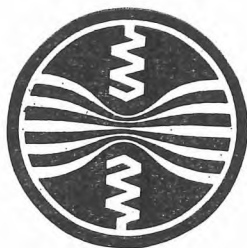


BULLETIN



**BRITISH SOCIETY
OF RHEOLOGY**

1969, No. 4, Vol. 12

Hon. Editor:

JOHN HARRIS,
Schools of Chemical Engineering
The University,
Bradford,
Yorks. U.K.

NOTICE TO INTENDING CONTRIBUTORS

The B.S.R. Bulletin is now available as a vehicle for several categories of communication by Members.

1. Technical papers (two copies required).
2. Descriptive papers of general interest.
3. Letters which may be either
 - (i) technical or
 - (ii) non-technical.

The technical papers will be refereed and so will technical letters but the latter only by one person. Descriptive and non-technical material will be published if it is of general interest

In addition, project reports and computer information will be published.

It is hoped that B.S.R. members will find rapid publication sufficiently attractive to warrant submitting work.

BULLETIN VOLUME NUMBERS

The Council has now decided that the *Bulletin* shall have the *same* volume numbering as Rheology Abstracts. Therefore those members of the Society who hold Number 1 and Number 2 of this year's (1969) editions should change the volume number from 1 to 12.

FOREWORD

With the fourth edition of the Bulletin now available the first numbered volume is complete and members are reminded that, following a Council decision, this is to be Volume 12 to conform with the present numbering on Rheology Abstracts. It is to be hoped that future generations of rheologists will not wonder whether a new system of numbers has been invented.

During the current year, Editorial efforts have been directed towards reflecting the slow but noticeable evolution of the Society away from the University type of club towards a rather more professional attitude, although of course a great deal of the old Rheology Club's convivial atmosphere still seems to pervade the Society's conferences. There are several forces which will, in the long run, produce change; most obviously the steady upward trend in membership numbers will continue in the future and on the technical side there will be greater emphasis on the applications of rheology and lesser interest in the mere cataloguing of material properties, most research organisations will already have taken definite steps in this direction, and the Gold Medal Competition terms of reference will be a powerful stimulus within the Society.

At the present time, future development of the Bulletin is under consideration and we may be able to look forward to a more substantial Bulletin which will reflect well both on the Society and on the subject of Rheology. There is no doubt that the Bulletin can and should be an essential element in the future development of the Society, this can certainly be achieved with the active co-operation of members of the Society and the flourishing of the subject of Rheology in the U.K. The time is opportune for further steps to be taken in shaping the Bulletin as a vehicle for communicating more than notices.

The Editor extends grateful thanks to every person who has contributed in any way to the current volume of the Bulletin.

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COUNCIL 1969-70

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Hon. Secretary: DR. B. S. NEUMANN, Laporte Industries Limited, Redhill, Surrey.

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DR. M. F. CULPIN, MR. A. EVANS, MR. A. T. J. HAYWARD,
MR. D. LAMB, MR. B. WARBURTON, Professor J. F. RAFFLE.

1969-70 COMMITTEE, VICTORIAN BRANCH (AUST.)

Chairman: MR. K. R. HALL, C.S.I.R.O., Division of Chemical Engineering.

Hon. Secretary: DR. D. V. BOGER, Department of Chemical Engineering, Monash University.

Hon. Treasurer: MR. K. G. MARTIN, C.S.I.R.O., Division of Building Research.

Committee: DR. E. J. DICKENSON, DR. D. H. MORTON, DR. J. STEARNE.

**Report on the Annual Conference (16th/18th September, 1969)
held at the Baird Hall of Residence, Glasgow**

ADVANCES IN RHEOLOGY

In addition to the usual lecture sessions, conference dinner and afternoon tour which is the traditional diet for the annual assembly, there was, in addition, the first presentation of the Society's Gold Medal jointly to Professors Dawson (Leeds) and Higginson (Durham). The competition submission on which the award was based is published with this edition of the Bulletin. To date, there is no report available from the Research Committee which made the Gold Medal award.

Impressions of the Glasgow conference by several contributors are set out below. As a different approach to that used previously, it was decided to sample the impressions of three people, one for each of three days' proceedings, rather than the opinions of one person. With a very full programme the task of commenting on the full three days would also have been an onerous one.

TUESDAY, 16th September.

(Mr. R. S. Lenk, Borough Polytechnic, London.)

It is not easy to point to a keynote theme which runs through the papers presented, except perhaps the fact that all dealt with liquids. The normal force bandwagon is still going strong and it is being used to attempt all manner of structural and viscosity correlations.

Other structural correlations were attempted in a number of papers (e.g. the paper by J. Ferguson and S. Y. Shirsavar), some with the aid of solution studies which were extrapolated into the solventless condition.

At least three papers treated molecular weight and molecular weight distributions as central issues and sought to relate viscoelastic behaviour to these parameters.

If one were to pick out highlights one ought to give special credit to H. J. M. A. Muras, whose simplicity and directness was characterised by the fact that he was using rheological measurements to gain a better understanding of materials rather than in order to promote pre-conceived ideas and theoretical models. Likewise, P. Feltham's paper, although mathematical, was never abstruse, nor did it lose touch with physical reality and the audience.

D. M. Bancroft and G. M. West, followed a particularly useful tack, namely that of examining rival rheological concepts (each of which has validity and devotees) in the light of their applicability in steady shear flow and recovery after steady shear flow of liquid polymers.

Whilst polymers were well to the fore, there was also P. Feltham's paper dealing with single crystals of inorganic solids. J. Jongepiers'



The President, Dr. L. Grunberg, with Professor R. Meredith, at the Annual Conference Dinner, held at the Baird Hall, Glasgow, on 17th September, 1969.



The President, Dr. L. Grunberg, congratulates Professor D. M. Dowson, one of the joint Gold Medal winners.

development of his work on bitumens using static and dynamic moduli, compliances and relaxation spectra for the characterisation and long term behaviour prediction of these important constructional materials, H. J. Buswell's paper on composite propellant rheology which took us into generally unfamiliar fields and J. M. P. Papenhuijen's work on the influence of salts on the rheological properties of detergent solutions. J. C. Weeks described the automation of an extrusion rheometer

The discussion sessions were in general brief and anaemic. The principal reason for this is probably the meagreness of the abstracts which delegates received and which were scarcely sufficient to prepare them adequately with what was to come. A number of papers were readily understood only by those who least needed to listen to them—that is to say, by the specialist himself and his immediate colleagues. A full pre-print would have ensured a more receptive audience which would then have been capable of initiating lively discussions.

Unfortunately, the physical conditions of the proceedings were also somewhat uncongenial—or perhaps one is spoilt by the opulence of proceeding years. The proper setting for B.S.R. Autumn meeting lectures is a good-sized lecture theatre equipped with note-taking facilities, first-rate slide reproduction equipment and sound amplifiers. It is to be hoped that these important details will not be overlooked again.

WEDNESDAY, 17th September.

(Dr. W. H. Banks, P.I.R.A., Leatherhead, Surrey.)

This session, chaired for the first four papers by Professor G. V. Vinogradov, was more diverse than previous ones. The opening paper by C. T. S. Dobson might well, in due course, rank as pioneering a new approach to the difficult but very topical problem of defining strain in heterogenous systems where in principle it is possible to select a region devoid of matter as in a piece of porous material like paper. Dobson showed how the limitations of a continuum approach in defining strain might be overcome by an appropriate geometrical statistical sampling procedure and a treatment based on the co-variance of the bulk modulus and dilatation and on their spacial auto-correlation, thus transforming the equation of state at points into macroscopic relations for observable zones in the two dimensional case. Extension to three demensions would seem to pose only problems of complexity.

A. Kaye followed with an attempt to improve the equations of state of Lodge and which lead to normal stresses that are independent of shear rate. Taking the relaxation time as dependent on the current state of stress in the material and by assuming a constant number of molecular entanglements G then becomes a function time

and the problem becomes one of finding its function of stress. This extension of Lodge's work predicts a shear viscosity falling with shear rate and an elongational viscosity having a maximum at some elongation rate. Applied to molten polystyrene at 300°F the agreement between theory and experiment is qualitative.

A paper by F. M. Leslie on a continuum treatment of the flow of liquid crystals (nematic and cholesteric types) coupled with experiments in Couette flow and Poiseuille flow implied that the viscosity of thin films near the walls of the viscometers is reduced, for the apparent viscosity is a universal function of (velocity $\times$ gap) and hence, as a function of strain rate, the viscosity must increase with gap. Similarly with Poiseuille flow, viscosity is smaller for tubes of smaller bore. These conclusions didn't appeal to the lubrication people but presumably the molecules of lubricants are different in size from the units comprising liquid crystals.

A short paper by M. M. Cross, more appropriate to earlier sessions, provided a salutary reminder of the dangers of log, log functions, and indeed went far to destroy one's confidence in the meaning of the critical molecular weight (M_c) so frequently derived from plots of zero shear viscosity against molecular weight on a log scale. It looks very much as though M_c is not a singularity but is a mathematical artifact that arises from the dependence of viscosity on a polynomial in even powers of M and which might be expected from the probability of primary and higher order enlargements as they affect flow.

Dr. Grunberg then took the Chair for the remaining papers from the Russian delegation.

Dr. Vinogradov presented a very detailed study of the behaviour of molten polymers in oscillating shear and steady flow. The action of vibration of finite amplitude is equivalent to steady flow with a definite finite shear rate. Both processes cause truncation of the part of the relaxation spectrum at high times.

Professor Tager presented a study of the specific viscosity of polyisobutene solutions. Disintegration of structure and orientation were proposed to explain the fall in viscosity with shearing rate. In concentrated solution, both shearing and solvent action increases disintegration. Energies of activation calculated from temperature coefficients confirmed the idea that in good solvents (high disintegration) the heat is independent of shear rate, in contrast with the case of poor solvents, where it is dependent on shear rate because of the greater disintegration possible.

THURSDAY, 18th September.

(Dr. K. Beasley, English China Clays, Cornwall.)

The first session of Thursday, Dr. van Tempel in the Chair, opened with three elastically oriented papers. The first of these,

by J. Batchelor, J. P. Berry and F. Horsfall, was read by the first-named author, and dealt with "Die swell of elastic and inelastic fluids." Using a modified Hounsfield tensometer as an extruder an elastic material (depolymerised natural rubber) and an inelastic one (a modified alkyd resin) were extruded and die swell observed and measured for both materials. With the inelastic (Newtonian) material, die swell was independent of shear rate, but swelling increased with increasing shear rate for the elastic material. This paper was followed by the third presented by our Russian visitors—"Viscoelastic and relaxation properties of molten polymers in axial extrusion" by G. V. Vinogradov, V. D. Fikhman, B. V. Radushkevich and A. Ya Malkin; the paper was read by Dr. Malkin. At low deformation rates, axial extension of polymer melts is accompanied by increasing viscosity and high-elastic modulus which, with increasing deformation rates, may give rise to a succeeding region of decreasing viscosity and modulus, with corresponding of relaxation processes, stationary flow regimes being attained. The authors presented exhaustive and convincing data in support of their thesis. Finally, F. N. Cogswell educated and entertained us with a paper on "Large elastic deformation in polymer melts." The author described measurements of shear and tensile modulus, the former being carried out by cone and plate measurements and analysis of die swell results. The relation between shear and tensile modulus agrees with that predicted by theory.

