagreement at high pressures with data derived from traction tests. This is discussed but no firm conclusions are reached.

ACKNOWLEDGEMENTS

It is impossible to show fully my gratitude to all who have helped in this project. There are many who has assisted in technical matters to whom I am extremely grateful. I have also greatly appreciated the encouragement from friends and colleagues both in and outside the laboratory. I hope they will forgive me if I do not mention them specifically by name.

I would however like to thank my supervisor Professor Cameron for his help, and Dr. Graham Paul for many useful and stimulating discussions. I also want to thank Ron Potter and Peter Saunders of the drawing office for their assistance in the early stages of this work, George Tindall for considerable aid with the photography, and Jane Miles for her patient and painstaking typing of this thesis. I am especially grateful to Reg Dobson and Tony Wymark for the enormous amount of help they have given me.

I would like to express my gratitude to Monsanto Industrial Chemicals Company for supporting me financially and to the Science Research Council for a grant to pay for the equipment. I am grateful also to Neil Thorpe at the time of Ransome Hoffmann Pollard Limited for the hardening and grinding of the tapered rollers used in the experiments.

Finally I want to record my thanks and praise to God for the wonder of his creation, and for the privilege of studying a tiny aspect of it. As King Solomon said:

"It is the glory of God to conceal a matter;
to search out a matter is the glory of kings".
(Proverbs 25:2)

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NOMENCLATURE

a	contact width
d	separation between reflecting surfaces
E	Young's modulus (reduced)
G	shear modulus of oil
$H_{\min}$	minimum film thickness
h	oil film thickness
$\bar{h}$	oil film thickness at $dp/dx = 0$ in the centre of the contact
L	length of the roller
$*N_i$	fringe order
n_{air}	refractive index of air
n_{glass}	refractive index of glass
n_{oil}	refractive index of oil
p	pressure
R	radius of the roller
U	speed (half the sum of the speeds of the contacting surfaces)
W	load per unit length of the roller
x	distance in direction of rolling
α	pressure-viscosity coefficient
η	viscosity
η_o	viscosity at atmospheric pressure
$*\theta_i$	angle of incidence in air
λ	wavelength of light
ρ	density of the oil
$\bar{\rho}$	density at $dp/dx = 0$ in the centre of the contact
τ	shear stress
ϕ	phase change
$*\psi_i$	angles of incidence in oil

*Subscript i 1 - Normal angle
 2 - Oblique angle

CHAPTER 1
LITERATURE SURVEY

1.1 Historical

Newton suggested in 1687 "The resistance arising from the want of lubricity in the parts of a fluid, is, other things being equal, proportional to the velocity with which the parts of the fluid are separated from one another" (1).

In more familiar terms this implies that the stress is proportional to strain. When Newton proposed his hypothesis he was considering the flow of fluids round rotating heavenly spheres, although it has much wider application and has come to be known as Newton's law of viscosity. Any fluid which obeys the relation is said to be Newtonian. Unfortunately it has come to be seen that such behaviour is only a special case and that fluids often do not obey the law. Oils subjected to conditions of high pressures, and shear rates in a lubricated contact can show considerable deviation.

Much of the early work on the viscosity of fluids arose as a result of the consideration of the motion of pendulums. Stokes in a paper in 1850 (2) showed how the attention of the scientific world had been focussed upon the effect of viscosity on the period of pendulums by a paper due to Bessel (3) although about fifty years earlier in 1786 his work had been anticipated by Dubuat (4).

Hagen in 1839 (5) was perhaps the first person to consider the viscosity of liquids as applied to their flow through tubes. Poiseuille (6) followed with his work on the flow of water through capillaries. As a physician he was trying to understand the flow of blood in the body. Fortunately for him he used water rather than blood in his investigations; had he used blood he may never have arrived at the relationship between the flow rate and the dimensions of the capillary, since blood is a non-Newtonian liquid. It is after Stokes and Poiseuille that the two common units of viscosity, Stoke and Poise are named.

Maxwell in his Bakerian lecture 1866 (7) first defined the coefficient of viscosity. He stated it in terms of the force

per unit area f acting upon adjacent laminae of air in the gap between two infinite parallel plates. The plates are separated by a distance a and the velocity of one relative to the other is v , so that the velocity gradient is given by v/a . The viscosity is then given by $\eta = f \times (a/v)$. This definition although applied to air can be used for any fluid where there is laminar flow. It is usually given in the form

$$\eta = \tau / \frac{dU}{dz}$$

where τ = force per area or shear stress
 $\frac{dU}{dz}$ = velocity gradient in the direction perpendicular to the velocity flow or shear strain or shear rate

Following the work of Poiseuille and others, capillary viscometry became widespread and was really the only reliable method of measuring viscosity until 1890 when Couette developed his rotational viscometer (8). This consisted of concentric cylinders, the torque being measured on the inner cylinder while the outer one was rotated. By using guard rings on the ends of the inner cylinder Couette reduced the end effects which had been a problem in this type of viscometry for so long.

The first reported investigation of the effect of pressure on the viscosity of a substance is that of Barus (9) in 1892, who measured the flow of marine glue through a large bore capillary viscometer. He suggested a relationship of the form

$$\eta = \eta_0 (1 + ap)$$

A year later he produced some more results which he fitted to this expression and came to the conclusion that viscosity was linearly dependent upon pressure (10). He remarked on the fact that a relationship of the form

$$\log \eta = a + b p$$

where a and b are constants would give linear isoviscous lines of temperature versus pressure. Although his comments on this fact were only in passing the exponential law which is used today

$$\eta = \eta_o e^{\alpha p}$$

has been attributed to his name.

Probably the first person to consider the effect of pressure on lubricating oils was Hersey in America in 1916 (11) using a rolling ball type of viscometer. In England pressure viscosity measurements were begun a year or two later at the National Physical Laboratory. Hyde first published these results in 1919 (12). He had used a capillary viscometer up to 12.60 kg/cm^2 (12 MN/m^2). Their papers show clearly the dramatic increase of viscosity with pressure even at comparatively low pressures. Bridgeman developed a falling weight viscometer which could reach pressures up to $12,000 \text{ kg/cm}^2$ (1.2 GN/m^2) and later 2.7 GN/m^2 (13). Much work has since been done using his type of viscometer, the most extensive study being that carried out at Harvard in 1953 (14).

1.2 Present Day Developments

Various workers have extended capillary viscometry to much higher pressures. Novak and Winer (15) developed a capillary viscometer capable of measuring at pressures up to 550 MN/m^2 . The main advantage of this type of viscometry over the falling weight method is that high rates of shear can be attained. Jones, Johnson, Winer and Sanborn (16) have shown that rate of shear has a significant effect on the viscosity of the fluid.

Another method that gives high shear rates but is limited to low viscosities ($<1 \text{Ns/m}^2$) is that employed by Philippoff (17). Based on a design of Mason (18) he measured up to pressures of 100 MN/m^2 using ultrasonics.

The viscosity of the liquid is determined from the effect the liquid has upon the response of a torsionally oscillating crystal. Kittel in a comment at the end of Mason's paper noted the importance of this technique for giving "a direct and clear

cut method for determining the relaxation time of the shear elasticity in viscous liquids". Barlow and Lamb and others (19-22) also using ultrasonics have shown that it is important to consider the elasticity as well as viscosity of liquids. In an elastohydro-dynamically lubricated (ehl) contact, if the relaxation time of the fluid is long compared to the transit time through the high pressure zone the fluid will behave elastically rather than in a viscous manner. Johnson and Roberts (23) in a beautifully devised experiment have shown that this does indeed occur. More will be said about this later. Hutton and Phillips (24) developed a Couette viscometer capable of measuring at high pressures and viscosities.

The disadvantages of the viscometer measurements mentioned so far is that they do not necessarily relate directly to an ehl contact. In a contact where the pressure is applied very rapidly the behaviour may be far from the equilibrium response obtained when the pressure is applied gradually. A method of evaluating the viscosity in rolling point contacts was employed by Foord, Hammann and Cameron (25) and Westlake and Cameron (26). They used optical interferometry to measure film thickness values. By comparison with a calibration oil they were able to calculate the pressure viscosity coefficients using a relationship derived from an empirical centre line film thickness formula similar to the Dowson Higginson equation (27). The values of viscosity predicted from their work correlates well with values determined under 'equilibrium' conditions. At this stage it is enlightening to trace the evolution of the Dowson Higginson formula for minimum film thickness.

1.3 Film Thickness Formula

In 1916 Martin (28) in attempting to show how a fluid film separating gear teeth could account for the absence of wear solved Reynolds' equation for a rigid cylinder on a plane. He assumed the lubricant viscosity was constant and obtained film thickness values much less than the machining marks on the gear teeth. Peppler in 1936 (29) and 1938 (30) incorporated the elastic distortion of the boundary surfaces into the equation which had a beneficial effect but still led to values which

were far too small. Gatcombe in 1945 (31) followed by many other workers incorporated pressure-viscosity dependency, but still using rigid cylinders. Again the results were disappointing.

In 1949 the work of Ertel was published "posthumously" (32) by Grubin (33) incorporating both elastic distortion and pressure-viscosity effects. Although the solutions did not completely satisfy the elastic and flow conditions, the work was a major step forwards in that film thicknesses orders of magnitude greater than the Martin solution were obtained. It was not until 1959 that Dowson and Higginson (34) obtained a full numerical solution, although several workers had attempted the problem. In 1961 they published their New roller-bearing lubrication formula, (35), which Dowson (27) modified later to correct the dimensional errors. He presented the formula in terms of four dimensionless parameters. The formula is given by

$$\left(\frac{H_{\min}}{R}\right) = 2.56 \times \left(\frac{U\eta_0}{E R}\right)^{0.7} \times \left(\frac{W}{LE R}\right)^{-0.13} \times \left(\alpha E\right)^{0.54}$$

A fuller description of the work leading up to this formula can be found in Dowson and Higginson's book (36).

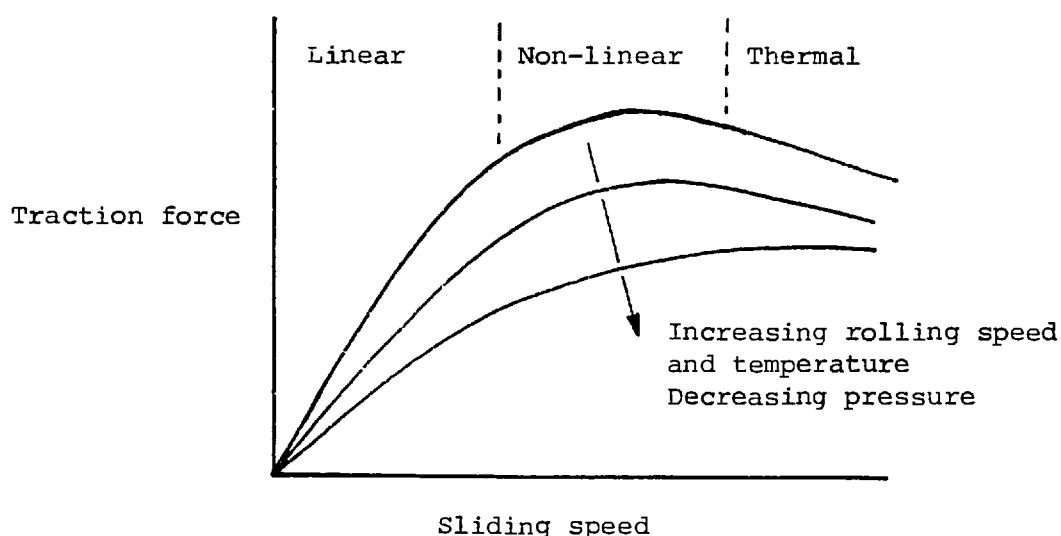
The formula is derived assuming a Newtonian viscosity with a pressure dependence given by the exponential law of Barus. Reasonable agreement with experimental film thickness values has been found (37, 38, 39). It is now realised that this agreement is due to the fact that the film thickness in a contact is determined by the fluid properties in the inlet region where the pressure is low and the viscosity generally Newtonian. It is for this reason also that the viscosity determined by the optical interferometric film thickness method (25, 26) are in reasonable agreement with equilibrium values measured by methods such as capillary viscometry.

1.4 Traction

In the previous section it has been seen that it is sufficient to know the ambient viscosity alone to calculate

film thickness values on the basis that the behaviour is Newtonian and follows the Barus law. In traction however this assumption about the behaviour is found to be far from satisfactory. The important area of the contact is now the high pressure central region where the viscosity is high. A typical family of traction force versus sliding speed curves are shown in fig 1.1.

Fig 1.1 TYPICAL TRACTION CURVES



There are essentially three regions, the linear, non-linear and thermal region. The traction rises linearly with sliding speed, but then begins to rise less steeply until a limiting traction is reached. At high sliding rates the traction force falls as heating effects become important.

Crook (40) discovered that the apparent viscosity derived from the traction data, decreased with increasing rolling speed. Extrapolating back to zero rolling speed however he obtained

values of viscosity in agreement with 'equilibrium' data. Previously Smith (41, 42) using a point contact in contrast to Crook's line contact had measured traction values which were also orders of magnitude lower than those predicted from the equilibrium data. Later Johnson and Cameron (43) showed that not only did the viscosity drop with rolling speed but that it tended towards a limiting value at pressures higher than those achieved by Crook (i.e. above $\cdot 7\text{GPa}$).

Much traction data has become available through the work of Plint (44), Poon and Haines (45) and Gentle (46) in a rolling point contact, Adams and Hirst (47), Bell, Kannel and Allen (48), Jefferis and Johnson (49) and Dowson and Whomes (50) in a rolling line contact, and Allen, Townsend and Zaretsky (51) in a spinning elliptical contact. In all this work it is apparent that a simple Newtonian viscosity even including shear heating effects such as the model proposed by Crook (52) does not account for the facts, particularly at high pressures. This has led to a host of new theories being put forward which essentially invoke four properties of the fluid, viscosity, critical shear stress, elasticity and the rate of response of the fluid to a change in pressure. A further consideration is that the fluid may be undergoing some sort of phase transition under pressure. Broad categories of these theories will be discussed.

The viscosity of a fluid can be sufficient to characterise the flow properties of a fluid provided the rate of shear is low. Unfortunately in a lubricated contact, the shear rates are very high especially in the inlet and when sliding is present. At these high shear rates two important effects may become apparent. The fluid can behave more like an elastic solid, or if the shear stresses are too great it can show characteristic plastic flow exhibiting a limiting shear strength.

1.4.1 Viscoelastic Theories

Crook (40) made the suggestion that viscoelasticity could explain his unexpected traction results. The presence of viscoelasticity was demonstrated by the experiments of Johnson and Roberts (23) which have already been mentioned. They showed

that the fluid makes a transition from a viscous response to elastic response, the transition point being characterised by the Deborah number ($\eta U/Ga$). The physical significance of this number can be understood if it is seen that η/G represents a viscoelastic relaxation time of the fluid, and a/U the transit time through the contact. Therefore at transit times shorter than the relaxation time the fluid will behave elastically rather than viscously.

Duckworth (53) has carried out similar experiments using optical interferometry to determine the film thickness, and has found good agreement with Johnson's results. Unfortunately the shear modulus of their experiments, even after correction for disc compliance is rather low in comparison to the oscillating measurements of Barlow and co-workers (22) and Hutton and Phillips (54). Johnson, Nyak and Moore suggest this may be due to a delay in the response of the fluid to pressure (55).

Dyson in a couple of papers attempted to develop the viscoelastic ideas of Crook. In the first paper (56) he used an Oldroyd model (57) to explain the results of Crook (40) and Smith (43), but found he was unable to predict satisfactorily the fall of viscosity with rolling speed at low sliding speeds. In his second paper (58) he used the model proposed by Barlow, Lamb et al (20, 21) to examine the results of Smith (41), Plint (44) and Johnson and Cameron (43). He achieved some measure of success but there were still some unexplained results, especially the non-linear region of the traction curve.

1.4.2 Limiting Shear Stress Theories

Smith (41) as a result of being unable to obtain a good agreement between his thermal Newtonian model and his results proposed the concept of the fluid shearing in a manner analogous to a plastic solid. Up to a certain stress the liquid behaves in a Newtonian manner, above which it deforms plastically. Plint (44) took up this idea by plotting his results as traction force against logarithm of sliding velocity. This showed up as a sharp discontinuity in the behaviour.

Johnson and Cameron (43) demonstrated that their results can be interpreted in the light of this hypothesis, the critical

level of shear stress probably depending only on pressure and temperature. They argue though that there is no sharp discontinuity in the fluid behaviour as Flint had done.

Hirst and Moore (59) have also utilised a limiting shear concept, though not exactly plastic, to explain their traction results. They argue that the departure from the linear portion of the traction curve is caused by the critical shear stress being exceeded and present a theory based on the Eyring molecular model (60) in terms of an energy barrier. They show an agreement of the molecular sizes of four liquids with the critical shear stresses. They also argue as did Adams and Hirst (47) that the dependence of traction on rolling speed is due to the lowering of the maximum pressure with rolling speed thus lowering the maximum critical shear stress. The basis for their arguments on this point is the pressure transducer measurements of Hamilton and Moore (61). This work was confined to low pressures, and care needs to be taken in extending the arguments to higher pressures.

Johnson and Trevaarwerk (62) have taken up the Eyring fluid concept to develop a non-linear viscoelastic model. At small strain levels the model approximates to a linear response, i.e. a Maxwell fluid displaying elastic and viscous behaviour, but at high strain levels the limit of linearity is exceeded and the behaviour is more characteristic of a plastic solid. This model is found to fit the experimental results reasonably well. As Johnson concluded in a recent review of lubricant rheology, there is not a great deal of difference between the concept of a plastic flow and non-linear viscoelastic flow (63).

1.4.3 Evidence for Solid Like Behaviour

Some evidence which supports the view that a lubricant will behave as a solid in an ehl contact has been reported by Jacobsen (64). He measured that at a time mean pressure of 1.2 GPa, a mineral oil solidified in 9 μ S. This is a considerably shorter time than typical transit times through a conjunction. Alsaad, Bair, Sanborn and Winer (65) have performed measurements on fluids in pressurisation and cooling procedures which reveal the point at which the fluids become solid like. They call this

the glass transition point because past the transition the lubricant properties are characteristic of an amorphous solid, and estimate that such behaviour will be observed in many high pressure contacts. Bair and Winer (66) have measured the shear strengths of lubricants under these conditions and find that the traction coefficients they predict compare favourably with the traction data of Johnson and Trevaarwerk (62), within the limitations of their model. Unfortunately their method does not reach pressurization rates anywhere approaching those of an ehl contact, although they do show that at higher rates the transitions occur at higher pressures. Paul and Cameron (67) using the impact microviscometer have also been able to measure the shear strength of fluids and find good correlation with values derived from traction.

1.4.4 Time Dependent Viscosity Theories

These theories invoke the idea that in a contact, the lubricant does not have time to respond to the changing pressure and therefore its properties are far from the equilibrium values. Such theories sometimes go under the very confusing name of compressional viscoelasticity.

Fein (68) was the first to suggest such a model to account for the decrease of apparent viscosity with rolling speed as determined from traction experiments. The faster the rolling speed the less time the fluid would have to respond resulting in a lower viscosity. Paul and Cameron (69) have produced evidence from the impact microviscometer for such theories. By determining the viscosity of oil in a normal approach entrapment, at different times after impact, they showed strong time dependence of the behaviour.

Harrison and Trachman (71), Trachman and Cheng (72) and Trachman (73) have developed a mathematical model along these lines. They used the Doolittle expression for the response of viscosity on free volume (74) as proposed by Kovacs (75). The model assumes that there is an instantaneous response to the pressure attributed to elastic compression of the liquid followed by a time dependent response in which molecular orientation is

taking place. Heyes and Montrose (76) have also proposed a similar sort of model utilising the concept of free volume.

Whilst this sort of model seems intuitively correct the evidence from Johnson and Roberts paper (23) is that in most ehl contacts above pressures of 0.7GPa the lubricant in the centre is likely to be behaving in an elastic or plastic manner and not viscously. A further disturbing feature in the evidence for the time dependence hypothesis is that the viscosities measured by Paul (70) at his shortest times fall an order of magnitude below that which is predicted by traction experiments. His shortest times (20ms) are longer than transit times in a contact. The question still remains to be answered, as to how the fluid properties such as the density and viscosity respond to very rapid changes in the pressure.

1.4.5 Granular Theory

Gentle (46) noticed the similarity of ehl traction results with powder bed experiments such as published by Golder (77). The important parameter was the packing density of the powder. This led Gentle to propose a model on a qualitative basis in which the fluid behaves like an array of granules, a granule being an agglomeration of molecules. Whilst there is little evidence to support this theory it has interesting concepts and in some ways is not too dissimilar to solidification ideas. The main test of this hypothesis is that under shearing the structure will become more loosely packed i.e. lower density. Paul, Gentle and Cameron (78) in a series of experiments in which they were able to vary the shear strain by including rotation of the ball in the impact microviscometer, have shown a possible trend in the density in that direction. This is however very speculative given the error margins that there are in the data.

Whilst this is by no means a comprehensive survey of all the models that have been proposed it gives broad outlines of the ideas that have been used to explain traction results.

1.5 Conclusion

Initial realisation of the fact that fluid flow can be characterised by its viscosity was followed by much work in measuring this property. It was discovered that the viscosity of liquids is dependent on pressure and follows an exponential pressure law. In the development of the elastohydrodynamic film thickness formula the viscosity determined from equilibrium measurements was found to be sufficiently accurate to give good correlation with experimental results. This is because the film thickness is determined by conditions in the inlet region. In traction the viscosity alone is no longer sufficient even if heating effects are taken into account. Definite evidence of the fluid behaving like a solid has been discovered in which it exhibits both elasticity and plasticity as well as viscous flow. There is also speculation as to the importance and magnitude of time-dependent processes taking place. Measurements on the solidification properties of fluids under pressure would suggest that almost certainly the lubricant in the contact is transformed to an amorphous solid state similar to a glass, although no measurements in a dynamic test have shown this definitely to be the case.

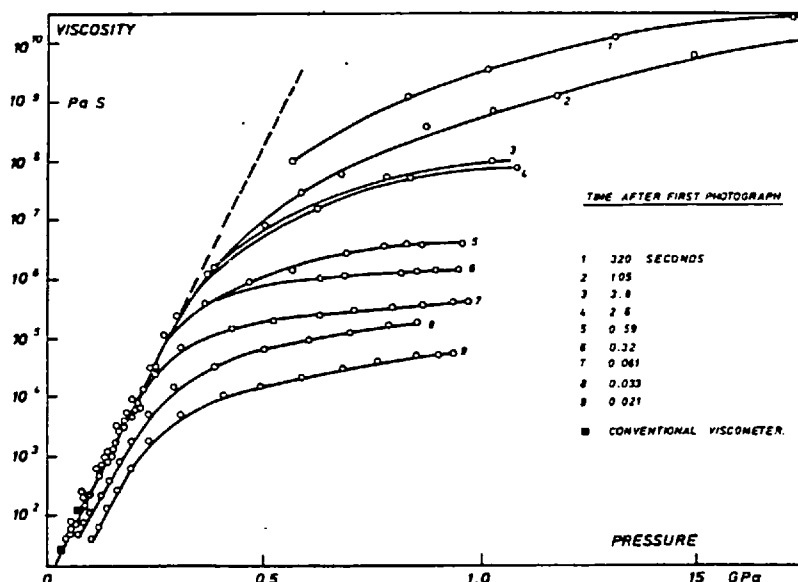
CHAPTER 2

CONCEPT AND THEORY OF THE EXPERIMENTS

2.1 The Impact Viscometer Results

The work of Paul (70) on the impact microviscometer has provided some very convincing evidence of time dependent behaviour of fluids following a pressure step. Using optical interferometry he measured the rate at which fluid leaked from an entrapment formed by the normal approach of a ball on a plate. This enabled him to calculate the viscosity of the fluid from Reynolds' equation, for various times after the initial impact. Some of his results are shown in figure 2.1.

fig 2.1 VISCOSITY VERSUS PRESSURE
Impact Viscometer BP 1065



As can be seen from the graph the viscosity is considerably below that predicted from measurements in which the pressure is applied more gradually. The times marked on the lines correspond to the period between the initial pressure step when the ball was dropped and the instant of measurement. At each sampling time the viscosity tends towards a limiting value at high pressure but the limiting value rises with increasing time. This suggests that the fluid does not have time to respond to the pressure, leading

to a lower viscosity. An understanding of this type of time dependent behaviour is of great importance in traction since the transmitted force is dependent upon the viscosity. Even if the fluid behaves in an elastic or plastic manner in the contact, this can only occur when the viscosity reaches a sufficiently high value.

Unfortunately the impact viscometer as constructed at present is limited to sampling times greater than 20 milli-seconds after the pressure pulse. This is one to three orders of magnitude greater than the time a fluid has to respond in a typical ehl contact. A further feature of Paul's results which is unexplained is that the traction predicted from the values measured at the shortest times are an order of magnitude smaller than that measured in traction experiments. A tentative explanation can be made for this in terms of adiabatic compressional heating, but is not very satisfactory since the entrainments are so thin that isothermal conditions can be expected.

2.2 The Aim of the Project

The aim of this project has been to endeavour to obtain information about the viscosity of fluids at times corresponding to transit times through an ehl contact. In a typical rolling contact the pressurisation rate is extremely high ($\sim 10^{12} \text{ Pa s}^{-1}$) and the temperature rise small because the film thickness is thin enough for any heat generated by compression to be rapidly conducted away.

Work has been done using high pressurisation rates in anvil cells but here adiabatic heating does become a significant factor because of the relatively large bulk of fluid involved. For this reason an ehl line contact has been utilised to compress the fluid although this has its own attendant problems. Reynolds' equation is used to calculate the viscosity in a manner similar to Paul's work. The major difficulty, and towards which most of the effort of these experiments has been directed, is to be able to obtain precise enough basic data.

Ranger (79) attempted to calculate viscosity from Reynolds' equation using the interferometric film thickness data supplied

by Wymer (80). To do this he had to assume that the density could be calculated from bulk moduli measured under equilibrium conditions at various pressures. The refractive indices, needed to obtain absolute film thicknesses, were also based on these equilibrium measurements. A further difficulty he encountered was that Wymer's data could not be resolved to much better than half an optical fringe order. Thus in the high load low speed experiments he was unable to define accurately the film thickness profile in the central region of the conjunction where it was close to being parallel. In fact he obtained negative viscosities using such data, but could, by changing the profile within the experimental error limits, get positive results. Only in the high speed case did he obtain reasonable values although they were unexpectedly low.

The initial goal therefore of this project was that the film thickness and density profiles could be defined accurately enough, particularly in the central flat region. Errors in these two values lead to the greatest inaccuracy in the viscosity in that region. Because knowing the density is a necessary step in the calculations it has provided a further parameter for investigating the time dependent behaviour of the fluids.

The general concept of the experiments is shown in figure 2.2. Using laser light, and a highly polished roller loaded against a glass disc, very precise interferograms of the contact zone were obtained. Interpolation between fringes was carried out using micro-photodensitometry. In order to be able to determine the refractive index and hence the absolute film thickness, the double interferogram method of Paul was employed. The density was derived from the refractive index using the Lorentz-Lorenz relationship. The pressure was calculated using an inverse elasticity solution, a computer program for this having been developed by Ranger (79). Finally the viscosity was calculated using the two dimensional form of Reynolds' equation.

2.3 Theory

The theory behind the experiments is given in this section.

FIG 2.2

EXPERIMENTAL CONCEPT

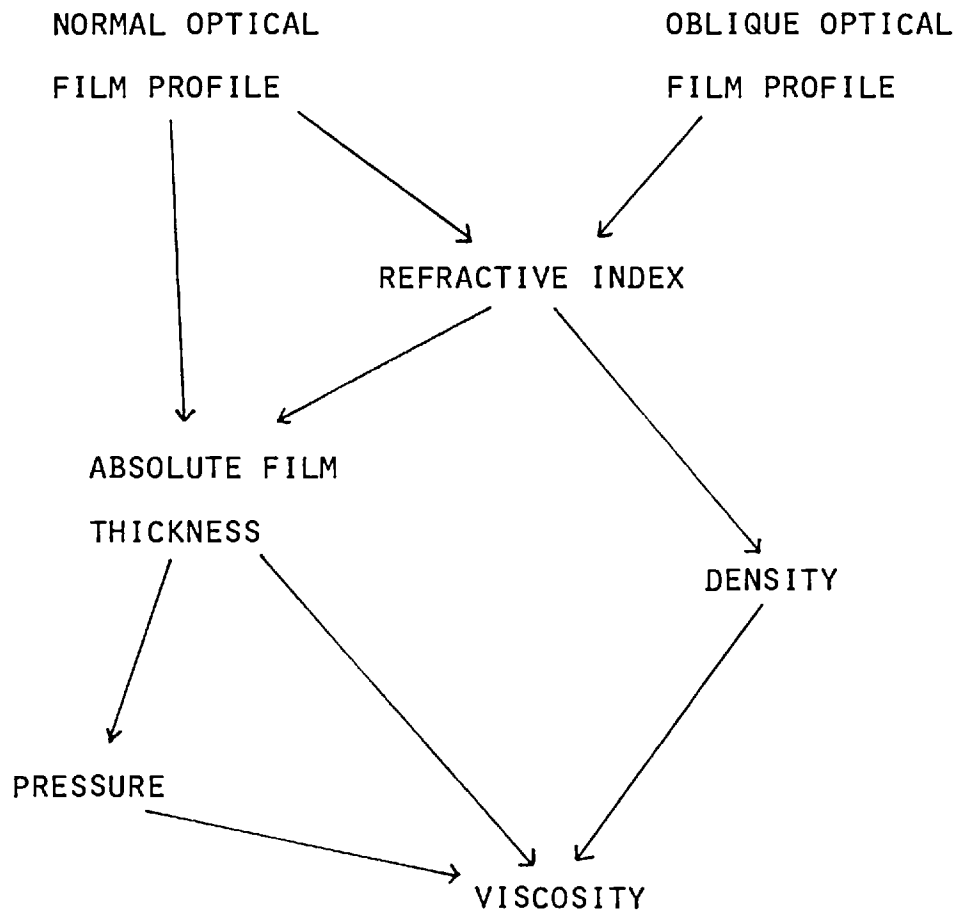
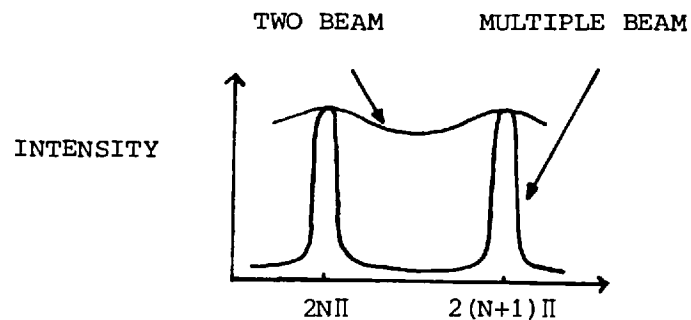
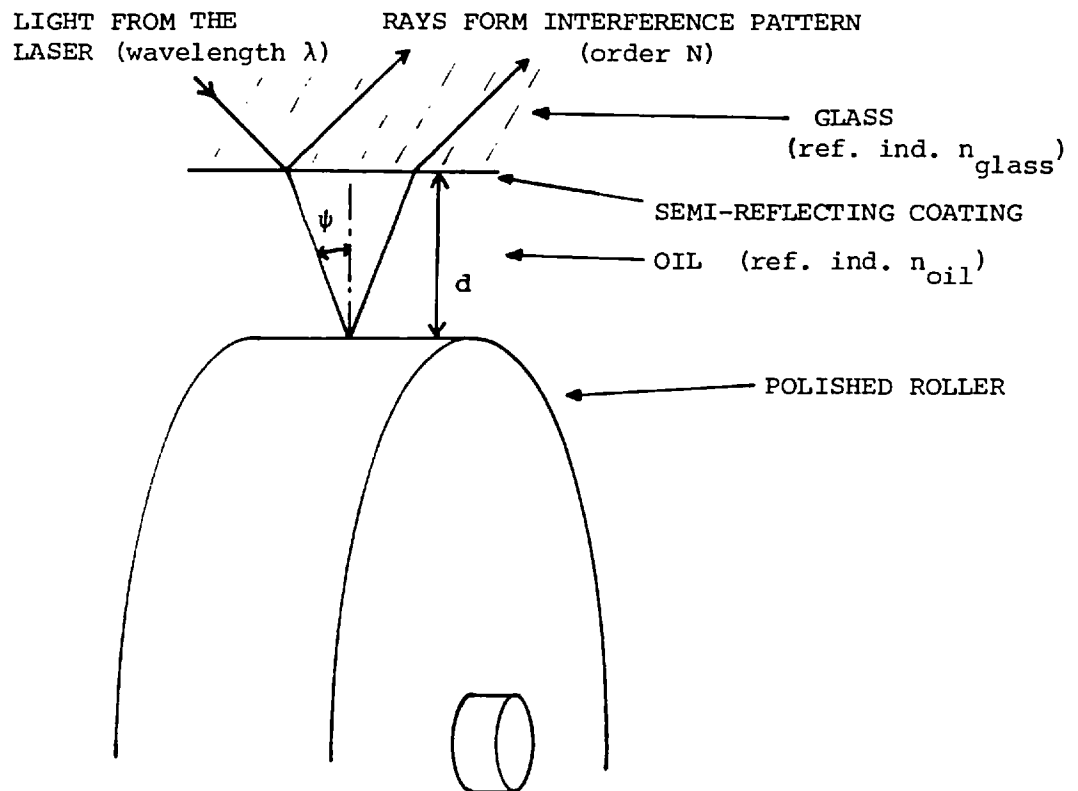


Fig 2.3

OPTICAL INTERFEROMETRY

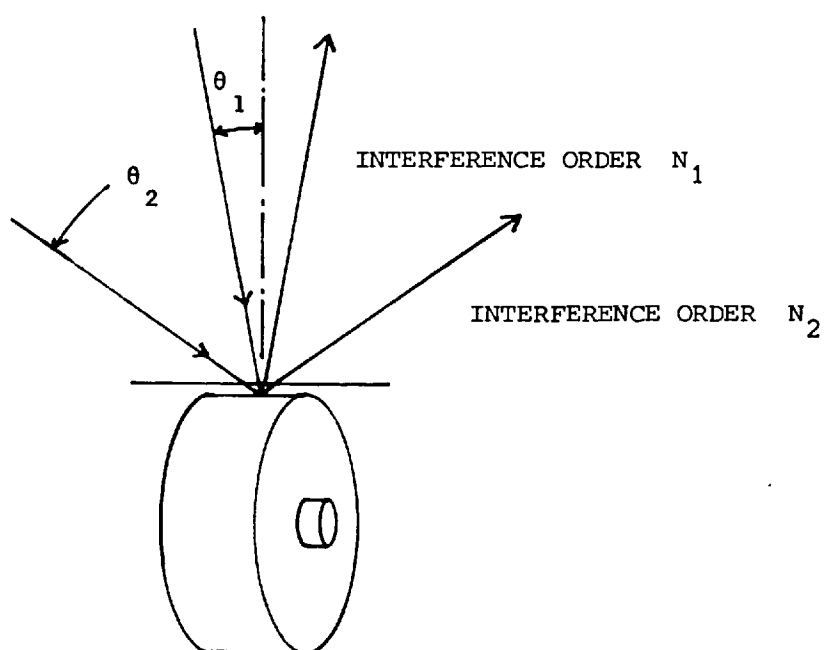


$$d = \left(N\lambda - \frac{\phi}{2} \right) \frac{1}{2n_{\text{oil}} \cos \psi}$$

ϕ - PHASE CHANGE

Fig 2.4

REFRACTIVE INDEX CALCULATION



$$n_{\text{oil}} = n_{\text{glass}} \left(\frac{N_1^2 \sin^2 \theta_2 - N_2^2 \sin^2 \theta_1}{N_1^2 - N_2^2} \right)$$

2.3.1 Optical Interferometry

The theory of optical interferometry can be found in text books (81, 82) and is therefore not reproduced in full. Briefly, two reflections are obtained, one off the roller and the other off the semi-reflecting coating on the lower face of the glass disc (fig. 2.3). When the path difference is a full number of wavelengths, a bright fringe is seen. Conversely when the path difference is exactly an odd number of half wavelengths a dark fringe is seen. In between the intensity varies in a manner dependent on the number of reflections that are significant. In these experiments it was preferable that the intensity variation with film thickness was approximately sinusoidal, which corresponds to the two ray interference system shown in the diagram. With multiple ray interference patterns obtained by having highly reflective surfaces the response becomes more peaked. This type of response would have made interpolation between fringes more difficult and less accurate.

