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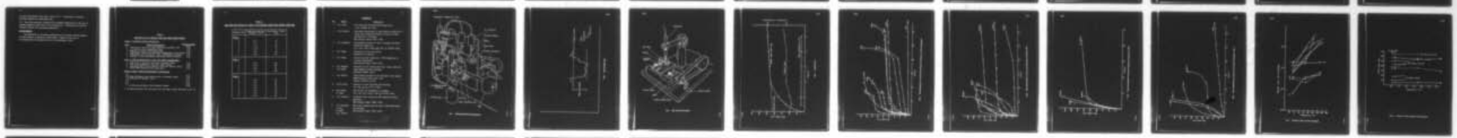

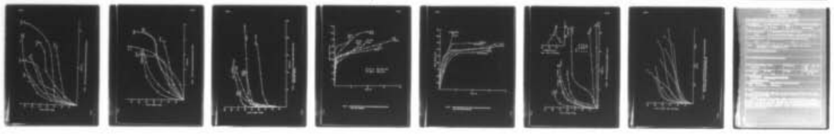

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WEAR PROPERTIES OF DRY BEARING LINERS AT AMBIEN AND ELEVATED TEMPERATURES A PRELIMINARY SURVEY

by

R.B. King

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⑥ WEAR PROPERTIES OF DRY BEARING LINERS AT AMBIENT AND ELEVATED TEMPERATURES - A PRELIMINARY SURVEY

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⑭ RAE-TR-78063

SUMMARY

The friction and wear properties of a wide range of dry bearing liners, both commercial and experimental, have been examined on a modified 'pin on ring' apparatus at temperatures up to 150°C.

Specific wear rates under ambient conditions differed appreciably, ranging from 0.07×10^{-6} mm^3/N m to 5.52×10^{-6} mm^3/N m. The application of additional heat generally increased the wear rate, although some materials had an optimum performance at temperatures above ambient. In general, liners containing synthetic reinforcing fibres, *eg* polyamide or polyester appear to exhibit superior wear properties to those containing glass fibres.

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1 INTRODUCTION

In recent years dry bearings have been used increasingly for aerospace applications to replace the more conventional grease-lubricated metallic bearings. Their advantages are most evident in areas where maintenance is difficult or costly, where contamination may occur, and in hostile environments where fluid lubrication is impossible, *eg* high or low temperatures. Typical uses are in the main rotor track rod and pitch control bearings of helicopters, manual flying control linkages, and aircraft undercarriage bearings. In most of these applications the total depth of wear which can be tolerated is very low, of the order of a few tens of micrometres, because this controls the degree of backlash in the bearing assembly.

Polytetrafluoroethylene (PTFE) is widely used as the main lubricating constituent of most dry bearing liners because of its low coefficient of friction and stability over a wide temperature range (approximately -260°C to +260°C)[1]. It may be present in fibre form, or sometimes dispersed as granules or flock, in a resin matrix. PTFE fibre is often interwoven with other synthetic fibres, such as polyamides, polyesters, or glass to give additional reinforcement. A further woven fibre or 'cloth' layer is also sometimes used as a backing, the whole assembly then forming a thin ($\simeq$ 250μm) laminate bonded to a metal substrate. The same matrix resin may be used as the adhesive, or alternatively a special bonding resin can be introduced.

This Report describes a preliminary investigation into the wear behaviour of thin, PTFE containing, bearing liners using a reciprocating line contact apparatus to provide accelerated wear data in a few hours, as opposed to the several months needed on more conventional, full-scale bearing test rigs. The investigation had three main objectives:-

(a) To compare the wear properties of a wide range of materials in constant conditions of sliding.

(b) To examine the effect of some of the parameters likely to influence wear, particularly load and temperature.

(c) To assess the changes in wear behaviour of one particular type of material by varying the type of matrix resin, reinforcement, and cure-cycle conditions.

It is obvious that accelerated wear tests cannot, by definition, simulate the sliding conditions experienced by dry bearings in service. Nevertheless, they are considered to be of value for the rapid screening of competitive products, and for identifying the most important parameters influencing wear. Information on the latter is an essential pre-requisite to the future development of improved bearing materials.

2 EXPERIMENTAL

2.1 Materials and preparation of test specimens

Table 1 lists the range of commercially-available materials examined and gives some details of their construction and composition. The first group comprises composites containing PTFE fibres interwoven, either with glass, or synthetic fibres such as Nomex, and impregnated with polyimide or phenolic resin. Some of these liners include, in addition, a glass fabric reinforced laminate backing.

The second group consists of PTFE flock, or granules dispersed in a synthetic resin matrix, reinforced and superimposed on a woven synthetic fibre fabric backing. A ceramic filled PTFE reinforced with bronze gauze is also included in this group for convenience.

The third group contains a number of experimental formulations supplied by one manufacturer. These were all constructions of woven PTFE/glass fibre in phenolic resin, with the exception of one in which the glass fibres were replaced by polyester. They differ in the particular types of weave used, and in the relative proportions of PTFE to other fibres.

Finally a number of experimental formulations were also prepared by using one particular type of material, adding a woven glass fibre backing and laminating with either phenolic, epoxy or polyimide resins.

All the test specimens consisted of a strip of the liner material, approximately 30 mm × 6.35 mm, bonded by a conventional epoxy-resin adhesive to a steel backing piece which had previously been randomly abraded and degreased. In some cases bonding of the bearing liner to the steel backing was undertaken by the manufacturer using proprietary techniques.

Table 1 also lists the elastic moduli of the commercial materials examined. These were estimated from the elastic recovery of ball indentations using a Rockwell Hardness Tester; the method has been described elsewhere[2].

2.2 Apparatus

Fig 1 shows the apparatus used, which is essentially a variant of the well established 'pin-on-ring' technique[3]. The bearing liner, together with its holder, 063 is attached to a loading arm which reciprocates over a distance of about 12 mm, approximately three times a minute, in contact with a 25.4mm diameter rotating steel ring. A fresh wear track is used for each test. The rings were made from AISI 440C steel, hardened to 700 VPN and were randomly abraded with 600 and 1200 grade silicon carbide paper, to give a mean surface roughness of approximately 0.06 μm Ra. The reciprocation mechanism was actuated hydraulically by a piston attached to the compressed air supply. Since the distance of the line contact from the pivot point varied by approximately ±5 per cent, the load also varied by about this amount over the 12 mm traverse. This did not, however, appear to affect the wear behaviour significantly. Friction was monitored continuously by the output signal from a torque-transducer being fed to a chart recorder.

Because the specimen slowly reciprocates, a Hertzian line contact stress is constantly maintained, except at the ends of each traverse. Thus the specimen gradually wears through over 12 mm with a relatively flat profile, as shown in Fig 2. Wear profiles were determined at successive intervals of time on the apparatus shown in Fig 3. Initially two wear-depth measurements were made approximately 1 mm from each edge of the bearing strip, and the mean then taken to compensate for any possible uneven wear; this was later found to be unnecessary however, and a single traversal down the centre was deemed adequate.

The Hertzian stresses were calculated from elasticity theory[4]:-

$$\text{Maximum compressive stress } S_c = 0.798 \sqrt{\frac{P}{D\left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right]}} \qquad (1)$$

where P = load per unit length
D = diameter of the ring
ν = Poisson's ratio
E = modulus of elasticity.

Since the modulus of the steel ring is some 400 times greater than that of the liner, its effect can be ignored and, assuming $\nu_1 = 0.35$ the above expression then reduces to:-

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$$S_c = 0.0835 \sqrt{\frac{PE}{D}} \text{ MPa} . \qquad (2)$$

The ring temperatures were also recorded at the end of each test by means of an electronic contact thermometer. Addditional heat, both preceding and during the test was provided, when necessary, by an infra-red heater.

2.3 Test conditions

Most experiments were made under constant conditions of 45 kg (441 N) load with the ring rotating at 100 rev/min (*ie* sliding speed = 0.13 m/s for a ring diameter of 25.4 mm) until, either the bearing liner had worn through, or until a steady-rate wear region had been defined.

The complete range of loads available was from 9 to 50 kg (88 to 491 N); these correspond to Hertzian stresses, as calculated above, of 44 to 103 MPa, assuming a typical modulus of 4.0 GPa.

Bearing materials were tested both under ambient conditions, during which the ring temperature sometimes reached 60°C, and with additional heat supplied to give ring temperatures of approximately 90, 120 or 150°C, dependent on whether or not the liner was expected to withstand these conditions. Some difficulty was experienced in the early stages with premature bonding failures during heated runs, but this was overcome with a more suitable choice of adhesive, and with attention paid to the bonding technique.

3 RESULTS AND DISCUSSION

3.1 General

Most of the results under the 'standard' test conditions of 45 kg load and 0.13 m/s speed (the effect of the reciprocating movement at 0.0006 m/s was ignored) were plotted as mean depth of wear against time, and a typical example is shown in Fig 4.

Wear is initially rapid but ultimately decreases to an approximately constant rate when steady-state conditions have been attained. The initial depth of wear corresponding to the 'knee' in Fig 4 is calculated by extrapolating the linear, steady-state portion back to zero time. A few materials did not follow this pattern exactly in that the 'knee' was rather ill-defined; for those the mean rate of wear was determined from the origin.

The steady-state wear rates for all the commercial materials evaluated, together with the wear depth corresponding to the 'knee', are listed in Table 2 for ambient conditions. The mean coefficients of friction are shown in brackets alongside all the individual wear-time curves in Figs 5 to 16.

The correlation coefficients of the wear rates of these materials with their respective elastic moduli are:-

Group 1	0.406
Group 2	0.781
Group 3	-0.408

Thus, despite the fact that deformation of the bearing liner is predominantly elastic rather than plastic there are no significant relationships between wear rates and linear elastic moduli; other parameters must therefore play a more important role in wear.

3.2 Wear of commercial liners at ambient temperature

Fig 5 shows the wear characteristics of materials in Groups 1 and 2 of Tables 1 and 2. It may be noted that there are:-

(a) large differences in the steady-state wear rates of the different types of materials;

(b) large differences in the initial depth of wear to the 'knee'.

Attempts to relate the wear behaviour to the composition and construction of the liner materials are difficult because the latter are not known in precise detail. However, certain trends are readily apparent. Materials with an interwoven construction of PTFE and glass fibres, (E, K and L) tend to exhibit considerably greater initial wear than similar constructions in which the glass is replaced by Nomex (B and C). The steady-state wear rates are not, however, greatly different. Replacing the phenolic resin, K, by polyimide E, whilst retaining a generally similar basic weave structure does not appear to improve the wear properties. The superior performance of B, therefore, is unlikely to result from the presence of the polyimide and is more probably a consequence of the replacement of glass by Nomex. The close similarity between the curves for materials B and C again suggests that the type of matrix resin is of minor significance in wear (at least at ambient temperatures).

