NASA CR-159428

FINAL REPORT

on

DETERMINATION OF LUBRICANT SELECTION BASED ON ELASTOHYDRODYNAMIC FILM THICKNESS AND TRACTION MEASUREMENT

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

and

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ABSTRACT

The project was conducted to aid in the development of an elastohydrodynamic specification for military lubricants. Experiments were conducted with a rolling disk apparatus designed to simulate a bearing or gear type contact. Measurements included lubricant film thickness, lubricant breakdown and traction for a range of loads, speeds, temperatures, and surface roughnesses. Several lubricants were used in the investigations including a traction fluid, two synthetic paraffinic lubricants and several lubricants conforming to MIL-L-7808 and 23699 specifications. Recommendations regarding an EHD specification are included.

SUMMARY

The objective of the project has been to conduct a series of experiments to aid in defining a lubricant-performance input to a military specification. The first task of the project was directed toward defining lubricant-performance criteria while the later tasks were directed toward definitive performance experiments.

Defining Lubricant Performance Factors

Three lubricant-performance factors as applied to bearings or gears were evaluated.

1. (1) Elastohydrodynamic (EHD) film thickness
2. (2) Extent of metallic contact through the lubricant film
3. (3) The traction (frictional) characteristic of the lubricant.

These three factors were experimentally evaluated as a function of the operating condition, i.e., load, speed (with up to 50 percent slip), temperature, and surface roughness.

A compilation of film thickness data was developed using the X-ray technique for three lubricants: a synthetic mineral oil without additive (XRM 109), a mineral oil with additive (XRM 177), and a traction fluid. The film thicknesses have been found to be a predictable function of viscosity, velocity, load, and surface roughness (see Equation (2) of the text).

The percent film measurements indicate that typical bearings or gears will tend to operate either in a full film mode or a high metallic contact mode of lubrication. The dividing line between these two modes of lubrication occurs over a small range of film thickness. Full film lubrication occurs only when the surfaces are very smooth, and the viscosity of the lubricant is very high. If, on the other hand, the viscosity is low or the surfaces are rough, a high percentage of metallic contact will occur. If, for example, the ratio of film thickness to surface roughness is less than 3-4, significant evidence of metallic contact will occur. Equation (3) in the text would predict a 50 percent film for this condition.

Traction is a strong function of surface roughness as well as lubrication type and load. Traction measurements are a good indicator of the lubricant behavior in the contact region.

To study the performance of currently qualified military lubricants, ten lubricants (six MIL-L-7808 and four MIL-L-23699 fluids) were evaluated using the three techniques discussed. Although none of the fluids evaluated had shown poor performance in service, there was scatter in the data indicating performance variations. A sample specification has been written for the characterization of lubricants based on their EHD lubricating characteristics.

DETERMINATION OF LUBRICANT SELECTION BASED ON ELASTOHYDRODYNAMIC FILM THICKNESS AND TRACTION MEASUREMENT

by

T. A. Dow, J. W. Kannel, and R. D. Stockwell

INTRODUCTION

Requirements for advanced air-breathing propulsion systems are continuously increasing in severity. These conditions are requiring continuous advancements in the areas of bearing materials, lubricants, and lubrication systems. One complication in the selection of appropriate lubricants is a general lack of lubricant performance data under real-engine operating conditions.

In recent years, significant progress has been made in the area of applied elastohydrodynamics (EHD) to the extend that EHD theory is now being used in many types of applications. One prime example is in the evaluation of fatigue life for aircraft jet engine bearings. In engine design, considerable effort is made to insure that the EHD film thickness is sufficiently thicker than the roughness of the bearing surfaces to optimize performance. EHD theory is also being used routinely in evaluating spacecraft and gyroscope bearings and is becoming an integral part of bearing cage dynamics analyses. Very recently, theoretical expressions for EHD film thickness have been incorporated into bearing design catalogs and are considered in evaluating other devices such as gears, traction drives, and cam followers. It is important, then, that a data-bank of EHD characteristics of lubricants be established to guide future bearing designs and lubricant selection.

The purpose of the research project at Battelle's Columbus Laboratories (BCL) has been to generate three types of EHD parameters:

(1) Film formation
(2) Film breakdown
(3) Traction-slip characteristics.

The end objective of the project is to yield input to aid in developing a specification for lubricants for engine bearing and gear applications which incorporates EHD considerations.

This report represents a summary of the BCL activities, conducted over a 3-year period toward this end objective. Essentially, this research was conducted in three major phases:

(1) Generation of film thickness and percentage of film data for three selected lubricants (XRM 109, XRM 177, and Santotrac 50) for a wide range of load, speed, slip temperature, and surface roughness conditions.

(2) Generation of traction data for XRM 109, XRM 177, and Santotrac 50 fluids.

(3) Experimental evaluation of several current engine lubricants which conform to the MIL-L-7808 or MIL-L-23699 specification using the techniques developed in (1) and (2).

EXPERIMENTAL PROCEDURES

Basic Apparatus

All of the experiments of the project were conducted on a twin disk apparatus. This apparatus is shown pictorially in Figure 1 and a photograph is given in Figure 2. Essentially the apparatus consists of two disks, each of which are driven by variable frequency induction motors. The shaft of the drive motors are integral with the disk drive shafts and are mounted in duplex ABEC-7 45 mm bearings. The electrical power to the motors is supplied by a variable frequency supply unit. During the course of the project, this frequency supply unit was modified to allow for different frequencies to be supplied to each disk at any preset frequency ratio. With the modified system disk speeds up to 20,000 rpm and continuously variable slip-ratios between the disks can be achieved.

The disk in all experiments were 36 mm in diameter. The upper disks contained a 140 mm crown so that an elliptically shaped contact region was formed between the disks. These disks were mounted on tapered stub-shafts which fit into the drive shafts. The upper disk surface was electrically isolated from its stub-shaft by means of an alumina sleeve between the disk and shaft, as shown in Figure 3. The lower stub-shaft contained four disks

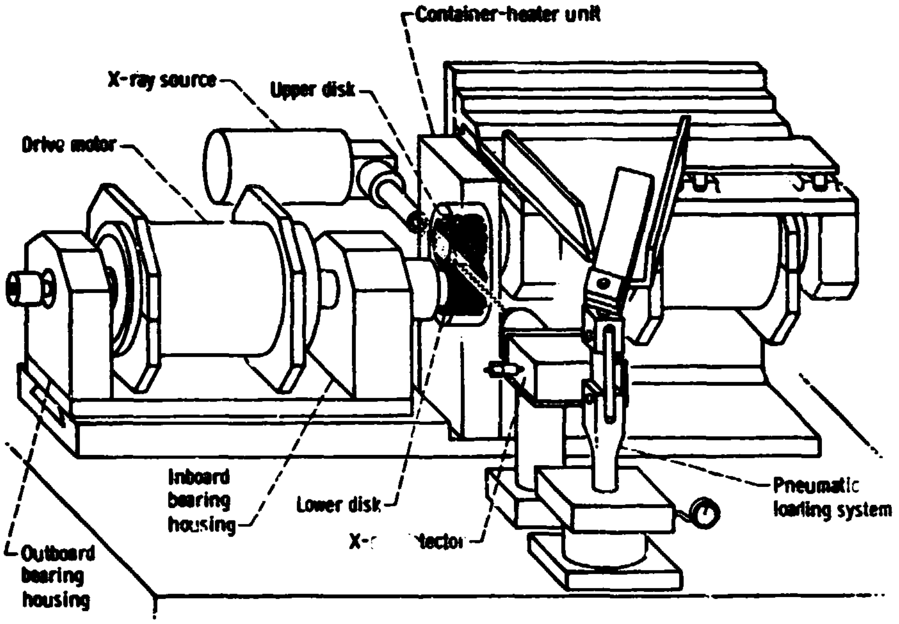

FIGURE 1. ROLLING-CONTACT DISK MACHINE

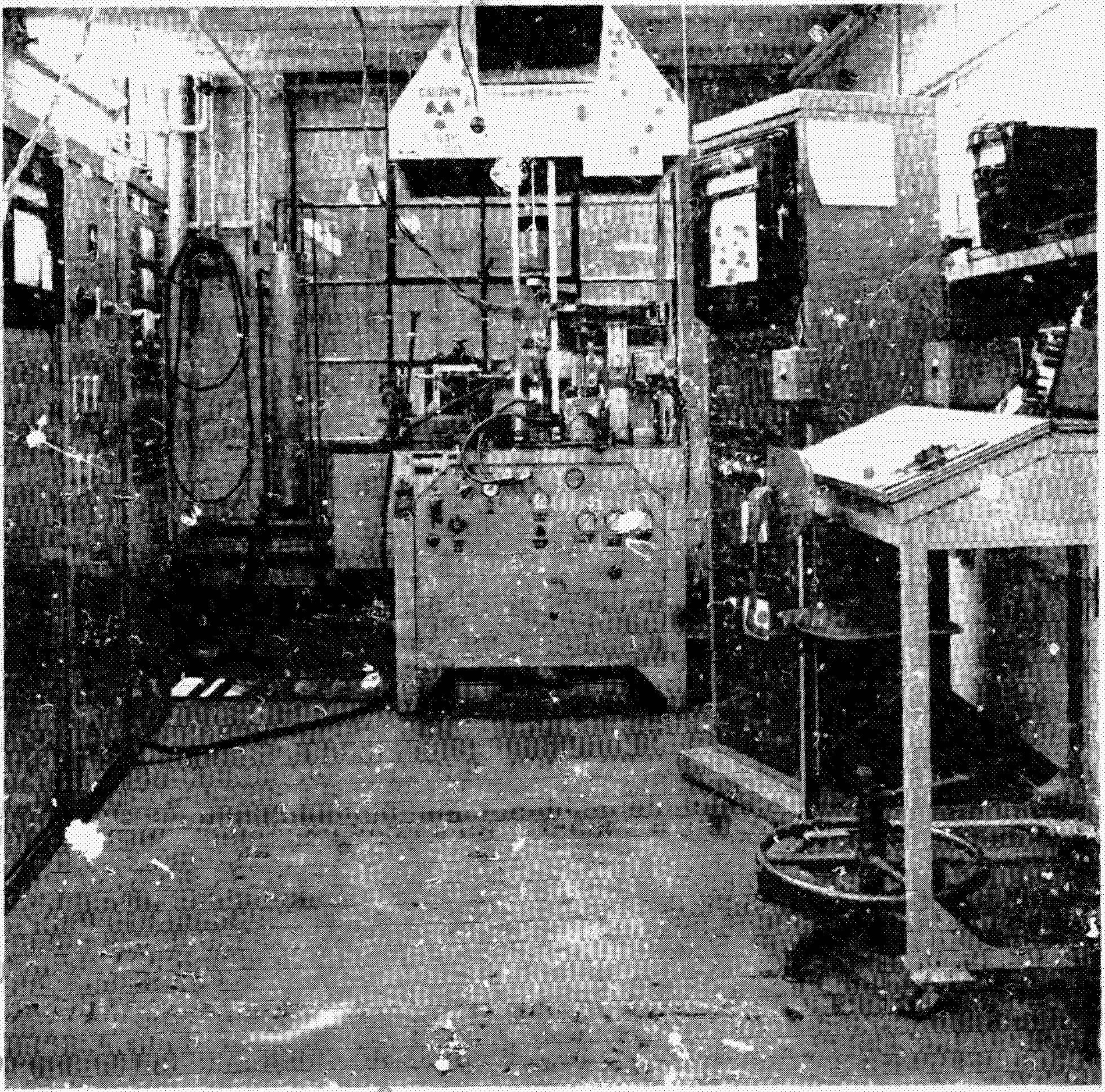

FIGURE 2. PHOTOGRAPH OF DISK APPARATUS

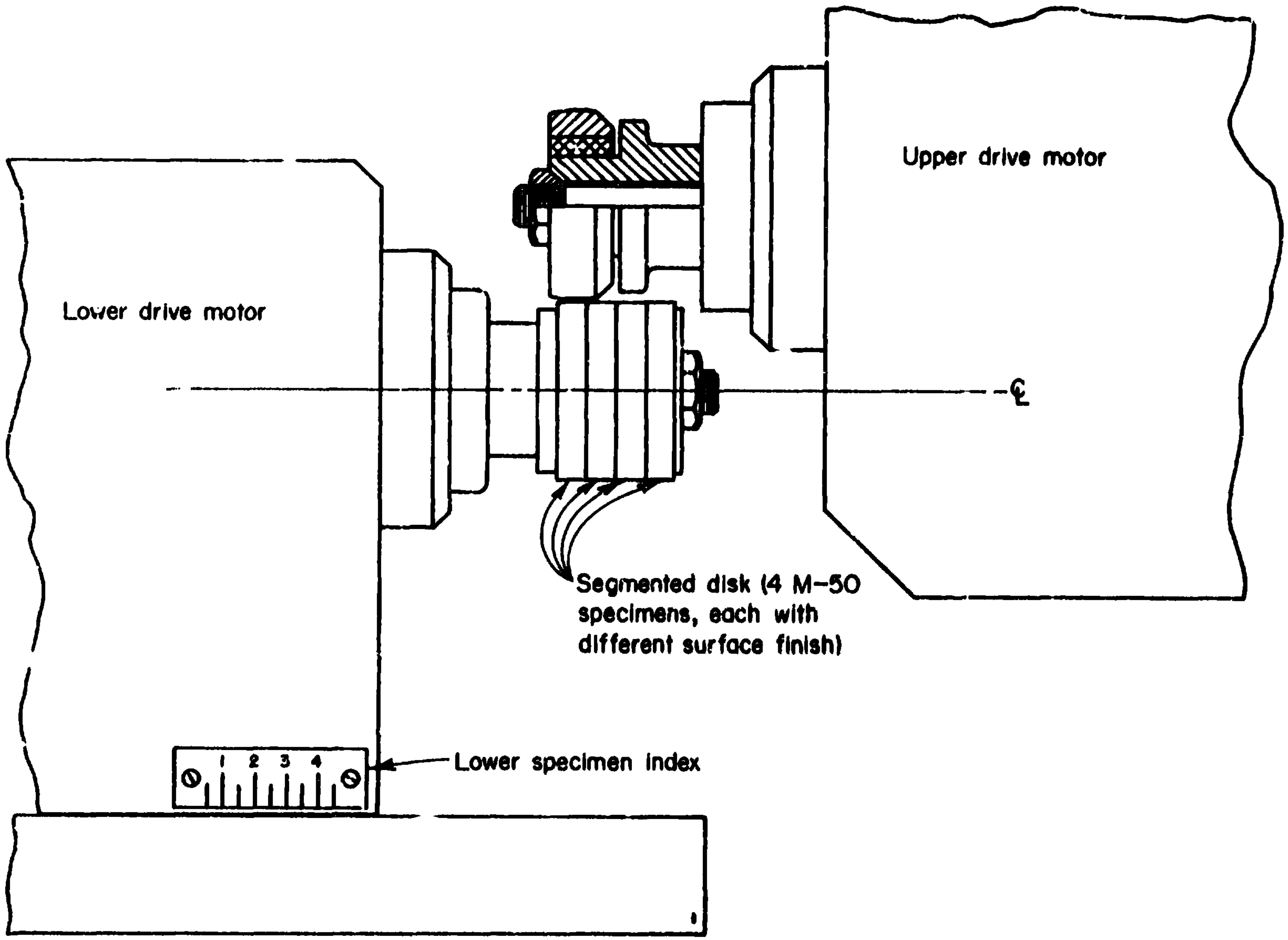

FIGURE 3. MULTIPLE DISK ARRANGEMENT PROPOSED FOR LUBRICANT-SURFACE FINISH EXPERIMENTS

which could be preferentially located under the upper disk. In some experiments, each of the lower disks had a different surface finish ranging from polished to 0.36 μm cla finish. Photographs of the disk stub-shaft arrangements are given in Figure 4. The method for finishing the disk is discussed in the next section.

Loading is achieved by a deadweight system with a mechanical advantage of approximately 12 (Figure 1). In the experiments, a pneumatic cylinder supports the load of the disks. This pneumatic arrangement also allows quick unloading of the disk when the experiments are terminated. The load-stress curve for the disk rig is given in Figure 5. As an example, a load 1000 N on the disks yields a contact stress 1.50 GPa (216,000 psi) and a contact ellipse with a half-width of 2.4×10^{-4} m (0.0096 inch) and a half length of 14.0×10^{-4} m (0.0566 inch).

Elevated temperature was achieved by means of a heat pipe on the disks and by preheating the lubricants being evaluated. Three temperatures were used in the experiments 65 C, 90 C, and 150 C. Both oil inlet and bulk disk temperature were monitored by standard thermocouples. For the disk temperature, the thermocouple was spot-welding to the upper disk and slip rings were used to transmit the signal from the rotating shaft. In the 65 C experiments, some increase in temperature (up to 70 C) normally occurred due to heating from the support bearings as well as from the disk contact region. For the higher temperature conditions, the disk temperature was within about 2 degrees of the desired value.

As shown in Figure 1 the upper disk support unit is on a hinge such that any tangential force originating at the disk contact region tends to swing the unit in the force direction. A load cell is used to constrain this motion and to monitor the magnitude of the force, as shown in Figure 6.

FIGURE 4. PHOTOGRAPH OF TYPICAL STUB SHAFT ARRANGEMENT OF LOWER DISKS

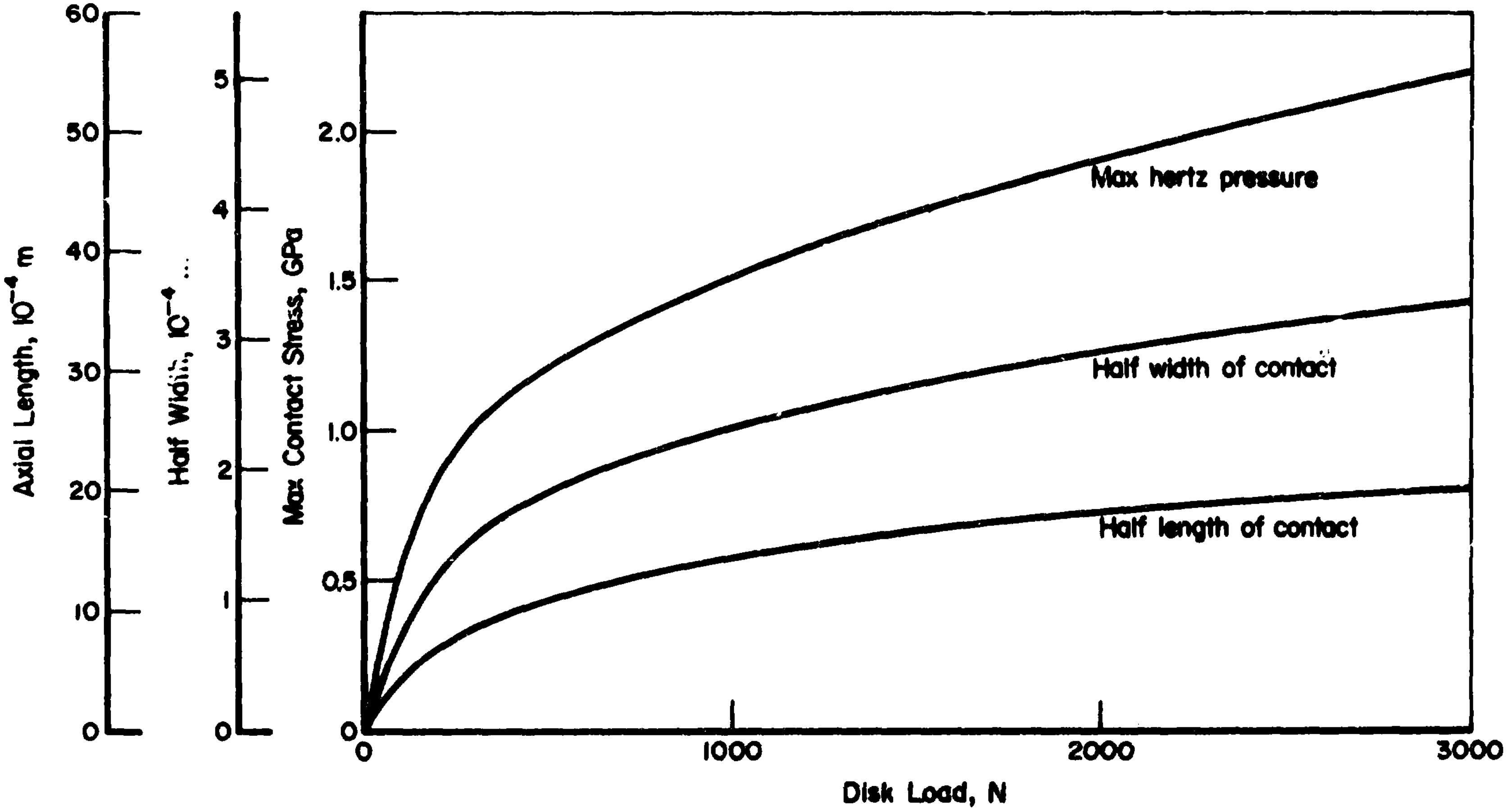

FIGURE 5. STRESS LOAD CHARACTERISTICS FOR BCL TWIN DISK APPARATUS

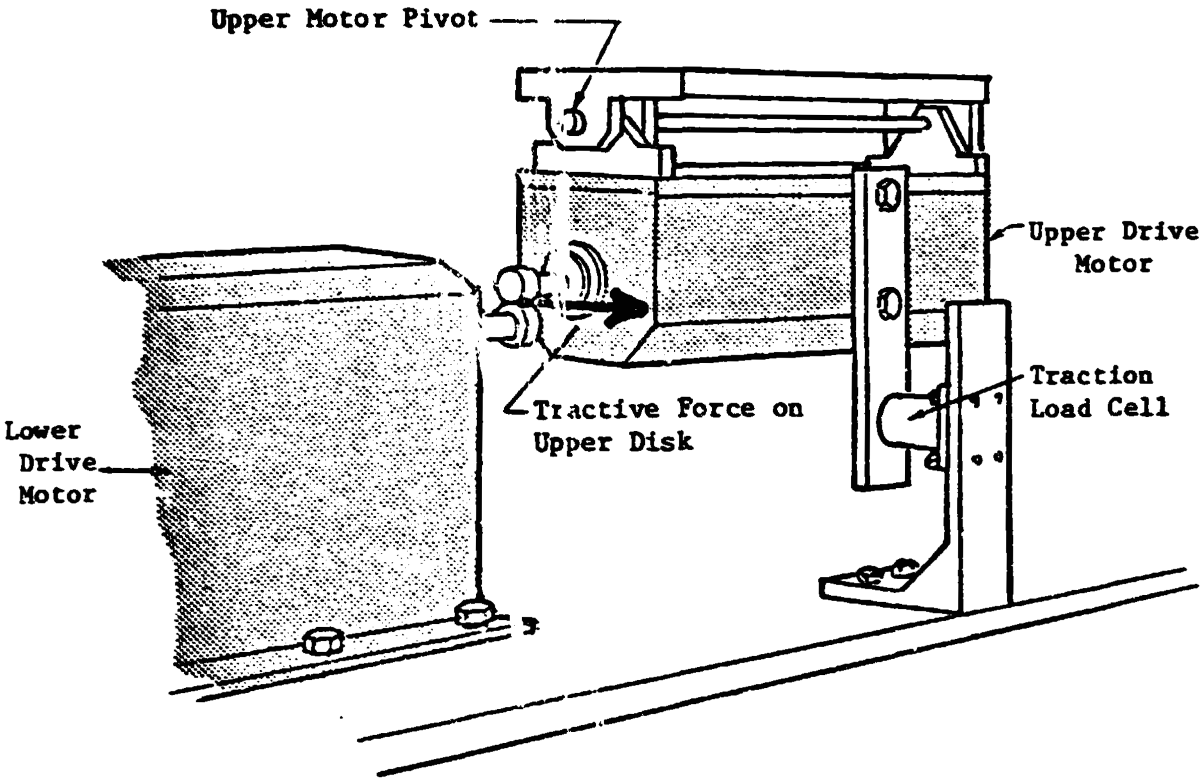

FIGURE 6. SCHEMATIC DRAWING OF DISK MACHINE ILLUSTRATING TRACTION MEASUREMENT

Preparation of Disk Surfaces

One major aspect of the experimental procedure was the preparation of the surface finish on the disk. During the experiment, five finishes were required as follows:

(1) Polished - .03 μm (1μin) cla

(2) Smooth-T - .15 μm (5-7 μin.) cla (transverse lay)

(3) Smooth-C - .15 μm (5-7 μin.) cla (circumferential lay)

(4) Rough - .33 μm (12-15 μin.) cla (transverse lay)

(5) Gear Finish - .54 μm (19-22 μin.) cla (transverse lay).

Since numerous disks were required, a reproducible method for preparing these surfaces was developed. The first step in the process was to polish the disks to generate an identical baseline finish. The surface for the polished lower disk was polished using a commercial cylindrical lap. The crown on the upper disk was lapped and polished on a pivot arm with a 140 mm (55 inch) radius. The polish was achieved with a felt pad bonded to the lap embedded with a diamond lapping compound.

After polishing each specimen, the specific finish was applied using the special fixture shown in Figure 7. This fixture consists of a drive unit for the disk stub shaft and a finishing wheel which is loaded against the disk. In the lapping process, commercial grit paper was cemented to the wheel. The following sequence was used to apply the desired surface roughness and lay:

(1) To achieve a circumferential lay finish, the disks were rotated in the fixture with the finishing wheel loaded onto the surface. This finish wheel was rotated much slower than the disk.

(2) To achieve a transverse lay finish, the disk was rotated very slowly while the finishing wheel was rotated at a faster rate. In the finishing operation, the disks were rotated a total of two revolutions.

(3) After finishing the disk finish was checked in a Talysurf and a log made of the information. All disks used were within the finish specification.