Depending on the system there is usually some zero film thickness phase change. This has to be taken into account in the calculations. The governing equation is thus given by

$$d = \left(N\lambda - \frac{\phi}{2\pi} \right) \frac{1}{2n_{oil} \cos \psi} \quad \dots 2.1$$

For good fringe visibility the roller and reflectance coating must have approximately the same reflectivity. Furthermore the surface roughness must be better than half a wavelength. These considerations were taken into account when the roller and glass disc were manufactured.

2.3.2 Refractive Index Calculation

Although the method of calculating the refractive index has been fully described by Paul (83), the theory has been reproduced in appendix 1 for ease of reference. By having two interferograms at different viewing angles the two unknowns, refractive index and film thickness can be obtained. The two

paths of light lie in a plane parallel to the roller axis and radial to the roller. (fig 2.4). The refractive index of the oil is given by

$$n_{oil} = n_{glass} \left(\frac{N_1^2 \sin^2 \theta_2 - N_2^2 \sin^2 \theta_1}{N_1^2 - N_2^2} \right)^{\frac{1}{2}} \dots 2.2$$

Because θ_1 is small, the greatest accuracy is obtained by making N_2 as small as possible. This is accomplished by making θ_2 as large as possible. The limit on θ_2 is determined by the maximum angle of incidence that can be tolerated. The considerations governing this are discussed more fully in the section on accuracy and errors (section 6.3).

2.3.3 Density Derivation

The Lorentz-Lorenz law is given by

$$\rho = \frac{n^2 - 1}{n^2 + 2} \dots 2.3$$

This law originally derived theoretically from both classical electromagnetic theory and elastic solid theory applies strictly to non-polar homogeneous materials. It does however apply reasonably well to polar liquids because of the random nature of the orientation of the molecules at visible frequencies. It has been checked experimentally up to a pressure of .7GPa for a paraffinic oil by Poutler, Richey and Benz (84), and shown to hold true to an accuracy of at least 0.6%. Unfortunately there has been no work carried out to see what effect a high speed of compression would have on the relationship but there is no reason to suppose that it will break down under such conditions. A treatment of the theory behind it can be found in Dekker (85) or Mathieu (86).

2.3.4 Inverse Elasticity Pressure Calculations

The pressure profile is calculated from the absolute film

thickness data using the program developed by Ranger (79). Because the problem is linear, a matrix of influence coefficients for the effect of pressure at one point of a grid on the deformation at any other point can be set up. The deformation is then given by

$$W_i = \sum I_{ij} p_j \quad \dots 2.4$$

W_i - deformation at point i
 p_j - pressure acting a point j
 I_{ij} - influence coefficient

The pressure is obtained by inverting the matrix and solving the simultaneous equations.

2.3.5 Viscosity

The viscosity is calculated from the two dimensional Reynolds' equation in the form

$$\eta = \frac{h^2}{12U} \frac{dp}{dx} \left(\frac{1}{1 - \frac{\bar{\rho} h}{\rho h}} \right) \quad \dots 2.5$$

The derivation of this formula can be found in most standard textbooks (87, 88). However it is worth considering the assumptions on which it is based. These are considered in the discussion of the results. (Section 7.3.4).

CHAPTER 3
EXPERIMENTAL SET UP

3.1 The Rig

The general layout of the rig is shown in figure 3.1 with a view of it in figure 3.2. A steel roller is loaded against a glass disc by an air bellows, the thrust on the glass disc being counteracted by a hydrostatic bearing. The disc is located axially on a spindle via a flexible coupling to allow for alignment against the hydrostatic bearing. The roller is driven via belts and flexible couplings from an electric motor with a fine speed control. The drive can be coupled through a reduction gearbox to give increased sensitivity of speed control at low revolutions. The speed is measured using an optical scanner to count the stripes on a reflective wheel. Technical specifications of the glass disc and roller can be found in appendix 2.

3.1.1 The Hydrostatic Bearing

The hydrostatic bearing is a thin land oil pressurised type. The thin land gives a high stiffness in order that vertical displacement of the glass disc which affects the focussing is minimised. The land is of PTFE which has the advantage that it can carry some load without damaging the disc. The oil is pressurised by a gear pump, its flow being controlled by a relief valve. Around the edge of the disc is a flinger so that after emerging from the bearing, the oil is collected in a drip tray and returned to the reservoir.

One advantage, from a mechanical point of view, of having a hydrostatic bearing, rather than other types of thrust systems, is that the reaction force is distributed evenly over a large area just above the load. There are therefore no large bending moments making it possible to use reasonably thin glass discs without fear of breaking (89). The limit therefore to the Hertzian pressure that can be achieved in the contact, is that which the glass can withstand without pitting. Evidence from micro-pitting tests (90) put this at about 1.5GPa for the size of roller used.

FIG 3.1

ROLLING LINE CONTACT VISCOMETER

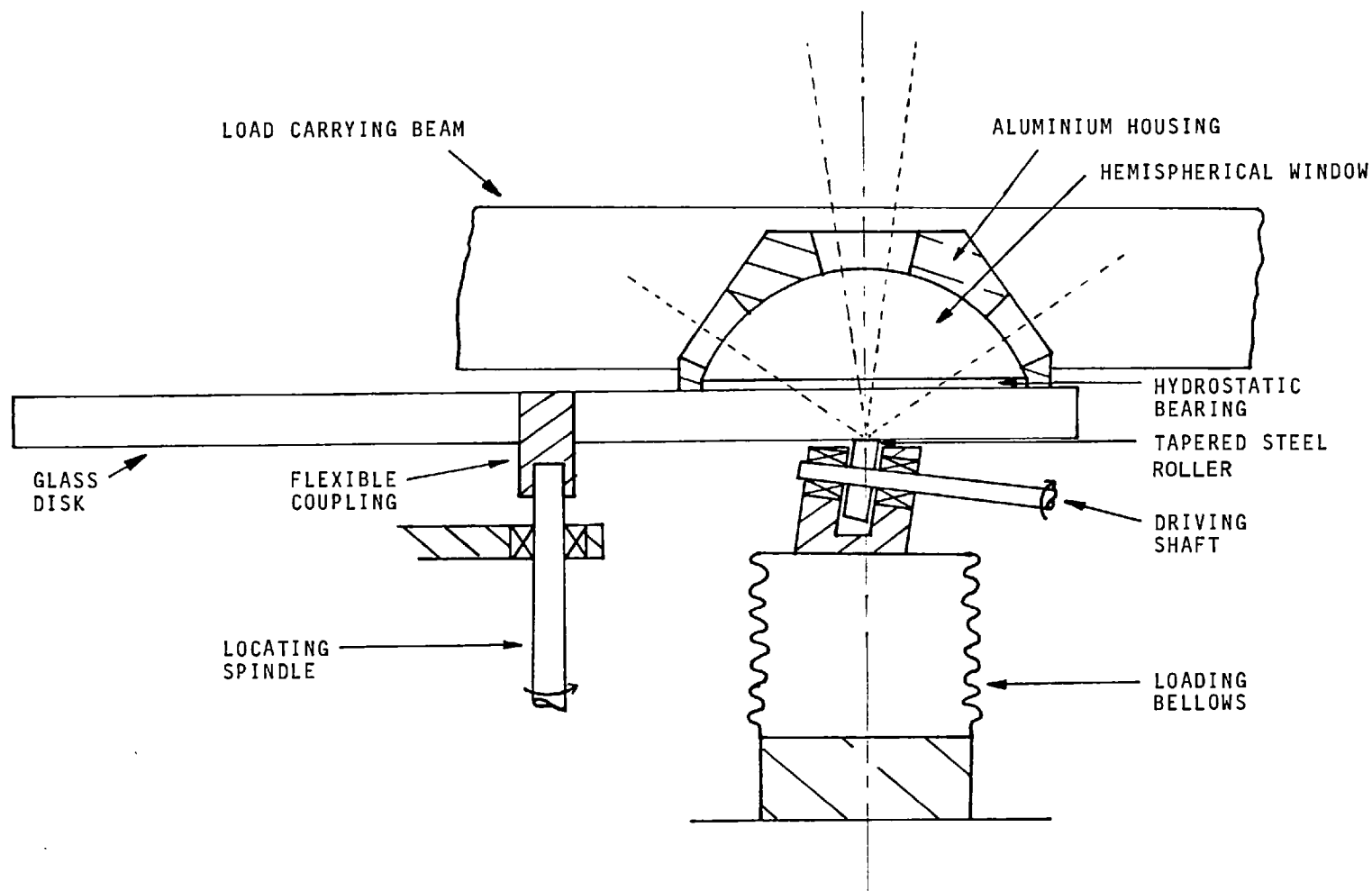


FIG 3.2

GENERAL VIEW OF THE LINE CONTACT VISCOMETER

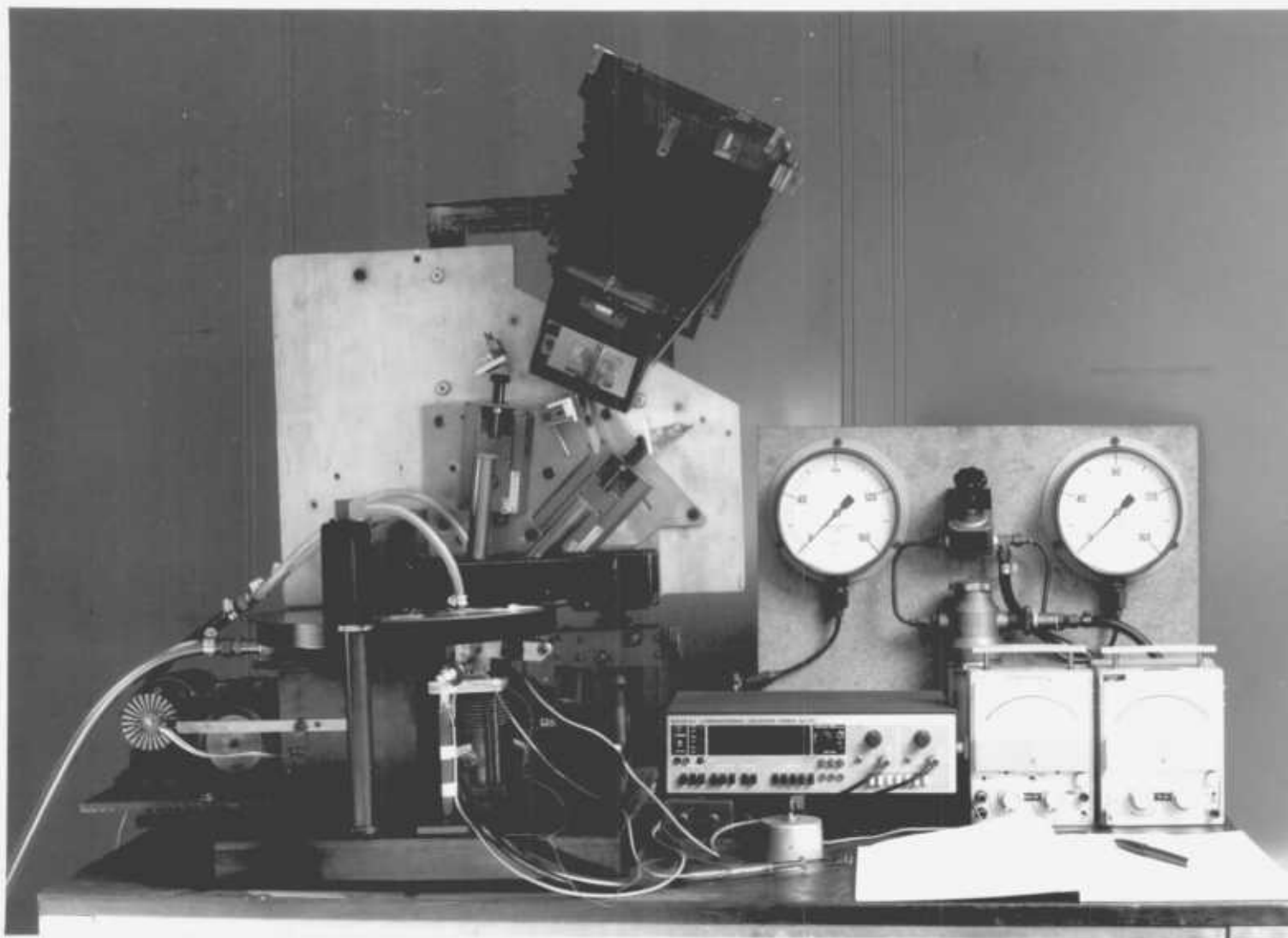


FIG 3.3 ROLLER HOUSING

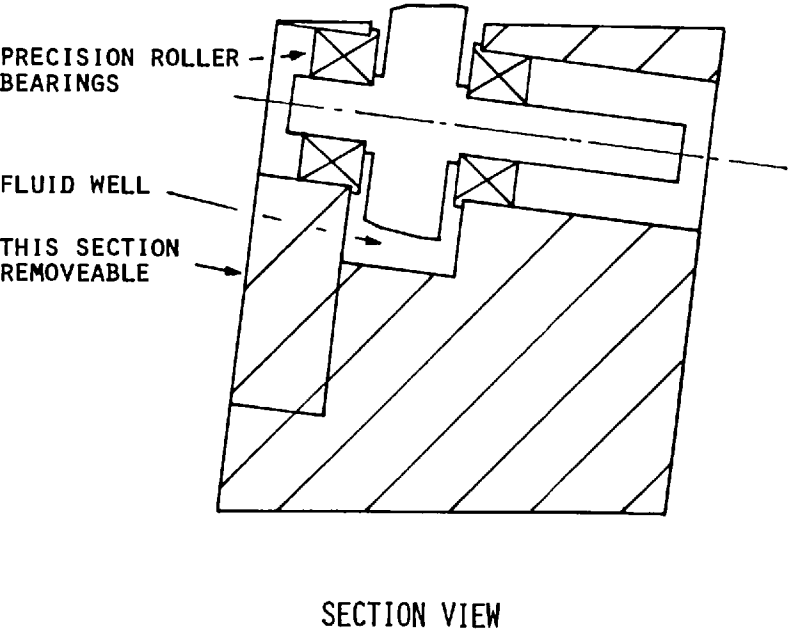
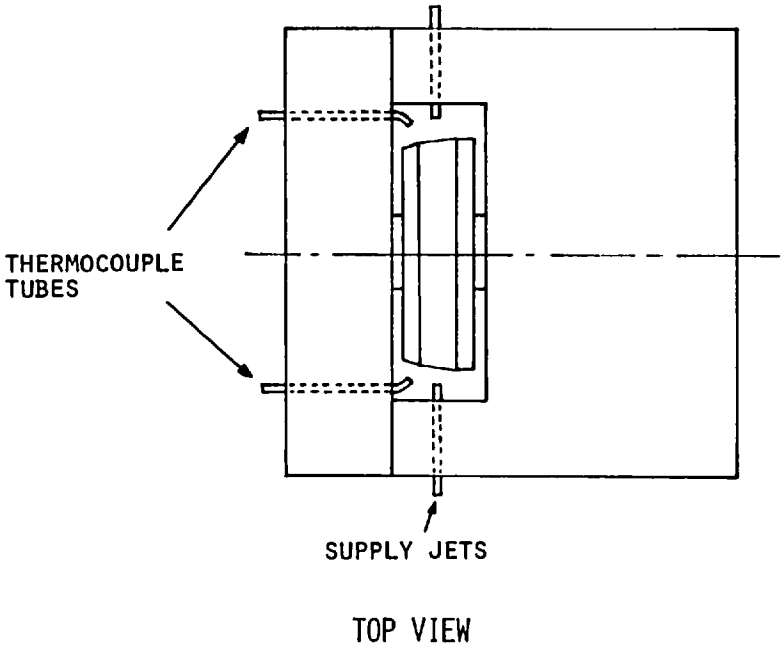
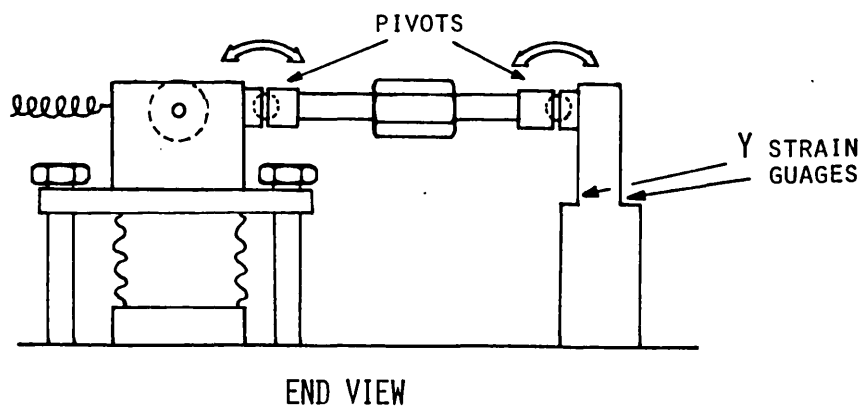
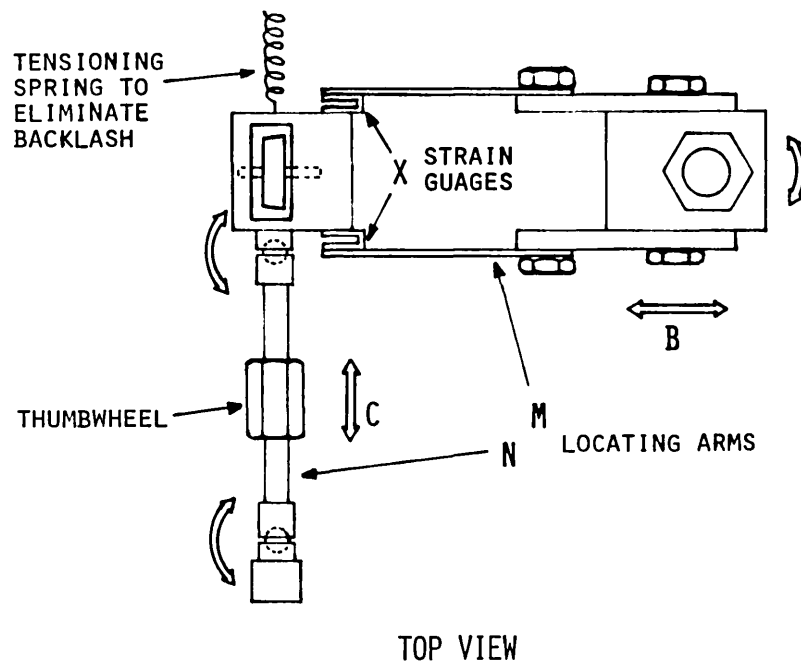
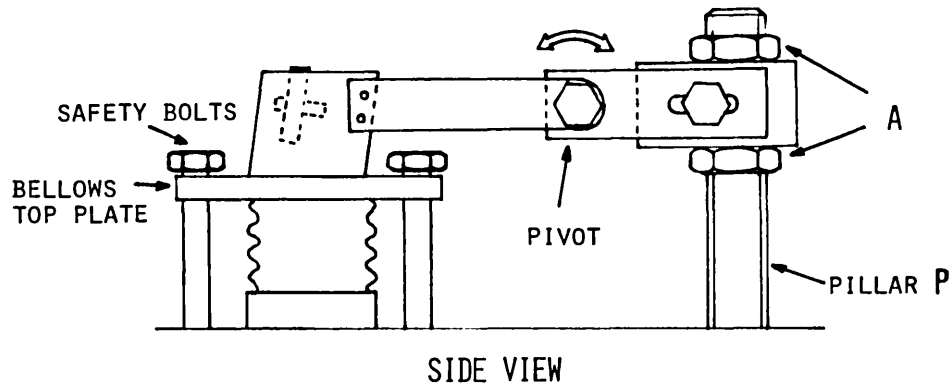


FIG 3.4

ROLLER ALIGNMENT



However experience has shown that for a reasonably long life the limit is only about half this value.

3.1.2 The Roller Housing

The roller is located in a housing (fig 3.3) by two precision ball bearings, with extremely accurate runout. The housing forms a small well to provide a reservoir of test fluid into which the roller dips. The bearings are sealed so that the test fluid is retained and does not become contaminated by the grease in the bearings. The housing and bearings can be disassembled for cleaning.

Fixed in the walls of the housing, near the top of the well, are four short lengths of hyperdermic tubing, pointing towards the area of contact that the roller makes with the glass disc. There are two each side of the roller, one for locating a thermocouple in the inlet of the contact, the other acting as an oil feed. The need for two each side is to enable the direction of rotation to be varied. In addition to the oil feed pipe a PTFE scraper, acting on the glass disc, is arranged to push back the excess oil into the track after being expelled on passing through the contact. This helps to ensure that starvation does not occur and that only small samples of oil are needed for each test.

3.1.3 Alignment of the Roller

In order to be able to conduct the experiments in conditions as close as possible to pure rolling, the roller needs to be extremely carefully aligned. In addition to this the tilt of the roller needs to be adjusted to give uniform loading along its length. The arrangement to do this is shown in figure 3.4.

The roller is tapered such that its axis coincides with the centre of the lower face of the glass disc when the alignment is correct (fig. 3.1). This ensures that the two contacting surfaces have the same velocities at each point along the length of the roller, although from one end to the other there is a small variation of speed. The tilt of the roller is adjusted by

the two nuts A (fig. 3.4) until a uniform width of contact pattern is obtained along its length.

The loading bellows provide sufficient flexibility for adjusting the tilt of the roller, whilst lateral displacements can be accommodated by allowing the roller housing to slide on the plate located on the top of the bellows. Four bolts passing through large clearance holes in this plate ensure that in the case of the glass disc breaking the bellows do not explode. The roller housing is held in position by two suitably pivoted horizontal arms M and N, at right angles to each other. A tensioning spring is necessary to eliminate backlash in the arm N.

To extend the life of the glass disc, adjustment at B allows a new track radius to be chosen when the old track becomes damaged. Further adjustment is achieved by moving the disc centering spindle. Unfortunately moving this does introduce some sliding in the contact but this is at most .5% at the ends of the roller. Since the measurements are made near the centre of the track the effect is insignificant.

The final adjustment is to eliminate skew of the roller. To determine whether there is any skew, strain gauges are mounted at X. Rotation of thumbwheel C pivots the bearing housing about pillar P. Reversing the direction of rolling reveals the presence of skewing forces by a reversal of any offset voltage from the strain gauges. The position of C is set so that the voltage swing is a minimum. Strain gauges Y can be used to obtain crude values of traction forces.

3.2 Optics

The main requirements of the optics are that they should lead to high resolution, minimal aberration and uniform intensity of the interferograms. The first two points are determined primarily by the design of a good system with high quality optical components. The uniform intensity is determined both by the system and by maintaining the optical surfaces in a clean state. The uniform intensity is important because of the method of analysis of the interferograms by micro-photodensitometry.

The problem of clean optical surfaces is primarily one of dust settling and can be minimised by arranging to have as many of the surfaces as possible pointing downwards. A general layout of the system is shown in figure 3.5.

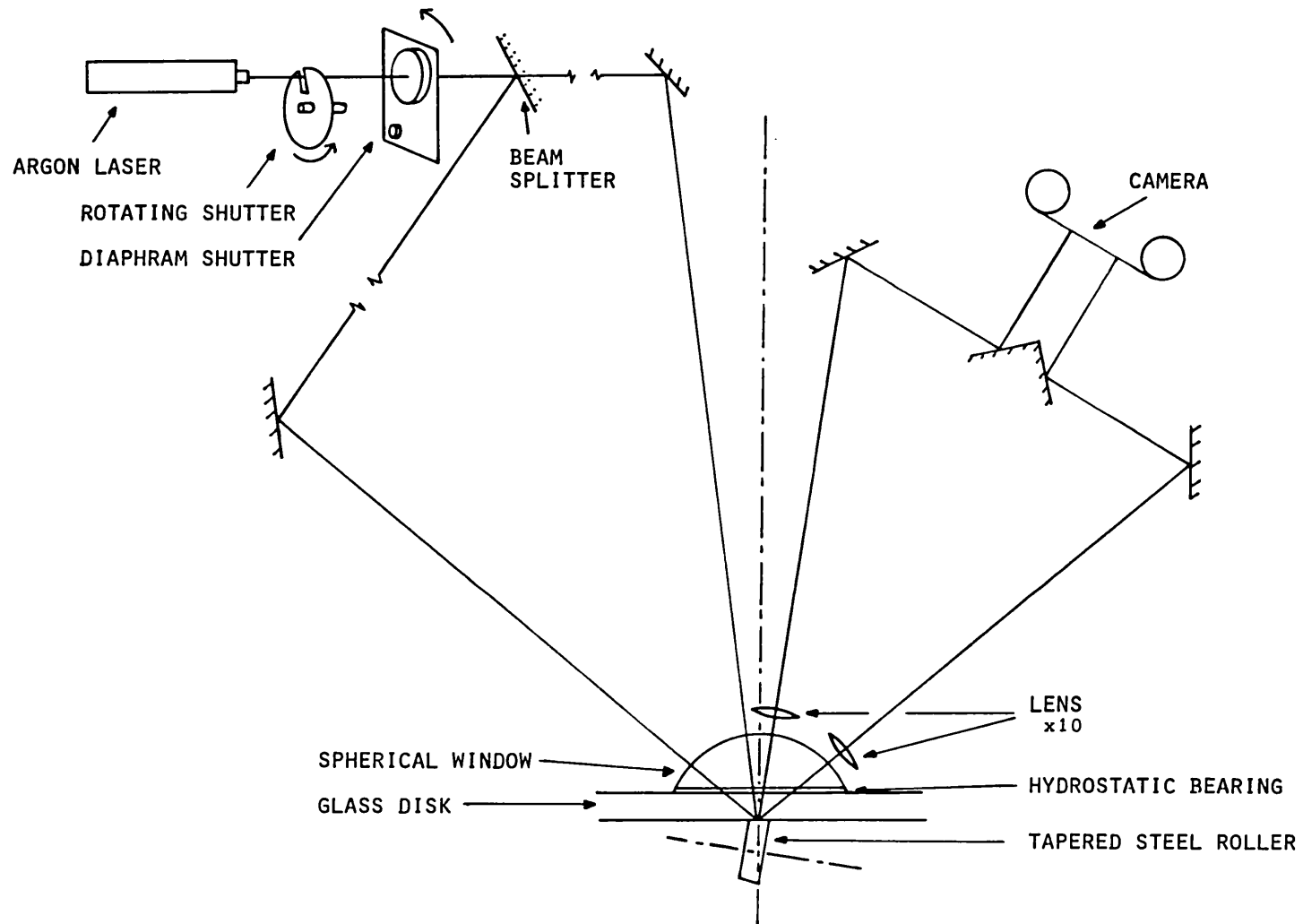
3.2.1 Illumination

Since the film thicknesses are up to twenty or more fringes, monochromatic illumination is the most suitable. White light from a tungsten lamp would be suitable only for a low number of fringes because of its short coherence length, whilst duochromatic or other multiwavelength systems become complicated through the need to resolve the colours. Colour photography can be used but is expensive and subject to processing variations. Fortunately an Argon laser has been made available and is used as the monochromatic source. Advantages of lasers over other monochromatic sources are that the beam is parallel and does not need collimating, the spectral line width is very narrow giving high definition of the fringes, and the intensity is sufficiently great to be able to use a high resolution film with short exposure times. There is in general a trade off of film speed against resolution. The disadvantage of laser light is that the long coherence length easily leads to spurious interference patterns. A simple solution to this problem however is to ensure that the incident light falls at a non-normal angle on critical surfaces so that the unwanted reflections are directed out of the optical path.

To obtain uniform illumination over the full contact area the beam has to be expanded. Since beam expanders are costly and can introduce unwanted fringes, the natural divergence of the beam is utilised. By using mirrors a sufficiently long path length can be obtained to achieve the required expansion. (It should be said that such practice is not usually encouraged by laser safety officers!) The beam also has to be split at some stage. This is carried out before expansion of the beam because it is easier to remove unwanted reflections when the beam is small in diameter. The light is therefore directed to the contact via two separate sets of mirrors.

FIG 3.5

OPTICAL LAYOUT



3.2.2 Imaging Optics

Figure 3.5 shows the light entering and leaving the contact and the formation of the image at the camera. The light is incident at two ranges of angle $0^{\circ} - 8^{\circ}$ and $45^{\circ} - 55^{\circ}$. For ease of nomenclature these are referred to as the 'Normal' and 'Oblique' angles. Part of the hydrostatic bearing is a window, the external surface of which is spherical with its centre of curvature at the point of contact between the roller and disc. The refractive index of the hydrostatic bearing oil is close to that of the window and glass disc, so that the light passes through the oil virtually undeviated. The spherical surface and matching of refractive indices make it possible to work at large angles of incidence. Without such an arrangement the light would be considerably deviated at the air glass interface setting a practical limit of maximum incidence at about 35° in the contact.

The effect of the spherical surface on the focussing of the system is to make it appear as though there is air not glass in the optical path. Therefore the minimum working distance of the lenses in air are necessarily greater than the radius of the window. The lenses are long working distance x 10 achromatic doublets details of which can be found in appendix 2. A full account of the design of these lenses may be found in Wymer's thesis (80). They are mounted at the end of tubes attached to focussing slides.

The mirrors are front surface aluminised plane reflectors which project the two interferograms onto the image plane of a half plate camera. The conventional shutter and lens of the camera have been replaced by a flap which can be swung away to give a very large aperture. When the flap is closed, the images are projected onto a viewing screen by a mirror mounted on the flap. This makes it possible to follow what is happening in the contact before and after a picture is taken.

3.2.3 Optical Coatings

To minimise reflections off the window, the external surface in contact with air is coated with an anti-reflection layer. The

lenses also have anti-reflection coatings. The internal surfaces of the hydrostatic bearing, i.e. the flat surface of the window and the upper surface of the glass disc, are left uncoated since these reflections are extremely weak because the refractive indices of the glass and oil so nearly match.

As has been stated already for good fringe visibility the reflectivity of the roller and lower surfaces of the glass disc needs to be the same. A further requirement on the reflectance coating is that it needs to be durable. Hardest coatings are obtained by sputtering but the size of the disc makes that prohibitively expensive. The next most durable type of coating is a vacuum deposited dielectric. Fortunately a quarter wave layer of Titanium dioxide (TiO_2) is found to perform admirably, being durable and having good reflectivity due to its high refractive index. It is also found with this coating that fringe visibility is good, and the response of intensity to film thickness is nearly sinusoidal, corresponding to the two beam system of interferometry. Surprisingly the coating gives good fringes at the oblique as well as the normal angle although it is not a quarter wave coating at this angle.

3.2.4 Roller Finish

The finish on the rollers is found to be a very important parameter in the generation of sharp interference patterns. Due to the unusual requirement of needing to mount the rollers on a shaft they have had to be specially manufactured. The rollers, once ground, are found to have a good finish but still require considerable polishing. One difficulty in polishing is that the profile should not be distorted, (this having been the cause of much despair in the past). A technique has been developed of mounting an electric hand drill in the tool post of a lathe which is set over to the taper angle. The rollers are held in a collet chuck and polished with felt bobs impregnated with a series of grades of diamond paste. It is estimated that the surface roughness is better than about a fifth of a fringe order, i.e. about $.03\mu m$. The quality of finish can be seen by the interferogram in the frontispiece. The fringes are extremely sharp. The bowing

of the pattern on the inlet side is due to leakage of fluid from the ends, this being quite pronounced due to the short length of the roller.

3.2.5 Exposure

The film that has been found to be suitable for the photography is a fine grained orthochromatic film. It thus has a relatively low speed but there is more than enough power in the laser to be able to use very high shutter speeds. High shutter speeds are used to freeze any motion of the fringes. Blurring, due to small vibrations and minute imperfections in the roller profile, which although small, are sufficient to lead to a loss of fringe visibility thus making the task of interpolation of fringes in the central region somewhat imprecise.

No cheap high speed shutters are available but short exposures are obtained by a double shutter arrangement. The first shutter is a rotating wheel with a single slit wide enough not to lead to Fraunhofer diffraction, chops the light up into pulses. The second shutter is a diaphragm which opens for less than one revolution of the wheel, an optical scanner ensuring that the synchronisation is correct. This shutter may be swung out of the way so that a continuous stream of pulses can pass for viewing the contact by eye. The diaphragm shutter is swung into place and triggered remotely since it is some way from the rest of the apparatus. Shutter speeds as short as 1/5000th of a second are easily achieved. This is sufficiently fast to freeze the fringe motion even in the exit region. This shows up clearly in the frontispiece.

3.2.6 Magnification

For the analysis of the results the magnification of the optical system must be known. Of greater importance than the absolute magnification is the relative magnification of the normal and oblique interferograms, since this significantly affects the refractive index determination.

The absolute magnification is measured off a pair of parallel lines etched into the track on the glass disc. For high

accuracy the lines are spaced considerably farther apart than a typical contact width and the measurements are made on the normal interferogram. Unfortunately due to the viewing angle the oblique interferogram shows considerable parallax and large errors can creep into the relative measurements. Therefore to obtain the relative magnification a static entrapment of oil in the centre of the roller is formed, and the distances across the contact to the positions of minimum film thickness are measured. From minute defects in the roller or glass disc it is possible to identify the same distance along the length of the roller in both interferograms. Thus although there is parallax in the fringes. Since the measurements are at the same point along the roller any error is negligible. All measurements of the profile are made subsequently at this point on the roller. This is also the point which is focussed on the camera plate before experiments are commenced. Focussing can be checked by replacing the camera plate with a ground glass screen.

3.2.7 Registration

As has just been mentioned the measurements are taken at one position along the roller at which the magnification is accurately known. To ensure that this point is used each time a marker is required. In addition to this, the centre of the roller in each interferogram must be known so that the profiles can be positioned relative to each other and to the undeformed shape.

Thin wires are located in the camera just in front of the photographic plate so that they give an unexposed line when the interference patterns are recorded. There is one wire running along the centre of both the contact images, and two perpendicular, one for each angle. The lines across the patterns at which measurements are to be made are positioned close to the relevant perpendicular wires by adjusting the tilt of the mirrors. From a static picture the centre of the roller in relation to the cross wires is found by measuring the fringe positions.

Obviously it is important that the camera should not vibrate or move and its mounting has been constructed with this in mind. Unfortunately however there is some movement of the roller housing as the drive is applied about which little can be done. To reduce this effect the static registration photograph is taken with some torque applied, not enough to overcome the starting friction but sufficient to take up most of the backlash.

The effect of this movement is discussed in the relevant sections (6.3.1 and 6.4.2) of the chapter on errors.

CHAPTER 4
EXPERIMENTAL METHOD AND ANALYSIS

4.1 Preparation of the Rig

Before each session of tests the alignment of the roller was inspected and the optical surfaces cleaned. Before each group of tests, a group being about six photographs, the optical alignment, the focussing and the positioning of the cross wires was checked and adjusted if necessary. All these alignment and set up procedures have been outlined in the previous chapter.