After coffee, the Chair was taken by Mr. R. Whorlow, and Professors Dowson and Higginson presented a paper on "The role of lubricant rheology in engineering applications of elastohydrodynamic lubrication," Professor Higginson delivering the lecture. This, of course, was the work which led to the award to the authors of the Society's first Gold Medal. To summarise this paper would be an impertinence; sufficient to say that Professor Higginson expounded simply, lucidly and comprehensively the work which led to the present understanding of this vitally important phenomenon, an understanding due to a very large extent to the work of the authors. For all who were privileged to hear it, this paper must stand out as the highlight of the meeting.

This was followed by a paper by J. W. Hayes and J. F. Hutton on "Measurement of the parameters of a second order fluid in flow along a curved tube," read by Mr. Hayes. The paper was in the nature of a progress report of work in which viscoelastic parameters of solutions are investigated by injecting dyestuff into a fluid flowing along curved tubes and measuring the course of stream lines in it. The morning session ended with one of Dr. Giesekus's excellent films. This one dealt with flow around a rotating sphere, the flow being made visible by Schlieren techniques based on changes in refractive index caused by the heat generated through viscous dissipation.

Lunch over, and with Dr. Walters in the Chair, we passed on to a paper given by Dr. W. M. Jones on "Onset of Taylor instabilities in

water and dilute polymer solutions in water," co-authored by himself, D. E. Marshall and D. M. Davis. Water and dilute polymer solutions were investigated in a concentric cylinder viscometer under flow conditions both below and above the critical Taylor number. The behaviour obtained was characterised by both the viscosities measured and by visual observation of the flow pattern. The next paper, "Normal stress measurements on viscoelastic liquids using capillary tubes," was delivered in two parts. Firstly, Mr. W. C. McSporran spoke on "Entrance region behaviour examined by means of the jet thrust method," showing how the changes in stress pattern and velocity profile which occur in capillary entrance region flow are reflected in the thrust of liquid jets issuing from short tubes. Dr. R. Oliver, following, spoke on "The entrance pressure drop and its correlation with jet thrust data," showing that for a viscoelastic fluid, the pressure drop required to cause flow of it into a capillary tube entrance may greatly exceed the total kinetic energy and viscous flow corrections associated with capillary flow of a Newtonian fluid.

So to tea, and the last session of the Conference; Dr. K. M. Beasley taking the Chair. This session dealt with suspension rheology, and consisted of two papers. Mr. R. W. Whorlow presented a paper by himself and Dr. D. J. Highgate on "Rheological properties of suspensions in non-Newtonian media" which gave results of measurements of shear and normal stress made on dilute suspensions of small spheres in non-Newtonian plastic fluids. It was shown that at constant shear stress, the relative viscosity of the suspension was a function of suspension concentration only, whereas at constant shear rate, this ratio was a function of both concentration and shear rate. Analogous relation appeared to hold for the ratio of normal stress to shear rate. Finally, R. R. Davidson and P. R. Saunders described "The rheology of concentrated suspensions of china clay and natural chalk whittings." Mr. Davidson showed that whiting suspensions had lower viscosities at a given concentration than china clay suspensions do, and that clays exhibited stronger rheological dilatancy than whittings do when anionically deflocculated. Nonionically deflocculated systems were less dilatant than ionically deflocculated ones and it was suggested that the rheological dilatancy was caused by shear induced flocculation.

A few words of benediction and valediction from the chairman, and the 1969 Autumn Conference closed. A successful conference, surely, with a great range of materials, techniques and approaches compressed into a very solid, and very useful, two-and-a-half days.

BRITISH SOCIETY OF RHEOLOGY

REPORT OF THE HONORARY SECRETARY 1968-69

The year under review was a normal satisfactory year with successful conferences and a steady rise of membership. Professor Charlesby, having completed his second year of office, was not eligible for re-election and, at the last Annual General Meeting, Dr. L. Grunberg was elected in his place. The new President since has chaired four out of six Council Meetings and was consulted on other matters of the Society in the interim periods, his guidance being much appreciated by the Council. Only one other executive office changed hands in September, 1968, that of the Editorship of the Bulletin, and this too went very smoothly.

Mr. K. R. Hall has been elected President of the Victorian Branch.

Finance

As usual, the Treasurer is submitting a separate report. Although for several years now we have been hinting at the possibility of making a change in the administration of the Society which could involve the necessity of raising the present very low membership fee, once again the Council decided against such a move. The main reason was that, having explored the possibilities, we discovered that the employment of paid officers or secretarial help, even on a shared basis, with a minimum of office space, is so expensive that any charge would necessarily be quite drastic. So, by making a few small changes in the organisation and by creating a new post of Assistant Editor of Abstracts, we have solved the problems for the present, and we are confident that we can continue running smoothly next year, as at present.

Membership

We have enrolled 45 new members. Two members died, and one resigned. There were again some scientists from overseas, including Africa and Eastern Europe, among those applying for membership of the B.S.R.

As announced last year, we decided to make a fresh survey of our members' rheological activities and interests and have, for this purpose, distributed some questionnaires. The response has been fairly good and we hope to publish a new membership list before the end of 1969.

Research Committee

The most important activity of the Research Committee has been the organisation and judging of the Gold Medal Competition. The Committee is presenting a separate report.

Meetings Held

As in the previous year, we held three meetings during the year under review. Two were joint meetings with other societies and one, the Annual Conference, was held on our own.

(a) *Mechanical Properties and Design*

Joint meeting with the Materials Science Club, Guildford, 31st March–1st April, 1969. This was a fairly specialised meeting which attracted an enthusiastic audience of about 60.

(b) *Practical Rheology in Polymer Processing*

Joint meeting with the Plastics Institute, London, 17th–18th April, 1969. The registration for this meeting was large, about 200. As indicated in the title, the subjects discussed were practical. Meetings of this type help to illustrate the essential utility of the study of rheology for industrial application.

(c) *Advances in Rheology*

Three-day meeting, Glasgow, 16th–18th September, 1969 (the present meeting). We have received 122 registrations, and we hope that the meeting will be as successful as our Annual Autumn Meetings usually are. This meeting may be considered slightly more theoretically biased though, for the first time in some years we decided not to set a definite central topic and the papers cover a wide range of subjects.

Meetings Projected

Arrangements have been made for an international meeting in April, 1970.

Yield, deformation and fracture of polymers

31st March–3rd April, Cambridge: This was mentioned in last year's report. It is planned as a large scale meeting, and the B.S.R. is one of seven societies organising it. In many ways, it is a new kind of venture, and we are awaiting it with great interest.

Other B.S.R. Meetings

We have no definite plans as yet for our other meetings next year. The possibility of holding a meeting on "Printing inks and paints," and one on "Applications of Theoretical Rheology," the latter possibly for next year's Autumn Conference, is being considered by the Council.

International Committee on Rheology

The International Congress on Rheology, held last year in Kyoto, was attended by a few of our members, and the Council was repre-

sent by Dr. K. Walters on the above Committee. This Committee has agreed on a constitution and Dr. P. U. A. Grossman, of the Victorian Branch, has been nominated as Australian Representative on the Committee.

The Council has supported a proposal to the International Committee that the next International Congress should be held in Lyon, France, in 1972.

Publications

Our two publications, the Bulletin and the Abstracts, have appeared regularly. The Bulletin has become somewhat larger and regularly contains long feature articles. We intend to continue this trend, and the Editor has plans for some changes which will make the Bulletin more like an ordinary scientific journal.

We have also re-issued our brochure in a new form. This was very necessary as the information given on our previous issue was largely out-of-date.

British Standards Institute—British Society of Rheology Joint Committee on Rheological Terms and Symbols

This Committee, set up in the previous year, has been very busy during the year. The items to be included have been listed and a first draft of proposals is being drawn up.

Victorian Branch

In addition to the Annual General Meeting, four Branch Meetings and one Joint Meeting were held in 1968–69.

As the result of the initial work of a sub-committee of the Branch on Rheological Terminology the Australian Standards Association has recently issued a draft document for public comment.

Overseas Liaison

As before, we have co-operated with our Australian Branches, and have maintained our good relations with rheological societies of other countries.

BRITISH SOCIETY OF RHEOLOGY
BALANCE SHEET as at 30th JUNE, 1969

	£	s.	d.	£	s.	d.
GENERAL FUND						
As at 1st July, 1968				2,867	19	7
Add: Excess of Income over expenditure for the year				115	8	4
				<u>£2,983</u>	<u>7</u>	<u>11</u>
<i>Represented by:</i>						
ASSETS						
Leatherhead UDC 6½% Bonds	1,500	0	0			
Debtors		68	17	2		
Cash at Lloyds Bank Ltd.	1,524	10	3			
Deposit Account						
Cash in hand		10	0	0		
				<u>3,103</u>	<u>7</u>	<u>5</u>
<i>Less</i> CURRENT LIABILITIES						
Sundry Creditors		76	15	3		
Lloyds Bank Ltd.						
Current Accounts overdrawn		43	4	3		
				<u>119</u>	<u>19</u>	<u>6</u>
NET ASSETS				<u>£2,983</u>	<u>7</u>	<u>11</u>

R. J. COLE, *Hon. Treasurer*

We have examined the above Balance Sheet and annexed Revenue Account together with the books and vouchers of the Society, and certify them to be in accordance therewith. We have not inspected the membership records.

The Market Hall,
 Redhill, Surrey.
 20th August, 1969.

ALFRED SIMMONS & Co.
Chartered Accountants

BRITISH SOCIETY OF RHEOLOGY

REVENUE ACCOUNT for the year ended 30th JUNE, 1969

INCOME

	£	s.	d.	£	s.	d.
<i>Annual Subscriptions and Entrance Fees</i>				541	1	7
<i>Rheology Abstracts and Bulletins</i>						
Publisher (Abstracts)	893	18	4			
Bulletin Subscriptions	3	1	0			
				896	19	4
<i>Investment Income—gross</i>						
Bank Deposit Interest	59	16	5			
Leatherhead 6½% Bonds	97	10	0			
				157	6	5
<i>Sale of Literature</i>				6	3	3
				<u>£1,601</u>	<u>10</u>	<u>7</u>

EXPENDITURE

	£	s.	d.	£	s.	d.	£	s.	d.
Clerical Services				14	2	0			
Printing and Stationery				86	6	9			
Postage				10	19	4			
Travelling									
Officers and Council	147	0	7						
Research Committee	150	6	6						
BSI Committee	75	19	9						
Abstracts Working Party	2	17	1						
				376	3	11			
Conferences									
Net expenditure per schedule				155	0	10			
Bulletins									
Production and Distribution Costs				571	4	6			
Membership Secretary—Expenses				192	17	11			
Professional Fees				36	5	0			
Gold Medal Competition Expenses				34	0	0			
General Expenses				9	2	0			
							1486	2	3

EXCESS OF INCOME OVER EXPENDITURE FOR THE YEAR

£115 8 4

THE BRITISH SOCIETY OF RHEOLOGY

CONFERENCES

Year ended 30th June, 1969

Net Expenditure:				£	s.	d.
Shrivenham 1968	...	...	...	38	16	6
Guildford 1969	...	...	...	9	5	2
Strathclyde 1969	...	...	...	42	0	0
Sheffield 1967	...	...	...	5	11	7
Joint Haemorheology 1968	...	...	...	59	7	7
As per Income and Expenditure Account				£155	0	10

BRITISH SOCIETY OF RHEOLOGY RESEARCH COMMITTEE

Annual Report June 1968—June 1969

1. *Membership*

At the beginning of this period the composition of the Committee was as follows:

Professor J. F. Raffle (Chairman)
Dr. M. F. Culpin
Mr. A. Evans
Mr. A. T. J. Hayward
Mr. P. Lamb
Dr. J. R. A. Pearson
Mr. B. Warburton
Dr. J. P. Berry (Acting Secretary)

Professor Raffle retired from his position as Chairman in September 1968 but remained on the Committee. Dr. Pearson took over the duties of Chairman, and Dr. Berry those of Secretary at the same time. Otherwise the composition of the Committee has remained unchanged throughout the year.