Materials A, D and H all consist of a relatively thick (75-100μm) layer of synthetic resin containing dispersed PTFE granules or flock superimposed on a Nomex or polyester fabric impregnated with the same resin/PTFE mixture. The results in Fig 5 suggest that this initial layer is largely worn away in the early stages of sliding, and steady-state conditions begin only when the underlying fabric begins to be exposed. From the similarity in wear behaviour of these three materials, it again appears that the type of resin binder is relatively unimportant in its effect on either the initial depth of the 'knee' or on the steady-state wear rate.

Material G is unique in the sense that it exhibits both the lowest wear 'knee' and steady-state wear rate of all the products examined. Its construction is a hybrid between Groups 1 and 2 since, although the structure is one of interwoven PTFE and Nomex fibres there is a thin fabric-free surface layer (<25 μm) of PTFE flock in phenolic resin. The result in Fig 5 again suggests that the steady-state wear regime begins following the removal of the overlay, and this suggestion is further reinforced, with material J, at the other end of the spectrum, which has a relatively thick approximately 175μm, layer of ceramic filled PTFE superimposed on an impregnated bronze gauze.

3.3 Wear of commercial liners at elevated temperatures

The relationships between wear depth and time for most of the materials described in the previous section are given in Figs 6 to 8 for temperatures of 90, 120 and 150°C respectively.

Figs 9 and 10 summarise the way in which temperature influences the steady-state wear rate and the depth of initial wear to the 'knee' in the wear-time relationships. In general, the wear rates tend to increase with temperature, but there are marked differences between different types of materials. Both D and H performed better at 90°C than at 20°C indicating that there is an optimum wear rate for some of these materials at temperatures well above 20°C.

Evans[5] has shown, on the basis of pin and disc tests, that the wear rates of PTFE composites increase most rapidly with temperature in the range 20 to 150°C when the fillers or reinforcing fibres are inorganic, *eg* glass, asbestos or carbon, and less rapidly, for organic fillers, *eg* polyimide, aromatic polyamide or polyphenylene sulphide. The difference is attributed primarily to the abrasive action of the inorganic filler impeding transfer film formation on the counterface at elevated temperatures. The present results are not wholly consistent with this pattern. Of the materials containing glass fibre, K and L show a marked increase in wear rate with temperature but E exhibits only a very slight increase. In addition, the wear rates of materials B and C increase rapidly with temperature, despite the fact that they contain only organic fibres. It is tempting to attribute the superior performance of E at high temperatures to the presence of the polyimide resin matrix compared to the phenolic in K and L, but material B, which also incorporates polyimide, shows a high wear rate at 150°C and D, G and H, incorporating phenolic exhibit lower wear rates. It is evident that the temperature dependence of wear must be influenced by a combination of parameters related to both composition and structure, and further work is required to define the relative importance of these.

In contrast to the varying effects of temperature on the steady-state wear rates of the different materials, Fig 10 demonstrates that there is little influence on the amount of initial wear. Although the modulus of elasticity of the materials must undoubtedly decrease with increasing temperature, leading to greater penetration of the rotating ring into the bearing liner under load, the depth of wear corresponding to the 'knee' in the wear-time relationships remains almost independent of temperature. This supports the earlier suggestion that the depth of the 'knee' is related more to the structure of the bearing material than to its composition.

3.4 Wear of experimental commercial liners at ambient temperature and at 120°C

The wear behaviour of several experimental liner formulations provided by one manufacturer is shown in Figs 11 and 12 for ambient temperature and 120°C; a summary of the mean specific wear rate and initial wear aspects under ambient conditions is given in Table 2 (Group 3). All of the materials, except one, are combinations of interwoven PTFE and glass fibres impregnated with phenolic resin and they differ mainly in the type of weave and the relative proportion of PTFE to glass in the liner surface. The exception, S, contains polyester fibre instead of glass whilst retaining the same weave structure as N. Figs 11 and 12 show that this substitution does not lead to improved wear performance at either ambient or elevated temperature. It is not possible in this Report to discuss the relationships between the individual weave structures and wear performance, but it is clearly evident from Fig 11 that the type of weave is a very significant parameter.

3.5 Wear of laboratory experimental formulations

Several experimental bearing liners were prepared in the laboratory using type K 'cloth' and impregnating with various commercial phenolic, epoxy or polyimide resins. Either 120 or 181 type glass-cloth was used as a backing to provide additional reinforcement.

Laminates were prepared by producing a pre-preg in the glass-cloth backing and subsequently pressing at elevated temperature to impregnate the PTFE-containing liner cloth itself. Variations included the amount of resin in the pre-preg and pressure and temperature during curing. Two types of epoxy resins were examined but only one of each of phenolic and polyimide.

It is evident that for any one resin system, the wear behaviour depends appreciably on the precise way in which the resin impregnation is achieved, and particularly so for the phenolic resin. With the latter, lowest initial wear and steady-state wear rate were obtained in conditions which produced a liner surface slightly resin-rich. Resin starvation was particularly deleterious - curves 1, 2 and 3 in Fig 13. Results with the epoxy and polyimide resins were less sensitive to pressing conditions and no significant differences were obvious between the two variants of the epoxy - Fig 14. Neither the epoxies nor the polyimide appear to offer any advantage over phenolic resin in improving wear behaviour at ambient temperature, and this supports the earlier suggestion that the type of resin is of lesser importance in wear than the weave structure of the liner material. The coefficients of friction, shown adjacent to the individual curves in Figs 13 to 15 are similarly almost insensitive to the type of resin matrix.

3.6 Effect of load

The influence of load over the range 9 to 50 kg (88 to 491 N) on the depth wear-time relationships for materials K and L is shown in Fig 16. The most obvious trend is a marked increase in the initial depth of wear with increasing load and similar results have been reported by Rowland and Wyles[6] and Barrett[7]. Within the plateau region, however, the specific wear rate (volume per unit sliding distance per unit load) varies only slightly with load, as shown by the inset to Fig 16. The latter results are only approximate because the wear plateau are somewhat ill-defined at the heaviest loads. At the lightest loads, however, material L exhibits a clear superiority in its wear behaviour to material K. For both materials the coefficients of friction decrease slightly with increasing load, in accordance with the general trend typical of most polymers and polymer based composites[8,9].

3.7 Comparison with bearing tests

Although the results obtained from the present series of accelerated tests have demonstrated very significant differences in the wear behaviour of different types of materials, the important question is to what extent these differences persist in bearing tests under service, or simulated service, conditions. This cannot be answered definitively at this stage because bearing test data in strictly comparable conditions of sliding is not yet available for all the commercial materials examined. The only commonality arises from specification testing, *eg* US Military Specification-B-81934, and for this purpose it is merely required that the bearing should exhibit a total wear of less than 0.0045 in (~115 μm) after 25000 cycles oscillation under a constant radial load. Some bearing test data is available, however, for materials K and L[10] and for the experimental products M to S in which the principal variant is the weave structure. Results obtained from tests on journal bearings are given in Fig 17 and by comparison with Figs 5 and 12 it can be seen that there are many similarities in behaviour. In both series of tests, materials K, M Q and S all exhibit a greater initial wear than O, P and N, whilst L is intermediate. The only serious anomaly occurs with material N which appears to perform better in a bearing configuration than in reciprocating line contact conditions. It would be unrealistic to expect more than these broad similarities because of the marked differences in the conditions of sliding. In a bearing, for example, the contact area is distributed and debris can be retained to facilitate the formation of third bodies on the surfaces of both the bearing liner and its counterface[11]. No systematic examination has yet been made of the worn surfaces generated during reciprocating line contact, but preliminary observations suggest that the film formation on the counterface does not seem to be a particularly significant feature of the wear process in these conditions. Despite this complication, the above comparison strongly suggests that the relationships between wear behaviour and material structure and composition, inferred from the present accelerated tests, could well be relevant to bearing operation.

4 CONCLUSIONS

(1) Under conditions of reciprocating line contact, there are marked differences in the wear behaviour of different types of dry bearing liner materials incorporating PTFE. One material, G, exhibits a clear superiority over all others at both ambient and elevated temperatures.

(2) For one particular series of experimental liner materials there is a close similarity between the wear characteristics obtained during reciprocating line contact conditions and those derived from tests on journal bearings.

(3) The type of weave structure of fabrics woven from PTFE and other fibres appears to play a much more important role in wear than the type of synthetic resin impregnant. However incomplete impregnation giving rise to resin starvation can be very deleterious to the wear properties.

(4) For those materials which incorporate an overlay of PTFE flock disposed in synthetic resin, the depth of initial wear prior to the establishment of a steady-state wear rate appears to be directly related to the thickness of the overlay.

(5) For two different interwoven PTFE fibre/glass fibre constructions, the depth of initial wear increases with load but the steady-state specific wear rates do

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not vary very greatly (less than a factor of 2). Coefficients of friction decrease slightly with increasing load.

(6) Wear rates generally increase with increasing temperature but the rate of increase depends on the form of liner construction. Coefficients of friction decrease slightly with increasing temperature.

Acknowledgments

The assistance of the numerous manufacturers who kindly provided samples of their products is gratefully acknowledged. Thanks are also due to D.M. Kingston-Lee who supplied some of the experimental liners.

Table 1

DESCRIPTION OF DRY BEARING LINERS AND THEIR ELASTIC MODULI

Group 1 Interwoven fibre constructions

Code*	Material description	Elastic modulus (GPa)
B	PTFE/'Nomex' fibres with high temperature polyimide resin	1.65
C	As B but with lower temperature resin	1.70
E	PTFE/glass fibres with polyimide resin	2.20
G	PTFE/'Nomex' fibres with thin PTFE flock/phenolic resin overlay	2.50
K	PTFE/glass fibres in phenolic resin. PTFE fibres at surface	3.65
L	Similar to K but additionally some glass fibres at surface	4.30

Group 2 PTFE flock/granules in resin with fabric reinforcement

Code*	Material description	Elastic modulus (GPa)
A	PTFE flock in synthetic resin with 'Terylene' fabric	1.63
D	PTFE flock in phenolic resin with 'Nomex' fabric	2.20
H	Granulated PTFE in vinyl phenolic resin with 'Dacron' fabric	2.65
J	Filled PTFE reinforced with bronze mesh	3.20

Group 3 Fibre reinforced experimental constructions

Code*	Material description	Elastic modulus (GPa)
M	Woven PTFE/glass fibre constructions of different weaves laminated with phenolic resin	4.34
N		4.04
O		4.17
P		4.67
Q		4.61
R		5.79
S	As above but polyester fibre instead of glass	3.68

* The above materials and code letters are the same as those described in Ref 10.