One parameter which was found to wander and which required close attention was the illumination levels. Vibrations seemed to affect some of the mirrors, putting them out of alignment, expecially if heavy machinery was operating nearby. Fortunately the tests could be conducted when the machines were not running. The laser was usually allowed to warm up for some time to ensure it remained stable. However where low temperatures were desirable the warm up time was kept short so that the room temperature did not rise too greatly as a result of the heat dissipated by the laser power supply.

4.2 The Tests

To facilitate the interpolation of film thickness in the centre of the contact it was found desirable to have a photograph of the static fringe pattern. From the static pattern any variations in the illumination intensity across the contact could be detected and allowed for. This was found to be particularly necessary in the oblique image. Unfortunately at this angle photoelastic effects caused a variation in the intensity from one point to another due to rotation of the plane of polarisation of the light. This effect is discussed at greater length in the chapter on errors.

In addition to this static information, the position of the cross wires and magnification needed to be recorded on static pictures. Sometimes all this data could be obtained off just one photograph, such photographs being taken at the start of

a series of tests. Usually a series consisted of a range of speeds at the same temperature and pressure.

Each test was carried out by counting up the normal angle central fringe order as the speed increased until the required film thickness was obtained. At this point the various flaps and shutters had to be opened and closed in the right sequence, (many photographs were spoiled), to enable an image to be recorded. The speed and temperature were also noted. During the test care was taken to ensure starvation did not occur, this being observable on the viewing screen. At signs of starvation more oil could be injected into the contact through one of the hyperdermic tubes on the roller housing.

As a check against correct counting of the central fringe order, the fringes were counted down at the end of each test. A separate calibration run of speed against fringe order gave a further check, as well as providing the relationship between the central fringe order at the normal angle to that at the oblique.

To be able to apply the illumination variation data of the static photographs to the dynamic tests, the photographs were usually processed in the groups of tests together. The plates were gripped in a frame holding up to eight negatives at once. In this way they were immersed and removed from the processing tank together so that the development times were exactly identical throughout that group of tests. A typical interferogram is shown in figure 4.1. Details of the film and processing can be found in Appendix 2.

4.3 Micro-Photodensitometry

To retrieve the data off the photographs two types of measurement were made. From the negative of the static pictures the magnifications and centre positions were obtained using a simple travelling microscope. The interferograms were analysed using a micro-photodensitometer. This is a machine which gives a measure of the density of the photographic emulsion from a small sample area. The negative is held on an X-Y table and an enlarged image of it projected onto a screen. The signal passing through a narrow slit in the screen is compared with a reference beam whose strength is attenuated by

FIG 4.1 A TYPICAL DOUBLE INTERFEROGRAM
(Fluid Bright Stock, Speed 0.725 m/S, Load 0.30 MN/m, Temperature 22.0 °C)

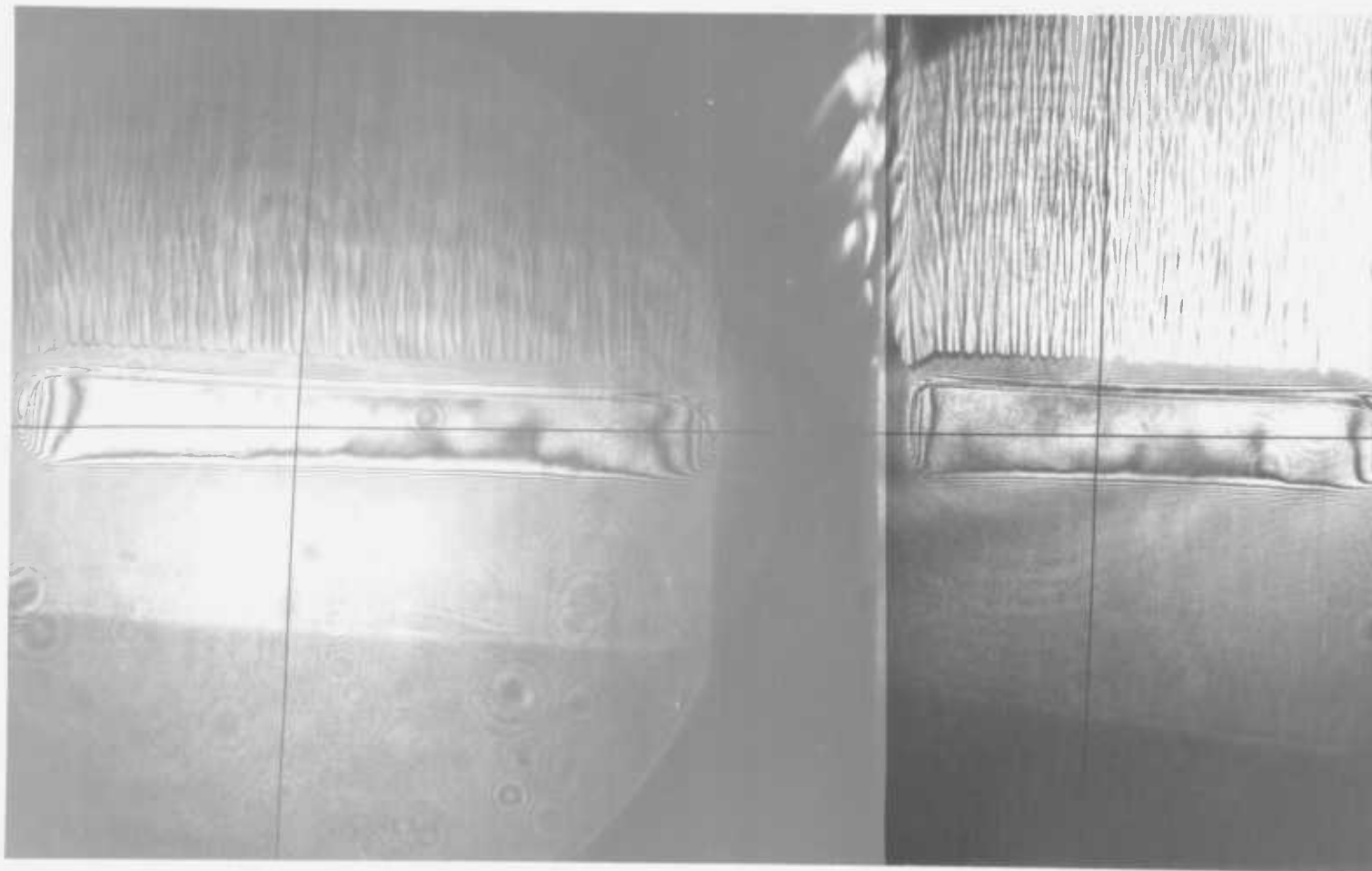
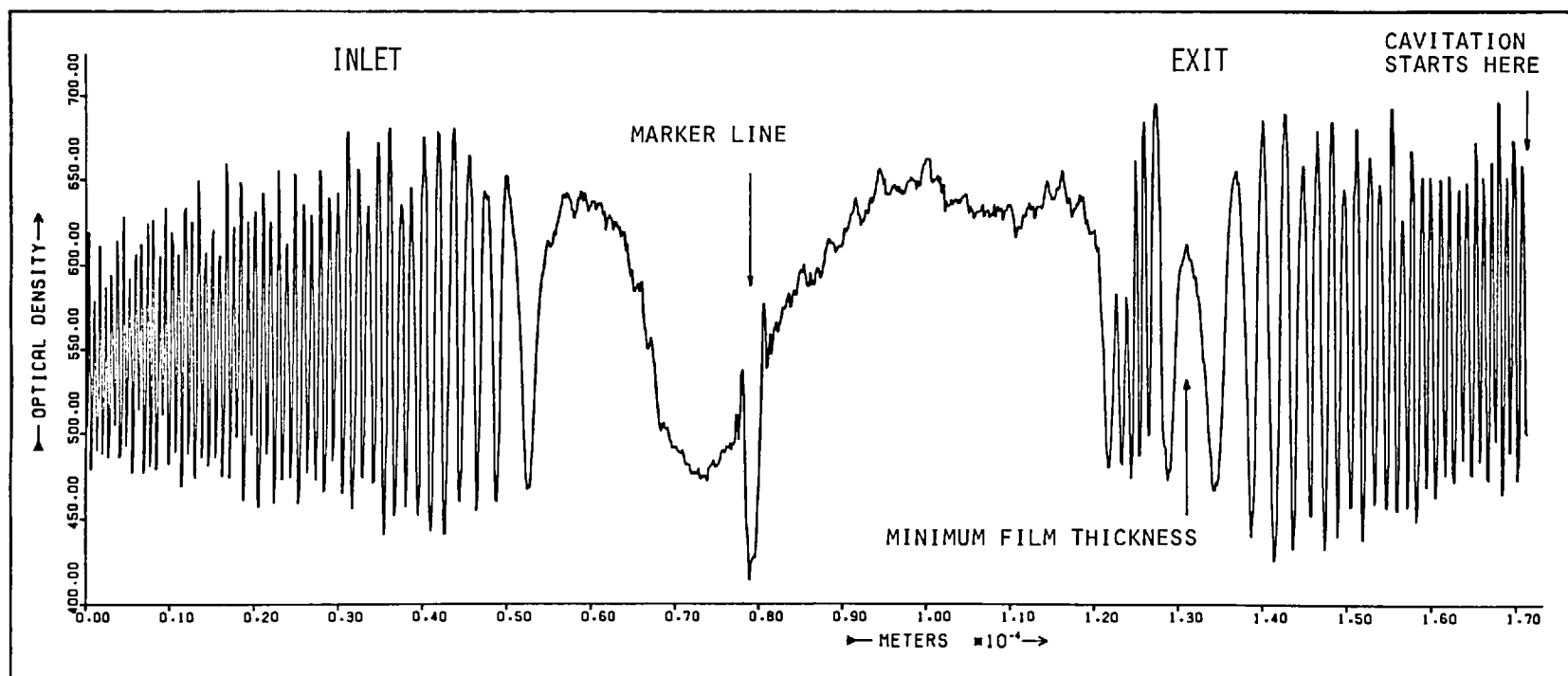


FIG 4.2

A TYPICAL PLOT OF NEGATIVE DENSITY VERSUS DISTANCE

FLUID	5P4E
SPEED	.325 M S
TEMP	24.5 °C
LOAD	.24 MN/M



a sliding grey scale until a balance is reached. A motor drives the table so that a continuous plot of the negative density is drawn (figure 4.2). The particular machine employed in this case incorporated the useful feature of being able to sample the negative at discrete intervals and punch out the balance positions of the grey scale onto a tape. The tape punch facility was used to feed the data into a computer.

The sampling step size was chosen so as to be able to pick out the fringe minima at the narrowest fringe spacing. This required at least four samples per fringe. The line of the scan across the contact corresponded to the point along the roller at which the magnification had been determined, i.e. close to the cross wire image. The negative was aligned so that parallax in the fringes was equal and opposite from one side of the contact to the other. The slit height was chosen to sample as much length of the roller as possible, the width being set to give good resolution at the finest fringe spacing. The slit width was thus approximately the same as a sample step.

In general it was found that from one end of the roller to the other there was a variation in film thickness especially at the higher speeds. This was due to the variation of roller diameter and speed due to the taper, and therefore it was not desirable to sample a greater length of contact than the limit set by the densitometer. The slit height was reduced by the appropriate amount when measuring the oblique angle interferogram to take into account the foreshortening. In this way the same areas of roller were sampled in both the normal and oblique measurements.

4.4 Computer Analysis

To have carried out the analysis by hand would have taken a considerable length of time. It was therefore decided to use a computer to do this incorporating the Ranger pressure program into a much larger program. It was also considered that using a computer would give marginally better accuracy. Like most data it suffered from noise and smoothing was necessary at various stages.

The general scheme for the calculation of the density and

viscosity has already been outlined in the overall description of the project (section 2.2, figure 2.2). The analysis was carried out on a graphics terminal and curve fitting and smoothing was done interactively.

To be able to interpolate between fringe orders, a calibration for the variation of density against fringe order was carried out (figure 4.3). The curve was fitted to data obtained from fringes a short way out from the Hertzian contact zone where the film thickness could be taken to be approximately linear with distance between adjacent fringes. The calibration was an average over several sets of fringes from different photographs.

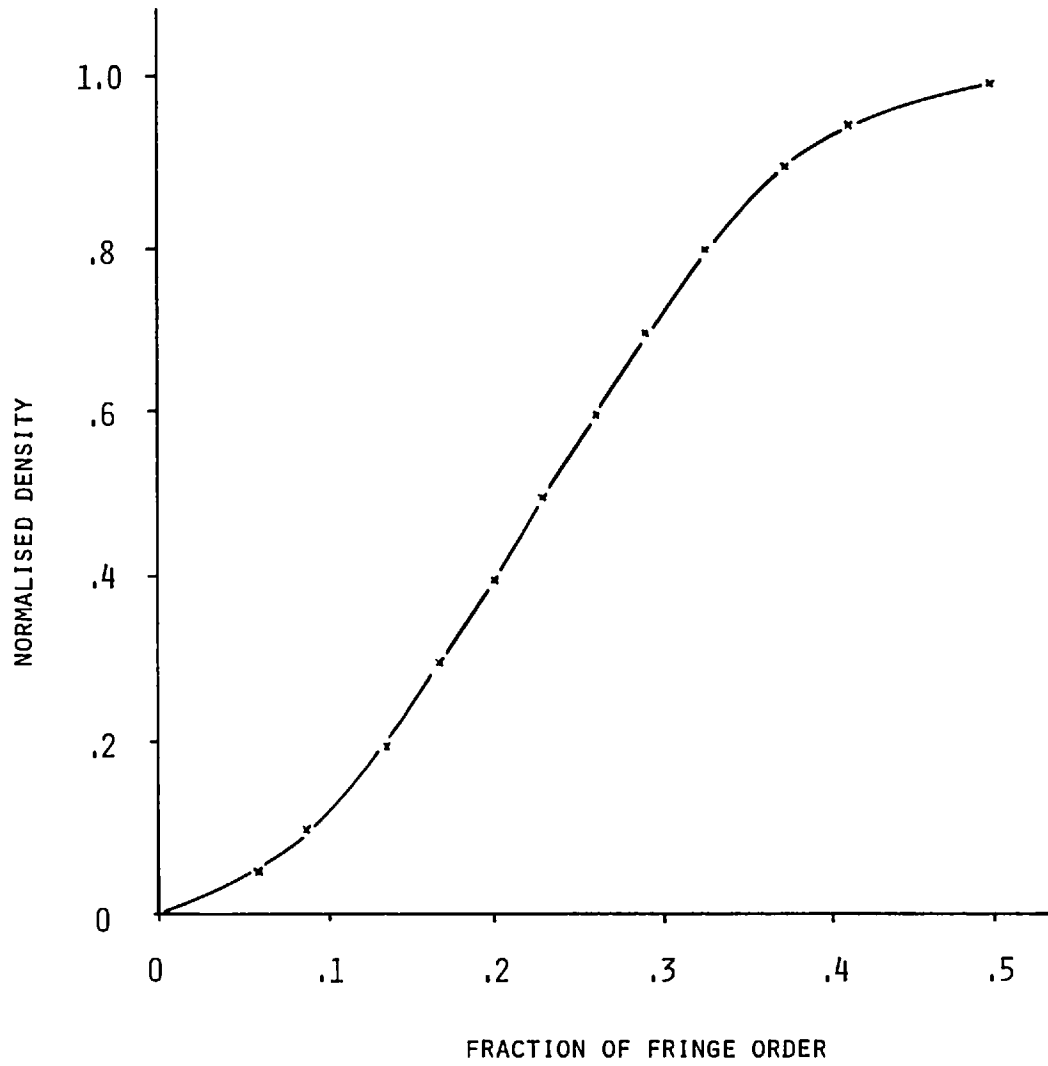
The illumination levels varied from photograph to photograph and so the maximum and minimum values corresponding to the light and dark fringes had to be obtained from the fringes at the edges of the contact region. The densitometry plots of the static contact were used to reveal dips or gradients in the illumination levels over the contact.

Smoothing was carried out at three stages, the optical profiles, the refractive index and the pressure. The most severe smoothing was on the refractive index and pressure, the most significant on subsequent calculations being the refractive index. Where there was a possibility of large errors being introduced because of the smoothing the calculations were repeated with different smoothing.

A brief description of the complete program is given in Appendix 3. A full listing however may be obtained from the author.

FIG 4.3

CALIBRATION CURVE



CHAPTER 5

RESULTS

5.1 Layout of the Results

In this chapter the results of the tests are presented. The chapter after this is an analysis of the errors, and discussion of the results will be found in chapter seven.

The graphs 5.2 to 5.11 are the relative density versus pressure curves whilst 5.12 to 5.21 show the viscosity. Each graph with between two and five curves represents either one or two groups of tests, a group being a series of tests at a particular load and temperature, but over a range of speeds. The number of curves on each graph has been limited to five curves for clarity, the curves within a group being presented in decreasing order of speed.

The tests have been assembled into blocks of results by fluids, the first graph of a block showing any comparative measurements that are available and the second showing typical error bars on one of the curves.

The loads are given in terms of the force per unit length of the roller and the temperature is that measured at the inlet to the contact.

5.2 The Fluids

Three fluids were tested, 5P4E, a synthetic paraffin XRM 109F and a hydrocarbon Bright Stock. The fluids were chosen so as to be the same as those tested by Paul (70) in his impact viscometer, or Duckworth (53) in his traction rig. Unfortunately when all the testing had been completed it was discovered that the Bright Stock was not the same as that tested by Duckworth, this in any case being slightly different from that investigated by Paul. Comparisons however can still be drawn. Some information about the fluids is given in appendix 4.

5.3 Conditions of the Tests

Tests were made at a range of speeds and at three different

loads. Most of the tests were carried out at room temperature, but one fluid, the Bright Stock was tested also near zero centigrade by enclosing the rig in Carbon Dioxide ice. The reason for the low temperature tests was to give greater accuracy by increasing the film thickness without increasing the rolling speed.

All the experiments that have been analysed were made with 'pure' rolling, the slide role ratio being less than 0.1%. The upper limit of the sideways skewing which was determined from the traction forces, could also be put at a similar value. Tests with pure sliding were attempted but without much success. The films were very thin as a result of the heating, and the reflectance coating was stripped off very rapidly. Intermediate values of slide role ratios were not attempted due to the difficulty of obtaining stable speeds of sliding.

5.4 Density Results

Figure 5.1 is a typical plot of pressure and relative density versus distance through the contact. These parameters are cross plotted as density versus pressure (Figures 5.2 to 5.11). The error bars drawn on figure 5.1 represent the typical magnitude of scatter that is obtained in a group of tests. The error bars shown on figures 5.3, 5.5 and 5.10 reflect the uncertainty in the relative shape of the profile but not the inaccuracy in determining the ambient value of the refractive index. Because of the lack of precision of determining the angle of incident light the levels to which the density rises at the high pressure varies considerably from one group of results to the next (see section 6.3). The shape of the curves does however reveal useful information as will be discussed later in chapter seven. In the exit region the relative errors become large due to the very rapid variation in film thickness at the pressure spike. The curves therefore show the values only up to the first maximum pressure.