The Committee met four times during the year, in June and October 1968 and in January and April 1969.

2. *Gold Medal Competition*

Eight entries for the Competition were received and it was recommended that medals should be awarded to Professor D. Dowson and Professor G. R. Higginson for their work on "Elastohydrodynamic Lubrication." The entry by Dr. D. C-H Cheng on "The Design of Pipe-line Systems" was also of high quality and it was agreed that this should be commended.

3. Joint Working Party on Non-Newtonian Flow

The Working Party completed its critical task of classifying and evaluating the published work on the rheology of non-Newtonian fluids and prepared a draft report. This report recommended that the possibility be examined of establishing Institute(s) for Rheological Research similar to the Institutes of Tribology. The report and its recommendation were discussed at a meeting of representatives of the British Society of Rheology, the Institution of Chemical Engineers, Research Associations, and other interested bodies, in January of this year. However there was no strong support for the idea of Rheological Research Institutes. The scheme for the classification of rheological research on non-Newtonian fluids, prepared by the Working Party, has now been adopted in Rheology Abstracts.

4. Working Party on the Classification of Rheological Research on Solids

This Working Party has now held three meetings and has been concerned exclusively with the formulation of an acceptable classification scheme. This task has been facilitated by the experience gained in establishing the classification scheme for fluids, especially since two members of that Working Party (Mr. Hayward and Mr. Lammiman) are members of the present one. Unfortunately progress has been slow because of the small number of people participating and this situation will be aggravated by the impending retirement of Mr. Hayward. It has therefore been decided to increase the size of the Working Party, but efforts to do so have, so far, met with little success.

5. Technical Enquiries

Three technical enquiries have been dealt with.

6. Purpose and future of the Research Committee

This is a topic which is of continuing concern to the Committee. Of the activities noted above, the Working Parties have an essentially independent existence, and the technical enquiries arise so infrequently that they could not justify the perpetuation of the Committee. The Gold Medal Competition calls for concentrated effort over a short period of time, but this would normally occur only every three years. The efforts to formulate a profitable and continuing programme have proved largely unavailing, in spite of active consideration by the present Committee, and indeed by the Research Committee since its inception.

VICTORIAN BRANCH

HONORARY SECRETARY'S REPORT FOR 1968-69

Committee

The members of the Branch Committee for 1968-69 were:

President: Mr. K. R. Hall

Hon. Secretary: Dr. D. V. Boger

Hon. Treasurer: Mr. K. G. Martin

Committee: Mr. B. C. Brown, Dr. E. J. Dickenson, Dr. D. H. Morton

Auditor: Mr. O. G. Ingles

Branch Meetings

In addition to the Annual General Meeting, four Branch Meetings and one Joint Meeting were held in 1968-69.

At the 1968 Annual General Meeting held on September 4th, 1968, Dr. G. Hibberd of the Bread Research Institute of Australia spoke on "Dynamic Viscoelastic Properties of Wheat Flour Doughs." Dr. Hibberd discussed the interpretation of results obtained from oscillatory deformation of Wheat Flour Doughs.

On November 6th, 1968, a Joint Meeting was held with APPITA. The speaker was Professor S. G. Mason, head of the Physical Chemistry Section of the Pulp and Paper Research Institute of Canada. Professor Mason spoke on "The Micro-Rheology of Dispersions." His lecture summarised an extensive series of theoretical and experimental studies of the rotations, deformations, orientations and n-body collisions of a variety of particle shapes, types and sizes in dilute and concentrated suspensions undergoing laminar shear flow.

On December 11th, 1968, Mr. K. R. Hall, the current President of the Society and Senior Research Scientist in the Chemical Engineering Division of C.S.I.R.O., discussed some of the highlights of the Autumn Conference of the British Society of Rheology held at Shrivensham in England, and the Fifth International Congress on Rheology in Kyoto, Japan.

The first meeting in 1969, held on March 5th, was highlighted by a presentation from Mr. A. L. Temby on "Rheology in Lubrication." Mr. Temby, who is the Manager of Technical Services of H. C. Sleight Ltd., discussed the significance of the Rheology of Lubricants, in relation to the theory and practice of hydrodynamic lubrication.

On April 23rd, 1969, Mr. R. H. Coates, Research Officer in the Polyethylene Section of I.C.I.A.N.Z. Central Research Laboratories discussed "The Morphology and Strength of Polypropylene." This

lecture considered the relationship between structure and mechanical properties in polypropylenes.

The final meeting for the 1968-69 programme was held on June 18th, 1969. Dr. J. R. Brotchie spoke on the "Deformation of the Earth's Crust." This presentation was concerned with an analytical description of the deformation of the earth's crust under superimposed loadings.

International Congress of Rheology

The By-Laws of the ICR were adopted by both the New South Wales and Victorian Branches. Dr. P. A. U. Grossman was nominated and has been accepted to represent Australia on the Committee.

Chemeca 70

During the year, the BSR-Victorian Branch has been a co-operating Society in the Symposium Session entitled "Rheology and Mixing."

SUB-COMMITTEES

Terminology

As a result of the initial work of the sub-committee, the Standards Association has recently issued a draft document for public comment.

Library

The contents of the Branches special library in Rheological Topics is now being supervised by Dr. D. H. Morton of Australian Paper Manufacturers Ltd., Alphington. A list of library holdings and new accessions will be available at each future meeting of the Branch.

Symposium on Behaviour of Viscoelastic Fluids

A symposium on the above topic has been scheduled for March 11th, 1970. The committee organising this event is:

Dr. P. A. U. Grossman

Dr. J. Stearne

Mr. O. Delatycki

PROGRAMME
40th ANNUAL MEETING
THE SOCIETY OF RHEOLOGY, INC.
October 20th-22nd, 1969

(Asterisks indicate invited paper)

MONDAY, OCTOBER 20th

GENERAL SESSION

8.30 a.m.* "Superposition in Rheology," D. J. Plazek, Hershel Markovitz.

SECTION A

Moderator, J. R. Knox

- A-1 9.30 a.m. "Molecular Motion in Block Copolymers," D. G. LeGrand.
10.00 a.m. Coffee break.
- A-2 10.15 a.m. "Physical Properties of Block Copolymers of Polydimethyl Siloxane and Polycarbonate," T. L. Magila and D. G. LeGrand.
- A-3 10.45 a.m. "Rheo-Optical Properties of Polyurethane Segmented Elastomers," G. M. Estes, R. W. Seymour, D. S. Huh, S. L. Cooper.
- A-4 11.15 a.m. "Non-Newtonian Viscosity of PPO-Polystyrene Melts," T. W. Huseby.
- A-5 11.45 a.m. "Characterisation of Linear Polyethylene Based on Steady State Flow Behaviour," Nobuyuki Nakajima.

LUNCH

Moderator, D. J. Cox

- A-6 2.00 p.m. "The Study of Lithographic Blankets as a Problem in Rheology," Harry H. Hull.
- A-7 2.30 p.m. "Rheology of Uniform Colloidal Spheres Dispersed in Organic Media," Y. S. Papir, I. M. Krieger.
3.00 p.m. Coffee break.
- A-8 3.15 p.m. "Estimating the Effective Viscosity During the Leveling of Paints," O. C. C. Lin.
- A-9 3.45 p.m. "Nonlinear Transient and Dynamic Behaviour in Bovine Muscle," C. T. Morrow, N. N. Mohsenin.
- A-10 4.15 p.m. "The Effect of the Degree of Agitation on the Rheological Properties of Clay Suspensions," Brajendra K. Sinha, Harvey T. Kennedy.

- A-11 4.45 p.m. "Variational Treatment of Suspension Viscosities," Stephen Prager.

SECTION B

Moderator, I. M. Krieger

- B-1 9.30 a.m. "Determination of Viscoelastic Constants for Polymers Using Non-Dispersive Strip Delay Lines," D. Hunston, R. R. Myers, M. Palmer.
10.00 a.m. Coffee break.
- B-2 10.15 a.m. "A Factor of Two," Robert A. Stratton, Allan F. Butcher.
- B-3 10.45 a.m. "Some New Experimental Measurements of the Second Normal Stress Difference," R. I. Tanner.
- B-4 11.15 a.m. "Normal Stress Measurements in Couette Flow," J. M. Broadbent, A. S. Lodge.
- B-5 11.45 a.m. "Couette Flow and Normal Stresses," L. J. Zapas, J. C. Phillips.

LUNCH

Moderator, E. B. Bagley

- B-6 2.00 p.m. "Precision Falling Sphere Viscometry," David A. Cygan, Bruce Caswell.
- B-7 2.30 p.m. "Theoretical Analysis of Two New Rheometers," Misazo Yamamoto.
3.00 p.m. Coffee break.
- B-8 3.15 p.m. "Modifications of an R-16 Weissenberg Rheogoniometer," K. H. Lee, K. Pandalai, Robert S. Brodkey.
- B-9 3.45 p.m. "Improved Techniques for Measuring Dynamic Viscoelastic Properties of Dilute Polymer Solutions from 0.01 to 4000 Hz," John L. Schrag, Dennis J. Massa, Robert M. Johnson.
- B-10 4.15 p.m. "A New Absolute Viscosity Determination," R. W. Penn, M. R. Brockman, E. A. Kearsley.
- B-11 4.45 p.m. "Cavitation in Viscoelastic Media," David H. Kaelble.

SPECIAL TOPIC DISCUSSION

8.30 p.m. "Superposition Principles in Rheology," Co-Chairmen D. J. Plazek, Hershel Markovitz.

TUESDAY, 21st OCTOBER

GENERAL SESSION

- 8.30 a.m.* "Composite Materials, Theory and Practice," John C. Halpin.

SECTION A

Moderator, N. Nakajima

- A-12 9.30 a.m. "A Normal Mode Analysis of Macromolecules Containing Branches and Loops," A. J. Chompff.
10.00 a.m. Coffee break.
- A-13 10.15 a.m. "Anomolous Heat Transfer in Viscoelastic Fluids," J. S. Ultman, M. M. Denn.
- A-14 10.45 a.m. "Deficiencies of Viscoelastic Theories as Applied to Filled Polymers," R. J. Farris, J. E. Fitzgerald.
- A-15 11.15 a.m. "Viscoelastic Relaxation Mechanism at Cryogenic Temperatures," A. Eisenberg, S. Reich.
- A-16 11.45 a.m. "An Analysis of Flow of Polymer Melts in a Screw Extruder," C. D. Han.

LUNCH

SOIL SYMPOSIUM

Moderator, A. S. Cakmak

Part I

- A-17 2.00 p.m.* "Rheology and Soil Mechanics," Werner E. Schmid.
- A-18 2.30 p.m.* "Dynamic Soil Rheology," Raymond J. Krizek.
- A-19 3.00 p.m.* "Effect of Micro Structure on Rheologic Behaviour of Clays," R. N. Yong.
- A-20 3.30 p.m. "Axial Fluid Flow in Swelling and Shrinking Porous Rods," R. A. C. Raats.
3.50 p.m. Coffee break.

Part II

- A-21 4.00 p.m. Panel Discussion on the Rheological Approach to Soil Mechanics: Panelists—W. E. Schmid, R. J. Krizek, R. N. Yong, M. Harr, R. Scott, A. S. Cakmak (moderator).