Table 2

WEAR RATES AND POSITION OF 'KNEE' OF DRY BEARING LINERS UNDER AMBIENT CONDITIONS

Material code	Steady-state wear rate ($mm^3/N\ m \times 10^{-6}$)	Wear depth at 'knee' (μm)
Group 1		
B	0.71	25
C	0.71	45
E	1.35	175
G	0.07	12
K	1.85	125
L	0.96	110
Group 2		
A	0.32	100
D	0.39	100
H	0.32	80
J	1.95	160
Group 3		
M	5.04	100
N	4.47	110
O	3.23	105
P	1.67	75
Q	5.52	125
R	1.71	40
S	2.95	150

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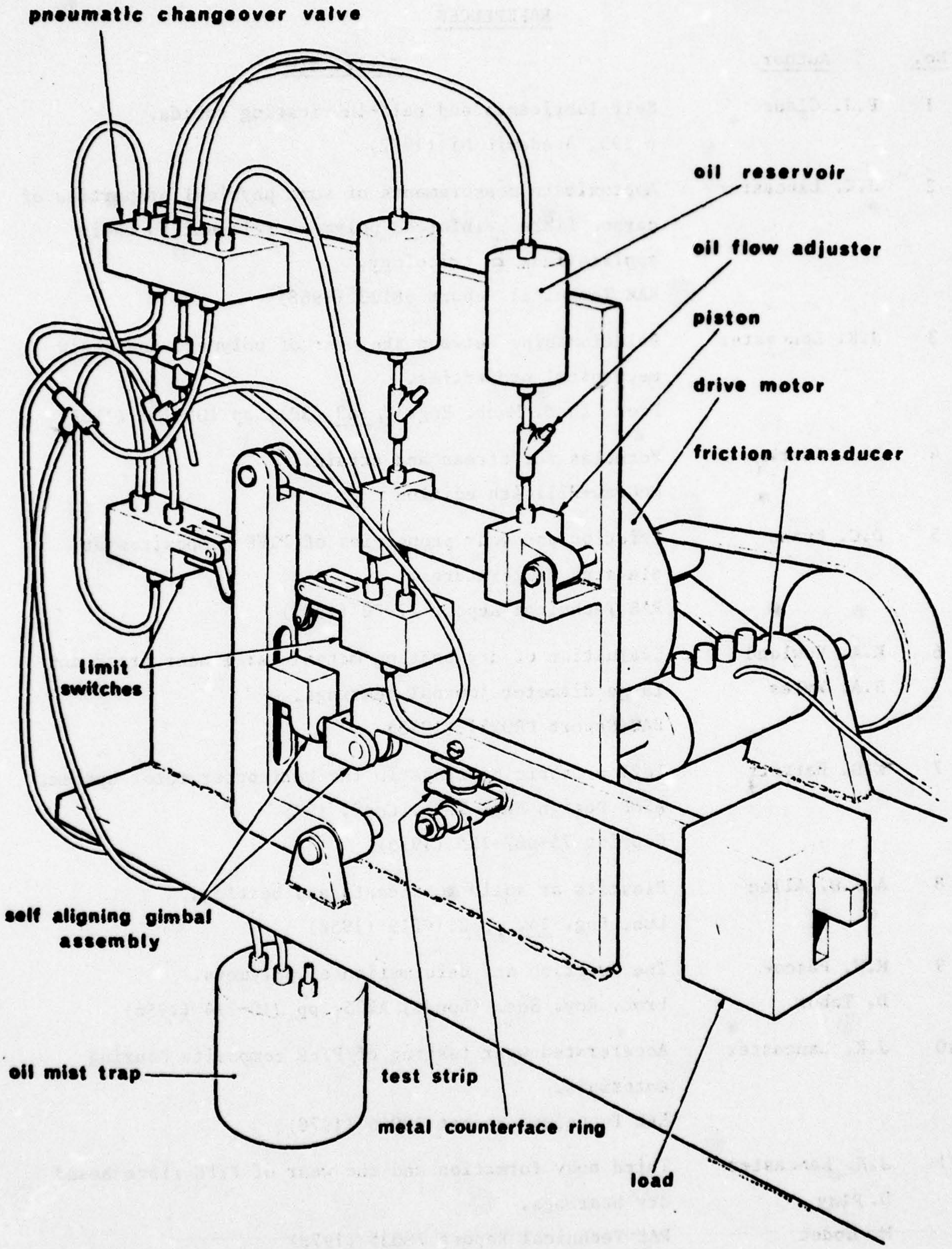

