REPORT

on

EVALUATION OF TRANSFER FILMS OF SALOX M ON 440C FOR HPOTP BEARING CAGE APPLICATIONS
(Contract No. NAS8-36192, Task 119)

to

NATIONAL AERONAUTICS AND SPACE ADMINSTRATION
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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by

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INTRODUCTION

The bearings in the turbopump for the Space Shuttle main engine (SSME) are critical to the success of the engine. Improvement of these bearings is mandatory if the target design life of 27,000 seconds is to be met for future Shuttle missions. Battelle has been assisting NASA in identifying means of extending SSME bearing life through a task order agreement. The previous tasks have involved failure analyses on bearings from test stand firings, bearing dynamics calculations, estimation of service loads, lubrication studies, wear studies, and analyses of the effect of thermal gradients on bearing performance. While significant improvements have been made in the bearings, bearing life is still limited by improper lubrication. Previous tasks have been directed at evaluating possible lubrication mechanisms such as hydrodynamic or precoated surface layer lubrication. However the most viable long term lubrication scheme appears to be the transfer of lubricant from cage to ball to race.

The current cage is fabricated from a glass-filled polytetrafluoroethylene (PTFE). The PTFE can transfer to the balls to form a solid lubricant film, although the glass fibers tend to inhibit the transfer process. The current task was directed at evaluating and characterizing alternate materials for a cage to provide long term transfer film characteristics. The specific objectives of the task were to evaluate transfer film characteristics of bronze-filled PTFE (Salox M) materials on coated and uncoated 440C bearing steel surfaces. The evaluations were to be obtained in the Battelle rolling disk machine and were to include assessments of transfer at room and cryogenic temperatures and the frictional behavior of the transferred films.

SUMMARY

The objective of the task was to evaluate the suitability of a bronze-filled PTFE (Salox M) as the cage material in SSME High Pressure Oxygen Turbo Pump (HPOTP) bearings. The role of the cage pocket material will be to provide a transferred lubricating interface at the ball-race contact region. The questions addressed in the task were:

(1) Will Salox M generate a transfer film at cryogenic temperatures?

(2) What is the wear rate of a Salox M material in comparison with the glass-filled PTFE cage material currently used?

(3) Does the bronze-filled material create less deleterious ball wear than seen with glass fibers?

(4) Is there a preferred bearing ball surface roughness to enhance transfer?

(5) Do precoated surface films affect transfer film lubrication?

(6) Can the bronze-filled PTFE cage pockets be incorporated into a reasonable cage configuration?

A series of experiments was conducted in an effort to answer these questions. The experiments involved block-on-ring tests (the block was the PTFE-filled material and the ring was through-hardened 440C steel) and high speed traction tests of two 440C disks with one disk rubbed with a PTFE block to generate a transfer film. Measurements included post test visual observations of the condition of the 440C, wear rate measurements of the blocks, and traction measurements between the disks.

In response to Question 1, it was observed that both Salox M and glass-filled PTFE (Armalon) transferred PTFE to 440C at cryogenic temperatures. Bronze is also transferred to uncoated 440C from the Salox M. At room temperature no PTFE transfer was observed in the high speed disk tests due to severe frictional heating, although bronze transfer still occurred with the bronze-PTFE Salox M material. Since the bearing will operate at cryogenic temperature, transfer films are very probable.

Salox M wore slightly, although probably tolerably, more than glass-filled PTFE against 440C. However, in response to Question 3, Salox

M is clearly less abrasive to 440C than is the glass-filled material. When the surface layer of PTFE is depleted from the glass-filled material (and transferred to the 440C), the glass fibers tend to seriously abrade the steel. This problem does not occur with Salox M.

The surface roughness studies (Question 4) indicate that smooth balls are quite reasonable for transfer films. No significant difference in wear rates of the candidate cage materials was observed when the 440C surface finish was increased from 0.025 μm (1 μin.) to 0.1 μm (4 μin.) cla. At higher levels of roughness, the wear rate increased. With regard to Question 5, two surface coatings (MoS_2 and TiN) were tested. The surface coatings tended to reduce the Salox M wear rate and reduce bronze transfer. PTFE transfer at cryogenic temperatures still occurred with the surface coatings.

Two cage design concepts are presented utilizing Salox M material. One design involves a metal-reinforced Salox M cage, while the second design uses Salox M inserts in a metal structure. These two concepts are shown in Figures 18 and 19.

SUGGESTED FUTURE WORK

The research conducted in this task order has been very productive in terms of investigating possible future cage materials for the SSME turbopump bearing. The next logical step is to evaluate these materials in a rolling contact situation. Eventually these evaluations must be conducted with full bearings in a turbopump environment. However, full bearing tests are very difficult and time consuming. Possible cage configurations for the bearings must be fabricated to very rigid specifications which can require a very long lead time. Under this type of procedure a study of more than a few preselected configurations would be difficult. If a particular experiment reveals the desirability of an alternate concept or material than prescheduled, it is difficult to alter the course of the experiments. Therefore, an intermediate step using a five-ball tester to evaluate materials prior to full bearing tests would be more reasonable for the next phase of development. In this configuration four balls which are free to rotate are separated by a cage as shown in Figure 1. The cage configuration is very simple in design and easy to fabricate. Tests would be conducted in LN_2 at a relatively low speed to eliminate dynamic effects but at a high enough speed as to be able to accumulate the number of cycles anticipated in an actual bearing.

Tests would be conducted with Salox M and Armalon retainers and with coated and uncoated balls. The balls would be examined periodically to determine the following:

(1) Are transfer coatings spontaneously occurring?

(2) Are the balls wearing and/or spalling?

These tests could be conducted in a relatively short time frame (such as 3 to 4 months after task initiation assuming a reasonable time for material procurement). Following this task a clear picture of the feasibility of Salox M cage would be developed. The task would form a very useful bridge from the current basic evaluation task to a bearing fabrication task.

In addition to the rolling contact tests, further studies should be made of the bearing-cage configuration. Cage materials with greater strength than Salox M (such as bronze-fiber reinforced materials) should

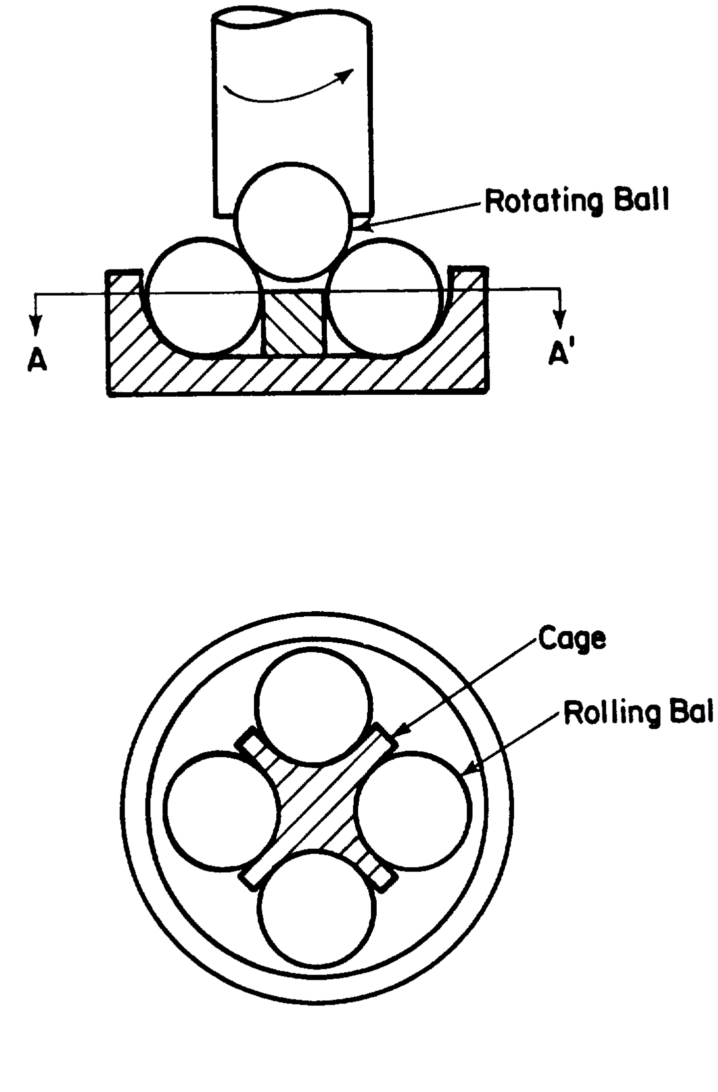

FIGURE 1. FIVE BALL TEST CONFIGURATION

be evaluated. Further design studies of metal-reinforced cages could also be made. Before selecting a test bearing as a replacement for the current design, a historical evaluation of the evolution of the bearing should be made. The goal of this evaluation would be to document Rocketdyne and NASA experiences with various contact angles, ball-cage clearances (including elongation), ball-race curvatures, bearing cooling, and other factors examined in the development of the SSME turbopumps. These data would be used by NASA to determine the most reasonable overall bearing design to incorporate the new cage configuration.

PROGRAM EFFORTS

Experiments have been conducted to determine the suitability of candidate cage materials intended for use in the HPOTP of the Space Shuttle main engine. The current material, Armalon, is under scrutiny due to its proven abrasiveness and its suspected inability to form lubricating transfer films on contacting bearing balls. Candidate material replacements were evaluated with respect to their relative ability to resist wear and ensure the generation of lubricating transfer films under simulated operating conditions.

Two types of sliding wear experiments were conducted using several candidate cage materials. The first set of experiments was conducted using a slow-speed apparatus [6.4 cm/s (2.5 in./s)], which used a geometry employing a stationary test block loaded against a rotating test ring. These initial experiments were conducted to examine the friction characteristics of the various combinations and to evaluate in a cursory fashion the effect of surface roughness on the transfer process. The second set of experiments was conducted at high speed [931 cm/s (366 in./s)] to examine the transfer and wear characteristics of the various candidate materials under conditions more representative of conditions present at the ball-cage interface of the HPOTP bearings. In these experiments, material performance was evaluated as a function of test ring surface roughness and the temperature surrounding the test section.