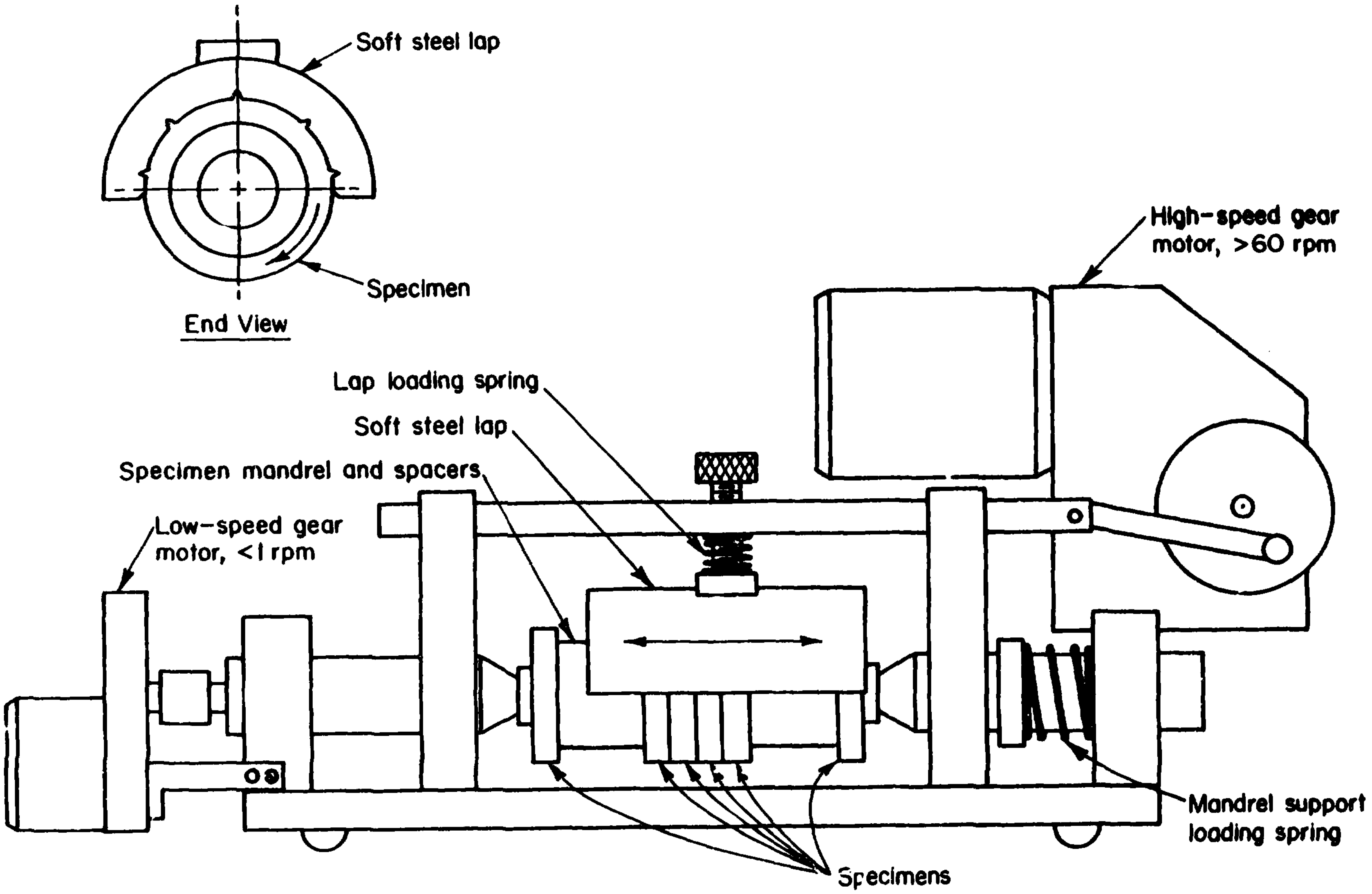

FIGURE 7. FIXTURE USED TO PREPARE SURFACE ROUGHNESS ON DISKS

In any experiment where a change in surface finish was suspected, the disks were retalysurfed and removed from service. As a result, the disks used in the experiments were available for inspection and further surface evaluation.

Instrumentation

Film Thickness Measurements

The disk machine is equipped with instrumentation to monitor several aspects of the disk contact zone phenomena. An X-ray technique is used to measure lubricant film thickness (See Figure 1). This technique has been described previously(1)* and consists of passing a collimated X-ray beam through the disk contact region and of monitoring the X-ray rate. Since the lubricants are much more transparent to the X-rays, than the steel disks, this X-ray transmission can be related to the film-gap between the disks. Calibration of the X-ray beam is achieved by spreading the disks apart by 2-½ to 5 μm and measuring the X-ray transmission for these known separations.

In addition to film thickness measurements with the X-ray technique, percent film measurements were made with an electrical continuity technique. For this technique, 100 mv a-c is applied across the lubricant film from the electrically isolated upper disks to the lower and the breakdown of the voltage measured. A block diagram of the percent film circuitry is shown in Figure 8. This circuit was adopted from a published circuit(2) and yields a value for percentage of lubrication.

Traction-Slip Instrumentation

As mentioned in the apparatus section, slip is induced between the disks by varying the electrical frequency to the upper disk drive motor. This slip is monitored by measuring the speed of each disk independently using magnetic pick-ups in conjunction with 60 tooth gears.

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* All references listed at the back of text on page 72.

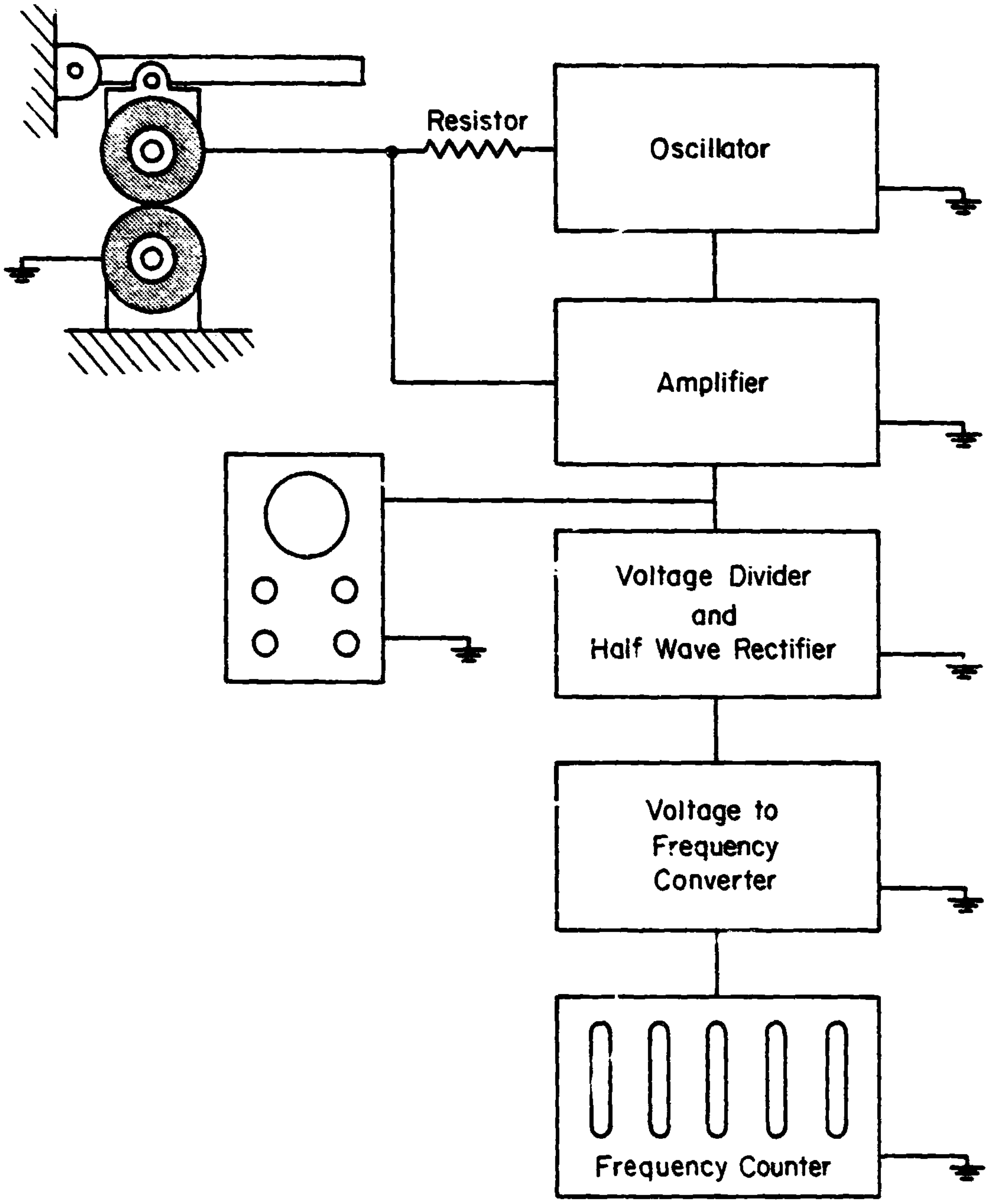


FIGURE 8. BLOCK DIAGRAM FOR CONTACT CONDUCTIVITY EXPERIMENTS

The output from the pick-ups are both fed into an electronic ratio meter which yields an electrical output proportional to percent slip.

Traction is detected by a commercial load-cell which senses the force required to constrain the upper disk support unit. The output from load cell transducer is fed into the y-axis of an x-y recorder, and the output from the speed ratio meter is fed into the x-axis.

In the traction experiments, the slip was varied continuously over a range from -5 percent to plus 25 percent, although a smaller range was used in the later lubrication specification experiments. Using the x-y recorder, this variation in slip produces a continuous traction-slip curve for the particular lubricant being evaluated.

Summary of Apparatus Capabilities

The BCL X-ray disk apparatus is an extremely versatile tool for evaluating applied elastohydrodynamic lubrication phenomena for a wide range of very practical conditions. Specifically, the following range of variables were used in the experiments:

- Loads - 0.7 GPa to 2 GPa
- Speeds - 5,000 rpm to 20,000 rpm
- Temperature - 65 C, 90 C, and 150 C
- Slip Conditions - up to 50 percent
- Surface Roughness - from polished (0.025 μm cla) to rough (0.33 μm cla) with lay either transverse or circumferential

The apparatus generated the following outputs:

(1) Lubricant film thickness

(2) Percent of lubricant film

(3) Traction between disk as a function of slip

(4) Worn disk surfaces for post-test visual examination

In general, then, the type of data from the disk apparatus should clearly define the EHD lubrication capability for a lubricant over a practical range of conditions. These data should, then, be sufficient to form the basis of a lubricant specification for MIL-spec lubricant.

FILM THICKNESS EXPERIMENTS

Discussion of Data

The first tasks of the project were directed toward compiling film thickness and percent film data for a range of conditions. Essentially the goal was to determine the effect on the EHD film thickness of

(1) Load
(2) Speed (including slip)
(3) Surface Roughness (including lay of finish)
(4) Temperature.

Three lubricants were used and their base viscosities are given in Table 1.

TABLE 1. LUBRICANT VISCOSITY DATA

Lubricant	Viscosity (Cp) T = 38 C	 T = 100 C
XRM 109 F	369	31.6
XRM 177 F	336	29.8
SANTOTRAC 50	29	4.8

Film thickness data are presented in Tables 2 through 11 and in Appendix A. The data are given in SI units. (To convert to English units, multiply μm by 39.3 to yield micro inches and GPa by 142,000 to get psi.) The data in the appendix are for the XRM 109 F and XRM 177 F lubricant for a wide range of conditions and form the background for the more specific data of Tables 2 through 11. In all cases the experiments were terminated when a percentage film reading of 15 to 20% were seen. In earlier experiments it was observed that this level of percent film would produce a noticeable surface change as shown in Figures 9 and 10.

As a result of these experiments, two general observations can be made:

(1) The film thickness for XRM-109F and XRM-177F are quite similar over the range of speeds, loads, and temperatures studied.

TABLE 2. FILM THICKNESS (μm) FOR XRM-109F AND MATING DISKS WITH SMOOTH SURFACES

Load, GPa	Film Thickness, μm											
	Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
	0	10	20	25	0	10	20	25	0	10	20	25
					65 C							
.75	1.7*	1.7	1.8	1.7	1.4	1.3	1.5	1.4	1.38	1.3	1.15	1.15
1.	1.2	1.1	1.2	1.2	1.1	1.1	1.1	1.0	1.2	1.1	1.1	1.1
1 4	1.2	1.1	1.0	1.0	0.9	0.85	0.8	0.75	0.9	0.7	0.7	0.7
					90 C							
.75	0.93	1.0	0.95	0.85	0.9	0.88	0.85	0.8	0.75	0.7	0.65	0.7
1.	1.0	0.93	0.9	0.9	0.88	0.83	0.85	0.85	0.75	0.8	0.75	0.75
1.4	0.56	0.53	0.53	0.50	0.73	0.7	0.6	0.6	0.68	0.65	0.63	0.53
					150 C							
.75	-	-	-	-	-	-	-	-	0.55	0.5	0.38	0.35
1.	0.4	0.45	0.43	0.4	0.48	0.43	0.45	0.45	0.35	0.33	0.33	0.33
1.4	0.45	0.4	0.38	0.35	0.35	0.3	0.35	0.35	0.3	0.28	0.28	0.26
1.75	-	-	-	-	-	-	-	-	-	-	-	-

* The percentage of film circuit showed no contact for any of these tests.

TABLE 3. FILM THICKNESS (μm) AND PERCENTAGE OF FILM DATA FOR XRM-109F AND MATING DISKS WITH 0.15 μm CLA CIRCUMFERENTIAL LAY FINISHED DISKS

Load, GPa	Speed, rpm											
	15,000 Slip, percent				10,000 Slip, percent				5,000 Slip, percent			
	0	10	20	25	0	10	20	25	0	10	20	25
						65 C						
1.	1.05* (100)	0.95 (100)	0.9 (100)	0.9 (100)	1.1 (100)	1.0 (100)	0.93 (100)	0.88 (100)	1.0 (100)	0.98 (100)	0.98 (100)	0.95 (100)
1.4	0.7 (100)	0.6 (100)	0.55 (67)	0.55 (55)	0.8 (100)	0.68 (100)	0.63 (78)	0.6 (52)	0.75 (100)	0.68 (95)	0.6 (75)	0.55 (55)
						90 C						
1.	0.93 (100)	0.9 (100)	0.88 (100)	0.88 (100)	0.78 (100)	0.75 (95)	0.73 (80)	0.73 (67)	0.65 (100)	0.58 (62)	0.48 (35)	0.48 (15)
1.4	0.68 (100)	0.65 (100)	0.58 (100)	0.58 (100)	0.6 (100)	0.58 (90)	0.48 (77)	0.48 (67)				
						150 C						
1.	0.48 (94)	0.45 (75)	0.45 (64)	0.43 (54)	0.38 (90)	0.35 (60)	0.35 (30)	0.35 (20)				
1.4	0.4 (88)	0.38 (65)	0.35 (52)	0.33 (50)								

*Film thickness (μm)
(percent film)

TABLE 4. FILM THICKNESS AND PERCENTAGE OF FILM DATA FOR XRM-109F AND MATING DISKS WITH 0.15 µm CLA TRANSVERSE LAY SURFACE FINISHES

	Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
GPa	0	10	20	25	0	10	20	25	0	10	20	25
					65 C							
1.	0.93* (100)	0.95 (100)	0.92 (100)	0.90 (100)	0.99 (100)	0.95 (100)	0.88 (100)	0.85 (100)	0.92 (100)	0.86 (100)	0.84 (100)	0.79 (100)
1.4	0.78 (100)	0.72 (100)	0.75 (100)	0.70 (100)	0.72 (100)	0.68 (100)	0.58 (100)	0.55 (100)	0.65 (100)	0.58 (100)	0.52 (100)	0.52 (100)
					90 C							
1.	0.73 (100)	0.65 (100)	0.65 (100)	0.62 (100)	0.75 (100)	0.68 (100)	0.66 (100)	0.66 (100)	0.45 (65)	0.40 (63)	0.38 (48)	0.35 (30)
1.4	0.5 (100)	0.42 (100)	0.39 (100)	0.35 (98)	0.41 (100)	0.34 (99)	0.28 (97)	0.25 (90)				
					150 C							
1.	0.35 (100)	0.30 (100)	0.30 (100)	0.30 (100)	0.3 (100)	0.3 (100)	0.28 (100)	0.25 (100)				
1.4	0.22 (100)	0.2 (97)	0.2 (93)	0.2 (90)	0.2 (90)	0.17 (65)	0.13 (55)	0.11 (25)				

*Film thickness (µm)
(percent film)

TABLE 5. FILM THICKNESS AND PERCENTAGE OF FILM DATA FOR XRM-109F AND MATING DISKS WITH 0.33 μm TRANSVERSE LAY SURFACE FINISHES

Load, MPa	Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
	0	10	20	25	0	10	20	25	0	10	20	25
					65 C							
1.	0.7* (100)	0.7 (100)	0.7 (100)	0.7 (100)	0.83 (100)	0.8 (100)	0.8 (100)	0.75 (100)	0.6 (100)	0.58 (100)	0.55 (100)	0.52 (100)
1.4	0.45 (100)	0.35 (98)	0.35 (95)	0.35 (90)	0.55 (100)	0.47 (98)	0.43 (90)	0.43 (75)				
					90C							
1.	0.55 (100)	0.5 (100)	0.45 (100)	0.55 (100)	0.52 (75)	0.50 (65)	0.48 (55)					
1.4	0.32 (100)	0.3 (96)	0.25 (84)	0.25 (82)	0.35 (96)	0.32 (55)	0.3 (37)	0.25 (19)				
					150 C							
1.	0.17 (86)	0.15 (74)	0.15 (51)	0.14 (36)	0.25 (100)	0.23 (100)	0.2 (100)	0.2 (100)				
1.4	0.24 (98)	0.20 (96)	0.17 (89)	0.17 (83)	0.15 (75)	0.12 (67)	0.1 (65)	0.1 (65)				

*Film thickness (μm)
(percent film)

TABLE 6. FILM THICKNESS (μm) AND PEPCENTAGE OF FILM DATA FOR XRM-177F AND MATING DISKS WITH SMOOTH SURFACES

Load, GPa	Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
	0	10	20	25	0	10	20	25	0	10	20	25
					65 C							
1.	1.3*	1.2	1.12	1.08	1.2	1.13	1.05	1.0	1.0	.97	.95	.90
1.4	1.10	1.05	.95	.90	1.2	1.15	1.05	1.0	.78	.76	.75	.75
					90 C							
1.	.90	.86	.78	.75	.75	.7	.60	.67	.60	.58	.55	.50
1.4	.8	.73	.65	.60	.75	.70	.65	.6	.55	.45	.40	.38
					150 C							
1.	.52	.50	.46	.43	.45	.42	.40	.38	.30	.27	.25	.25
1.4	.42	.4	.4	.38	.35	.33	.30	.28	.30	.27	.25	.23

*The percentage of film circuit showed no contact for any of these tests.

TABLE 7. FILM THICKNESS AND PERCENTAGE OF FILM DATA FOR XRM-177F AND MATING DISKS WITH 0.15 μm CLA CIRCUMFERENTIAL LAY FINISH

Load, GPa	Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
	0	10	20	25	0	10	20		0	10	20	25
					65 C							
1.	1.0* (100)	.97 (100)	.90 (100)	.80 (100)	1.0 (100)	.95 (100)	.85 (100)	.80 (100)	.80 (100)	.75 (98)	.70 (92)	.60 (80)
1.4	.88 (100)	.80 (100)	.72 (100)	.66 (100)	.92 (100)	.82 (100)	.75 (98)	.70 (98)	.7 (96)	.67 (90)	.63 (50)	.60 (25)
					90 C							
1.	.8 (98)	.75 (95)	.72 (92)	70 (80)	.75 (97)	.74 (93)	.72 (75)	.70 (60)	.5 (97)	.46 (93)	.42 (82)	.41 (63)
1.4	.60 (98)	.60 (96)	.52 (85)	.49 (72)	.60 (96)	.52 (96)	.48 (90)	.40 (77)				
					150 C							
1.	.40 (93)	.36 (90)	.30 (80)	.28 (70)	.30 (96)	.30 (96)	.22 (80)	.20 (70)	.21 (62)	20 (78)	.20 (70)	.19 (70)
1.4	.25 (90)	.25 (68)	.23 (55)	.20 (55)	.26 (93)	.25 (91)	.23 (82)	.21 (76)				

*Film thickness (μm)
(percent film)

TABLE 8. FILM THICKNESS AND PERCENTAGE OF FILM DATA FOR XRM-177F AND MATING DISKS WITH 0.15 μm CLA TRANVERSE LAY FINISH

Load, GPa	Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
	0	10	20	25	0	10	20	25	0	10	20	25
					65 C							
1.	.80* (100)	.75 (100)	.70 (99)	.65 (94)	.85 (100)	.77 (100)	.72 (95)	.65 (80)	.58 (97)	.56 (92)	.54 (76)	.52 (52)
1.4	.72 (100)	.67 (98)	.57 (73)	.50 (45)	.72 (94)	.67 (87)	.57 (49)	.54 (33)				
					90 C							
1.	.63 (94)	.58 (64)	.53 (47)	.5 (38)	.55 (100)	.52 (98)	.5 (93)	.49 (86)	.4 (96)	.38 (70)	.33 (55)	.32 (40)
1.4	.40 (93)	.33 (55)	.25 (37)	.21 (25)	.51 (98)	.48 (80)	.42 (44)	.39 (28)				
					150 C							
1.	.40 (93)	.37 (72)	.31 (52)	.29 (42)	.35 (85)	.31 (50)	.29 (40)	.27 (27)				
1.4												

*Film thickness (μm)
(percent film)

TABLE 9. FILM THICKNESS AND PERCENT FILM DATA FOR XRM-177F AND MATING DISKS WITH 0.3 µm TRANSVERSE LAY FINISH

Load, GPa	15,000				10,000			
	Slip, percent				Slip, percent			
	0	10	20	25	0	10	20	25
				65 C				
1.	.60* (92)	.52 (80)	.50 (50)	.45 (41)	.65 (80	.56 (32)	.53 (28)	.50 (25)
1.4	.45 (62)	.35 (25)						
				90 C				
1.	.45 (94)	.40 (69)	.38 (35)	.30 (15)				

*Film thickness (µm)
(percent film)

TABLE 10. FILM THICKNESS AND PERCENTAGE OF FILM DATA FOR SANTOTRAC 50 AND ROUGHENED DISKS AT 65 C

Load, GPA	Disk Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
	0	10	20	25	0	10	20	25	0	10	20	25
	Circumferential Lay Finish (0.15 µm cla)											
1.0	.29** (61)	.24 (55)	.19 (44)	.15 (43)	.22 (63)	.17 (46)	.13 (41)	.11 (35)	.21 (30)	.19 (20)	.18 (19)	.16 (14)
1.4	.23 (67)	.18 (59)	.13 (55)	.10 (52)	.19 (50)	.15 (47)	.10 (45)	.07 (44)	.14 (39)	.12 (33)	.10 (23)	.08 (13)
	Transverse Lay Finish (0.15 µm cla)											
1.0	.34 (30)	.28 (19)	.18 (10)	.14 (7)								
1.4												
	Transverse Lay Finish (0.30 µm cla)											
1.0	.30* (60)	.25 (56)	.20 (45)	.18 (45)								
1.4												

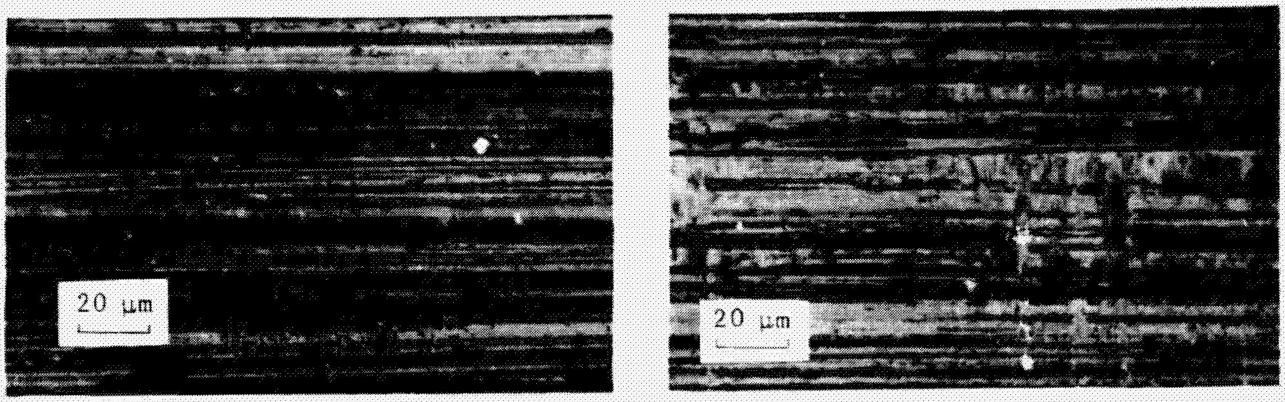
* Both mating disks were obviously worn after this run so the accuracy of the data is questionable.

** Film Thickness - (µm)
(Percentage of Film)

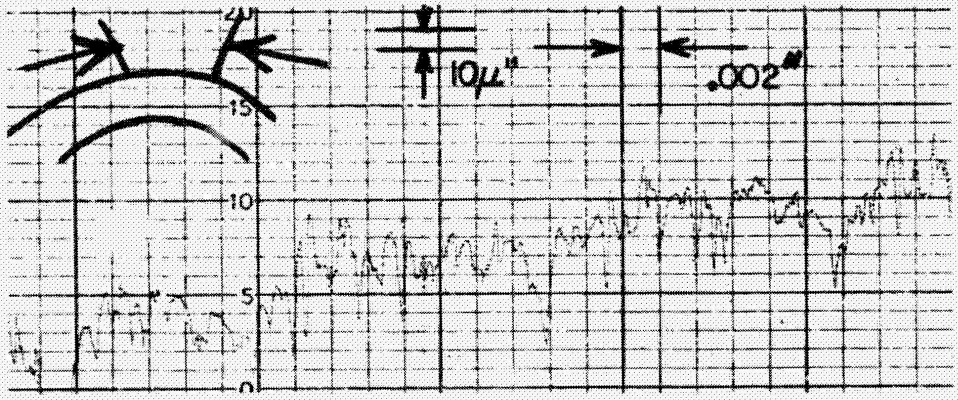
TABLE 11. FILM THICKNESS AND PERCENTAGE OF FILM DATA FOR SANTOTRAC 50 FLUID AND MATING DISKS WITH SMOOTH SURFACES

	Disk Speed, rpm											
	15,000				10,000				5,000			
	Slip, percent				Slip, percent				Slip, percent			
Load, GPa	0	10	20	25	0	10	20	25	0	10	20	25
					65 C							
1.0	.35* (100)	.30 (100)	.28 (100)	.26 (98)	.35 (98)	.33 (97)	.32 (95)	.30 (90)	.25 (98)	.23 (91)	.21 (71)	.20 (45)
1.4	.27 (100)	.25 (96)	.20 (63)	.18 (22)	.25 (97)	.20 (94)	.18 (51)	.16 (18)	.15 (97)	.14 (72)	.13 (21)	.12 (5)
					90 C							
1.0	.28 (100)	.24 (95)	.21 (92)	.18 (89)	.23 (100)	.22 (98)	.20 (95)	.19 (90)	.23 (98)	.19 (88)	.18 (63)	.16 (45)
1.4	.30 (100)	.25 (92)	.23 (72)	.20 (28)	.23 (100)	.19 (89)	.12 (44)	.09 (23)				
					150 C							
1.0	.16 (90)	.13 (72)	.12 (54)	.11 (51)	.18 (63)	.17 (34)	.16 (25)	.16 (18)				
1.4												

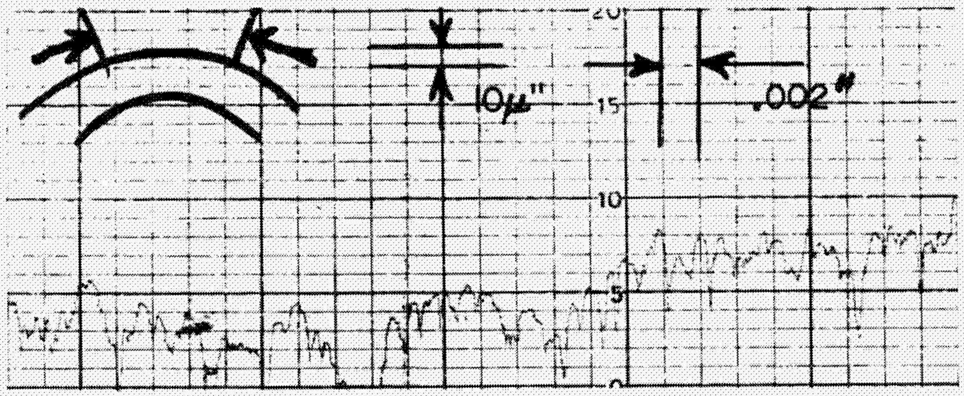
* Film Thickness - (μm)
(Percentage of Film)



a. Surface before experiment. b. Surface after experiment.