Fig 1 Reciprocating line-contact apparatus

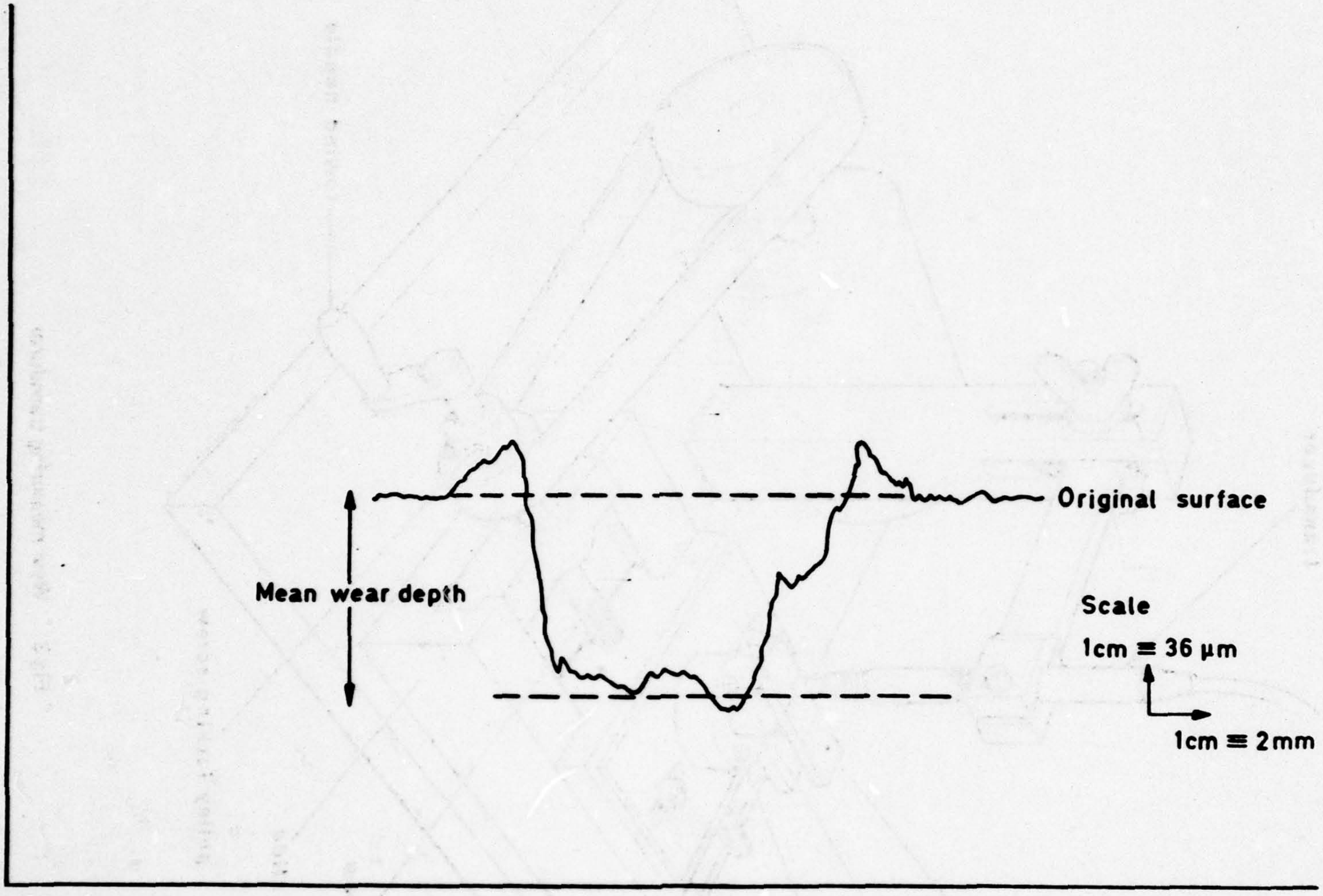

Fig 2 Typical profile trace

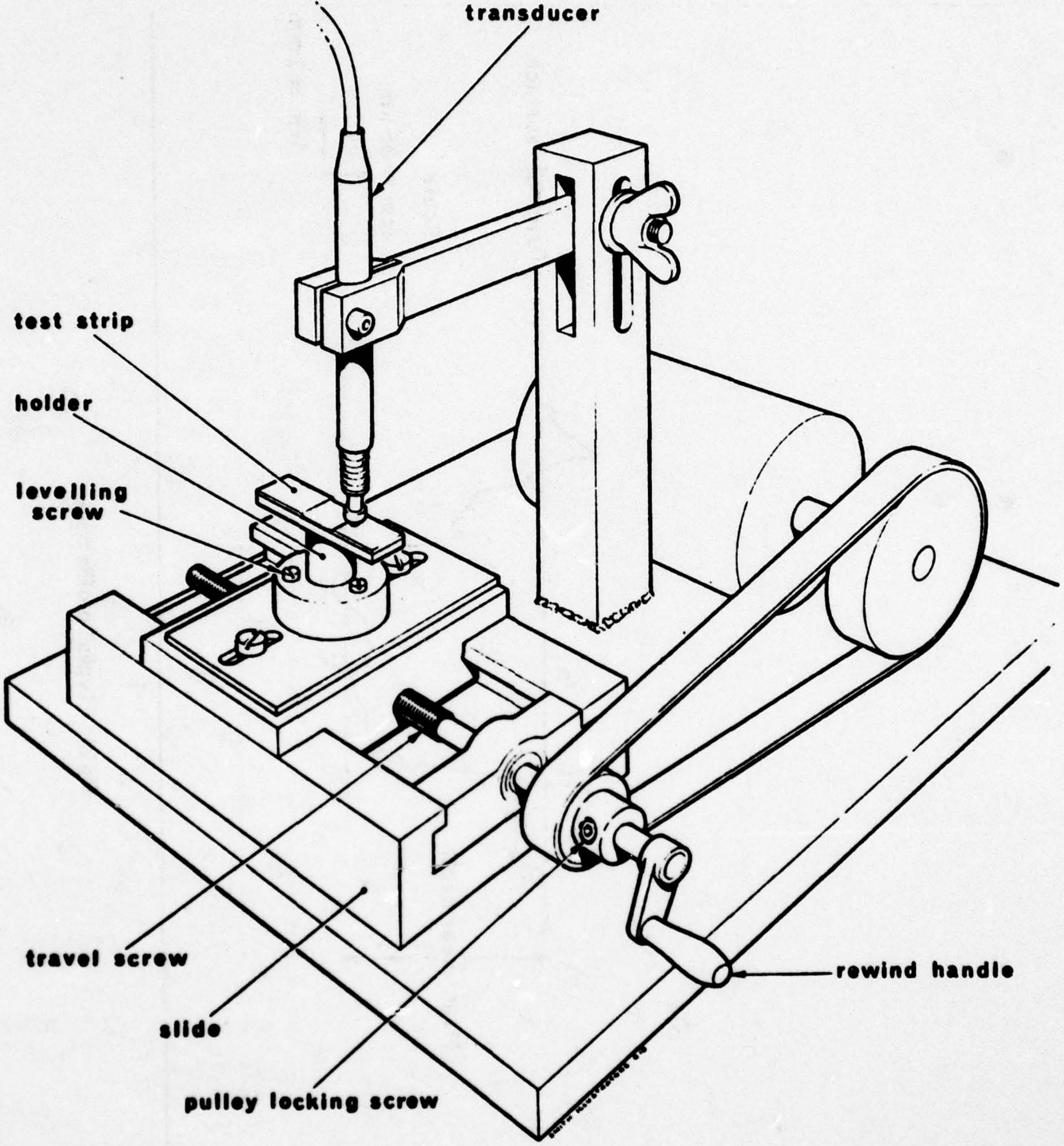

Fig 3 Wear measuring transducer

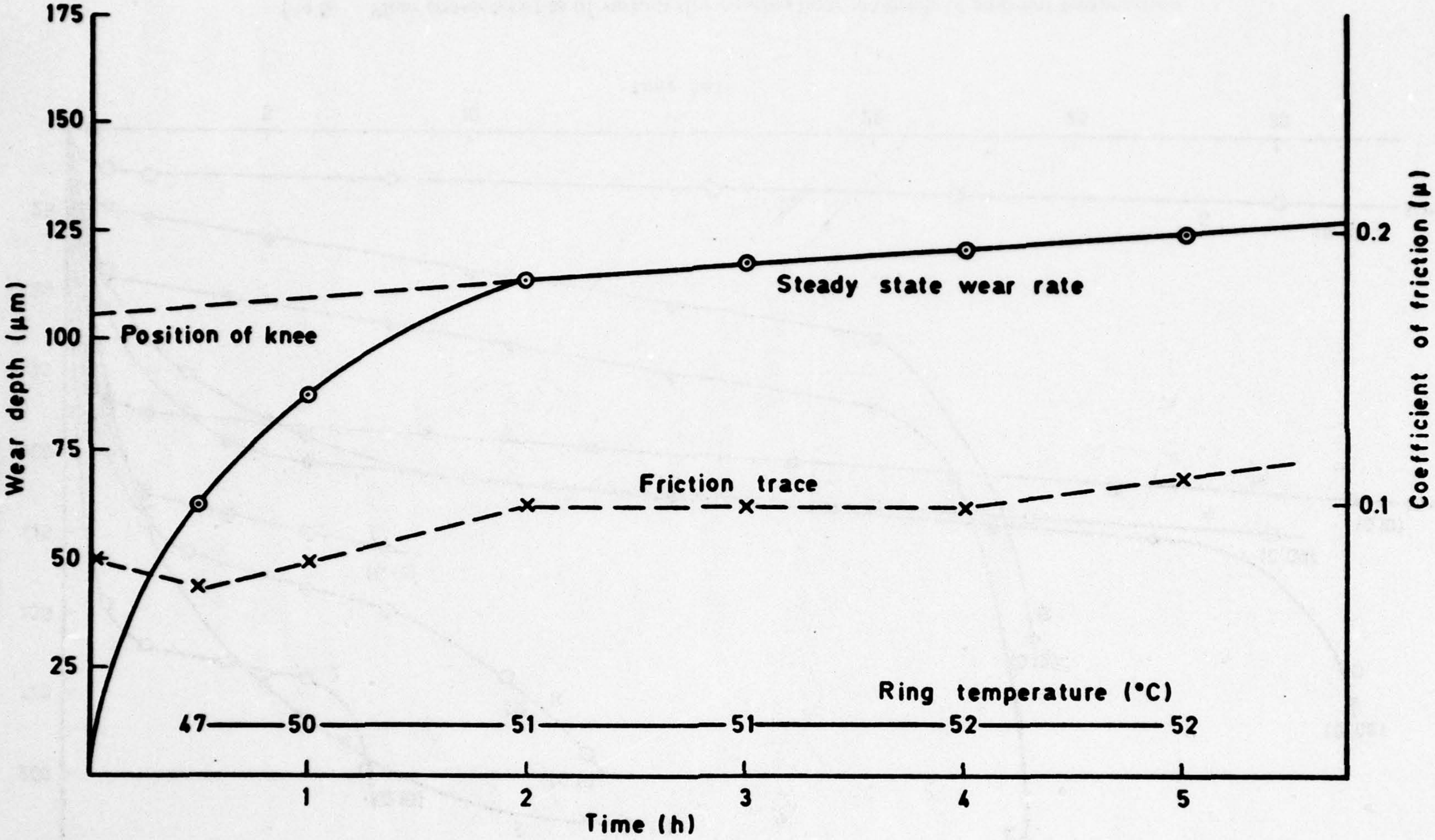

Fig 4 Typical test run

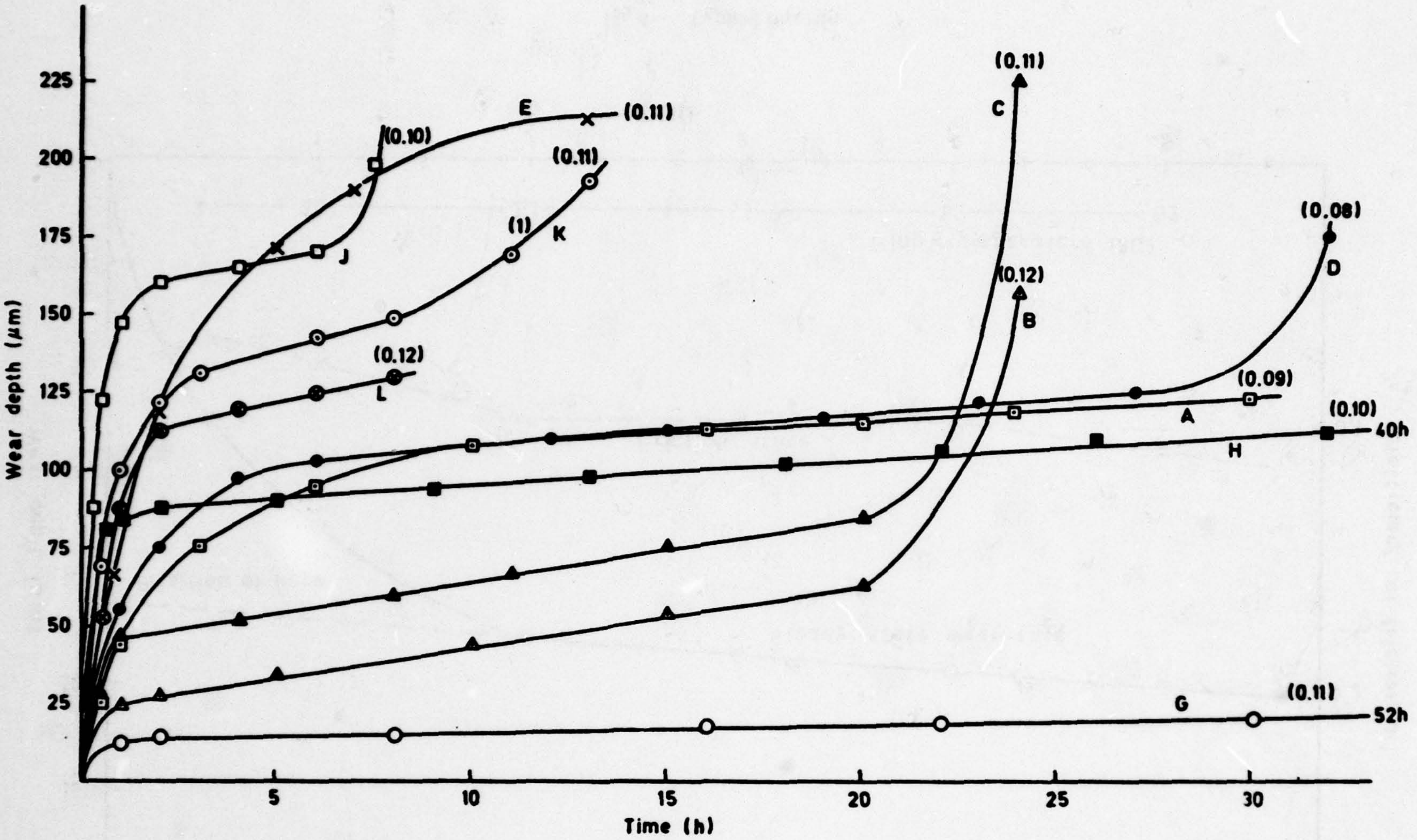

Fig 5 Wear characteristics of various dry bearing liner materials at ambient temperature