The ability of the various materials to generate lubricating transfer films on the test disk surfaces was determined in two ways. First, the disk surface was examined under optical and scanning electron microscopy to detect the presence of transferred material. Second, the rheological characteristics of the transfer films were estimated by conducting slip-traction experiments. In these experiments, a rotating crowned disk was loaded against the rotating test surface of the test disk. The speed variation between the two surfaces was varied and the resulting traction force was measured. In this way, a slip-traction curve was generated for the transfer layer on the test disk surface.

Specific details regarding the experimental apparatus, procedures, and results are presented in the following sections of the report.

Background

Review of Cage-Ball Contact Conditions

The ball-race friction coefficient has been shown to strongly affect ball-cage forces during operation. Figure 2 shows calculated estimates of ball-cage forces as a function of ball-race friction coefficient. Assuming a friction coefficient between 0.10 and 0.15, which would be typical for a steel bearing ball contacting steel bearing races, ball-cage forces can range from between 116 to 170 N (26 to 38 lb_f), depending upon the radial load. Since ball and ball pocket wear and bearing instability are related to ball-cage forces, bearing life and operation can be improved by reducing ball-race friction by means of lubrication.

A wear scenario for the current HPOTP bearing system can be formed based on estimated operating conditions and observed component wear. Initial bearing wear performance is determined by the MoS_2 coating used to lubricate the bearing balls and ball pocket areas. To provide lubrication during start-up, the ball-pocket areas are coated with molybdenum disulfide to a thickness of approximately 2.5 μm (100 μin.). In addition to providing lubrication, this coating may also prevent the glass fibers of the composite from abrading the bearing balls.

An estimate of the operating life of the MoS_2 coating in the ball pocket areas can be made assuming a simple linear wear equation:

$$V = \frac{KLX}{3P}$$

where,

V = wear volume,

L = load,

X = sliding distance

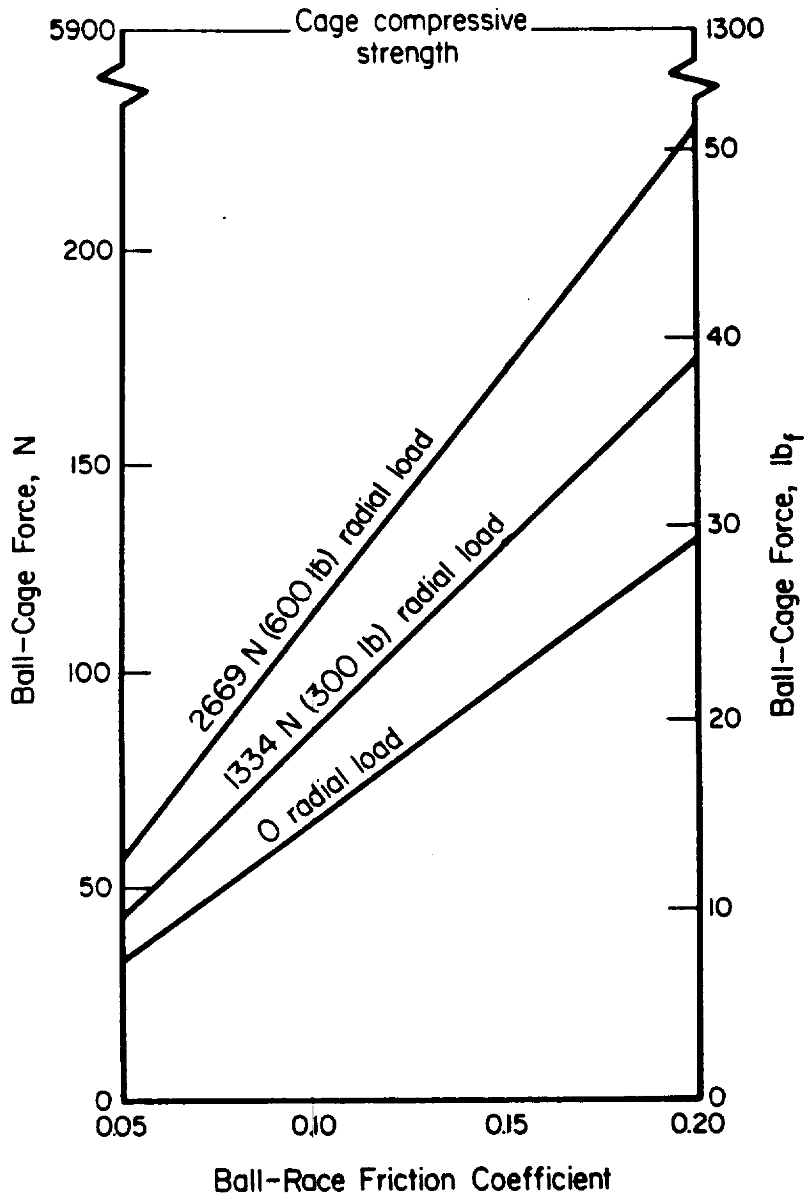

FIGURE 2. MAXIMUM BALL-CAGE FORCES, PREDICTED BY BASDAP, UNDER STABLE OPERATING CONDITIONS, FOR VARIOUS RADIAL LOADS.

Axial Load - 4450 N (1000 lb)
Shaft Speed = 3100 rpm

K = wear coefficient, and

P = penetration hardness.

Work by B. C. Stupp (1) has established values for MoS_2-Ni friction coefficients and wear characteristics. Assuming a representative friction coefficient of 0.07, the corresponding ball-cage load is estimated to be 89 N (20 lb_f). From reference (1), using wear data presented, the quantity (K/P) is estimated to be on the order of 8.4×10^{19} mm^2/kg. The wear volume corresponds to the volume of coating present on the 12.7 mm (1/2 inch) diameter bearing balls. Under these assumptions, the coating life would be approxi-mately 13 minutes at an operating speed of 30,000 rpm.

Wear-through of the MoS_2 coating will result in two situations leading to accelerated wear of the bearing balls. First, ball-cage loading will increase due to increased friction at the ball-race interface. Second, abrasive wear of the bearing balls from contact with glass fibers in the Armalon will occur. Estimates of bearing ball wear can be made based on the measured abrasivity of the Armalon material against 440C[(2)]. An expression for abrasive wear is as follows:

$$V = \frac{\tan \theta \, LX}{\pi P} ,$$

Where

tan θ = abrasive wear coefficient.

Assuming a ball-cage load of 170 N (38 lb_f) and an abrasive wear coefficient of 2.5×10^{-6}, a bearing ball would be expected to wear 1.5 μm (60 μin.) on the diameter after 10 minutes, or approximately 5 μm (0.0002 in.) after three 10-minute Shuttle launches. Ball wear would be expected to be higher if instability forced cage-ball loads higher.

This program investigated possible candidate cage materials that could be used to improve performance of the HPOTP bearings. Two criteria were particularly important: the ability to generate lubricant transfer films and the reduced tendency to promote ball wear through repeated sliding contact with the cage.

Materials Selected and Procured

Candidate cage materials were selected based on the results of earlier work conducted at Battelle and elsewhere. Table 1 lists these materials. The Salox M materials are composites of bronze and PTFE in varying weight percentages. The PTFE in the composite matrix is an inert low friction constituent, while the bronze provides strength to the matrix. Under certain interfacial conditions, the PTFE in the matrix will transfer to adjoining sliding surfaces providing for a low friction lubrication situation. Salox M has been shown to be less abrasive then the current Armalon[2].

Table 1 also shows the different counterface materials and surface finishes investigated in the program. Earlier investigations showed that surface finish affected the generation of transfer films. The case-hardened test rings were used during preliminary slow-speed screening experiments conducted on a block-ring apparatus (LFW-1), while the 440C test rings were used in high-speed, room temperature and cryogenic sliding experiments. Surface finishes were measured using a Talysurf profilometer trace taken in the axial direction across the direction of grinding.

Surface coatings of MoS_2-Ni and TiN were also applied to substrates of 440C* and evaluated under sliding contact with the candidate materials. Molybdenum disulfide was co-sputtered with nickel to produce a more tenacious, self-lubricating solid film. The thickness of this film was approximately 2 μm (80 μin.). In addition to the molybdenum disulfide film, titanium nitride hard coatings were also investigated. These coatings were applied using an arc deposition process rather than chemical vapor deposition to prevent substrate heating from occurring.

During this program period, two types of sliding wear experiments

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* All coatings were applied by Hohman Plating of Dayton Ohio.

TABLE 1. SUMMARY OF MATERIALS AND SURFACE CONDITIONS INVESTIGATED IN THIS PROGRAM

Cage Materials

60 Percent PTFE - 40 Percent Bronze(1)
40 Percent PTFE - 60 Percent Bronze(1)
40 Percent PTFE - 55 Percent Bronze - 5 Percent MoS_2(1)
Armalon

Test Ring Materials

Slow Speed Experiments

SAE 4620, Case-hardened, 0.05 μm (2 μin.) cla
SAE 4620, Case-hardened, 0.25 μm (10 μin.) cla

High Speed Experiments

440C SS, 0.025 μm (1 μin.) cla
440C SS, 0.1 μm (4 μin.) cla
440C SS, 0.3 μm (12 μin.) cla
440C - Coated with TiN(2)
440C - Coated with MoS_i-Ni (2)

(1) Allegheny Plastics, Thorn Run Road, Coraopolis, Pennsylvania, 15108, under the trade name of Salox M.

(2) Supplied by Hohman Plating, Dayton, Ohio.

were conducted using these candidate cage materials. The first set of experiments was conducted using a slow-speed apparatus [6.4 cm/s (2.5 in./s)], which used a geometry employing a stationary test block loaded against a rotating test ring. These initial experiments were conducted to examine the friction characteristics of the various combinations and to evaluate in a cursory fashion the effect of surface roughness on the transfer process. The second set of experiments was conducted at high speed [931 cm/s (366 in./s)] to examine the transfer and wear characteristics of the various candidate materials at conditions more representative of conditions present at ball-cage interface of the HPOTP bearings.