FIG 5.1

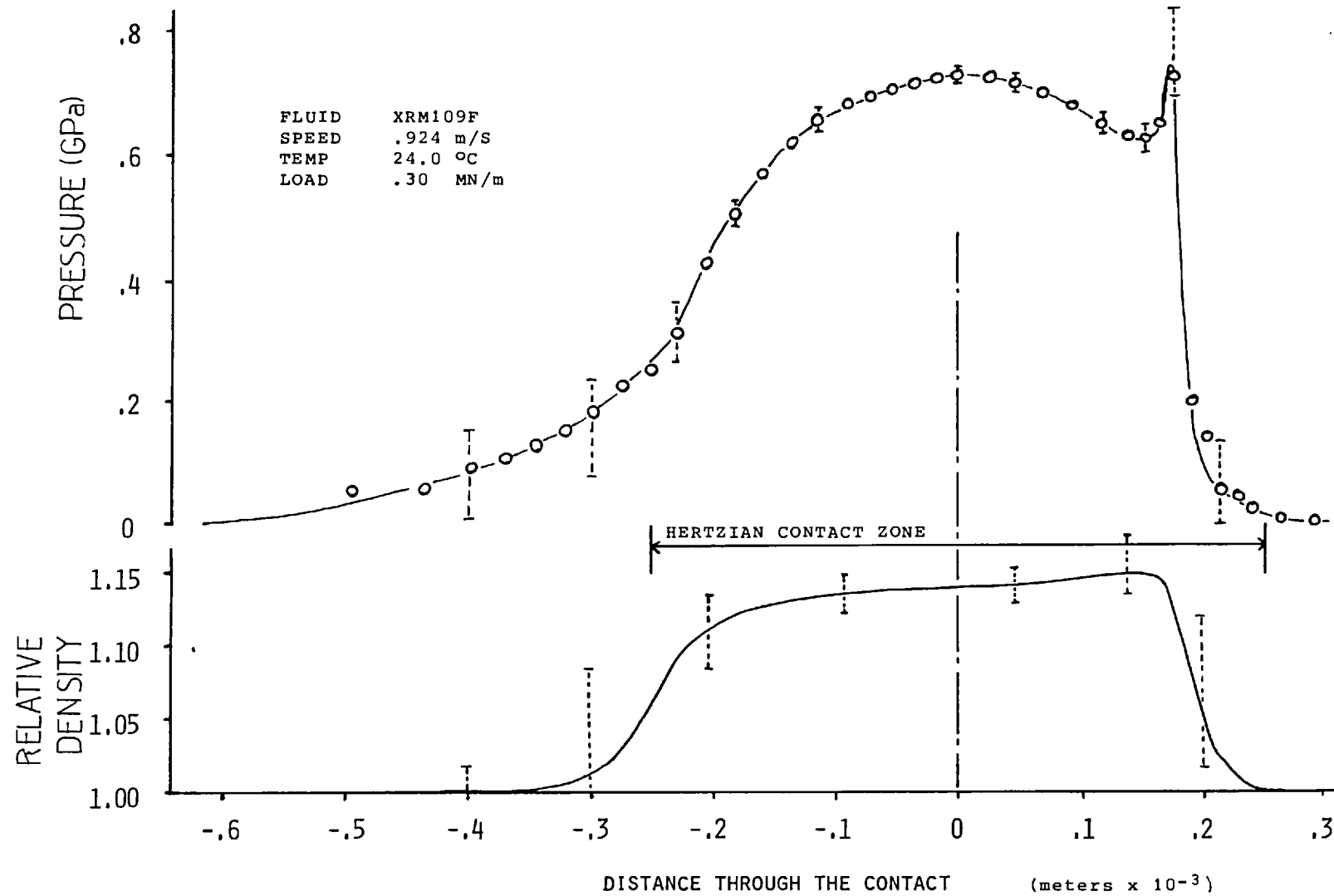
PRESSURE AND RELATIVE DENSITY VERSUS DISTANCE

FIG 5.2

RELATIVE DENSITY VERSUS PRESSURE

FLUID XRM109F

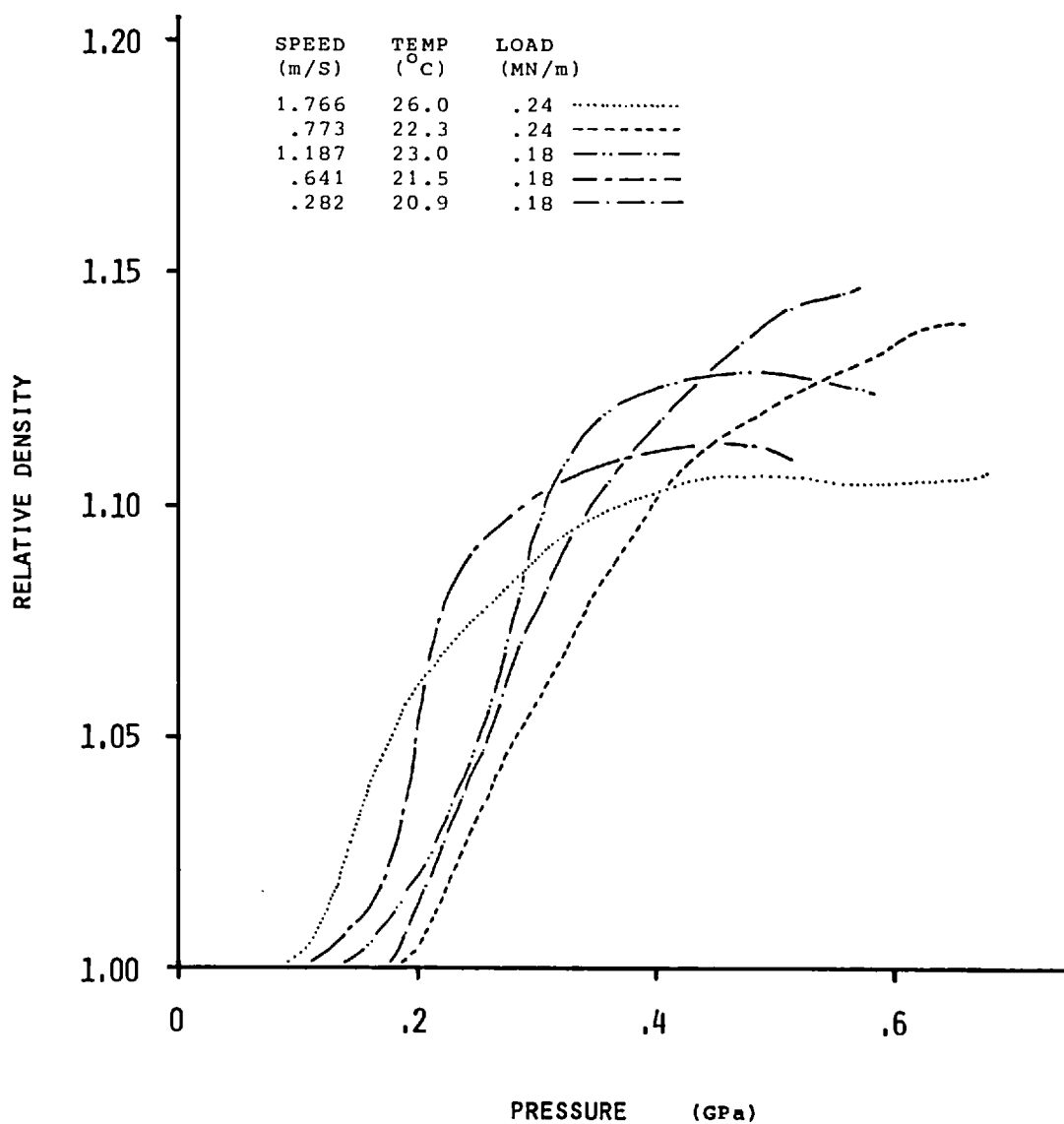


FIG 5.3

RELATIVE DENSITY VERSUS PRESSURE

FLUID XRM109F

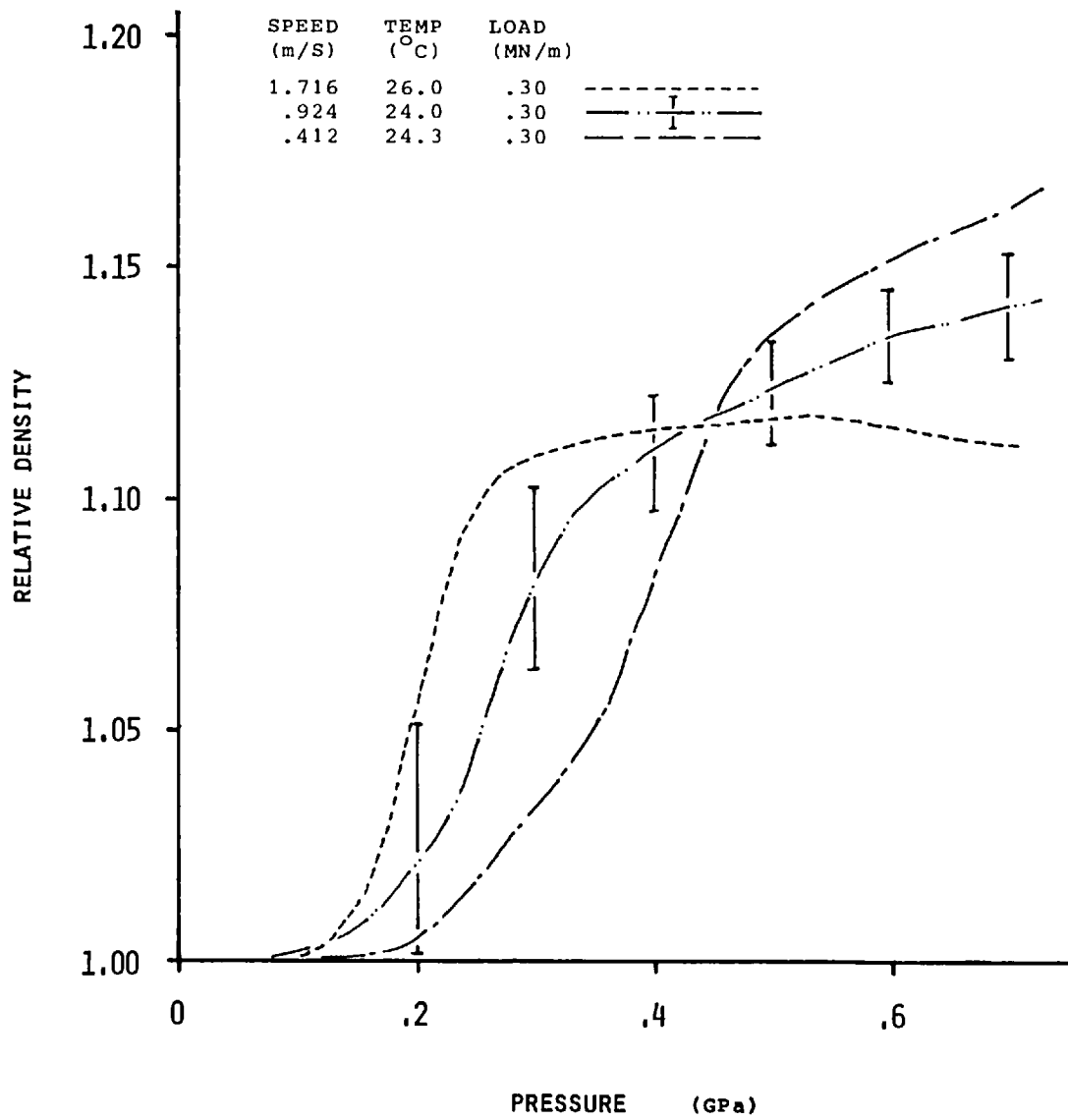


FIG 5.4

RELATIVE DENSITY VERSUS PRESSURE

FLUID BRIGHT STOCK

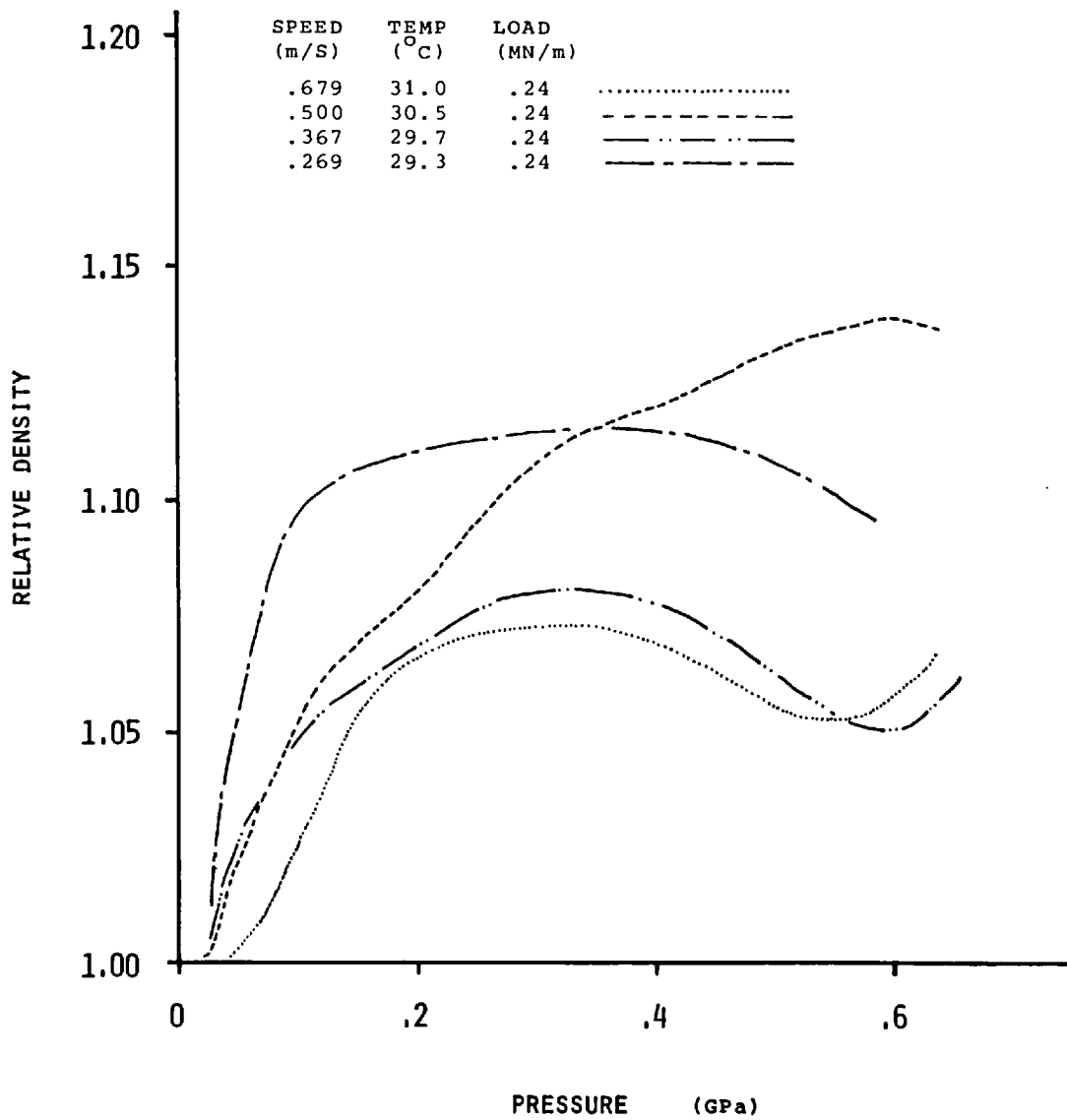


FIG 5.5

RELATIVE DENSITY VERSUS PRESSURE

FLUID BRIGHT STOCK

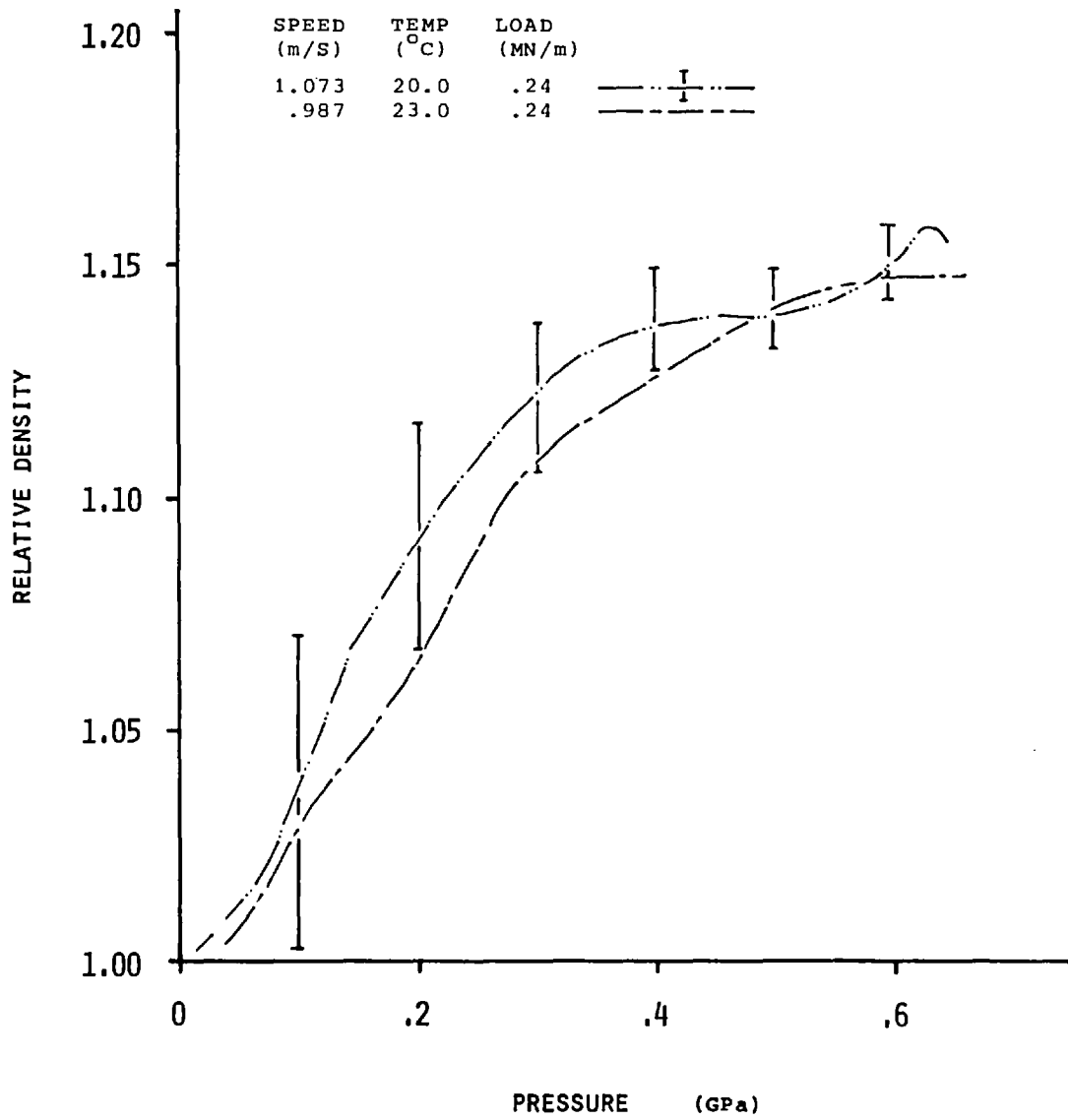


FIG 5.6

RELATIVE DENSITY VERSUS PRESSURE

FLUID BRIGHT STOCK

LOW TEMPERATURE

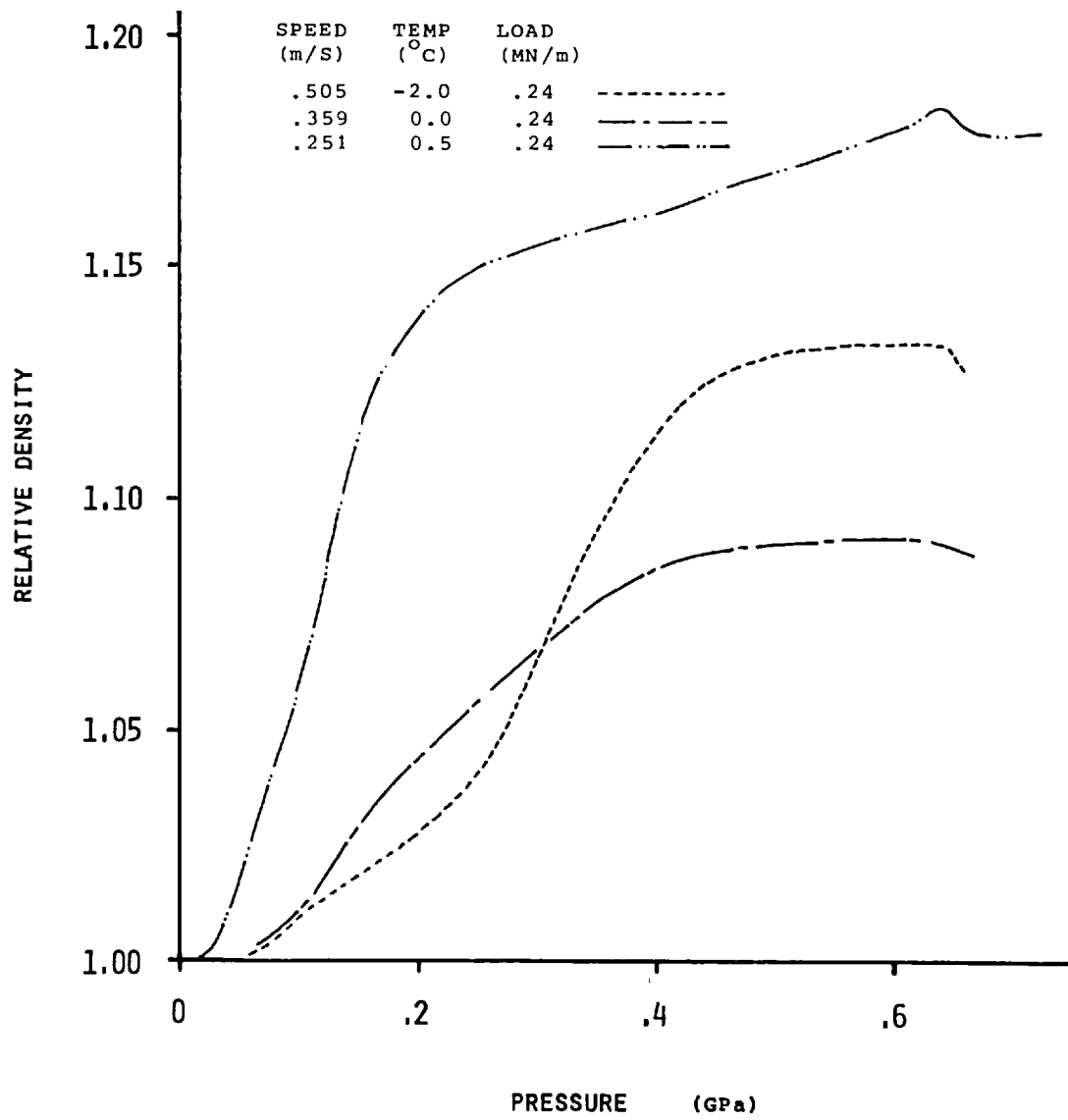


FIG 5.7

RELATIVE DENSITY VERSUS PRESSURE

FLUID BRIGHT STOCK

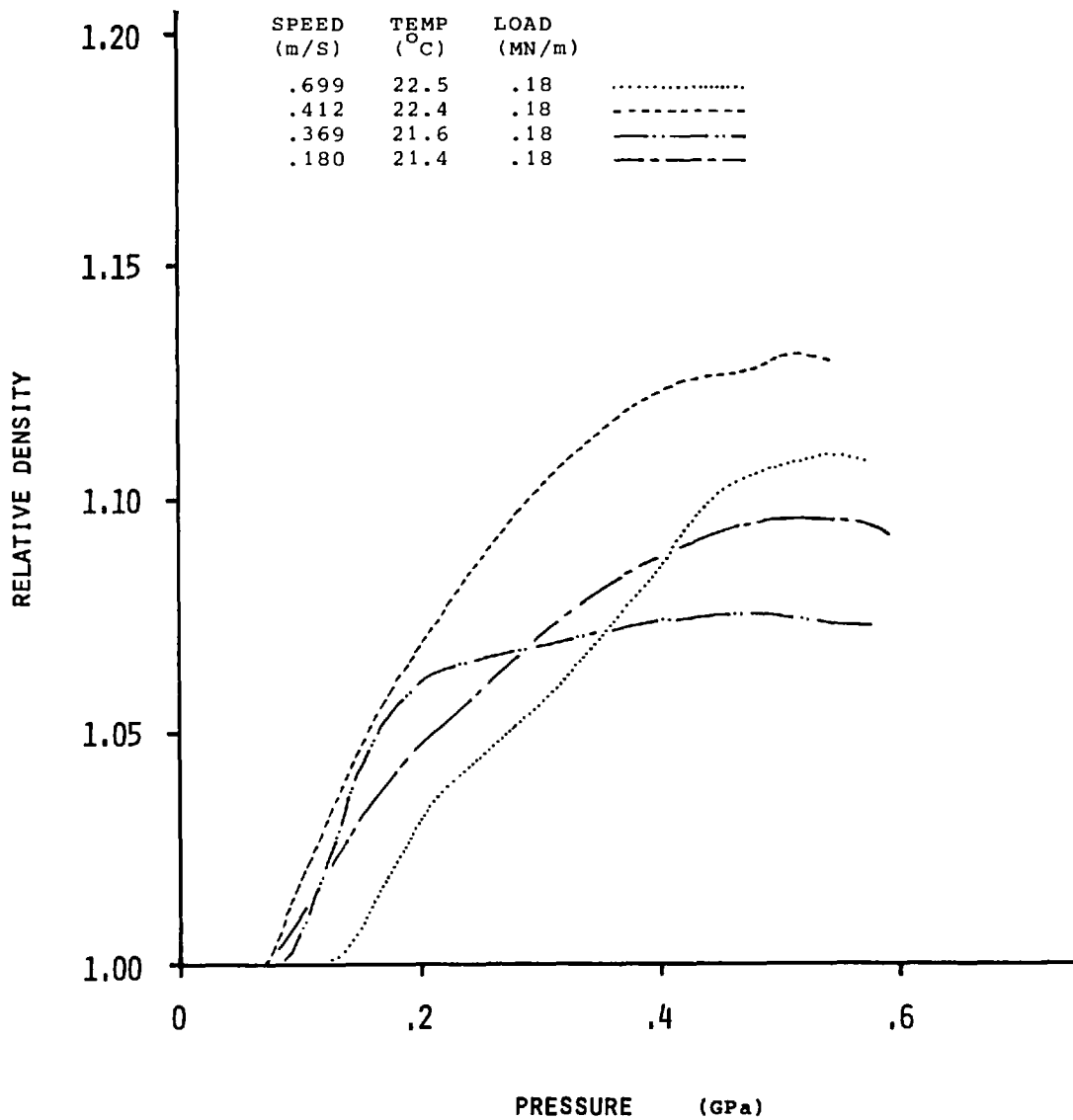


FIG 5.8 RELATIVE DENSITY VERSUS PRESSURE

FLUID BRIGHT STOCK

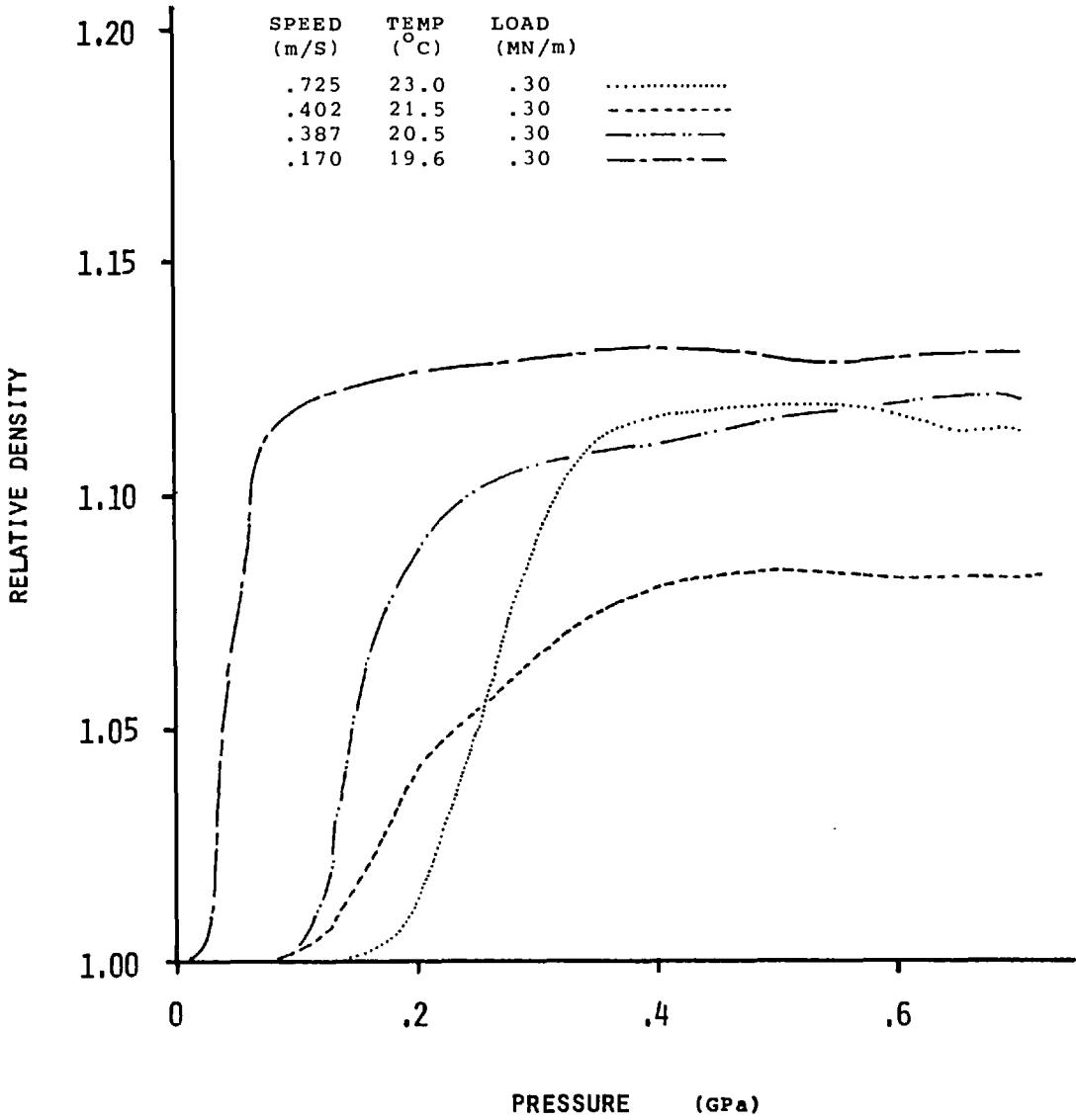


FIG 5.9

RELATIVE DENSITY VERSUS PRESSURE

FLUID 5P4E

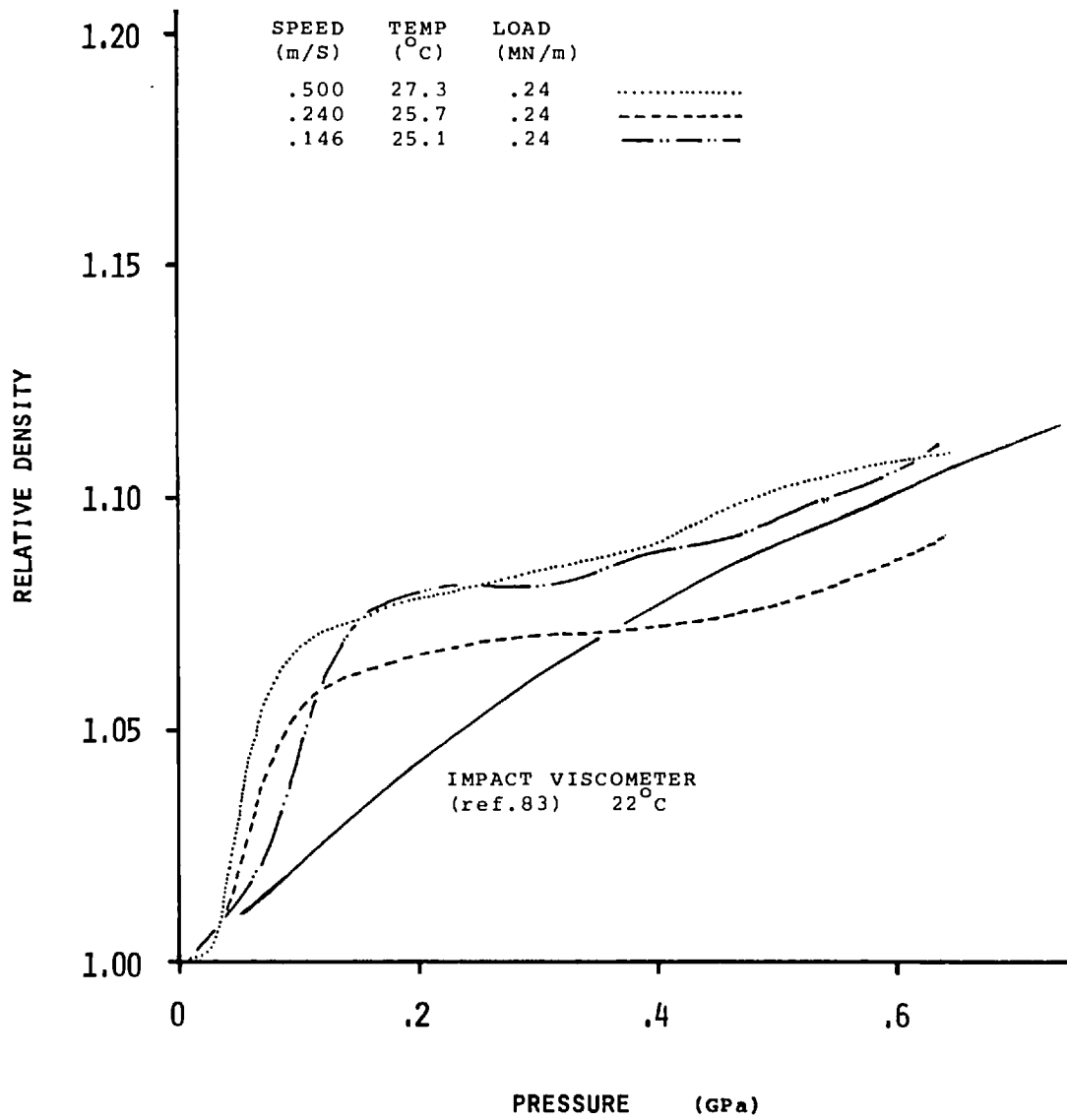


FIG 5.10

RELATIVE DENSITY VERSUS PRESSURE

FLUID 5P4E

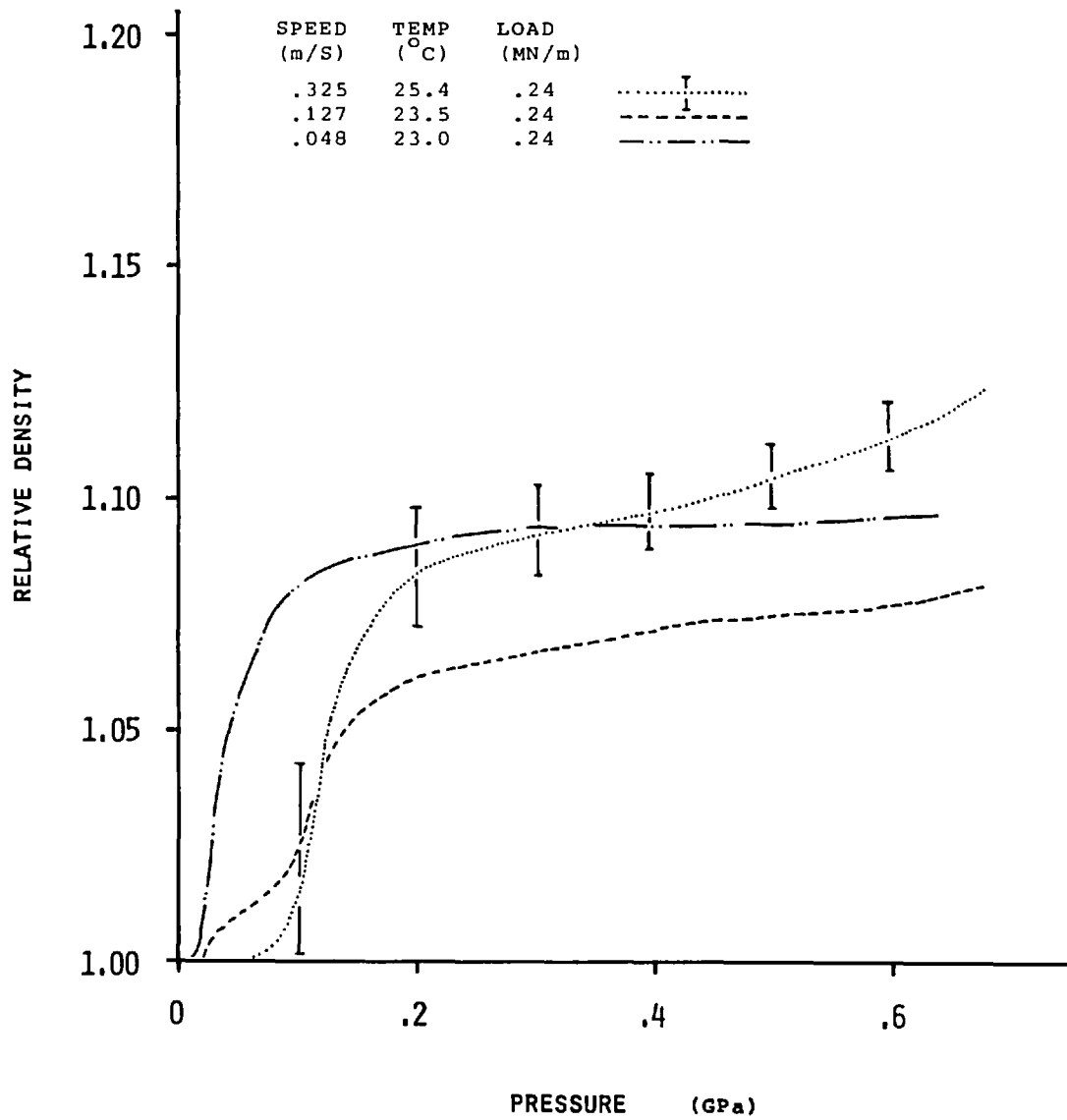
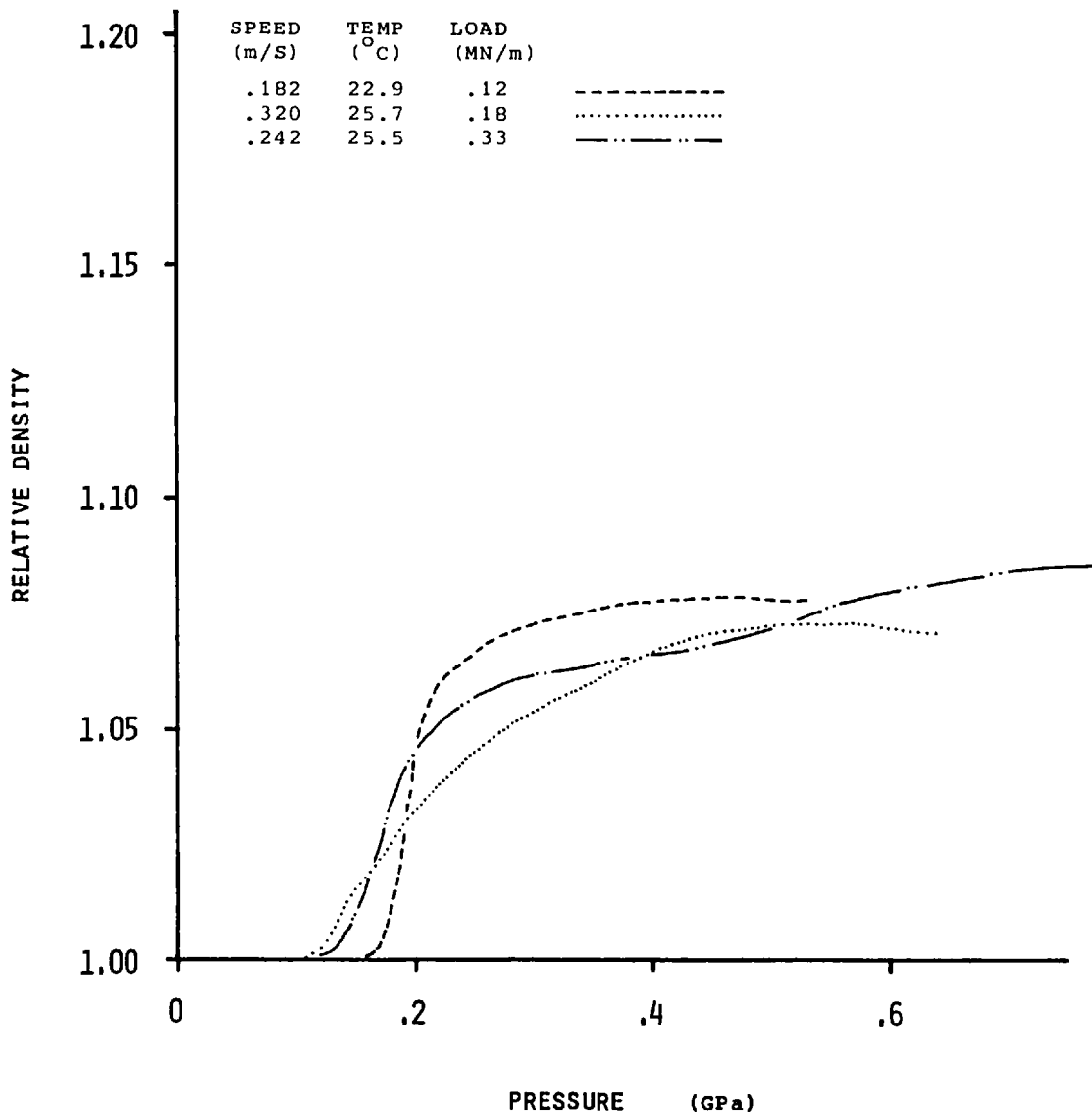


FIG 5.11

RELATIVE DENSITY VERSUS PRESSURE

FLUID 5P4E



5.5. Viscosity Results

As with the density results, the curves (figures 5.12 to 5.21) are drawn up to the first maximum pressure and do not include the values from the exit region. The error bars (figures 5.13, 5.15 and 5.20) reflect two main effects. In the low pressure region the errors arise mostly from the poor definition in the pressure gradient, whilst in the high pressure zone the term in the Reynolds' equation $\left(1 - \frac{\bar{\rho} \bar{h}}{\rho h}\right)$ becomes dominant. These effects will be discussed more fully in the next chapter.

Figure 5.22 is a plot of central optical film thickness versus rolling speed for the three test oils and a calibration oil of known pressure viscosity coefficient (α -value). From this graph the coefficient of the test oils has been calculated using the method of Foord, Hamman and Cameron (25) and Westlake and Cameron (26). These are given in the table below the graph along with the temperature and ambient viscosity at which the measurements were made. Using these values viscosity lines have been drawn on figures 5.12, 5.14 and 5.19. The significance of these results will be outlined in the discussion.

