Polytetrafluoroethylene and Fluorinated Ethylene-Propylene Grease Lubricants

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Requirements for grease lubricants that can operate under extreme environmental conditions at high speeds and high loads over extended periods of time suggested re-evaluation of fluorinated polymers as grease thickeners. Commercial PTFE and FEP powders were evaluated and a wide range of properties were observed. It was thought that fluorinated polymers with good thermal stability, high surface area, high critical surface tension, and uniform particle size and shape would be preferred components of grease compositions. Oil absorption was shown to correlate most directly to critical surface tension and surface area. Grease compositions were prepared with the powders in both a perfluoroalkylether and trifluoropropyl methyl silicone. Separation and penetration values were in agreement with predictions based on fluorocarbon powder data. The greases were also evaluated for wear properties. Results indicated the greases investigated are suitable for use in many types of aerospace applications.

INTRODUCTION

Present demands and anticipated demands for lubrication in a variety of extreme environments have engendered development of many advanced grease formulations. While a grease in its simplest form consists of a lubricating fluid thickened with a solid sufficient to impart a semisolid consistency, the problems associated with specific applications have led to the evolution not only of advanced fluid and solid materials, but additional third and fourth components. Various developments selectively insured better antibleed, extreme pressure, wear, thermal, or high speed properties.

Traditional soap thickeners, namely lithium, calcium, and sodium stearates predominate in general-purpose greases. They are economical and, in a temperature range of 65 F-300 F, lend sufficient consistency to most mineral oils for the majority of low-speed applications. Nonsoap thickeners like silica, fiberglass, and asbestos are often treated to reduce surface activity. Together with carbon blacks and boron nitrides, these yield greases that are stable to higher temperatures (350 F through 400 F) at significantly reduced loadings. The difficulty with many inorganic thickeners lies in their inability to provide extreme pressure and wear properties. Additives like pentachlorophenylmercaptoacetic acid are often employed to help eliminate these deficiencies.

While thickener technology helped to advance the useful temperature range of grease formulations, lubricating fluids underwent a first-order change. The thermal stability and volatility of hydrocarbons (mineral oils are the most conspicuous example) very often limited service of a grease formulation. In more extreme applications, multipurpose greases were quickly superseded by silicone and polyether-based formulations. The lack of aliphatic carbon-hydrogen bonds on the structural backbones of these compounds eliminated much thermal degradation due to oxidation. The more recently introduced fluorosilicones and perfluoroalkylethers preserve these properties and offer both low surface tension and improved oxidation and chemical resistance (1).

Like the lubricating fluids, the organic thickening agents gradually eliminated aliphatic carbon-hydrogen bonds from their skeleton. Triazines (ammeline), arylureas, polyimides, and fluorinated polymers represent various solutions to the problem of thermal stability. In general, they require higher loadings, and formulations are subject to greater oil separation. Among the thickeners listed above, fluorinated polymers appear to have immediate interest. High temperature stability and low coefficient of friction are salient features of fully fluorinated polymers. Compounds like polychlorotrifluoroethylene were eliminated early in studies. Unlike carbon-fluorine bond energy which is higher than carbon-hydrogen bond energy, car-

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bon-chlorine bond energy is lower. Thus, polychlorotrifluoroethylene thickeners, as well as halocarbon oils, have even less stability than polytrifluoroethylene. Most previous work with fluorinated polymers eliminated their use as grease thickeners for other reasons. The surface energy of fluorinated materials is so low they are not wet by many lubricating fluids and thus, no thickening is effected. The authors found that lubricating greases based on silicone oils and fluorinated polymers were readily formed when the TL resins were used as thickeners. The TL thickeners produced no grease-like structure when combined with other fluids such as mineral oils and esters.

Recently, new extreme environmental demands have caused more interest in the subject of fluorinated polymers in greases. Aerospace is one area responsible. Greases that can operate over a greater temperature range, ultrahigh vacuum conditions at high speeds, and heavy loads are examples of some of these requirements (*2*). Fortunately, advances in both lubricating fluid technology and fluorinated polymer powder technology have been accomplished. Perfluoroalkyl ether and fluorinated silicones of low volatility and, more importantly, low surface tension are now available. The availability of polytetrafluoroethylene (PTFE) powder has been augmented with the addition of many new grades and types. Fluorinated ethylenepropylene powders are also now available.