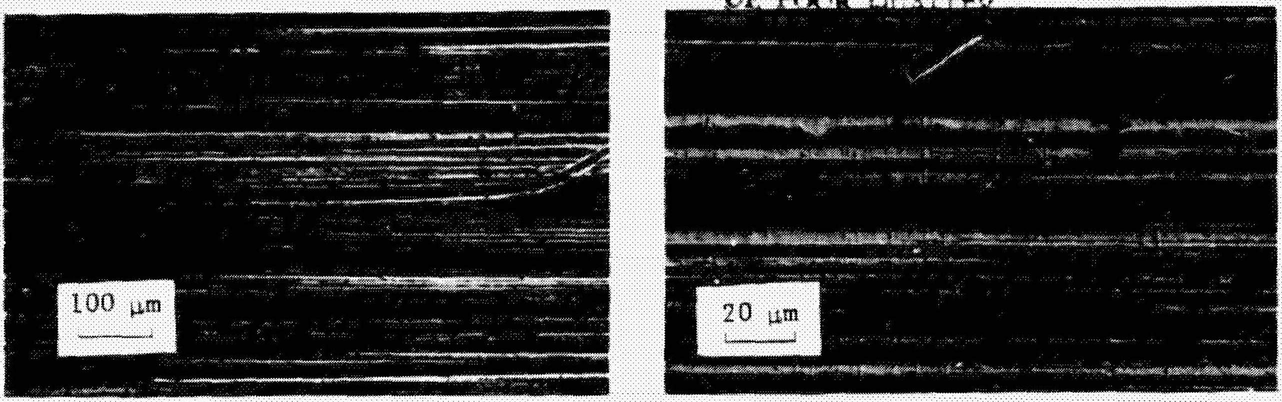
c. Surface profile before experiment (0.36 µm, cla.).



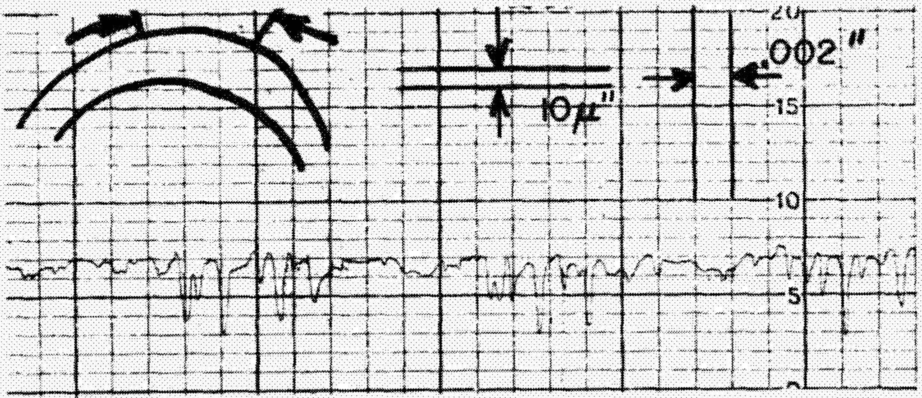
d. Surface profile after experiment (0.31 µm, cla.).

FIGURE 9. MICROGRAPH AND SURFACE TRACE OF MEDIUM LOWER DISK SURFACE BEFORE AND AFTER ROLLING/SLIDING EXPERIMENT

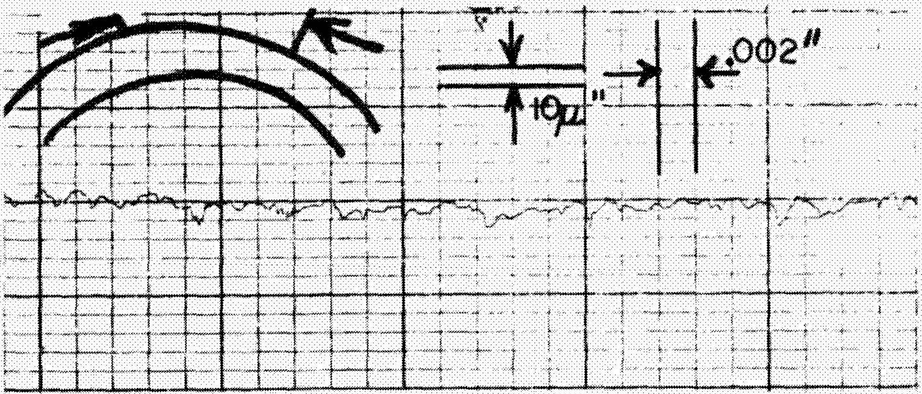
Test Conditions: Maximum Hertz stress = 0.689 GPa (100 ksi)
Lower disk: speed = 10,000 rpm
Upper disk: speed = 7500 rpm, roughness = 0.15 µm
Lubricant temperature: 339 K (150 F)
Film thickness (µm)/percentage of film = 0.13/10



a. Surface after experiment. b. Surface after experiment.



c. Surface profile before experiment (0.28 µm, cla.).



d. Surface profile after experiment (0.20 µm, cla.).

FIGURE 10. MICROGRAPH AND SURFACE TRACE OF LOWER DISK SURFACE AFTER ROLLING/SLIDING EXPERIMENT

Test Conditions: Maximum Hertz stress = 0.689 GPa (100 ksi)
Upper disk: speed = 3750 rpm, roughness = 0.30 µm
Lower disk: speed = 5000 rpm
Lubricant temperature: 422 K (300 F)
Film thickness (µm)/percentage of film = 0/0

(2) The percentage of film for the additive-free XRM-109 was significantly less than for the XRM-177 which contains an additive package. Under high-slip, high-temperature conditions (150 C) where extremely thin films were measured with either oil, the percent film was nearly 100 percent for the 177, but zero for the 109.

Increasing the slip causes only a slight drop in film thickness for the 109 or 177 lubricant. This drop is due to two effects:

(1) A net decrease in total rolling speed

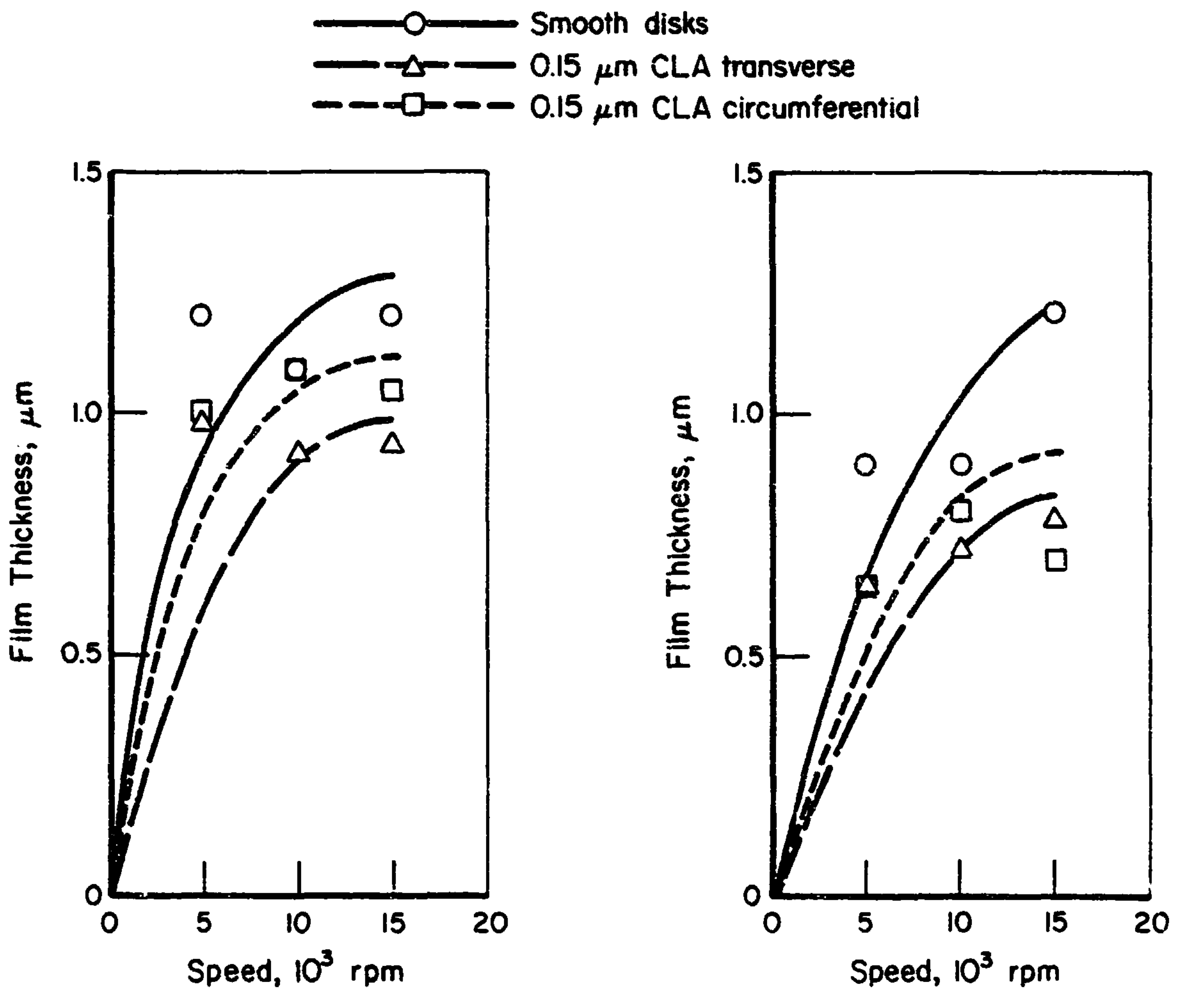
(2) A slight increase in temperature.

For the Sanotrac 50 fluid the film thickness decreased significantly with slip indicating a very large temperature rise with this fluid under slip conditions. Such a temperature rise would be expected as a result of the high tractions associated with fluid. (Tractions are discussed later in the report.) In addition, surface temperature measurements (3) made at BCL showed very high temperatures with the Santotrac fluid.

Graphs showing measured film thickness as a function of speed for two loads (1 and 1.4 GPa contact stress), two temperatures (65 C and 90 C), and three types of roughness (smooth, 0.15 μm cla circumferential lay, and 0.15 μm cla transverse lay) are given in Figures 11 through 15 for the three lubricants. As can be observed the amount of increase in film thickness with speed drops considerably at the highest speed condition and, in some cases, (at 15,000 rpm) a slight drop in film thickness occurs. This is most likely due to a temperature rise resulting from high speed shearing of the lubricant. In many cases, it was literally impossible to maintain the target equilibrium temperature at the high speed condition especially for the high speed experiments.

In all cases the film thickness data associated with the rough (0.15 μm cla) disk were less than the smooth disk data. This film thickness reduction was roughly on the order of magnitude of the combined surface roughness of the two disks. One very interesting feature of the data is that the film thickness associated with the circumferential lay finish was always thicker than with the transverse lay finish. This effect was further substantiated by the indications of metallic contact using the percent-film measurements. In the case of the traction fluid only a very meager amount of data could be obtained with the transverse lay finish due to excessive contact.

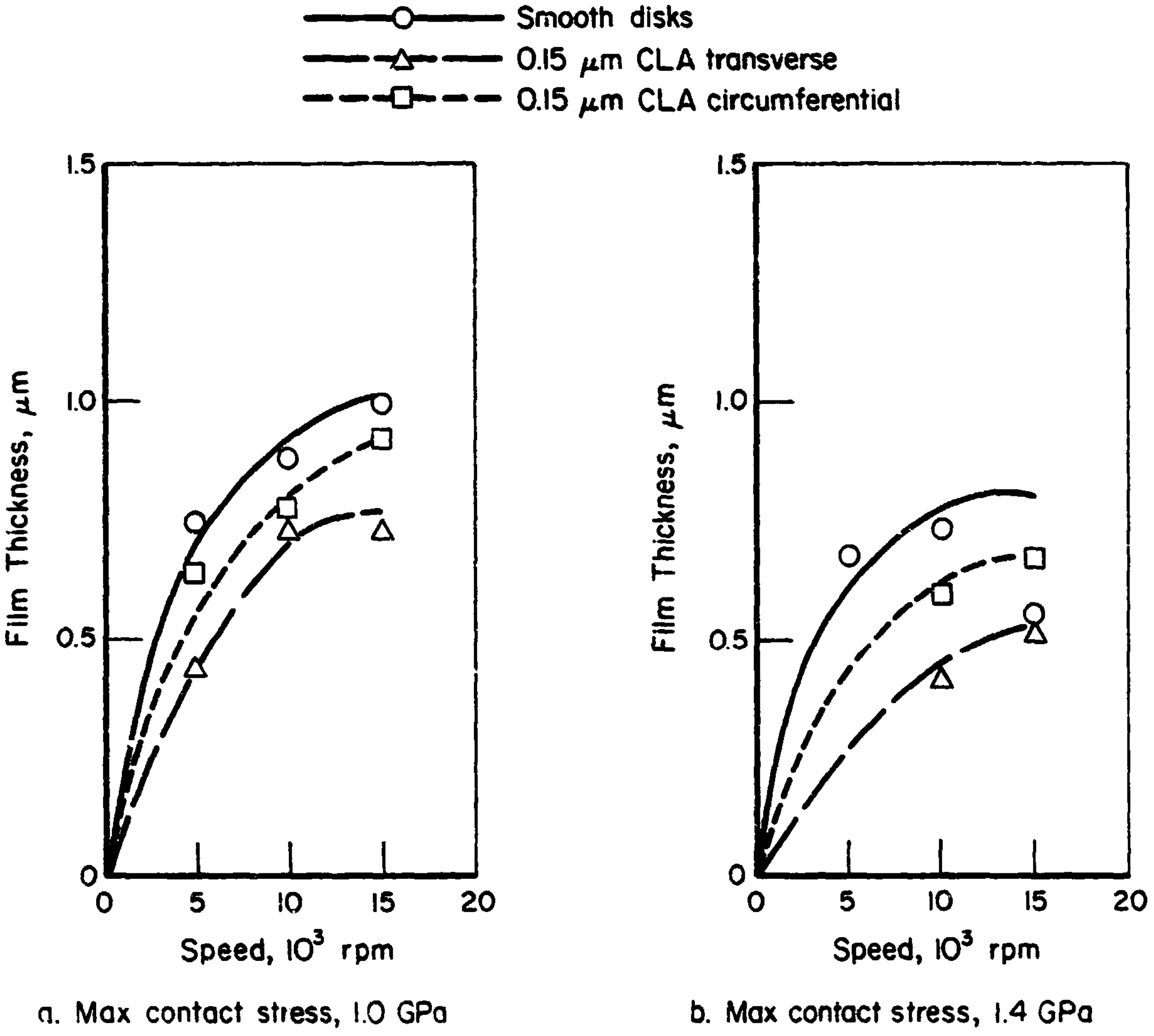
The reason for the film-thickness surface-roughness phenomena are, at this time, not well understood. In EHD theory where the film thickness is



a. Max contact stress, 1.0 GPa

b. Max contact stress, 1.4 GPa

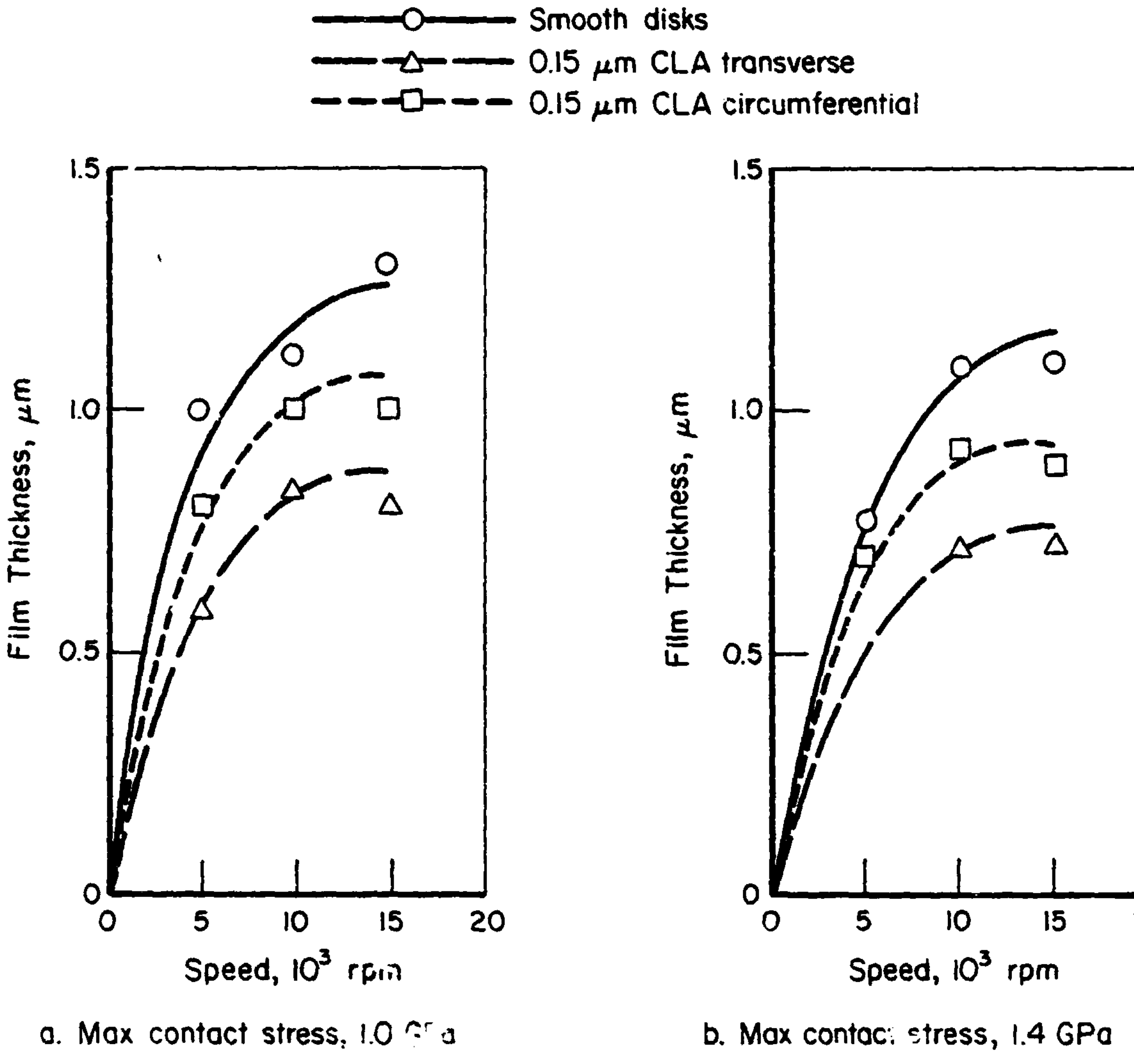
FIGURE 11. FILM THICKNESS AS A FUNCTION OF DISK SPEED FOR VARIOUS LEVELS OF SURFACE ROUGHNESS FOR XRM-109F AT 65 C



a. Max contact stress, 1.0 GPa

b. Max contact stress, 1.4 GPa

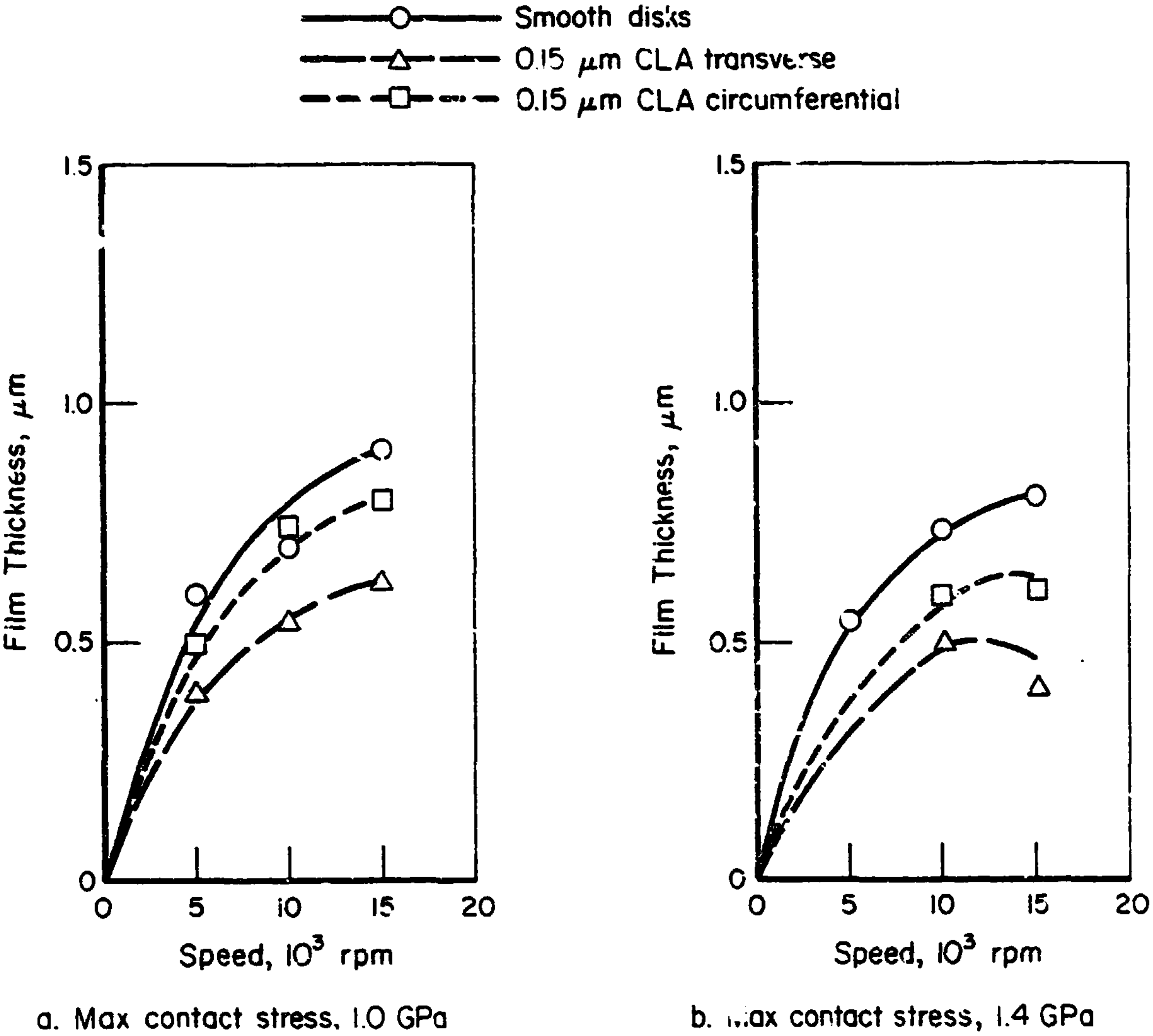
FIGURE 12. FILM THICKNESS AS A FUNCTION OF DISK SPEED FOR VARIOUS LEVELS OF SURFACE ROUGHNESS FOR XRM-109F AT 90 C



a. Max contact stress, 1.0 GPa

b. Max contact stress, 1.4 GPa

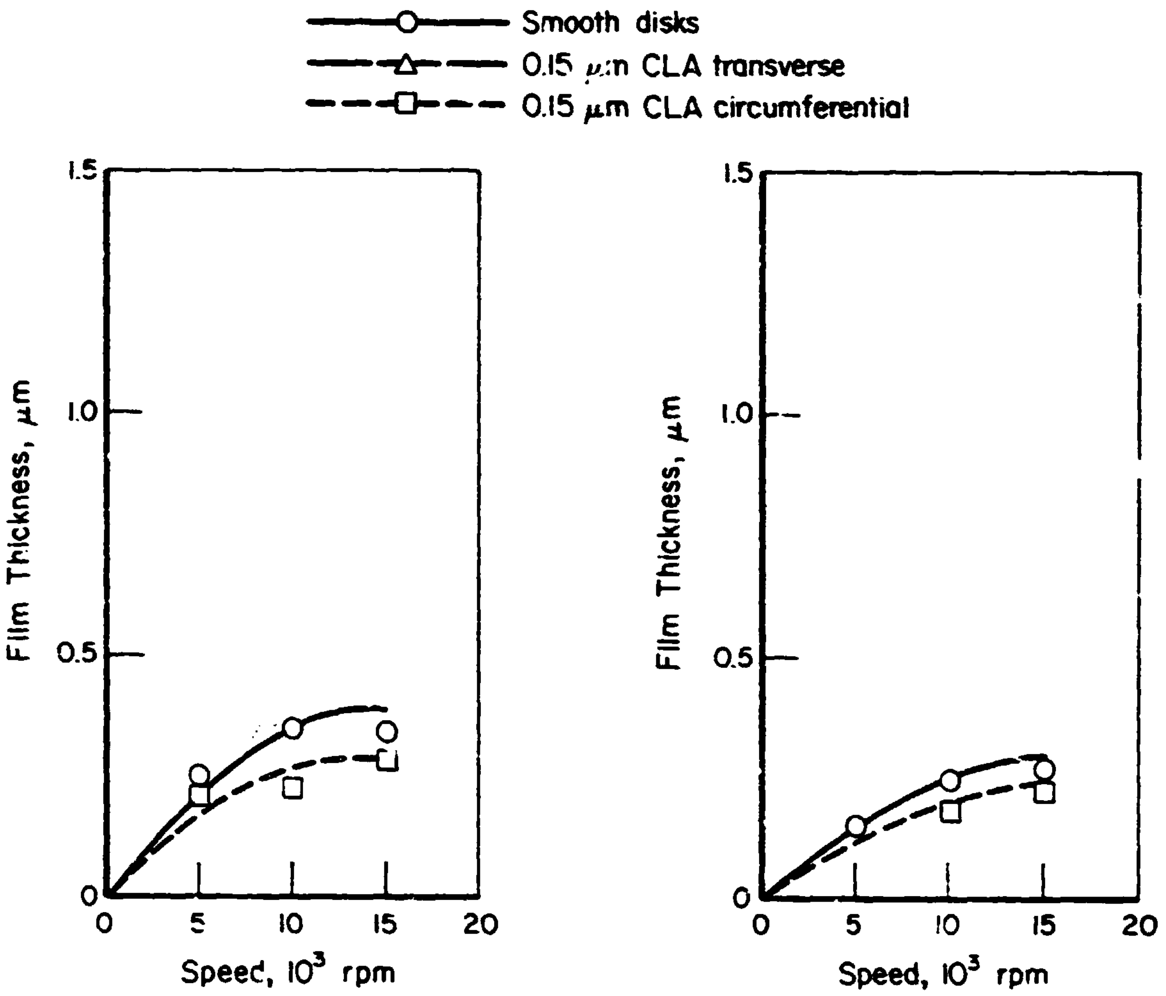
FIGURE 13. FILM THICKNESS AS A FUNCTION OF DISK SPEED FOR VARIOUS LEVELS OF SURFACE ROUGHNESS FOR XRM-177F AT 65 C



a. Max contact stress, 1.0 GPa

b. Max contact stress, 1.4 GPa

FIGURE 14. FILM THICKNESS AS A FUNCTION OF DISK SPEED FOR VARIOUS LEVELS OF SURFACE ROUGHNESS FOR XRM-177F AT 90 C



a. Max contact stress, 1.0 GPa

b. Max contact stress, 1.4 GPa

FIGURE 1[illegible]. FILM THICKNESS AS A FUNCTION OF DISK SPEED FOR VARIOUS LEVELS OF SURFACE ROUGHNESS FOR SANTOTRAC 50 AT 65 C the order of the surface roughness, some enhancement of the film thickness is predicted especially for a transverse lay finish. No quantitative evidence of such enhancement was seen though very few experiments were conducted in this very thin film range. Since the X-ray film thickness system is a "shadow" technique for measuring minimum film thickness, it is, of course, possible that the decrease in film is partially the result of an X-ray blockage by asperities. Further, since transverse asperities are variable (at random height) with respect to the contact region and are perpendicular to the X-ray path, it is reasonable that they would produce some type of shuttering of the X-ray stream. However, these shuttering asperities also produce metallic contact between the disks under thin film conditions.