FIG 5.12

VISCOSITY VERSUS PRESSURE

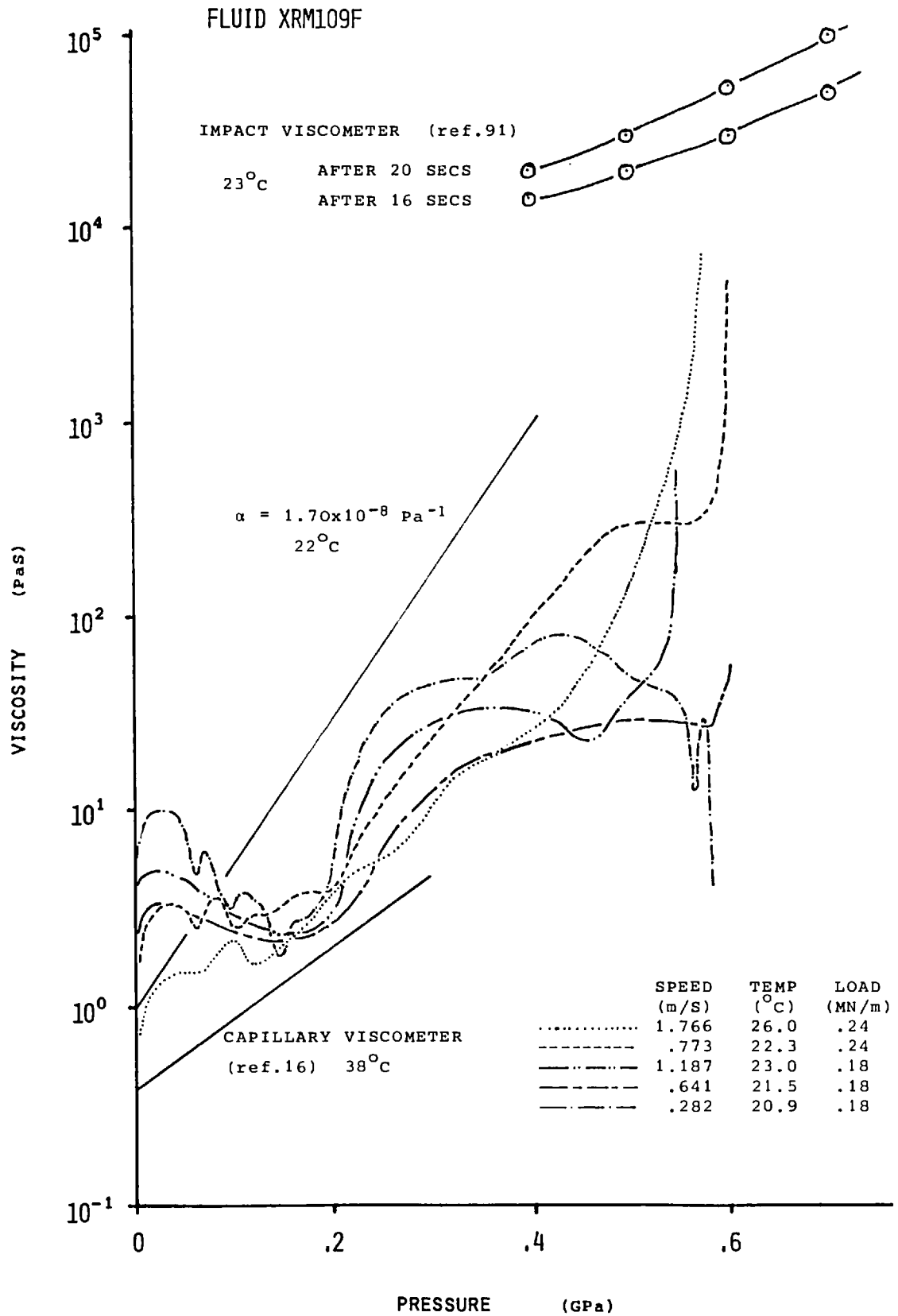


FIG 5.13

VISCOSITY VERSUS PRESSURE

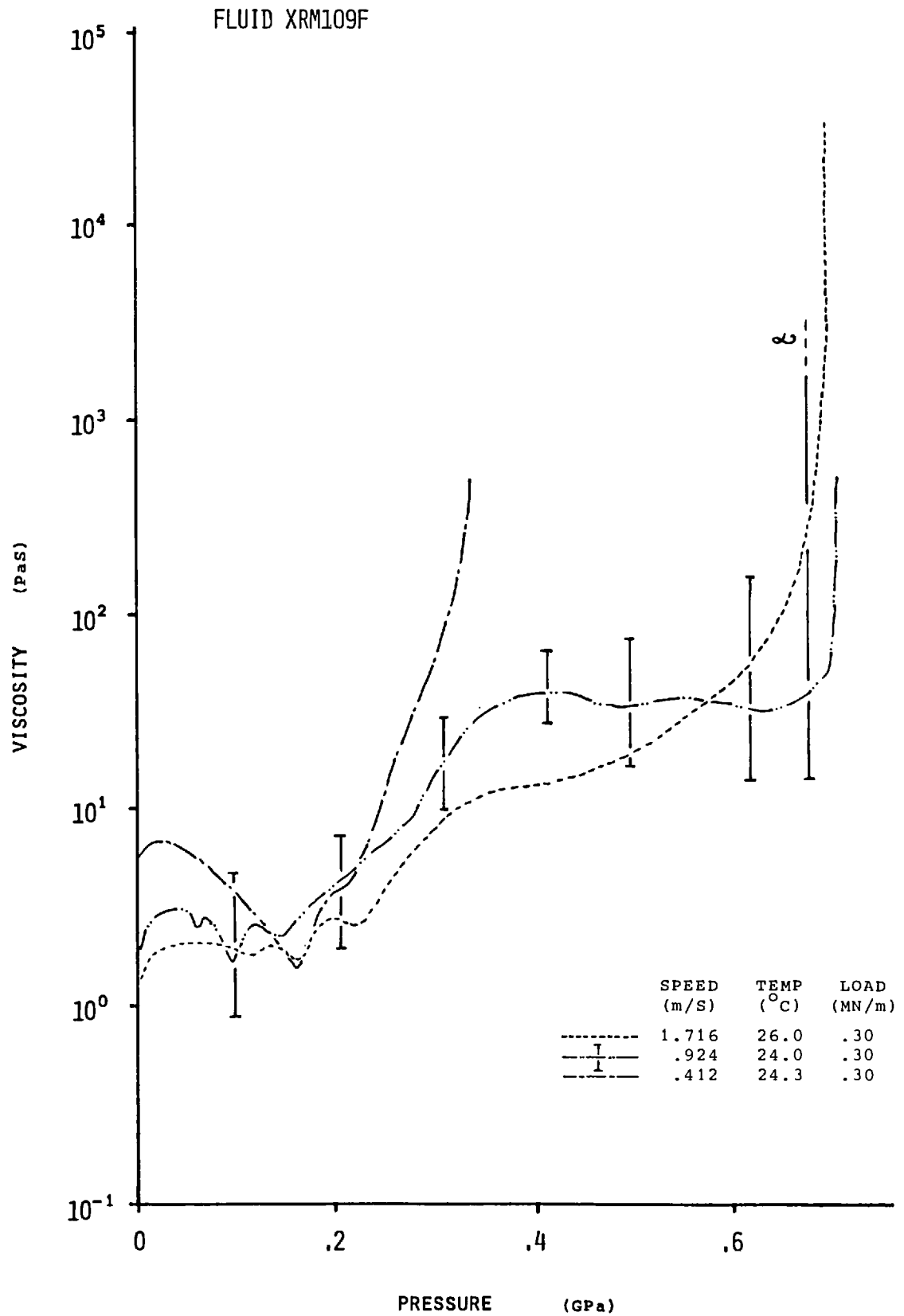


FIG 5.14

VISCOSITY VERSUS PRESSURE

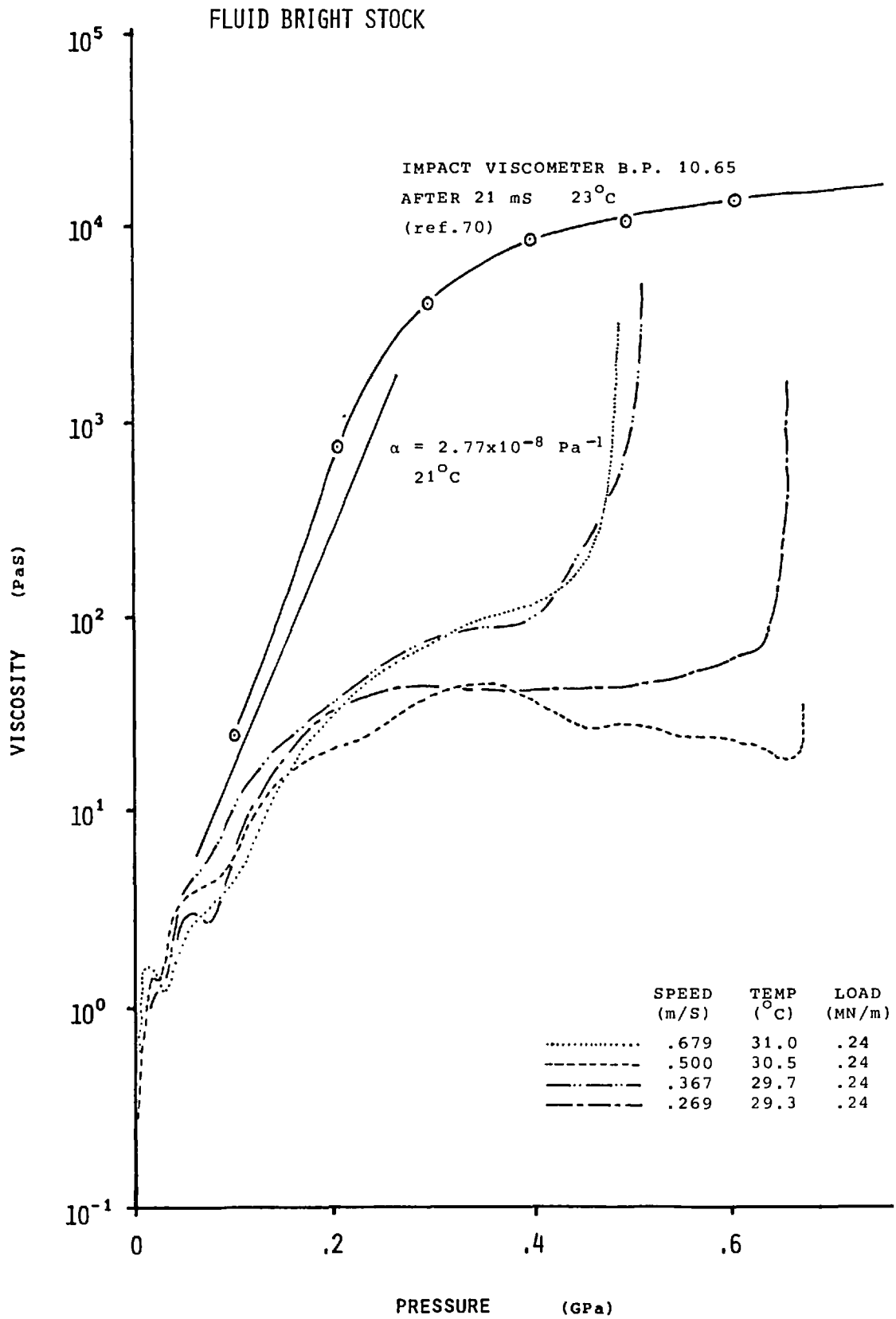


FIG 5.15

VISCOSITY VERSUS PRESSURE

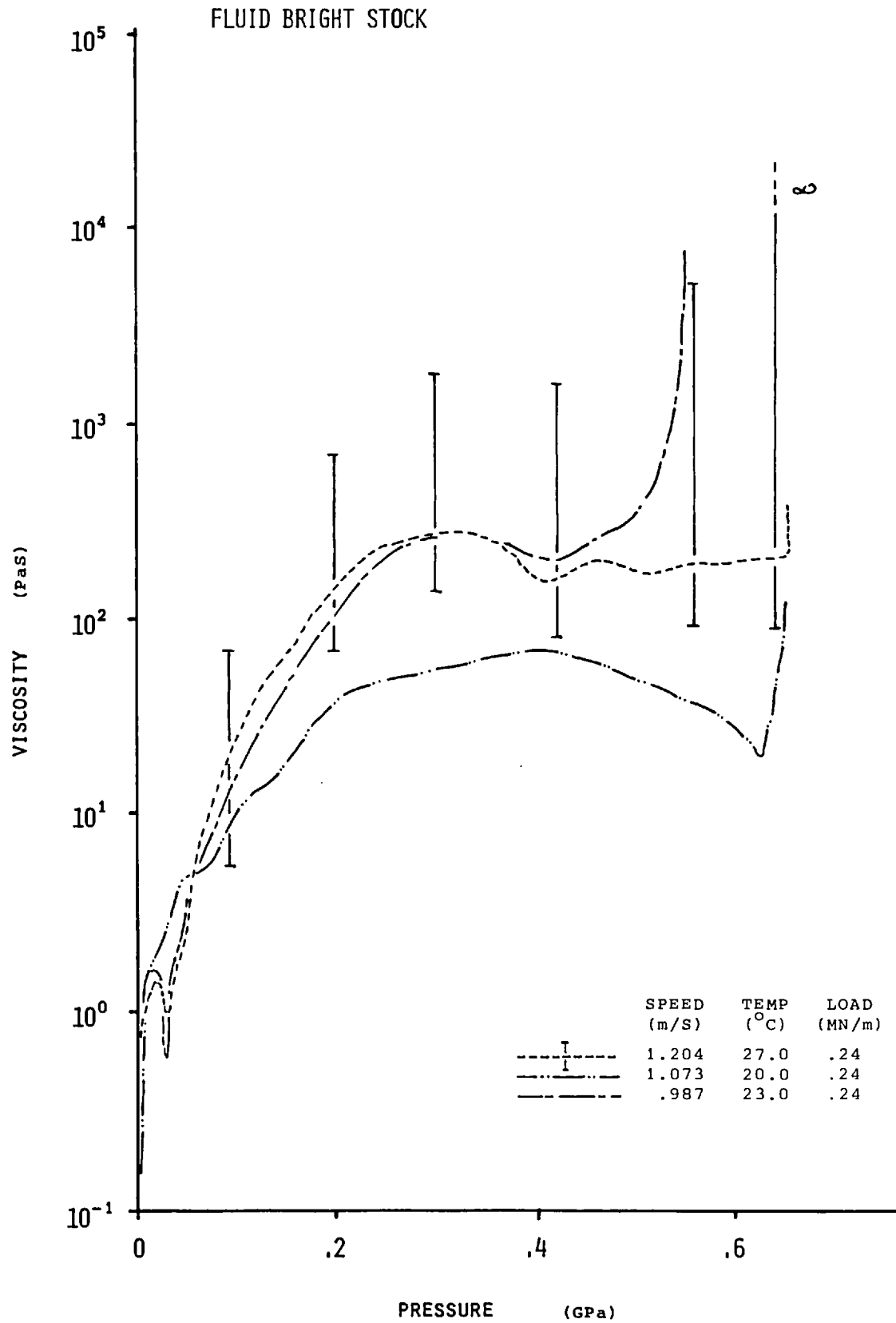


FIG 5.16 VISCOSITY VERSUS PRESSURE

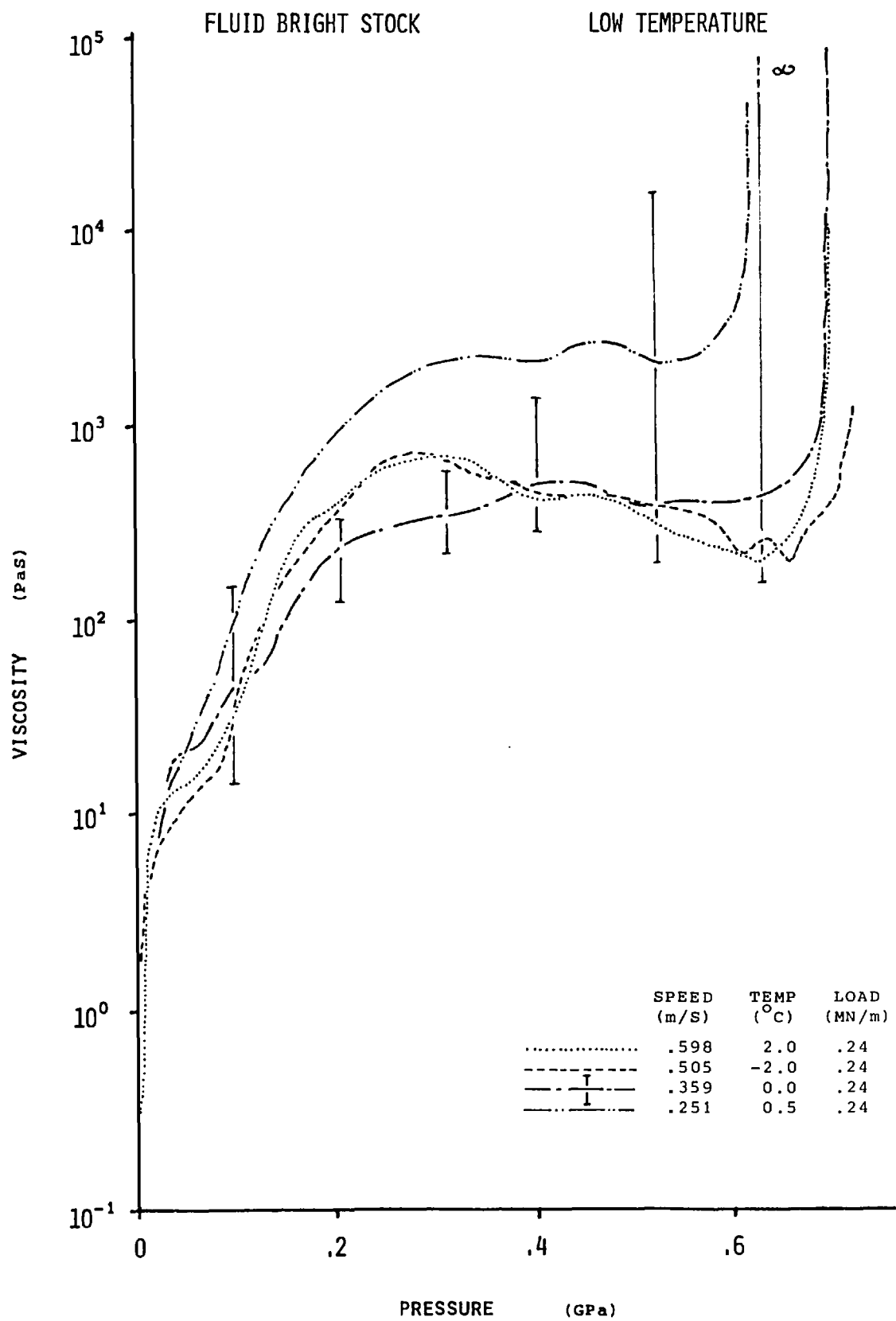


FIG 5.17

VISCOSITY VERSUS PRESSURE

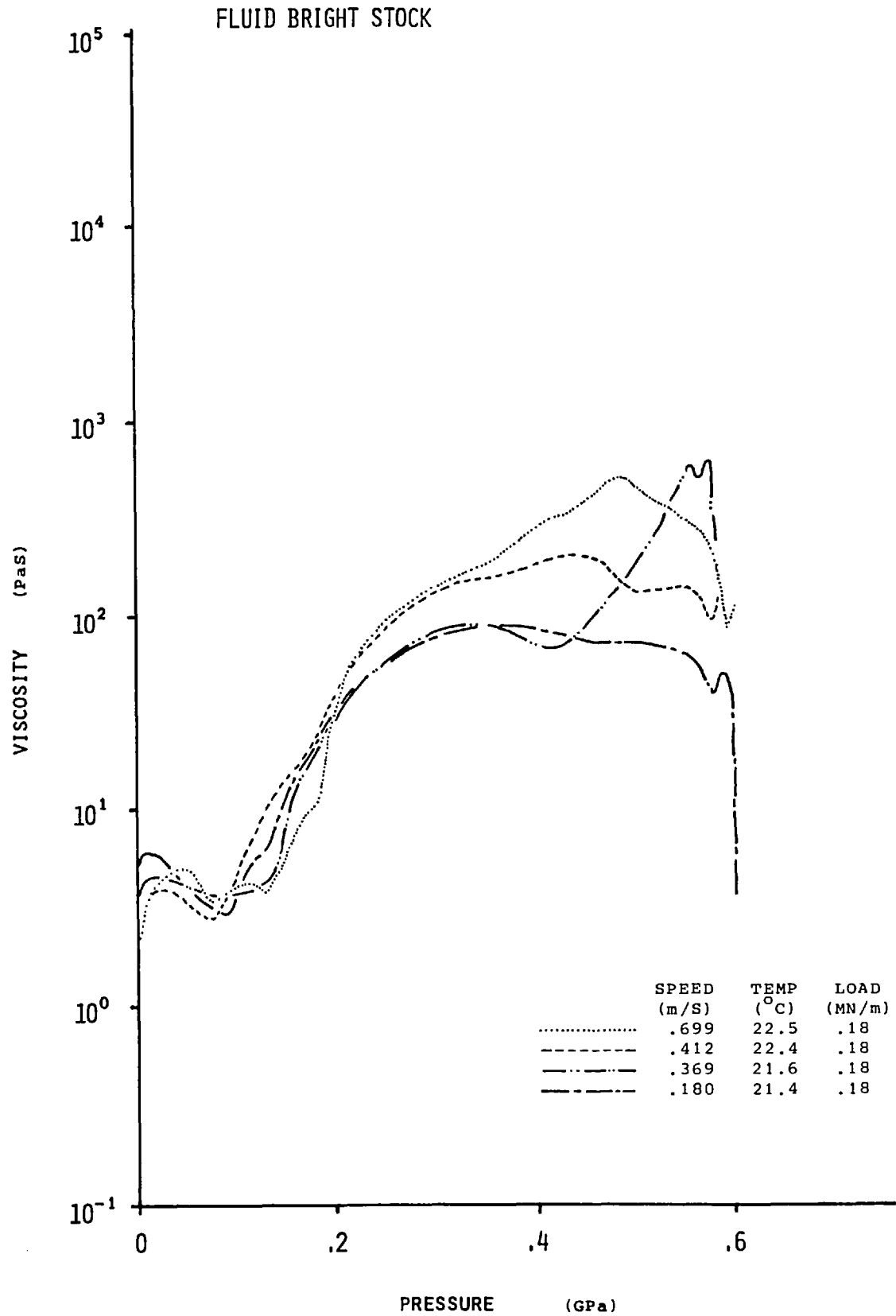


FIG 5.18

VISCOSITY VERSUS PRESSURE

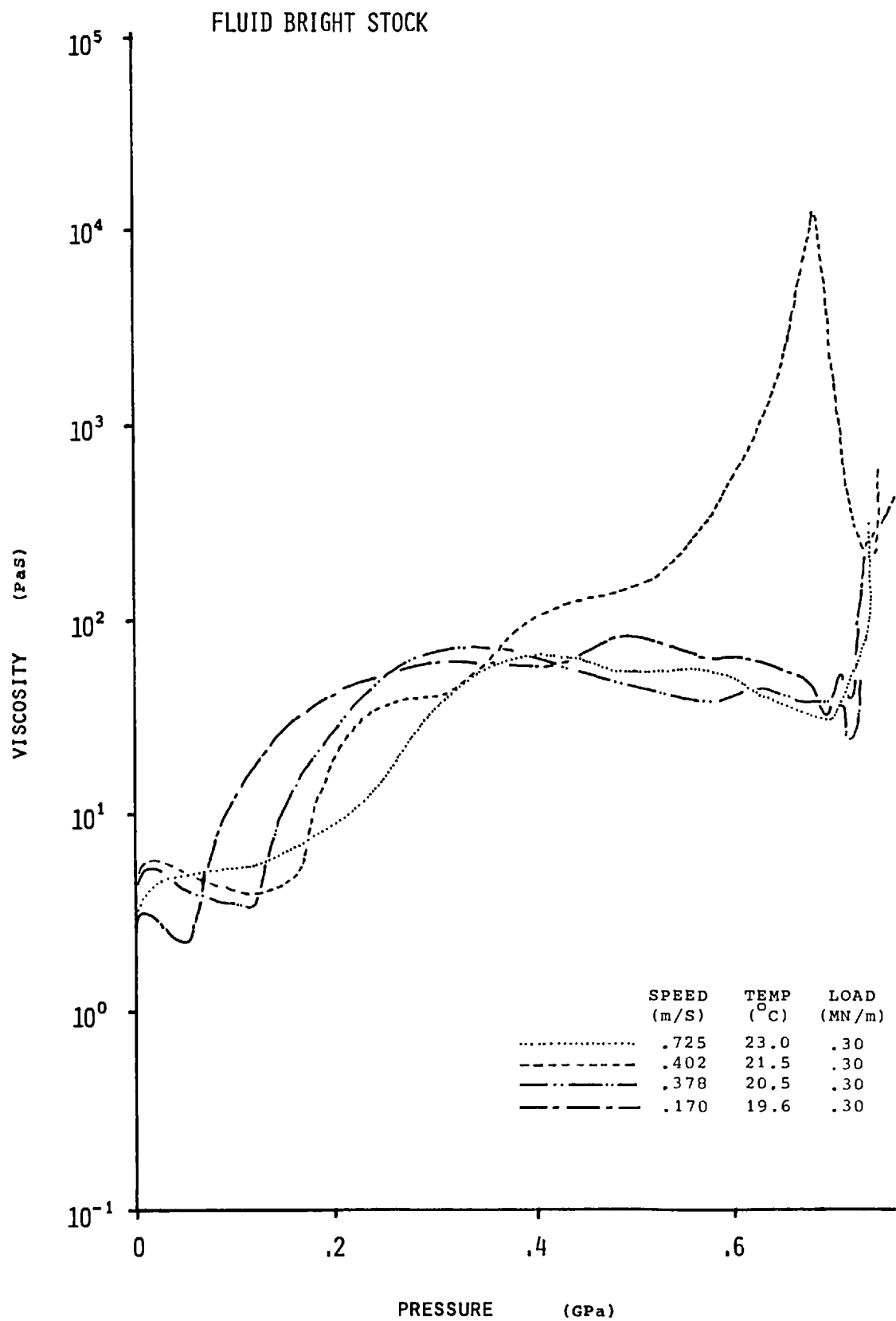


FIG 5.19

VISCOSITY VERSUS PRESSURE

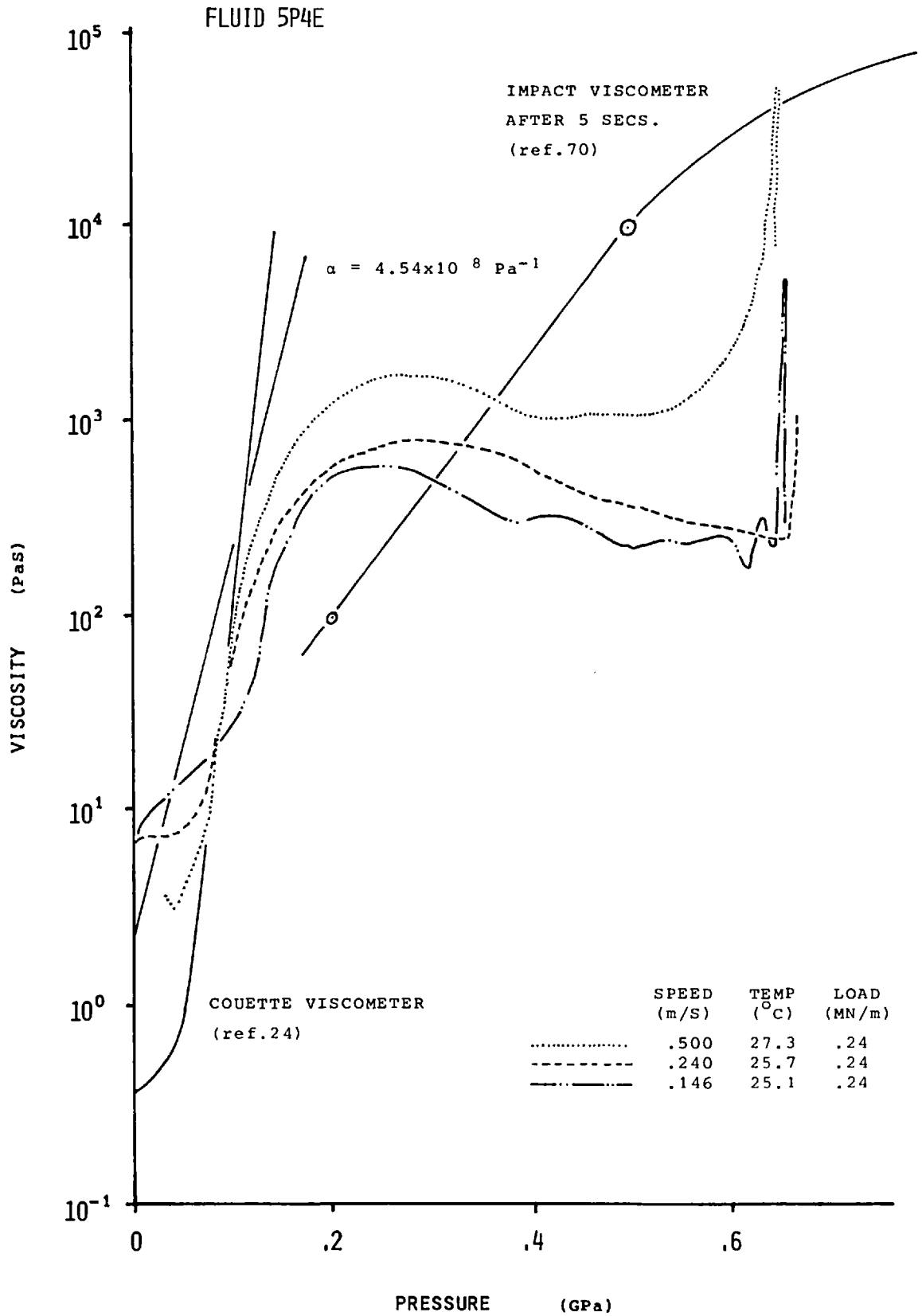


FIG 5.20

VISCOSITY VERSUS PRESSURE

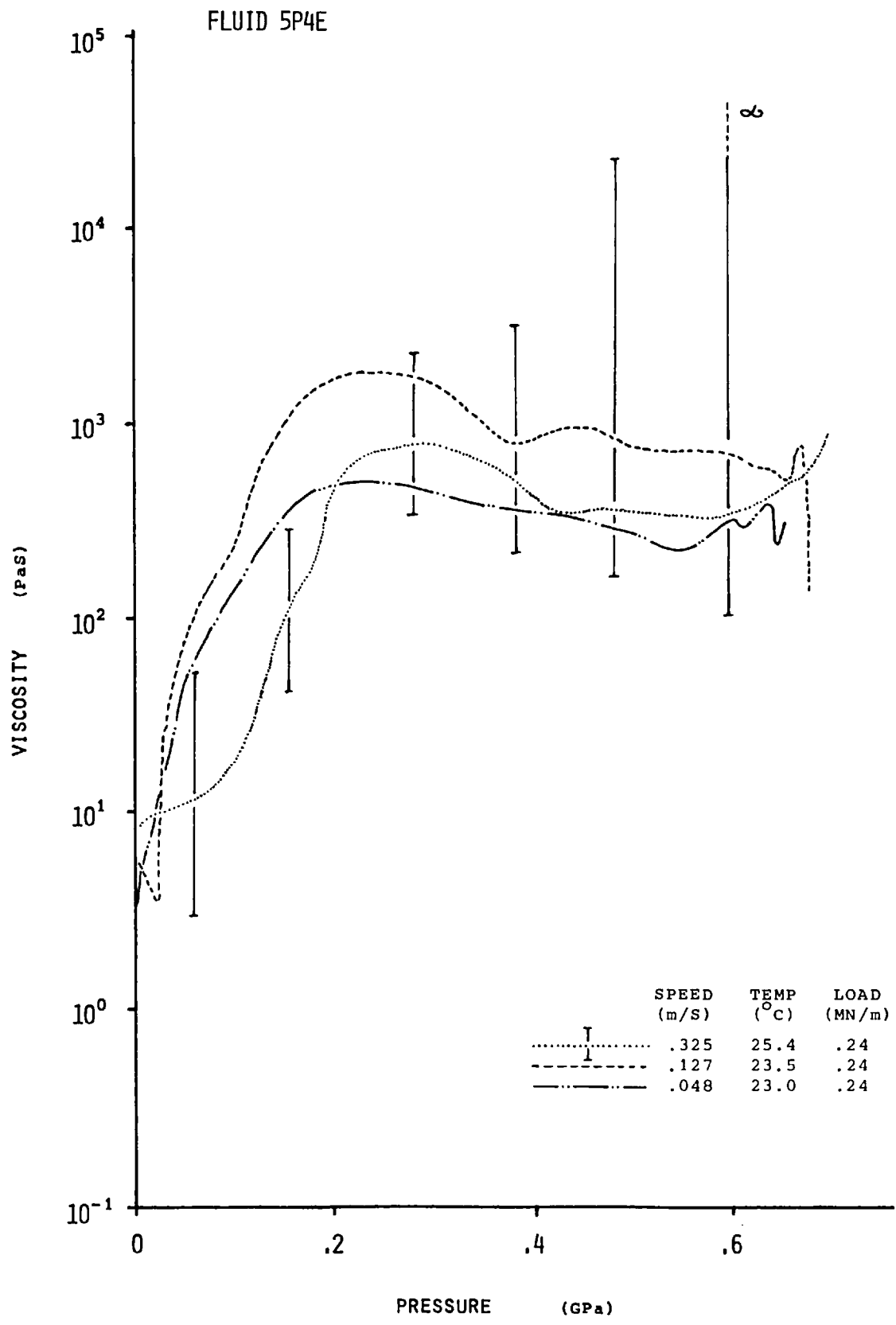


FIG 5.21

VISCOSITY VERSUS PRESSURE

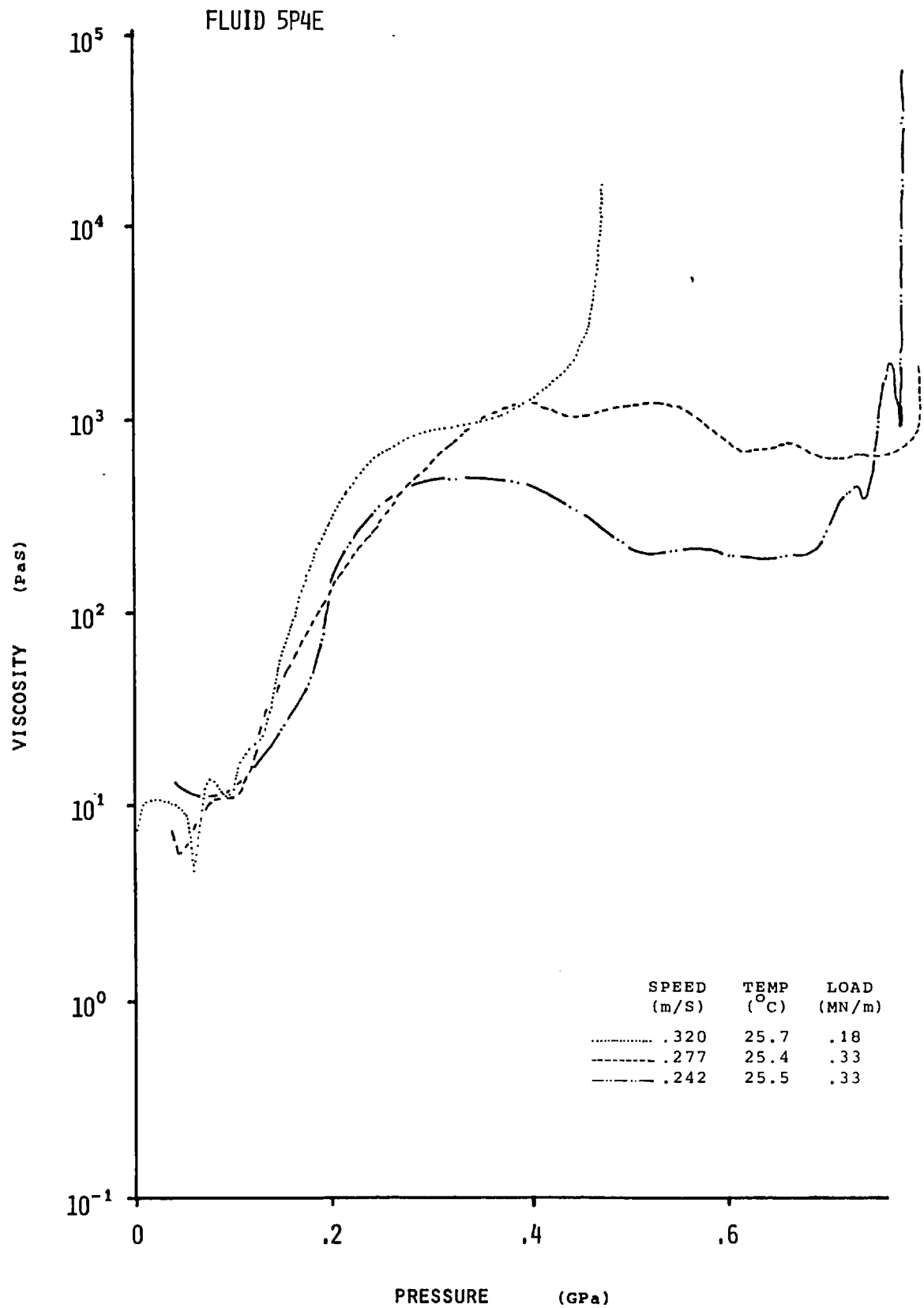
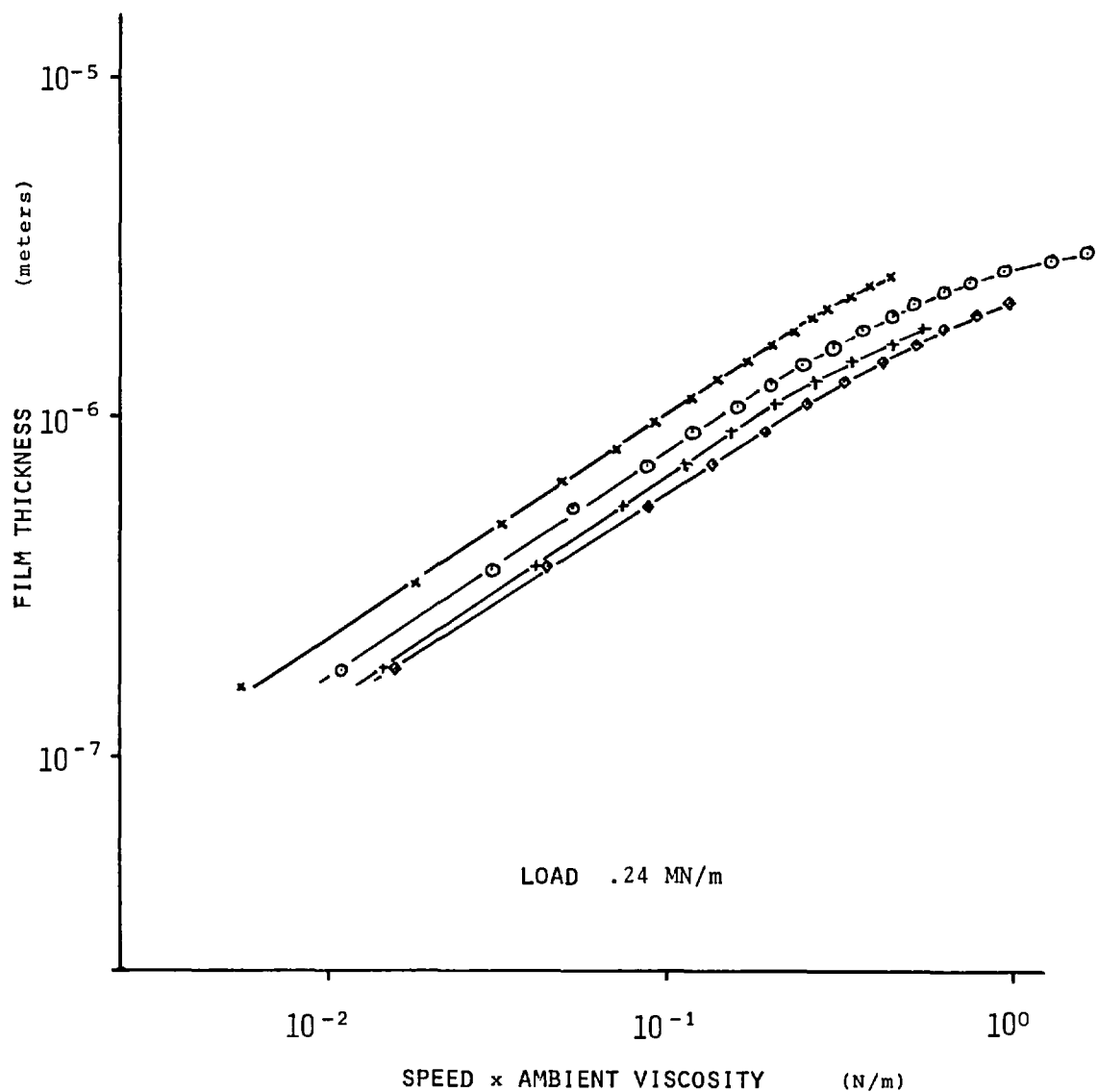


FIG 5.22 CALIBRATION FOR PRESSURE – VISCOSITY COEFFICIENT



	AMBIENT VISCOSITY (PaS)	TEMPERATURE (°C)	PRESSURE – VISCOSITY COEFFICIENT (Pa ⁻¹)
+ CALIBRATION OIL	.320	25	2.12 x 10 ⁸
◊ XRM109F	.999	22	1.70 x 10 ⁸
○ BRIGHT STOCK	1.09	21	2.77 x 10 ⁸
x 5P4E	1.95	25	4.54 x 10 ⁸

5.6 Traction Values

Table 5.1 shows typical experimental values of traction coefficient for comparison with values calculated from the viscosity profiles. The line contact viscometer results were measured under conditions either close to pure rolling, in which case the traction is not the maximum possible, or at pure sliding where rapid heating took place. Values from Duckworth's work (53) have been included as these reflect more closely the maximum traction obtainable. Unfortunately the conditions of his tests were slightly different, being a point rather than a line contact and the speeds being generally lower whilst the pressures and temperatures slightly higher. A fuller version of table 5.1 can be found in appendix 6 which shows the conditions of the tests.

The calculated values were obtained by assuming a constant 1% slip which unfortunately leads to the wrong type of speed dependence of traction increasing with speed rather than decreasing. The viscosities in the case of the Bright Stock and 5P4E were taken to be flat throughout the width of the contact at the plateau value which has probably led to a slight overestimate of the calculated traction coefficient. In the case of XRM109F an average value was used. Despite the many assumptions and differing conditions of the tests, to a first approximation, comparisons can be made their significance being discussed in chapter seven.

Table 5.1 Traction Results

<u>Fluid</u>	<u>Traction Coefficient</u>
<u>I Measured Values</u>	
a) Line Contact Viscometer	
Bright Stock	.005 ('Pure rolling')
	.15 ('Pure sliding')
5P4E	.07 ('Pure rolling')
	.1 ('Pure sliding')
b) Duckworth (ref 53)	
XRM109F	.015
Bright Stock	.01
5P4E	.07
 <u>II Calculated Values</u>	
XRM109F	.0004
Bright Stock	.0003 (Room Temperature)
	.001 (Low Temperature)
5P4E	.0005

CHAPTER 6 ACCURACY AND ERRORS

6.1 Types of Errors

In order to be able to discuss the results and draw conclusions an understanding of the possible causes of error and the effect on the final result is essential. Errors may arise either through inaccurate data or incorrect theory in the analysis of it. The possibility of inappropriate assumptions being made on which the calculations are based is discussed in the next chapter, the purpose here being to consider the accuracy of the results assuming the analysis is correct. Not only are the sources and effects of errors on the results considered, but also the steps taken to minimise them. Initially the causes and magnitude of inaccuracies in the optical film thickness are investigated, and then the accuracy of the derived parameters are considered.

6.2 Optical Film Profiles

All the calculated quantities the refractive index, density, pressure and viscosity are derived from the optical film profiles. Hence the final results, are sensitive to errors in this parameter, the most sensitive being the viscosity as outlined later. It is helpful to see the difference between those errors which are random, and those which are systematic. The errors in the calibration for film thickness versus negative density can be viewed as a random factor, whilst errors in the phase change, the magnification, the measurement of the angles of incidence, the registration of one profile to the other and the positioning of the centre are all systematic. Some of these factors more directly affect the derived parameters and are therefore discussed in those sections.