SECTION B

Moderator, E. Collins

- B-12 9.30 a.m. "Dynamic Mechanical Properties of Polyethylene Melts: Calculation of Relaxation Spectrum from Loss Modulus," Ramesh N. Shroff.
10.00 a.m. Coffee break.

- B-13 10.15 a.m. "Relation Between Steady-Flow and Dynamic Viscosity for Polyethylene Melts," Ramesh N. Shroff, Mitsuzo Shida.
- B-14 10.45 a.m. "A Molecular Approach to Polymer Chain Entanglement," A. E. Tonelli.
- B-15 11.15 a.m. "Analysis of Elongational Flows," D. C. Bogue, J. O. Casey.
- B-16 11.45 a.m. "Fluids with Micro Stretch," Teoman Ariman.

LUNCH

Moderator, A. P. Metzger

- B-17 2.00 p.m. "Rheology of Binary Polymer Mixtures," H. Van-Oene, Y. F. Chang.
- B-18 2.30 p.m. "Melt Flow Instability in Ethylene Polymers," L. L. Blyler, Jr., A. C. Hart, Jr.
3.00 p.m. Coffee break.
- B-19 3.15 p.m. "Non-Newtonian Flow and the Steady State Shear Compliance," W. M. Prest, Jr.
- B-20 3.45 p.m. "Die Swell in Polystyrene," W. W. Graessley, S. Glasscock, R. Crawley.
- B-21 4.15 p.m. "Viscoelastic Efforts in the Extrusion of Filled Polyethylene," E. B. Bagley, H. J. Duffey, L. R. Schmidt, S. Guber.

SOCIETY OF RHEOLOGY BUSINESS MEETING

4.45 p.m.

BINGHAM AWARD PRESENTATION

8.30 p.m.

WEDNESDAY, 22nd OCTOBER

SECTION A

Moderator, L. J. Zapas

- A-22 8.30 a.m. "The Drainage of Viscoelastic Liquids Entrained on a Vertical Surface," C. D. Denson.
- A-23 9.00 a.m. "Linear Viscoelastic Materials with Environmental Dependent Properties—Steady Environments," D. C. Stouffer, A. S. Wineman.

- A-24 9.30 a.m. "Linear Viscoelastic Materials with Environmental Dependent Properties—Transient Environments," D. C. Stouffer, A. S. Wineman.
10.00 a.m. Coffee break.
- A-25 10.15 a.m. "Constitutive Equations for Polymer Solutions Derived from Zimm's Bead/Spring Model," A. S. Lodge, Yeen-jing Wu.
- A-26 10.45 a.m. "Transient Phenomena in Polymer Solutions," W. Philippoff.
- A-27 11.15 a.m. "Superposed Parallel Flow for Dilute Polymer Solutions," Ian F. Macdonald.
- A-28 11.45 a.m. "Oscillatory Shear of Non-Linear Fluids," James S. Dodge, Irvin M. Krieger.

LUNCH

Moderator, S. Prager

- A-29 2.00 p.m. "Stability of Viscoelastic Fluids: Plane Couette Flow with Superimposed Temperature Gradient," L. V. McIntire, W. R. Schowalter.
- A-30 2.30 p.m. "Relations Between Certain Non-Viscometric and Viscometric Material Functions," R. R. Huilgol.
3.00 p.m. Coffee break.
- A-31 3.15 p.m. "A Special Theory of Viscoelastic Fluids," R. M. Christensen.
- A-32 3.45 p.m. "Application of Prony Series to Linear Viscoelasticity," J. E. Soussou, F. Moavenzadeh, M. H. Gradowczyk.
- A-33 4.15 p.m. "Viscoelastic Tests Under Finite Strain and Variable Strain Rate," Ronald J. Flowers, G. Lianis.
- A-34 4.45 p.m. "Determination of the Instantaneous Response of Viscoelastic Materials from Plate Impact Experiments," Karl W. Schuler.

SECTION B

Moderator, R. A. Mendelson

- B-22 8.30 a.m. "Master Stress Relaxation Curve for Poly (methyl methacrylate) from a Model for Computer Shifting," R. E. Coulehan, R. W. Morosani.
- B-23 9.00 a.m. "Rheological and Thermodynamic Interaction Effects in Plasticized Polyvinyl Chloride Compounds," H. P. Schreiber.
- B-24 9.30 a.m. "The Degradation of Polystyrene During Extrusion," Kunio Arisawa, Roger S. Porter.
10.00 a.m. Coffee break.

- B-25 10.15 a.m. "Rheological Implications of the Exit Pressure and Die Swell in Steady Capillary Flow of Polymer Melts," C. D. Han, M. Charles, W. Philippoff.
- B-26 10.45 a.m. "Rheological Behaviour of Some Powders," Kenneth B. Larson, Lawrence E. Nielsen.
- B-27 11.15 a.m. "The Performance of a Drag Reducer in Small and Large Diameter Lines," John D. Culter.
- B-28 11.45 a.m. "Interpretation of Non-Newtonian Flow in Porous Media," J. C. Reed.

LUNCH

Moderator, V. Kolpe

- B-29 2.00 p.m. "The Entrance Pressure Loss in Capillary Flow for Nearly Newtonian Fluids," Ray D. Hoffman.
- B-30 2.30 p.m. "Flow Patterns of Polymer Melts in the Entry Region of a Capillary Die," T. F. Ballenger, J. L. White.
- B-31 3.15 p.m. "Determination of the Rheological Properties of Polymeric Systems from the Spectrum of Scattered Light," T. F. Reed, J. E. Frederick.
- B-32 3.45 p.m. "Molecular Motions of Polystyrene in Dilute Solution from Rayleigh Line-Broadening Measurements," J. E. Frederick, T. F. Reed.
- B-33 4.15 p.m. "An Integral Constitutive Equation Based on Molecular Network Theory," Bernard J. Meister.
- B-34 4.45 p.m. "Viscoelastic Flow in the Disc and Cylinder System," M. W. Johnson, Jr., J. M. Kramer.

RHEOLOGY IN MEDICINE AND PHARMACY

It is proposed to hold a conference of the above title for two days, Tuesday and Wednesday, 14th and 15th April, 1970. The venue will be at The School of Pharmacy, in London. Detailed arrangements will be announced later.

The first day of the meeting, Tuesday, will be devoted to rheology in medicine and will be divided into two parts:—

- (1) **Morning Session:**—Rheology of Body Fluids, e.g. Blood, Lymph, Mucus, Saliva, Synovial Fluid.
- (2) **Afternoon Session:**—Rheology of Body Tissues, e.g. Bone, Connective Tissue, Cartilage, Muscle, Skin, Tendon, Vessel Wall.

The second day of the meeting, Wednesday, will be devoted to rheology in pharmacy and biochemistry and will be divided into two parts:—

- (3) **Morning Session:**—Rheology of Pharmaceutical Formulations, e.g. Injections, Emulsions, Creams, Suspensions, Pastes, Gels, Solutions.
- (4) **Afternoon Session:**—Rheology of Liquid/Liquid and Liquid/Air Interfaces, e.g. Mechanical Properties of Interfacial Films of Hydrocolloids, Proteins. Use of surface rheological techniques to monitor changes (physical and chemical) in interfacial films.

Authors are invited to submit in one of the above categories. The papers should be either a review of work in the field designated or original scientific research. It will be assumed that most of the submissions will be of experimental work; however, any theoretical work of a mathematical nature, where relevant to a session, will be especially welcome.

The time for presentation of papers will be twenty minutes with a maximum of ten minutes for discussion.

It would be appreciated, from an administrative point of view, if titles could be received from prospective authors as soon as possible and a detachable form is provided, for the purpose, at the end of this notice.

It is hoped to be able to publish the proceedings of the conference with discussion in a suitable Rheological Journal. *Summaries of not more than 400 words should be sent in to the Conference Convenor not later than December 31st, 1969, to:—*

B. Warburton, Esq.,
 R.M.P. Conference Convenor,
 Department of Pharmaceutics,
 The School of Pharmacy,
 29/39 Brunswick Square,
 London, W.C.1.

SIXTH INTERNATIONAL CYBERNETICS CONGRESS

The International Association for Cybernetics was founded in Namur (Belgium) on 6th January, 1957. It has taken as its objective the establishment of permanent and organised liaison between scientists who, in many countries, are carrying out works relative to the various aspects of Cybernetics.

It has organised five International Congresses in 1956, 1958, 1961, 1964 and 1967. The fifth Congress in particular enjoyed an outstanding success: more than 150 papers were read by scientists and research workers representing thirty countries. His Majesty the King of the Belgians honoured the concluding academic session by his presence.

Besides the publication of the Proceedings of the Congresses, the Association has, since 1958, been producing a quarterly review: *Cybernetica*.

The sixth Congress will be held in Namur, from 7th to 11th September, 1970. The organisers hope that this occasion will bring together in Namur all those who are interested, in any capacity, in the development of Cybernetics and its ever more numerous applications.

The questions dealt with in the course of the Congress will be divided into five groups: the bases and methods of Cybernetics—Semantic machines—Automation—Cybernetics and the science of man—Cybernetics and life.

The official languages of the Congress will be French and English.

Those wishing to become a member of the Association, to take part in the Congress or to obtain information concerning the publications of the Association are requested to apply to the Secretariat of the International Cybernetics Association, Palais des Expositions, Place André Rijckmans, Namur (Belgium).

THE SOCIETY LIBRARY

The Society owns a number of books and journals concerned with rheological subjects, some of historic interest. A recent addition is a proof copy of "The Principles of Rheological Measurement" which is a report of a conference of the British Rheologists' Club held in London in October, 1946. This was kindly presented by Dr. Scott Blair.

The collection includes incomplete runs of the following journals:

Transactions of the (U.S.) Society of Rheology.

Cahiers du Groupe Francais d'Etudes de Rheologie.

Bulletin of the British Hydromechanics Research Association.

J. Japan Soc. Test. Matls.—Special Rheology Issues.

J. Soc. Matl. Sci., Japan.—Special Rheology Issues.

Reports on Progress in Polymer Physics in Japan.

Scientia Sinica.

Berichte der Deutschen Rheologischen Gesellschaft e. V.

Rheologica Acta.

These journals and other items in the collection (a list of which is available) may be borrowed by members. Requests should be sent to Mr. R. W. Whorlow, Department of Physics, University of Surrey, Guildford, Surrey.

"CHEMECA" 70
CHEMICAL ENGINEERING CONFERENCE
AUSTRALIA 1970

Melbourne 18th-21st August. Sydney 24th-26th August

Topics

1. Particle Mechanics: Including mineral processing, comminution, classification, froth flotation, agglomeration, dust and mist collection.
2. High Temperature Processes: Including pyro-metallurgy, glass and refractory manufacture.
3. Chemical Reaction Engineering: Including reaction systems, kinetics, electrochemical and hydrometallurgical processes, reactor performance, petrochemicals.
4. Biochemical and Biomedical Engineering: Including biological fermentation, biological leaching and extraction, food engineering, biomedical processes and devices.
5. Rheology and Mixing: Including engineering aspects of rheology and mixing of non-Newtonian fluids.
6. Diffusional Processes: Including heat, mass and energy transfer operations.
7. Process Dynamics and Control: Including computer control and optimisation.
8. Scientific Management: Decision making applied to the planning and use of resources; to R & D; to design; to process operation.

Addresses for communications:

General

The Secretary, Chemeca 70,
Australian Academy of Science,
Gordon St.,
Canberra City, A.C.T.,
Australia 2601.

Technical Programmes

Assoc. Prof. J. R. Norman,
Dept. of Chemical Engineering,
University of N.S.W.,
P.O. Box 1,
Kensington, N.S.W.,
Australia 2033.