Specific activities and results of both experimental efforts are described in the following section.

Evaluation of Candidate Materials At Low Sliding Speed

Experiments were conducted using a standard LFW-1 wear test apparatus which employs a stationary block of material loaded against a rotating ring. Table 2 lists the conditions and materials used for these experiments. Although the test ring material was not 440C SS, the intent of these experiments was to investigate the rotative performance of the various candidate materials under similar sliding conditions. Two ring surface finishes were used: a ground surface finish having a value of about 0.05 μm (2 μin.) cla, and a grit-blasted ring having a surface finish of around 0.25 μm (10 μin.). The grit-blasted ring exhibits a random asperity orientation in the surface finish, while the ground ring exhibits directional asperity orientation.

Experiments were conducted by applying a dead-weight load to the block in contact with the rotating ring and measuring the resulting friction and wear. Table 3 lists the results of these slow-speed experiments. Values of the friction coefficient both at test initiation and completion are listed. Armalon exhibited the highest friction while straight unfilled PTFE exhibited the lowest friction.

TABLE 2. MATERIALS AND EXPERIMENTAL CONDITIONS USED FOR LOW SPEED SLIDING EXPERIMENTS

Experimental Conditions

Sliding Speed	- 2.5 in./sec (6.4 cm/sec)
Duration	- 6.1×10^4 to 14.3×10^4 cm (2.4×10^4 to 5.64×10^4 inches)
Contact Load	- 133 N (30 lb_f)
Contact Stress	- 6.6 MPa (960 psi)

Test Block Materials

100 Percent PTFE
60 Percent PTFE - 40 Percent Bronze
40 Percent PTFE - 60 Percent Bronze
40 Percent PTFE - 55 Percent Bronze - 5 Percent MoS_2
Armalon

Test Rings

SAE 4620 steel, case-hardened, ground to 0.05 μm (2 μin.) cla
SAE 4620 steel, case-hardened, grit-blasted to 0.25 μm (10 μin.) cla

TABLE 3. RESULTS OF LOW SPEED SLIDING WEAR EXPERIMENTS

Ring Material	Block Material	Initial Friction Coefficient	Final Friction Coefficient	Block Wear Scar Width / Sliding Distance ($x10^{-4}$)
Ground SAE 4620	Armalon	0.2	0.3	1.0
Ground SAE 4620	55 Bronze 40 PTFE 5 MoS_2	0.17	0.19	0.8
Ground SAE 4620	40 Bronze 60 PTFE	0.16	0.15	1.2
Ground SAE 4620	60 Bronze 40 PTFE	0.17	0.16	1.1
Grit-Blasted SAE 4620	40 Bronze 60 PTFE	0.14	0.14	0.6
Grit-Blasted SAE 4620	60 Bronze 40 PTFE	0.13	0.16	0.5
Ground SAE 4620	PTFE	0.11	0.11	(extreme wear)

The three candidate cage materials exhibited friction levels slightly lower than the friction demonstrated by the Armalon. These materials were loaded against both ground rings and grit-blasted rings. Contact with the ground rings typically resulted in a transfer of bronze from the filled composite to the ring surface. For these low-speed experiments, the use of roughened races prepared by randomly orienting the asperities through grit blasting appeared to aid in the transfer process. The net effect was to reduce friction coefficients and relative composite wear, compared with results obtained using ground surfaces.

Evaluation of Candidate Materials At High Sliding Speed

For these experiments, conditions were selected to more closely simulate conditions perceived to exist at the ball-cage interface in the HPOTP bearings. A brief examination of these conditions is presented, followed by a description of the experimental condition and presentation of results.

Experimental Conditions

Due to the high rotation speed of the HPOTP, ball rotational speed is high. Assuming a shaft speed of 31,000 rpm and a contact angle of 20 degrees, the ball surface speed is approximately 64 m/s (12,600 ft/min). Assuming a ball-cage normal load of 45 N (10 lb_f) and a cage contact area defined by a 6.4 mm (0.25 in.) diameter contact patch, the PV level for this sliding situation is approximately 8.8×10^7 MPa m/s (2.5×10^6 psi ft/m).

To simulate these load and sliding conditions, an apparatus employing a high speed rotating ring of 440C stainless steel was used. The end of a cylindrical test sample was loaded against the edge of the rotating ring. Table 4 lists the conditions used for these high-speed sliding experiments. For the majority of the experiments, the cylindrical specimen was loaded against the ring surface at a load of 35 N (8 lbs),

TABLE 4. TEST CONDITIONS FOR HIGH-SPEED TRANSFER EXPERIMENTS

Test Ring

Material:	440C SS
Diameter:	3.56 cm (1.4 in.)
Width:	0.64 cm (0.25 in.)
Surface Speed:	930 cm/s (1832 ft/min)
Duration:	40 minutes (typical)
Surface:	0.025 μm (1 μin.)
Roughness*:	0.028 μm (1.1 μin.) 0.11 μm (4.5 μin.) 0.36 μm (12 μin.)

Test Specimen

Materials:	60 percent PTFE - 40 percent Bronze 40 percent PTFE - 60 percent Bronze 40 percent PTFE - 55 percent Bronze - 5 percent MoS_2 Armalon
Contact Geometry:	0.476 cm (0.1875 inch) - diameter circular contact
Contact Load:	17.8 - 35.6 N (4-8 lb_f)

* As measured by a profilometer trace transverse to direction of grinding.

which resulted in a PV rating of 1.9 x 10^7 MPa m/s (5.3 x 10^5 psi ft/m). Figure 3 shows a test ring and candidate cage sample specimen.

Experiments were conducted under both room temperature and under cryogenic temperatures. These experiments were typically 40 minutes in duration. Sample wear was determined by using a micrometer to determine length change and volume loss in the candidate specimen. As indicated in Table 4, several different test ring surface roughnesses were investigated.

Results of Room Temperature Experiments

Figure 4 illustrates the results of the wear experiments under room temperature conditions. The quantity used to evaluate performance was the volume loss per unit of sliding distance. Wear results for the Armalon material were difficult to obtain with certainty for the room temperature experiments with the test specimen configuration shown in Figure 3. Under room temperature conditions, frictional heating of the Armalon specimens caused the weave matrix to separate and deteriorate under load, so that measurement of specimen height changes using a micrometer did not yield representative results. For later experiments with Armalon, a 4.8 mm (3/16 in.) wide "skid" of Armalon was loaded against the test ring. This configuration appeared to be more resistant to deformation under load at high frictionally-induced temperatures.

Figure 4 shows how an increase in surface roughness from about 0.11 μm (4 μin.) cla to 0.36 μm (11 μin.) cla resulted in an increase in wear by almost a factor of five. We originally hoped that the increased surface roughness may promote the generation of a lubricating transfer film, thus precluding any further specimen wear. However, the thickness of any transfer film on the 0.36 μm (11 μin.) cla specimen was apparently too low to prevent further abrasive wear of the candidate cage specimens from occurring. The experiments did suggest, however, that an increase in ball surface finish from 0.025 μm (1 μin.) cla to 0.1 μm (4 μin.) cla does not greatly affect cage wear rate.

Visual examination of the disk surfaces showed little evidence of transferred PTFE, although ring surfaces slid against bronze-filled