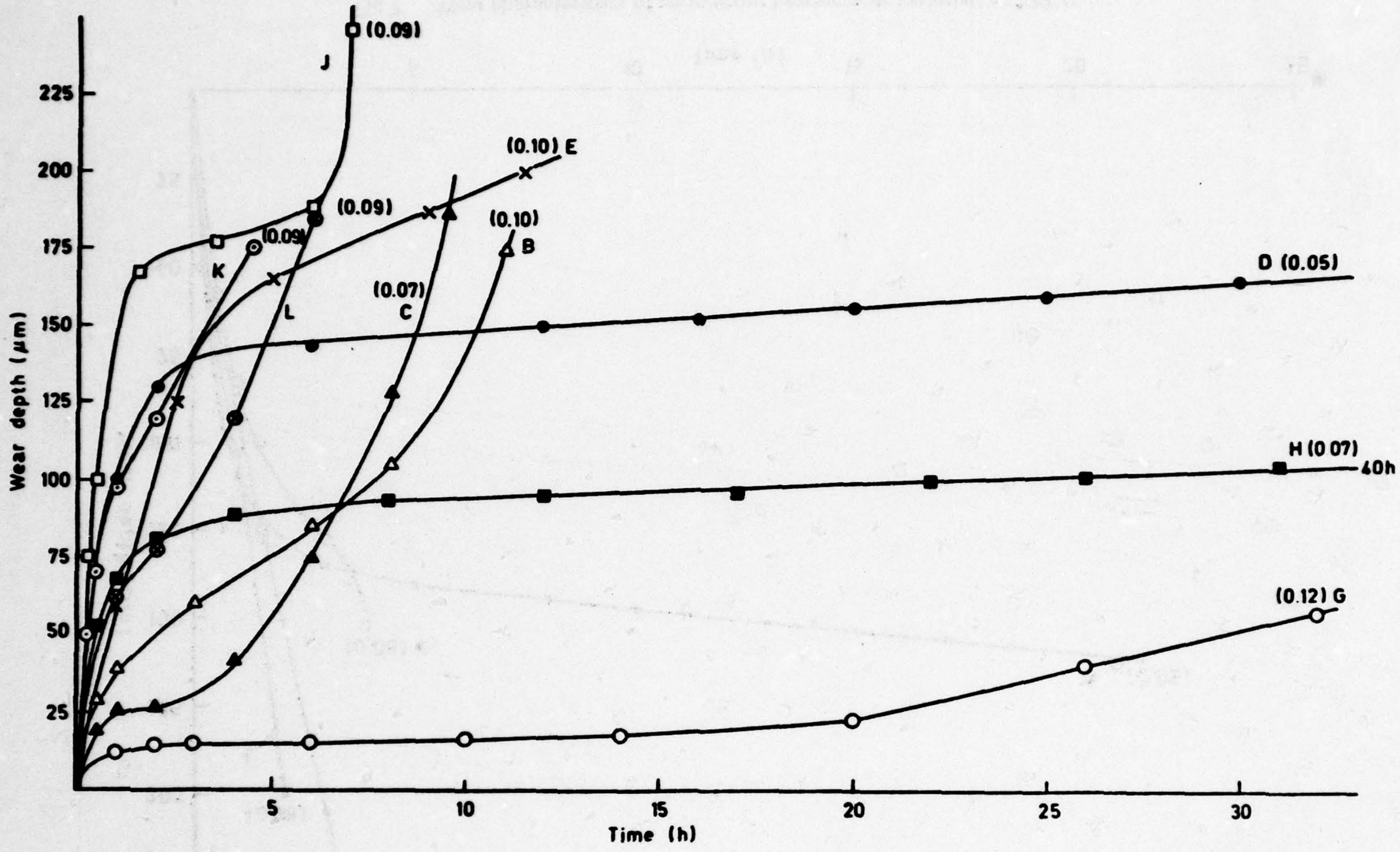

Fig 6 Wear characteristics of various dry bearing liner materials at 90°C

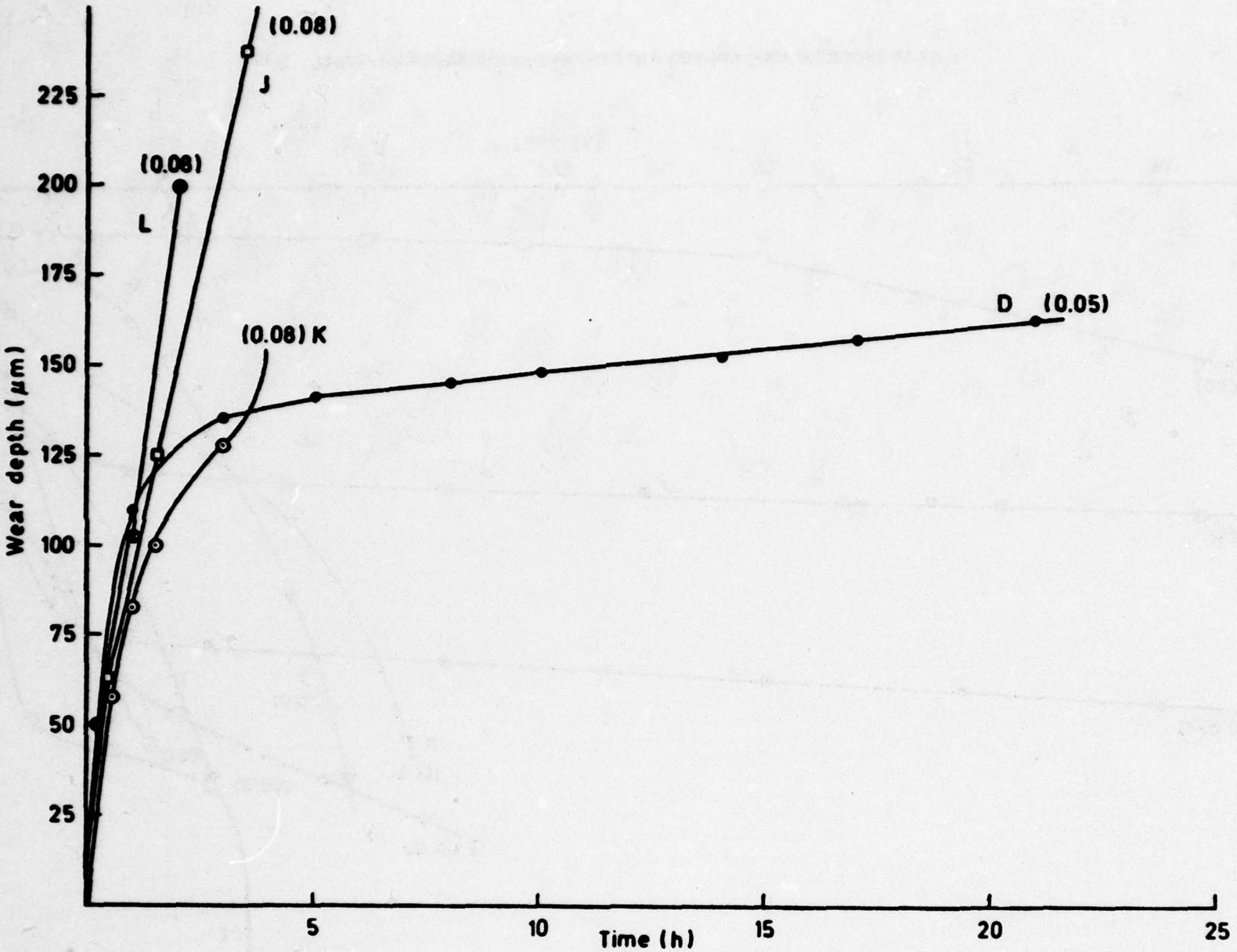

Fig 7 Wear characteristics of various dry bearing liner materials at 120°C

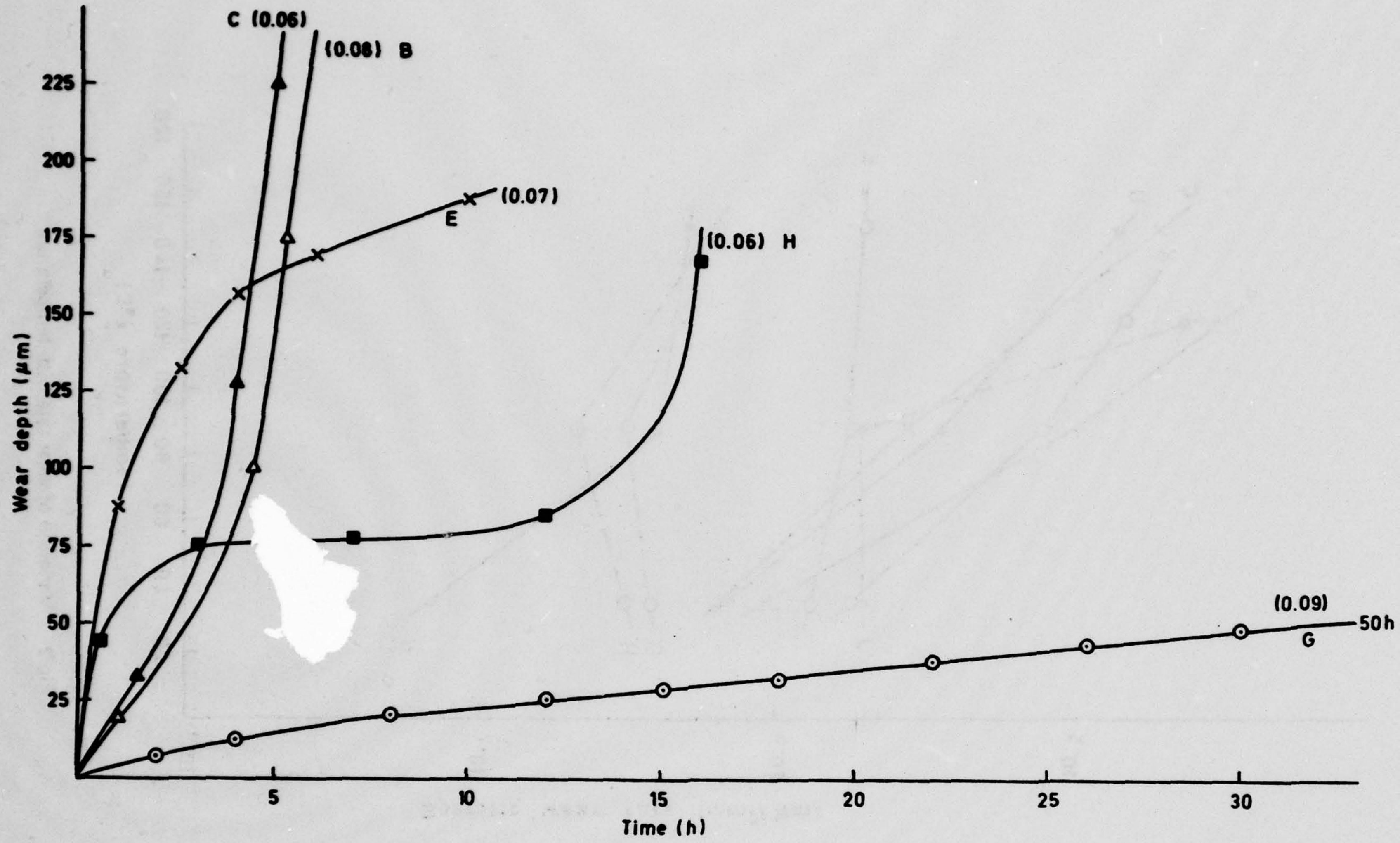

Fig 8 Wear characteristics of various dry bearing liner materials at 150°C