6.2.1 Calibration of Fringes

The data for the calibration curve that has been used in the calculations was collected in two groups from different sets of photographs, curves being fitted separately to each group.

The discrepancy between the two curves was found to be extremely small. It is to be recognised however that near the points of maximum and minimum intensity significant errors may arise. This is because at such points the rate of change of film thickness with negative density is very rapid and the true maximum and minimum levels are difficult to determine due to local fluctuations in the illumination. This last point was particularly noticeable with the oblique interferogram. A type of Brewster angle effect gave rise to a fringe pattern analogous to photoelastic fringes, and was present especially at high angles of incidence. The Brewster effect is where light polarised parallel to the surface is reflected more strongly than that polarised perpendicularly. Due to stresses in the glass disc, caused by loading, the angle of polarisation is rotated so that one part of the light beam is reflected more powerfully than another. Attempts to overcome this was made by rotating the incoming plane of polarisation, and circularly polarising the light but without much improvement. A compromise, sacrificing some the inherent accuracy of the refractive index, was achieved by reducing the oblique angle of incidence until the effect was small. Allowances could also be made by reference to the static fringe densitometry plot.

However the strongest argument for errors in the calibration not being too significant is that, because the fringe patterns change, a certain randomness is introduced. In one photograph the pattern would show a decreasing intensity through part of the contact, whilst in another the level would be increasing. This would give rise to errors of opposite sign. Furthermore within a single photograph the sign could change where the fringes passed through a turning point, and so be smoothed out. It is for this reason that these effects give rise to randomness and account for a large amount of the scatter in the results. A typical limit of accuracy would be a tenth of a fringe order, (approximately 15nm) though of course relative errors are less than this.

6.2.2 Phase Change

In optical interferometry it is often found that a phase change arises from the reflecting surfaces so that the zero

film thickness does not correspond to a whole number of fringes. With a quarter wavelength dielectric accurately deposited to give maximum reflectivity there is usually a phase change of π (or 180°) resulting in a dark zeroth fringe. In this case, the phase change at the normal angle, was expected to be approximately π though at the oblique angle it is complicated to know what it will be. In fact it was found that in both the normal and oblique angles the phase change appeared to be close enough to π to be able to assume it to be such. Certainly in both cases the error in this assumption is less than $\pi/4$. At the normal incidence the effect could have lead to a maximum error in the viscosity of less than 5% which is small in comparison to the random errors. Errors in the oblique value only influence the absolute level of refractive index, and has been taken into account by other means as will be outlined.

6.3 Refractive Index and Density

Since the density is derived directly from the refractive index, using the Lorentz-Lorenz relation any error in the refractive index is also present in the density, though the percentage error becomes doubled. In the main, uncertainties in the film thickness lead to random scatter in the results but systematic errors can come in through lack of precision in determining the incident angles, magnification and registration of one interferogram on the other. A further distinction needs to be made between the error in the angle of incidence, which leads to an overall increase or decrease in refractive index, and inaccuracies in registration and magnification which lead to relative errors in the profile. The most serious are the systematic type leading to relative effects since they are the hardest to detect.

6.3.1 Registration

The coincidence of the two optical profiles is determined from the cross wires in the camera. This means that vibrations of the camera could lead to poor registration. Another cause is if the roller housing position moves. Vibrations in the

camera are unlikely in view of the sturdiness of the mounting and the smoothness of the rig. However the roller position was observed to move and so care was taken to see that backlash in the locating arms was taken up before the static pictures were taken.

Despite these precautions it was found that the registration was at fault in some tests. This could be detected from the point near the pressure spike where the film profiles changed rapidly. These points could in fact be used to make corrections during the computer processing. This effect is not significant therefore in the final results.

6.3.2 Relative Magnification

Only the relative magnification between the normal and oblique patterns needs to be known for the refractive index calculations. It can be argued that since this is obtained from static fringes there is not much room for inaccuracy. Possibly spherical aberration particularly in the oblique angle of viewing could lead to local errors. Certainly outside the Herzian region the calculated refractive index shows a tendency to rise probably due to aberration. The magnification however is obtained from the edges of the Hertzian region where it is most important to know the precise value. Any effect can only be small.

6.3.3 Angles of Incidence

The angles of incidence of the two light beams are very difficult to define. The reason is that when the incoming light is not normal to the spherical surface of the window in the hydrostatic bearing, it undergoes a deviation. It is almost impossible to tell when the light is normal except by eye, and even then the light may be refracted at one of the other surfaces through the plate not being parallel. Fortunately however, looking at equation 2.2, because θ_1 is so small compared to θ_2 , then $\sin^2 \theta_1$ is insignificant. The equation therefore is linear in $\sin^2 \theta_2$. By comparing the edges of the contact where the calculated refractive index should be at the ambient value with the true ambient value,

a correction throughout the contact can be made by addition or subtraction of a small amount. The correction should strictly be a multiplication but this error is insignificant compared to other effects. Although this correction is primarily for angle of incidence inaccuracies, at this stage deviations of the phase change from π are also taken into account, since it is impossible to separate out the two errors. The error bars (figures 5.3, 5.5, 5.10) do not reflect these effects and subsequent corrections.

When it comes to calculating the absolute film thickness from the normal optical profile, error due to the incident angle is again insignificant since it does not introduce relative errors. A small adjustment is made for the slight deviation as the light enters the test lubricant.

6.3.4. Refractive Index of Glass

The refractive index of the glass has been supplied by the manufacturers, as was the Youngs modulus and has also been checked on an Abbe Refractometer. It is known to three decimal places. It should be pointed out however that under pressure the refractive index will increase. The increase in this can only be small compared to that of the oil since the modulus of glass is approximately fifty times greater. The change of refractive index also means the light will be derivated. Fortunately however the changes in the index and direction cancel each other out so that there is no nett effect on the calculated value for the oil.

6.4 Pressure

The program for the calculation of pressure has already been extensively used by Wymer (80) and found to give sensible values of pressure over a wide range of speeds and loads. Nevertheless a check was carried out by inputing a Hertzian film profile and seeing what pressures were calculated. Unfortunately a completely symmetric shape cannot be handled, and so a very small shift of the centre was made. The calculated pressures correlated very well with the Hertzian pressure profile, apart from the extreme edges, where probably due to the very rapid

change of film thickness, and the slight shift of the centre, small perturbations were obtained. As the important property in the calculation of viscosity is the pressure gradient rather than pressure the program was accepted as being accurate enough for the purpose of these experiments.

Certain unsatisfactory features have occurred however in a few of the calculations. A plot showing these effects is given in figure 6.1. In the inlet region there was often a slight dip in the pressure at the start of the Hertzian zone, i.e. at about .1Gpa. It was also found to occur in the exit region just after the pressure spike where the values sometimes even went negative. Ranger (79) also found this and attributed it to the springing back of the roller after the pressure spike. There is no other independent investigation with a similar observation which would support this explanation and the effect could just be due to the programme itself. In these zones therefore it has been necessary to apply some smoothing and accounts partly for the large error bars in the viscosity determinations at low pressures.

The pressure spike was often found to be unusually large but the likely explanation for this is that the film thickness profile did not have a proper correction for refractive index at that point. Due to the very rapid change in film thickness the refractive index is somewhat lacking in accurate definition, and so any spike in this parameter similar to the pressure spike is smoothed out. This leads to values of film thickness which are too great, which in turn leads to the pressure spike being exaggerated. In a few cases however the refractive index and density were obtained from equilibrium pressure-density data using an iterative procedure which will be outlined in chapter seven, so that rapid transients were not smoothed out. There still was found a large spike in the pressure. Since it might be expected that the density and refractive index will not have time to respond fully to the pressure spike it may be that the spike shown in figure 6.1 is not too greatly exaggerated. This does therefore point to evidence for the existence of a spike similar to that predicted by theory, although other experimental results (61) would suggest otherwise. Whatever is the case, since viscosities are not calculated in the exit region, for the

FIG 6.1 PRESSURE VERSUS DISTANCE

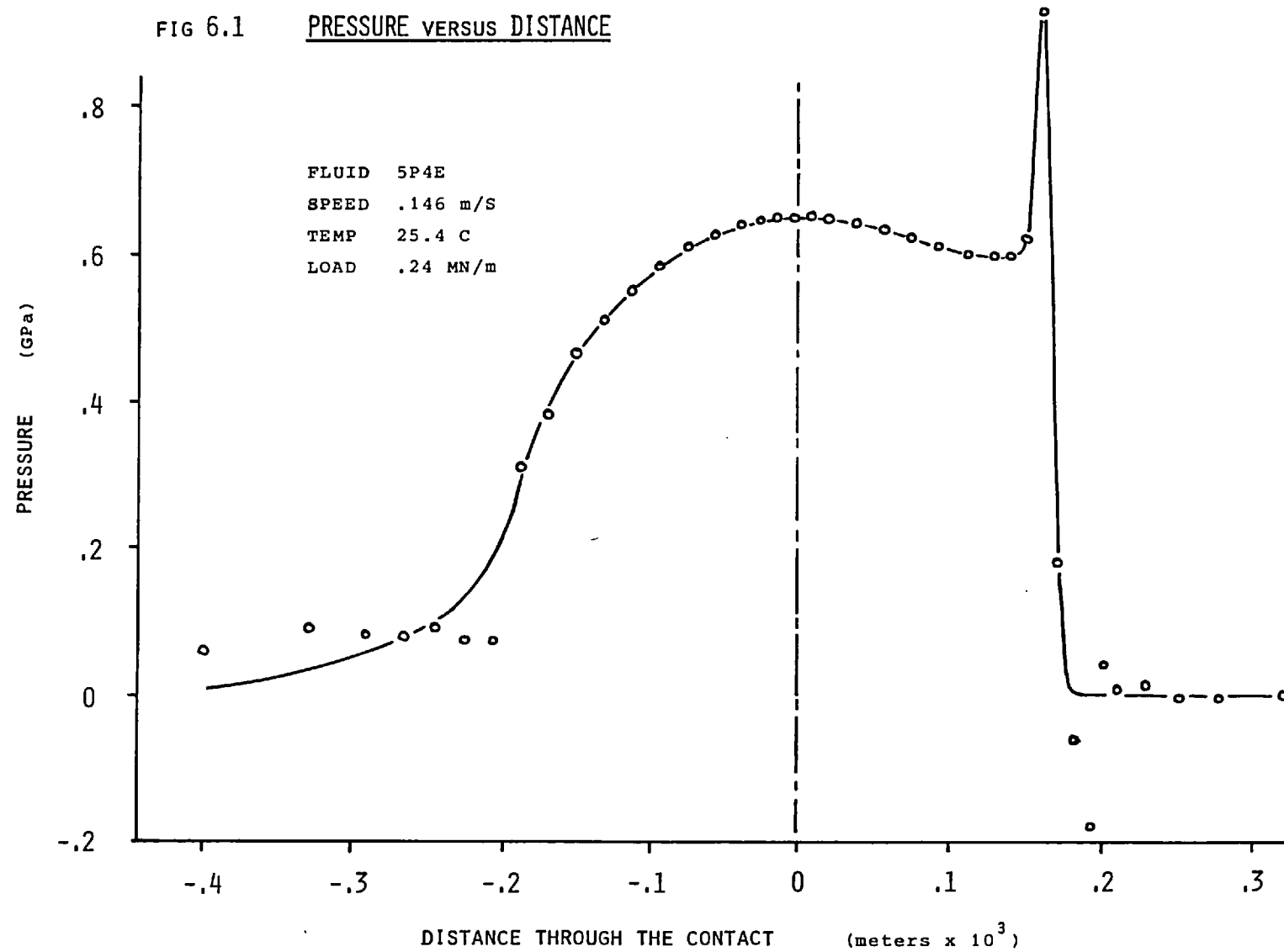
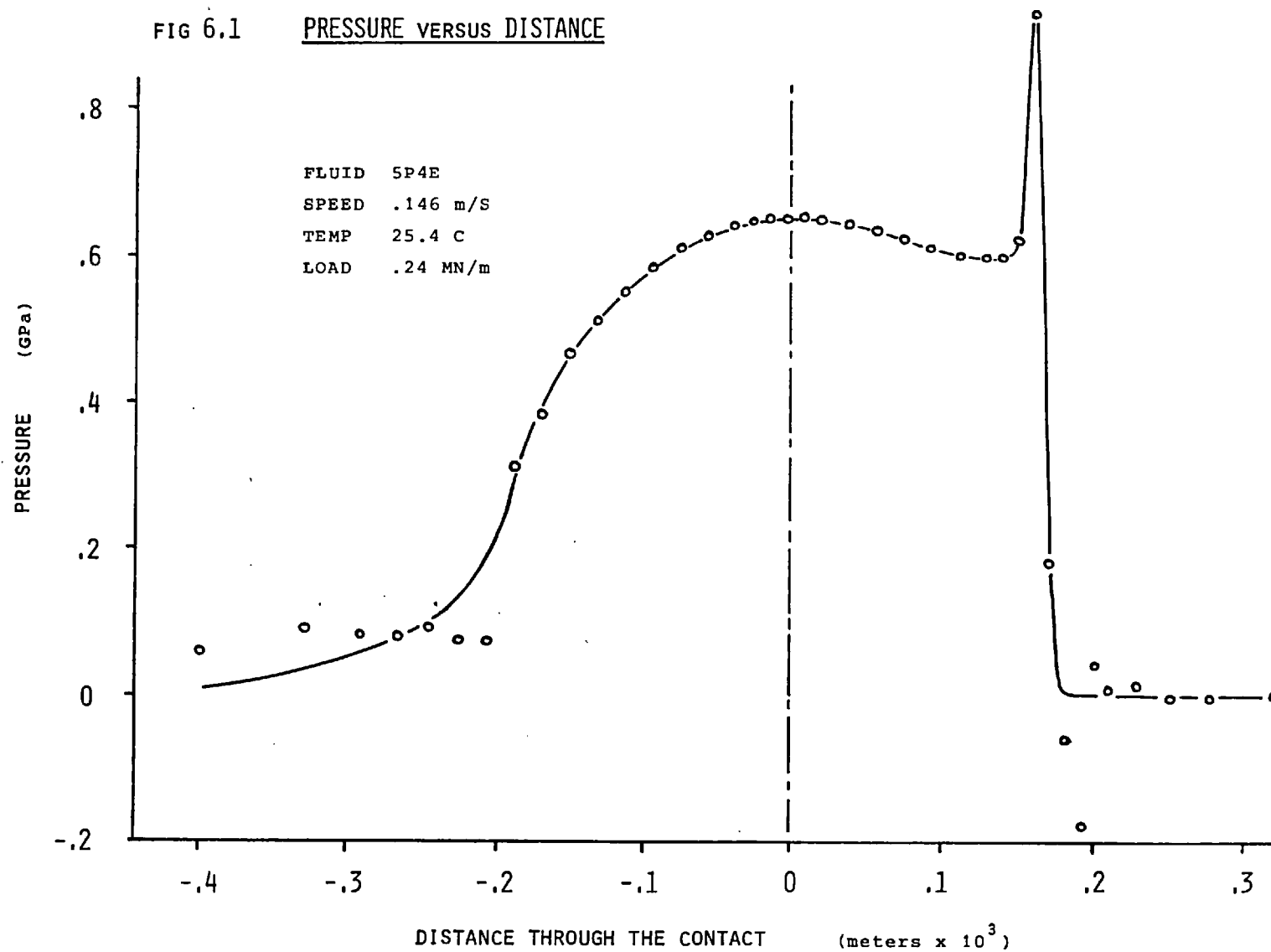


FIG 6.1 PRESSURE VERSUS DISTANCE



purposes of this work the effect may be ignored. Two important measurements which affect the pressure are the magnification and the position of the centre. These will be discussed in turn.

6.4.1 Absolute Magnification

The estimated level of error in the magnification is set at about 5%. In the far extremes of the profile, often it was found that the pressures could be considerably out. Usually the first point in the calculation was two to three half widths from the centre, and the last point was at the position of air entrainment in the exit region. In these positions the film thickness has considerable gradient and therefore an error in magnification gives a large error in film thickness. In the centre however the profile is very flat and so is relatively insensitive to the magnification. The pressure is completely independent of the centre line film thickness since only the deformations matter. This means that phase changes have no effect.

6.4.2 Position of the Centre

For the same reasons that the registration of the fringe patterns was not always exact (see section 6.3.1) it can be assumed that the defined centre of the profile was also not exact. This in fact appeared to be the case. The pressure program has the facility for trying the center in various positions. The program also performs an integration of the pressure to yield the load per unit length of roller. This can be used as a check to see when the centre has been correctly positioned. Also, the profile can be observed to see when the values in the inlet and exit regions give sensible shapes following reasonably smooth curves towards the base line. Generally it was found that when this was obtained the integrated pressure agreed well with the known load. The centre was generally not shifted more than a tenth of a contact width and produced agreement of the calculated and true loads within 5%.

6.5 Viscosity

In the calculation of viscosity there are two terms in the Reynolds' equation (equation 2.5) which are very sensitive to errors, the pressure gradient which has already been mentioned and the bracket $(1 - \bar{\rho}\bar{h}/\rho h)$. The error bars drawn on figures 5.13, 5.15, 5.16 and 5.20, show these two terms combined. As was mentioned in the results at low pressures the errors arise through poor definition of the pressure near the inlet, while at high pressures the value of $\bar{\rho}\bar{h}/\rho h$ becomes very close to unity leading to ill conditioning. The only other variable term which comes into the equation is the speed. This can easily be defined to better than 1%.

6.5.1 The Bracket Term

The bracket term $(1 - \bar{\rho}\bar{h}/\rho h)$ cannot obviously be taken completely in isolation from the pressure since the values of $\bar{\rho}$ and $\bar{h}$ depend on the point at which the pressure gradient is zero. It is found though that the pressure gradient in the centre region is relatively insensitive to the film thickness profile. Since the important parameters are the relative values of ρ and h with respect to $\bar{\rho}$ and $\bar{h}$, all of the error can be thought of as occurring in ρ and h whilst taking $\bar{\rho}$ and $\bar{h}$ as accurate. The absolute value of film thickness is of the order of 5%, but the ratio $\bar{h}/h$ is much better than this and depends on position in the contact. At the inlet edge of the contact the error is of the order of 0.5% and becomes smaller further into the contact. The same order of magnitude errors are true of the refractive index, usually slightly larger. This shows the importance of the distinction between relative errors in the profile and absolute errors. The distinction between the systematic and random errors also is important. The effect of the known systematic errors is estimated to be smaller than that due to random errors but it is exceedingly difficult to attach a meaningful figure to this. The random errors account for the large scatter in the results but systematic errors are much harder to detect. More will be mentioned on this point in the discussion of the results.

There is a beneficial effect in the combination of ρ and h . Because the absolute thickness is obtained by dividing the normal angle optical value by the refractive index, errors in the film thickness as a result of the refractive index are offset by the errors in the density. So for instance, an error of +1% in the refractive index gives a value of h 1% too low, but the density is about 2.5% too high. The overall error in ρh is then +1.5%.

If the consideration of errors is taken a stage further back it can be seen that there is a further playing off of errors against each other. Table 6.1 shows how an error of 1% in either of the optical film profiles affects the product ρh . It can be seen that a 1% error in the normal optical film thickness leads to only a 1% error in ρh of opposite polarity, whilst an equivalent error in the oblique value gives 2% of the same polarity. The magnitude of these errors are chosen only to show their effects and do not reflect the actual sizes which are dependent on position in the contact as already stated.

Table 6.1 Effect of Errors in Optical Film Thickness on Density Times Absolute Film Thickness

Normal Optical Film Thickness	Oblique Optical Film Thickness	Refractive Index (n)	Absolute Film Thickness (h)	Density (ρ)	Density x Abs. Film (h x ρ) Thickness
$\pm 1\%$	0%	$\pm 1.3\%$	$\pm 2.3\%$	$\pm 3.3\%$	$\pm 1.0\%$
0%	$\pm 1\%$	$\pm 1.3\%$	$\pm 1.3\%$	$\pm 3.3\%$	$\pm 2.0\%$

CHAPTER 7

DISCUSSION OF RESULTS

In both the density and the viscosity, the magnitude of the errors has made it difficult to draw firm conclusions. However trends can be picked out and give evidence of certain phenomena occurring in the contact. The major part of the discussion is on the viscosity since this is the most important of the two parameters in an ehl contact, and consequently a fuller comparison of this work with other results can be made.

7.1 Density

As has already been mentioned, the large scatter of maximum density is due to the lack of precision in the measurement of the angles of incidence. However the relative shape of the profiles does reveal some insight into the behaviour of the fluid.

All the curves (figures 5.2 to 5.11) show a tendency towards what would seem to be an unusually low density at low pressures. This would tie in with the granular concept of Gentle (46) and Gentle Paul and Cameron (78). Their theory predicts that in a region of high shearing such as that found in the inlet zone of an ehl contact, the densities will have depressed values to allow the granules room to slide over one another. Another explanation could be that shearing in the inlet produces a temperature rise leading to a lower than expected density. A more likely explanation however is that this effect is due to the errors of defining the pressure in the inlet region. At less than .2GPa there is considerable scatter in the pressure points calculated and the pressure profile is dependent on the type of smoothing that is assumed. Therefore little significance is attached to this apparent effect.

A pressure density plot for 5P4E from the impact viscometer (83) is shown in figure 5.9. The time between the ball dropping and the moment of measurement for this curve is unknown but it is a few orders of magnitude greater than the time scale for these experiments. A comparison of all the curves for this

fluid (figures 5.9 to 5.11) emphasises the sharp change of gradient at about .2GPa compared to the impact viscometer curve. The other two fluids (figures 5.2 to 5.8) do not exhibit the same sharp change of gradient on such a consistent basis. This behaviour could be explained by the results of Alsaad, Bair Sanborn and Winer (65). They show on the basis of light scattering and dilatometry experiments, that a fluid may easily undergo a glass transition in the high pressure region of a contact. The reason for 5P4E showing this behaviour and not the other two fluids is that at room temperature 5P4E has a very low glass transition pressure, compared to other fluids. Their light scattering data shows that at 25°C the liquid would transform at about .15GPa although from their dilatometry data the transition is nearer .3GPa. If the rates of compression are taken into account this would bring the transition point to a close agreement with the pressure of the knee in the density curve. The two other fluids at room temperature would almost certainly not show such behaviour in the pressure range of these experiments.

It is tempting to speculate that a transition can be seen in the low temperature Bright Stock results (figure 5.6) at about .4GPa which would correspond to the transition values for hydrocarbon oils given by Alsaad et al. More will be said about this point in the discussion of the viscosity results.

The response of the 5P4E to pressure is similar to the behaviour predicted by Heyes and Montrose (76). They develop a model based on free volume theory in which the fluid instantaneously occupies the free volume, followed by a structural rearrangement. Their theory may account for the difference between the impact viscometer and the line contact viscometer pressure density profile for 5P4E. In the impact viscometer the fluid has time to adjust but not in the short times of these experiments. Unfortunately however their theory does not explain the difference of behaviour between the fluids since it would be expected to show the sharp knee for all of them. The truth may lie in a combination of both a phase transition and a structural reorientation following an instantaneous density rise.

A discussion of time dependency of the density will be given later along with a consideration of the effect in the viscosity.

7.2 Viscosity

The most striking feature of the viscosity curves is the way in which 5P4E exhibits an apparent limiting viscosity with a very pronounced turnover point at about .2GPa (figures 5.19 to 5.21). The viscosity above this pressure does not seem to rise and in some cases even drops. A similar behaviour is exhibited by the Bright Stock at the low temperature tests (figure 5.16). At normal temperature only some of the Bright Stock tests show a limiting viscosity (figures 5.14, 5.15, 5.17 and 5.18), and with XRM most of the tests show the viscosity continuing to rise (figures 5.12 and 5.13).

The XRM curves show peculiar effects in the low pressure region but this is attributed to errors in the pressure gradient. The effect is most noticeable with XRM 109F because the rolling speeds were generally higher than for the other two fluids thus bringing the experiments closer to hydrodynamic conditions. This would make errors in the pressure gradient more likely.

The viscosities as derived from the exponential viscosity relationship using the α -values calculated from film thickness measurements are used as a basis of comparison at low pressures (figures 5.12, 5.14 and 5.19). Also included on these graphs are the viscosities measured in the impact viscometer (70,91), the plot obtained by Jones et al. (16) for XRM 109F (figure 5.12), and the Couette viscometer results of Hutton and Phillips (24) for 5P4E (figure 5.19).

Agreement of the viscosities derived from α values with the low pressure region of the curves is reasonable for 5P4E and Bright Stock but less good for XRM 109F. It is interesting to note that Duckworth (53) using the same method obtains a lower α value for this fluid than that measured here, and at a temperature closer to that at which most of the tests were carried out. Jones et al. made their measurements at considerably higher temperatures. At low pressures therefore the agreement with other methods is good when the magnitude of the error bars is considered.

Comparison at higher pressures can be made by consideration of the maximum traction obtainable assuming the viscosity remains unaltered for typical traction peaks. Even assuming a 1% slide role ratio, which is an overestimate of the sliding, table 5.1 reveals that poor agreement is reached. Although it is true that the conditions of the tests

particularly those carried out by Duckworth do not match those under which the viscosity measurements were made, it is very apparent that the predicted values are one to two orders of magnitude lower than the measured values. The discrepancy is largest for 5P4E and the Bright Stock at low temperature if the temperature is taken into account, although it is still significant for the other tests. It must be noticed however that the XRM 109F curves are continuing to rise and therefore the calculated values may be artificially low.

This discrepancy is not an isolated discovery in that Paul (70) found that with a Bright Stock at the shortest sampling time the viscosity was one order of magnitude below that expected from traction measurements, (see figure 2.1), as was discussed in the Literature Survey. This result was not considered too significant in view of the fact it could have been due to compressional heating. The results here however indicate that it is significant.

Various theories have been considered to account for the anomaly and will be outlined. Before this is attempted however, in view of the ill conditioning of this method particularly in the high pressure region a further consideration of errors will be discussed.

7.3 Error Effects

Although a complete chapter on errors and accuracy has been presented, the purpose here is twofold; to look for systematic errors of a particular nature which would account for the discrepancy, and to consider the possible failure of the theory on which the calculations are based. Part of the approach of investigating these possibilities has been to work backwards. By assuming a result on the basis of the traction measurements, values of parameters have been calculated which would give such a result. Experimental errors are possible in the pressure gradient, the density and the film thickness. Failure in the theory could be either in the breakdown of the Lorentz-Lorenz relationship, or in the conditions of Reynolds' equation not being satisfied.

7.3.1 Pressure Gradient

Errors in the pressure gradient which would account for the low viscosities can be discounted. A possible factor of ten could be found by considerably altering the pressure profile to one akin to a hydrodynamic shape. But since the factor is nearer one hundred and the experiments are conducted far from hydrodynamic conditions this error can be ruled out.

7.3.2 Density

Because the density is so susceptible to the errors in the raw data, equilibrium pressure density data was tried out instead. The data used was that of Paul's (83) (figure 5.9) for 5P4E. This data has been found to agree with equilibrium bulk modulus values. The pressure calculation program was used in an iterative mode (see appendix 3) whereby the refractive index was calculated from the pressure after each loop and a correction applied to the film thickness until convergence was reached. The density was related to the refractive index by the usual Lorentz-Lorenz equation. The only raw data that was required therefore was the normal angle optical profile, which is the more accurate of the two interferograms.

This procedure was carried out on three of the 5P4E results and in none of the cases was the viscosity significantly higher. If anything the curves were more erratic showing a dip in the centre.

Another method of looking at the error in the density was to work in reverse. Guessing a viscosity profile, the density that would give such a profile was calculated. The refractive index was not varied so the absolute film thickness remained the same. Peculiar effects were obtained in the two tests looked at this way. In one, a 5P4E run, a dip in the density on the inlet side of the contact was obtained. In the other a Bright Stock test a rapid increase of density up to the position of zero pressure gradient near the centre was found. One further test was conducted in which the refractive index was coupled to the density via the Lorentz-Lorenz law and hence the film thickness varied. This gave no better results. From these three strange results and the

other checks it can be inferred that an error in the density alone will not be sufficient to account for the discrepancy.

Another consideration is whether the Lorentz-Lorenz law is breaking down under the rapid changes in the contact. This is difficult to know since no work has been done to check the law under rapid changes of pressure. However in the checks just mentioned, in which the density alone and then the density coupled with refractive index was varied to give the guessed viscosity, it was not obvious that such a failure would be the cause. The theoretical consideration behind the law also gives no indication that it would break down under rapidly varying pressure.

7.3.3 Film Thickness

A process, similar to that for calculating the density using an assumed viscosity profile, was applied to the absolute film thickness. The densities used for these calculations were those obtained from the iteration of the three 5P4E tests mentioned earlier. The film thicknesses were calculated by working backwards via the Reynolds' equation.

The slopes thus obtained were significantly outside the maximum experimental error. These tests were in effect, not just tests of the absolute film thicknesses but also, checks of the validity of the Lorentz-Lorenz relationship. The variation in absolute film thickness can be viewed as a variation of the refractive index since it is the largest source of error in the film thickness. Because the densities in these tests were determined from equilibrium measurements, the refractive index was thus being varied independently of the density. The outcome of the tests revealed that only if the densities in the inlet were lower whilst the refractive indices were higher within experimental error would the viscosities be higher. This could occur if say the refractive index of the fluid was affected most by the compression of the hydrogen to carbon bonds in the molecules which could move rapidly under pressure. The density however might be controlled more by the carbon to carbon and ring bonds and the orientation of the molecules which would be a slower moving

process. However against this argument it must be said that the refractive index would have to consistently be higher than measured to give the higher viscosities and so seems unlikely. Unfortunately there is no way of checking this idea from these experiments and it must be left to be investigated by some other method.

7.3.4 Combined Errors

Assuming the theory is valid, experimental errors in refractive index and density, film thickness, and pressure can only combine to give constantly low viscosities if there are systematic errors in the raw data. Working backwards to find what changes in this would be necessary to fit a guessed viscosity profile is extremely complicated and uncertain and therefore has not been attempted. Knowing how the margin of random errors in the raw data affects the final result does give some idea of what changes would be necessary, although this does not include an evaluation of how changes in the raw data affect the pressure. However in consideration of what would give a systematic error leading to low viscosities it is difficult to envisage such a mechanism. It must be concluded therefore, that although the possibility of the unexpected viscosities being due to some unknown systematic experimental error cannot be ruled out entirely, it does not seem great.

7.3.5 Failure of Reynolds' Equation

Failure of Reynolds' equation to correctly calculate the viscosities may occur if one of the assumptions in the derivation is invalid. The assumptions are

- (1) The body forces are negligible, i.e. no gravitational, magnetic forces etc.
- (2) Lubricant inertia is neglected.
- (3) The radius of curvature is much greater than the film thickness, i.e. there is no change in the direction of motion.
- (4) The flow is laminar.

- (5) The pressure is constant throughout the thickness of the film.
- (6) The viscosity is constant throughout the thickness of the film
- (7) There is no slip at the boundaries.
- (8) The viscosity is Newtonian.

It is reasonable to assume that the first five assumptions are valid although the fourth and fifth are more intuitive than there being any evidence for them. There is a real possibility that the sixth is violated and this is dealt with in the section considering shear thinning at boundary surfaces (Section 7.6). The seventh also falls somewhat into this last point. There is no known way of checking these two assumptions. The eighth point is definitely violated in certain cases where shear stresses become large, for instance in the inlet and exit regions (47, 59, 63). However there is no reason why an effective viscosity may not be calculated. Thus in these experiments the parameter calculated is called the 'viscosity'. The implication is however that it is really an effective viscosity i.e. the ratio of shear stress to shear strain, which may be dependent on the stress.

7.4 Traction Dependent Viscosities

Since these experiments are conducted in nearly pure rolling it could be argued that the viscosity has a low value under such conditions and only rises when traction is applied, for instance if traction somehow caused an alignment of the molecules which increased its viscosity. Attempts were made as has already been stated to conduct tests with pure sliding but with little success. However since plots of traction coefficient versus slide-roll ratio are linear at low sliding, such effects would also have to be linear with sliding speed. This seems to be highly unlikely.

7.5 Elastic Compliance of the Fluid

Elastic compliance of the fluid could perhaps account to some extent for the low value of calculated viscosity. It was

attempted using the theory of Milne (92) to take this into account. Using a Maxwell viscoelastic model, elastic terms are incorporated into the Reynolds' equation. Although the Maxwell model applies strictly only for small strains, since these experiments are conducted in nearly pure rolling this approximation would not be greatly inaccurate in the central region where the shear stresses are low. The elastic modulus assumed was taken from Duckworth's results (53) which is a factor of ten too low compared to high frequency method determinations. The effect was very small, altering the viscosity by only about 1%. Even if the modulus value is ten times greater the effect is still insignificant compared to the magnitude of the discrepancy. This elastic compliance correction does not account for the facts.

7.6 Shear Thinning at Boundary Surfaces

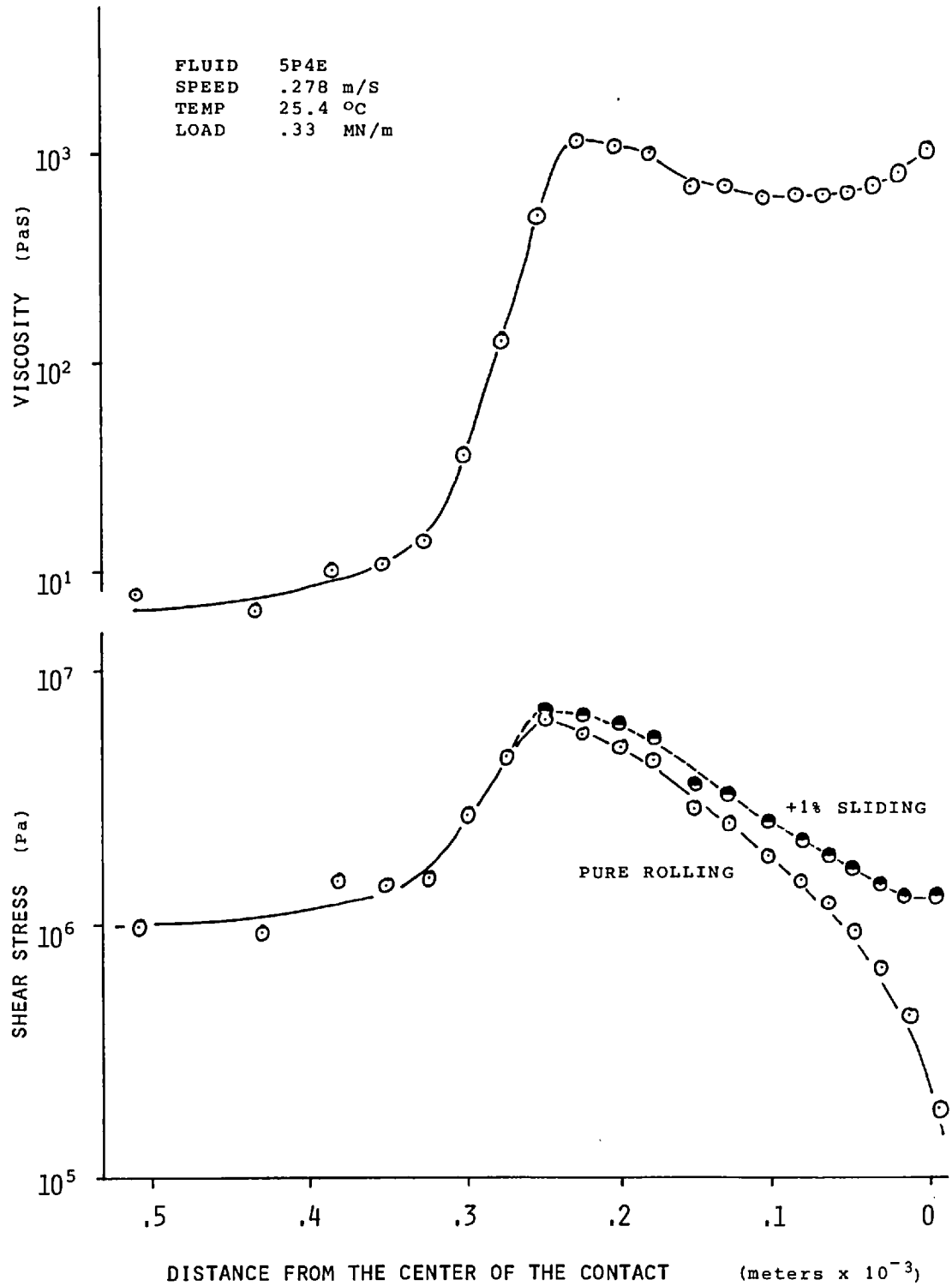
The shear stresses experienced in a typical 5P4E contact at the boundary surfaces, calculated using the expression

$$\tau = \frac{dp}{dx} \times \frac{h}{2}$$

are plotted out in figure 7.1. It can be seen that the point of maximum shear stress roughly corresponds to the point of the knee in the viscosity pressure curve. Also of interest is the fact that the levels of maximum shear stress correspond approximately to those measured by Duckworth (53). While it seems very likely that the fluid is reaching a limiting shear stress, the difficulty is understanding why the viscosity does not rise when the shear stresses drop nearer the centre. To make sure that this could not be because of some sliding in the contact, the shear stresses due to a 1% slide to roll ratio were added on. The shear stress profile still shows a drop in the centre of the contact, yet the measured sliding was less than 0.1%.