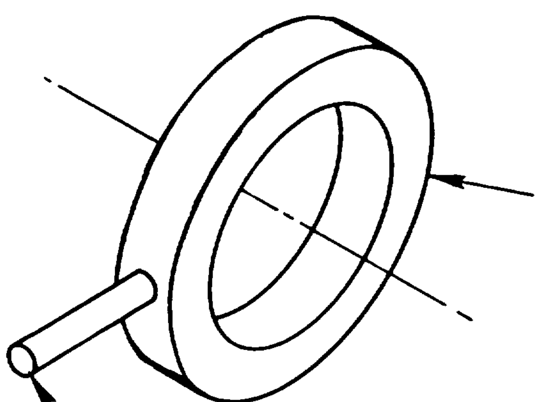


FIGURE 3. TEST GEOMETRY EMPLOYED FOR HIGH SPEED WEAR EXPERIMENTS

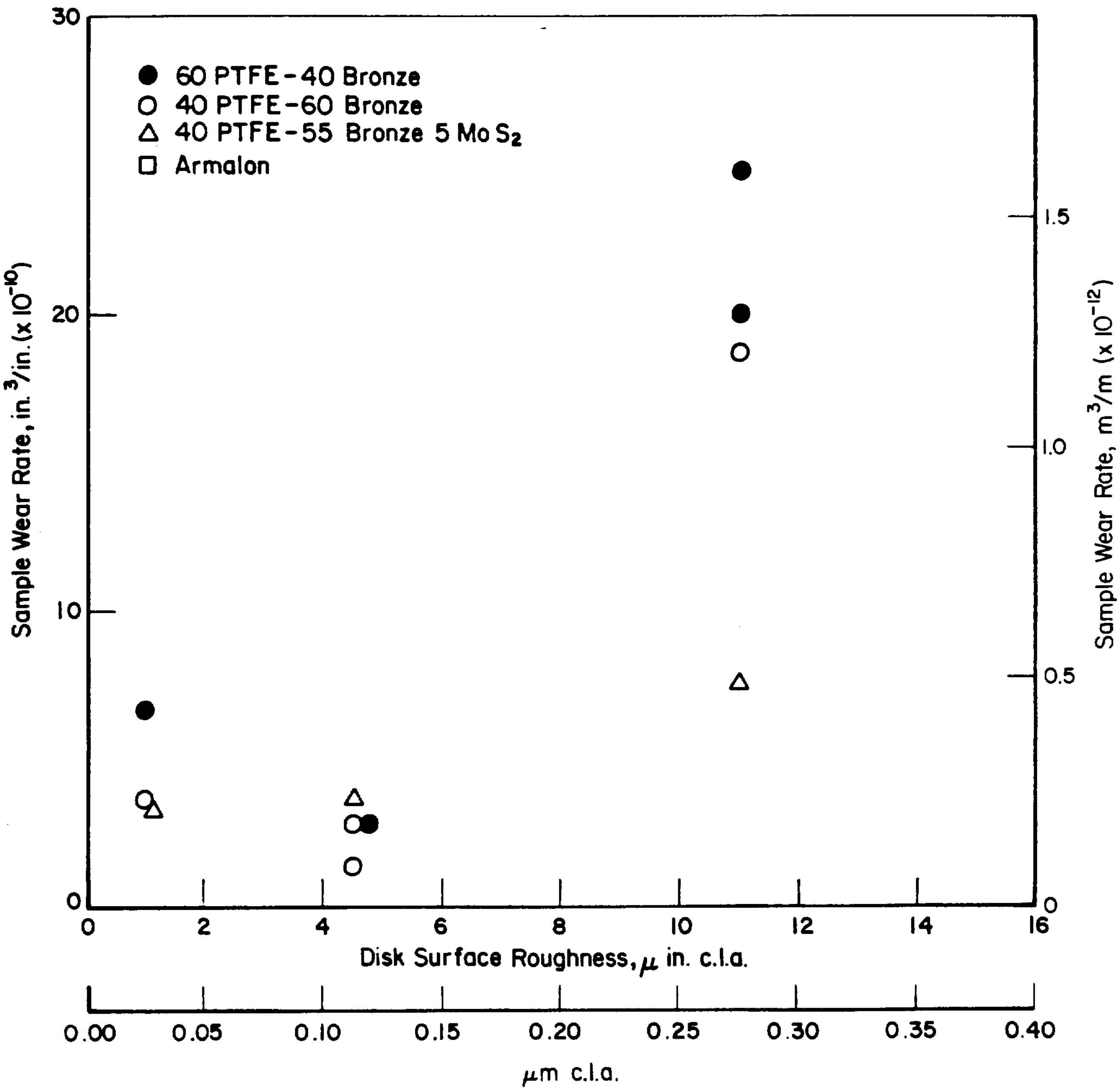


FIGURE 4. RESULTS OF HIGH SPEED ROOM TEMPERATURE SLIDING WEAR EXPERIMENTS, 2 MPa APPARENT CONTACT PRESSURE

PTFE did show evidence of bronze transfer. In some cases, "bluing" of the portions of the disk was evident, indicating that specimen temperatures generated through frictional heating had gotten high enough to cause the formation of surface oxides.

These experiments demonstrated that under the high sliding speeds typical of ball-cage contact the presence of a cryogenic fluid is required to prevent degradation of the Armalon material. The Salox M composites were capable of structurally withstanding the extreme thermal input, although PTFE transfer was marginal under the high temperatures generated. In addition, these experiments demonstrated that relatively high surface finishes did not successfully promote the generation of lubricating transfer films. For the high-speed cryogenic experiments, test rings of only the lower surface finishes were used.

Results of Cryogenic Experiments

Cryogenic experiments were conducted by flooding the test section with liquid nitrogen for the duration of sliding. Prior to the test, the test chamber was purged using nitrogen gas to prevent condensation and freezing of atmospheric water vapor. For some experiments, a thermocouple was placed in contact with the side of the test disk in order to monitor the bulk temperature of the disk during sliding. Although this thermocouple did not provide information about the interface temperature, the temperature reading gave an indication as to whether liquid nitrogen flow around the specimens was adequate. Thermocouple signals were transferred by means of a slip ring to a stationary reference frame.

Specimen wear was determined by measuring the change in specimen length over the test period. Two techniques for monitoring wear were used. The first technique used a (linear variable displacement transducer) (LVDT) to track the movement of the loading arm as the specimen wore. The second technique consisted of simply measuring the change in length with a micrometer. Results obtained using the LVDT correlated closely with measured wear of the specimen. Relative material performance was determined by dividing the sample volume wear by the sliding distance.

Figures 5 and 6 summarize the results of the cryogenic wear experiments. Between two and five duplicate experiments were conducted for each condition. Error bars reflect the standard deviation observed for the specimens.

Because of earlier success with the 60 percent PTFE - 40 percent bronze Salox M composite, most experiments were conducted with this material in contact with a ground surface of 440C SS. The other two materials, 40 PTFE - 60 bronze and 40 PTFE - 55 Bronze - 5 MoS_2, were selectively evaluated.

As shown in Figure 6, wear rates for the 60 PTFE - 40 Bronze Salox M material were higher than wear rates observed for Armalon in contact with uncoated 440C. However, in terms of wear rates, the difference is not particularly disturbing. Typically one becomes concerned when wear rates vary by factors of 10 or more. Wear rates for the 60 PTFE - 40 bronze material in contact with 440C coated with either MoS_2-Ni or TiN were lower than for the same material in contact with uncoated 440C. No experiments were conducted with Armalon in contact with coated 440C test rings.

The reduction in specimen wear due to the application of an MoS_2 coating was most likely due to a reduction in friction. Although the application of a thin film may reduce surface finish somewhat, the effect on wear for these experiments was thought to be minimal.

Wear of the 60-40 Salox M material was found to be directly related to applied load as expected, although the relationship did not appear to be linear. For the data presented in Figure 5, wear appears to be dependent upon load to the 1.6-1.7 power, approximately.

Due to our focus on 60 PTFE - 40 Bronze Salox M as a cage material, a limited number of experiments were conducted on the other two Salox M versions. However, wear data generated suggests that the wear behavior of these two materials is not appreciably different from the behavior of the 60 PTFE - 40 Bronze composite. Figure 6 shows the relationship between wear rate and counterface material for the 55 bronze - 40 PTFE - 5 MoS_2 composite. Wear rates for this material were similar to those observed for the 60 PTFE - 40 bronze material. We observed a reduc-