BRITISH SOCIETY OF RHEOLOGY

Computer Program Catalogue

Publication Abstract

1. Author
2. Establishment
- Tel. No.
3. Program Abstract
-
- Input Data
-
- Output Data
4. Program date
5. Language
6. Computer requirements
-
7. Type of Input/Output
8. References
-
-
-
9. Related programs
-
10. Available for copy/data processing
-

Return to: Dr. J. Harris,
Postgraduate School of Chemical
Engineering,
University of Bradford,
Bradford 7, U.K.

Additional blank abstract sheets are available as required from the above address.



The President, Dr. L. Grunberg, congratulates Professor G. R. Higginson, one of the joint Gold Medal winners.



Professor G. V. Vinogradov, flanked by Professor Dowson and Professor Higginson and backed by the President, Dr. L. Grunberg, makes a firm point in an impromptu after-dinner speech.

BRITISH SOCIETY OF RHEOLOGY

Computer Program Catalogue

Publication Abstracts

1. Author
David Mitchell
2. Establishment
University of Bradford
Tel. No. 33466-1104
3. Program Abstract
Computers, real and imaginary components of Viscosity (or rigidity) for each frequency input
Input Data
Readings from rheogoniometer
Output Data
Tabulates results as in section 3 above
4. Program date
April, 1960
5. Language
Algol
6. Computer requirements
Core 7040
7. Type of Input/Output
Card reader input, line printer output
8. References
The analysis of frequency—response experiments for rheological characterisation
J. Harris and W. C. Wilkinson, Chem. Eng. Sci. 1969, Vol. 24, pp. 1-6
9. Related programs
None
10. Available for copy/data processing
Yes

RECENT ELECTIONS

NAME AND ADDRESS	INTERESTS
G. Abbott, U.C. Wales, Aberystwyth, Cards., Wales.	General; Theory, Experiments, Rubbers, Polymers, Polymer solutions.
H. Oya Alpar, School of Pharmacy, Brunswick Sq., London, W.C.1.	Particulate solids, oils, greases.
F. H. Assioma, Ethylenique Plastique, B.P. Res. Centre, 62 Mazingarbe, France.	Solid and molten polymers.
R. W. Bryant, Mintech E.R.D.E., Waltham Abbey, Essex.	Liquid-solid systems, adhesive joints.
P. Shadwick, School of Maths. and Physics, University of East Anglia, Norwich, U.K.	Metals, alloys, composites, solid polymers, liquid-liquid systems, liquid-solid systems, theory.
J. E. Cordwell, Dept. of Metallurgy and Materials Science, University of Liverpool, U.K.	Metals, alloys.
I. J. Davies, Dept. of Chemical Engineering, University College, Swansea, Glam., U.K.	General, rubbers, polymers, solutions, emulsions, suspensions, etc.
J. A. Dormandy, Dept. of Physiology, Royal College of Surgeons of England	Biological Materials.
G. Evans (Miss), B.P. Chemicals (U.K.) Ltd., Sully, Penarth, Glam., U.K.	Polymers; liquid-liquid, liquid-solid and particulate solids.
R. T. Fenner, Dept. Mechanical Engineering, Imperial College, London, S.W.7.	General, metals, rubbers, polymers, polymer solutions.
J. Fernandez, Escuela Técnica Superior de Arquitectura, Avda. Genralísimo Franco, 1001 Barcelona—14, Spain.	Composites.
I. C. Geddes, Dept. Anaesthesia, Liverpool University, U.K.	Molten or dissolved polymers, biological materials.
G. P. Ginliani, Sham Progetti/LRSR/POL5331 20097 S. Donato. Milano, Italy.	Solid polymers, molten or dissolved polymers.
J. W. Hayes, c/o Thornton Research Centre, P.O. Box 1, Chester (1969 only).	Molten or dissolved polymers, liquid-solid systems.

NAME AND ADDRESS

INTERESTS

P. J. Hunter,
Chemicals Division,
B.P. Research Centre,
Sunbury-on-Thames, Middx., U.K.

Solid polymers, molten or dissolved polymers, particulate.

M. K. Kislau glu,
School of Pharmacy,
29-39, Brunswick Sq., London, W.C.1.

Liquid-liquid systems, particulate solids.

F. D. Kunst,
Watts, Blake, Bearne & Co. Ltd.,
Park House, Courtney Park,
Newton Abbot, Devon, U.K.

Liquid-solid systems, particulate solids, glasses, ceramics.

J. V. Leysen,
Phillips Petroleum International
Technical Centre,
355, Steenweg op Brussel-overijse
(Brabant), Belgium.

Composites, solid polymers, molten or dissolved polymers.

P. F. McNally,
Phillips Petroleum International
Technical Centre,
355, Steenweg op Brussel-overijse
(Brabant), Belgium.

Solid polymers, molten or dissolved polymers, liquid-liquid systems, liquid-solid systems, particulate solids.

J. A. Milburn,
Dept. Botany,
University of Glasgow, U.K.

Natural fibrous materials, liquid-solid systems, particulate solids, biological materials.

D. B. Mistry,
School of Pharmacy,
29-39, Brunswick Sq., London, W.C.1.

Liquid-liquid systems, liquid-solid systems.

G. Nuki,
Centre for Rheumatic Diseases,
Baird St., Glasgow, U.K.

Molten or dissolved polymers, biological materials, theoretical materials.

A. J. Palfrey,
St. Thomas's Hospital Med. School,
London, S.E.1.

Natural fibrous materials, liquid-liquid systems, liquid-solid systems, oils, greases, biological materials.

T. J. F. Pickup,
Dept. of Chemical Engineering,
Pembroke St., Cambridge, U.K.

Molten or dissolved polymers, liquid-liquid systems, oils, greases, theoretical materials.

A. Prastaro,
Nentecatini Edison—Centro Ricerche,
Piazza Douegani 2—44100 Ferrara,
Italy.

Solid polymers, molten or dissolved polymers, liquid-liquid systems, liquid-solid systems, theoretical materials.

van Roosmalen,
Nederlandse Cyamid
Maatselappy, N.V.
Boslek—Holland.

Printing inks, disperse systems

J. Rothwell,
Dept. of Food Science,
The University, London Road,
Reading RG1 5AR, U.K.

Liquid-liquid systems, liquid-solid systems, foodstuffs.

K. G. Schmidt,
Forsvarets for Skningsintitut,
2007 Kjeller, Norway.

Metals, alloys.

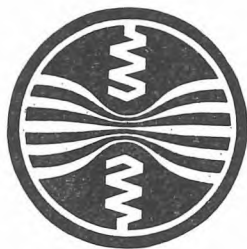
NAME AND ADDRESS	INTERESTS
J. Shapiro, Dept. of Chemical Engineering, Pembroke St., Cambridge, U.K.	Molten or dissolved polymers.
T. L. Smith, I.B.M. Research Laboratory, San Jose, California 95114, U.S.A.	Solid polymers, molten or dissolved polymers, liquid-solid systems.
C. R. Tottle, School of Maths. Sci., Bath University of Technology, Bath, Somerset, U.K.	Metals, alloys, composites, solid poly- mers, glasses, ceramics, building and road materials.
R. L. Turner, Kodak (Aust.) Pty. Ltd., Elizabeth St., Coburg, Victoria, Australia.	Gelatin, polymer gels.
A. J. Willson, Dept. of Mathematics, University of Leicester, U.K.	Molten or dissolved polymers, liquid- liquid systems, theoretical materials.

DIARY

1970

- 7-9 January. Conference—Polymer chain flexibility. British Polymer Physics Group. Essex University, Colchester.
- 19-20 February. Convention—The use of grease as an engineering component. I.Mech.E., London.
- 23-25 March. Convention—Thermodynamics and fluid mechanics. I.Mech.E., Glasgow Univ.
- 24 March. Conference—Product performance testing. Plastics Inst.
- 31 March-3 April. Conference—Physical and structural lines of the yield, deformation and fracture of polymers. Joint I.P.P.S. Brit. Poly. Phys. group, B.S.R., I.R.I. and Matl. Sci. Club meeting at Cambridge.
- 1-4 April. International Conference—Thermodynamics. Inst. Phys., Univ. Coll., Cardiff.
- 2-3 April. Symposium—Pulsating Flow Measurement. Inst. Measurement and Control, Univ. Surrey.
- 6-10 April. 4th International Conference on Stress Analysis: Experimental Stress Analysis and Its Influence on Design. I.Mech.E., Cambridge.
- 7-10 April. Conference—2nd European Conference on Thermophysical Properties. I.P.P.S., B.C.S., S.C.I., U.K.A.E.A., Warrington.
- 13-17 April. Short Course—Basic Strain Measurement. B.S.S.M. South Birmingham Technical College.
- 14-15 April. Conference—Rheology in Medicine and Pharmacy. B.S.R., School of Pharmacy, London.
- 16-17 June. Conference—Polymers in High Performance Applications. Joint Soc. of Plast. Engrs. and Plastics Institute at Inst. Elec. Engrs., London.
- 1-3 September. International Conference—The Hydraulic transport of solids in pipes. B.H.R.A., Coventry.
- 29 September-1 October. Conference—Advances in polymer science and technology No. 3. Chemistry of liquid and thermoplastic co-polymers. Plastics Inst.

BULLETIN



**BRITISH SOCIETY
OF RHEOLOGY**

1969, No. 4, Vol. 12 (Supplement)

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ENGINEERING APPLICATIONS OF
ELASTOHYDRODYNAMIC LUBRICATION**

Hon. Editor:

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Bradford,
Yorks. U.K.

B.S.R.
GOLD MEDAL AWARD PAPER

**THE ROLE OF LUBRICANT RHEOLOGY
IN ENGINEERING APPLICATIONS OF
ELASTOHYDRODYNAMIC LUBRICATION**

by

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INTRODUCTION

In this paper we shall describe the basic theory of elastohydrodynamics, with particular emphasis on the physical nature of the fluid. We shall then examine some of the applications.

The mode of lubrication aimed at by engineers is full-film lubrication, in which the solid bodies involved are completely separated by a film of fluid; the friction is low and the wear of the solids is practically zero. Load is transmitted from one body to the other by pressure in the fluid. The pressure may be generated externally—hydrostatic lubrication—or it may be generated internally by virtue of the viscosity of the fluid and the motion of the solids—hydrodynamic lubrication. If the bodies are of high geometrical conformity, such as a shaft in a plain bearing, this separation can be achieved fairly easily, provided the mating parts are accurately manufactured. The effective area of lubricant film is large, and realistic loads can be carried by modest lubricant pressures; under such pressures components made of metals (or other solids of comparably high elastic modulus) can be treated as rigid. If on the other hand the mating solids are of poor geometrical conformity, for example two convex bodies, or if one of them has low elastic stiffness, the contribution of the deformation of the solids to the geometry of the lubricant film cannot be neglected.

We can therefore define elastohydrodynamic lubrication as the regime in operation in lubricating films between elastically deformable solids. Although in recent years much attention has been given to applications involving soft solids, such as rubber seals and human joints, the origins of the subject and most of its short history are in the small, highly stressed areas of contact between gear teeth and between roller or ball and track in rolling bearings.

Gears and rolling bearings, and no doubt other machine elements, are known to have enjoyed hydrodynamic lubrication for very many years, but only during the last twenty or so has this been widely recognised, and only during this decade has the classical lubrication theory been sufficiently modified to be reconciled with practical observations. Before this there was a long-standing conflict between observations such as the running of loaded gears for thousands of hours with virtually no tooth wear, and the theoretical prediction of a film thickness which was minute compared with the surface irregularities on the teeth.