Regardless of the mechanism for surface roughness effect on film thickness the following conclusions from the data can be made:

(1) Surface roughness reduces the beneficial effect of EHD film thickness between rolling elements.

(2) The magnitude of this reduced effectiveness is of the order of magnitude of the roughness.

(3) Transverse lay finish such as occurs in gear teeth is more detrimental to lubrication than circumferential film thickness such as occurs in rolling element bearings.

Modelling Surface Roughness Effects

Model Development

The results of the formal investigation of film thickness and percent film between two identical mating disks yielded some interesting results with regards to the effect of roughness on film thickness and percentage of contact. It is reasonable, then, to investigate these observations more closely to determine if a definite pattern exists which can be mathematically modelled. To achieve an accurate modelling process, it was desired to have consistent data, expecially percentage of film data. Such data can best be obtained by using four different roughnesses on the lower multidisk stub shaft and a single, polished upper disk.

Table 12 presents a summary of film thickness and percent film data using a single upper disk for two of the lubricants of Table 1. Several loads were used in these experiments to aid in establishing load effects on the measurements. In addition, data were obtained for two speeds and two temperatures. In general, the range of conditions were selected, based on previous experience, to minimize conditions producing metallic contact.

The analytical model used to evaluate the film thickness data was of the form

$$H = C_1 \ v^{n_1} \ \mu^{n_2} \ p_h^{\ n_3} \ \sigma^{n_4} \qquad (1)$$

where H is the film thickness (μm)

v is the velocity of the disk surface (10^3 rpm)

p_h is the contact stress (GPa)

μ is the viscosity of the oil (c_p)

σ is the cla surface roughness (μm)

A least squares fitting process was used to fit the equation to the experimental data. The optimum fit can be written as

$$H = 0.0145 \ v^{.23} \ \mu^{.68} \ p_h^{\ -.8} \ \sigma^{-.36} \qquad (2)$$

The equation for the percent film data is in the form

$$P = [1- \exp \ (\frac{-.28 \ H}{\sigma})]^n \qquad (3)$$

where P is the percent film and

$n = 1.2$ for transverse lay finish and 1.4 for circumferential lay.

The computer print-out showing a comparison between the measured and the fitted data is given in Appendix B. In general a very good fit was achieved for the film thickness data. Despite the rigorous effort to control all variables the fit for the percent film was somewhat poorer than the film thickness. The problem here, of course, is associated with the fact that percent film tends to be a step function varying between 0 to 100 over a very short range of film thicknesses. Small uncertainties in the operating conditions or surface roughness are greatly amplified in the fitting process. Considering this problem, the percent film fit is reasonable.

TABLE 12. SUMMARY OF FILM THICKNESS (µm)/PERCENT OF CONTACT FOR SMOOTH UPPER DISK IN CONTACT WITH LOWER DISKS WITH VARIOUS ROUGHNESSES

Lubricant	Temp, C	Lower Disk Roughness CLA	- 10,000 RPM - Load - GPa					- 5,000 RPM - Load - GPa				
			1.0	1.2	1.4	1.6	1.8	1.0	1.2	1.4	1.6	1.8
XRM-109	65	Smooth (0.5 µm)	1.6/100*	1.4/99	1.3/99	1.3/99	1.1/98	1.5/100	1.2/100	1.1/99	1.0/99	.93/96
	65	.15 µm Cir	1.14/99	.97/92	1.1/92	1.1/90	1./88	.96/97	.73/75	.95/65	.73/50	-
	65	.15 µm Trans	1.3/99	.93/98	1.1/97	.91/97	.65/95	1.2/96	.86/94	.72/92	.73/88	.43/80
	90	Smooth	1.3/100	.93/100	.88/96	.73/98	.65/97	.86/100	.82/99	.82/99	.75/99	.75/93
	90	.15 µm Cir	.9/93	.71/82	.68/74	.54/40	41/15	.54/10				
	90	.15 µm Trans	.72/100	.66/96	.55/91	.57/88	.43/65	.61/60	.50/50	.4/25		
XRM-177	65	Smooth	1.5/100	1.35/100	1.15/100	1.03/100	.9/100	1.3/100	1.3/100	1.1/100	1.03/100	.9/100
	65	.15 µm Cir	1.3/95	1.0/90	.73/88	.8/80	.68/50	1.1/93	1.0/90	.95/80	.82/70	.75/30
	65	.15 µm Trans	1.1/99	1.1/98	.62/95	.52/90	.45/65	.96/99	.82/95	.6/85	.6/80	.47/50
	90	Smooth	1.04/100	.91/100	.93/96	.9/95	.71/94	.88/100	.82/98	.71/97	.7/90	.61/87
	90	.15 µm Cir	.79/50	.79/35	.75/10							
	90	.15 µm Trans	.63/80	.63/55	.57/44	.54/26	.91/10	.54/15				

* Film Thickness (µm)/Percent Film.

Comparison With Mating Roughness Disk Experiments. Equations (2) and (3) were developed from data generated with a polished upper disk. It is interesting, however, to compare the predictions of these equations with the data of Tables 2 through 11 for mating disks with the same roughnesses. For this comparison, the composite roughness (σ) of the pair of disks was used; that is

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{4}$$

where

σ_1 and σ_2 are the roughnesses of each disk.

For the case of mating identical disks

$$\sigma = 1.41\ \sigma_1$$

Table 13 presents a comparison of predictions from Equations 2 and 3 with experimental data. These data were selected entirely at random. In general, it is apparent that the trends from Equations (2) and (3) are quite consistent with the measurements.

TRACTION EXPERIMENTS

In addition to the film thickness and percentage of film measurements, traction data for the lubricants were generated. This data was produced by reducing the speed of the upper disk relative to the lower disk and, thus, generating slip across the lubricant film. Slip between the disks produced a shear stress in the film which resulted in a traction force on the upper motor tending to drive it in the direction of the lower disk surface speed. This tractive force was measured by constraining the upper motor with a load cell, as shown in Figure 6. The upper motor is suspended in roller bearing pivots so that it is free to move in response to the tractive force. The load cell constrains this motion and produced an output proportional to the traction.

An example of a traction/slip curve is shown in Figure 16. The vertical axis is tractive force in Newtons and the horizontal axis is slip; that is, the difference in speed between the disks divided by the speed of the lower disk. The curve has been generated from negative to positive slip; that is, from the condition where the upper disk is moving faster than the lower disk to when the upper disk is moving slower than the lower disk.

TABLE 13. RANDOM DATA EVALUATIONS WITH FILM THICKNESS — PERCENT FILM MODEL

Lubricant	Temperature/ Viscosity, C/Cp	Load, GPa	Speed, 10^{-3} rpm	Roughness, μm-lay	Film Thickness		Percent Film	
					Measured μm	Predicted μm	Measured*	Predicted
109 F	65/100	1.	15	Smooth	1.2	1.8	100 (100)	100
		1.4	10	Smooth	.9	1.3	100 (100)	100
	90/32	1.	15		1.	.84	100 (100)	99
		1.4	5		.68	.51	100 (100)	93
	150/12	1.	10		.48	.40	100 (100)	86
		1.4	10		.35	.31	100 (100)	79
	65/100	1.0	15	.15 Cir	1.05	1.08	100 (100)	88
	90/32	1.4	10	.15 Cir	.6	.36	100 (15)	43
	150/12	1.4	15	.15 Cir	.4	.20	58 (50)	24
	65/100	1.4	5	.15 Trans	.65	.67	100 (100)	74
	90/32	1.0	5	.15 Trans	.45	.39	65 (30)	51
	150/12	1.4	10	.15 Trans	.2	.19	90 (25)	27
	90/32	1.0	10	.33 Trans	.52	.34	75 (10)	30
177 F	65/100	1.	15	Smooth	1.3	1.8	100 (100)	100
	150/12	1.4	5	Smooth	.30	.27	100 (100)	73
	65/100	1.4	5	.15 Cir	.7	.67	96 (25)	70
	150/12	1.0	5	.15 Cir	.21	.20	82 (70)	23
	65/100	1.	5	.15 Trans	.58	.84	97 (52)	81
	150/12	1.	10	.15 Trans	.35	.23	85 (27)	33
	65/100	1.	5	.33 Trans	.65	.64	80 (25)	51
SANOTRAC 50	65/12	1.	5	Smooth	.15	.33	97 (5)	81
	150/22	1.	10	Smooth	.18	.13	63 (18)	43
	65/12	1.4	10	.15 Cir	.19	.19	58 (44)	27
	65/12	1.0	15	.15 Trans	.34	.26	30 (7)	36

* Includes data from 0 and 25% slip.

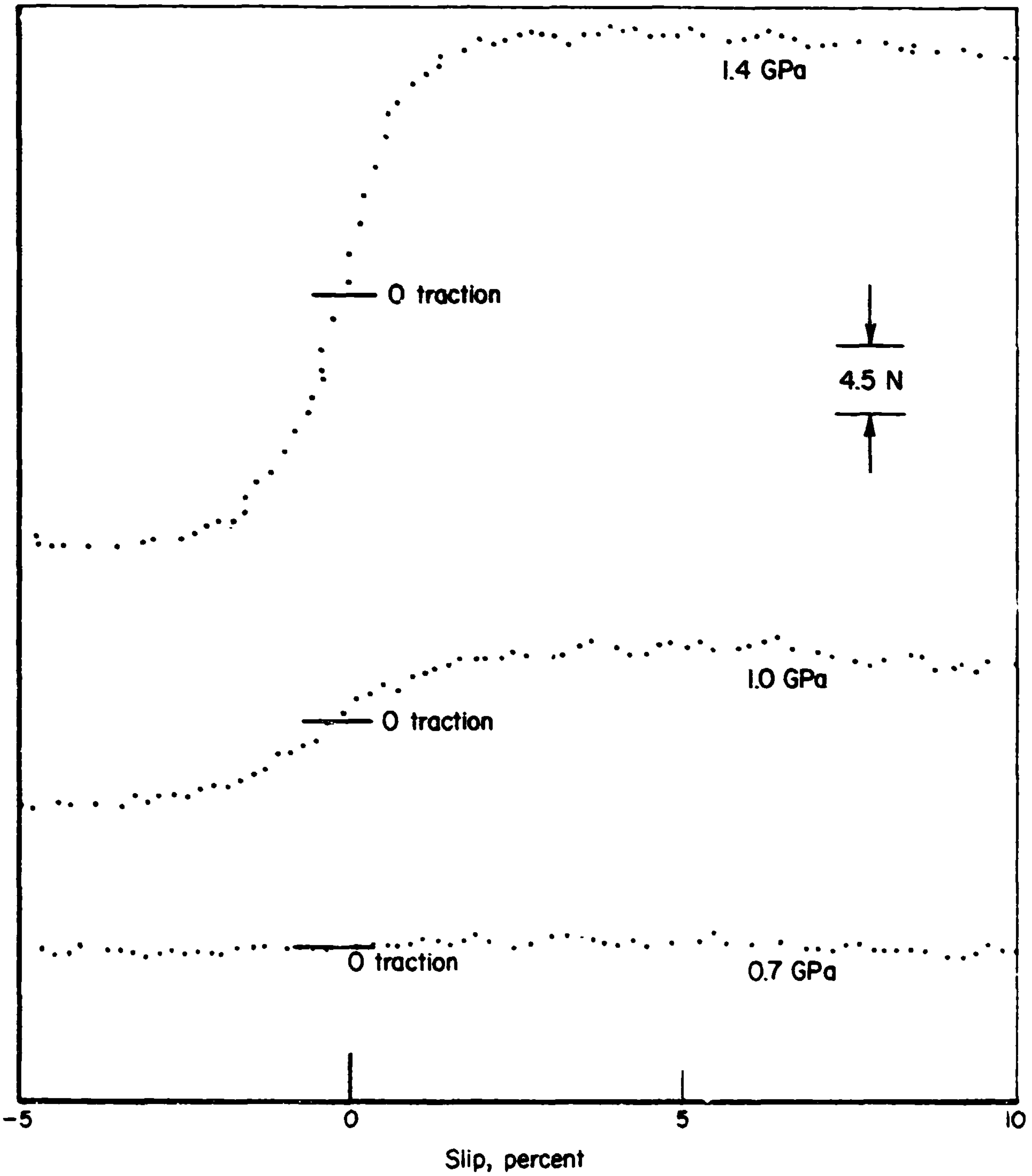


FIGURE 16. TRACTION/SLIP CURVES FOR SYNTHETIC PARAFFINIC FLUID (XRM-109) AT 10,000 RPM AND 65 C

This will produce a symmetrical traction curve around zero slip and will allow the location of the zero traction condition. This condition may not occur exactly at the indicated zero slip value because of small differences in disk diameter. From this type of data, traction/slip curves such as shown in Figure 17 were drawn. To ease in evaluation of the traction curves, the data has been arranged in tabular form in Appendix C. The tables show the magnitude and location of the peak traction for each load, speed, and temperature condition in the experimental program.

The value of peak traction for the lubricants studied are plotted in Figures 18 to 20. Figure 18 shows the peak traction for XRM-109 at 65 C. These traction values occur at different values of slip but represent the maximum shear force which can be produced in the conjunction region. In general, the data show a slight drop in peak traction with speed. The traction values are shown for polished mating disks as well as mating pairs of disks having 0.15 μm cla surface finishes with their lay in the transverse direction, in one case, and the circumferential direction in the other. The effect of the rougher surfaces is to increase the peak traction. The circumferential surface lay produces the largest increase in traction. This surface has also been shown to produce the largest percent contact between the surfaces.

One explanation for the large traction values measured for the circumferential lay surface involves the geometry of the contact. The contact patch is an ellipse which is six times wider than it is long. Since the spacing of the surface roughness peaks is similar for the different lay finishes, more peaks will be in the contact zone for the circumferential lay finish. This will produce a higher percentage of contact as well as increased traction.

The results for the XRM-109 at 90 C and 150 C shown in Figures 19 and 20 show similar results to those discussed for the 65 C temperature except that the peak traction values are slightly reduced as the temperature is increased.

The results of the traction experiments using the XRM-177 lubricant are shown in Figures 21 to 23. These curves are similar to those shown for the XRM-109 lubricant. There is a decrease in traction with increased temperature and speed. The effect of surface roughness is to increase the peak traction with the circumferential lay finish giving the greatest value.

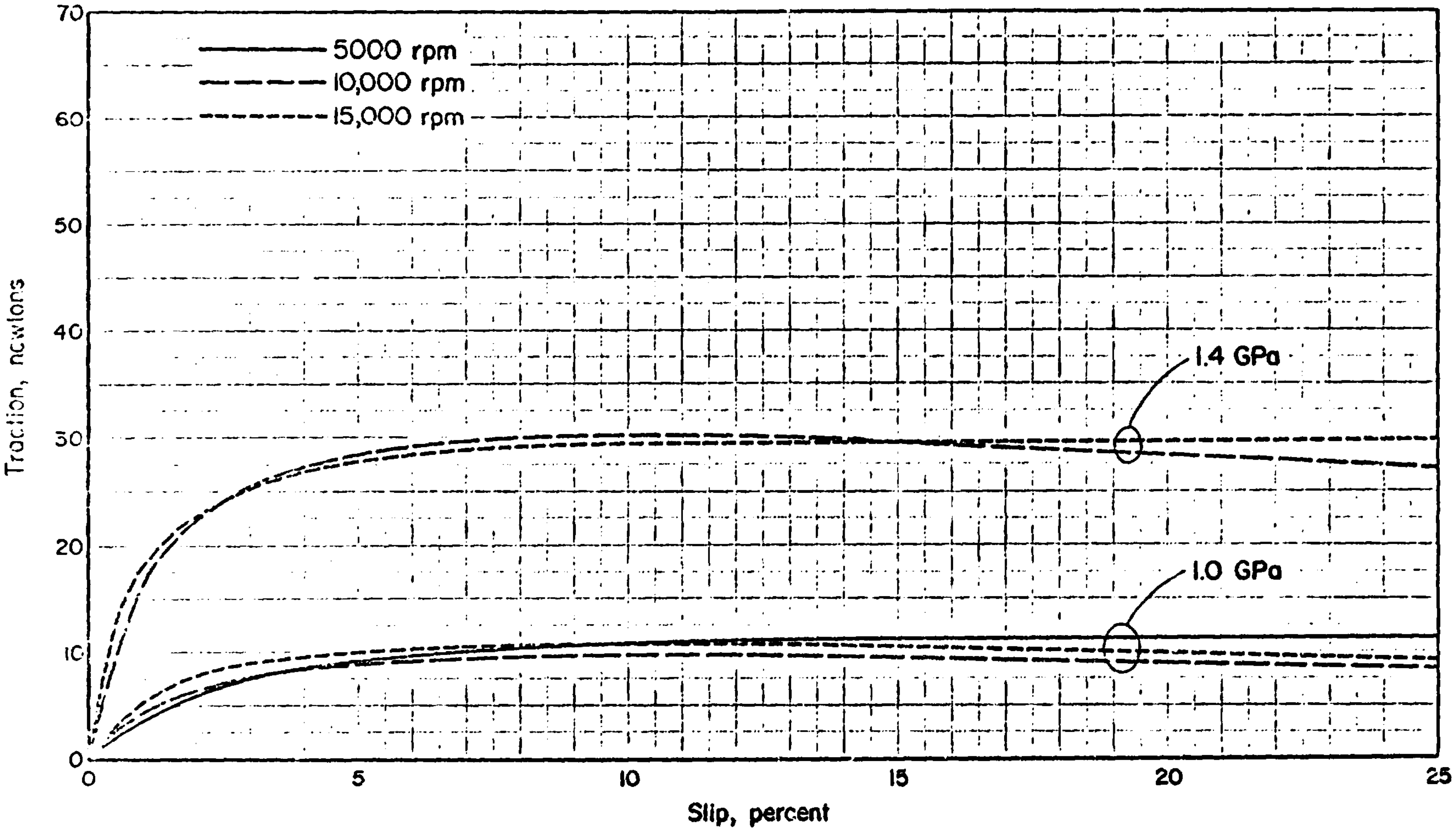


FIGURE 17. TRACTION-SLIP CURVES FOR XRM-177F AT 90 C USING ROUGHENED MATING DISKS WITH 0.15 μm (6 μin.) CLA TRANSVERSE LAY FINISH