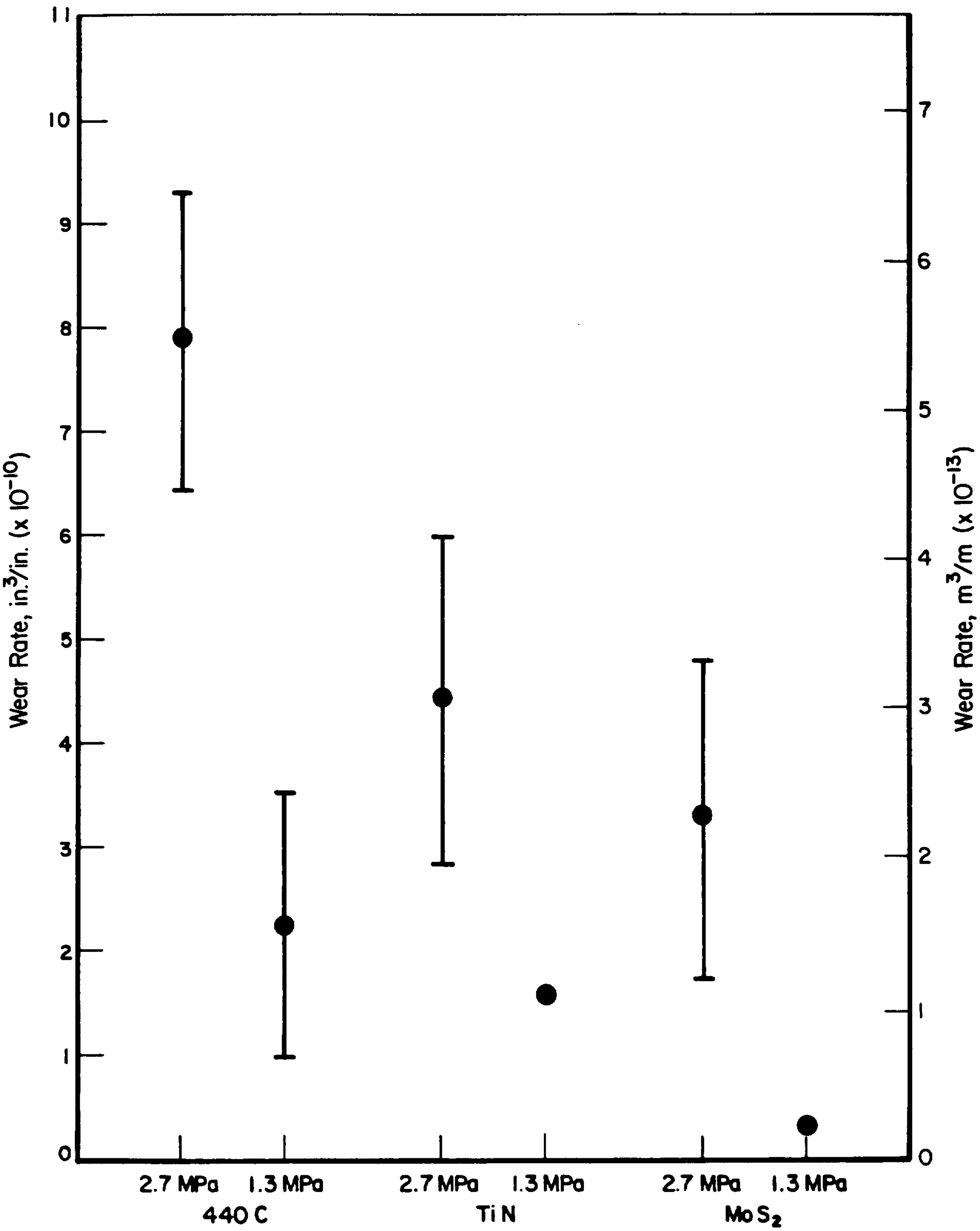


FIGURE 5. EFFECT OF APPARENT CONTACT STRESS AND TEST RING SURFACE CONDITIONS ON WEAR OF SALOX M

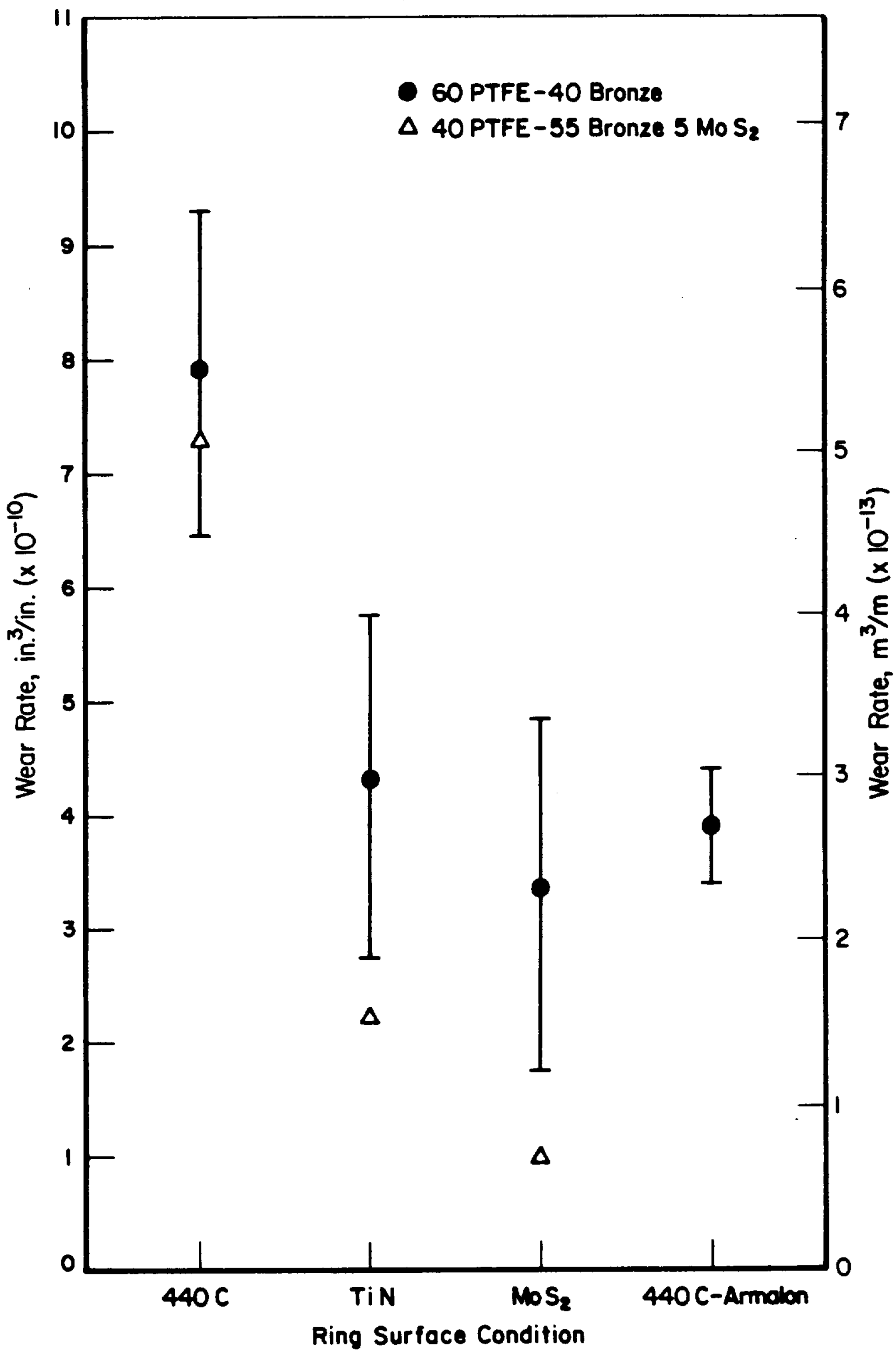


FIGURE 6. RESULTS OF CRYOGENIC WEAR EXPERIMENTS CONDUCTED ON SALOX-M (COMPARED WITH PERFORMANCE OF ARMALON)

tion in wear rate of this composite while in contact with the MoS_2-Ni coated 440C ring. This may be due to the low friction coefficient of the MoS_2-Ni coating and the possibility that transferred MoS_2 originating from the composite may have acted to preserve the low friction condition.

Examination of Transfer Film Morphology

Surfaces of test disks from the high speed sliding wear experiments were examined with optical and scanning electron microscopy to determine the general morphology of the film. Despite much work in this area, little is known about the mechanism governing PTFE transfer. Past work has found little correlation between counterface material and the tendency to form PTFE transfer films (3), although the presence of water has been shown to interfere with the generation of such films. With respect to films generated from the Armalon material, the generation of PTFE transfer films is affected by the removal of such films by the abrasive fibers of the matrix.

Transfer films generated from the Salox M materials containing bronze were expected to be affected by the composition of the test disk surface. Since copper, tin, and steel are all metallurgically "compatible", the transfer of bronze from the composite matrix to the surface of uncoated 440C is expected to occur (4). However, the application of non-metallic coatings, such as TiN and MoS_2, may interfere with the transfer of bronze from the matrix but may have no effect on the generation of PTFE transfer films.

The use of Salox M as a source of lubricating transfer films may have several advantages over the current Armalon material. First, the life of a ball coating may be extended by the elimination of abrasive fibers in the cage composite. Under this condition, the cage wear is expected to be comparable to current Armalon cages, but without severe ball wear. Second, ball-cage friction for the Salox M material is expected to be lower than for the Armalon material after coating wear-through. The latter advantage may also reduce adhesive wear of the ball and therefore extend the life of both coated and uncoated bearing balls.

Due to the extreme temperatures generated during the high speed room temperature experiments, no evidence of PTFE transfer film was seen, although transfer of bronze from Salox M composites was observed. In order to observe conditions more similar to actual HPOTP operation, attention was focused on results obtained during cryogenic experiments.

Armalon Versus Uncoated 440C SS

Figure 7 shows an optical micrograph of the 440C test surface after contact with Armalon in the wear tests described previously (see Table 4). The surface of the transfer film has been purposely scratched to illustrate its presence. From the optical photograph, the transfer film is apparently PTFE deposited in an uneven fashion. Portions of the film have been darkened, either through exposure to elevated temperatures or by contamination by oxides. Film thickness appears to vary across the width of the 440C surface.

Scanning electron photographs of the scratched portion were taken to observe the fracture characteristics of the film and to estimate film thickness. The film thickness appears to be on the order of 1 μm (40 μin.) less, and the film fracture mode in similar to what would be expected of a brittle solid rather than a ductile, elastic material. Portions of the disk surface shown in Figure 8 show very little film in contrast to the relatively thick film observed in the center of the photograph.

Despite the generation of this transfer film, abrasion of the disk surface by the glass fibers of the Armalon was observed. Figure 9 shows the scratches produced in the surface of the 440C disk. Evidence of transfer films in the vicinity of the scratches is apparent.

Salox M (60 PTFE-40 Bronze) Versus Uncoated 440C

Figure 10 shows an optical micrograph of a surface of the uncoated 440C SS after contact with the 60 PTFE - 40 bronze Salox M under cryogenic conditions. The surface has been scratched to show the presence of a

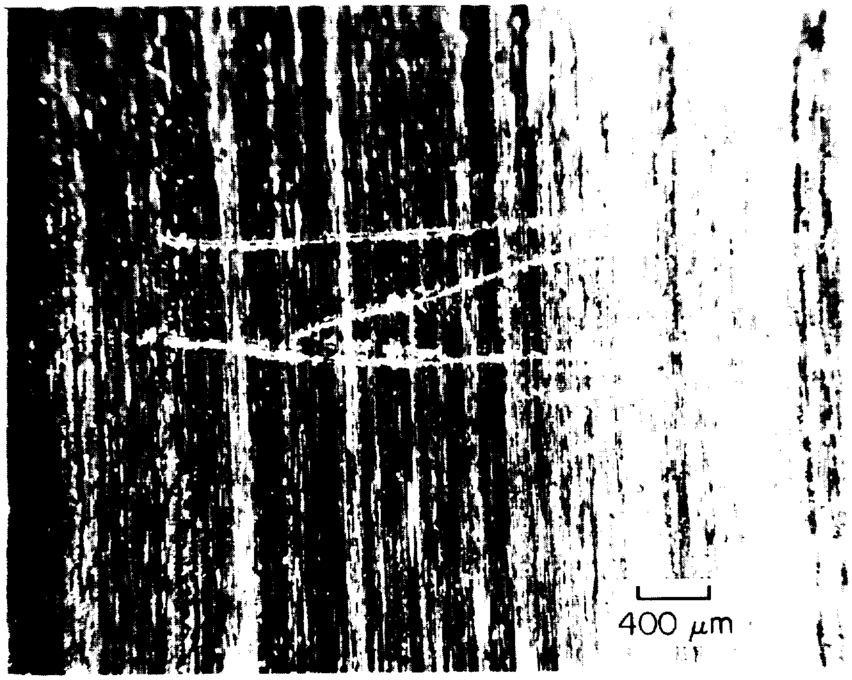
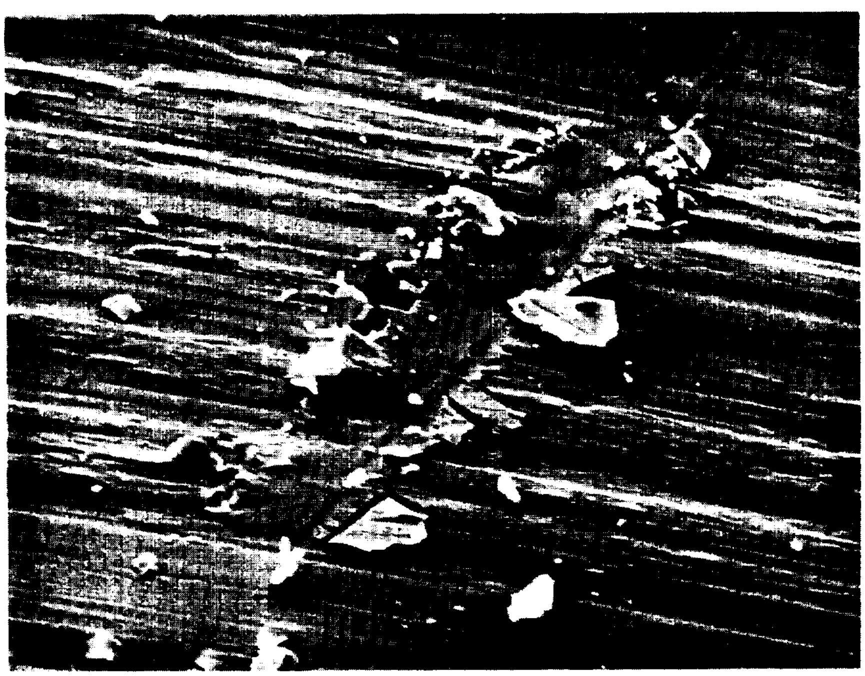