THEORETICAL WORK

Historical Background

The theory has been largely concerned with elements in nominal line contact, such as straight spur gears or roller bearings. These geometries have been further simplified by representing the bodies in contact by two parallel cylinders, or an equivalent cylinder and plane. The model of this situation in terms of traditional lubrication theory is:

Two *smooth rigid* cylinders lubricated by an *incompressible isoviscous Newtonian* fluid.

The words in italics are in varying degrees inaccurate, but they were introduced into the formulation of the simple model to make it tractable. It was in terms of this model that in 1916 Martin¹ raised little hope of full-film lubrication in gear teeth, estimating film thicknesses in the region of 2×10^{-8} m, a figure much smaller than the height of the surface irregularities (of order 10^{-6} m). This discrepancy stood for many years, but recently progress has been made by removing in turn some of the restrictions described by the words in italics.

Since the work of Hertz on bodies in contact was published in 1881, it has been known how two convex elastic bodies pressed together deform to accommodate the load over a finite area of contact. The effect of this sort of deformation on the geometry of a lubricated contact is an obvious, but difficult, correction to make to the simple model, and a number of attempts to do so have been made in the past (see²). More recently a number of workers reported on the theoretical effect arising from the vast influence of high pressure on the viscosity of the lubricant (while still treating the solids as rigid). Both these effects, acting separately, were shown to be beneficial in increasing the film thickness under a given load; but the increases were modest—far short of that required to account for practical observations.

The difficulty of including both effects can be seen by looking at the equations to be solved. For the case of two cylinders lubricated by an incompressible Newtonian fluid with pressure—dependent viscosity they are: (see figure 1).

$$\frac{dp}{dx} = 12\eta u \left(\frac{h-h_0}{h^3} \right) \quad (1)$$

$$h-h_0 = \frac{x^2}{2} \left(\frac{1}{R_1} + \frac{1}{R_2} \right) - \frac{2}{\pi E'} \int_{s_1}^{s_2} p(s) \ln(x-s)^2 ds \quad (2)$$

The first is the Reynolds equation governing pressure generation in the fluid film. The second gives the shape of the fluid film, the first term being the gap between two undeformed cylinders in contact and the second the effect of elastic deformation. These must be solved simultaneously in accordance with appropriate boundary conditions. It will be noted that no allowance is made for thermal effects except in the use of an appropriate value of viscosity at the entry to the high pressure zone. This simple-looking problem turns out to be difficult to solve because in realistic conditions the obvious iterative attack (pressure $\rightarrow$ deformation $\rightarrow$ film shape $\rightarrow$ pressure) does not always converge. A further look at the equations shows why. The viscosity η varies roughly exponentially with pressure, reaching in the contact zone values several orders of magnitude above its atmospheric value. Therefore if dp/dx is to have reasonable values, $(h-h_0)$ in equation (1) must be very small indeed; i.e. $h \approx h_0$ throughout the high-pressure zone. In the second equation the two terms on the right-hand side are both much bigger than h_0 , and are therefore orders of magnitude bigger than $(h-h_0)$, yet it is their difference which is used to calculate $(h-h_0)$. The calculation is plainly very ill-conditioned.

A big step forward was taken in 1949 by Grubin³ in an approximate but very effective analysis which yielded a formula for film thickness. This gave results in realistic cases of something like a hundred times the Martin values. An outstanding feature of the analysis was that it applied to high loads, where the elastohydrodynamic effects are most pronounced, and most beneficial. The derivation of the formula was based on two simplifying assumptions: (1) that the deformed shape of the cylinders is the same as that in dry contact and (2) that an extremely high pressure is developed in the entry region to the Hertzian zone. The first of these obviates the need for a simultaneous solution to the two governing equations, but the analysis takes account of both effects.

In 1954 Weber and Saalfeld published a number of solutions obtained by a convergent iteration, but only at loads so small as to be of little practical interest. At higher loads the iteration failed to converge.

Modern theory

The first rigorous solutions of the isothermal elastohydrodynamic problem at high loads were published in 1959⁴ and 1960⁵. Convergence in these early results was achieved by an essentially manual relaxation which employed the "inverse hydrodynamic procedure." This procedure determines the film geometry responsible for the generation of a given pressure distribution, whereas the usual integration of the Reynolds equation produces a pressure distribution from a given film shape. The film shapes corresponding to a given pressure curve were determined by the inverse hydrodynamic procedure and by the elasticity equation, and compared. The relaxation consisted of

modifications to the pressure curve to minimise the discrepancy between the two shapes.

If material properties appropriate to steel cylinders lubricated by a mineral oil are used in the calculation, pressure curves which can only be described as fantastic emerge. Figure 2 shows pressure curves for a constant load and a wide range of speeds. The related film shapes are shown in Figure 3. (It is a testimony to Grubin's remarkable insight that he predicted the main features of these diagrams on the basis of physical argument.) Figure 2 shows how the pressure departs from Hertzian as the speed increases, leading to maximum values far in excess of the Hertzian maximum. Apart from other, intuitive, objections to the pressure curves, these high values plainly raise doubts about the assumption of incompressibility of the lubricant. The next step therefore was to remove this restriction. Figure 4 shows that compressibility very much reduces the heights of the peaks in the pressure curves, although the minimum film thicknesses remain virtually unaltered.

All the theoretical results for minimum film thickness can be closely represented by the formula:

$$h = 1.6 \alpha \cdot 6 (\eta_0 u)^{-7} (E')^{.03} R^{.43} W^{-.13} \quad (3)$$

Studies of elastohydrodynamic lubrication have been extended to spherical solids and the table in Figure 5 summarizes the equations for film thickness in nominal point and line contacts. The equations resulting from classical hydrodynamic lubrication theory are listed alongside those for elastohydrodynamic conditions. (It should be emphasised that these formulae apply only to the conditions of the calculations, viz. metals in contact under high loads and lubricated by a fluid with the viscosity/pressure relationship resembling that of a mineral oil.)

At about the time that these results were produced, reliable experimental measurements of film thickness and film shape were being made. These were all made on disc machines, notably by Crook⁶, Sibley and Orcutt⁷, and Dyson, Naylor and Wilson⁸. The last of these are generally recognised as the most accurate. Figure 6 shows a typical comparison between measured and calculated film thicknesses for steel rollers and a mineral oil. This graph is for measurements taken at a constant load; the same investigation showed that film thickness varied with load according to $h \propto W^{-.15}$, compared with the theoretical variation $h \propto W^{-.13}$ given by equation (3). Very elegant experiments by Crook and by Sibley and Orcutt showed that the *shape* of the oil film was in general agreement with the shapes shown in Figure 3, including the small "bump" at the exit end. Clearly, for film thickness and shape, the gap between theory and experiment was closed by the mid-sixties.

It is interesting to note at this stage the actual form of equation (3); the indices are all less than one and some very much smaller. So although the problem is very sensitive and defiant analytically, the

phenomenon itself, at any rate the film thickness, is very insensitive. The value of the film thickness is almost independent of some very important physical characteristics, and once the fluid film is established it appears to be almost unassailable.

Despite the accurate prediction of film thickness, which had rightly taken first priority in elastohydrodynamics, it must be remembered that the theory still assumed smooth solids, isothermal conditions and a Newtonian fluid. The assumption of isothermal conditions is really equivalent to the restriction of the motion of the cylinders to pure rolling, with no sliding. It is known that the viscous energy dissipation in pure rolling causes only a small temperature rise in the fluid. On the other hand it is plain that the addition of sliding to the rolling motion will lead to significant viscous dissipation with corresponding temperature rises; these must affect at least the surface tractions, and one would expect also effects on the film thickness and pressure distribution. However, the experiments of Crook showed that the film thickness was unaffected by sliding, so long as its interpretation was in terms of the *inlet* viscosity value for the fluid at the bulk temperatures of the solids; the magnitude of fluid flow through the pressure zone is determined in the entry region, and the fluid, once in at the front has to come out at the back, whatever may be the heating in the pressure zone. This was confirmed by the later experiments of Dyson, Naylor and Wilson and is demonstrated in Figure 6.

Theoretical confirmation of the last paragraph comes from papers which take account of thermal effects by Cheng and Sternlicht⁹, Cheng and Orcutt¹⁰ and Dowson and Whitaker¹¹. A surprising, but unanimous, feature of these papers is that the height of the theoretical pressure peaks is practically unaltered even by a high sliding component in the motion, although Cheng and Orcutt suggest (on the basis of a crude physical model) that viscoelastic effects in the fluid might remove the peaks altogether. Further reference will be made to viscoelastic effects later.

Turning briefly to the question of surface finish, disc machine experiments primarily concerned with the measurement of film thickness have normally used specimens of the highest quality attainable, but a number of experiments have investigated specifically the effects of surface roughness (Dawson¹², Dowson and Whomes¹³ and Jefferis and Johnson¹⁴). Dawson's important series of experiments was concerned with life to failure by pitting, and he established a consistent relationship between life and the ratio of surface roughness to elastohydrodynamic film thickness. Jefferis and Johnson sought a connection between Dawson's findings and the friction tractions between discs of a wide range of surface roughnesses. They concluded firmly that no correlation exists between the bulk shear stresses introduced by the tractive force and the fatigue life.

Surface quality would be expected to influence friction coefficients of lubricated rolling and sliding contacts whenever the film thickness

was sufficiently small to be comparable to the size of surface irregularities and this has been noted in the experiments carried out on a disc machine by Dowson and Whomes.

The pressure distribution in a rolling or sliding contact is of secondary practical importance to the film thickness, but it is of importance in determining the stresses in the solids, and it is of great academic interest because of its extraordinary theoretical shape. Confirmation or denial of the existence of the sharp peak presents a formidable experimental problem, very largely due to the scale of things. In short, theory predicts the existence of a "spike" only if the solids have an elastic stiffness about as high as that of steel and the fluid has a pressure/viscosity relationship similar to those of mineral oils. If the experiment is to be feasible in terms of load, the solid specimens (discs) cannot have a radius of more than a few cm. In these circumstances the theoretical pressure spike will be only about $10\text{ }\mu\text{m}$ wide (transit time of order 10^{-6} sec) and possibly $3 \times 10^9\text{ N/m}^2$ high. The most successful attempt so far to measure the pressure distribution is by Kannel¹⁵, using a pressure transducer consisting of a deposited manganin strip $5 \times 10^{-5}\text{ m}$ wide. Figure (7) shows that the possibility of the spike is very much alive, when it is remembered that the transducer is several times wider than the spike itself. Indeed the width of the whole pressure drop from its maximum to zero is about the same as the width of the transducer, indicating that the near-vertical pressure gradients at outlet in Figure (4) are correct.

Lubricant rheology

Within our definition of the subject a prerequisite for elastohydrodynamic lubrication is deformability of the solids, and although the employment of soft solids is certainly conducive to hydrodynamic lubrication¹⁶, the principal interest has so far been in metallic components. Between metals the characteristics of the mechanism can be summarised as follows:

(i) The film thickness is determined by the conditions and the fluid behaviour in the entry region where the shear rates and the temperature rises are relatively low, even with sliding. This accounts for the great success of this aspect of the theory which is based on the very simple rheological model of compressibility

$$\frac{\rho}{\rho_0} = 1 + \frac{\beta p}{1 + \alpha p} \text{ and Newtonian viscosity } \eta = \tau / \frac{\partial u}{\partial y};$$

η varies with pressure according to $\eta = \eta_0 e^{\alpha p}$ and η_0 is an "entry viscosity" which depends on the surface temperature of the solids at entry to the high-pressure zone. This viscosity variation with pressure displayed by common lubricants is the decisive feature of the mechanism (it is a mercy to railway operators that the viscosity of rainwater is very

insensitive to pressure—the theoretical film thickness under a locomotive wheel on a wet rack is therefore only about 10^{-8} m).

