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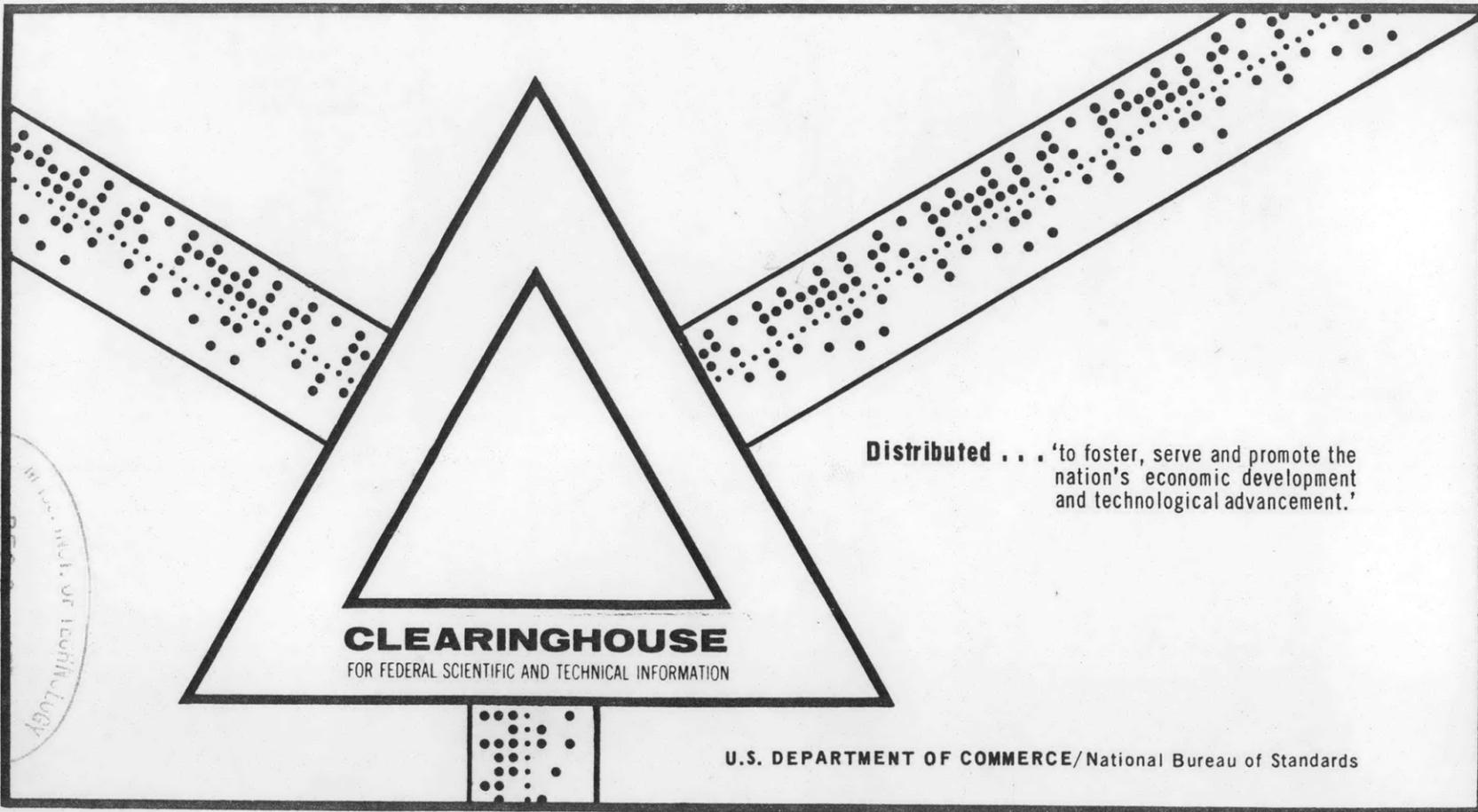


STERIC FACTORS AFFECTING FRICTION AND WEAR OF POLYALKENES

Paul Lagally, et al

Naval Ship Research and Development Laboratory
Annapolis, Maryland

October 1969



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STERIC FACTORS AFFECTING
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By
Paul Lagally and Robert Nagy

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MATERIALS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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STERIC FACTORS AFFECTING
FRICTION AND WEAR OF POLYALKENES

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ABSTRACT

The sliding performance of polyalkenes in rubbing contact with a metal (oxide) surface is controlled by structural order and molecular symmetry.

High-density polyethylene surpasses, in its overall sliding performance, the substituted crystalline polyalkenes. The ability of the conventional (branched) polyethylene to function as a low friction contact when water is the lubricant is attributed to the presence of amorphous regions also present in the linear type. The erratic sliding of isotactic polybutene (and other homologs) is explained by internal friction in the rubbing interface resulting from polymorphic transitions.

Cross-linking with a peroxide increases friction of polyethylene, but it reduces the abrasive wear of the composites containing carbon black. The use of highly reactive channel blacks requires no free radical source, and a further reduction in abrasive wear can be achieved by auxiliary cross-linking agents such as ethylene imine which reacts exothermally with the acidic surface of the carbon black present in the composite structure.

The ratio of crystalline and amorphous conformations governs the overall sliding performance of polyalkenes. Frictional effects due to different mating surfaces are explained by material transfer and interfacial phase elastic phenomena.

ADMINISTRATIVE INFORMATION

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STERIC FACTORS AFFECTING
FRICTION AND WEAR OF POLYALKENES

By
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INTRODUCTION

The search for materials to be used in sliding contact applications is rapidly moving into areas where conventional bearing designs usually fail. This is particularly true for machine elements lubricated by water. New approaches are required to overcome problems ordinarily not encountered.

In the predominantly nonhydrodynamic regime, where the rubbing surfaces are in frequent contact, vibration free sliding characteristics and a sufficient load bearing capacity are requirements. To keep corrosion and wear within the bearing design at a minimum, one of the two rubbing surfaces should be nonmetallic. This makes organic polymers, because of their almost unlimited chemical and structural versatility, promising candidates for the mating bearing materials.