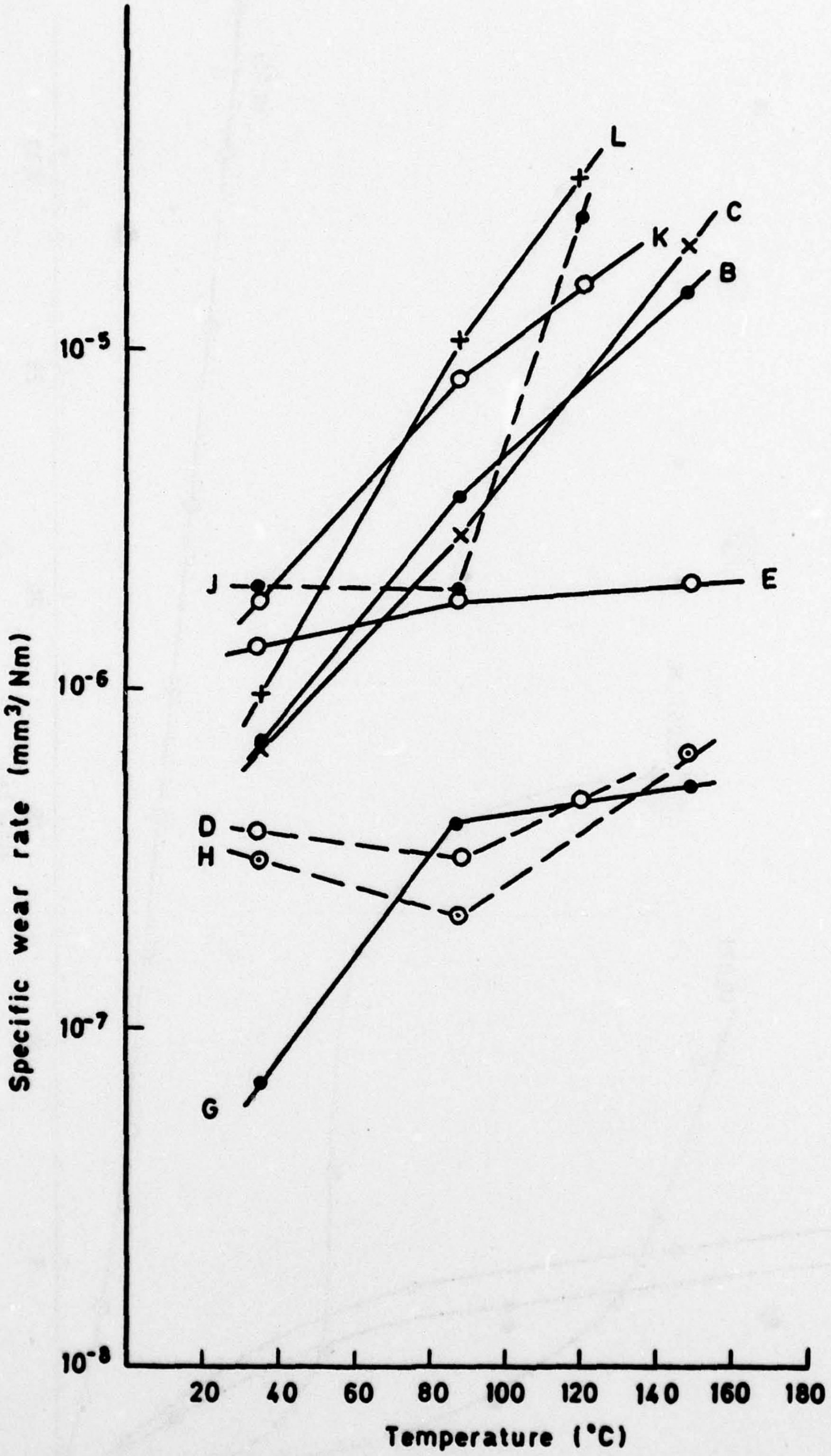

Fig 9 Variation of wear rate with temperature

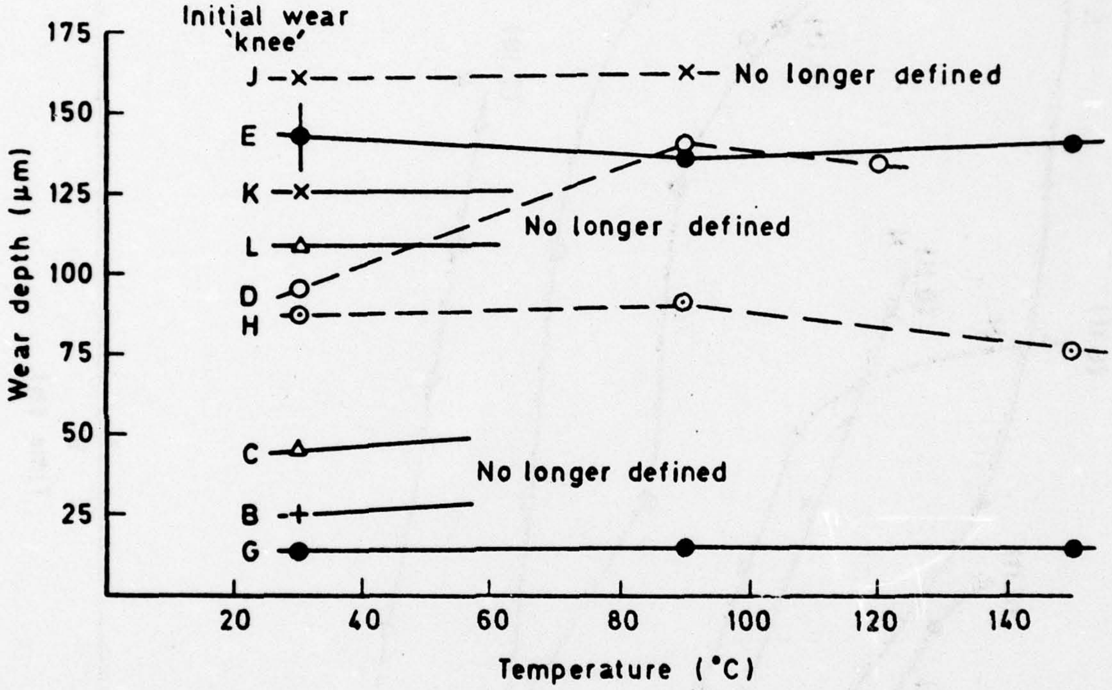

Fig 10 Variation of "knee" position with temperature

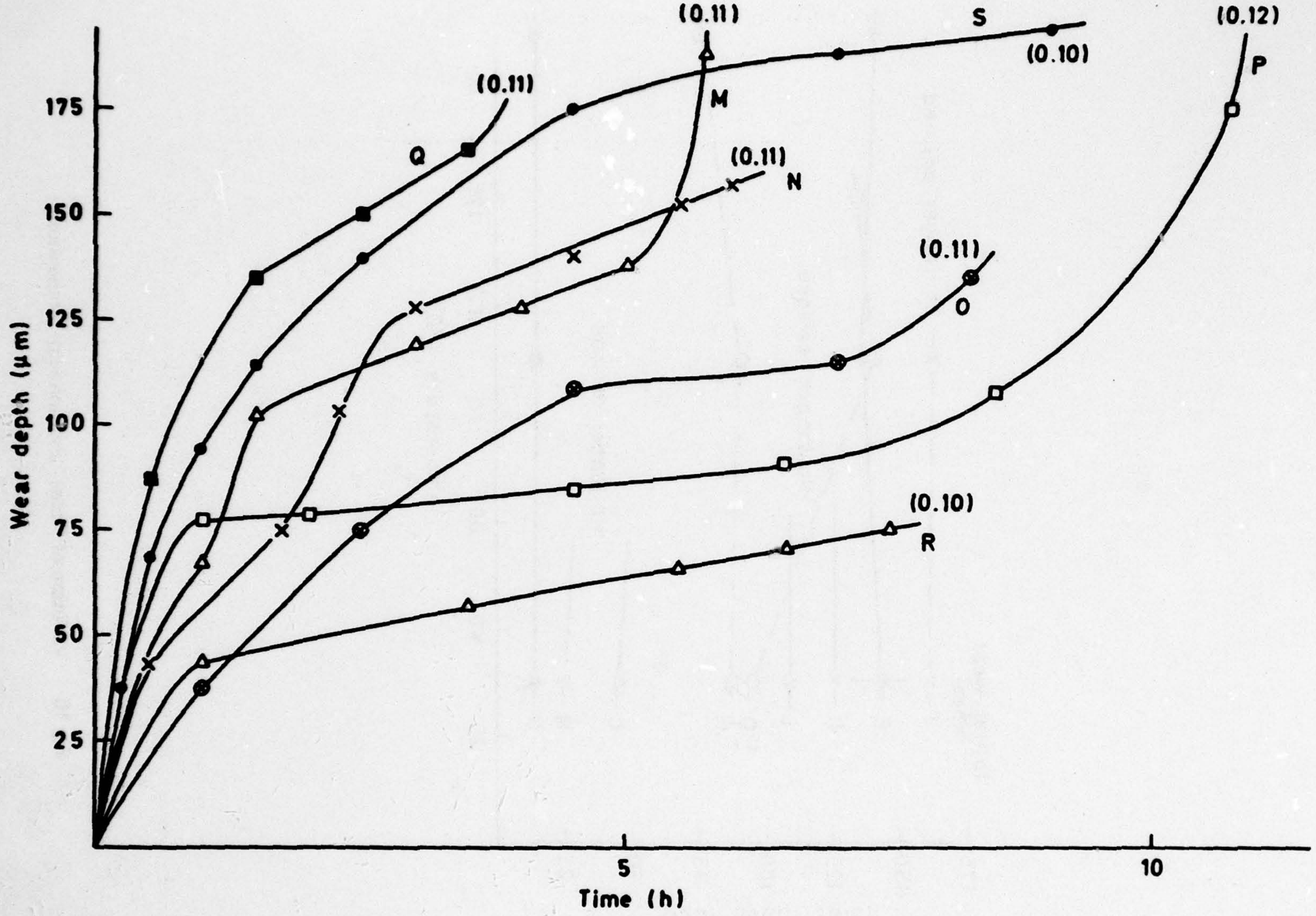

Fig 11 Wear of commercial experimental liners at ambient temperature

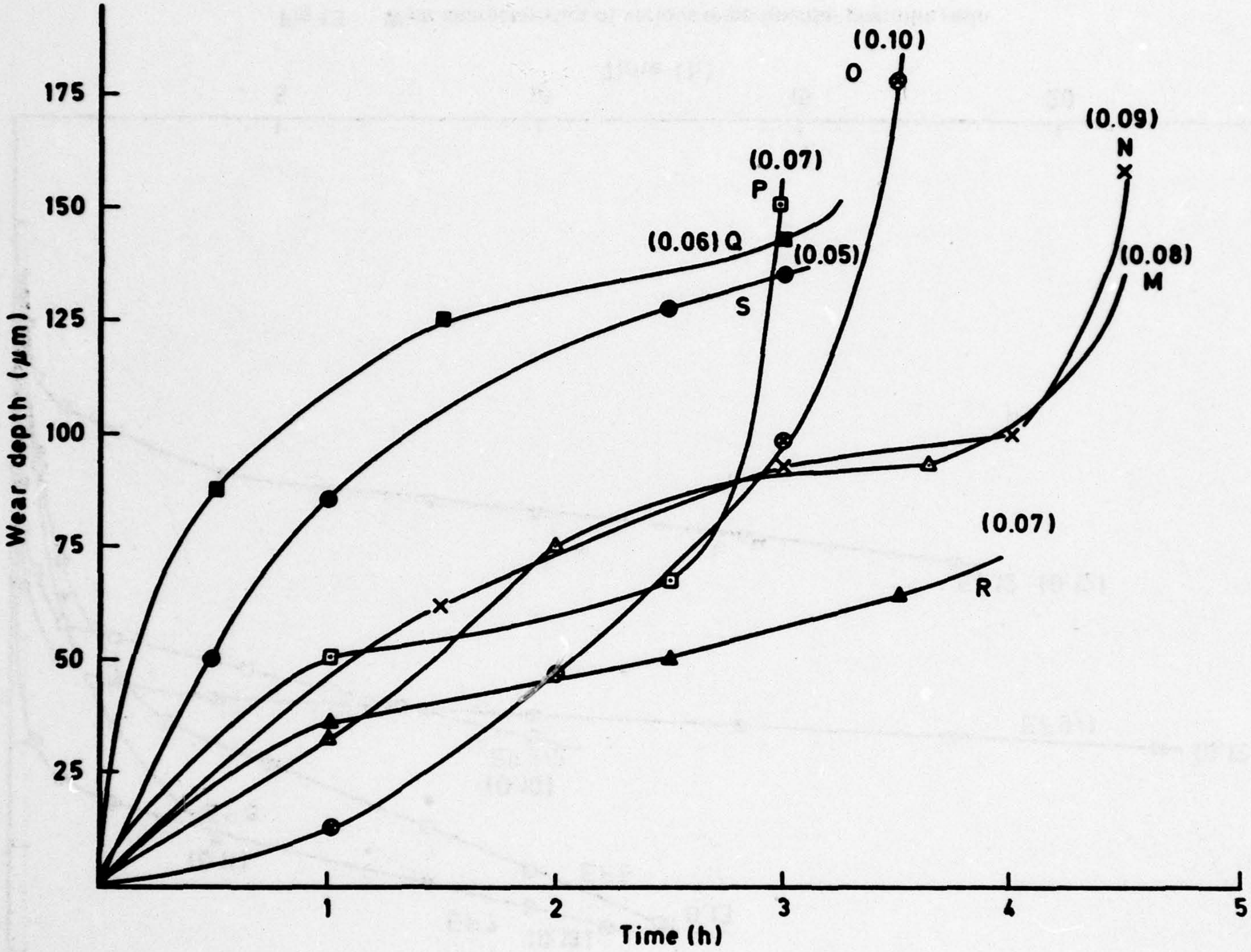