This investigation was undertaken in two phases. First, various parameters were defined that would allow characterization of the fluorocarbon lubricant powders. Tests were then conducted by appropriate methods to give data on the particle size, particle distribution, surface area, critical surface tension, particle configuration, coefficient of friction, and bulk density of the powders (*3*). Results of the first phase suggested trends that may be observed in grease formulations. In the second phase, two series of greases were prepared, and data concerned with oil separation, wear, extreme pressure, and penetration properties were collected. Results indicate not only the predictability of fluorocarbon polymers to act as grease thickeners but also that the compositions produced have low volatility and excellent thermal stability, and their lubricating properties are sufficient for many long-term extreme-pressure and antiwear applications.

THICKENER CHARACTERIZATION

The behavior of fluorinated polymers in grease compositions varies widely. This is true even for polymers of the same molecular composition. PTFE solid lubricants are manufactured by a variety of techniques including grinding, cryogenic pulverizing, molecular chain scission, and pyrolysis. It has become evident that physical properties apart from particle size and distribution are not uniform for these powders. Fluorinated ethylenepropylene (FEP) powders present entirely different characteristics.

The low speed coefficient of friction for PTFE and FEP (0.04–0.06) is lower than graphite (0.09) and molybdenum disulfide (0.12). The static coefficient of friction of PTFE is lower than the dynamic coefficient of friction, insuring nonstick-slip properties (*4*). The low surface energy of the fluorocarbon resins means that little shear energy is required to form a soft, continuous film of lubricant. The chemical resistance of fluorocarbons is excellent over a temperature range of —400 F to 500 F. Antistick properties are another advantage; the critical surface tensions of fluorocarbon polymers are below the surface tensions of most liquids. An unusual consequence of this is that most lubricating greases in which PTFE is a thickener exclude water from interface boundaries and thus reduce hydrolytic corrosion (*5* and *6*). Another feature of grease compositions containing fluorinated resins is the clean white color which allows application in textile and pharmaceutical machinery (*7*).

Scanning electron micrographs (SEM) reveal particle configuration directly. Figure 1 is a SEM of Tetrafluoroethylene Lubricant 115 (TL-115), a PTFE lubricant powder, the earliest one introduced and typical of the powders most widely marketed. It is immediately evident that the nominal particle-size diameter in microns (10^{-4} cm), which is ordinarily used in describing TL's, is misleading since the particles are neither round nor of uniform size. As will be demonstrated below, this powder is not optimally suited for grease compositions for reasons other than its dendritic shape. It is perhaps unfortunate that this material is representative of the TL's most often tested in grease compositions. Figure 2, TL-120, is fluorinated ethylenepropylene (FEP) powder of substantial submicron size. The particles are quite spherical. Due to its uniformity, low coefficient of friction, and high surface area, this material is gaining acceptance in lubricating greases and oils. Figure 3 depicts TL-102, the smallest-particle PTFE powder presently manufactured. This material, manufactured by molecular chain scission, is practically spherical and is currently used in film-forming and aerosol compositions. It is physically similar to TL-120 and was considered of interest in grease compositions. Figures 4 through 6 depict other TL's currently available. Figure 4

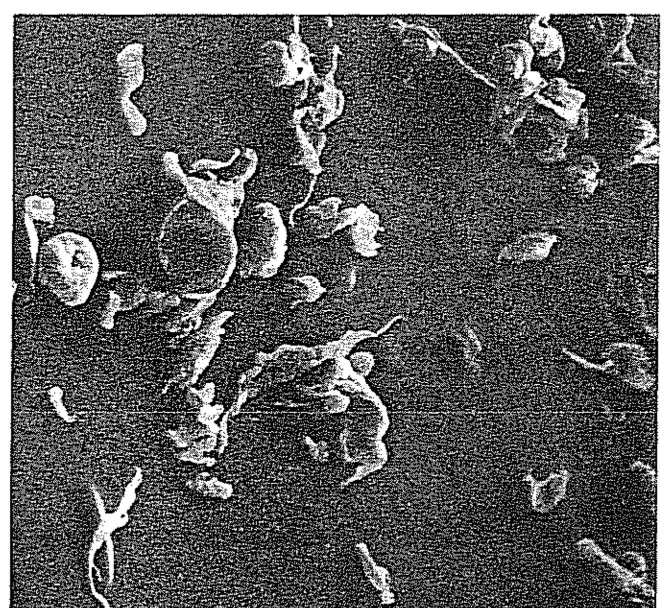

Fig. 1—TL-115 (1000 × magnification)