A plastic bearing must be dimensionally stable and free from deflections. This requires a chemically inert matrix with a modified surface capable of meeting lubrication conditions in both the dry and wet states. Polyalkenes were selected as models because their structures can be changed without substantially affecting the overall composition. Polymeric structures under investigation comprised the amorphous and crystalline forms and the cross-linked species obtained through free radical routes which included composites containing modifying additives, particularly carbon black.

Since material transfer mechanisms are bound to come into play, steric factors are even more decisive in producing a unique rubbing interface that can display the sliding qualities of the transferred material yet retain the strength characteristics of the supporting phase.

STRUCTURAL ASPECTS

Crystalline polyalkenes with recurring functional groups attached to the organic backbone were expected to have sufficient strength yet display a variety of lubricating effects depending on their structure. Since polymers of decene-1 and octadecene-1, with aliphatic substituents of sufficient chain length, were not accessible, isotactic polybutene was used in initial experiments, along with polypropylene and crystalline poly (4-methylpentene-1). These materials are stereospecific polymers of high regularity, low solvent absorption, and with a melting range well above the boiling point of the water used as lubricant.

All substituted polyalkenes were surpassed by the parent polyethylene, particularly the crystalline high-density type which displays superior dimensional stability and friction and wear behavior (Figure 1). Polypropylene containing different levels of isotactic material, as determined by the decalin extractables, showed approximately equal but lower frictional qualities than polyethylene. Isotactic polybutene has even less attractive sliding qualities (Figure 2). Plastic flow and a high-frequency squeal observed during dry sliding indicate interfacial friction at the rubbing interface which is attributable to the well known polymorphic transformations of isotactic polybutene.^{1,2} However, under initial low loading, the sliding performance can take a different course, leading to a strongly adhering coating film which permits isotactic polybutene to operate with less friction.

MOLECULAR SYMMETRY

The foregoing observations emphasize the interdependence of morphology and reactivity of polyolefines. They suggest that, besides structural order, the molecular symmetry in the plastic bearing material is a significant parameter which determines the sliding contact mechanism. The rather attractive friction values observed with the polymerized ether "Penton" derived from 3,3-bis(chloromethyl) oxetane, a crystalline and symmetrical compound, add more supporting evidence to the advanced structural concept, Table 1.

¹Superscripts refer to similarly numbered entries in Appendix A.

Table 1
Coefficient of Friction of Stereoregular
Polymers in Sliding Contact with Bronze
(50 rpm, 13 lb = 78 psi)*

Material	Coefficient of Friction	
	Dry	Wet
Polyethylene, High Density ¹	0.16	0.09
Polypropylene, Isotactic ² 2.58% Decalin Soluble	0.45	0.25
6.1% Decalin Soluble	0.45	0.28
11.1% Decalin Soluble	0.39	0.31
Polybutene - 1 (Isotactic)	0.74	0.40
Poly-(4-methyl) Pentene-1	-	0.25
Poly-3, 3-Bis(Chloromethyl) Oxetane "Penton"	0.30	0.17

*Microthene ML 708 (product of USI Chemicals Company).

²Experimental samples.

Although high-density polyethylene is the preferred matrix material, the conventional type appears to have structural units which improve sliding when water is the lubricant. This is attributed to the presence of amorphous fractions which can undergo preferential oxidation more easily⁴ and form hydroxy and carbonyl functions in the wear track, as evidenced by infrared spectroscopy. Polar sites thus formed raise the surface energy of polyethylene and increase adhesion.⁵ Directional forces emanating from the mating journal surface can cause orientation of the adsorbed macromolecular micelles resulting in a protective and self-repairing coating.

*Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.

In addition, the sliding performance of low-density, polyethylene is affected by the molding technique employed. Temperature cycles and annealing techniques, but particularly molding pressure, are important factors which control the polymer morphology. Since phase transformations of a polymer can be brought about by increasing the pressure,⁶ it is not surprising that such structural changes have a significant effect on the sliding performance. If conventional polyethylene is molded at low pressure, friction profiles recorded during alternate water cycles display intermittent adhesion and lubrication effects which show that different polymeric conformations are in sliding contact with the mating surface (Figure 3, top profile). This erratic pattern changes eventually into a frictional profile which is obtained with the same low-density polyethylene molded at high pressure (Figure 3, center profile). Linear polyethylene, having a much higher inherent conformational order, shows the same regular pattern but slides with lower dry friction and has a higher load bearing capacity (Figure 3, bottom profile).

CHEMICAL MODIFICATIONS

A comprehensive search for a matrix material with even higher overall sliding qualities revealed the versatility of high-density polyethylene. Modification with hydrophilic or hydrophobic groups resulted primarily in a depression of the elastic modulus. Such additives as octadecene, vinyl stearate, vinyl silanes or esters of silicon, aluminum and titanium, and even a fluorinated siloxane caused, in many instances, cross-linking accompanied by polymer chain scission but did not improve the sliding performance of high-density polyethylene. A variety of copolymers of ethylene containing alkyl and polar hydroxy groups resulting from hydrolysis of acyloxy functions showed in all cases depressed sliding characteristics.⁷

To match the other performance parameters, low-density polyethylene, which has a potential for water lubrication, was modified with carbon black as a high modulus additive and cross-linked with dicumyl peroxide. Even when elastic moduli approach those of the high-density type, friction peaks reveal a structurally different material, Table 2. In contrast, analogous experiments with high-density polyethylene showed that additives of carbon black, or a peroxide, reduced the elastic modulus and increased the abrasive wear, but when physical and chemical cross-linking techniques were employed simultaneously, a synergistic effect came into play, resulting in increased elastic modulus and minimum wear, Table 3.