Fig 12 Wear of commercial experiment liners at 120°C

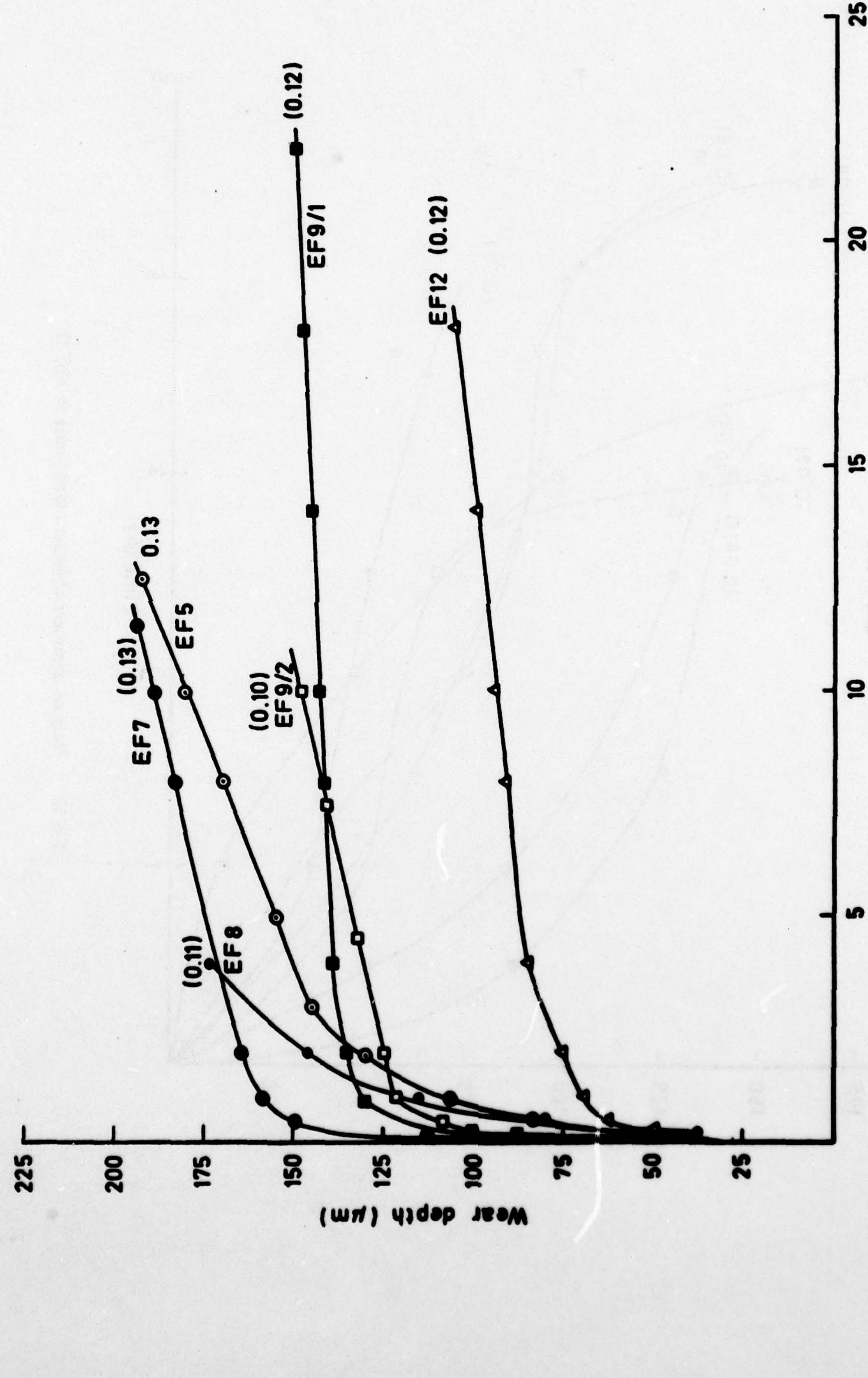

Fig 13 Wear characteristics of various experimental phenolic resin matrix liner materials

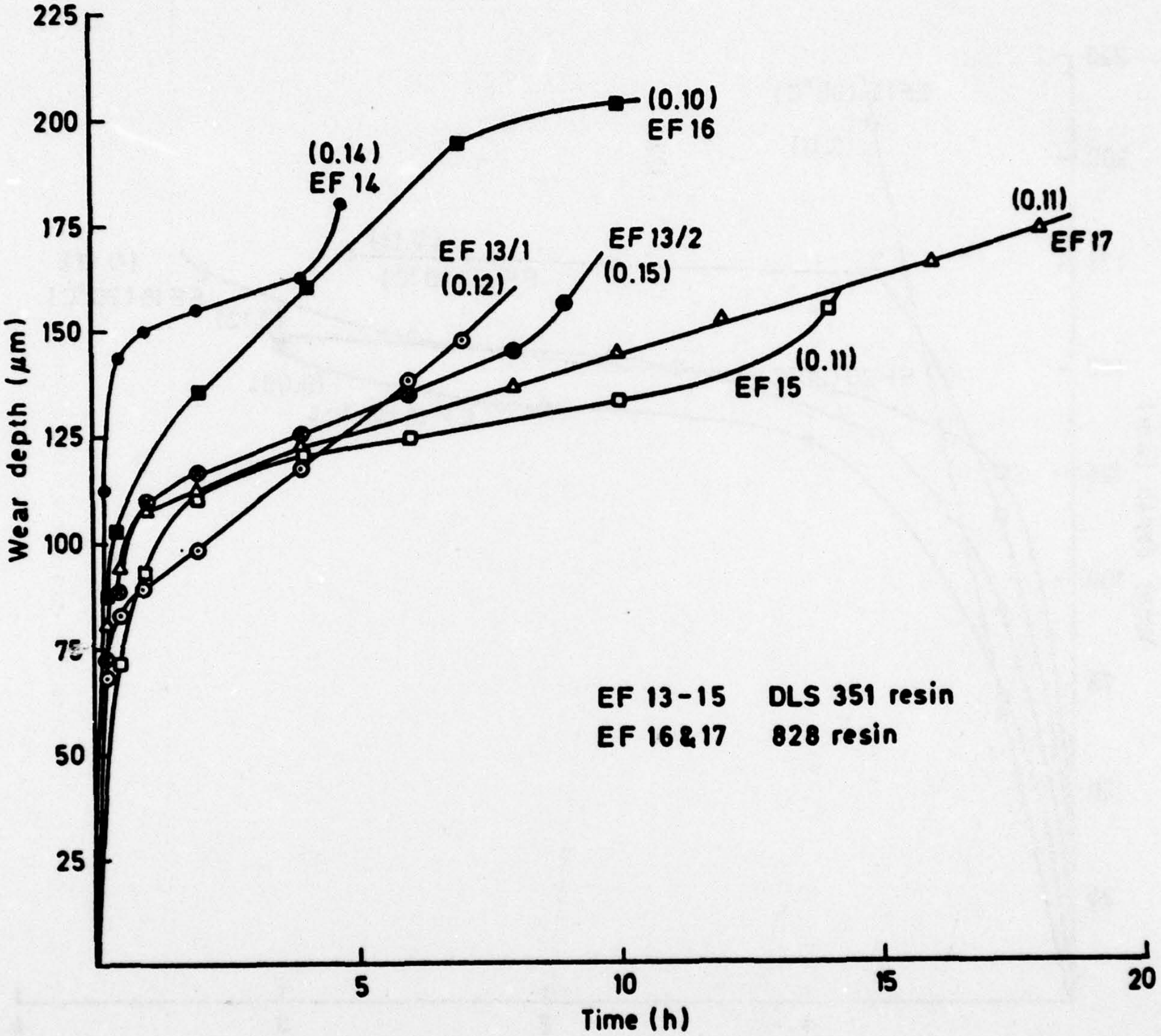

Fig 14 **Wear characteristics of various experimental epoxy resin matrix liner materials**