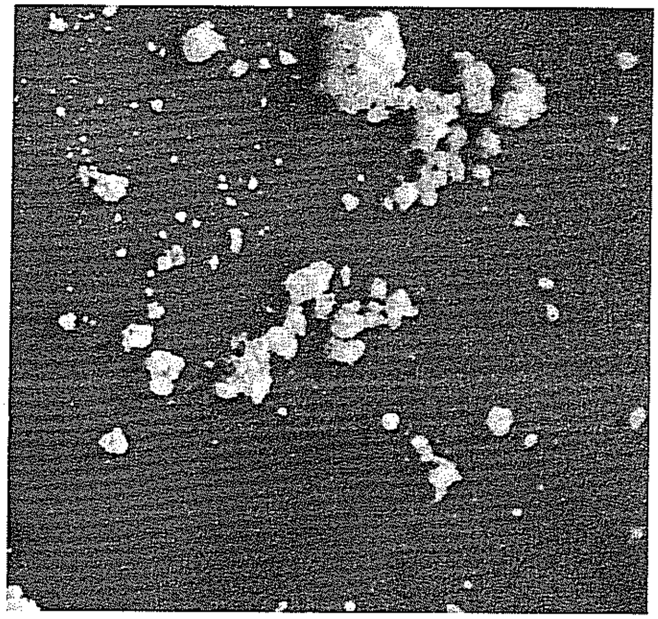

Fig. 2—TL-120 (1000 × magnification)

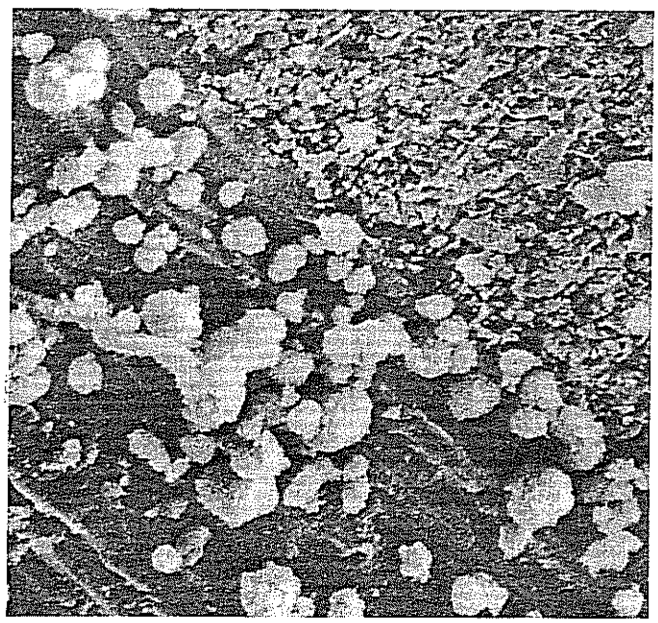

Fig. 3—TL-102 (1000 × magnification)

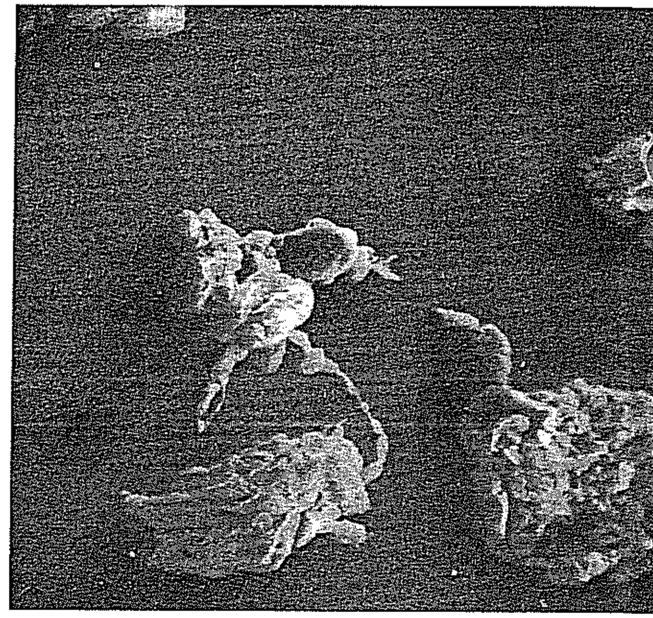

Fig. 4—TL-125 (1000 × magnification)