(ii) The pressure distribution under high loads is largely determined by the elastic deformation of the solids; this is much greater than the fluid film thickness and so the surface pressure cannot, overall, be much different from that in the absence of fluid, viz. Hertzian. Departures from this are the inlet sweep and of course, the spike; it should be noted however that the spike, although high, is very narrow and contributes very little to the load and much less than might be expected to the stresses in the solids. The spike is not, incidentally, inseparably linked with the “bump” in the film shape. The bump is there for reasons other than the spike, and has been shown to exist in reality.

(iii) Finally, surface tractions, particularly in sliding, are critically dependent on conditions prevailing in the fluid in the high pressure zone. They are therefore much more sensitive than the other characteristics to departures of the fluid from the simple rheological model. Archard¹⁷ has written “Of all the information obtained from experiments in elastohydrodynamic lubrication, coefficients of friction are, in general, the easiest to obtain but the most difficult to interpret.”

The pioneer in this aspect of elastohydrodynamics, as in so many others, was Crook¹⁸, who obtained results exemplified by Figure 8. As the sliding speed increases, the traction rises rapidly, linearly at first but soon at a diminishing rate until a maximum is reached, beyond which it declines relatively slowly. Crook first analysed these results in terms of heat generation due to shear within the film; this provided an explanation over much of the range, but left discrepancies which increased as the *rolling* speed increased. Crook suggested that the importance of the higher rolling speeds lay in the shorter transit times, and that viscoelastic effects were responsible for the discrepancies.

A number of attempts have been made (Milne¹⁹, Tanner²⁰ for instance) to embody viscoelasticity into lubrication theory, but these have been handicapped by the lack of an adequate mathematical description of the behaviour of viscoelastic fluids. In elastohydrodynamics in particular the most comprehensive and successful attempts so far are those of Dyson^{20, 21}. The second of these employs the very promising theoretical model²³ proposed by Barlow, Erginsav and Lamb after many years of elegant experimental work by themselves and their colleagues on liquids in oscillatory shear. Adapting this model to continuous shear, Dyson goes a long way towards reconciling experiment and analysis, but points out that some features of this speculative and difficult work still require explanation.

APPLICATIONS

Gears

Questions about the lubrication of gears were responsible for the origin of elastohydrodynamics as a theoretical subject, and although some of the important questions have been answered, much art and mystery remain in the design and functioning of gears, especially in those with more than usually complicated geometry. The accurate analysis of the lubrication mechanism throughout the meshing cycle of any combination of gears, taking full account of lubricant rheology, will clearly be a formidable undertaking. A first attempt for involute gears by the authors ²⁴ estimates film thickness through the meshing cycle. Values at the pitch point are presented in charts in a form convenient for designers.

Dudley ²⁵ describes a retrospective study of several actual gear case histories "to determine how the elastohydrodynamic theory of lubrication fits with the facts that have been observed." The cases examined cover a wide range of running conditions in a number of precision gears. Dudley demonstrates that the calculated elastohydrodynamic film thickness at the pitchpoint correlates reasonably well with gear experience, in the sense that conditions which give rise to a substantial film thickness also give long gear life—"spur and helical gears running at high pitch-line velocity will operate for as much as a billion tooth contacts without enough wear occurring to remove machining marks 15 millionths of an inch deep."

The relationship between surface quality and fatigue noted by Dawson in disc machine experiments has recently been reported for gears. This represents a major step forward in the understanding of the role of lubrication in gear design and it appears that the designer has now been provided with a reliable guide for the steps to be taken to minimise the possibility of surface distress during normal running. These recommendations are being incorporated into standard gear design procedures and it is not uncommon to call for elastohydrodynamic predictions of the pitch line film thickness at the design stage.

Variable speed drives

In recent years there has been much interest in the development of smooth variable speed drives for machinery and vehicles. One general device which readily suggests itself calls for the transmission of traction through a thin oil film between a disc, wheel or sphere driven by the prime mover and a second rotating component connected to the output side of the machine or vehicle.

It is necessary to minimise slip between the two lubricated components in order to maintain a high efficiency but the lubrication must be adequate to protect the surfaces from excessive wear and to provide adequate life. The contact conditions are similar to

those found in rolling element bearings and it is clear that the lubrication regime is elastohydrodynamic under many conditions. A typical example is the Perbury gear.²⁶

Clearly, the rheological characteristics of the lubricant are of great significance and it is important that the relationship between shear stress and "slip" or shear-rate should be studied for a variety of potential lubricants for this application. An important feature of the traction/slip characteristics of most lubricants under elastohydrodynamic conditions is that the traction sometimes exhibits a maximum value at a slip speed determined by the load, geometry and rheological properties of the lubricant. Crook¹⁸, Dowson and Whomes¹³ and Plint²⁷ have reported this feature of experimental results from various forms of disc machines.

It is known that high temperatures are generated in elastohydrodynamic films at high shear rates and that the resulting effective viscosity might be lower than at low shear rates. This effect could account for the observed maximum in the traction curve but Crook¹⁸ has shown that this explanation cannot account for the reduction in traction observed at low shear rates. It is possible that non-Newtonian characteristics are important in this region of operation. In an interesting discussion of traction in elastohydrodynamic contacts Plint²⁷ has suggested that there is evidence of the existence of a limiting shear strength in the lubricant.

Rolling bearings

The countless designs and wide variety of basic geometries amongst rolling bearings have attracted much attention in the field of applied mechanics. So far, however, most of the elastohydrodynamic research on rolling bearings has been on the geometrically simple cylindrical roller bearing shown in Figure 9. Apart from its geometry the cylindrical roller bearing is typical of the whole range. It is made from high-strength materials to great accuracy with high quality surfaces; it runs, often in hostile environments, over a vast range of speed (0–20,000rpm) and load (up to Hertzian stresses of $3 \times 10^9 \text{ N m}^{-2} \approx 200 \text{ ton/in}^2$) with a coefficient of friction down to 0.001. Even with this low friction quite a small bearing running at high speed and load may be dissipating 1 kW; as a power loss this will be negligible compared with the power being transmitted, but it presents a cooling problem.

In spite of the simple geometry of the roller bearing, it is much more complex than a pair of discs. It has many contact points, geometrical imperfections (very small, but in some ways influential) and a complicated sharing of the radial load between the rollers. A theoretical study of the mechanics of roller bearings²⁸ shows that even with a modest load, the elements operate in the elastohydrodynamic regime; the oil film thickness will under most conditions be significant compared with the roughness of the surfaces, and the

motion of the assembly will be essentially epicyclic even with a complete oil film at all the contacts. With extremely light loads (less than about 1% of the capacity) gross sliding at the contacts is predicted, leading to major departures from epicyclic motion. Later theoretical and experimental work^{29, 30, 31} on cylindrical roller bearings examined in some detail the nature of the lubrication, the friction and the kinematics.

The film thickness has not so far been measured, but a useful qualitative guide to the nature of the lubrication is given by measurements of the electrical resistance between the inner and outer tracks. There is, of course, a pair of possible contacts for each roller, and so the measurements give only an overall picture, but Figure 10 demonstrates clearly the transition from metal-to-metal contact to full film lubrication (at one of each of the pairs of contacts, at least). The photographs were taken with a load of 6,000 lb. on a 2 in. diameter bearing. The critical range of speed shown is fairly narrow and the theoretical film thickness increases by only about 2.5 to 1. A large number of measurements of time-average resistance over a wide range of load and speed is shown in Figure 11; the sum of the centre-line-average roughnesses for track and roller was 20×10^{-9} m (8μ in.). It is clear that once a film thickness equal to the sum of the c.l.a. roughness values has been established, virtually complete fluid film lubrication has been secured.

The friction torque of a properly lubricated bearing is very small. Figure 12 shows friction torque for a range of load and speed for a bearing on a 2 inch shaft with the minimum amount of lubricant to maintain full film lubrication. As a power loss the energy dissipated is small, but as an energy input to the bearing it may be large; in addition the bearing may be in a high temperature location in the machine of which it forms a part. It is instructive therefore to try to identify the principal sources of friction. There are many possible contributions, only a few of which can be calculated with any confidence, but it appears that the rolling viscous traction is quite the largest and that elastic hysteresis of the solids makes a significant contribution at high loads. Between them these two account for about 80% of the friction torque over most of the range.

Under most operating conditions the motion of the components of a roller bearing is epicyclic; in other words pure rolling at all the contacts. Even with a full oil film, the viscous tractions are sufficient to prevent gross sliding. If however the bearing is very lightly loaded and there is a diametrical clearance and an ample supply of lubricant, roller slip may occur; for example aircraft turbine engine bearings of very high load capacity carry little more than the weight of the rotor in straight flight. Slip or skidding causes surface damage and may lead to an early failure of the bearing; it has therefore received a good deal of attention^{32, 33}.

In recent experiments on the 2 inch bearing Boness³¹ has investigated the influence of load, speed, viscosity and clearance on roller and cage slip. Figure 13 shows how, for this bearing, the application of a small load eliminates cage slip; the capacity of the bearing is over 10,000 lb.

These examples have shown that a simple theory, based on an elementary rheological model of the lubricant, and complicated only by numerical difficulties, has made much progress in the field of rolling contact lubrication. There remain many points of attack for the analysts: full thermal solutions over a wide range of conditions, the development of a satisfactory viscoelastic model of lubricants and its inclusion in a full elastohydrodynamic theory, and when they are mastered there will doubtless remain the human joint, where non-Newtonian thixotropic synovial fluid separates two layers of porous articular cartilage with non-linear stress/strain/liquid-content relations.

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ACKNOWLEDGEMENT

The authors are grateful to the Institution of Mechanical Engineers for their permission to reproduce several of the diagrams.