One postulation is, that since the maximum shear stress occurs at the boundaries, a type of plug flow happens. Once the limiting shear stress is reached the fluid begins to shear on

FIG 7.1 COMPARISON OF VISCOSITY AND SHEAR STRESS VERSUS DISTANCE



planes along the walls through the central portion of the contact. It can be conceived that the viscosity of the fluid on these planes retains a low value due to shearing but the bulk of the fluid becomes more viscous. If the planes are very thin the traction forces can still be large. An attempt to put in some figures into a modified version of Reynolds' equation was made using a very simple theory (appendex 5), but this did not give any sensible results. The values of viscosity that were calculated were even lower than before. Whilst the concept seems feasible the maths does not give positive evidence to back up this postulate although the assumptions in the calculations are largely guesswork. A type of shear thinning on the walls could possibly be taking place in the impact viscometer which could account for the low viscosity at the shortest times. This theory of shearing along the boundary walls cannot be completely dismissed but there is no conclusive evidence for it.

7.7 Phase Transitions

This theory is in a sense a variation or extension of the previous theory. If a phase transition were taking place then it would be expected that plastic flow would have to occur in the solid or glass-like region. The observations of Alsaad et al. (65) of the glass transition pressure for 5P4E fit in very well with the point of the knee in the pressure viscosity curve. In addition the transition point of their hydrocarbon oil, although not the same as the Bright Stock used here, occurs at about 0.4GPa at a temperature of zero celsius. The room temperature transition of this oil and XRM 109F they show to be above 0.7GPa, the limit of pressure in this apparatus. Such evidence coupled with the evidence from the density measurements does suggested that a phase transition from liquid to glass might be taking place. It would be expected that at the transition point Reynolds' equation would break down. The fact of the boundary conditions in the equation lying within the glassy region need not necessarily invalidate the values measured outside, since $\bar{\rho} \times \bar{h} \times u$ represents the total mass flow through the contact. Inside the glassy region a type of plug flow could be expected with any sliding taking place by plastic shear at the boundaries, so that $\bar{\rho} \times \bar{h} \times u$ is still the mass flow.

Unfortunately it is not known what the effect a phase

transition has on the Lorentz-Lorenz relationship. It is conceivable that as a consequence the densities are inaccurate and could help to account for the strange viscosity results. However the fact that the XRM 109F and high temperature Bright Stock results are not accounted for by this hypothesis suggests that this is not the correct explanation.

7.8 Time Dependence

Although there is a large discrepancy between the traction and viscosity results an investigation into how the fluid properties are affected by transit times in the contact was made. A dependence was looked for of density and viscosity on rolling speed in which the variation was over a factor of at least five with each fluid.

7.8.1 Density Time Variations

Due to the difficulty of defining the absolute level to which the density rose in the centre, direct comparisons were hard to make. However an alternative comparison was achieved by investigating the slope of the pressure-density curves at one particular pressure. The point chosen was 0.4GPa because this gave the best accuracy with a reasonably high value of pressure. This was also the point at which the viscosities were compared. Above this value the viscosity became too inaccurate to make meaningful comparisons.

The slopes of the density pressure curves have been plotted against rolling speed in figures 7.2, 7.3 and 7.4 for the three fluids. On all these graphs open circles represent the middle range of loading at which most tests were made, whilst circles with the upper half blackened are the higher loading and the reverse for the lower.

Owing to the small number of tests with the XRM 109F and 5P4E at each load no distinctions have been drawn between the different conditions. It is apparent that the XRM 109F shows some type of inverse dependence and 5P4E a linear dependence on rolling speed. If the XRM 109F results are plotted as

FIG 7.2

DENSITY/ PRESSURE GRADIENT VERSUS ROLLING SPEED

FLUID XRM109F

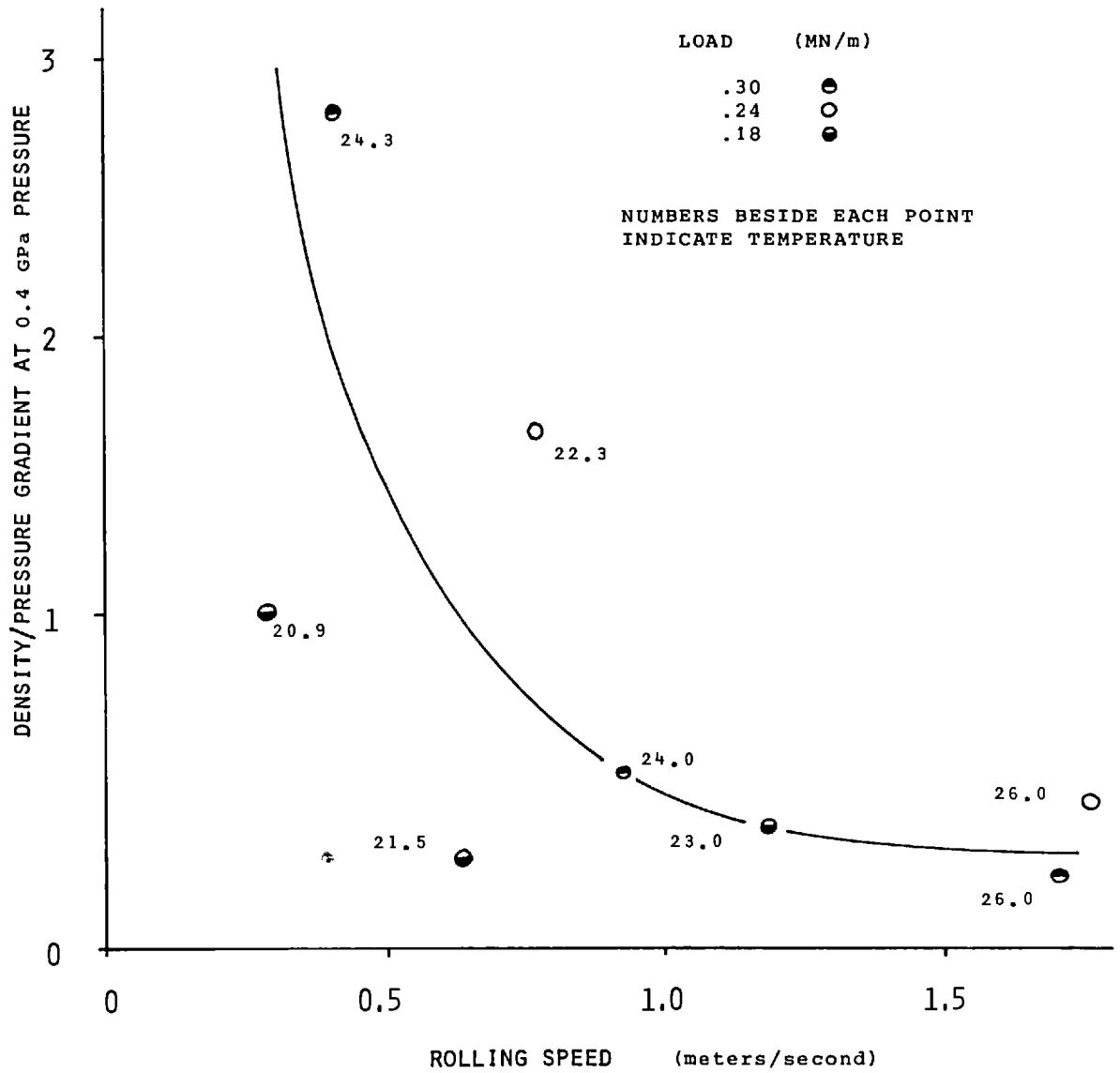


FIG 7.3 DENSITY/PRESSURE GRADIENT VERSUS ROLLING SPEED

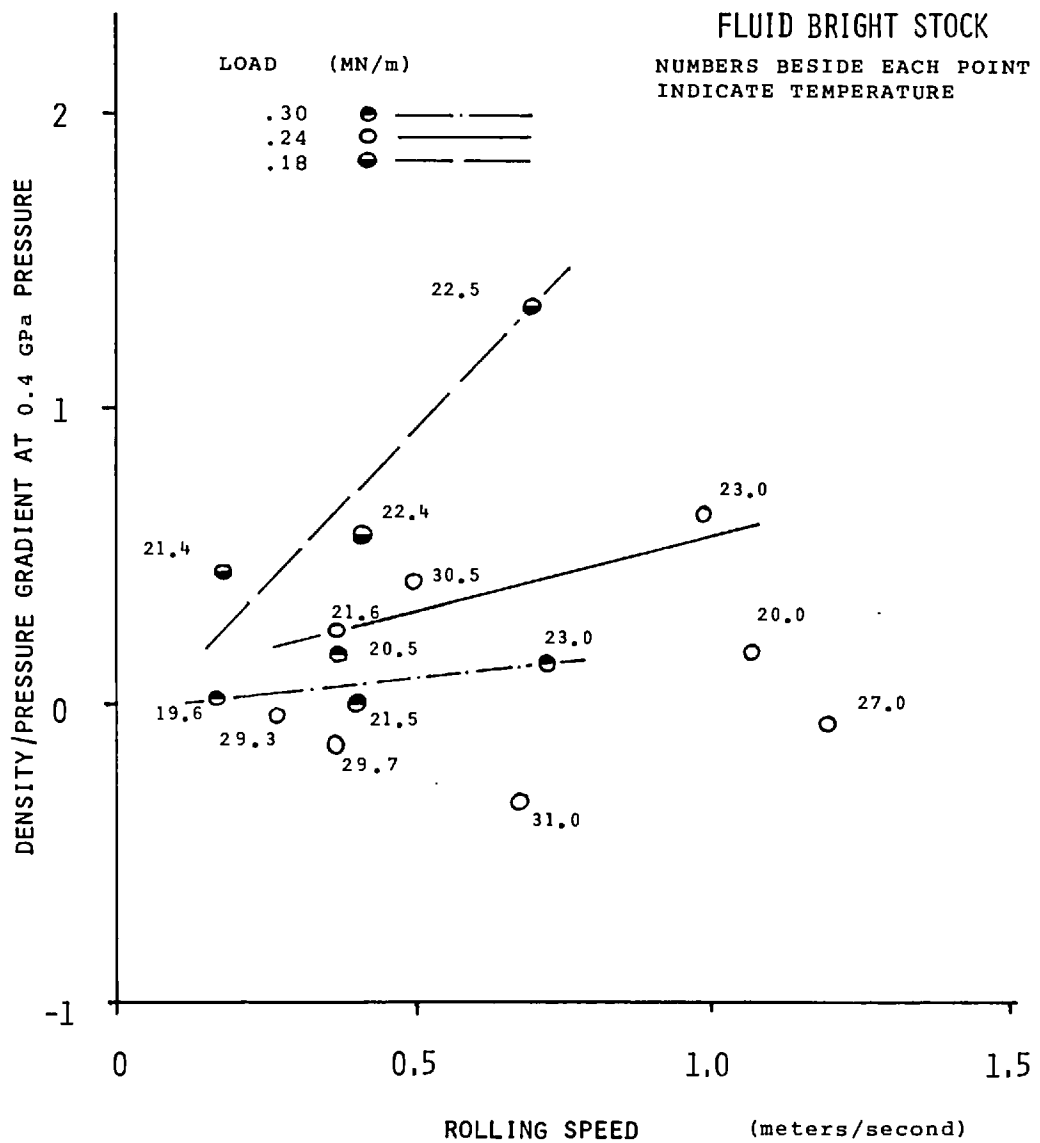


FIG 7.4

DENSITY/PRESSURE GRADIENT VERSUS ROLLING SPEED

FLUID 5P4E

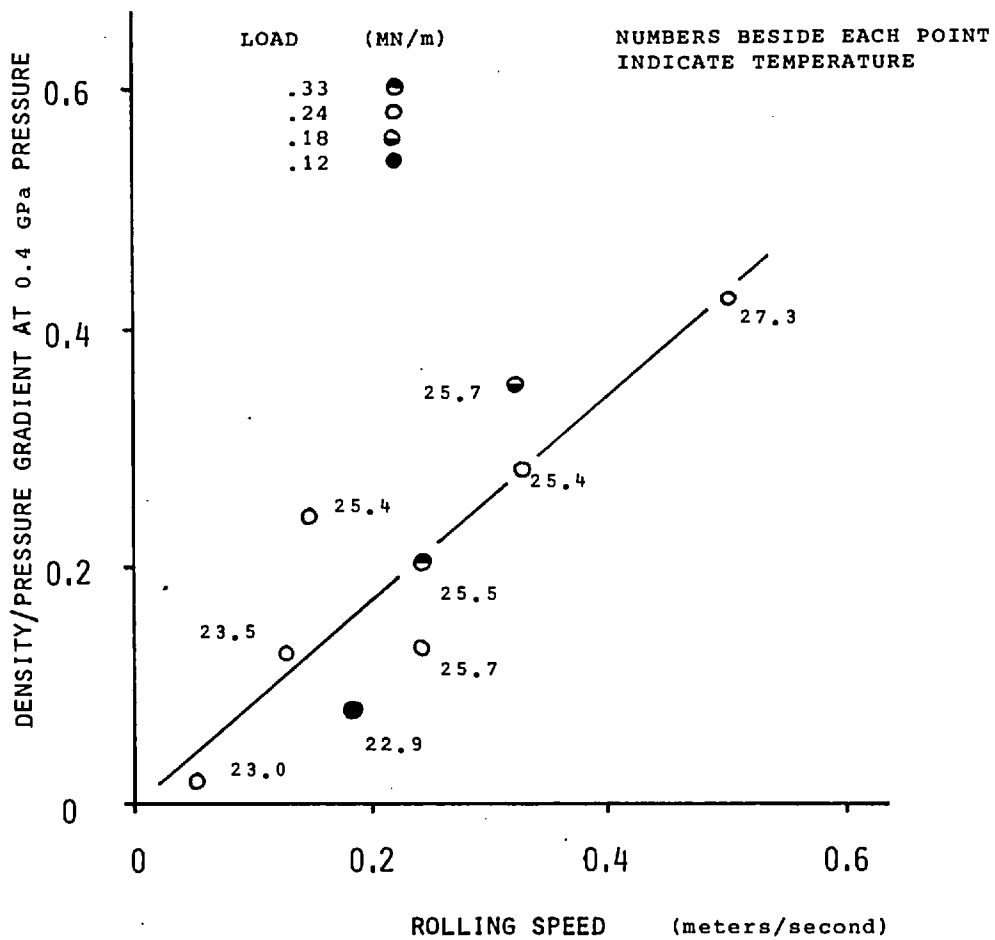


FIG 7.4

DENSITY/PRESSURE GRADIENT VERSUS ROLLING SPEED

FLUID 5P4E

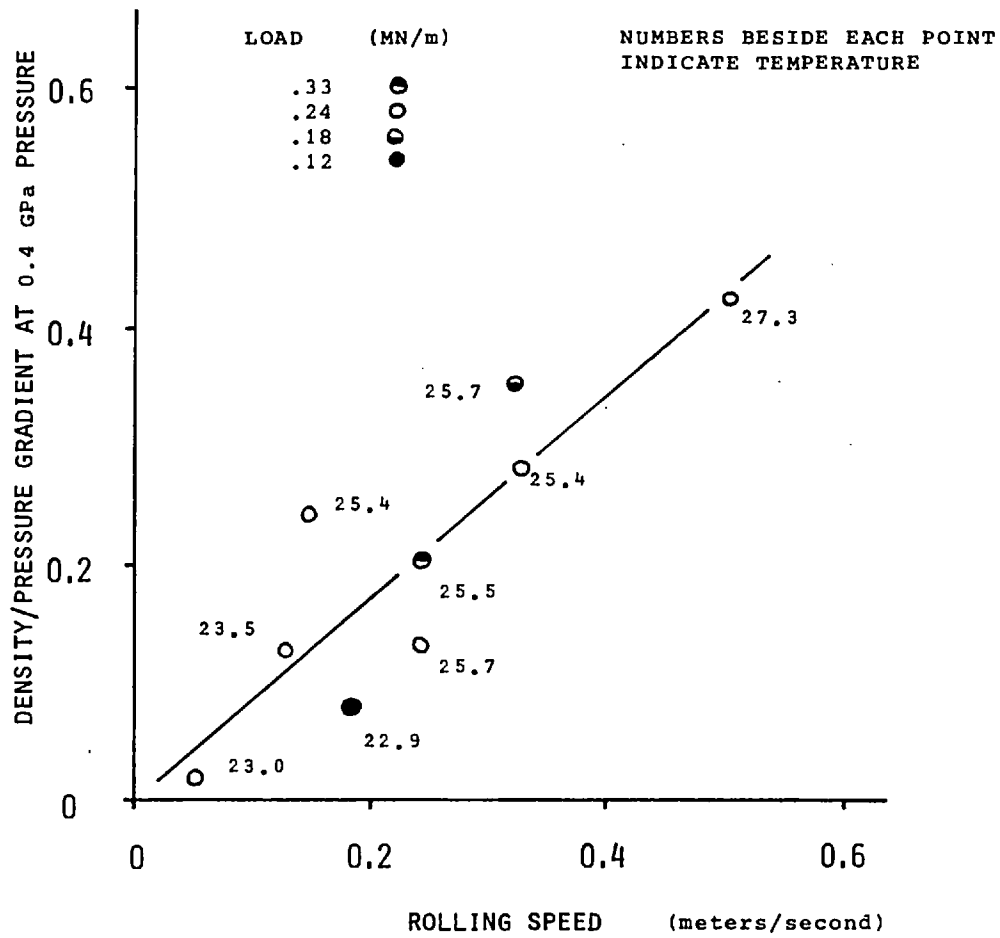
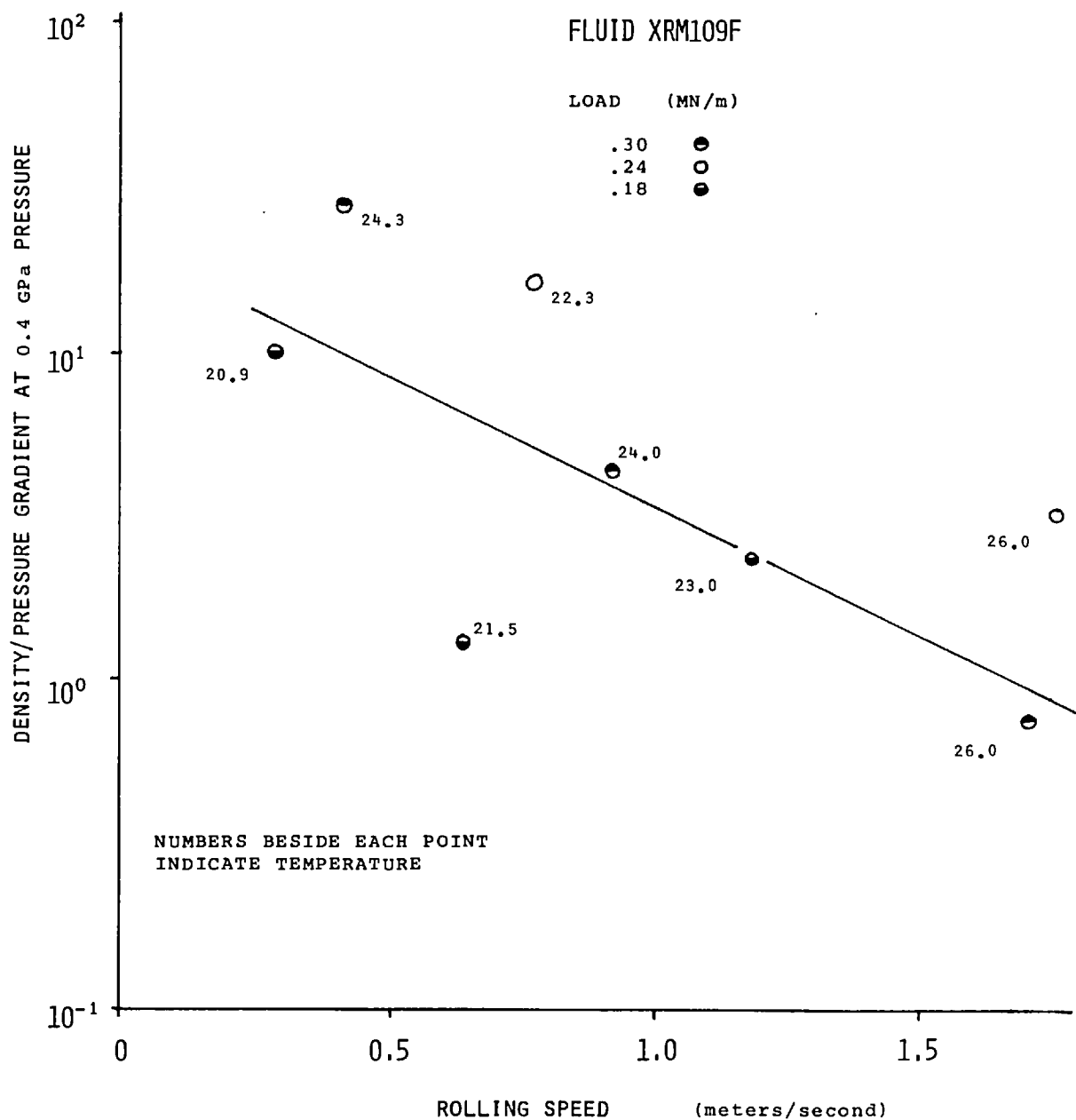


FIG 7.5 LOGARITHM OF DENSITY/PRESSURE GRADIENT VERSUS ROLLING SPEED



logarithm of the slope versus speed a straight line is obtained (figure 7.5). With Bright Stock there are enough tests at each load to make comparisons. It can be seen that at all three conditions the values follow an approximately linear relationship to the rolling speed. Unfortunately there is a lot of scatter in the middle range of loading with even some negative values. If these negative results are discounted as being unlikely a reasonable line can be drawn. It can be seen that the gradients of the lines are low for the high load with nearly no speed dependence and high for the low load. Before discussing the interpretation of this data the viscosity results will be considered.

7.8.2 Viscosity Time Variations

The viscosities at 0.4Pa pressure have been plotted as logarithm of viscosity versus speed in figures 7.6, 7.7 and 7.8. Again a similar pattern to the density results emerges of a linear relationship for 5P4E, an inverse linear relationship for XRM 109F and a linear dependence with slope varying according to load for Bright Stock.

It needs to be pointed out that there is no obvious dependence on temperature. Temperatures have been marked near each point and show that their consideration does not make any significant difference to understanding these graphs. The low temperature Bright Stock results have been omitted.

Interpretation of the results presents some difficulties. The parameter against which real comparisons should be made is the time for which the fluid has been subjected to pressure. This is rather complicated to define since the rate of pressurisation is not constant with distance through the contact, nor is the pressure gradient at a particular point constant with respect to rolling speed. To a first approximation however, the time the fluid is subjected to pressure is inversely proportional to the rolling speed.

It would be expected that at higher rolling speeds the fluid would have less time to respond to the pressure. This would lead to a lower density and viscosity. The slope of

the pressure density curve would therefore be greater at lower rolling speeds since the plot of density versus pressure is in a sense a plot of density versus distance through the contact, or density versus time. Lower speeds would give longer time span in the contact. On the other hand there could be an effect working against this in that, if the density is reaching a plateau at some particular pressure, then it would be closer to its equilibrium value and so would be responding more slowly. This would give lower gradients at lower speeds. If, however, the former of the two mechanisms is considered to be dominant then it can be seen that there is good correlation between the density and viscosity time dependence of the three fluids. In fact in the case of XRM 109F figures 7.5 and 7.6 can be nearly superimposed. However this leaves the problem of explaining why there should be one type of dependence with one fluid with the opposite for the other two. The XRM 109F is the fluid which displays the expected behaviour, i.e. lower viscosity at shorter times or higher speeds. It may be significant that the Bright Stock and 5P4E values represent the limiting viscosities i.e. the plateau values whereas the XRM 109F points are determined from curves in which the viscosity is generally continuing to rise with pressure.

One hypothesis to explain the Bright Stock and 5P4E results is that in the inlet zone pressure gradients at low speeds are greater than at high values. Thus the fluid may be experiencing a faster rate of pressurisation in the critical compression stage at the lower speed. This is shown diagrammatically in figure 7.9. This idea will also explain why there is a load dependence since at a higher load the pressurisation rate is higher.

To check this theory the pressure gradients of 5P4E and Bright Stock were investigated. Unfortunately the pressure region that is probably most important, at slightly less than 0.2GPa is poorly defined. With 5P4E at 0.2GPa there was not a large range of values in the pressure gradient such as would explain the inverse dependence on time. At 0.3GPa and 0.4GPa the same was also true. It could be that the critical stage is at very low pressures where the range might be much larger.

FIG 7.6

VISCOSITY VERSUS ROLLING SPEED

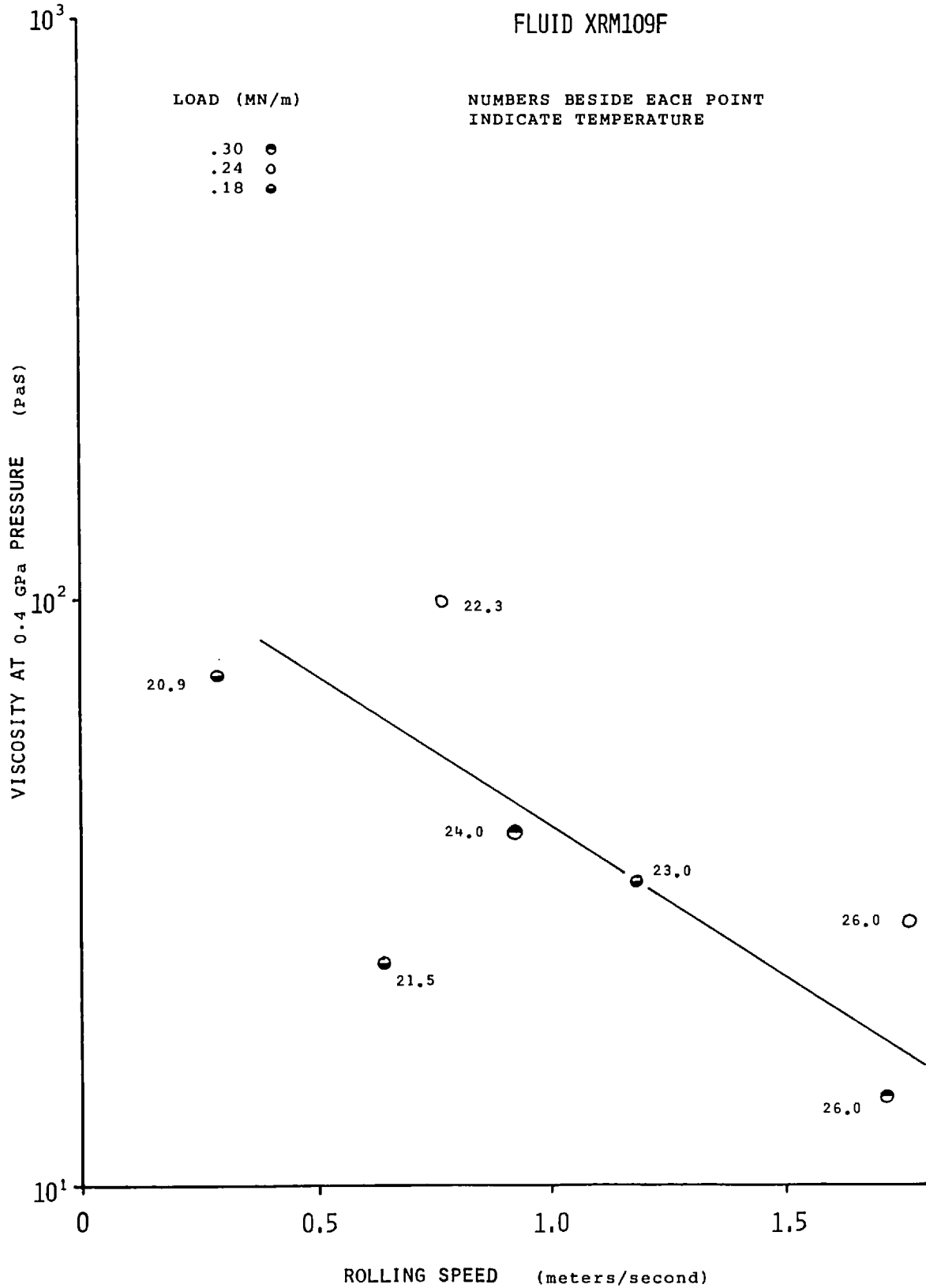
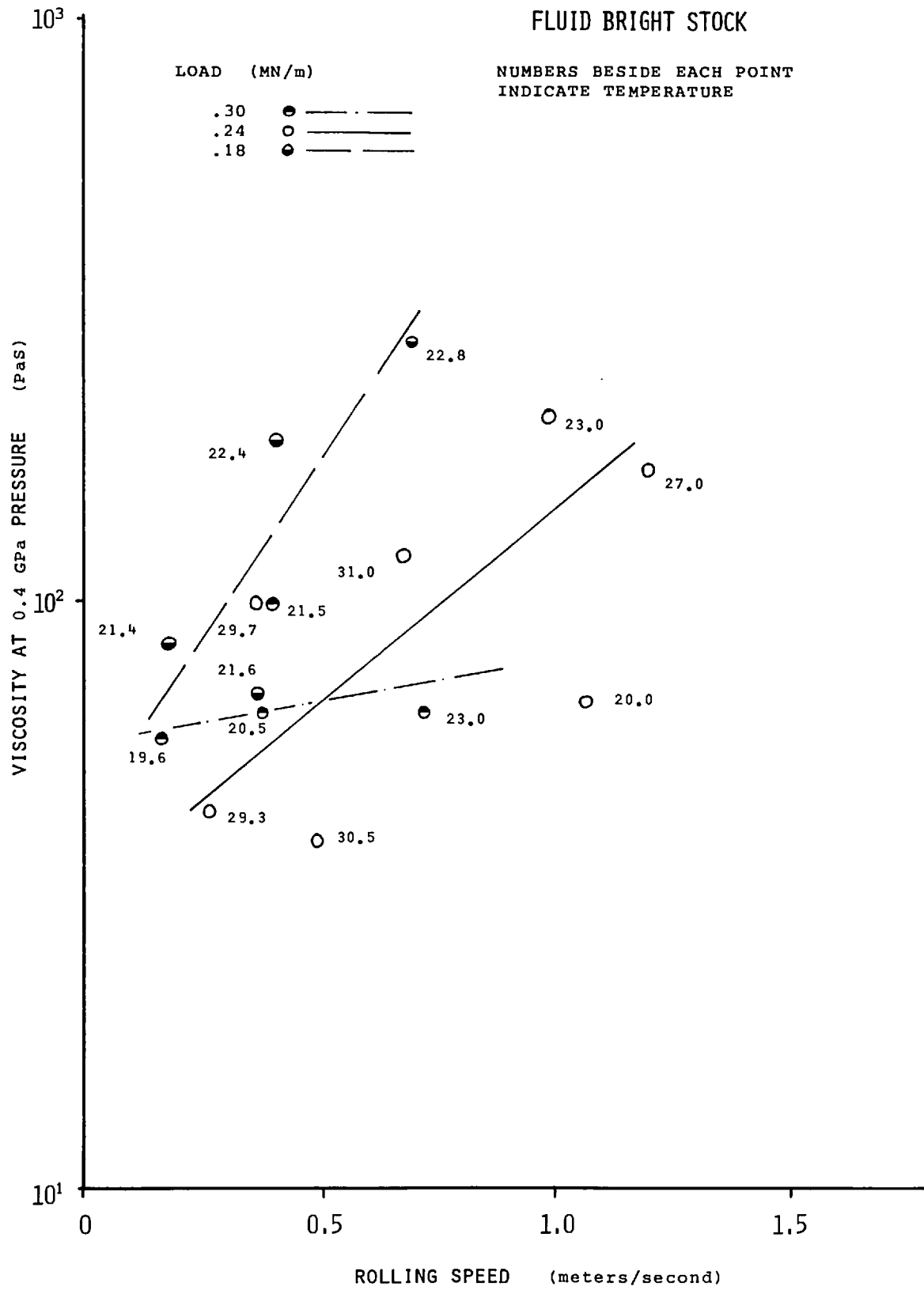