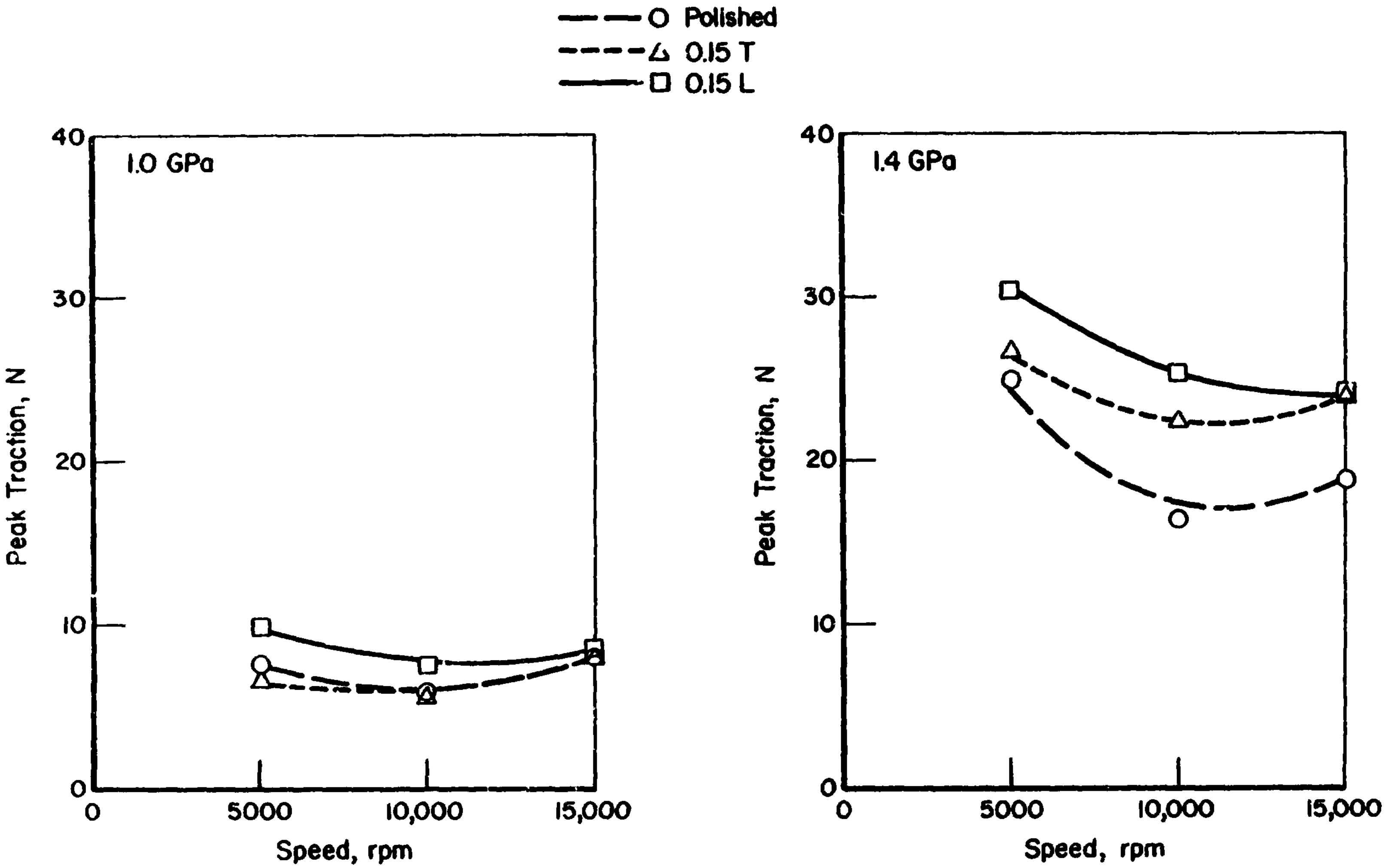


FIGURE 18. PEAK TRACTION FOR XRM-109 F AT 65 C

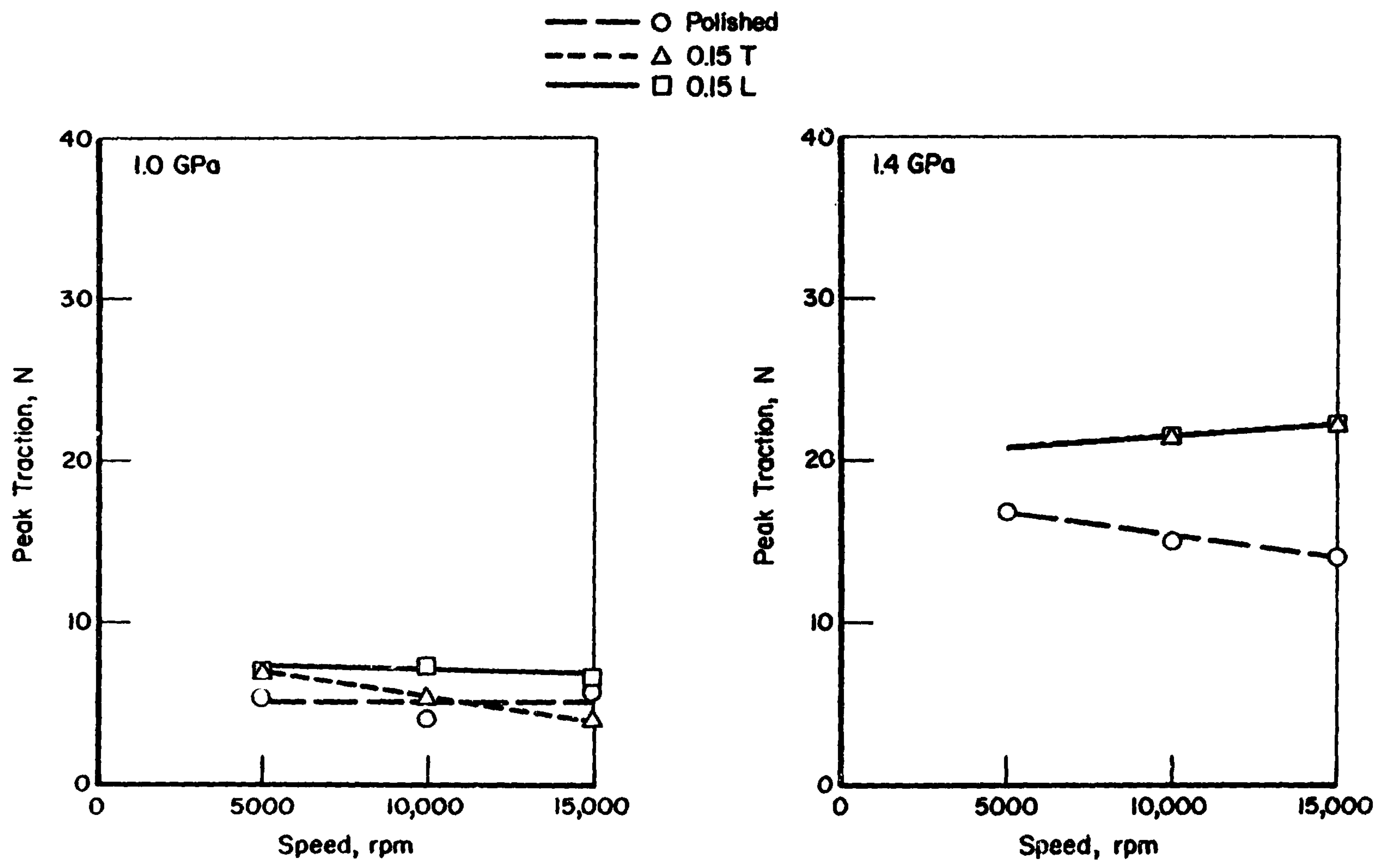


FIGURE 19. PEAK TRACTION FOR XRM-109 F AT 90 C

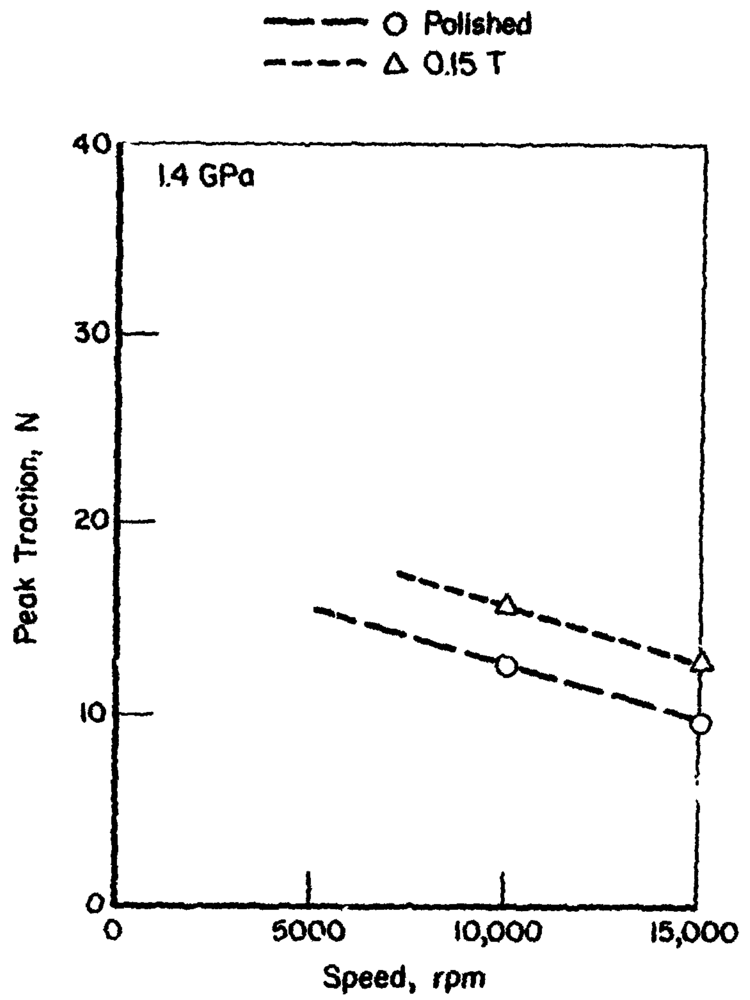


FIGURE 20. PEAK TRACTION FOR XRM-109 F AT 150 C

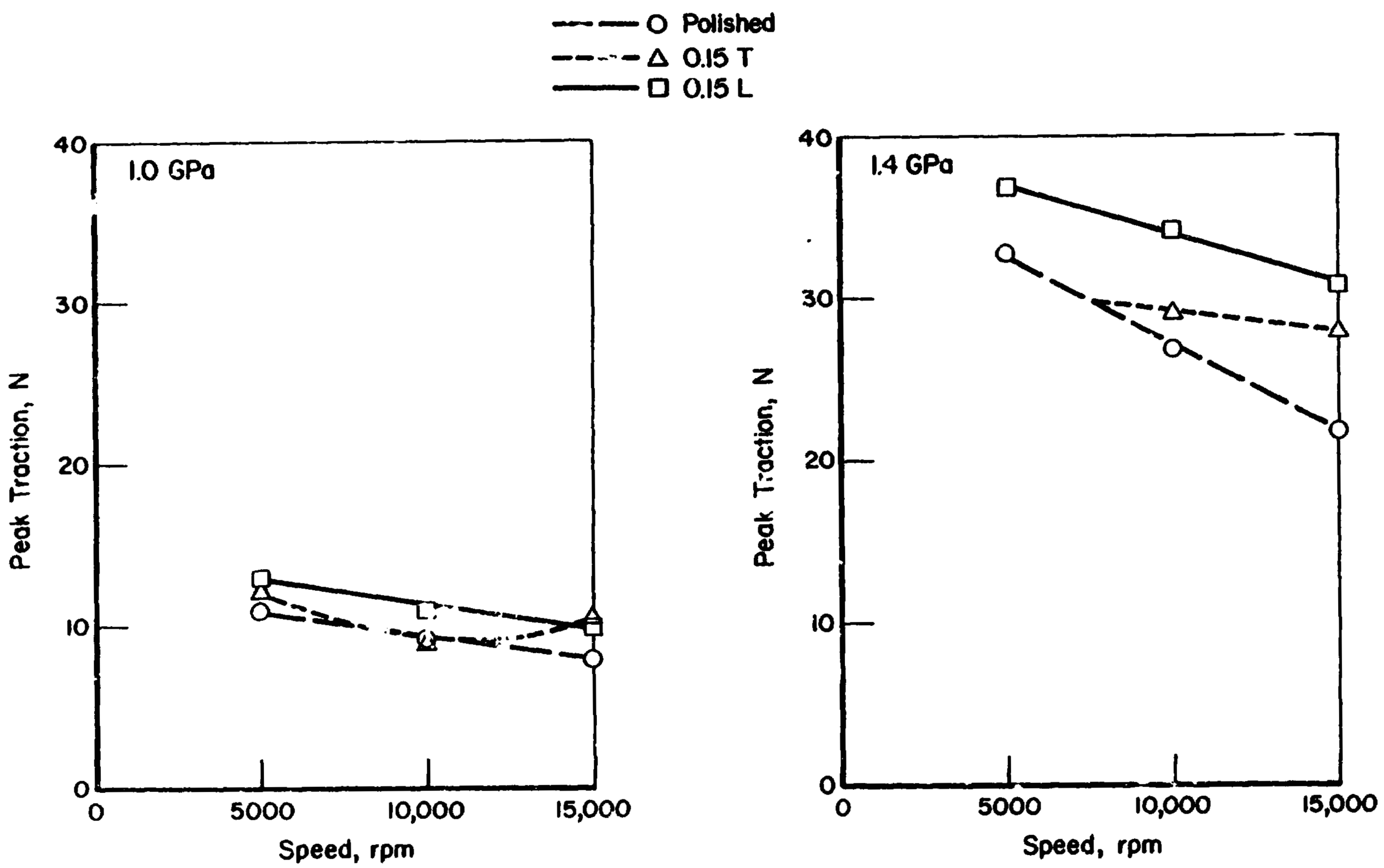


FIGURE 21. PEAK TRACTION FOR XRM-177 AT 65 C

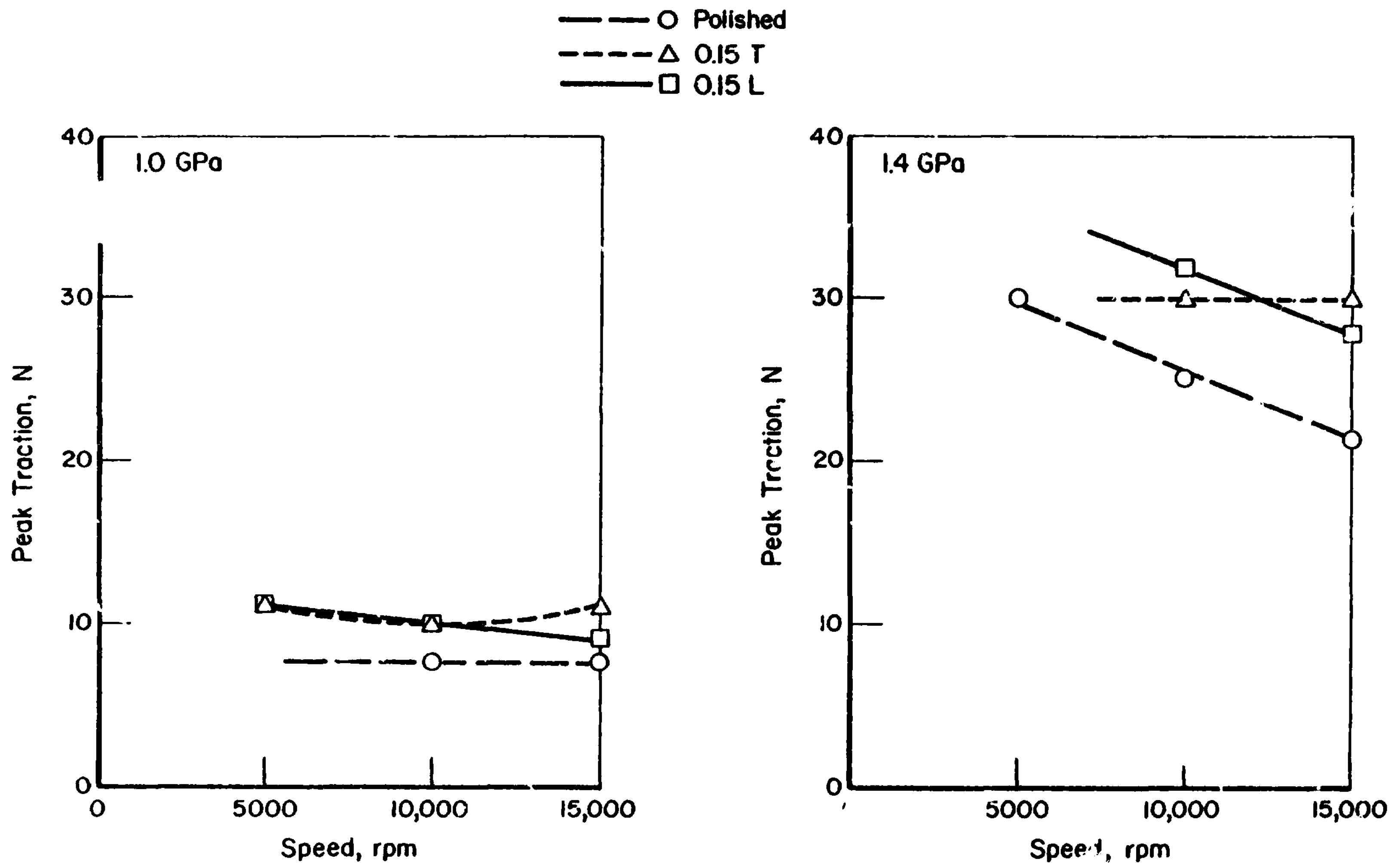


FIGURE 22. PEAK TRACTION FOR XRM-177 AT 90 C

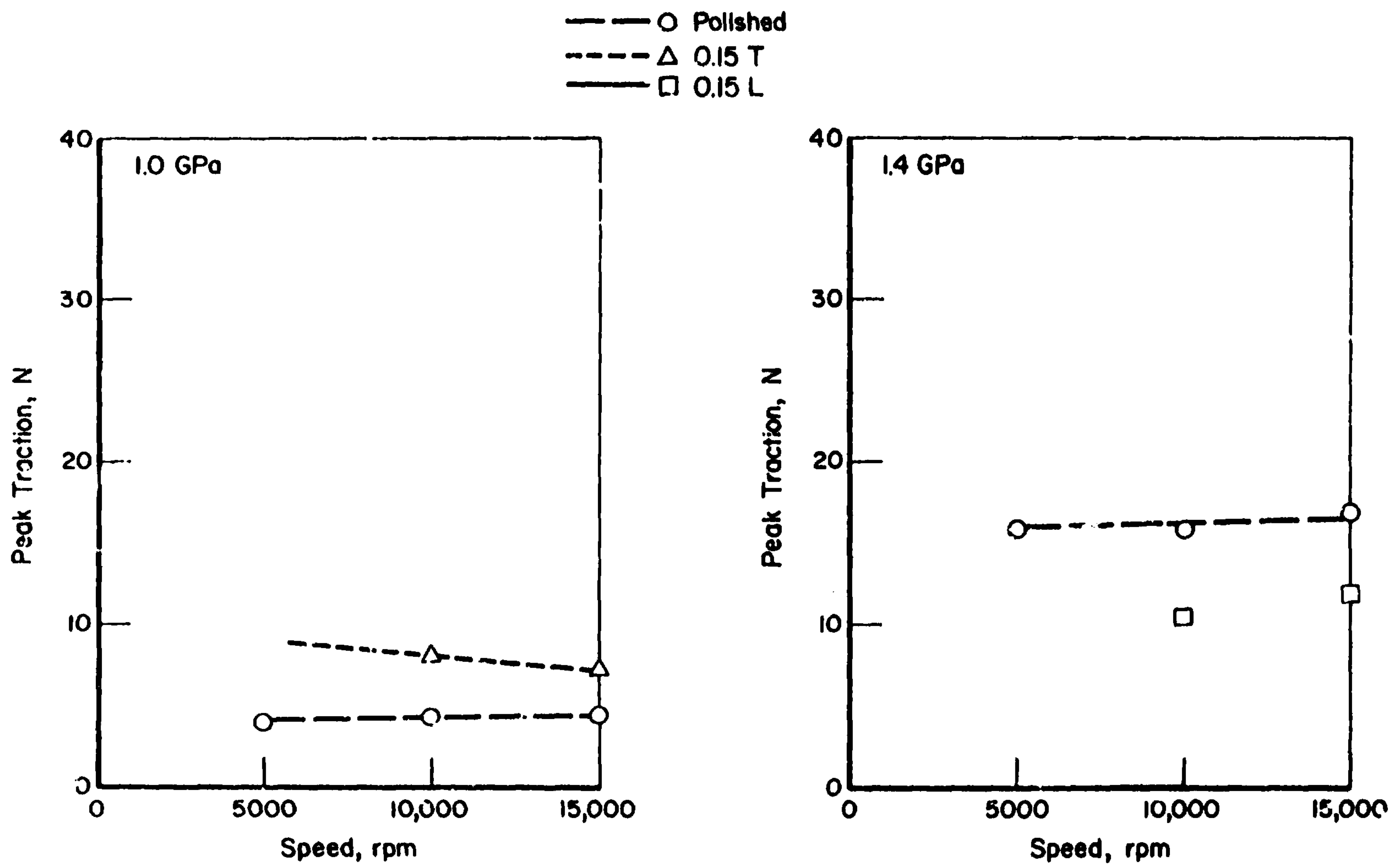


FIGURE 23. PEAK TRACTION FOR XRM-177 AT 150 C

The peak traction values measured using Santotrac 50 are shown in Figures 24 and 25. The values of peak traction for this lubricant were about four times those measured for the XRM-109 and XRM-177. For the Santotrac fluid, there is a slight increase in traction with speed rather than the decrease shown in with the previously discussed lubricants. Also, the surface finish has less effect on the traction values. However, it should be noted that much thinner lubricant films were measured with the Santotrac 50 and that range of possible operating conditions were severely limited by "damage" to the disk surfaces. At 90 C, only the polished disks could be run over the entire speed range (Figure 25).

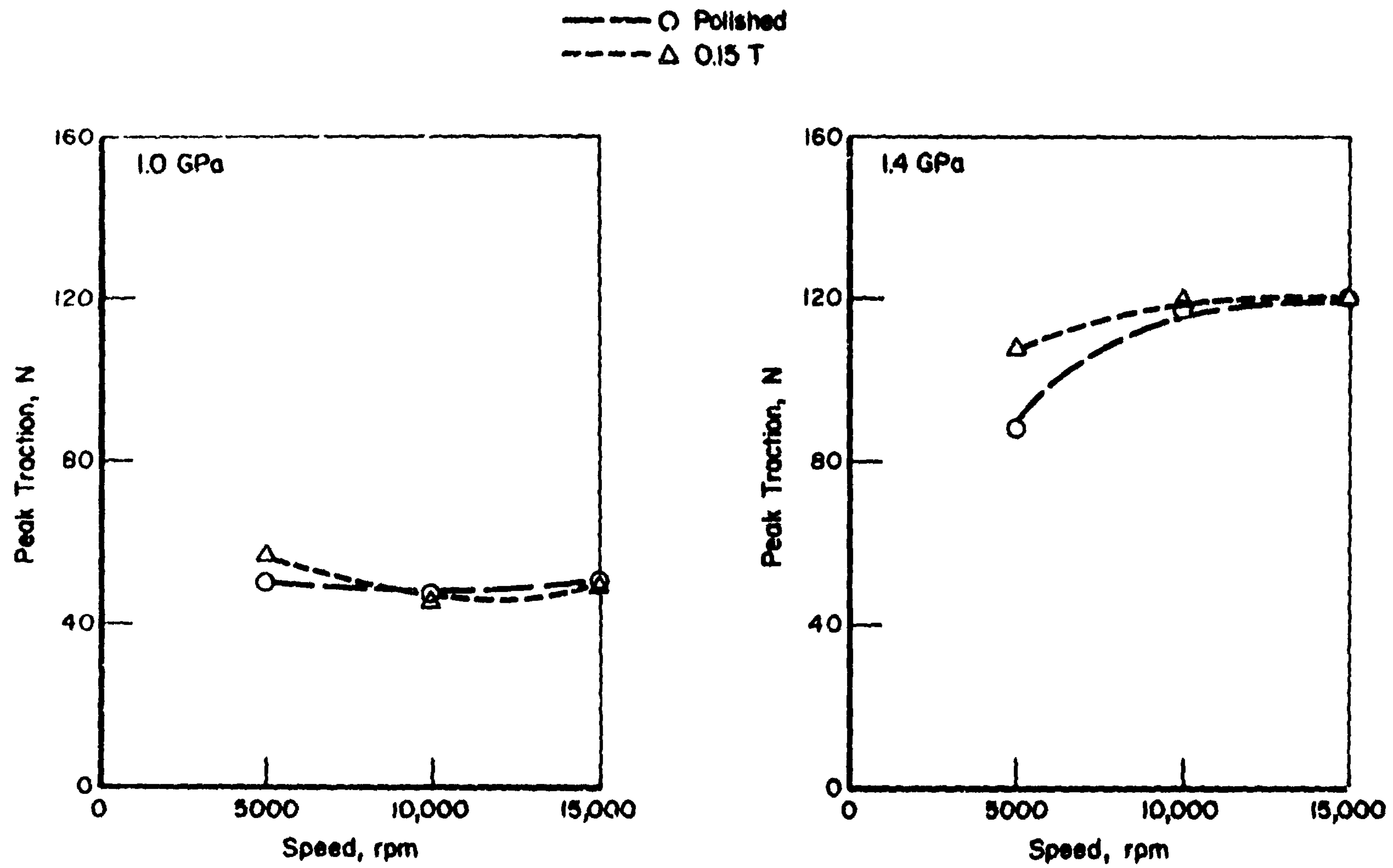


FIGURE 24. PEAK TRACTION FOR SANTOTRAC 50 AT 65 C

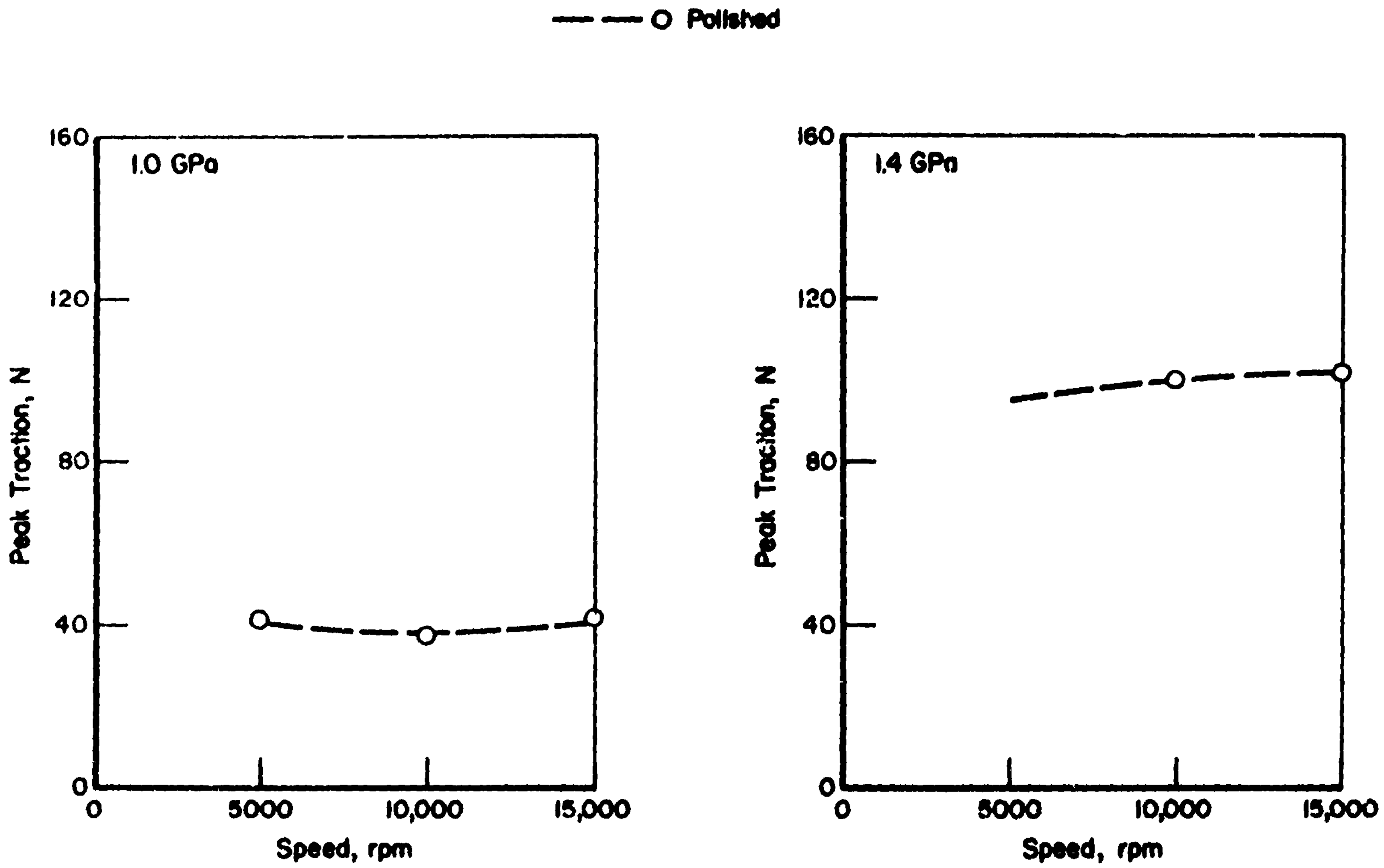


FIGURE 25. PEAK TRACTION FOR SANTOTRAC 50 AT 90 C

DEVELOPMENT OF LUBRICANT SPECIFICATION

The research program reported here has been divided into four tasks with the ultimate objective being to use the information obtained to define a specification for lubricants based on their performance in an EHD contact.

The current military specifications (MIL-L-7808 or MIL-L-23699) include composition, ambient pressure viscosity, and the physical properties (sediment, foaming) of the lubricant. The specification also includes several performance tests. These tests require specified performance in a Ryder gear machine and for a 100 hour test in a J-57 engine. The gear machine would be a measure of the boundary lubricating capability of the lubricant (EP additives principally) and the 100 hour engine test would expose extremely poor lubricants.

Design of concentrated contact bearings (ball and roller bearings) are based on the concept of EHD lubrication; that is, the life of the bearing is influenced by the lubricant films formed between the elements. From fatigue considerations, (these would not be significant in either the gear test or the 100 hour engine test) the bearing life can be predicted from the ratio of operating EHD film thickness to average surface roughness of the mating elements.

To find the EHD films formed by a given lubricant, more information than is available from either the MIL-L-23699 or MIL-L-7808 specification is required. Since these lubricants are used in bearings and gears, a modified specification which addressed the EHD film forming capability of the lubricant would be of interest. The lubricant specification, as now written, defines the chemistry of the fluids and is based on past experience with such fluids. Changes in lubricants based by cost or availability considerations may require chemistry changes and how such changes are reflected in EHD performance should be included in the specification.

The BCL disk machine is a standardized method of studying bearing lubricants and evaluating their EHD film-forming capabilities. It can also be operated with rough surfaces at severe operating conditions to study the effectiveness of the boundary lubricants formed at the interface.

As a result of the initial work with XRM-109, XRM-177, and Santotrac 50, a series of experiments were defined which would show the film-forming capability and the boundary lubricating effectiveness of several 23699 and 7808 type lubricants. The initial intent was to study both "good" lubricants (those that behaved well in operation) and "bad" lubricants (those which were known to give trouble in engine or gearbox operation). Unfortunately, the lubricants with a history of unsatisfactory operation were not available and only good lubricants were available. The results of the experiments showed a wide range of operating film thicknesses and percentages of film. Since these are all "good" lubricants, such a range must be acceptable for operation. However, it is clear from the data that the lubricants are different and under some operating conditions, the choice of one specific oil may increase the life of the mechanism.

Experiments for Lubricant Specification

Based on evaluation of the data generated earlier in the program, the following conditions were pursued for the specification evaluations:

(1) Speeds = 5,000-15,000 rpm
(2) Loads (contact pressure) = 1.0 to 1.4 GPa
(3) Temperature = 65-150 C
(4) Slip condition = up to 10 percent
(5) Surface finish = four levels

Specifically, four traction slip graphs for each fluid were generated.

- Graph I. Speed Effects on Traction. A graph of traction versus slip was generated for one load (1.4 GPa), one temperature (90 C), one surface finish (.025μm), and three speeds (5,000, 10,000, and 15,000 rpm).
- Graph II. Load Effects on Traction. A graph of traction versus slip was generated for one speed (10,000 rpm), one temperature (90 C), one surface finish (.025μm), and three loads (1.0, 1.2, and 1.4 GPa).

- Graph III. Temperature Effects on Traction. A graph of traction versus slip was generated for one speed (10,000 rpm), one load (1.4 GPa), one surface finish (.025 μm), and three temperatures (65, 90, and 150 C).
- Graph IV. Surface Finish Effects on Traction. A graph of traction versus slip was generated for one speed (10,000 rpm), one load (1.4 GPa), one temperature (90 C), and four surface finishes on the lower disks (.025, .13 trans, .13 long, and .3 trans μm cla). The upper disk finish was 0.025μm.

These four graphs can be used to define the operation of the lubricant over the range of conditions typical of bearing and gear contact.

Test Lubricants

For the experiments, ten lubricants were supplied by the Army and Air Force. Four lubricants were qualified under MIL-L-23699B, and six were qualified under MIL-L-7808G. The Designation of the lubricants is as specified in Table 14 below.

TABLE 14. DESIGNATION OF LUBRICANTS

Lubricant Number	Type	Identification	
1	7808G	DSA-600-76-C-2116	Qual 15D-1
2	23699B	DSA-600-75-C-1853	" 09C-1
3	"	DSA-600-76-C-1231	" 07A
4	"	DSA-600-76-C-1527	" 0-5A-2
	"	DSA-600-76-C-1975	" 0-5A-1
6	7808G	DSA-600-77-C-0634	" 15D-1
7	"	ATL-7072	(polyol ester)
8	"	ATL-7073	(mixture of polyol & diester)
9	"	ATL-7074	(mixture of polyol & diester)
10	"	ATL-7075	(diester)

The major difference between the requirements for 7808 and 23699 oils are given in Table 15. The major difference at operating conditions is the increased viscosity requirement for the 23699 oil.

TABLE 15. LUBRICANT PROPERTY REQUIREMENTS

	7808	23699
Viscosity (CS) @ 98.9 C max	3.0	5.0
Viscosity (CS) @ 98.9 C min	-	5.5
Viscosity (CS) @ 37.8 C min	11.0	25
Viscosity (CS) @ -65. C max	13000	-
Viscosity (CS) @ -40. C max	-	13000
Pour Point (°C) max	-60	-54
Flash Point (°C) min	204	246
Total acid no. (%) max	.30	.50

Experimental Results

The results of the experimental sequence for the ten oils is shown in Figures 26 to 28, and in tabular form in Appendix D.

Influence of Speed on Film Thickness

A plot of the data generated for film thickness as a function of rotating speed of the mating disks is shown in Figure 26. Two bands of data are shown which represent the range of data for the two types of lubricant (23699 and 7808).
In general, the 23699 specification lubricants produced a higher film thickness over the entire range of speed.

Influence of Hertz Stress on Film Thickness

The data for film thickness at a given rolling speed and temperature for maximum Hertz stresses from 150 to 200 ksi (approximately 1.0 to 1.4 GPa) are shown in Figure 27. The graph of this data shows again a somewhat higher level for the 23699 specification oils. The variation of data among the oils of each type is quite high, ranging up to 50 percent increase in film thickness for the 23699 oils at 1.0 GPa. The data for the 7808 oils show much less variation.

Influence of Temperature on Film Thickness

Data showing the influence of temperature on the EHD film thickness for the ten test oils is shown in Figure 28. The temperature of both disks and the oil sump were kept at the temperature value shown. The 23699 oils exhibit a generally higher value of film thickness and show a range of values about 50 percent higher than that of the 7808 fluids. The 7808 fluids show less variation among the different test oils.