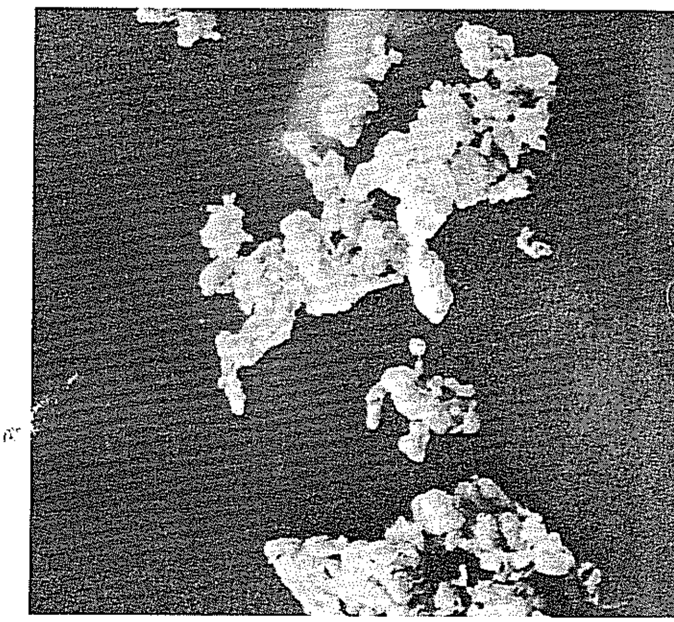

Fig. 5—TL-126 (1000 × magnification)

is TL-125, a hard granular PTFE powder which, in some instances, has been found to have considerable thickening action. Figure 5 is TL-126, a general-purpose lubricant. Figure 6, TL-103f, is most widely used in bonded film applications (*7*).

Particle size and distribution of the fluorinated powders are measured by several methods. Traditional sieve analysis is not employed since the particles are smaller than screens commonly available. Two methods of choice are Micromerograph and Coulter Counter. The Micromerograph operates by exploiting Stoke's law for particle sedimentation in air under the influence of gravity. For particles of constant density, this means that particle diameter (D) equals the time for sedimenting in a 7-foot column divided into an instrumental constant, $D = \frac{K}{t}$. The Coulter Counter operates by dispersing the TL in an electrolyte and drawing the mixture through a conductivity bridge. Displacement of electrolyte by a TL particle results in a decrease in conductivity which may be used to calculate particle volume. This is then converted to micron diameter by assuming a spherical volume. Results of these methods for the materials investigated are reported in Table 1. For both methods, accuracy diminishes in measuring particles smaller than two microns in diameter.

For comparative purposes, Fisher Subsieve data were obtained. The method is not considered to be accurate enough for use with particles in the size range of those used in this investigation. It operates by measuring pressure drop through a sample (a function of surface area) and assigning an average particle diameter (*8*).

Coefficient of friction was determined for the various

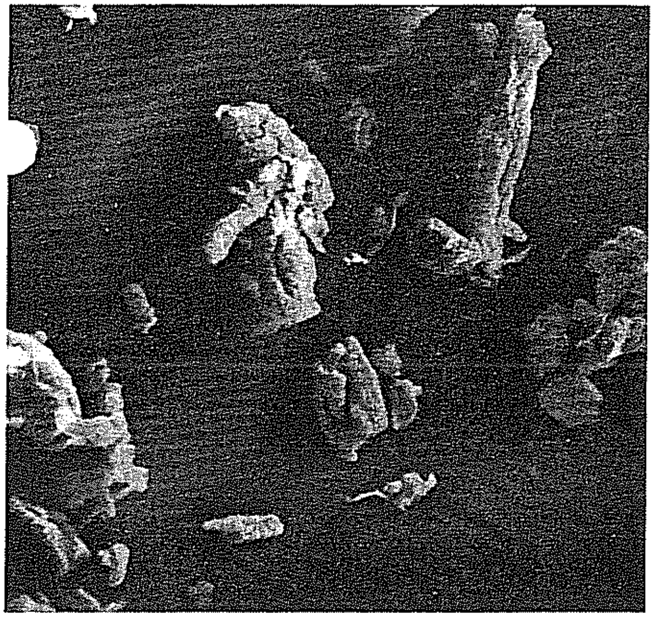

Fig. 6—TL-103f (1000 × magnification)