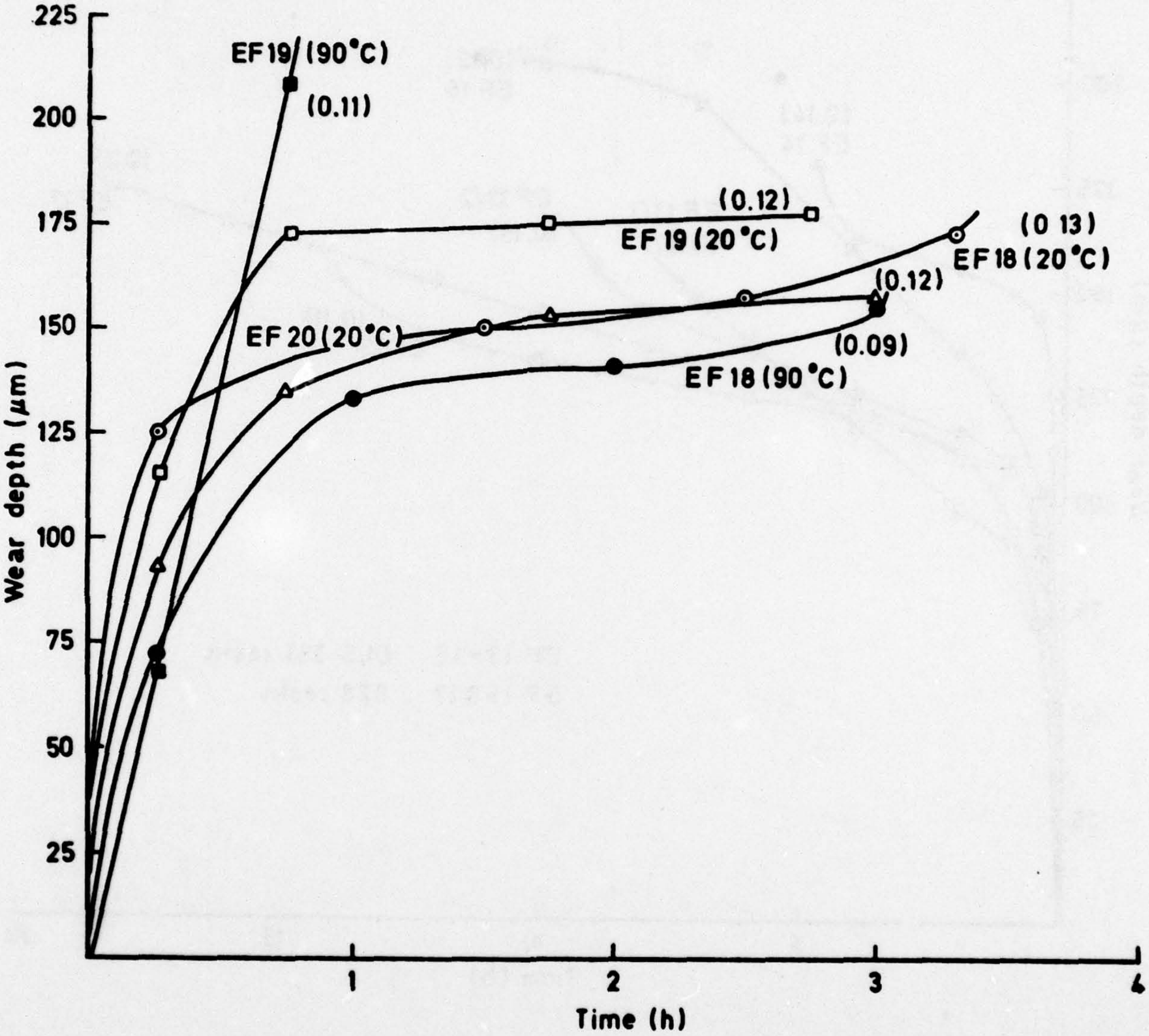

Fig 15 Wear characteristics of various experimental polyimide resin matrix liner materials

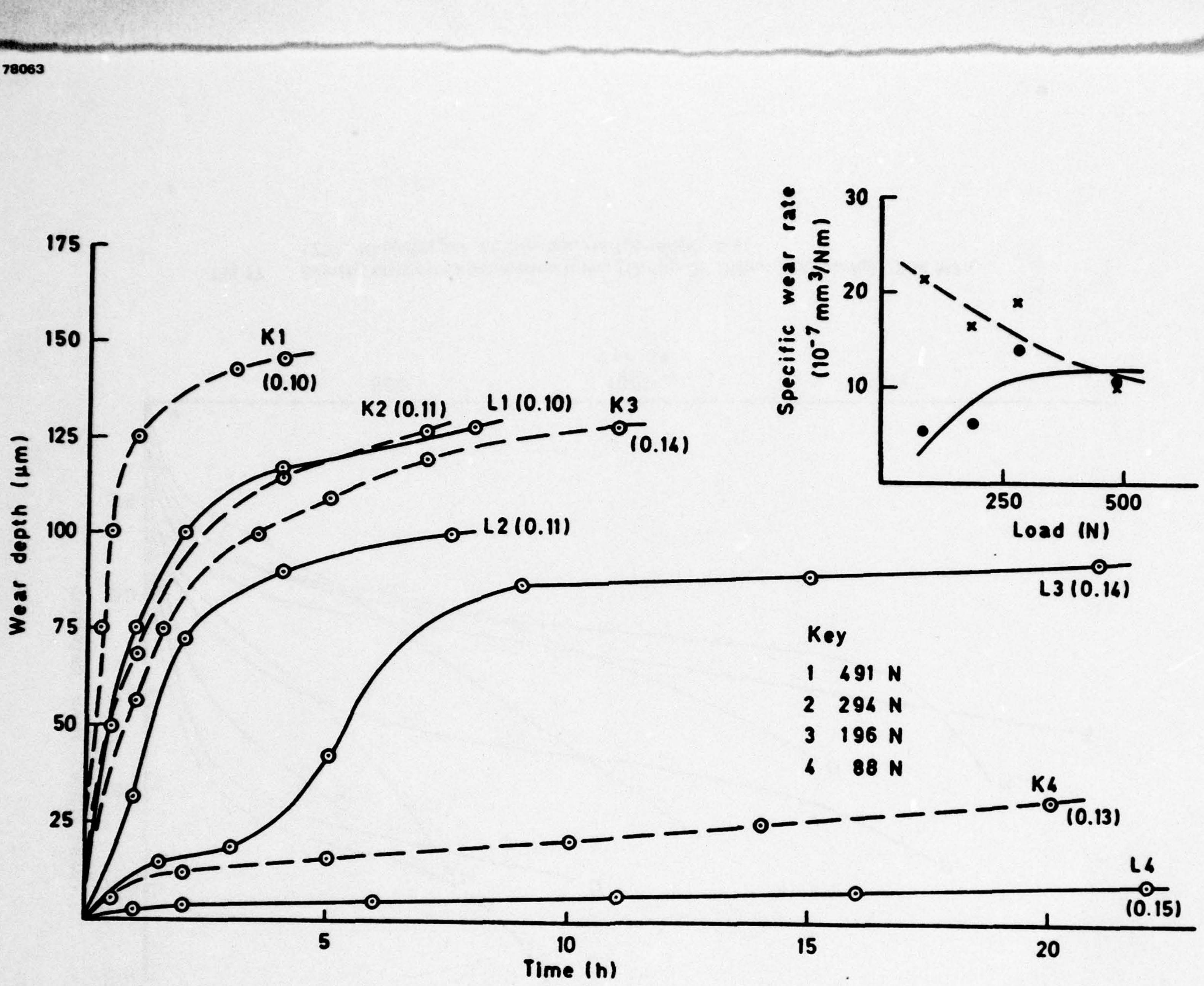

Fig 16 Effect of changing load on materials K and L

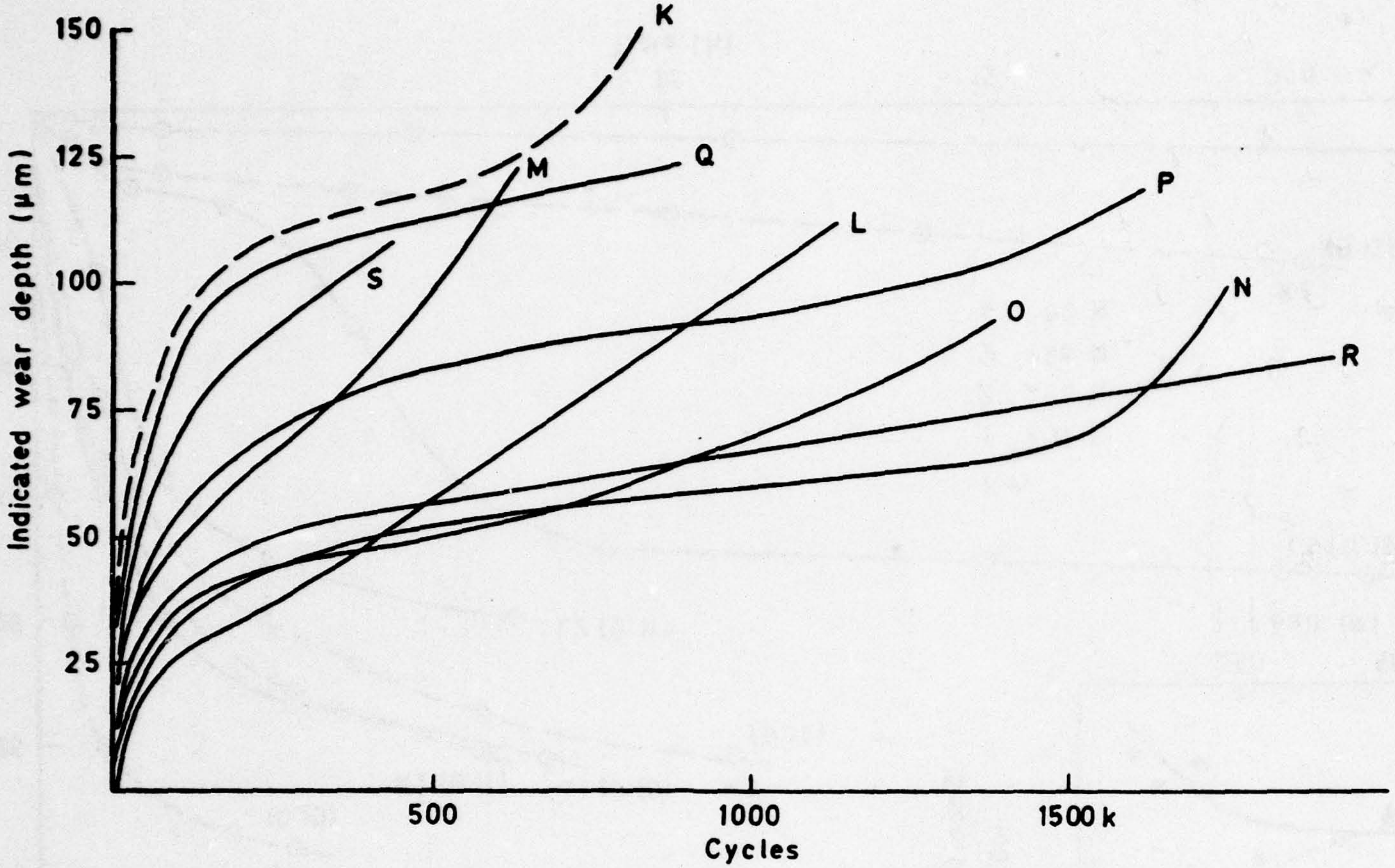

Fig 17 Bearing tests on experimental liners (Group 3). ½in x ½in journals, 234 MPa, ±25°, 40 cycles per minute, counterface 440C steel

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

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15. Distribution statement

(a) Controlled by – [redacted]

(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Water. Dry bearings. Lubrication.