Table 2 - Coefficient of Friction of Low-Density Polyethylene (Microthene ML 718) Modified with Carbon Black and Dicumyl Peroxide as Compared to High-Density Polyethylene (Microthene ML 708)

Material	Compressive Modulus psi	Coefficient of Friction					
		Dry			Wet		
		Pounds					
		6	13	19	6	13	19
Low-Density Polyethylene	37,000	0.63	-	-	0.13	-	-
Low-Density Polyethylene with 5% Dicumyl Peroxide	24,500	0.71	-	-	0.23	-	-
Low-Density Polyethylene with 50% Regal 300	110,000	0.42	0.38	-	0.23	0.23	-
Low-Density Polyethylene with 50% Regal 300 and 5% Dicumyl Peroxide	60,000	0.50	0.54	-	0.26	0.27	-
Low-Density Polyethylene with 50% Sterling V	89,000	0.33	0.33	0.32	0.23	0.26	0.28
Low-Density Polyethylene with 50% Sterling V and 5% Dicumyl Peroxide	71,000	0.51	0.51	-	0.26	0.27	-
Low-Density Polyethylene with 50% Sterling MT-FF	72,000	0.19- 0.32	0.24- 0.33	0.25- 0.39	0.17	0.21	0.21
Low-Density Polyethylene with 50% Sterling MT-FF and 5% Dicumyl Peroxide	37,000	0.48	0.52	-	0.22	0.25	
High-Density Polyethylene	110,000	0.16	0.16	0.18	0.13	0.09	0.08

Table 3 - Compressive Modulus, Coefficient of Friction and Abrasive Wear of High-Density Polyethylene as a Function of Physical and Chemical Cross-Linking (Carbon Black and Peroxide)

Sample	Compressive Modulus, psi	Coefficient of Friction						Relative Abrasive Wear (%)
		Dry			Wet			
		Pounds						
		6	13	19	6	13	19	
PSI						Wear (%)		
36	78	114	36	78	114			
Polyethylene	77,000 ⁽²⁾ 110,000	0.16	0.16	0.18	0.13	0.09	0.08	1.0
Polyethylene 5% Peroxide ⁽⁴⁾	49,000	-	0.23	0.23	-	0.14	0.11	3.7
Polyethylene 50% Carbon Black ⁽⁴⁾	58,000	-	0.22	0.22	-	0.09	0.10	10.6
Polyethylene 50% Carbon Black, 5% Peroxide	120,000	-	0.23	0.23	-	0.09	0.10	2.0

¹Calculated from weight loss of bearing and journal.

²Degradation due to calendaring.

³2,5-dimethyl-2,5-di(t-butylperoxy)hexyne-3.

⁴Regal 400.

Extensive experiments with polyalkenes containing high modulus fillers show that cross-linking can be beneficial if it increases the structural order by unifying the constituents of a composite. Friction profiles of isotactic polybutene containing graphite, which cannot be cross-linked through free radical routes, revealed during alternate water cycles severe stick-slip motions, but polyethylene containing mechanically dispersed carbon black facilitates smooth sliding after chemical cross-linking (Figure 4). These surface-chemical changes convert the carbon black from an abrasive into a solid lubricant which retains its elastic properties and, at the same time, the sliding qualities of the polyethylene.

The structural changes of a commercial, high-density, polyethylene-carbon black composites,* which occur during the heat cure, furnish additional evidence that cross-linking can reduce abrasive wear. Exhaustive extraction with toluene revealed the presence of an insoluble gel fraction even in the uncured composite. This may be attributed to those functions in the surface of the carbon black which can form adhesive bonds with the polyethylene even in the absence of a free radical initiator, thus minimizing polymer chain scission (Figure 5).

A more reactive channel black** formed an insoluble gel with high-density polyethylene, when submitted to hot calendaring, even when no peroxide was present. A still higher degree of cross-linking and reduction in abrasive wear was achieved by the exothermic interaction of this composite with ethylene imine.

Polyalkenes resist bearing and journal wear better than their derivatives containing reactive substituents (e.g., fluorine, chlorine, or oxygen) which may interact with the mating metal surface. A comparison of different materials is shown in Figure 6. Cross-linked polyethylene-carbon black composites surpass in their overall sliding performance Buna N, an established bearing material for water lubrication, because they contain structural elements known to have inherent frictional qualities. The fact that Buna N causes high journal wear shows that extensive cross-linking can be disadvantageous to the overall sliding performance if it prevents material transfer from the bearing to the journal surface (Table 4).

INTERFACIAL PHENOMENA

The various forms of polyethylene reveal their improved performance only when in sliding contact with a suitable mating surface. When rubbing against each other, they have high coefficients of friction which are nearly equal in the dry and wet state (Figure 7). Although it is known that low polymer friction requires a hard backing,⁸ it could not be anticipated that a highly hydrophobic substance would function as a bearing material for water lubrication. The difference between dry and wet friction, Table 5, which depends also on the mating journal, Table 6, suggests the presence of an adhesion mechanism in the sliding interface.

*Petrothene XL 6310

**Carbolac 1

Table 4
Correlation of Friction and Abrasive Wear
for Various Bearing Materials

Material	Coefficient of Friction		Abrasive Wear grams		
	Dry	Wet	Bearing	Journal	Σ
High-Density Polyethylene (HPE)	0.16	0.13	0.09	0.13	0.22
Low-Density Polyethylene (LPE)	0.63	0.13	0.08	0.12	0.20
Isotactic Polybutene (PB)	0.74	0.40	0.05	0.11	0.16
Polyethylene-Carbolac (PE-C)	0.17	0.12	0.30	0.08	0.38
Polyethylene-Carbolac-Ethylene Imine (PE-CEI)	0.26	0.11	0.23	0.07	0.30
Polyvinylidene Fluoride (PF)	0.44	0.27	0.41	0.09	0.49
Penton P	0.30	0.17	0.40	0.08	0.46
Eterna N E	0.61	0.38	0.04	0.13	0.17

Table 5
Coefficient of Friction of Conventional
and High-Density Polyethylene

Bearing	Journal	Coefficient of Friction	
		Dry	Wet Water ¹
Polyethylene Low Density	Polyethylene Low Density	0.57	0.51
Polyethylene High Density	Polyethylene High Density	0.48	0.43
Polyethylene High Density	Polyethylene Low Density	0.47	0.47
Polyethylene Low Density	Polyethylene High Density	0.51	0.52
Polyethylene High Density	Bronze	0.15	0.11
Polyethylene Low Density	Bronze	0.63	0.15
Bronze	Bronze	0.32	0.21

¹Slow speed sliding range (50 rpm); loading = 13 pounds (78 psi).