TL's by employing the Dow Corning Compression-Fit Test. A 0.7510-in pin is forced through a 0.7500-in bushing at a constant rate. By determining the normal force due to interference and the maximum applied force, a dynamic coefficient of friction may be obtained. Values typically obtained for PTFE and FEP are less than those achieved by lubricating oils and greases. The PTFE powder designated TL-102 was found to have the lowest coefficient of friction, 0.06–0.08. An FEP powder demonstrated a somewhat higher value of 0.07–0.11. The remaining PTFE powders evaluated had slightly larger coefficients. Since FEP in fabricated pieces normally has a higher coefficient of friction than PTFE, the results here indicate the greater ability of TL-120 to form a film over the contact surfaces. The coefficient of friction of polytetrafluoroethylene powders has been shown to be independent of temperature to 500 F.

Surface area is a useful parameter when used in conjunction with particle-size distribution in estimating the surface roughness and covering area of a fluorocarbon powder. These properties are important when fluorocarbon lubricants are employed as grease thickeners. One of the most successful methods for determining the surface area of fluorocarbons is the BET extension for Langmuir monolayer adsorption. In this method, a monolayer of nitrogen is adsorbed on a known amount of solid. From the volume of nitrogen required and the cross-sectional area of the nitrogen molecule (15.8 $Å^2$) the surface area of the solid may be calculated (*9*). Since surface area is related to thickening action of a solid, the authors would predict the following order of utility for the TL's investigated: TL-120 > TL-102 > TL-126 > TL-103f > TL-125 > TL-115.

Critical surface tension is also related to thickening action. More importantly, it furnishes information on the behavior of fluorocarbon powders in oils and greases (as well as aerosols and resin binders). Liquids with surface tensions below the critical surface tension of TL solids will wet the surface and show a contact angle of 0-degree. The lower the surface tension of a lubricating fluid with respect to the critical surface tension of a solid powder, the greater the thickening action of the solid. Critical surface tension was determined from the contact angle of a drop of *n*-dodecane on a block of fluorocarbon powder compressed at 2,000 psi. This method probably de-emphasizes the difference in critical surface tension of the variation due to processing techniques—the compression destroys particle surface integrity (*5* and *6*).

The data collected suggest the thickening action is as follows: TL-120 > TL-125 > TL-102 > TL-103f > TL-126 > TL-115. Table 1 tabulates the data. Table 2 is a comparator of the critical surface tension of the fluorocarbons and other resins against lubricating fluids and other liquids often used with the TL's. It indicates that, as a whole, the TL's would appear to have poor thickening

Table 1—FLUOROCARBON LUBRICANT (TL) PROPERTIES

Designation	Units	TL-102	TL-103f	TL-115	TL-120	TL-125	TL-126
Polymer Base		PTFE	PTFE	PTFE	FEP	PTFE	PTFE
Specific Gravity		2.18 to 2.28	2.18 to 2.28	2.15 to 2.20	2.12 to 2.18	2.16 to 2.24	2.16 to 2.28
Particle Size	microns						
Micromerograph Maximum		17	28	34	16	32	24
90% below		13	18	20	10	20	16
50% below		5	8	10	2	10	8
Coulter Counter Maximum	microns	20	32	33	19	26	20
90% below		15	20	16	10	15	14
50% below		6	9	8	2	7	3
Scanning Electron Microscope	microns	3 to 8	8 to 30	6 to 25	1 to 2	8 to 25	6 to 25
Fisher subsieve Sizer	microns	1 to 2	1 to 4	1 to 4	<1	1 to 4	1 to 3
Surface Area	meters²/gram	7.6	5.3	1.2	10.1	2.1	6.5
Coefficient of Friction		0.06 to 0.08	0.07 to 0.11	0.08 to 0.14	0.07 to 0.10	0.08 to 0.12	0.06 to 0.012
Critical Surface Tension	dynes/cm	20.9	20.7	19.4	21.9	21.5	20.2
Bulk Density (Uncompacted)	grams/liter (±25 g/l)	425	525	475	400	425	400
Useful Temperature Range	°F	−400 to +500	−400 to +500	−400 to +500	−400 to +450	−400 to +500	−400 to +500
Oil Absorption Number	lbs oil/lbs TL	40.9	43.9	34.7	47.3	44.4	38.4