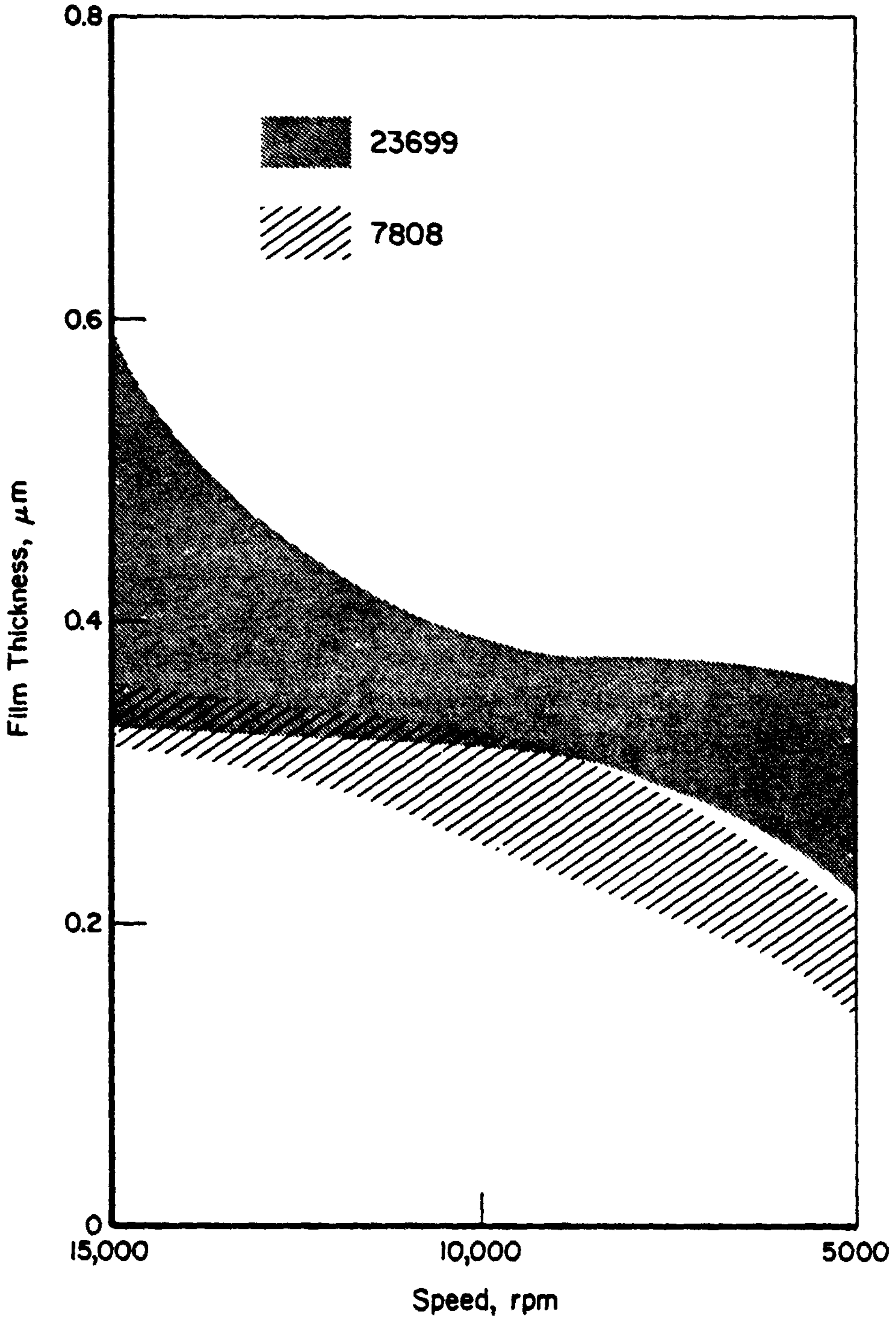


FIGURE 26. EFFECT OF SPEED ON FILM THICKNESS FOR MIL-L OILS

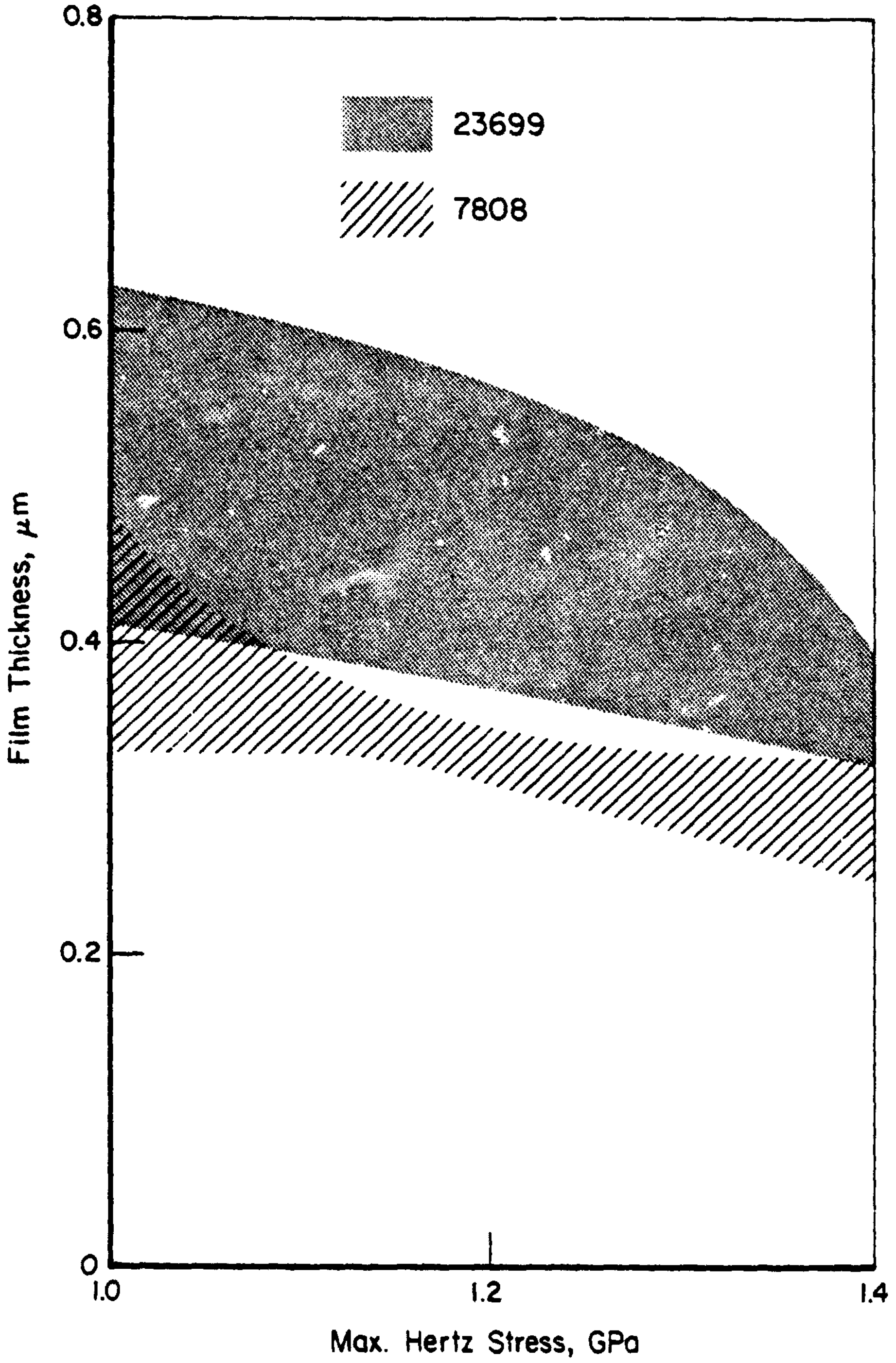


FIGURE 27. EFFECT OF HERTZ STRESS ON FILM THICKNESS FOR MIL-L OILS

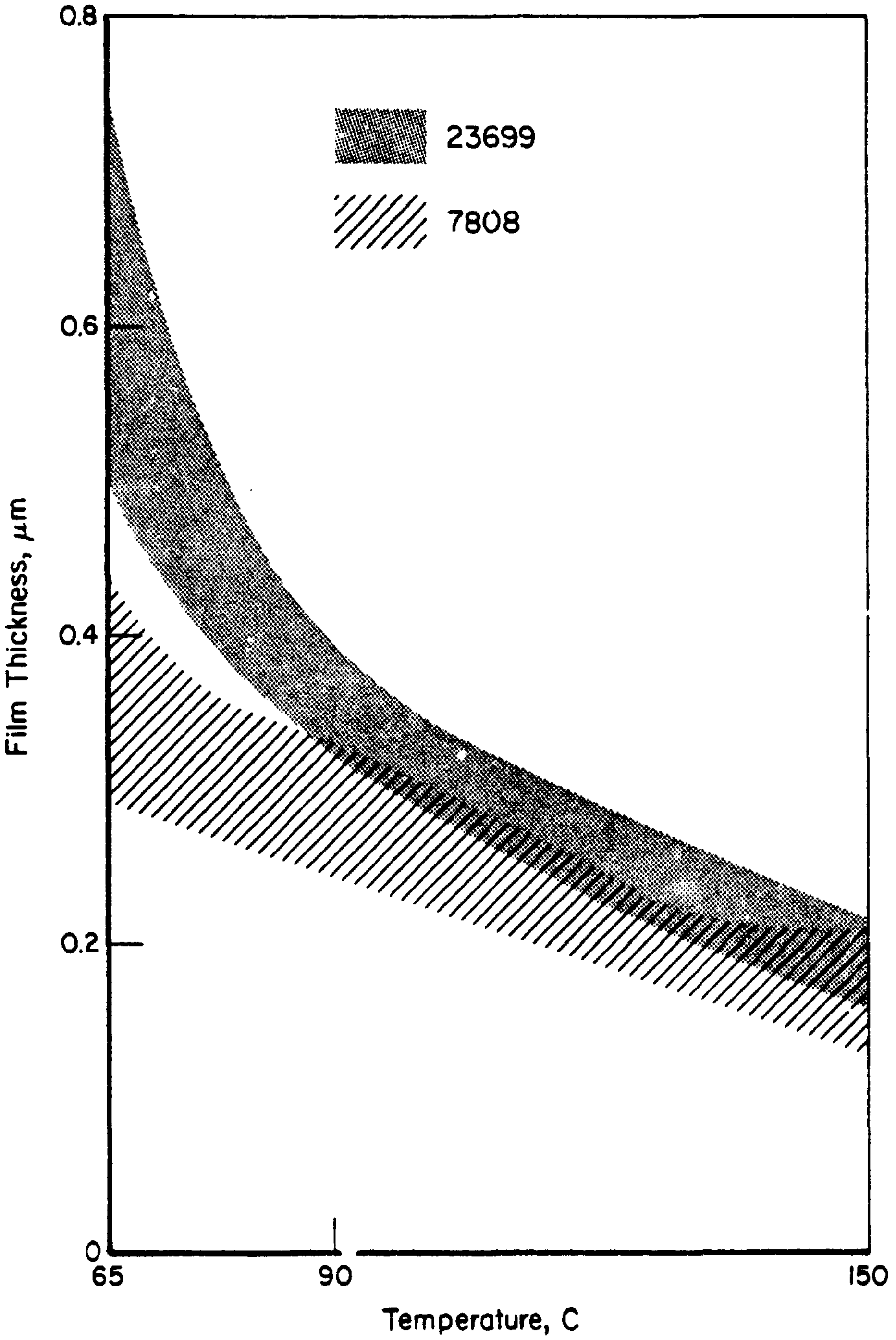


FIGURE 28. EFFECT OF TEMPERATURE ON FILM THICKNESS FOR MIL-L OILS

Effective Viscosity at Contact Pressure

The effective viscosity of each lubricant can be calculated (4) using the film thickness and traction data for a series of maximum Hertz stresses. The results of this calculation are shown in Figure 29 at a maximum Hertz stress of 1.2 GPa (175 ksi). The 23699 lubricants have a higher base viscosity at this temperature (6 cp versus the 3 cp value for 7808 lubricants at 90 C) and result in a larger viscosity. However, both lubricants are quite similar in their increase in viscosity with pressure; that is, the viscosity increases about 1000 times from atmosphere pressure up to 1.2 GPa contact stress.

Effect of Surface Roughness

The previous experiments were performed using polished mating disks with an average roughness of less than 1 μin. (0.025 μm). This surface finish is more highly polished than typical for commercial bearings or gears. To understand the influence of surface roughness on the EHD films formed and to show the influence of additives on the percentage of contact between surfaces, a series of experiments were performed at 10,000 rpm, 1.4 GPa, and 90 C while changing the average surface roughness, and the lay of that roughness, on the lower disk specimen.

The results of the experiments are presented in Figures 30 to 32. Figure 30 shows the film thickness measured for the four surfaces studied (polished, 0.13 μm cla circumferential lay finish, 0.13 μm cla transverse-lay finish, and 0.30 μm cla transverse-lay finish). The upper curve is for the polished mating disks. The lower curves show the film thicknesses measured using the polished upper disk and the rougher lower disks. No clear differences are apparent between these three finishes. One point which should be noted is that the average value of film thickness for the rougher surfaces is near or below the surface roughness of the lower disk. This indicates that considerable surface contact is taking place, a fact which will be apparent when we consider the percentage of film measured for these conditions.

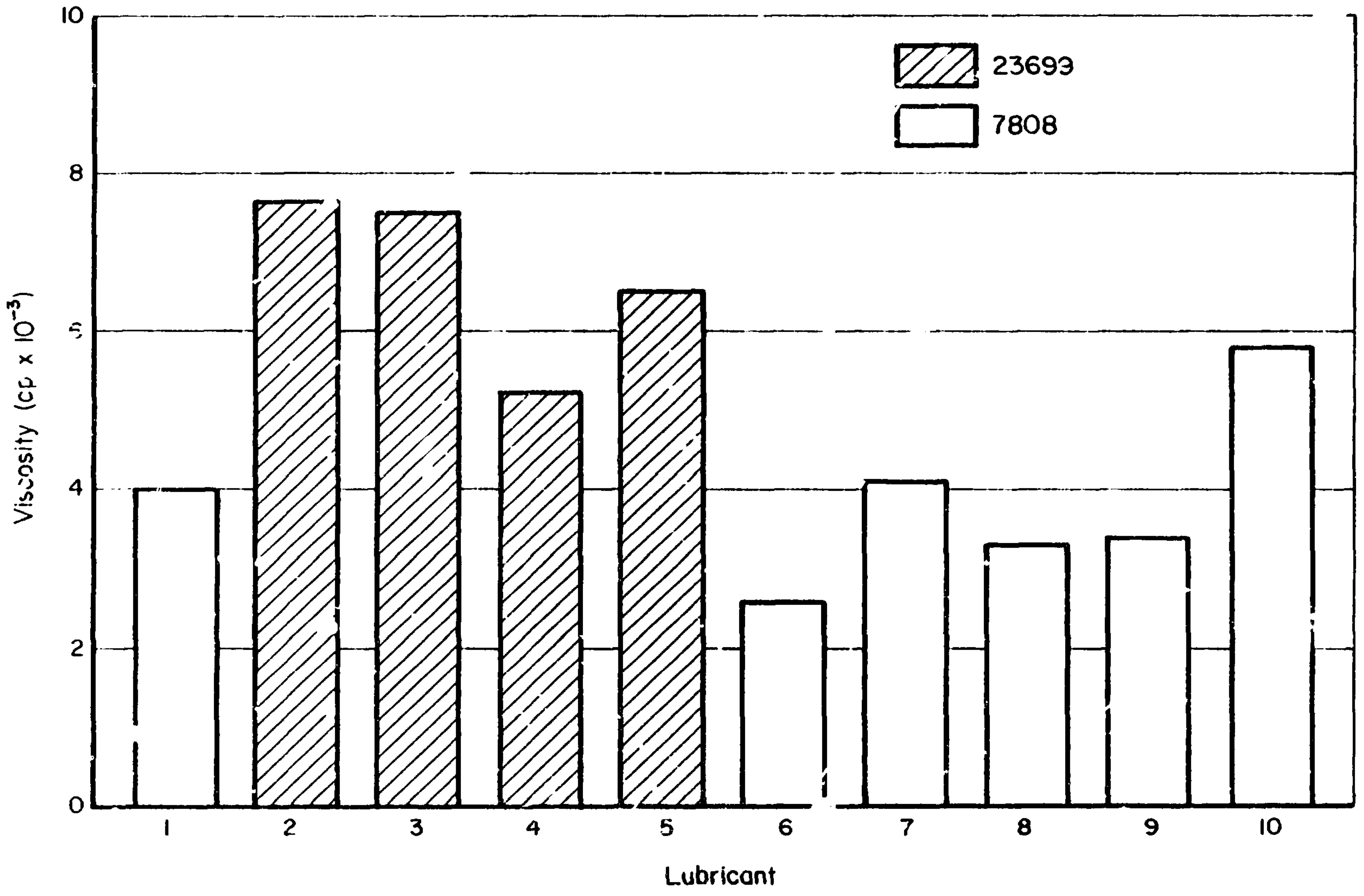


FIGURE 29. EFFECTIVE VISCOSITY OF THE LUBRICANT AT 1.2 GPa CALCULATED FROM THE TRACTION AND FILM THICKNESS DATA

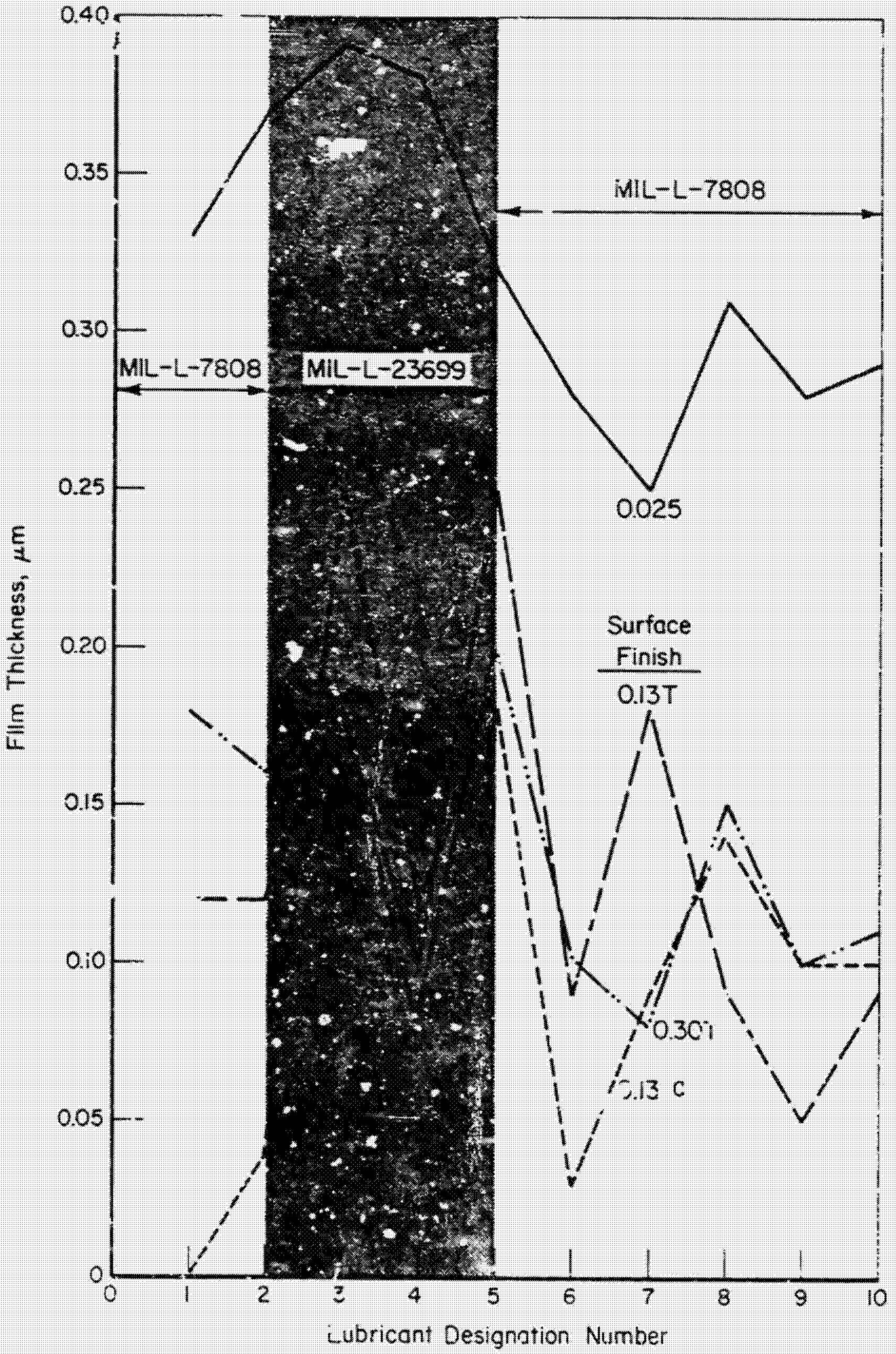


FIGURE 30. COMPARISON OF FILM THICKNESS FOR DIFFERENT SURFACE ROUGHNESS ON LOWER DISK

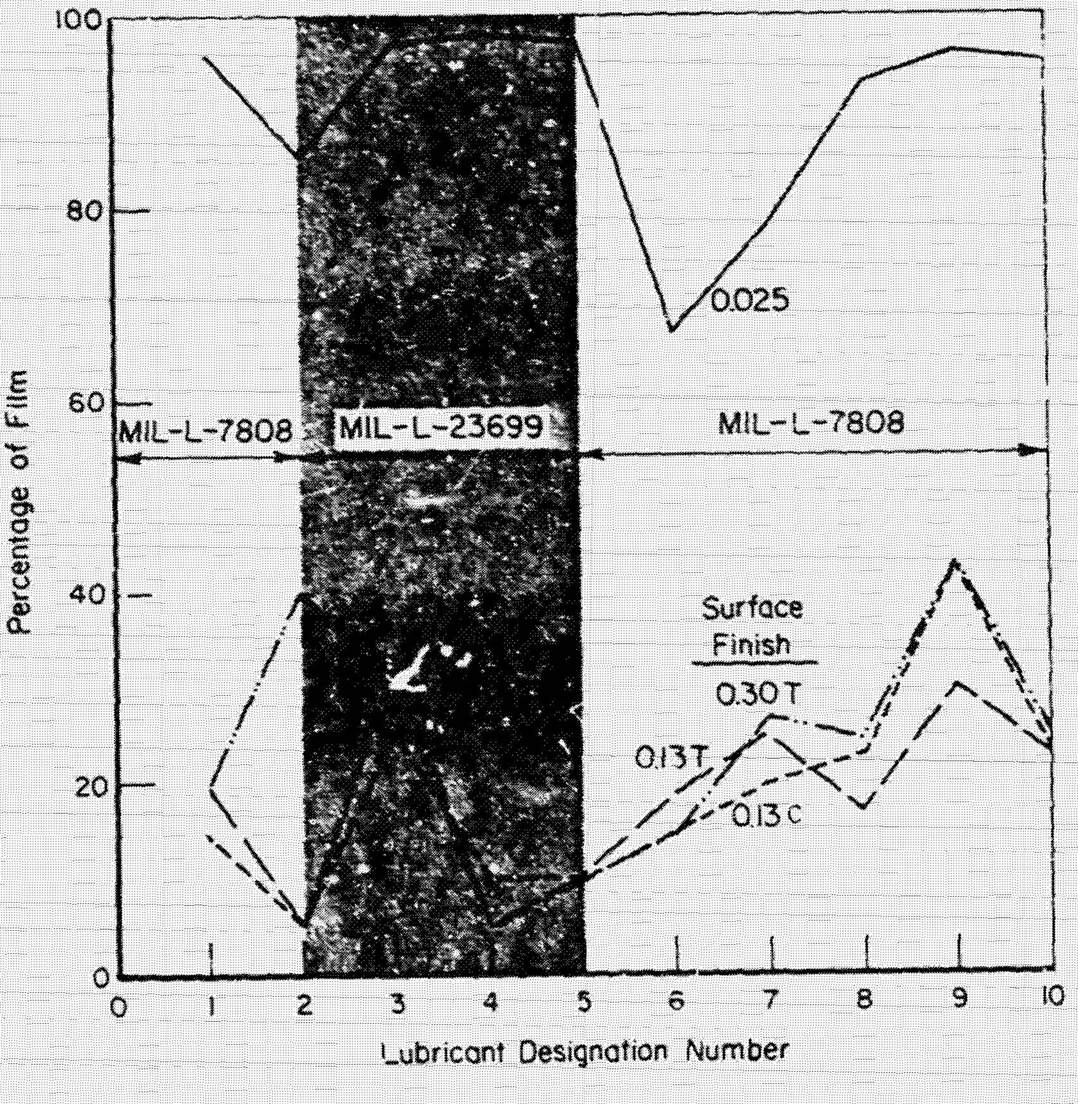


FIGURE 31. COMPARISON OF PERCENTAGE OF FILM FOR DIFFERENT SURFACE FINISHES ON THE LOWER DISK

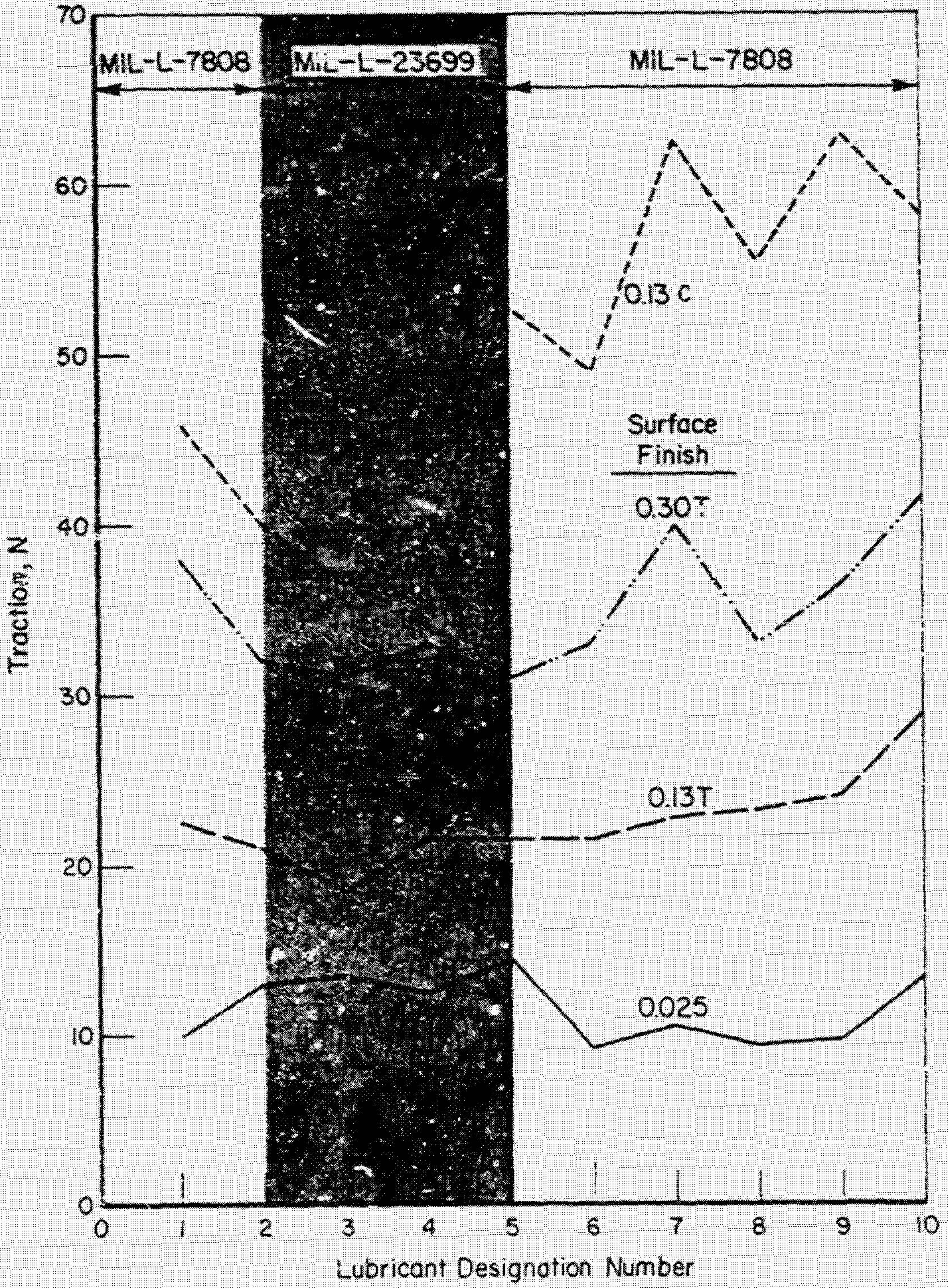


FIGURE 32. COMPARISON OF TRACTION VALUES FOR DIFFERENT SURFACE ROUGHNESS ON LOWER DISK

Figure 31 shows the percentage of film measured for the ten test lubricants. For the polished surfaces, the films separate the surfaces, except for lubricants 6 and 7 which were shown in Figure 30 to have the lowest values of film thickness. The rest of the surfaces are nearly the same indicating percentages of film averaging 20 percent.