Table 6
Coefficient of Friction of High-Density
Polyethylene Sliding Against
Different Mating Surfaces

Bearing	Journal	Coefficient of Friction	
		Dry	Wet (Water) ⁽¹⁾
Polyethylene High Density	Titanium (Pure)	0.15	0.15
	Titanium-Alloy ⁽²⁾	0.12	0.05
	Zirconium (Pure)	0.23	0.16
	Aluminum-Alloy ⁽³⁾	0.17 - 0.25 ⁽⁴⁾	0.09
	Chromium (Pure)	0.17	0.11
	Copper (Pure)	0.18	0.10
	Stellite 6	0.18	0.10

¹Slow speed sliding range (50 rpm); loading = 13 pounds (78 psi)

²Ti-7Al-2Cb-1Ta

³Al 7075-T-7351

⁴Friction peak.

Such a mechanism becomes even more obvious when the sliding characteristics of polyethylene and Teflon are compared. Perfluorination weakens or eliminates those functions which facilitate lubrication with water. As a result, stick-slip motions increase and the coefficients of friction coincide in the dry and wet state (Figure 8).

METHODS

Kinetic friction was determined by pressing a block of material against a rotating metal journal and determining the

torque by a system of planetary gears with a pendulum yoke (Figure 9).⁹ The regime of semifluid lubrication,¹⁰ where vibrational motions occur most frequently, was established by the bearing load or pressure and sliding velocity where the viscosity parameter approaches its minimum with a negative slope

$$\mu = f \left(\frac{Z \cdot N}{P} \right)$$

where:

μ = coefficient of friction

Z = viscosity of lubricant (100 centipoise for water)

N = number of rpm (50 to 100 rpm)

P = nominal pressure (> 50 psi).

Friction profiles taken during alternate water cycles revealed those sliding characteristics (adhesion or lubrication) effective when only traces of lubricant were present in the rubbing interface or the ability of the plastic bearing to function as a solid lubricant.

Abrasive wear was determined by a modified test derived from the standard method.¹¹ Since striations, which represent a deterrent to the acquisition of accurate data, occur primarily along the edge of the bearing surface sliding against the outer perimeter of the rotating (1/2-inch-wide) journal, the width of of the bearing was reduced to 1/4 inch.

Compressive moduli were determined with a Rockwell tester and computed to standard values according to ASTM:D 695-63T.¹²

The degree of cross-linking, as expressed by insoluble gel fractions, was determined by exhaustive extraction with toluene.¹³

MATERIALS

Conventional and high-density polyethylene with the following properties (Table 7) was used.

Table 7
Properties of Polyethylene

Polyethylene	Microthene ¹		Marlex ²
	MN 71B	ML 70B	TR 960
Melt Index	8.0	5.0	6.0
Density	0.915	0.950	0.962
Mesh Size	35	35	35

¹USI Chemicals Co.

²Phillips Petroleum Co.

It was modified with a highly reactive channel black (Carbolac 1)* and with different furnace blacks (Table 8).

Table 8
Properties of Carbon Blacks

Carbon Black	Surface Area m ² /g	Volatile Matter %	pH
Carbolac 1	950	16.0	3.0
Regal 400	95	2.5	4.5
Regal 300	80	1.0	7.5
Sterling V	30	1.0	7.5
Sterling MT-FF	7	0.5	9.5

*Cabot Corporation.

The carbon blacks were dispersed in polyethylene on a steam heated roller mill. Composites containing conventional polyethylene, and basic carbon blacks, were cross-linked with dicumyl peroxide; for the high-density type (and Regal 400), 2,5-dimethyl-2,5-bis(t-butylperoxy)hexyne-3 was used as the free radical initiator. The felt-like materials were ground in a blender and molded in a Pasadena Press at 130° to 140° C either at 2,000 psi (low pressure) or at 10,000 psi (high pressure).

A commercial, cross-linkable, high-density polyethylene-carbon black composite containing a peroxide (Petrothene XL 6310)* was tested in both the uncured and cured state. Extraction tests revealed insoluble gel fractions of 20% and 93%, respectively.

To keep polymer chain scission at a minimum, Carbolac-1 (25 g) was dispersed in Marlex TK 960 (50 g). The resulting composite contained 50.0% of the polyethylene as an insoluble gel fraction. A ground sample of this composite (30 g, reacted exothermally with ethylene imine⁴ to yield a cross-linked bearing sample (76.4% insoluble gel; 5.3% N) of reduced abrasive wear.

All other polymers were used as furnished by the suppliers: the various forms of polypropylene by Hercules, Inc., isotactic polybutene (Type XB 100 and a composite containing 23% graphite) by Petrotex Company, and the Methylpentene Polymer by ICI America. All bearing specimens and journals were ground to a surface finish of 6 microinches rms.

DISCUSSION

In plastics technology, it is well established that the chemical and mechanical characteristics of polymeric materials are determined predominantly by the molecular weight, the forces acting between the molecules, and particularly the geometry of the macromolecular micelles. Crystallinity, stereoregularity, and strong interchain forces improve chemical inertness, hardness, and superior strength behavior.¹⁵ Since friction and wear studies reveal dynamic interactions which are not observable when the surfaces are at rest, they reveal significant interfacial sliding parameters and represent a powerful tool for the identification of complex polymeric structures and for the synthesis and design of new plastic bearing composites.¹⁹

*USI Chemicals Co.

A comparison of the conventional and high-density polyethylene with isotactic polybutene helps in understanding the structural parameters which govern the sliding mechanism in the rubbing interface. The fact that the different types of polyethylene coincide in their semisolid friction when water is the lubricant suggests a participation of the amorphous regions in the polymeric micelles. This is supported by a new concept of amorphous surface layers (Peterlin)⁴ which have a preferential location in the crystal surface. The different sliding behavior of polyethylene and isotactic polybutene, on the one hand, and the coincidence of minimum wear, on the other hand, can be attributed to the distribution of crystalline and amorphous regions in the surface, or in the interior of the polymeric micelles.