TABLE 2—SURFACE TENSION COMPARISON

Solid Polymer	Critical Surface Tension dynes/cm	Liquid Surface Tension dynes/cm	Liquid
		9.0	dichlorodifluoromethane
		12.5	dichlorotetrafluoroethane
		16.2	methyl chloride
		16.0–16.7	perfluoroalkylethers low MW
		17.3	carbon tetrachloride
		17.3	trichlorotrifluoroethane
		18.2	n-propyl chloride
		18.4	n-hexane
		17.7–18.5	perfluoroalkylethers medium MW
Polytetrafluoroethylene....	18.5		
		19.0	trichlorofluoromethane
		19.3–20	perfluoroalkylethers high MW
TL 115 PTFE...........	19.4		
		19.7	n-butylamine
		19.9	polydimethylsiloxane (pentamer)
TL 126 PTFE...........	20.2		
		20.4	n-heptane
		20.7	t-butanol
TL 103 PTFE...........	20.7		
TL 102 PTFE...........	20.9		
		21.2	acetaldehyde
TL 125 PTFE...........	21.5		
		21.8	n-octane
TL 120 FEP.............	21.9		
		22.3	ethanol
		22.6	methanol
		24.0	n-decane
Polytrifluoroethylene......	25.0		
		25.2	trifluoropropylmethylpolysiloxane
		25.4	n-dodecane
		26.5	methylene chloride
		26.7	n-tetradecane
Polyvinylfluoride.........	28.0		
		28.8	benzene
		30–32	400 MW mineral oil
Polyethylene.............	31.0		
Polychlorotrifluoroethylene.	31.0		
		32.3	carbon disulfide
Polystyrene..............	33.0		
Polyvinyl Alcohol.........	37.0		
Polyvinyl Chloride........	39.0		
Nylon 11................	39.0		
		72.5	water

action with mineral oils, nominal thickening action with nonfluorinated silicones, and appreciable thickening action with fluorinated compounds.

Oil absorption number provides a direct test for the relative absorbtion action of TL's. Critical surface tension and surface area generate useful, but in many instances inconclusive, data which oil absorption tests can resolve. This method (ASTM D-1483) involves titration of linseed oil onto a known amount of TL until free oil appears. The number is reported as pounds of oil per 100 lbs of TL. Both critical surface tension and surface area indicate that TL-120 and TL-115 would have the greatest and least thickening action respectively. This is supported by oil absorption data in Table 1. One unusual result is the relatively high thickening action of TL-125. Surface area measurements suggest poor results but actual results show high sensitivity to critical surface tension.

These data suggest that the utility of various TL's in grease compositions would be TL-120 > TL-125 > TL-103f > TL-102 > TL-126 > TL-115. This order is affected by the volume of material tested. In this method of evaluation, TL-102, for example, is present in larger volume than TL-103f, although weights are the same. Bulk densities are reported in Table 1. At low levels of addition, bulk density is of lesser importance since intensive dispersion would give results dependent on actual particle density. At higher levels where process parameters are more important, bulk density as well as particle configuration, become more important. For these reasons, TL-102 should rise in our ranking and also, to a lesser degree, TL-126.

OIL CHARACTERIZATION

This investigation was limited to the study of only two base oils for use in the grease formulations. Both of the base oils, a trifluoropropylmethyl polysiloxane and a perfluoroalkyl ether, are high density materials, the ether having the higher density of the two. The ether, also, has the higher viscosity. These oils were selected on the basis of their predicted response to thickening of the PTFE and FEP powders. The distinguishing characteristics of these base oils are given in Table 3.