Figure 32 shows the traction data for the ten test lubricants. The value shown is the traction at 2-1/2 percent slip. In this graph, a clear difference is noted among the lubricants as a function of the surface roughness of the lower disk. The lowest traction values were measured for the polished mating surfaces. The two transverse lay finishes each show increased traction values. The highest traction was measured with the circumferential lay finish.

CONCLUSIONS FROM THE LUBRICANT SPECIFICATION EXPERIMENTS

The ten fluids studied were representative samples of mil-spec lubricants now in service. These lubricants exhibited a broad range of operational performance even though they had met one of two similar specification requirements. Since all of these lubricants perform adequately in service, the experimental sequence must be more severe than the lubricants see in service. However, it is clear from the results of the experiments that some of the lubricants perform better than others and under some conditions, these specific lubricants can increase the life of the mechanism of interest.

As a result of these experiments, EHD requirements for 23699 and 7808 oils can be formulated. A sample specification for the oils studied can be written in the following form:

Sample Specification

EHD Properties

The film thickness, percentage of film and traction for the qualification test sample shall be determined using the method of the Specification Method (page 66). The disk surfaces should be polished to produce a surface roughness less than 0.03 μm (cla). The oil shall be supplied by a lubricant jet at a rate of at at least one liter per minute. Both disk and oil supply shall be at the same temperature (± 5 C). The disks shall be loaded together so as to produce a contact stress of 1.4 GPa and shall be rotated at 10,000 rpm.

The lubricant must have the following minimum characteristics.

MIL-L-7808G

Minimum film thickness: 0.25 μm at 90 C and 0.10 μm at 150 C
Minimum percent film : 60 percent at 90 C and 50 percent at 150 C
Traction : at 90 C the traction at 3 percent slip shall be between 7 to 15 N

MIL-L-23699B

Minimum film thickness: 0.3 μm at 90 C and 0.1 μm at 150 C
Minimum percent film : 80 percent at 90 C and 70 percent at 150 C
Traction : at 90 C the traction at 3 percent slip shall be between 7 and 15 N

SPECIFICATION METHOD

Experimental Procedures

Basic Apparatus

The specification experiments shall be conducted on the twin disk apparatus shown pictorially in Figure 33. The apparatus consists of two disks, each of which are driven by variable frequency induction motors. The shaft of the drive motors are integral with the disk drive shafts and are mounted in duplex ABEC-7 45 mm bearings. The electrical power to the motors is supplied by a variable frequency supply unit. Disk speeds up to 20,000 rpm and continuously variable slip-ratios between the disks can be achieved.

The disk in all experiments shall be 36 mm in diameter. One disk shall contain a 140 mm crown and the other shall be cylindrical or both shall have a 280 mm crown so that an elliptically shaped contact region is formed between the disks. These disks are mounted on tapered stub-shafts which fit into the drive shafts. The upper disk surface is electrically isolated from its stub-shaft by means of an alumina sleeve between the disk and shaft.

Loading is achieved by a deadweight system with a mechanical advantage of 12 (Figure 33). in the experiments, a pneumatic cylinder supports the load of the disks. This pneumatic arrangement also allows quick unloading of the disk when experiments are terminated. Elevated temperature is achieved by means of a heat pipe on the disks and by preheating the lubricants being evaluated. Both oil inlet and bulk disk temperature shall be monitored by standard thermocouples. For the disk temperature, the thermocouple is spot-welding to the upper disk and slip rings are used to transmit the signal from the rotating shaft. The disk temperature shall be within 5 degrees of the desired value.

As shown in Figure 34, the upper disk support unit is on a hinge such that any tangential force originating at the disk contact region tends to swing the unit in the force direction. A load cell is used to constrain this motion and to monitor the magnitude of the force.

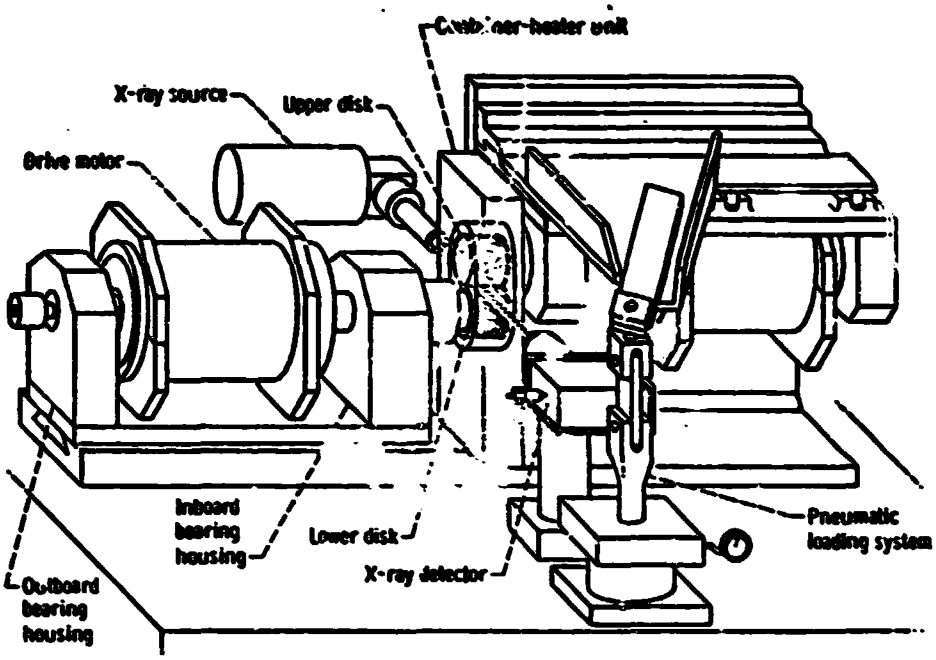


FIGURE 33. ROLLING-CONTACT DISK MACHINE

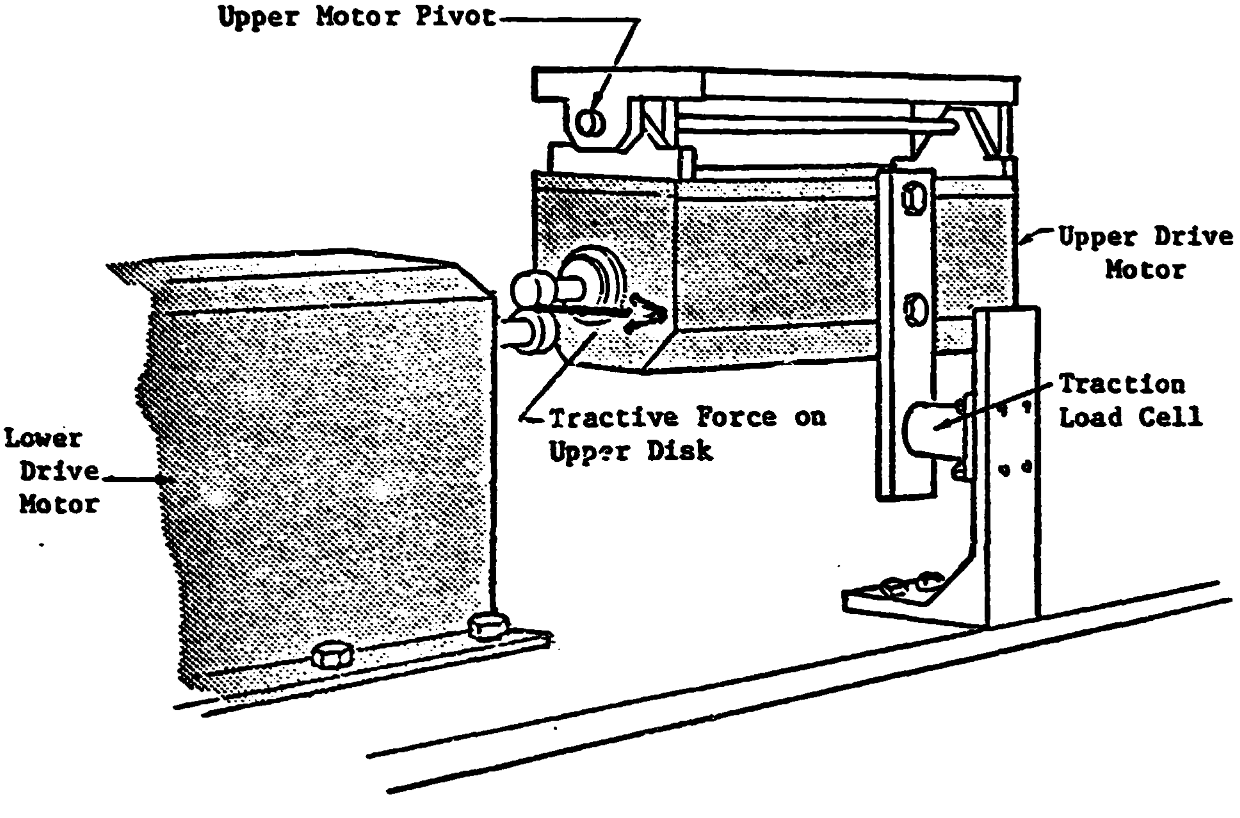


FIGURE 34. SCHEMATIC DRAWING OF DISK MACHINE ILLUSTRATING TRACTION MEASUREMENT

Instrumentation

Film Thickness Measurements. The disk machine is equipped with instrumentation to monitor several aspects of the disk contact zone phenomena. An X-ray technique is used to measure lubricant film thickness (see Figure 33). This technique consists of passing a collimated X-ray beam through the disk contact region and of monitoring the X-ray rate. Since the lubricants are much more transparent to the X-rays than the steel disks, this X-ray transmission can be related to the film-gap between the disks. Calibration of the X-ray beam is achieved by spreading the disks apart by 2-1/2 to 5 μm and measuring the X-ray transmission for these known separations.

In addition to film thickness measurements with the X-ray technique, percent film measurements are made with an electrical continuity technique. For this technique, 100 mv a-c is applied across the lubricant film from the electrically isolated upper disks to the lower and the breakdown of the voltage measured.

Traction-Slip Instrumentation. Slip is induced between the disks by varying the electrical frequency to the upper disk drive motor. This slip is monitored by measuring the speed of each disk independently using a pulsed source on each shaft. The output from the pick-ups are both fed into an electronic ratio meter which yields an electrical output proportional to percent slip.

Traction is detected by a commercial load-cell which senses the force required to constrain the upper disk support unit. The output from load cell transducer is fed into the y-axis of an x-y recorder, and the output from the speed ratio meter is fed into the x-axis.

In the traction experiments, the slip is varied continuously over a range from -5 percent to +5 percent. Using the x-y recorder, this variation in slip produces a continuous traction-slip curve for the particular lubricant being evaluated.

SUMMARY OF RESULTS

The objective of the project has been to conduct a series of experiments to aid in defining a lubricant-performance input to a military specification. The first task of the project was directed toward defining lubricant-performance criteria while the later tasks were directed toward definite performance experiments.

A compilation of film thickness data was developed using the X-ray technique for three lubricants: a synthetic mineral oil without additive (XRM 109), a mineral oil with additive (XRM 177), and a traction fluid. The film thicknesses have been found to be a predictable function of viscosity, velocity, load, and surface roughness [see Equation (2) on page 35].

The percent film measurements indicate that typical bearings or gears will tend to operate either in a full film mode or a high metallic contact m of lubrication. The dividing line between these two modes of lubrication occurs over a small range of film thickness. Full film lubrication occurs only when the surfaces are very smooth, and the viscosity of the lubricant is very high. If, on the other hand, the viscosity is low or the surfaces are rough, a high percentage of metallic contact will occur. If, for example, the ratio of film thickness to surface roughness is less than 3-4, significant evidence of metallic contact will occur. Equation (3) in the text would predict a 50 percent film for this condition.

As a result of the EHD evaluation, the following observations were made:

(1) The film thickness measured by the X-ray system increased with speed and viscosity and decreased with load [See Equation (1)].

(2) An increase in surface roughness decreased the film thickness and the percentage of film.

(3) The lay of the surface finish had an effect on film thickness and percent film. The circumferential lay finish produced the thickest film but resulted in lower percent film indications presumably because of the number of asperities in the elliptically shaped contact region.

(4) The film thicknesses measured with XRM 109F and XRM 177F were very similar for the range of conditions studied, although the percent film indications tended to be higher with the XRM 177F.

(5) In all case experiments, Santotrac 50 produced thinner films and lower percentage of film than the XRM 109 or XRM 177 due to its lower viscosity.

(6) The measured tractions for the Santotrac 50 were significantly higher than for the XRM 177F and XRM 109F which were similar.

(7) Ten lubricants (six MIL-L-7808 and four MIL-L-23699 fluids) were evaluated. Although none of the fluids evaluated had shown poor performance in service, there was scatter in the data indicating performance variations. A sample specification has been written and is enclosed.

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APPENDIX A

INITIAL FILM THICKNESS/PERCENT FILM DATA RECORDED FOR XRM-109 F AND XRM-177 LUBRICANTS

TABLE A-1. INITIAL FILM THICKNESS (μm)/PERCENTAGE OF FILM FOR XRM-109 LUBRICANT AND POLISHED MATING DISKS

Hertz Stress, GPa	No Slip Speed, rpm x 10^{-3}				50 Percent Slip Speed, rpm x 10^{-3}			
	20	15	10	5	20	15	10	5
				65 C				
1.05	1.4/98	1.3/97	1.2/97	1.0/91	1.0/97	.94/93	.89/93	.84/65
1.41	1.1/95	1.1/95	1.0/94	.94/89	.89/89	.69/88	.56/93	.51/83
1.76	.97/97	.94/97	.89/98	.81/91	.33/88	.33/76	.25/78	.2/85
2.11	.81/97	.75/95	.66/87	.56/78	.1/90	.1/90	0/65	0/65
				90 C				
1.05	1.2/99	1.1/97	1./95	.76/93	.84/99	.77/99	.71/99	.46/99
1.41	.94/98	.76/98	.71/94	.64/99	[illegible]	.5/97	.36/90	.30/97
1.76	.81/97	.69/88	.64/93	.51/98	.3[illegible]/95	.25/88	.2/56	.12/85
2.11	.68/95	.58/92	.49/88	.36/7[illegible]	.15/78	.1/65	.1/61	.1/75
				150 C				
1.05	.66/97	.61/94	.51/83	.36/27	.3/78	.33/49	.2/10	
1.41	.36/98	.31/97	.23/89	.2/25	.2[illegible]/49	.22/14		
1.76	.30/91	.25/91	.23/72	.13/<5	.20/28	.1/13		
2.11	.23/88	.18/73	.16/38	.1/<5	.1/16	0/6		

TABLE A-2. INITIAL FILM THICKNESS (μm)/PERCENTAGE OF FILM FOR XRM-109 LUBRICANT USING MATING DISKS WITH .25 μm CLA CIRCUMFERENTIAL AND TRANSVERSE SURFACE FINISH LAYS

Hertz Stress GPa	No Slip Speed, rpm x 10^{-3} 20	15	10	5	50 Percent Slip Speed, rpm x 10^{-3} 20	15	10	5
Circumferential Lay								
65 C								
1.05	1.1/96	1.11/95	1.0/88	.89/71	.69/15	-	-	-
1.41	.91/95	.87/84	.84/70	.71/35	-	-	-	-
1.76	.69/64	.69/49	.64/37	.56/15	-	-	-	-
2.11	.56/48	.53/38	.59/43	.53/<10	-	-	-	-
90 C								
1.05	.89/90	.82/78	.79/63	.69/20	.38/0	-	-	-
1.41	.7[illegible]/84	.7[illegible]/53	.66/33	.51/<10	-	-	-	-
1.76	.[illegible]/75	.43/20	-	-	-	-	-	
150 C								
1.05	[illegible]/18	.33/8	-	-	.13/8	-	-	-
1.41	-	-	-	-	-	-	-	-
Transverse Lay								
65 C								
1.05	1.0/91	.91/68	.87/87	.71/75	.64/80	.56/70	/<30	-
1.41	.73/93	.79/84	.71/74	.66/42	-	-	-	-
1.76	.56/84	.46/67	.38/5[illegible]	.[illegible]8/[illegible]	-	-	-	-
2.11	.46/84	.46/52	.38/36	.38/12	-	-	-	-
90 C								
1.05	.89/8[illegible]	.71/87	.64/68	.56/16	.59/45	.51/30	-	-
1.41	.51/[illegible]7	.46/72	.41/50	-/<15	-	-	-	-
150 C								
1.05	.5[illegible]/[illegible]5	.33/[illegible]	-	-	.13/0	-	-	-

TABLE A-3. INITIAL FILM THICKNESS (µm)/PERCENTAGE OF FILM FOR XRM-109 LUBRICANT USING MATING DISKS WITH TRANSVERSE LAY ROUGHNESS

Hertz Stress, GPa	No Slip Speed, rpm x 10^{-3}				50 Percent Slip Speed, rpm x 10^{-3}			
	20	15	10	5	20	15	10	5
				.35 µm cla Finish				
				65 C				
1.05	.86/78	.81/71	.66/30	.56/10	.59/15	-	-	-
1.41	.51/73	.43/42	.36/22	-	-	-	-	-
1.76	.33/44	.25/43	/<15	-	-	-	-	-
				90 C				
1.05	.71/45	.56/30	/<10	-	.23/6	-	-	-
				150 C				
1.05	.81/30	.71/25	-	-	.1/20	-	-	-
				.54 µm cla				
				65 C				
1.05	.84/35	.59/20	.33/ 10		.05/10			
				90 C				
1.05	.33/5	-	-	-	0/0	-	-	-
				150 C				
1.05	.45/20	-	-	-	0/0	-	-	-

TABLE A-4. INITIAL FILM THICKNESS (μm)/PERCENTAGE OF FILM FOR XRM-177F LUBRICANT AND POLISHED MATING DISKS

Load, GPa	No Slip Speed, rpm x 10^{-3} 20	15	10	5	50 Percent Slip Speed, rpm x 10^{-3} 20	15	10	5
				65 C				
1.05	1.7/100	1.3/100	1/2/100	1.1/100	1.0/100	.94/100	.84/100	.74/100
1.41	1.1/100	1.1/100	1.1/100	.94/100	.64/100	.61/100	.56/100	.48/100
1.76	.76/100	1.0/100	.94/100	.83/100	.43/99	.41/98	.31/94	.25/92
2.11	.71/100	.71/100	.66/100	.61/100	.26/90	.1/85*		
				90 C				
1.05	.91/100	.79/100	.71/100	.61/100	.74/100	.66/100	.59/100	.48/100
1.41	.73/100	.73/100	.66/100	.56/100	.51/100	.46/100	.43/100	.33/100
1.76	.71/100	.66/100	.59/100	.48/100	.71/100	.15/100	.1/100	.10/100
2.11	.64/100	.59/100	.53/100	.43/100	.10/100	.10/99	.1/98	.10/94
				150 C				
1.05	.64/100	.51/100	.41/100	.33/100	.40/100	.33/100	.25/100	.20/100
1.41	.36/100	.43/100	.33/100	.25/100	.23/100	.25/100	.20/100	.10/99
1.76	.33/100	.33/100	.24/100	.23/100	.23/100	.20/99	.15/99	.10/96
2.11	.38/100	.33/100	.28/100	.18/100	.1/99	.1/97	0/95	0/90

*Percent film was dropping on this run. Disks were taken out of contact at 65 percent.

TABLE A-5. FILM THICKNESS (μm)/PERCENTAGE OF FILM FOR XRM-177F LUBRICANT USING MATING DISKS WITH 0.15 μm CLA CIRCUMFERENTIAL AND TRANSVERSE SURFACE FINISH LAYS

	No Slip				50 Percent Slip			
	Speed, rpm x 10^{-3}				Speed, rpm x 10^{-3}			
Load, GPa	20	15	10	5	20	15	10	5
				Circumferential Lay				
				65 C				
1.05	1.0/96*	.94/96	.87/91	.71/30	.71/22			
1.41	.84/98	.84/90	.76/85	.69/25				
1.76	.76/97	.76/90	.74/82	.51/30				
				90 C				
1.05	.76/97	.59/98	.38/45	-/<5	.25/20			
				150 C				
1.05	.43/44	.38/25			.20/25			
				Transverse Lay				
				65 C				
1.05	1.1/97	.87/96	.76/94	.64/84	.81/98	.69/94	.64/90	.56/60
1.41	.66/96	.66/94	.59/91	.51/67	.51/80	.35/75	.31/15	
1.76	.69/95	.64/97	.59/93	.51/74				
2.11	.43/95	.31/89	.18/84	.10/37				
				90 C				
1.05	.71/80	.51/70	.43/50	-/<15	.71/99	51/98	.46/93	.31/60
1.41					.25/95	.18/13		
				150 C				
1.05	.64/30	.33/15			0/0			

*Film Thickness (μin.)/Percentage of Film.

TABLE A-6. INITIAL FILM THICKNESS (μm)/PERCENTAGE OF FILM FOR XRM-177 LUBRICANT USING MATING DISKS WITH TRANSVERSE LAY ROUGHNESS

Load,	0 Slip				50% Slip			
	Speed, rpm x 10^{-3}				Speed, rpm x 10^{-3}			
GPa	20	15	10	5	20	15	10	5
				.35 μm cla Finish				
				65 C				
1.05	.94/75	.71/90	.62/90	.51/40	.33/99	30/60	.20/40	
1.41	.53/80	.43/90	.43/90	.38/12				
1.76								
2.11								
				90 C				
1.05	.56/85	.46/60	.31/50	.20/-	.31/30	.20/15		
				150 C				
1.05	.18/60	.13/40	.10/30	.10/10	.1/10			
				.54 μm cla Finish				
				65 C				
1.05	.56/25	.33/15	.20/3	-/0	.31/5			
				90 C				
1.05	.31/35	.23/10			.20/30	.10/30		
				150 C				
1.05	.18/3				0/12			

APPENDIX B

COMPUTER PRINT-OUT OF FILM THICKNESS/PERCENT FILM CURVE FIT MODEL

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TABLE B-1 MEASURED AND PREDICTED FILM THICKNESS FROM CURVE FIT MODEL

Viscosity, cp	Load, GPa	Velocity, 10^3 rpm	Roughness, µm	Measured Film, µm	Predicted Film, µm	Predicted Percent Film	Measured Percent Film
.10000E+03	.10000E+01	.10000E+02	.50000E-01	.17000E+01	.16937E+01	.99992E+00	.99900E+00
.10000E+03	.12000E+01	.10000E+02	.50000E-01	.14000E+01	.14621E+01	.99969E+00	.99900E+00
.10000E+03	.14000E+01	.10000E+02	.50000E-01	.13000E+01	.12912E+01	.99920E+00	.99900E+00
.10000E+03	.16000E+01	.10000E+02	.50000E-01	.13000E+01	.11594E+01	.99831E+00	.99900E+00
.10000E+03	.18000E+01	.10000E+02	.50000E-01	.11000E+01	.10543E+01	.99693E+00	.99900E+00
.10000E+03	.10000E+01	.50000E+01	.50000E-01	.15000E+01	.14464E+01	.99967E+00	.99900E+00
.10000E+03	.12000E+01	.50000E+01	.50000E-01	.12000E+01	.12486E+01	.99858E+00	.99900E+00
.10000E+03	.14000E+01	.50000E+01	.50000E-01	.11000E+01	.11027E+01	.99766E+00	.99900E+00
.10000E+03	.16000E+01	.50000E+01	.50000E-01	.10000E+01	.99013E+00	.99558E+00	.99900E+00
.10000E+03	.18000E+01	.50000E+01	.50000E-01	.93000E+00	.90042E+00	.99266E+00	.96000E+00
.10000E+03	.10000E+01	.10000E+02	.15000E+00	.11400E+01	.11450E+01	.93922E+00	.99000E+00
.10000E+03	.12000E+01	.10000E+02	.15000E+00	.97000E+00	.98642E+00	.90646E+00	.92000E+00
.10000E+03	.14000E+01	.10000E+02	.15000E+00	.11000E+01	.87289E+00	.87168E+00	.92000E+00
.10000E+03	.16000E+01	.10000E+02	.15000E+00	.11000E+01	.78379E+00	.83652E+00	.90000E+00
.10000E+03	.18000E+01	.10000E+02	.15000E+00	.10000E+01	.71277E+00	.80201E+00	.88000E+00
.10000E+03	.10000E+01	.50000E+01	.15000E+00	.95900E+00	.97781E+00	.90370E+00	.97000E+00
.10000E+03	.12000E+01	.50000E+01	.15000E+00	[illegible]	.84412E+00	.86122E+00	.75000E+00
.10000E+03	.14000E+01	.50000E+01	.15000E+00	[illegible]	.74546E+00	.81869E+00	.65000E+00
.10000E+03	.16000E+01	.50000E+01	.15000E+00	.[illegible]3000E+00	.66936E+00	.77758E+00	.50000E+00
.10000E+03	.10000E+01	.10000E+02	.15000E+00	.1[illegible]000E+01	.11450E+01	.95187E+00	.99000E+00
.10000E+03	.17000E+01	.10000E+02	.15000E+00	.93000E+00	.98642E+00	.92444E+00	.98000E+00
.10000E+03	.14000E+01	.10000E+02	.15000E+00	.[illegible]1000E+01	.87289E+00	.89595E+00	.97000E+00
.10000E+03	.16000E+01	.10000E+02	.15000E+00	.[illegible]1000E+00	.78379E+00	.86693E+00	.97000E+00
.10000E+03	.18000E+01	.10000E+02	.15000E+00	.[illegible]5000E+00	.71277E+00	.83819E+00	.95000E+00
.10000E+03	.10000E+01	.50000E+01	.15000E+00	.12000E+01	.97781E+00	.92218E+00	.96000E+00
.10000E+03	.12000E+01	.50000E+01	.15000E+00	.86000E+00	.84412E+00	.88734E+00	.94000E+00
.10000E+03	.14000E+01	.50000E+01	.15000E+00	.72000E+00	.74546E+00	.85211E+00	.92000E+00
.10000E+03	.16000E+01	.50000E+01	.15000E+00	.73000E+00	.66936E+00	.81770E+00	.88000E+00
.10000E+03	.18000E+01	.50000E+01	.15000E+00	.63000E+00	.60871E+00	.78477E+00	.48000E+00
.55000E+02	.10000E+01	.10000E+02	.50000E-01	.13000E+01	.11236E+01	.99793E+00	.99900E+00
.55000E+02	.12000E+01	.10000E+02	.50000E-01	.93000E+00	.97000E+00	.99505E+00	.99000E+00
.55000E+02	.14000E+01	.10000E+02	.50000E-01	.88000E+00	.85662E+00	.99060E+00	.98000E+00
.55000E+02	.16000E+01	.10000E+02	.50000E-01	.73000E+00	.76916E+00	.98455E+00	.98000E+00
.55000E+02	.18000E+01	.10000E+02	.50000E-01	.65000E+00	.[illegible]9949E+00	.97715E+00	.97000E+00
.55000E+02	.10000E+01	.50000E+01	.50000E-01	.86000E+00	.95959E+00	.99475E+00	.99[illegible]00E+00
.55000E+02	.12000E+01	.50000E+01	.50000E-01	.82000E+00	.82839E+00	.98898E+00	.9[illegible]00E+00
.55000E+02	.14000E+01	.50000E+01	.50000E-01	.82000E+00	.73157E+00	.98094E+00	.99600E+00
.55000E+02	.16000E+01	.50000E+01	.50000E-01	.75000E+00	.65689E+00	.97094E+00	.99000E+00
.55000E+02	.18000E+01	.50000E+01	.50000E-01	.75000E+00	.59737E+00	.95934E+00	.63000E+00
.55000E+02	.10000E+01	.10000E+02	.15000E+00	.90000E+00	.75961E+00	.82548E+00	.93000E+00
.55000E+02	.12000E+01	.10000E+02	.15000E+00	.71000E+00	.65575E+00	.76935E+00	.82000E+00
.55000E+02	.14000E+01	.10000E+02	.15000E+00	.68000E+00	.57911E+00	.71737E+00	.74000E+00
.55000E+02	.16000E+01	.10000E+02	.15000E+00	.54000E+00	.51999E+00	.67006E+00	.40000E+00
.55000E+02	.18000E+01	.10000E+02	.15000E+00	.41000E+00	.47288E+00	.62732E+00	.15000E+00
.55000E+02	.10000E+01	.50000E+01	.15000E+00	.54000E+00	.64871E+00	.76498E+00	.10000E+00
.55000E+02	.10000E+01	.10000E+02	.15000E+00	.72000E+00	.75961E+00	.85776E+00	.99900E+00
.55000E+02	.12000E+01	.10000E+02	.15000E+00	.65000E+00	.65575E+00	.81077E+00	.96000E+00
.55000E+02	.14000E+01	.10000E+02	.15000E+00	.55000E+00	.57911E+00	.76665E+00	.91000E+00
.55000E+02	.16000E+01	.10000E+02	.15000E+00	.57000E+00	.51999E+00	.72593E+00	.88000E+00