Notation

h	film thickness
p	pressure
s	additional co-ordinate in x-direction
u	$\frac{1}{2} (u_1 + u_2)$, mean surface velocity
w	load per unit length of cylinders
w'	load on spherical contact
x, y	co-ordinates
E'	equivalent elastic modulus of solids
G	dimensionless materials parameter $\alpha E'$
H	dimensionless film thickness $\frac{h}{R}$
R_1, R_2	radii of cylinders in contact
R	effective radius $R_1 R_2 (R_1 + R_2)$
U	dimensionless speed $\eta_0 u E' R$
W	dimensionless load $w E' R$ (cylindrical contacts)
W'	dimensionless load $w' E' R^2$ (spherical contacts)
α	pressure exponent of viscosity $\eta = \eta_0 \exp(\alpha p)$
η	viscosity
η_0	viscosity at atmospheric pressure and the temperature at inlet to the contact
ρ	density

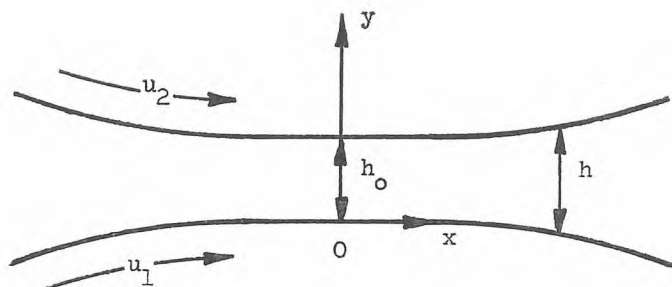


Fig. 1. Geometry and Coordinates

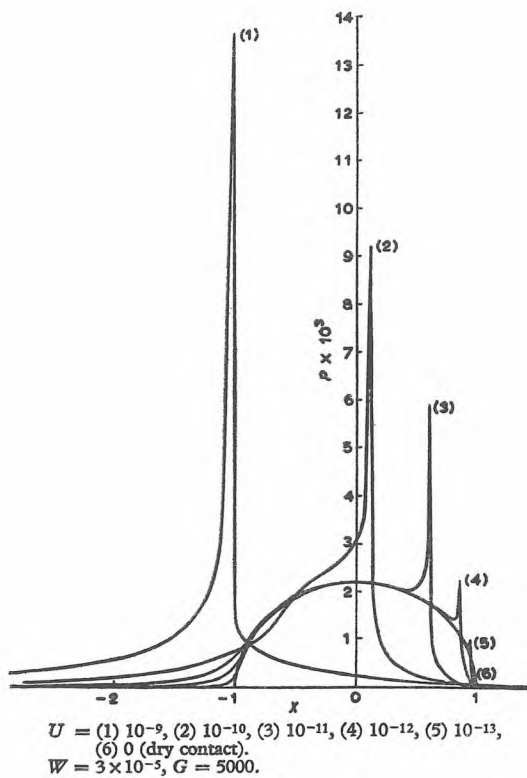


Fig. 2. Pressure distributions for an incompressible lubricant

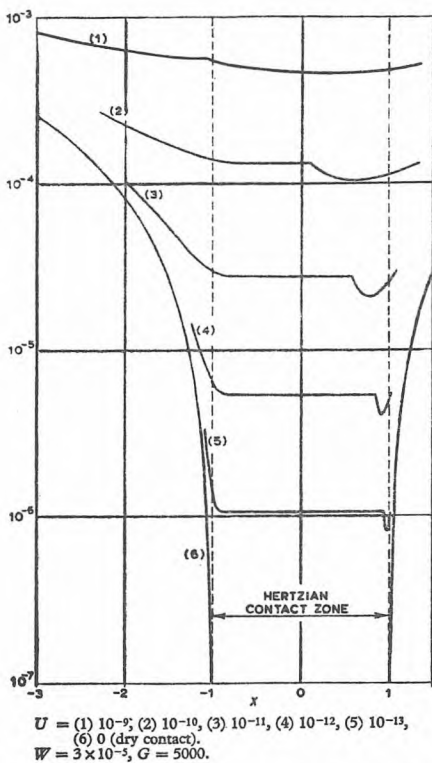


Fig. 3. Film shapes for an incompressible lubricant

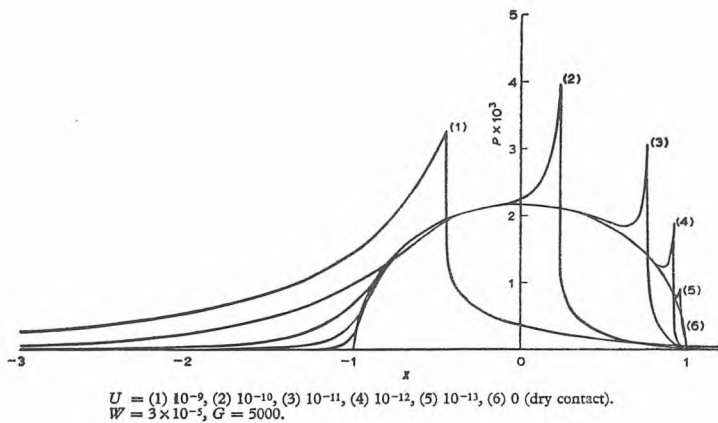


Fig. 4. Pressure distributions for a compressible lubricant

Geometry	Film Thickness Equation	
	Rigid Solids Isoviscous Fluid	Elastohydrodynamic
<u>Cylinder near a plane</u>		
load w/unit length $W = \frac{w}{E'R}$	$H_{min} = 4.9 \frac{U}{W}$	$H_{min} = 2.65 \frac{G^{0.54} U^{0.70}}{W^{0.13}}$
<u>Sphere near a plane</u>		
total load w' $W' = \frac{w'}{E'R^2}$	$H_{min} = 113.7 \left(\frac{U}{W'} \right)^2$	$H = 1.40 \frac{(GU)^{0.74}}{(W')^{0.074}}$

Fig. 5. Film thickness equations

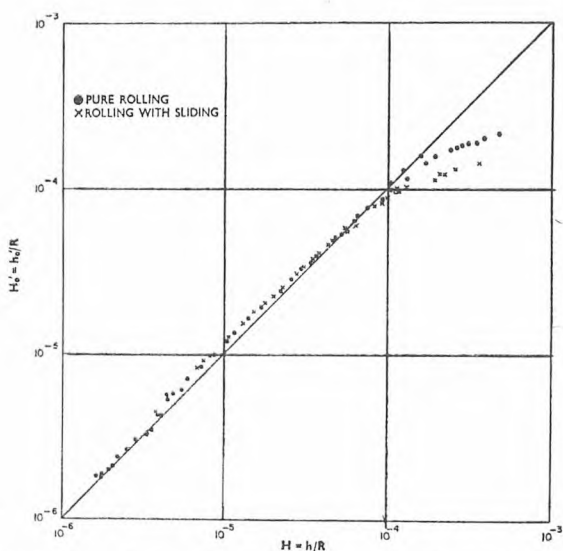


Fig. 6. Lubricant B: comparison of measured non-dimensional oil-film thickness $H_o' = h_o'/R$ with predicted values $H = h/R$

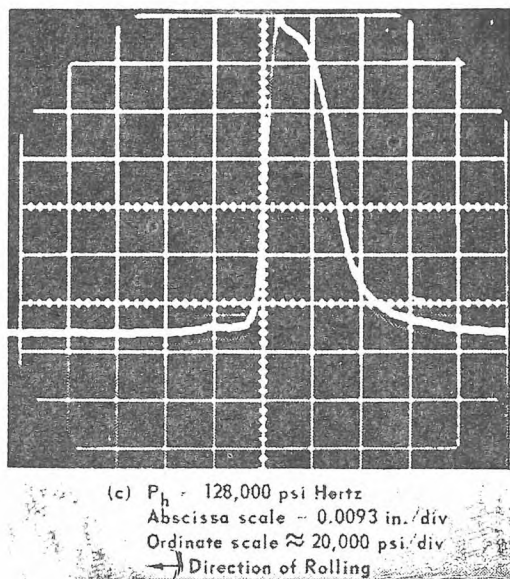
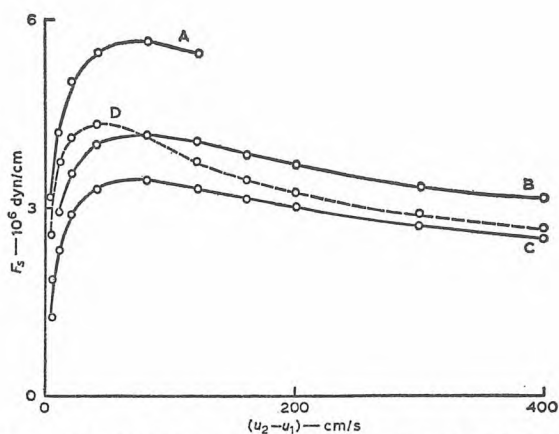


Fig. 7. Pressure measurements between steel discs



$b \ w = 12.5 \times 10^7$ dyn/cm and different values of u (cm/s).
 $\eta_s \approx 0.4 \text{ P}$, $u = 120$ (A), 400 (B), 600 (C), $\eta_s \approx 0.7 \text{ P}$, $u = 400$ (D).

Fig. 8. Frictional traction, F_s , as a function of sliding speed

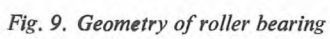
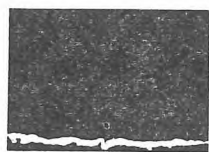


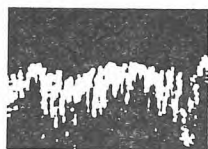
Fig. 9. Geometry of roller bearing



$8 \times 10^{-9} \text{ m}$



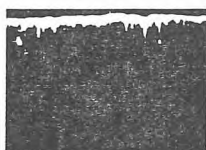
$10 \times 10^{-9} \text{ m}$



$13 \times 10^{-9} \text{ m}$



$16 \times 10^{-9} \text{ m}$



$19 \times 10^{-9} \text{ m}$

**FIG.10. OSCILLOSCOPE TRACES
THEORETICAL FILM THICKNESSES**

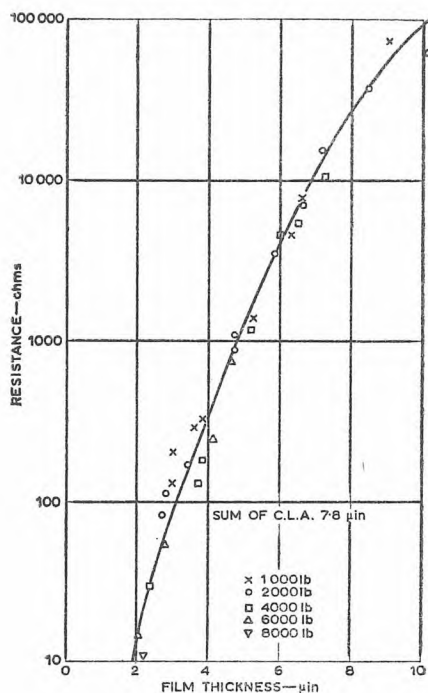


Fig. 11. Resistance and film thickness

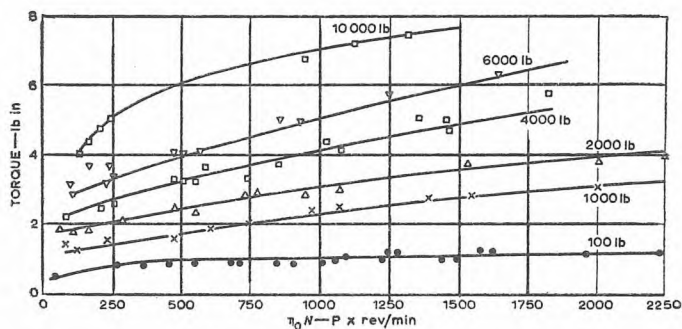
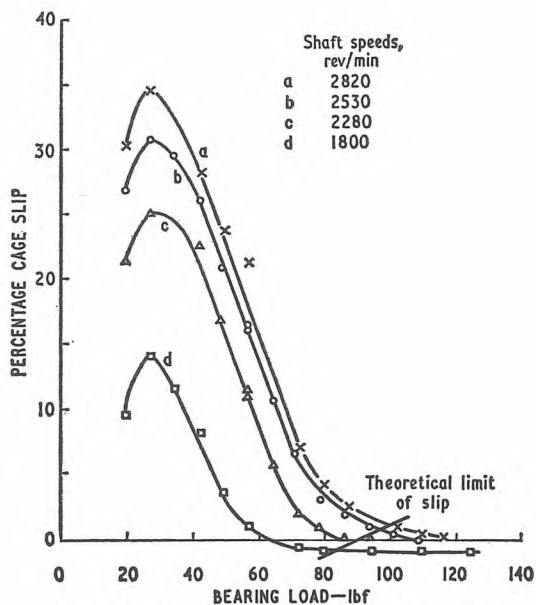


Fig. 12. Torque curves for roller bearing



Lubricant H.V.I. 160S; radial clearance 0.002 in.

Fig. 13. Effect of load and speed on cage slip