GREASE CHARACTERISTICS

In the preparation of the greases, the base oil and thickener were intimately mixed, and final dispersion was accomplished by milling for six passes on a high speed three-roll mill equipped with dual hydraulic roll adjustment and pressure equalizers. Milling was conducted at 150 psi pressure on the back roll and 175 psi on the front roll.

The six TL thickeners were used in 30 percent concentrations with the perfluoroalkyl ether base oil. The consistencies of these greases ranged from 233 to 260 ASTM penetrations (NLGI Grade 3), the penetration of the greases being the depth in tenths of a millimeter that a standard cone penetrates the sample under prescribed conditions of weight, time, and temperature. Upon working for 10,000 double strokes, consistencies of the greases were from 262-290 (NLGI Grade 2). This working only subjects the grease to the shearing action of the standard grease worker. TL-103f and TL-115 yielded greases with the greatest change in consistency on working. These two also had the highest total oil separation at 400 F. This was predicted earlier by surface area and critical surface tension data. Steel-on-steel wear and dropping point data did not indicate any significant differences among this class of greases. These data are given in Table 4.

TABLE 3—OIL CHARACTERISTICS

	TRIFLUORO-PROPYLMETHYL POLYSILOXANE	PERFLUORO-ALKYL ETHER
Density, g/cc @ 77 F	1.2160	1.9050
Surface Tension, dynes/cm @ 77 F	25.2	17.9
Pour Point, °F	−65	−30
Viscosity @ 0 °F	1,880	33,000
Viscosity @ 100 F	75.4	279.0
Viscosity @ 210 F	14.5	26.3

Greases were prepared from the trifluoropropylmethyl polysiloxane oil and five of the six thickeners. Thirty-five percent thickeners produced greases with ASTM penetrations ranging from 313 to 342 (NLGI Grade 1). Only TL-115 failed to produce a grease in concentrations as high as 40 percent. Four of the five greases had penetrations ranging from 303 to 339 after 10,000 strokes of working. The grease prepared from TL-103f softened to a 380 penetration (NLGI Grade 0). These results were also predicted by surface area and critical surface tension data. The TL-102 grease showed a significantly stiffer consistency after 10,000 strokes of working. These data are shown in Table 5.

Formulated greases employing antimony dialkyldithiacarbamate as an extreme-pressure antiwear additive were prepared from the trifluoropropylmethyl polysiloxane to demonstrate the performance potential of one class of grease utilizing the PTFE and FEP thickeners. Only TL-115 failed to produce a grease. All of the other thickeners except TL-103f showed similar thickening efficiency. TL-103f produced a slightly softer consistency. TL-102 and TL-125 greases showed similar high temperature performance characteristics in 20-mm bearings when tested in accordance with FTMS 791-333. Their average performance was 700 to 800 hours. Performance lives of all other greases ranged from 1,300 to 1,500 hours. Table 6 shows these data.

SUMMARY AND CONCLUSIONS

The stability or instability of greases produced from perfluoroalkyl ether and trifluoropropylmethyl polysiloxane oils thickened by PTFE or FEP thickeners were predicted in this study. The predictions were based on surface

TABLE 4—PERFLUOROALKYL ETHER GREASES

	A	B	C	D	E	F
Perfluoroalkyl ether fluid, %	70	70	70	70	70	70
TL-102, %	30					
TL-103f, %		30				
TL-120, %			30			
TL-125, %				30		
TL-115, %					30	
TL-126P						30
Penetration, 0 stroke, mm/10 @ 77 F	240	239	233	235	260	238
Penetration, 60 strokes, mm/10 @ 77 F	257	275	260	242	279	257
Penetration, 10,000 strokes, mm/10 @ 77 F	266	285	262	262	290	273
Dropping Point, °F	397	355	411	360	385	391
Oil Separation, 30 hrs @ 400 F, %	12.1	17.0	12.6	14.3	18.8	12.3
Oil Separation, 30 hrs @ 450 F, %	16.5	20.7	19.9	19.6	18.6	16.5
4-Ball Wear, mm*	0.91	0.97	0.89	0.93	0.99	0.92

* 1,200 rpm, 450 F, 40 kg, 2 hrs, M-10 steel.