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TABLE B-1. (Continued)

Viscosity, cp	Load, GPa	Velocity, 10^3 rpm	Roughness, µm	Measured Film, µm	Predicted Film, µm	Predicted Percent Film	Measured Percent Film
.55000E+02	.18000E+01	.10000E+02	.15000E+00	.43000E+00	.47288E+00	.68864E+00	.[illegible]5000E+00
.55000E+02	.10000E+01	.50000E+01	.15000E+00	.61000E+00	.64871E+00	.80709E+00	.60000E+00
.55000E+02	.12000E+01	.50000E+01	.15000E+00	.50000E+00	.56002E+00	.75419E+00	.50000E+00
.55000E+02	.14000E+01	.50000E+01	.15000E+00	.40000E+00	.49456E+00	.70637E+00	.25000E+00
.10000E+03	.10000E+01	.10000E+02	.50000E-01	.15000E+01	.16937E+01	.99992E+00	.99300E+00
.10000E+03	.12000E+01	.10000E+02	.50000E-01	.13580E+01	.14621E+01	.99969E+00	.99900E+00
.10000E+03	.14000E+01	.10000E+02	.50000E-01	.11500E+01	.12912E+01	.99920E+00	.99900E+00
.10000E+03	.16000E+01	.10000E+02	.50000E-01	.10300E+01	.11594E+01	.99831E+00	.99900E+00
.10000E+03	.18000E+01	.10000E+02	.50000E-01	.90000E+00	.10543E+01	.99693E+00	.99900E+00
.10000E+03	.10000E+01	.50000E+01	.50000E-01	.13000E+01	.14464E+01	.99967E+00	.99900E+00
.10000E+03	.12000E+01	.50000E+01	.50000E-01	.13000E+01	.12486E+01	.99898E+00	.99300E+00
.10000E+03	.14000E+01	.50000E+01	.50000E-01	.11000E+01	.11027E+01	.99766E+00	.99900E+00
.10000E+03	.16000E+01	.50000E+01	.50000E-01	.10300E+01	.99013E+00	.99558E+00	.99900E+00
.10000E+03	.18000E+01	.50000E+01	.50000E-01	.93000E+00	.90042E+00	.99266E+00	.99900E+00
.10000E+03	.10000E+01	.10000E+02	.15000E+00	.13000E+01	.11450E+01	.93922E+00	.95000E+00
.10000E+03	.12000E+01	.10000E+02	.15000E+00	.10000E+01	.98842E+00	.90646E+00	.90000E+00
.10000E+03	.14000E+01	.10000E+02	.15000E+00	.73000E+00	.87289E+00	.87168E+00	.88000E+00
.10000E+03	.16000E+01	.10000E+02	.15000E+00	.80000E+00	.78379E+00	.83652E+00	.80000E+00
.10000E+03	.18000E+01	.10000E+02	.15000E+00	.68000E+00	.71277E+00	.80201E+00	.50000E+00
.10000E+03	.10000E+01	.50000E+01	.15000E+00	.11000E+01	.97781E+00	.90370E+00	.93000E+00
.10000E+03	.12000E+01	.50000E+01	.15000E+00	.10000E+01	.64412E+00	.66122E+00	.90000E+00
.10000E+03	.14000E+01	.50000E+01	.15000E+00	.95000E+00	.74546E+00	.81869E+00	.80000E+00
.10000E+03	.16000E+01	.50000E+01	.15000E+00	.82000E+00	.66936E+00	.77758E+00	.78000E+00
.10000E+03	.18000E+01	.50000E+01	.15000E+00	.75000E+00	.60871E+00	.73863E+00	.30000E+00
.10000E+03	.10000E+01	.10000E+02	.15000E+00	.11000E+01	.11450E+01	.95107E+00	.99000E+00
.10000E+03	.12000E+01	.10000E+02	.15000E+00	.11000E+01	.98842E+00	.92444E+00	.98000E+00
.10000E+03	.14000E+01	.10000E+02	.15000E+00	.62000E+00	.87289E+00	.89595E+00	.95000E+00
.10000E+03	.16000E+01	.10000E+02	.15000E+00	.52000E+00	.78379E+00	.86693E+00	.90000E+00
.10000E+03	.18000E+01	.10000E+02	.15000E+00	.45000E+00	.71277E+00	.83819E+00	.65000E+00
.10000E+03	.10000E+01	.50000E+01	.15000E+00	.56000E+00	.97781E+00	.92218E+00	.99000E+00
.10000E+03	.12000E+01	.50000E+01	.15000E+00	.82000E+00	.84412E+00	.88734E+00	.95000E+00
.10000E+03	.14000E+01	.50000E+01	.15000E+00	.60000E+00	.74546E+00	.85211E+00	.85000E+00
.10000E+03	.16000E+01	.50000E+01	.15000E+00	.50000E+00	.66935E+00	.81770E+00	.80000E+00
.10000E+03	.18000E+01	.50000E+01	.15000E+00	.47000E+00	.60871E+00	.78477E+00	.50000E+00
.55000E+02	.10000E+01	.10000E+02	.50000E-01	.10400E+01	.11236E+0	.99793E+00	.99900E+00
.55000E+02	.12000E+01	.10000E+02	.50000E-01	.91000E+00	.97000E+	.99505E+00	.99900E+00
.55000E+02	.14000E+01	.10000E+02	.50000E-01	.93000E+00	.85662E+	.99060E+00	.96000E+00
.55000E+02	.16000E+01	.10000E+02	.50000E-01	.90000E+00	.76[illegible]E+00	.98[illegible]55E+00	.95000E+00
.55000E+02	.18000E+01	.10000E+02	.50000E-01	.71000E+00	.69949E+00	.97715E+00	.94000E+00
.55000E+02	.10000E+01	.50000E+01	.50000E-01	.68000E+00	.95959E+0	.99475E+00	.99900E+00
.55000E+02	.12000E+01	.50000E+01	.50000E-01	.82000E+00	.82839E+0	.98895E+00	.98000E+00
.55000E+02	.14000E+01	.50000E+01	.50000E-01	.71000E+00	.73157E+00	.98094E+00	.97000E+00
.55000E+02	.16000E+01	.50000E+01	.50000E-01	.70000E+00	.65689E+00	.97094E+00	.90000E+00
.55000E+02	.18000E+01	.50000E+01	.50000E-01	.61000E+00	.59737E+00	.95934E+00	.87000E+00
.55000E+02	.10000E+01	.10000E+02	.15000E+00	.79000E+00	.75961E+00	.82546E+00	.50000E+00
.55000E+02	.12000E+01	.10000E+02	.15000E+00	.79000E+00	.65575E+00	.76935E+00	.35000E+00
.55000E+02	.14000E+01	.10000E+02	.15000E+00	.75000E+00	.57911E+00	.71737E+00	.10000E+00
.55000E+0	.10000E+01	.10000E+02	.15000E+00	.63000E+00	.75961E+00	.85776E+00	.80000E+00
.55000E+02	.12000E+01	.10000E+02	.15000E+00	.63000E+00	.65575E+00	.81077E+00	.55000E+00
.55000E+02	.14000E+01	.10000E+02	.15000E+00	.57000E+00	.57911E+00	.76665E+00	.44000E+00
.55000E+02	.16000E+01	.10000E+02	.15000E+00	.54000E+00	.51999E+00	.72593E+00	.26000E+00
.55000E+02	.18000E+01	.10000E+02	.15000E+00	.41000E+00	.47288E+00	.68864E+00	.10000E+00
.55000E+02	.10000E+01	.50000E+01	.15000E+00	.54000E+00	.64871E+00	.80709E+00	.15000E+00

APPENDIX C

SUMMARY OF TRACTION DATA FOR VARIOUS LUBRICANTS

TABLE C-1. TRACTION DATA USING XRM-109F LUBRICANT (POLISHED DISKS)

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
			1.3	3.5
1.0	5,000	65	7.6	4.0
1.4	5,000	65	24.9	6.0
			0.9	3.0
1.0	10,000	65	5.8	5.0
1.4	10,000	65	16.5	3.5
1.0	15,000	65	0.9	1.0
1.4	15,000	65	18.7	4.0
1.0	20,000	65	4.5	3.0
1.4	20,000	54	17.8	6.0
			0.2	5.0
1.0	5,000	90	5.3	12.0
1.4	5,000	90	16.9	10.0
1.0	10,000	90	4.0	6.0
1.4	10,000	90	15.1	8.0
			1.3	5.0
1.0	15,000	90	5.8	3.0
1.4	15,000	90	14.2	6.0
1.0	20,000	90	--	--
1.4	20,000	90	14.5	3.5
			49.0	4.0
1.0	5,000	150	--	>25.0
1.4	5,000	150	--	>25.0
1.0	10,000	150	--	--
1.4	10,000	150	12.9	15.0
1.0	15,000	150	--	--
1.4	15,000	150	9.8	10.0
1.0	15,000	150	--	--
1.4	15,000	150	--	--
			15.6	11.0

TABLE C-2. TRACTION DATA GENERATED USING XRM-109F AND MATING DISKS WITH 0.15 μm TRANSVERSE LAY SURFACE FINISHES

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	5,000	65	6.7	7.5
1.4	5,000	65	26.7	6.5
1.0	10,000	65	5.8	5.0
1.4	10,000	65	23.6	4.5
1.0	15,000	65	8.0	8.5
1.4	15,000	65	24.0	5.5
1.0	20,000	65	(a)	(a)
1.4	20,000	65	(b)	(b)
1.0	5,000	90	--	>25.0
1.4	5,000	90	(c)	(c)
1.0	10,000	90	5.1	7.0
1.4	10,000	90	17.4	6.5
1.4	10,000	90	21.4	8.0
1.0	15,000	90	3.8	6.0
1.4	15,000	90	22.3	6.5
		90	16.0	8.0
1.0	20,000	90	(a)	(a)
1.4	20,000	90	(a)	(a)
1.5	20,000	90	30.0	5.0
1.0	10,000	150	--	>25.0
1.4	10,000	150	15.8	15.0
1.0	15,000	150	2.4	8.0
1.4	15,000	150	12.9	11.0
1.5	20,000	150	21.8	12.0

(a) Vibration was too great to obtain a reading.

(b) Temperature could not be maintained at 65 C.

(c) Surface damage condition.

TABLE C-3. TRACTION CHARACTERISTICS OF XRM-109F FLUID FOR 0.15 μm CLA CIRCUMFERENTIAL SURFACE FINISH

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	5,000	65	9.8	8.0
1.4	5,000	65	30.5	9.0
1.0	10,000	65	7.3	8.0
1.5	10,000	65	25.4	6.0
1.0	15,000	65	8.5	8.0
1.5	15,000	65	24.3	7.5
1.0	20,000	65	7.1	6.5
1.5	20,000	65	17.3	3.0
1.0	5,000	90	6.9	11.0
1.5	5,000	90	(a)	(a)
1.0	10,000	90	7.1	10.0
1.5	10,000	90	21.8	10.0
1.0	15,000	90	6.2	7.0
1.5	15,000	90	22.5	8.5
1.0	20,000	90	(b)	(b)
1.5	20,000	90	20.2	3.0
1.0	5,000	150	(c)	(c)
1.5	5,000	150	(c)	(c)
1.0	10,000	150	--	>25.0
1.5	10,000	150	(d)	(d)
1.0	15,000	150	7.8	9.0
1.5	15,000	150	9.0	10.0
1.0	20,000	150		
1.5	20,000	150	18.7	14.0

(a) Surface damage would exist at this condition.

(b) Vibration problems.

(c) Test not run because of possible damage.

(d) Too much contact at last condition.

TABLE C-4. TRACTION DATA GENERATED USING XRM-109F AND MATING DISKS WITH 0.30 µm TRANSVERSE LAY SURFACE FINISHES

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	5,000	65	9.8	10.0
1.0	10,000	65	7.4	7.5
1.4	10,000	65	20.8	4.0
1.0	15,000	65	4.9	5.0
1.4	15,000	65	20.9	5.0
1.4	20,000	(a)	(a)	(a)
1.0	10,000	90	6.3	6.0
1.4	10,000	90	22.0	5.0
1.0	15,000	90	5.0	6.0
1.4	15,000	90	20.5	5.0
1.4	20,000	(b)	(b)	(b)
1.0	10,000	150	7.0	10.0
1.4	10,000	150	23.1	10.0
1.0	15,000	150	7.1	10.0
1.4	15,000	150	25.8	10.0

(a) Temperature could not be maintained at 65 C.

(b) Temperature could not be maintained at 90 C.

TABLE C-5. TRACTION DATA FOR XRM-177F USING POLISHED MATING DISKS

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	15,000	65	8.0	5.0
1.4	15,000	65	22.5	3.5
1.0	10,000	65	9.0	8.0
1.4	10,000	65	27.0	4.0
1.0	5,000	65	11.0	9.0
1.4	5,000	65	33.0	5.0
1.0	15,000	90	--	>25.0
1.4	15,000	90	21.5	5.0
1.0	10,000	90	7.7	6.5
1.4	10,000	90	25.0	8.0
1.0	5,000	90	7.5	11.0
1.4	5,000	90	30.0	14.0
1.0	15,000	150	4.5	22.0
1.4	15,000	150	17.0	20.0
1.0	10,000	150	4.0	8.0
1.4	10,000	150	15.5	13.0
1.0	5,000	150	3.5	13.0
1.4	5,000	150	16.5	19.0

TABLE C-6. SUMMARY OF TRACTION DATA FOR XRM-177F USING ROUGHENED MATING DISKS WITH 0.15 μm CLA TRANSVERSE LAY FINISH

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	15,000	65	10.5	10.0
1.4	15,000	65	28-0	10.0
1.0	10,000	65	9.0	6.0
1.4	10,000	65	29.2	5.0
1.0	5,000	65	12.0	8.0
1.0	15,000	90	10.8	10.0
1.4	15,000	90	30.0	>25.0
1.0	10,000	90	9.7	11.0
1.4	10,000	90	30.0	11.0
1.0	5,000	90	11.5	>25.0
1.0	15,000	150	7.2	>25.0
1.0	10,000	150	8.2	>25.0

TABLE C-7. SUMMARY OF TRACTION DATA FOR XRM-177F USING ROUGHENED MATING DISKS WITH 0.15 μm CLA CIRCUMFERENTIAL LAY FINISH

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	15,000	65	10.0	3.0
1.4	15,000	65	31.0	4.0
1.0	10,000	65	11.0	8.0
1.4	10,000	65	34.5	5.0
1.0	5,000	65	13.0	10.0
1.4	5,000	65	37.0	5.0
1.0	15,000	90	9.0	20.0
1.4	15,000	90	28.0	17.0
1.0	10,000	90	10.0	15.0
1.4	10,000	90	32.0	11.0
1.0	5,000	90	11.0	13.0
1.0	15,000	150	12.0	>25.0
1.4	15,000	150	35.0	>25.0
1.0	10,000	150	10.5	19.0
1.4	10,000	150	41.0	>25.0
1.0	5,000	150	26.0	>25.0

TABLE C-8. SUMMARY OF TRACTION DATA FOR XRM-177F USING ROUGHENED MATING DISKS WITH 0.30 μm CLA TRANSVERSE LAY FINISH

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	15,000	65	7.5	15.0
1.4	15,000	65	29.0	6.0
1.0	10,000	65	7.5	25.0
1.0	15,000	90	7.0	12.0

TABLE C-9. SUMMARY OF TRACTION DATA FOR SANTOTRAC 50 USING POLISHED MATING SPECIMENS

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
1.0	15,000	65	50.0	1.3
1.0	10,000	65	46.0	2.5
1.0	5,000	65	50.0	2.5
1.4	15,000	65	120.0	1.0
1.4	10,000	65	118.0	1.5
1.4	5,000	65	89.0	3.0
1.0	15,000	90	42.0	1.7
1.0	10,000	90	37.0	3.7
1.0	5,000	90	41.0	5.0
1.4	15,000	90	103.0	2.0
1.4	10,000	90	101.0	2.0
1.0	15,000	150	23.0	2.0
1.0	10,000	150	23.0	6.0

TABLE C-10. SUMMARY OF TRACTION DATA FOR SANTOTRAC 50 USING ROUGHENED MATING DISKS

Test Conditions			Peak Traction	
Load, GPa	Speed, rpm	Temperature, C	Magnitude, N	Location, percent
		Circumferential Lay Finish (0.15 μm cla)		
1.0	15,000	65	50.0	1.5
1.0	10,000	65	47.0	[illegible].2
1.0	5,000	65	58.0	3.5
1.4	15,000	65	120.0	2.0
1.4	10,000	65	120.0	2.2
1.4	5,000	65	108.0	4.2
		Transverse Lay Finish (0.15 μm cla)		
1.0	15,000	65	48.0	1.5
		Transverse Lay Finish (0.3 μm cla)		
1.0	15,000	65	43.0	1.5

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APPENDIX D

DISK MACHINE DATA FOR MIL-L-23699 AND MIL-L-7808 OILS

TABLE D-1. DISK MACHINE DATA FOR OIL NO. 1

Lubricant — MIL-L-7808G
DSA — 600-76-C-2116
Qual — 15D-1

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, μm cla	Film, μm	Percent Film	Traction N
I	15	1.4	90	.025	.35	93	15
	10	1.4	90	.025	.33	96	10
	5	1.4	90	.025	.14	87	6.5
II	10	1.0	90	.025	.49	98	3
	10	1.2	90	.025	.33	98	5
	10	1.4	90	.025	.33	96	10
III	10	1.4	65	.025	.37	98	17.5
	10	1.4	90	.025	.33	96	10
	10	1.4	150	.025	.14	75	4
IV	10	1.4	90	.025	.33	96	10
	10	1.4	90	.13 Long	0	15	46
	10	1.4	90	.13 Trans	.12	20	22.5
	10	1.4	90	.3 Trans	.18	20	38

TABLE D-2. DISK MACHINE DATA FOR OIL NO. 2

Lubricant — MIL-L-23699B(2)
DSA — 600-75-C-1863
Qual — 09C-1

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, µm cla	Film, µm	Percent Film	Traction N
I	15	1.4	90	.025	.39	90	16
	10	1.4	90	.025	.37	85	13
	5	1.4	90	.025	.37	70	11
II	10	1.0	90	.025	.47	95	3
	10	1.2	90	.025	.47	95	7.5
	10	1.4	90	.025	.37	85	13
III	10	1.4	65	.025	.59	90	18.5
	10	1.4	90	.025	.37	85	13
	10	1.4	150	.025	.14	70	4
IV	10	1.4	90	.025	.37	85	13
	10	1.4	90	.13 Long	.04	5	40
	10	1.4	90	.13 Trans	.12	5	21
	10	1.4	90	.3 Trans	.16	40	32

TABLE D-3. DISK MACHINE DATA FOR OIL NO. 3

Lubricant — MIL-L-23699B(2)
DSA — 600-76-C-1231
Qual -- 07A

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, μm cla	Film, μm	Percent Film	Traction N
I	15	1.4	90	.025	.43	95	17
	10	1.4	90	.025	.39	97	13.5
	5	1.4	90	.025	.27	96	10
II	10	1.0	90	.025	.63	97	2.5
	10	1.2	90	.025	.57	97	5
	10	1.4	90	.025	.39	97	13.5
III	10	1.4	65	.025	.76	98	18
	10	1.4	90	.025	.39	97	13.5
	10	1.4	150	.025	.18	95	7
IV	10	1.4	90	.025	.39	97	13.5
	10	1.4	90	.13 Long	.25	25	36.5
	10	1.4	90	.13 Trans	.18	32	18.5
	10	1.4	90	.3 Trans	.18	30	31

TABLE D-4. DISK MACHINE DATA FOR OIL NO. 4

Lubricant — MIL-L-23699B AMZ
DSA — 600-76-C-1527
Qual — 0-5A-2

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, µm cla	Film, µm	Percent Film	Traction N
I	15	1.4	90	.025	.61	100	14.5
	10	1.4	90	.025	.38	98	12.4
	5	1.4	90	.025	.31	94	10.0
II	10	1.0	90	.025	.51	100	4.0
	10	1.2	90	.025	.47	98	6.0
	10	1.4	90	.025	.38	98	12.4
III	10	1.4	65	.025	.51	98	21.0
	10	1.4	90	.025	.38	98	12.4
	10	1.4	150	.025	.22	75	5.0
IV	10	1.4	90	.025	.38	98	12.4
	10	1.4	90	.13 Long	.12	10	39.0
	10	1.4	90	.13 Trans	.10	5	21.5
	10	1.4	90	.3 Trans	.08	5	33.5

TABLE D-5. DISK MACHINE DATA FOR OIL NO. 5

Lubricant — MIL-L-23699B(2)
DSA — 600-76-C-1975
Qual — 05A-1

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, μm cla	Film, μm	Percent Film	Traction N
I	15	1.4	90	.025	.33	82	17.5
	10	1.4	90	.025	.32	97	14.5
	5	1.4	90	.025	.22	97	9.5
II	10	1.0	90	.025	.41	98	3.5
	10	1.2	90	.025	.37	98	6.5
	10	1.4	90	.025	.32	97	14.5
III	10	1.4	65	.025	.51	80	23.5
	10	1.4	90	.025	.32	97	14.5
	10	1.4	150	.025	.16	85	4.5
IV	10	1.4	90	.025	.32	97	14.5
	10	1.4	90	.13 Long	.18	5	53
	10	1.4	90	.13 Trans	.25	10	21.5
	10	1.4	90	.3 Trans	.20	10	31

TABLE D-6. DISK MACHINE DATA FOR OIL NO. 6

Lubricant — MIL-L-7808
DSA — 600-77-C-0634

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, µm cla	Film, µm	Percent Film	Traction N
I	15	1.4	90	.025	.32	94	14
	10	1.4	90	.025	.28	67	9.1
	5	1.4	90	.025	.22	17	7
II	10	1.0	90	.025	.37	92	3.3
	10	1.2	90	.025	.34	88	5.5
	10	1.4	90	.025	.28	67	9.1
III	10	1.4	65	.025	.39	60	17
	10	1.4	90	.025	.28	67	9.1
	10	1.4	150	.025	13	65	4.5
IV	10	1.4	90	.025	.28	67	9.1
	10	1.4	90	.13 Long	.03	15	49
	10	1.4	90	.13 Trans	.09	19	21.5
	10	1.4	90	.3 Trans	.10	15	33.5

TABLE D-7. DISK MACHINE DATA FOR OIL NO. 7

Lubricant — MIL-L-7808
DSA — ATL-7072

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, µm cla	Film, µm	Percent Film	Traction N
I	15	1.4	90	.025	.35	85	13.8
	10	1.4	90	.025	.25	78	10.5
	5	1.4	90	.025	.16	47	9.0
II	10	1.0	90	.025	.40	94	2.3
	10	1.2	90	.025	.31	92	5.3
	10	1.4	90	.025	.25	78	10.5
III	10	1.4	65	.025	.29	60	18.5
	10	1.4	90	.025	.25	78	10.5
	10	1.4	150	.025	.13	57	2.8
IV	10	1.4	90	.025	.25	78	10.5
	10	1.4	90	.13 Long	.09	20	62.5
	10	1.4	90	.13 Trans	.18	25	22.7
	10	1.4	90	.3 Trans	.08	27	39.8

TABLE D-8. DISK MACHINE DATA FOR OIL NO. 8

Lubricant — MIL-L-7808
DSA — ATL-7073

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, μm cla	Film, μm	Percent Film	Traction N
I	15	1.4	90	.025	.36	98	13.5
	10	1.4	90	.025	.31	93	9.3
	5	1.4	90	.025	.21	50	8.0
II	10	1.0	90	.025	.33	97	3.5
	10	1.2	90	.025	.33	94	4.5
	10	1.4	90	.025	.31	93	9.3
III	10	1.4	65	.025	.41	88	17.5
	10	1.4	90	.025	.31	93	9.3
	10	1.4	150	.025	.13	80	4.3
IV	10	1.4	90	.025	.31	93	9.3
	10	1.4	90	.13 Long	.14	23	55.3
	10	1.4	90	.13 Trans	.09	17	23.3
	10	1.4	90	.3 Trans	.15	25	33.0

TABLE D-9. DISK MACHINE DATA FOR OIL NO. 9

Lubricant — MIL-L-7808
DSA — ATL-7074

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, μm cla	Film, μm	Percent Film	Traction N
I	15	1.4	90	.025	.32	99	10.8
	10	1.4	90	.025	.28	96	9.7
	5	1.4	90	.025	.18	75	7.8
II	10	1.0	90	.025	.39	98	2.5
	10	1.2	90	.025	.31	98	4.3
	10	1.4	90	.025	.28	96	9.7
III	10	1.4	65	.025	.44	98	18
	10	1.4	90	.025	.28	96	9.7
	10	1.4	150	.025	.22	68	5.0
IV	10	1.4	90	.025	.28	96	9.7
	10	1.4	90	.13 Long	.10	43	63
	10	1.4	90	.13 Trans	.05	30	24.3
	10	1.4	90	.3 Trans	.10	43	36.5

TABLE D-10. DISK MACHINE DATA FOR OIL NO. 10

Lubricant — MIL-L-7808
DSA — ATL-7075

Graph	Speed, k, rpm	Load, GPa	Temperature, C	Surface, µm cla	Film, µm	Percent Film	Traction N
I	15	1.4	90	.025	.36	96	16
	10	1.4	90	.025	.29	95	13.5
	5	1.4	90	.025	.18	40	12
II	10	1.0	90	.025	.39	96	3
	10	1.2	90	.025	.35	85	6.5
	10	1.4	90	.025	.29	95	13.5
III	10	1.4	65	.025	.40	80	23
	10	1.4	90	.025	.29	95	13.5
	10	1.4	150	.025	.40	95	13.5
IV	10	1.4	90	.025	.16	68	6.2
	10	1.4	90	.13 Long	.10	23	58
	10	1.4	90	.13 Trans	.09	23	29
	10	1.4	90	.3 Trans	.11	25	42