FIGURE 7. SURFACE OF 440 C SS AFTER SLIDING CONTACT WITH ARMALON

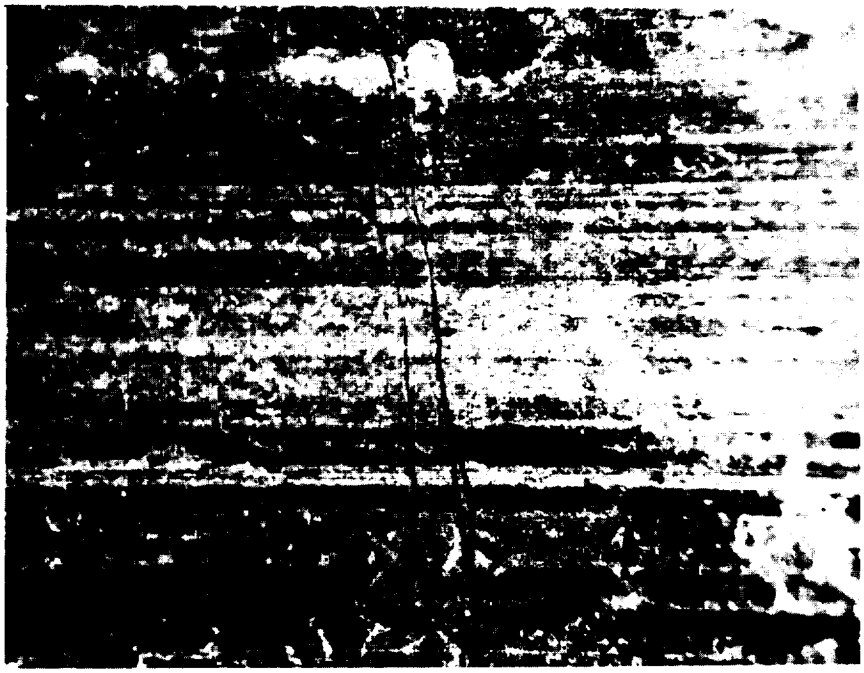


500X S-4537

FIGURE 8. ELECTRON MICROGRAPH OF ARMALON TRANSFER FILM

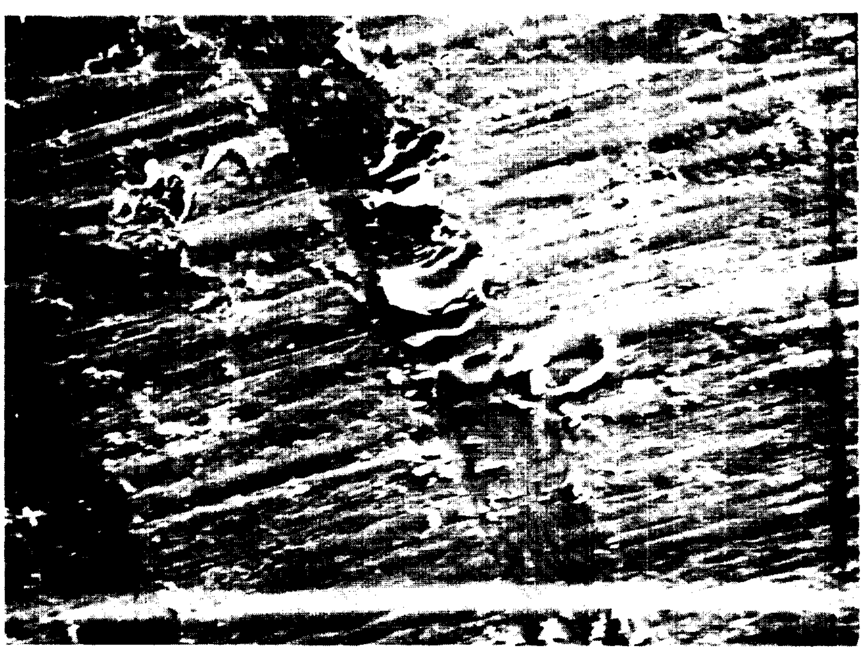
500X S-4530

FIGURE 9. SURFACE OF 440 C DISK AFTER CONTACT WITH ARMALON. SURFACE SCRATCHES AND TRANSFER FILM EVIDENT.



sliding direction ⟶ 25X

a. optical micrograph



500X S-4627

b. SEM photograph

FIGURE 10. SURFACE OF UNCOATED 440 C DISK AFTER SLIDING CONTACT WITH SALOX M (60 PTFE-40 BRONZE)

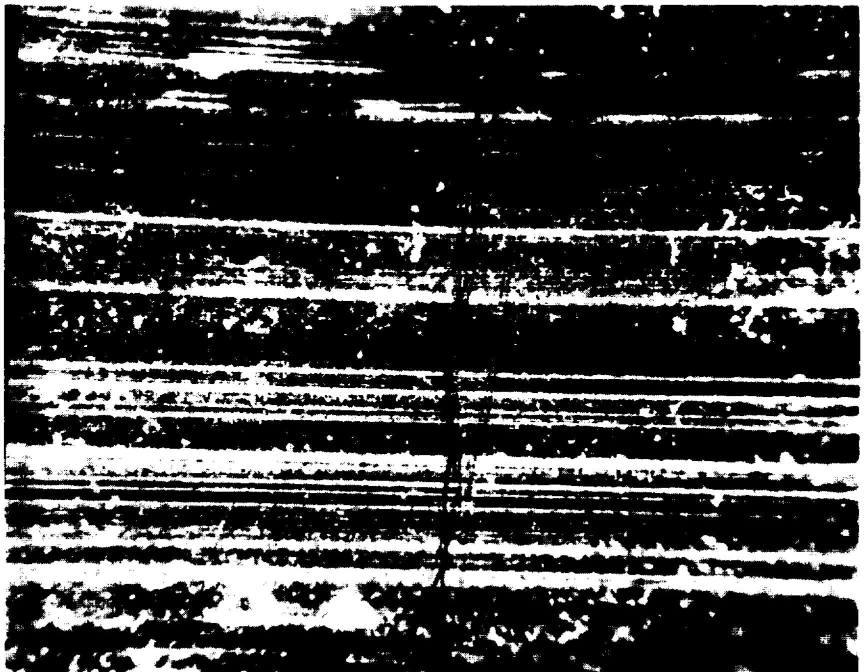
film. Two types of transfer films are evident. The surface is discolored from a transfer film of bronze from the Salox M, while a thin banded film of PTFE is visible over the bronze transfer film and the original stainless steel surface. The scanning electron photograph shows the film in the scratched region. The thickness of the film is similar to that observed for the Armalon material, although no evidence of surface abrasion is present. Film thickness appears to vary from point to point along the contact area. These experiments show the ability of the Salox M material to generate transfer films on uncoated 440C stainless steel.

Salox M (60 PTFE-40 Bronze) Versus Coated 440C

As previously indicated, 440C test rings having a surface finish of 0.028 μm (1.1 μin.) cla were coated with MoS_2-Ni and TiN. Wear rates for the 60 PTFE-40 bronze Salox M material in sliding contact with coated rings were similar to wear rates measured for Armalon in contact with uncoated 440C.

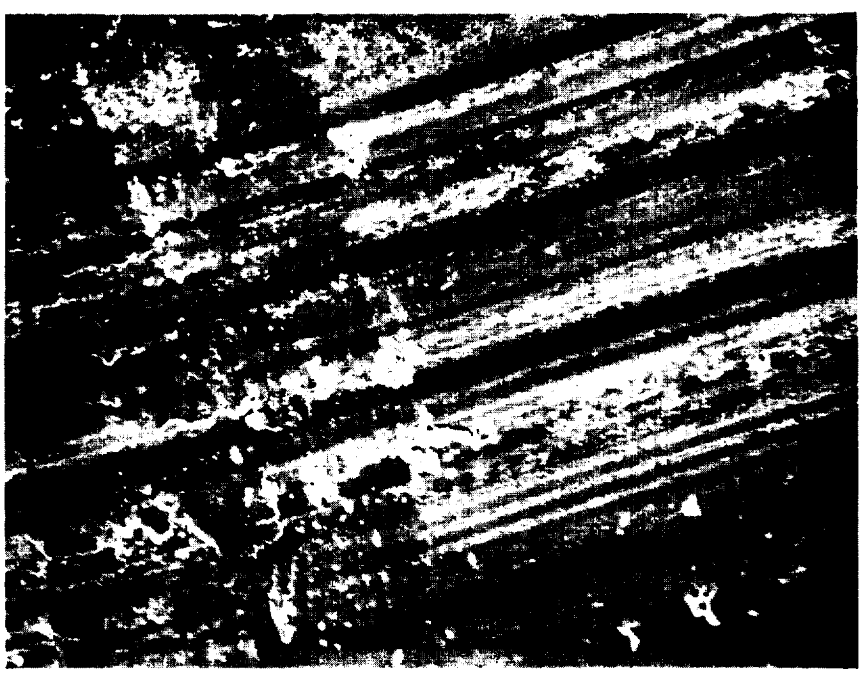
Figure 11 shows the film (scratched) generated on a TiN-coated ring after 40 minutes of sliding contact under cryogenic temperatures. In contrast with the films generated on uncoated 440C, no evidence of transferred bronze is visible. Thin banded films of PTFE can be seen on the surface. The morphology of this film, as seen in the SEM photograph, is different from the film produced on uncoated 440C. The PTFE film was easily disrupted with no identifiable thickness, and the TiN coated surface is easily visible in the uncoated region of the contact zone.