How the geometry of the polymeric micelles affects the sliding behavior can be demonstrated in a number of ways. Crystallization of polyethylene from various molecular weight fractions has no noticeable effect on its morphology, but the reorganization of the crystallites is suppressed by cross-linking which increases molecular weight and friction.¹⁴ As compared to the smooth and noiseless sliding of polyethylene which crystallizes in the form of planar trans chains,¹⁷ the polymorphism of isotactic polybutene is responsible for its erratic melting and annealing behavior,¹⁸ and it controls the transfer to the mating journal and the structure of the resulting coating.

These observations give further evidence that steric factors, which play a role in most sliding contact situations, control friction and wear of the transferred material. That a gaseous or liquid substance entering the field of a solid phase can acquire shape elasticity, which it did not have in the bulk, is well established.¹⁹ The frictional behavior of graphite, for instance, is due to adsorbed contaminants but not attributable to cleavage parallel to the basal hexagon networks.²⁰ Similar phase transitions may affect the aggregation, and the boundary state, of a solid compound supported by a material with an elastic modulus many times higher. This explains why polyethylene, rubbing against itself or another material, can create a variety of frictional phenomena and display hydrophilic effects when transferred to a suitable substrate. For a similar reason, Teflon in sliding contact with a mating surface to which it does not adhere, produces in the presence of water a reversed boundary layer resulting in coincident dry and wet friction. However, since the ratio of crystalline and amorphous polymeric conformations can be affected by the nature of the mating surface (crystallinity

of nucleated polyethylene increases with the surface energy of the substrate)²¹ and by high pressures,⁶ new morphological forms can be produced with a wide spectrum of sliding characteristics. This indicates that the bulk parameters of different polymeric materials are insufficient to correlate their sliding qualities which are governed by interfacial phenomena.

Although directional forces emanating from the journal surface control the structure of the sliding interface, they cannot prevent plastic flow or melting of the bulk bearing materials. To meet extreme load supporting requirements, curing mechanisms must be employed which convert the thermoplastic bearing material into a network which is dimensionally stable. Conventional cross-linking techniques through free radical routes are no remedy because they can cause simultaneous polymer chain scission resulting in structural disorder and reduced sliding qualities. However, the addition of carbon blacks with a variety of surface reactive groups permits the control of composite structures. Highly acidic channel blacks contain, in addition to free radical sites, phenolic, lactone,^{22 23} and even carboxylic groups,²⁴ which can be cross-linked by suitable additives. Since ethylene imine reacts only with the carbon black, structural composites with reduced wear can be prepared which have good frictional qualities because they contain practically unmodified polyethylene entities.

A new structural concept can be derived which correlates the frictional behavior of polyalkenes to their conformational order at the rubbing interface. Abrasive wear is controlled by long-range and cross-linking effects of the bulk material. Supporting evidence are the polymorphic transitions of isotactic polybutene which increase friction without affecting abrasive wear, the high-friction and low-wear characteristics of Buna N, a copolymer of low structural order, as opposed to a cross-linked carbon black network containing polyethylene in crystalline conformation, and the effect of pressure on the sliding characteristics as observed in polyethylene or Teflon.

CONCLUSIONS

Results of this study reveal that the sliding characteristics of synthetic high polymers are determined by geometrical considerations such as regularity, crystallinity, or morphology. The superior performance of high-density polyethylene as a bearing material is attributed, at least in part, to its planar structure which is shared by few other polymers. As long as its structural features prevail, linear polyethylene can also be present as a

film coating, which is supported by another solid phase, or it can serve as a matrix. High modulus bearing surfaces containing carbon blacks, metals, or ceramics can be engineered which display undiminished sliding qualities.

FUTURE WORK

The inert nature of high-density polyethylene precludes most chemical modifications without altering its degree of crystallinity. However, those linear types, which are terminated by an olefinic end group, invite vinyl addition reactions. It has been established that hydrogenation has no adverse effect on crystallinity. Isomerized linear polyethylene and the crystalline copolymer of ethylene and butadiene have recurring olefinic groups and represent new candidates for chemical modification. And an almost unlimited number of reactive groups can be introduced by incorporating low molecular polybutadienes which are amorphous but do not affect the crystallinity of linear polyethylene. They can be terminated by polar functional groups which may undergo secondary substitution or chain extension reactions.

Further advances in the design of sliding contact couples containing a load bearing solid lubricant are anticipated by future work in the following areas:

- Studying the effect of vinyl functions present in isomerized linear polyethylene which may contain butadiene moieties in 1,2-addition or polybutadiene resins containing terminal polar groups.

- Altering material transfer mechanisms and control galling or scuffing phenomena by the use of linear polyethylene containing protective halide or sulfide groups resulting, for instance, from vinyl addition of iodine or mercaptans.

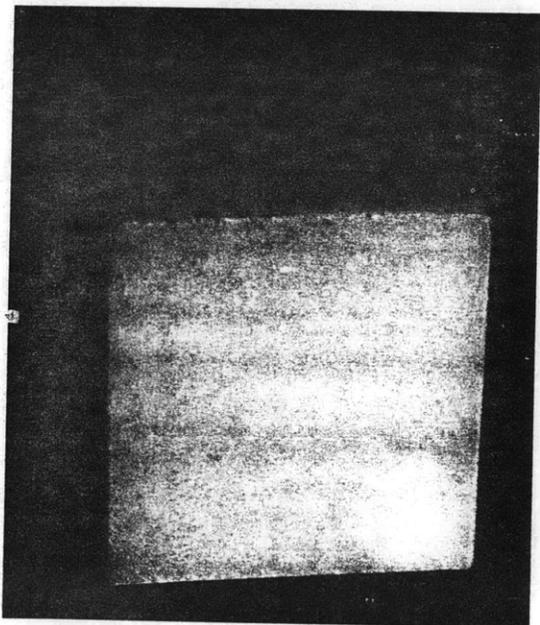


Figure 1
Wear Track on High-Density
Polyethylene (Bearing) Sliding
Against High-Density Polyethylene, Top
and Bronze, Bottom (Journal)