TABLE 5—TRIFLUOROPROPYLMETHYL POLYSILOXANE GREASES

	G	H	I	J	K	L
Trifluoropropylmethyl polysiloxane fluid, %	65	65	65	65	60	65
TL-102, %	35					
TL-103f, %		35				
TL-120, %			35			
TL-125, %				35		
TL-115, %					40	
TL-126P, %						35
Penetration, 0 stroke	328	342	313	309	400+	332
Penetration, 60 strokes	322	367	335	324	400+	335
Penetration, 10,000 strokes	303	380	339	318	400+	328
Dropping Point, °F	464	404	449	425	...	476
Oil Separation, 30 hrs @ 400 F, %	18.3	19.4	19.8	18.3	...	18.4
Oil Separation, 30 hrs @ 450 F, %	22.4	24.8	26.3	26.4	...	25.5
4-Ball Wear, mm*	1.61	1.67	1.62	1.63	...	1.69

* 1,200 rpm, 450 F, 40 kg, 2 hrs, M-10 steel.

TABLE 6—FORMULATED TRIFLUOROPROPYLMETHYL POLYSILOXANE GREASES

	M	N	O	P	Q	R
Trifluoropropylmethyl polysiloxane fluid, %	62	62	62	62	62	62
TL-102	33					
TL-103f		33				
TL-120			33			
TL-125				33		
TL-115					33	
TL-126P						33
Antimony dialkyldithio carbamate, %	5	5	5	5	5	5
Penetration, 0 stroke, mm/10 @ 77 F	298	330	384	300	400+	304
Penetration, 60 strokes, mm/10 @ 77 F	311	346	313	303	400+	311
Penetration, 10,000 strokes, mm/10 @ 77 F	310	345	315	310	400+	311
Dropping point, °F	412	391	426	388	...	426
Oil Separation, 30 hrs @ 450 F, %	23.5	29.5	25.6	26.3	...	25.1
4-Ball Wear, mm*	0.91	1.19	1.14	1.19	...	1.24
4-Ball Wear, mm†	1.55	1.46	1.38	1.49	...	1.37
4-Ball Wear, mm‡	1.25	0.67	1.00	1.15	...	0.98
High Temperature Performance Hours§	795	1550	1325	685	...	1495

* 1,200 rpm, 450 F, 40 kg, 2 hrs, M-10 steel.
† 1,200 rpm, 450 F, 40 kg, 2 hrs, 440C stainless steel.
‡ 1,200 rpm, 167 F, 40 kg, 2 hrs, 52–100 steel.
§ 10,000 rpm, 450 F, 5 lbs, 20 hours per day.

area, critical surface tension, particle size, and oil absorption data on the thickeners, and surface tension data on the base oils. It was predicted that the most stable greases would be produced from the TL solids having the smallest particle size, the highest oil absorption and surface area, and the highest critical surface tension with respect to the surface tension of the oil. TL-120 fluorinated ethylene-propylene was found to be the most exemplary of the TL materials in regard to these parameters. The reverse was true of TL-115. Based on grease consistency and retention of consistency during shearing, greases prepared from TL-120, TL-125, and TL-102 were the most stable while those prepared from TL-115, TL-103f, and TL-126 were the least stable. The experimental thickening characteristics of the TL powders as determined by ASTM penetration versus predictions of thickening by surface area, critical surface tension, and oil absorption are ranked in descending order in Table 7. There is some agreement between the experimental results and the predictions when the parameters are examined individually. When all of the parameters are considered collectively, there is very close agreement between the theoretical predictions and the experimental consistency results. These data show that the thickening characteristics of at least one class of solids are related to the surface characteristics, surface area, critical

TABLE 7—RANKING OF TL POWDER THICKENING CHARACTERISTICS, EXPERIMENTAL VERSUS THEORETICAL

Surface Area	Critical Surface Tension	Oil Absorption	Consensus	Penetration
TL-120	TL-120	TL-120	TL-120	TL-120
TL-102	TL-125	TL-125	TL-125	TL-125
TL-126	TL-102	TL-103f	TL-102	TL-102
TL-103f	TL-103f	TL-102	TL-103f	TL-126
TL-125	TL-126	TL-126	TL-126	TL-103f
TL-115	TL-115	TL-115	TL-115	TL-115

surface tension, and oil absorption. Similar investigations can be conducted to determine if these findings are true for other classes of grease thickeners.

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