Figure 12 shows the scratched film adherent to the surface of a 440C disk coated with MoS_2-Ni. Although the film does not appear to cover the entire contact region completely, film adhesion appears to be high. The scratched area of the film is shown in the scanning electron micrograph in Figure 12b. The film in the region of the scratch is still intact. A buckled portion of the film in right hand side of the photograph demonstrates film thickness and ductility. Film composition, as seen in the optical photograph, appears to be primarily PTFE; no evidence of transferred bronze is seen in the optical photographs.



sliding direction ⟶ 25X

a. optical micrograph



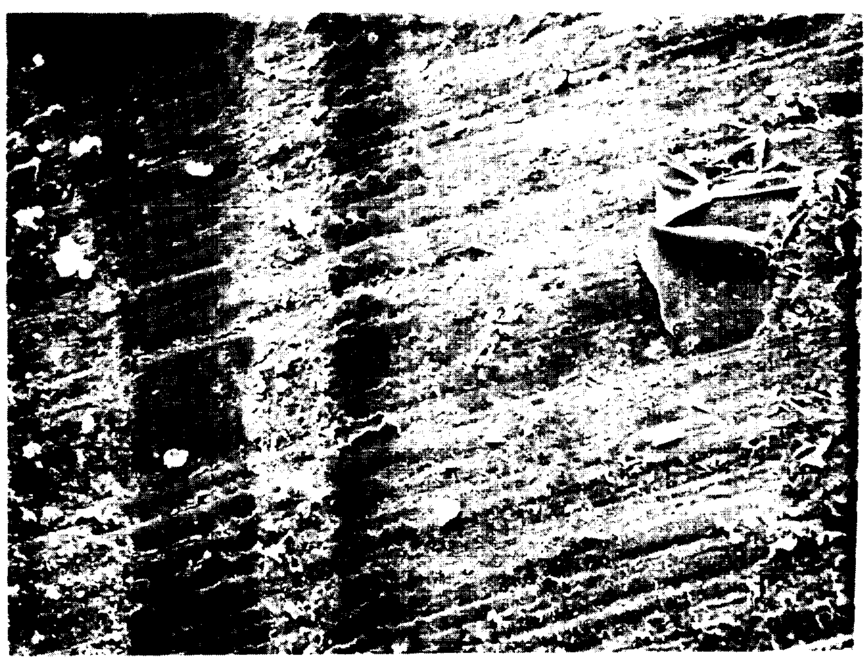
500X S-4629

b. SEM photograph

FIGURE 11. SURFACE OF Ti-N-COATED 440 C AFTER SLIDING CONTACT WITH SALOX M (60 PTFE-40 BRONZE UNDER CRYOGENIC TEMPERATURE

sliding direction ⟶ 25X

a. optical micrograph



500X S-4631

b. SEM photograph

FIGURE 12. SURFACE OF MoS_2-Ni COATED 440 C AFTER SLIDING CONTACT WITH SALOX M (60 PTFE-40 BRONZE) UNDER CRYOGENIC TEMPERATURES

Summary of Transfer Film Examinations

The morphology and composition of transfer films generated under cryogenic temperatures were dependent upon the surface properties of the rotating test ring. Armalon was shown to generate a transfer film similar in appearance to PTFE when loaded against uncoated 440C stainless steel in sliding contact. However, the surface of the steel test ring showed evidence of abrasive wear from the glass fibers of the Armalon weave.

The Salox M (60 PTFE-40 Bronze) showed a tendency to generate transfer films on uncoated PTFE, although apparent PTFE transfer was also accompanied by bronze transfer from the composite to the surface of the uncoated 440C. On disks coated with TiN or MoS_2, bronze transfer from the composite was eliminated, but transfer films of PTFE were still evident.

These results indicate that during HPOTP operation, Salox M may provide for the generation of PTFE transfer films on the surface of MoS_2 or TiN coated bearing balls. In the event of film ablation, the Salox M may then provide a second transferred material, bronze, which could act as a soft thin metal film lubricant. In addition, the Salox M material shows a reduced abrasivity compared with Armalon.

The rheological properties of transferred films were measured to estimate the effects of such films on bearing performance. These experiments are described in the next section.

Slip-Traction Experiments

Slip-traction experiments were conducted on transfer films generated during cryogenic experiments. The purpose of these experiments was twofold: to affirm the presence of a transfer film quantitatively and to generate data that could be used at a later date to estimate stable bearing operating conditions.

Experiments were conducted using Battelle's rolling disk apparatus depicted in Figure 13. Briefly, the apparatus consisted of two rotating spindles fitted with test disks. The lower test disks for these experiments

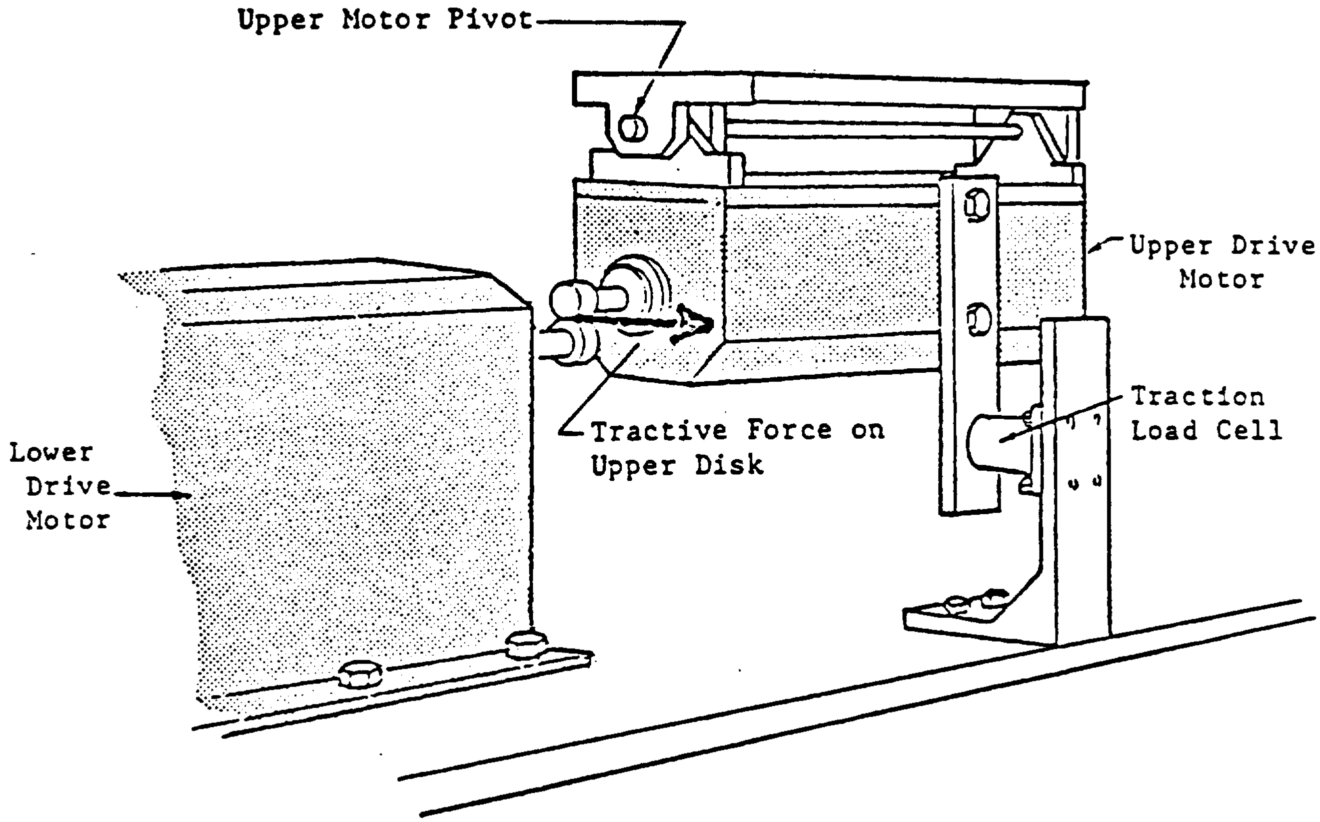


FIGURE 13. SCHEMATIC DRAWING OF DISK MACHINE ILLUSTRATING TRACTION MEASUREMENT

were the 440C test disks used in the wear experiments, while the upper test disk was a crowned disk of 440C. Nominal spindle speed for each spindle was 5,000 rpm, which gave a nominal surface of 944 cm/s (371 in./s). Typically, traction experiments were conducted after wear experiments to evaluate any films that may have been generated through sliding contact.

Experiments were conducted using the following procedure. A sample of candidate cage material was loaded against the outer diameter of a rotating test disk, as depicted in Figure 3. Contact was continued for approximately 40 minutes to generate a transfer film on the surface. The rotating crowned top disk was then brought into contact with the surface of the lower disk and the resulting traction force was recorded. The two disks were then removed from contact, the speed of the upper disk was adjusted, and the two disks were brought into contact again. A slip-traction curve was generated by varying the speed difference between the two disks and reading the traction coefficient at occasion of contact.

Traction curves were determined at peak Hertzian contact stress levels of 862 MPa (125 ksi), 1030 MPa (150 ksi), 1207 MPa (175 ksi), and 2068 MPa (300 ksi). Most experiments were conducted at lower stress levels to preserve the transfer film. The candidate cage specimen was loaded against the lower disk for the duration of the traction experiments in order to regenerate any transfer worn away by the test procedure. Experiments were conducted under cryogenic conditions.

Results of Traction Experiments

Figure 14 summarizes the slip-traction measurements taken at a peak Hertzian contact stresses of between 862 MPa (125 ksi) and 1030 MPa (150 ksi). Appendix A lists the individual curves for the various experimental conditions. Compared with measurements taken in the absence of any transfer film, both Armalon and Salox M (60 PTFE-40) appeared to produce films exhibiting reduced slope and lower traction coefficients. Figure 15 shows a curve generated for Armalon at 2068 MPa (300 ksi).