FIG 7.7

VISCOSITY VERSUS ROLLING SPEED



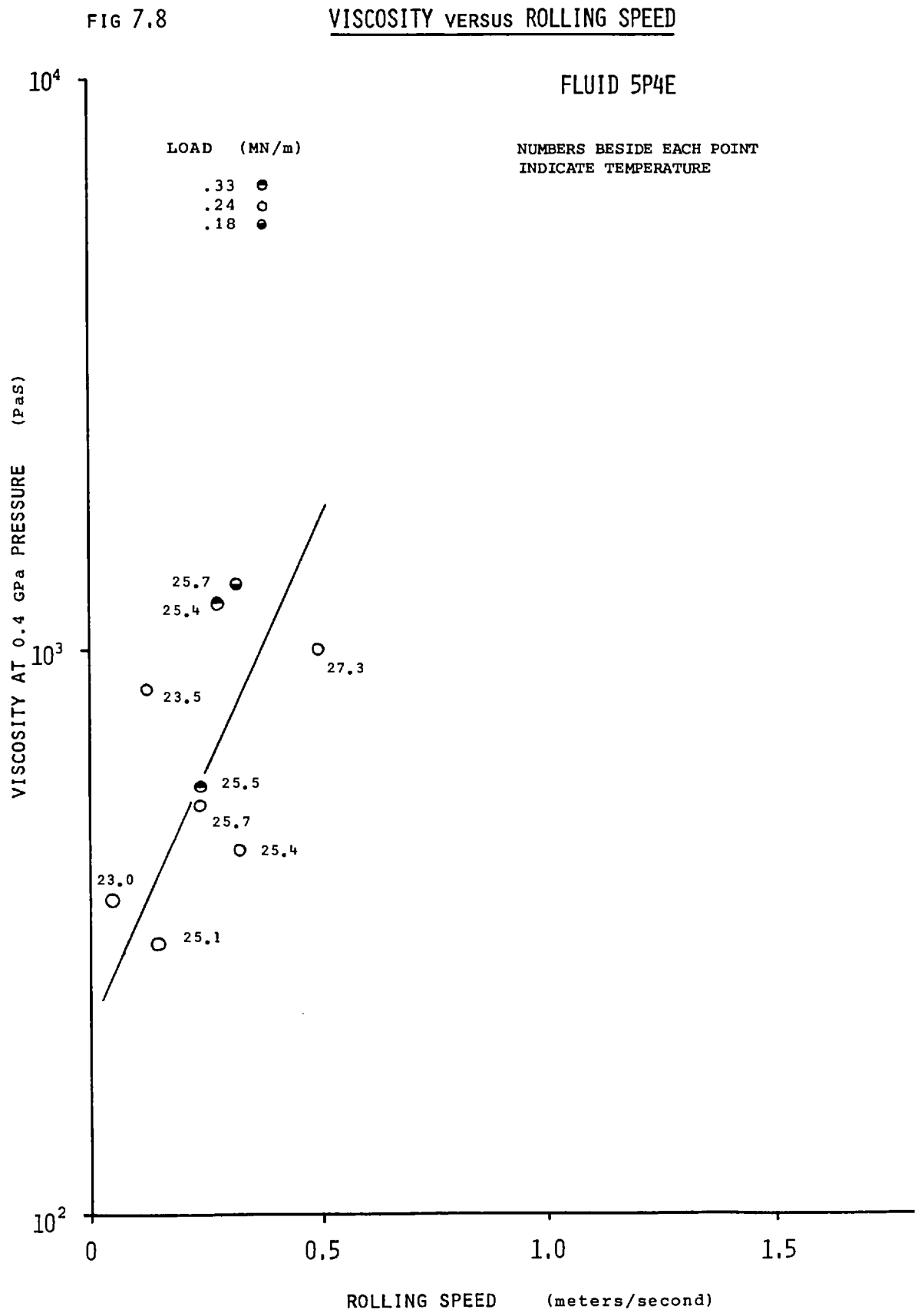
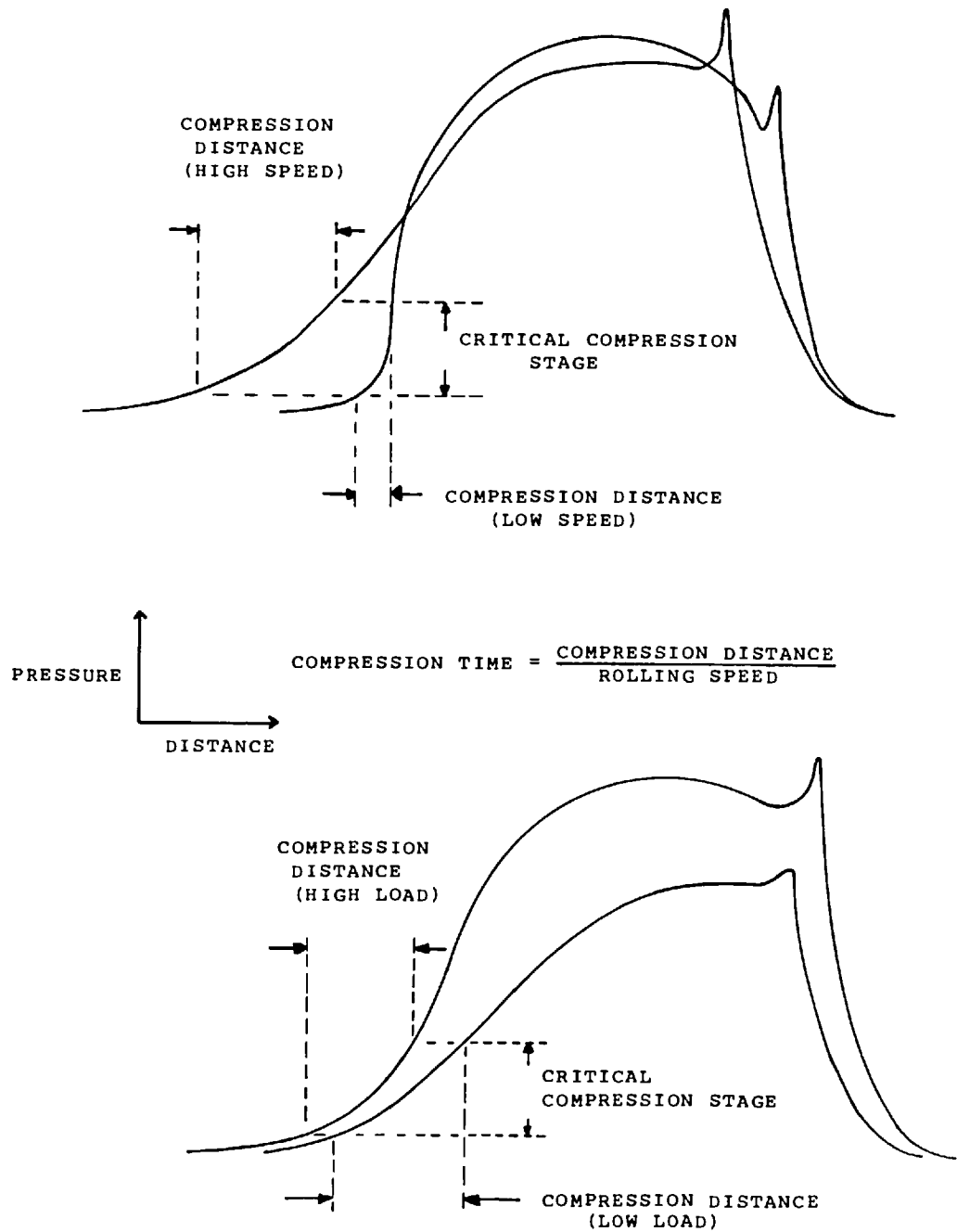


FIG 7.9 EFFECT OF SPEED AND LOAD ON COMPRESSION TIME



Unfortunately the gradient is so imprecise in this region as to render the values meaningless. With Bright Stock at 0.2GPa the correlation was better showing that the gradient fell with increasing speed particularly at the lowest and highest loading. In addition the gradient at the low load was lower than for the high case as would be expected if the theory is correct. Unfortunately the scatter for the middle load range was again large making comparisons difficult. In the light of this evidence the hypothesis is probably correct although by no means proved.

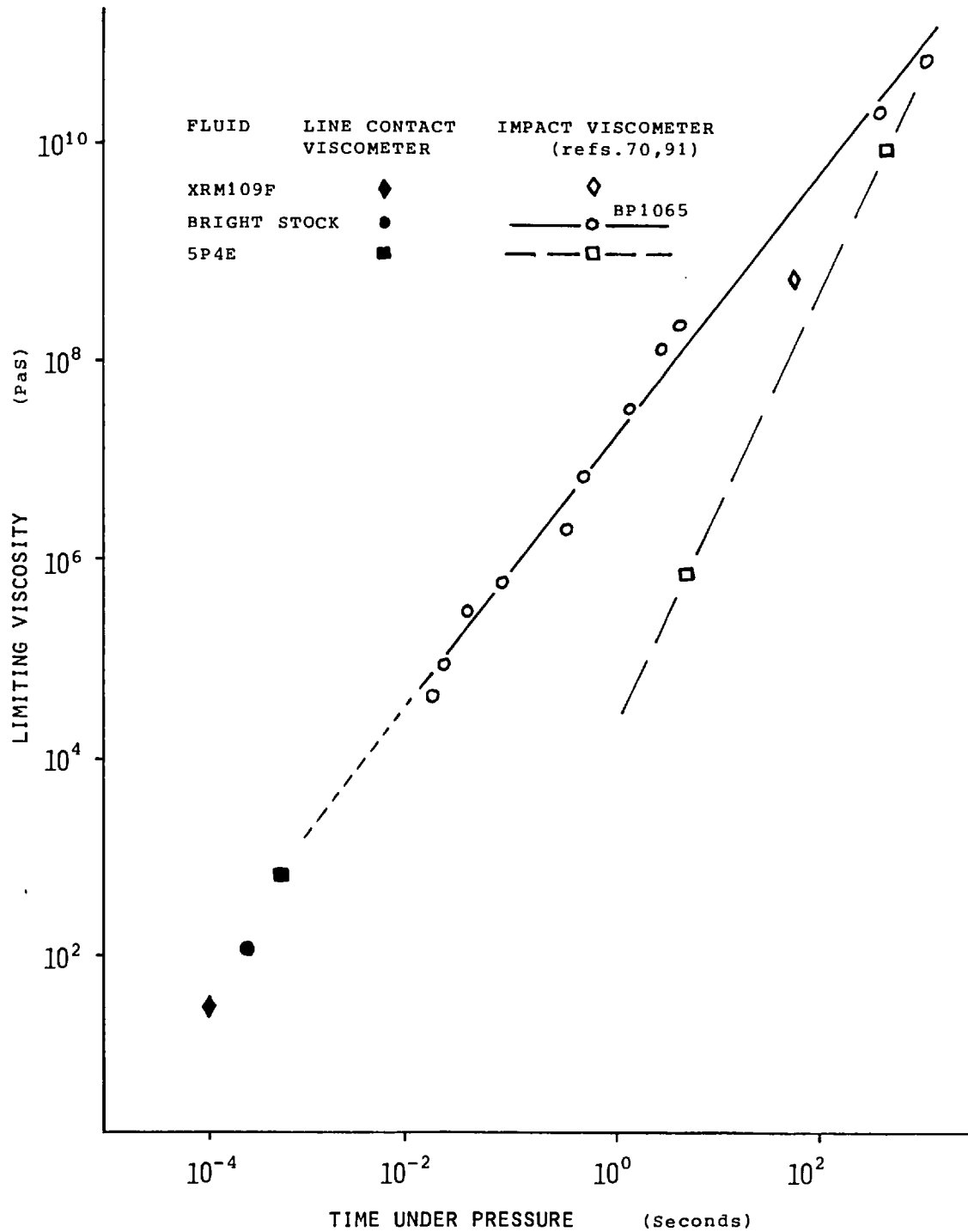
7.8.3 Comparison with Impact Viscometer

Comparisons of this work with some results from the impact viscometer (70, 91) are shown in figure 7.10. The graph plots limiting viscosity against time. Unfortunately there is a scarcity of values for 5P4E and XRM 109F from the impact viscometer. Again the problem of defining how long the fluid has been under pressure in the contact presents itself, but an estimate has been made. The line contact results are shown as points and reflect the average of the range of both time and viscosity for each fluid. It should be remembered that the XRM 109F line contact value does not represent the limiting viscosity as is the case of the other two fluids since at 0.4GPa the viscosity is still tending to rise. For this fluid therefore the comparison is of limiting viscosity in one case against viscosity at a particular pressure in the other.

The graph shows that the two methods of measuring viscosity tie in extremely well in the case of Bright Stock. The linear dependence found with the impact viscometer continues down to shorter time intervals. The agreement is less good in the case of 5P4E, and the case of XRM 109F there are too few points for a real comparison. The fact of 5P4E not giving such good agreement would suggest that the critical compression stage starts a long way out of the contact and is over a much longer period. This would back up the idea that the inverse dependence of viscosity and density is as a result of the critical compression stage occurring at very low pressures.

FIG 7.10

LIMITING VISCOSITY VERSUS TIME



Overall considering the difficulties of making the comparison between the two methods the agreement is remarkably good. It must be that the parameter measured in the two methods is the same in both cases. This may not be the true viscosity and more appropriately should perhaps be termed 'effective viscosity'. The agreement is not all that surprising since, although the geometry of the contacts is vastly different and the time scales are separated by two orders of magnitude, the analysis is similar.

7.8.4 Time Dependent Shear Strengths

The impact viscometer has shown that time dependence exists although at relatively long periods. This present work has shown that time related phenomena also occur at much shorter intervals typical of those achieved in ehl contacts. This is apparent from both the density and viscosity measurements. Although it is not clear from this work alone of what nature the time dependence of 5P4E takes it is reasonably certain from the agreement with the impact viscometer that there is a lowering of viscosity at shorter time intervals. It follows that there is a lowering of the density also. From these experiments evidence has been found of this particular fluid experiencing glass transitions, which is expected from other work as has already been discussed. This points therefore to the fact that even in a glassy or solid like region time dependent phenomena are occurring. The fluid is undergoing some structural reorientation. One suggestion is that although the molecules may not be free to move past one another once in the solid like state, yet individual bonds are still able to make adjustments. If this is the case it could be the explanation of why traction coefficients are found to be speed dependent. If the theory is accepted that the coefficients are determined by the limiting shear strengths of the fluids (see section 1.4.2), it would be reasonable to assume that this parameter is dependent on the fluid structure and hence time dependent also. At high rolling speeds the structural reorientation is less than at low, and so the maximum traction attainable would be decreased.

This work also backs up the conclusion reached by Johnson, Nayak and Moore (55) that the discrepancy between elastic moduli

measured from traction tests and those determined in oscillatory shear experiments is as a result of the finite time required for the fluid to reach equilibrium inside an ehl contact.

CHAPTER 8
CONCLUSIONS

This work has utilised the only method known to date which allows measurement of the density and viscosity of an oil under conditions which normally prevail in a lubricated contact. Despite the fact that the measurement of viscosity is generally ill conditioned this investigation has revealed some interesting behaviour of the oils in the conjunction.

1. The density versus pressure plots show a surprisingly slow rate of increase at high pressures, particularly for the Polyphenyl ether and Bright Stock.

2. The viscosity measurements at low pressures agree well with other types of measurements.

3. The viscosities at high pressures are up to two orders of magnitude lower than those expected from typical traction coefficients. It has been seen that this could be accounted for by experimental inaccuracy but the consistently low values make this seem unlikely.

4. There is good correlation between the time dependence displayed in the density and in the viscosity although an unexplained and surprising inverse dependence of the Polyphenyl ether and Bright Stock was found.

5. There is good correlation between the limiting viscosities measured on the impact viscometer and those measured on the line contact rig.

From all this evidence no clear picture has emerged although the following conclusions can be drawn.

1. There is a dependence of the fluid properties on time even at periods as short as the residence times in an ehl contact, although changes of pressure gradient with rolling speed may mask the effect. The significance of this is that it may account for the decrease of traction coefficient with increasing rolling speed.

2. There may be a breakdown of the Lorentz-Lorenz relationship. It is also possible that the conditions governing the use

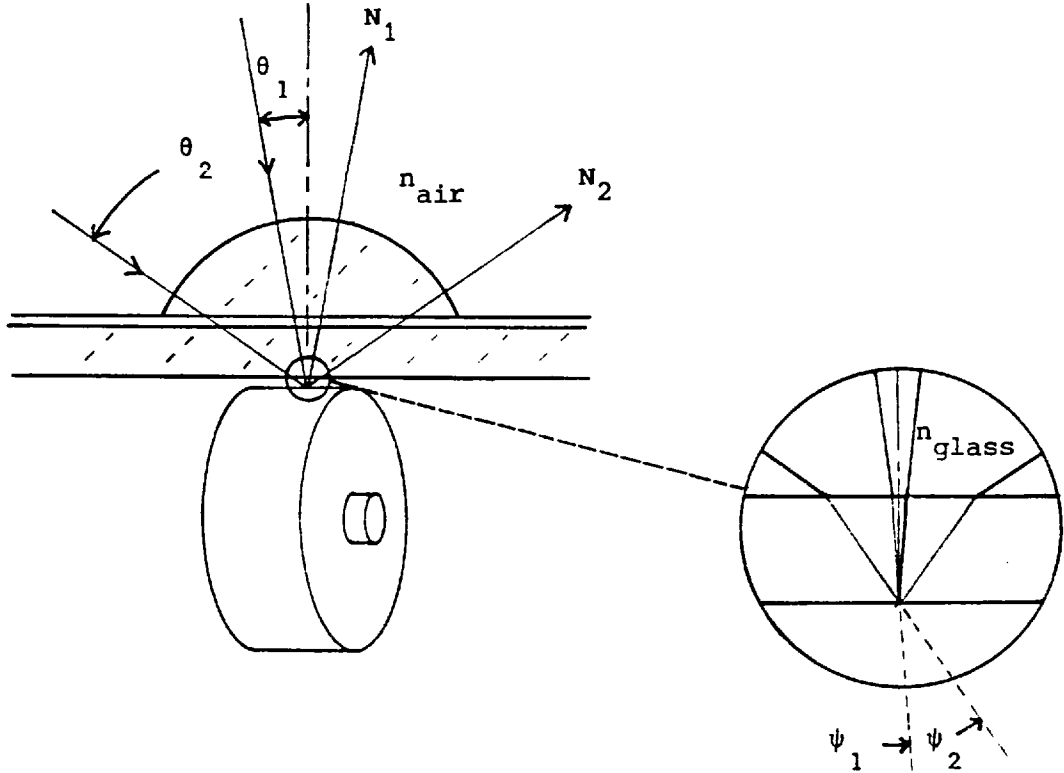
of Reynolds' equation in a line contact are being violated. One or both of these two explanations almost certainly account for the discrepancy between measured viscosities and values derived from traction.

3. There is evidence in the 5P4E results of a change of phase in the contact from a liquid to an amorphous solid.

4. The correlation between the impact viscometer and line contact viscometer is due to the similarity of the analysis used in both work.

It is suggested that a different method of investigating the time dependence of fluid response to pressure be utilised which will give more accurate results. Such a method could be found in Raman Spectroscopy. This might also give insight into the validity of the Lorentz-Lorenz relationship under rapidly varying pressures by comparing the response of different spectral lines corresponding to different types of bonds.

APPENDIX 1
REFRACTIVE INDEX CALCULATIONS



Neglecting phase changes equation 2.1 gives

$$N_1 \lambda = 2dn \cos \psi_1$$

$$N_2 \lambda = 2dn \cos \psi_2$$

therefore

$$N_1 \cos \psi_2 = N_2 \cos \psi_1$$

therefore

$$N_1^2 \cos^2 \psi_2 = N_2^2 \cos^2 \psi_1$$

$$N_1^2 (1 - \sin^2 \psi_2) = N_2^2 (1 - \sin^2 \psi_1)$$

Snells law gives

$$\frac{n_{oil}}{n_{glass}} = \frac{\sin \theta_1}{\sin \psi_1} = \frac{\sin \theta_2}{\sin \psi_2}$$

Substituting for $\sin^2 \psi_1$ and $\sin^2 \psi_2$ gives

$$N_1^2 - N_2^2 = \frac{n_{\text{glass}}^2}{n_{\text{oil}}^2} (N_1^2 \sin^2 \theta_2 - N_2^2 \sin^2 \theta_1)$$

therefore rearranging this gives

$$n_{\text{oil}} = n_{\text{glass}} \left(\frac{N_1^2 \sin^2 \theta_2 - N_2^2 \sin^2 \theta_1}{N_1^2 - N_2^2} \right)^{\frac{1}{2}}$$

APPENDIX 2
TECHNICAL SPECIFICATIONS

Roller

Material: EN31
Surface Finish: Not measured, Final polishing 1/10 μ
diamond paste
Centre Track Diameter: 1.905×10^{-2} m
Taper: Half cone angle 7.13°
Track Width: 3.8×10^{-3} m
Elastic Modulus: 2.1×10^{11} Pa
Poisson Ratio: 0.295

Glass Disc

Material: Float Crown glass
Thickness: 1.25×10^{-2} m
Coating: $1/4 \lambda$ TiO₂ reflectance layer
Elastic Modulus: 7.45×10^{10} Pa
Poisson Ratio: 0.23
Refractive Index: 1.519

Lenses

Type: Achromatic Doublet
Power: x 10
Diameter: 1.91×10^{-2} m
Focal Length: 4.65×10^{-2} m

Photographic Film

Type: Ilford SP348 Estar Base (1.8×10^{-2} m thick) for
high dimensional stability
Sensitivity: Orthochromatic (fine grain)
Development: Approximately 90 seconds in P.Q. Universal
diluted 1 + 9
Exposure: Approximately 1/5000 second

APPENDIX 3
COMPUTER CALCULATIONS

A.3.1 General Program

The general flow diagram of the calculations are shown in figure A.3.1. The program is interactive, the process being carried out on a graphics terminal. These terminals display continuous line graphs and positional and other information is entered via crosswires which can be called up on the screen.

The bulk of the data is entered from the punch tape generated by the densitometer. Additional data such as the roller diameter etc. is entered from a file permanently stored in the system. At any stage, before the calculation of pressure, steps can be repeated if not satisfied even if it is several operations back. Subsequently only those processes which are directly affected by the repeat will be carried out until the program returns to its previous point.

In generating the optical film profile from the new data the computer automatically picks out the fringes in the inlet and exit regions with an override where necessary. In the central region because of the noise in the profile the crosswires are used to enter the points. Smoothing is carried out by passing a cubic spline through the points. The position and number of knots and weighting can be varied until a curve judged to be satisfactory by eye is achieved. The picture can be magnified in any selected region for high precision.

The grid is generated so that it gives a tighter spacing in regions where the profile varies more rapidly such as at the pressure spike or where it is important to have a high accuracy in the central region. The refractive index is calculated automatically and further smoothing applied.

In the pressure calculations the facility for shifting the centre is available. The load integrated from the pressure indicates when this is correct. The viscosity is calculated at about two hundred points up to the pressure maximum to give the continuous line curves shown in the results. This explains why the viscosity results are not shown as smoothed curves.

Output of the results is onto printed tables and microfilm with the facility of plotting any two variables against each other.

A.3.2 Iterative Solutions for Refractive Index and Pressure

Figure A.3.2 show a modified form of the pressure calculation which includes an iteration loop for calculating the refractive index measurements. Initially the refractive index is set to its ambient value throughout the contact. The pressure is calculated and from equilibrium pressure density measurements the refractive index is adjusted to take account of the compression. The film thickness is corrected with the new refractive index using some under relaxation and the cycle repeated until convergence is achieved. The density and refractive index are related by the Lorentz-Lorenz law. The pressure calculations use the same method as the unmodified program. Input and output in this case is via cards and the line printer or telex.

Fig A.3.1

GENERAL FLOW CHART OF COMPUTER PROGRAM

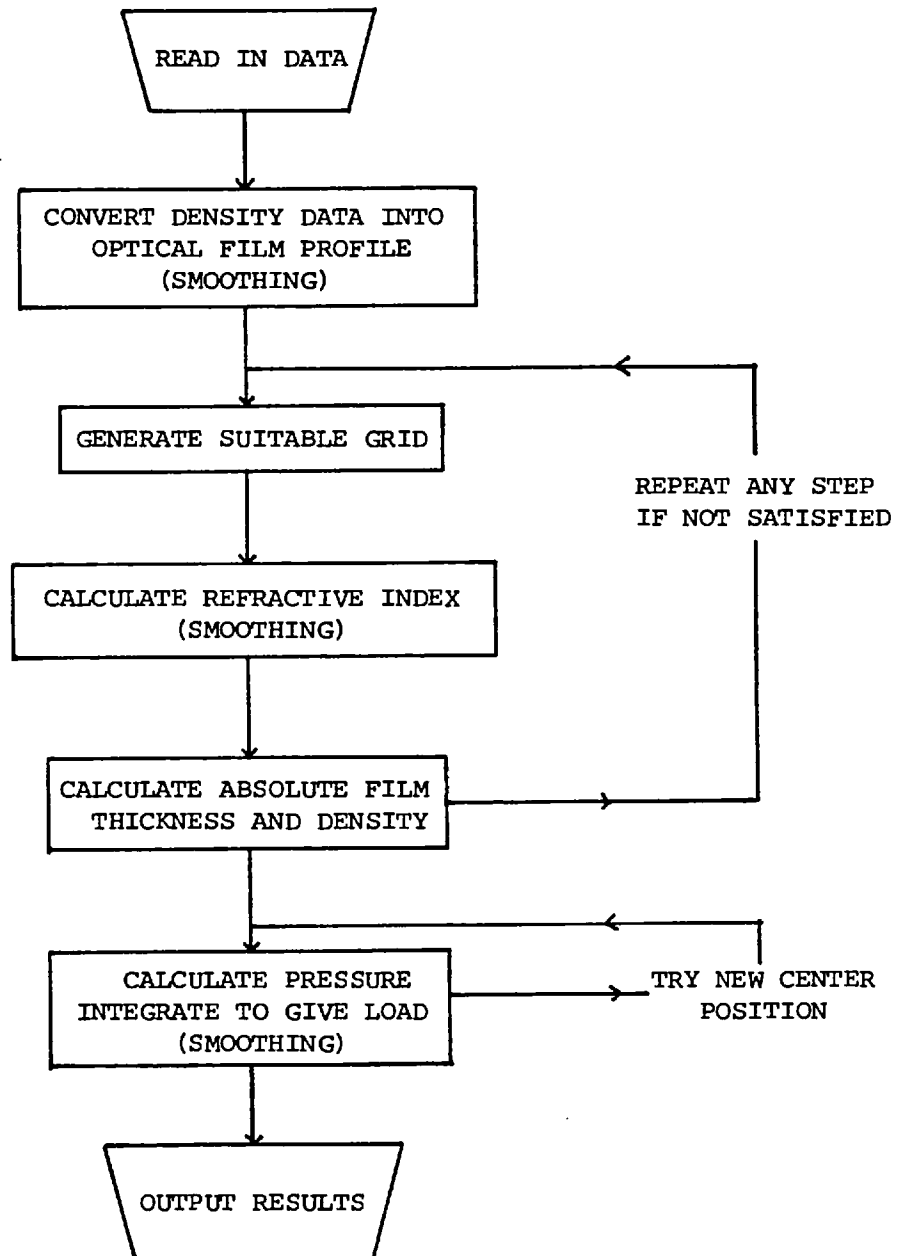
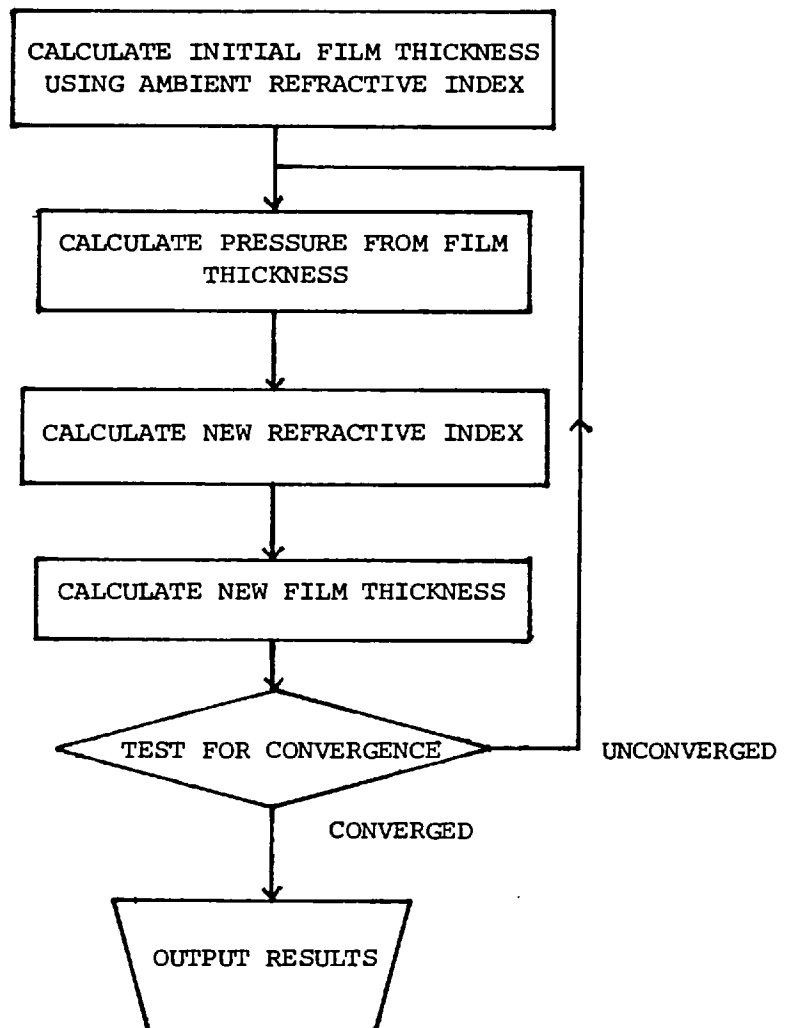


Fig A.3.2

FLOW CHART SHOWING ITERATION FOR REFRACTIVE INDEX



APPENDIX 4
FLUID SPECIFICATIONS

The data is that which has been supplied with the fluid except where marked * which indicates the measurements have been carried out in this project.

XRM 109F (Lot 4)

This is a synthetic hydrocarbon supplied by Mobil.

<u>Viscosity</u> (cs)	<u>Temperature</u> (°F)
37000	0
447	100
40.4	210

<u>Density</u> (g/ml)	<u>Temperature</u> (°F)
0.8389	100
0.8082	200
0.7777	300

<u>Refractive Index</u>	<u>Temperature</u> (°F)
1.4689	78.8

5P4E (CS124)

This is a Polyphenyl Ether supplied by Monsanto

<u>Viscosity</u> (cs)	<u>Temperature</u> (°F)
363	100
13.1	210
2.1	400

<u>Density</u> (g/ml)	<u>Temperature</u> (°F)
1.19	100
1.14	210
1.06	400

<u>Refractive Index</u>	<u>Temperature</u> (°F)
1.6306	78.8

Bright Stock

This is a hydrocarbon bright stock supplied by Monsanto.

Viscosity

Temperature

395 cs

100°F

* 10.36 Poise

22°C

* 8.22 Poise

26°C

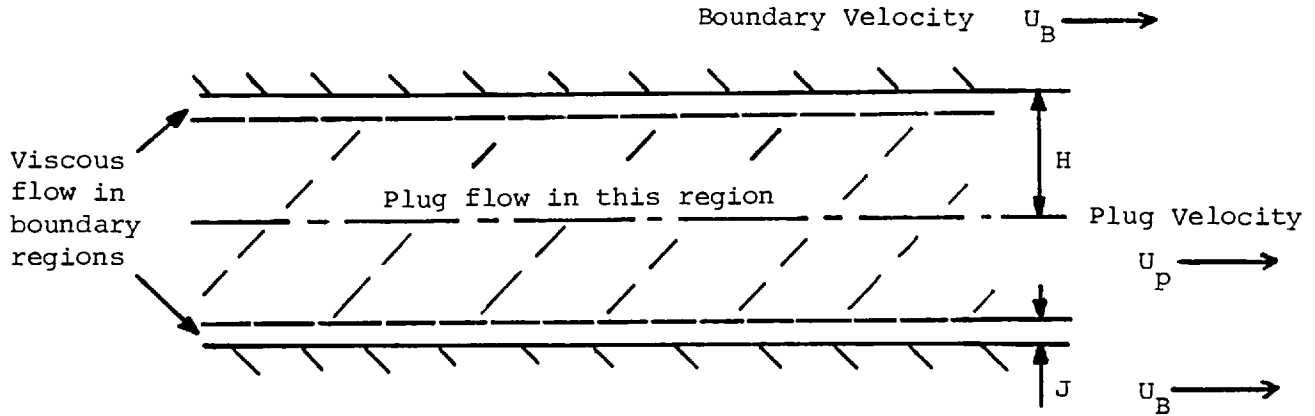
Refractive Index

Temperature

* 1.4932

22°C

APPENDIX 5
VISCOSITY INCLUDING SHEAR THINNING AT BOUNDARIES



Consider the flow for half the bearing.

From Reynolds' equation, by assuming the flow in the viscous region is taking place between two surfaces with velocities U_B and U_P

$$q_v = \frac{-J^3 \rho}{12\eta} \frac{dp}{dx} + \left(\frac{U_B + U_P}{2} \right) J\rho \quad A,1$$

Flow in the plug region assuming the density is the same in both the viscous and plug region is

$$q_p = U_P \rho (H - J) \quad A,2$$

Combining A,1 and A,2 gives

$$q_{total} = \frac{J^3 \rho}{12\eta} \frac{dp}{dx} + \left(\frac{U_B + U_P}{2} \right) J\rho + U_P \rho (H - J) \quad A,3$$

Boundary conditions at $\frac{dp}{dx} = 0$ $H = \bar{H}$, $J = \bar{J}$, $\rho = \bar{\rho}$

$$q_{total} = \left(\frac{U_B + U_P}{2} \right) \bar{J}\bar{\rho} + U_P \bar{\rho} (\bar{H} - \bar{J}) \quad A,4$$

Therefore substituting A,4 into A,3 gives

$$\begin{aligned} & \left(\frac{U_B + U_P}{2} \right) (J\rho - \bar{J}\bar{\rho}) + U_P \{ \rho (H - J) + \bar{\rho} (\bar{H} - \bar{J}) \} \\ & = \frac{J^3}{12\eta} \rho \frac{dp}{dx} \end{aligned} \quad A,5$$

A simplifying assumption needs to be made and has been done in two ways

1) Take J to be constant, then

$$\begin{aligned} \left(\frac{U_B + U_p}{2} \right) J (\rho - \bar{\rho}) + U_p (\rho_H - \bar{\rho}_H) - U_p J (\rho - \bar{\rho}) \\ = \frac{J^3}{12\eta} \rho \frac{dp}{dx} \end{aligned} \quad A,6$$

giving

$$\eta = \frac{\frac{J^3 \rho}{12} \frac{dp}{dx}}{(\rho - \bar{\rho}) \left(\frac{U_B - U_p}{2} J + U_p (\rho_H - \bar{\rho}_H) \right)} \quad A,7$$

The value of J needs to be guessed but can be taken to be about H/100.

If now $U_B - U_p = 0$
then A,7 reduces to

$$\eta = \frac{\frac{J^3 \rho}{6} \frac{dp}{dx}}{U_p (\rho_H - \bar{\rho}_H)} \quad A,8$$

which gives values of viscosity 100^3 times lower than the normal Reynolds' equation. This last assumption is a means of showing the trend in the viscosity although it is unlikely that $(U_B - U_p)$ would be zero and the bottom line of A,7 is likely to be smaller than $U_p (\rho_H - \bar{\rho}_H)$. However at this stage the theory becomes complete quesswork.

2) Take H_p constant, then

$$\left(\frac{U_B + U_p}{2} \right) (J\rho - \bar{J}\bar{\rho}) - U_p (J\rho - \bar{J}\bar{\rho}) = \frac{J^3}{12\eta} \rho \frac{dp}{dx} \quad A,9$$

giving

$$\eta = \frac{J^3 \rho \frac{dp}{dx}}{(J\rho - \bar{J}\bar{\rho})(U_B - U_p)} \quad A, 10$$

Again the theory degenerates to guess work but it seems exceedingly unlikely that higher viscosities will result in view of the factor of 100^3 reduction on the top line from the conventional Reynolds' equation.

APPENDIX 6
TRACTION RESULTS

<u>Fluid</u>	<u>Traction Coefficient</u>	<u>Maximum Pressure</u>	<u>Speed (m/S)</u>	<u>Sliding (%)</u>	<u>Temperature (°C)</u>	
<u>Measure Values</u>						
Bright Stock	.001	.68	.04	.1%	27	
	.005	.68	.5	.1%	27	
	.15	.58	.24	100	27	Line Contact
5P4E	.008	.58	.14	.1%	23	Viscometer
	.07	.79	.24	.1%	25	
	.1	.58	.11	100	27	
XRM 109F	.015	.82	.096	.7	25	
	.03	1.25	.096	1.0	25	
Bright Stock	.01	.82	.15	.5	30	
	.002	.82	.57	1.0	30	Duckworth
5P4E	.06	1.08	.44	.6	29	(ref. 53)
	.08	1.08	.022	.2	29	
	.07	.65	.010		26	
	.03	.65	.034		26	

Values Calculated from Viscosity

XRM 109F	.006	.68	1.766	1.0	26
	.0004	.58	.641	1.0	22
Bright Stock	.0015	.68	1.204	1.0	27
	.0003	.58	.699	1.0	23
	.001	.68	.359	1.0	0.0
5P4E	.001	.68	.126	1.0	25
	.001	.79	.277	1.0	25
	.0005	.79	.242	1.0	26

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