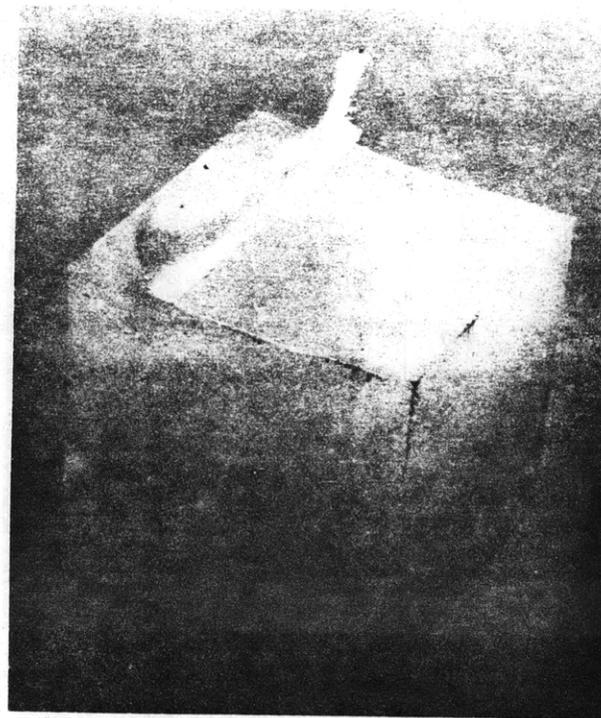


Figure 2
Wear Track on Isotactic Polybutene (Bearing)
Sliding Against Bronze (Journal)

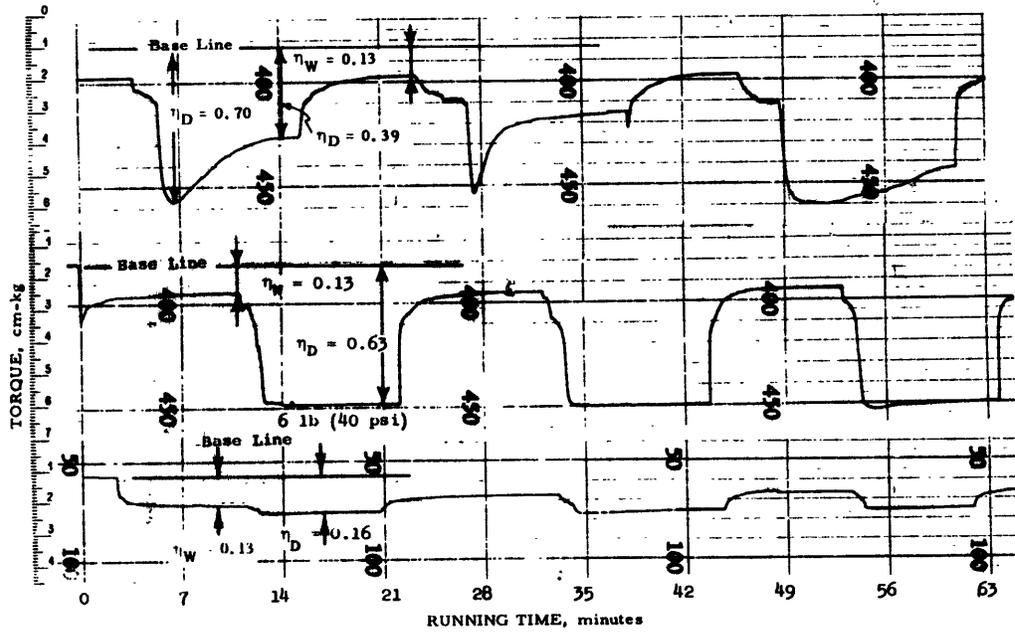


Figure 3
 Effect of Increasing Structural Order on Friction Profile (Alternate Water Cycles)
 Conventional Polyethylene (Bearing) Molded at Low and High Pressure (Top and Center)
 and High-Density Polyethylene (Bottom) Sliding Against Bronze (Journal)

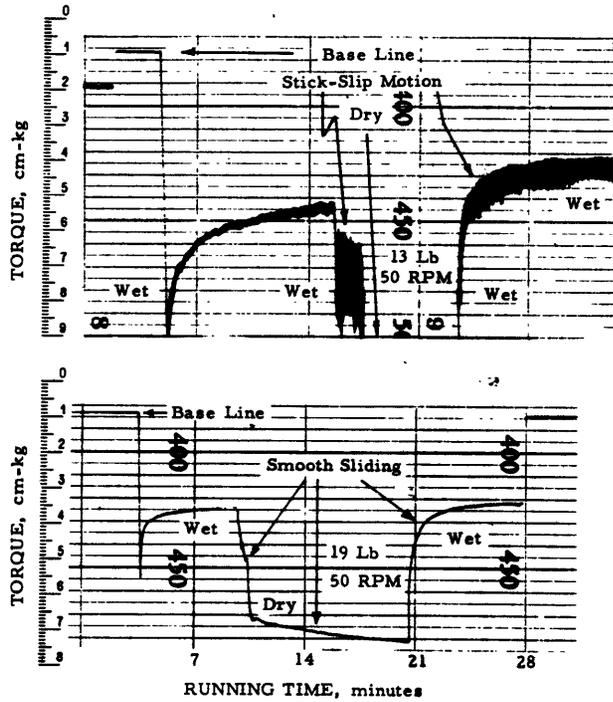


Figure 4
Friction Profile (Alternate Water Cycles)
of Isotactic Polybutene Containing
Graphite (Physical Mixture), Top
High-Density Polyethylene Containing
Carbon Black (Cross-Linked), Bottom
(Sliding Against Bronze Journal)

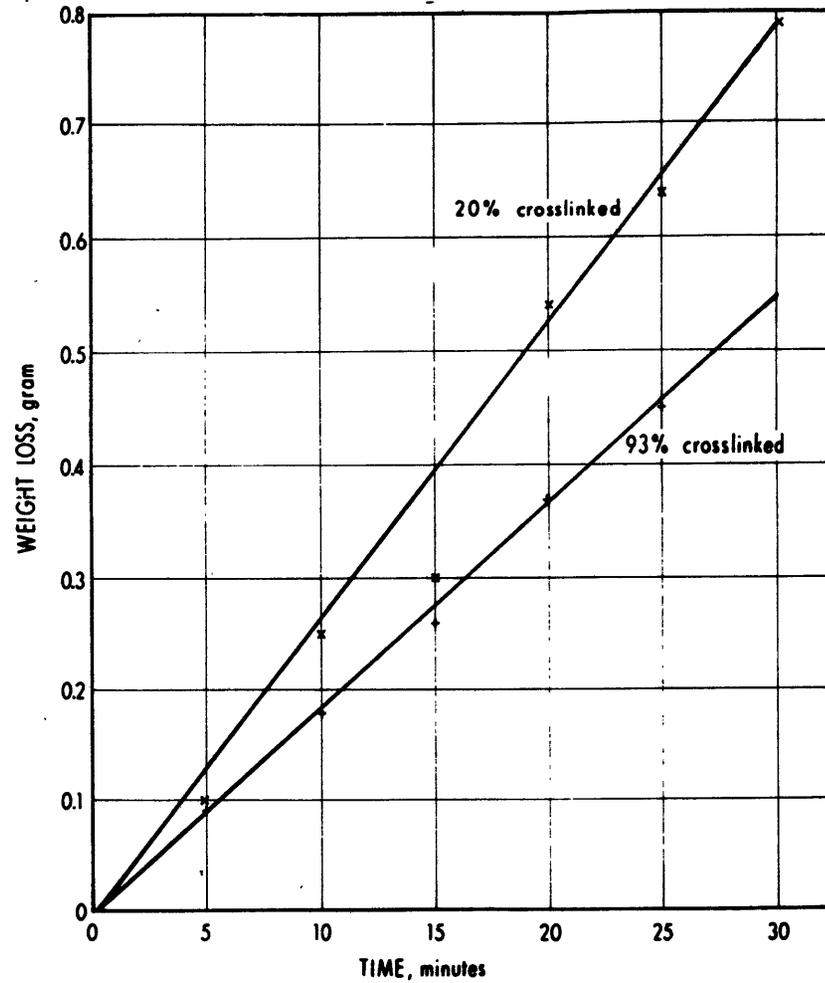


Figure 5 - Effect of Free Radical Cross-Linking on
Abrasive Wear of a Polyethylene-Carbon Black Composite
(Combined Weight Loss of Bearing and Monel Journal)

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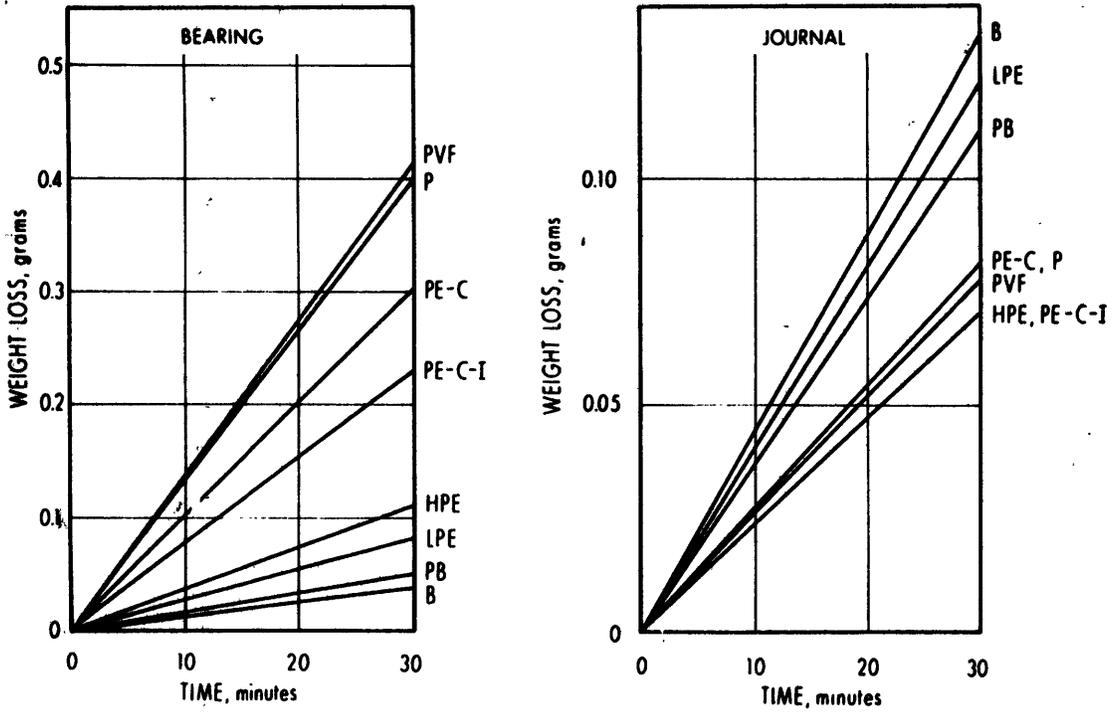


Figure 6 - Structural Relationship Between Various Bearing Composites and Abrasive Wear (Bearing and Journal)



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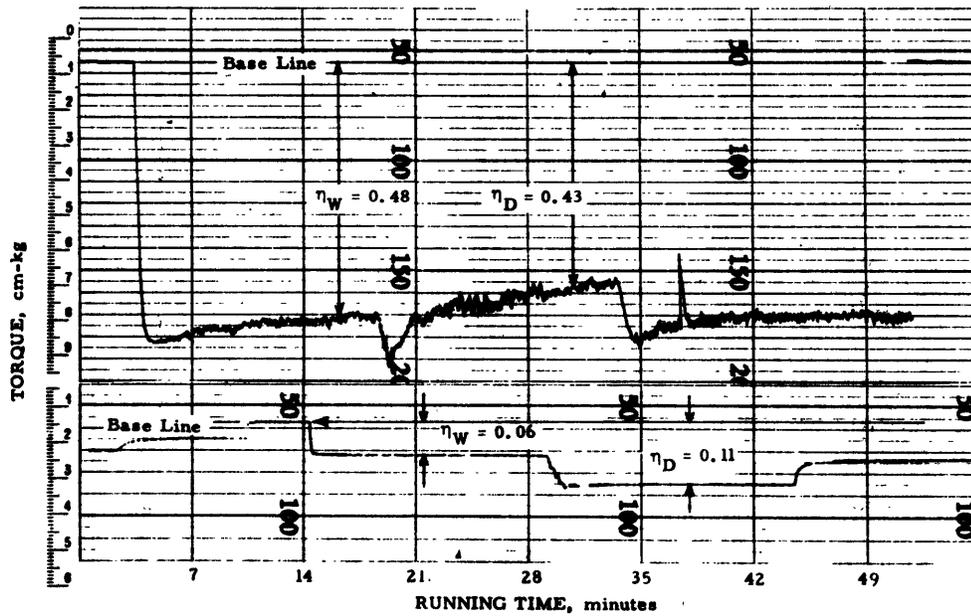


Figure 7
Friction Profile (Alternate Water Cycles) of High-Density Polyethylene (Bearing) Sliding Against High-Density Polyethylene, Top, and Titanium Alloy (Ti-Al-2Cb-1Ta), Bottom (Journal)

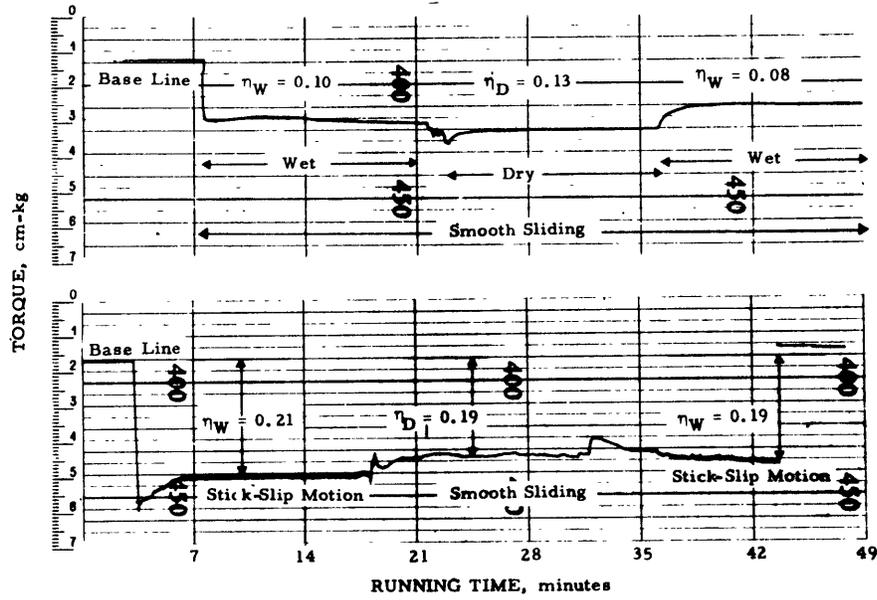


Figure 8
Friction Profile (Alternate Water Cycles)
of High-Density Polyethylene, Top,
and Teflon, Bottom (Bearing)
Sliding Against Bronze (Journal)

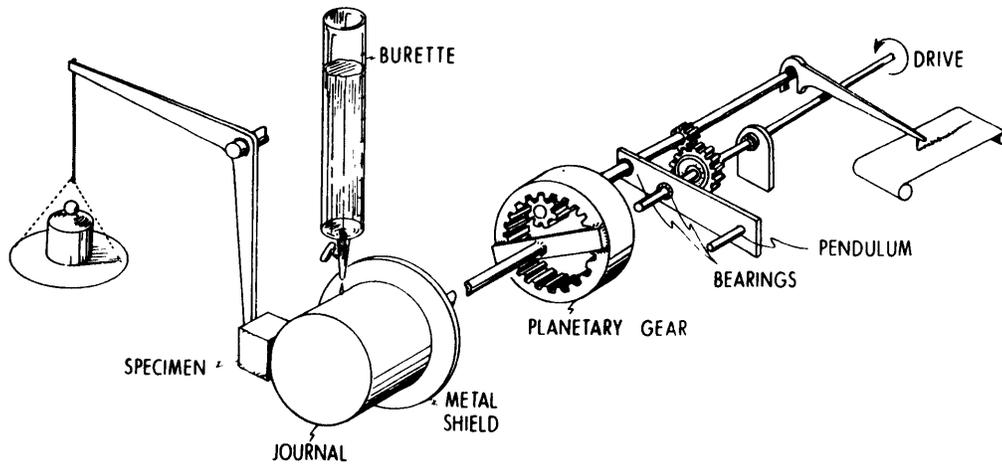


Figure 9
Amsler Machine

Appendix A

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<p>The sliding performance of polyalkenes in rubbing contact with a metal (oxide) surface is controlled by structural order and molecular symmetry. High-density polyethylene surpasses, in its overall sliding performance, the substituted crystalline polyalkenes. The ability of the conventional (branched) polyethylene to function as a low friction contact when water is the lubricant is attributed to the presence of amorphous regions also present in the linear type. The erratic sliding of isotactic polybutene (and other homologs) is explained by internal friction in the rubbing interface resulting from polymorphic transitions. Cross-linking with a peroxide increases friction of polyethylene, but it reduces the abrasive wear of the composites containing carbon black. The use of highly reactive channel blacks requires no free radical source, and a further reduction in abrasive wear can be achieved by auxiliary cross-linking agents such as ethylene imine which reacts exothermally with the acidic surface of the carbon black present in the composite structure. The ratio of crystalline and amorphous conformations governs the overall sliding performance of polyalkenes. Frictional</p> <p style="text-align: right;">(over)</p>		

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	Kinetic friction Wear Polyethylene Microthene Marlex Channel beads Carbon black Volatiles Composites Polymers Plastics Sliding contact behavior					
<u>Abstract (Cont)</u> effects due to different mating surfaces are explained by material transfer and interfacial phase elastic phenomena. (Authors)						

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