The slope of the slip-traction curve in the low slip region is a measure of the film shear strength and thickness. High-strength, low

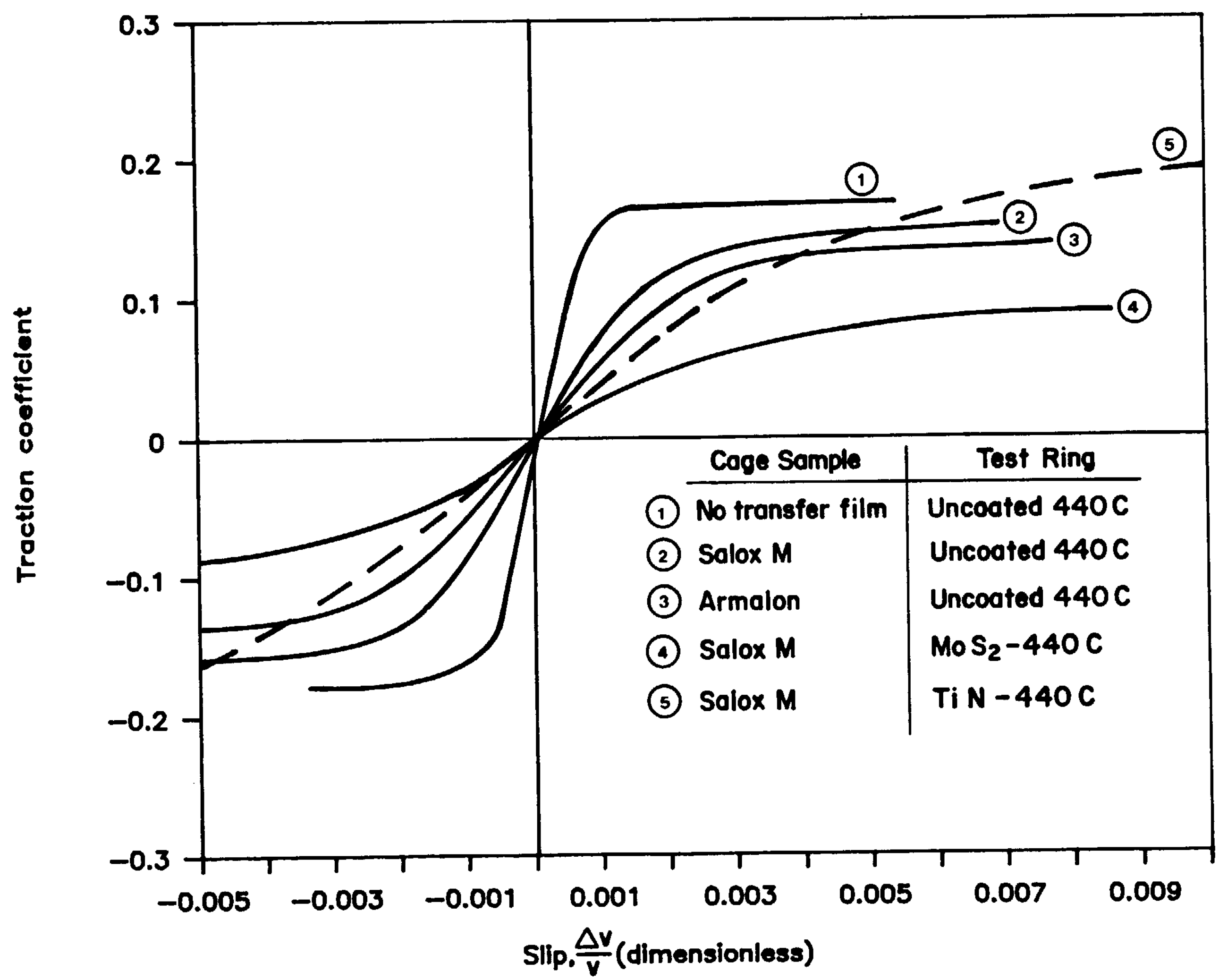


FIGURE 14. SUMMARY OF SLIP-TRACTION CURVES FOR VARIOUS SLIDING CONTACT COMBINATIONS

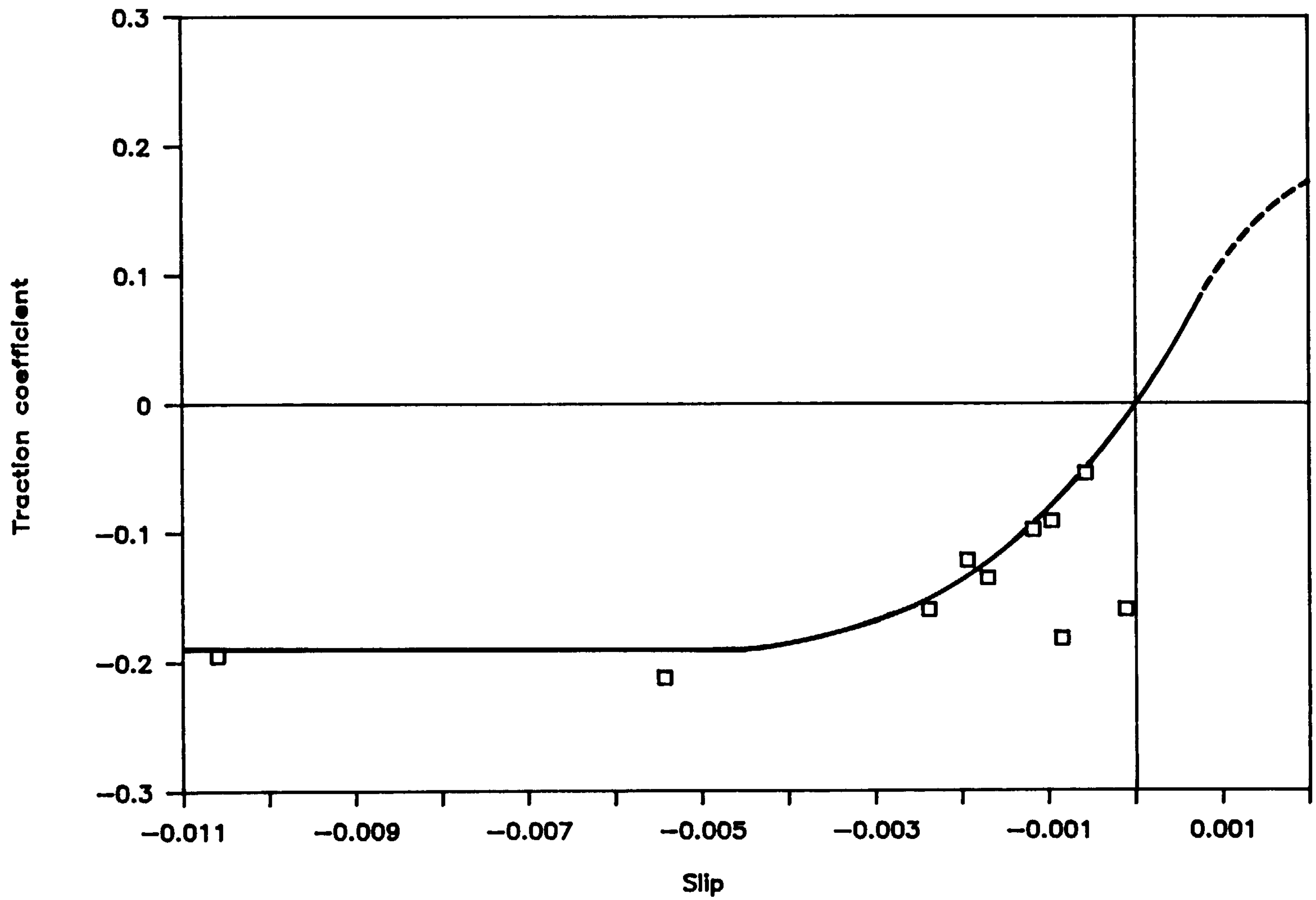


FIGURE 15. SLIP-TRACTION CHARACTERISTICS OF FILM ON 440C TEST RING, ARMALON, 2068 MPa (300 ksi) PEAK HERTZIAN CONTACT STRESS

thickness films would be expected to exhibit high slopes in this region, compared with the lower slopes typically exhibited by low shear strength, thick films associated with film lubrication. Table 5 lists the slopes measured for the curves illustrated in Figures 14 and 15. The rheological behavior of the film produced by Salox M and Armalon on uncoated 440C appears to be similar based on slope values. The lowest slope and traction coefficient values were produced by the MoS_2-coated 440C by virtue of the low shear strengths and friction of MoS_2 coating itself.

Discussion of Traction Experiment Results

The traction experiments have indicated that surface coatings and/or transferred layers can alter the surface tractions in a disk machine and presumably in a bearing. These analyses were conducted to evaluate the credibility of the disk test to ascertain that the data generated are realistic. In the disk machine, traction experiments the disks were in rolling/sliding contact as illustrated in Figure 16. A point on the upper disk moves with velocity v_1 and a point in the lower disk moves with a velocity v_2. For conditions where no slip occurs the surface of the interface must stretch tangentially by an amount $(v_1-v_2)t$ where t is time in contact. In terms of x position,

(1) $t = x/v_1$ or

(2) $\delta = (\Delta v/v)x$

Where δ is the tangential deflection and x is position.

Because the interface is elastic, the surface stretching will generate elastic shear stresses at (and near) the surface provided the stress is less than a limit defined as the coefficient of friction times the normal pressure. When the shear stress exceeds this limit slippage occurs either locally or totally. The relationship between elastic shear stress and local deflection for solid cylinders can be written:

$$\delta(x) = 4\ (1-\nu^2)/\pi E \int_0^{2b} \tau(x')\ \ln\ (x-x')\ dx'$$

TABLE 5. SLOPES OF SLIP-TRACTION CURVES MEASURED IN LINEAR REGION

Cage-Ring Combination	Peak-Hertzian Contact Stress MPa (ksi)	Slope (dimensionless)
Salox M - 440C	1034 (150)	36
Salox M - MoS_2 on 440C	1034 (150)	16
Salox M - TiN on 440C	1034 (150)	36
Armalon - 440C	861 (125)	45
Armalon - 440C	2068 (300)	85
Uncoated 440C	1207 (175)	214

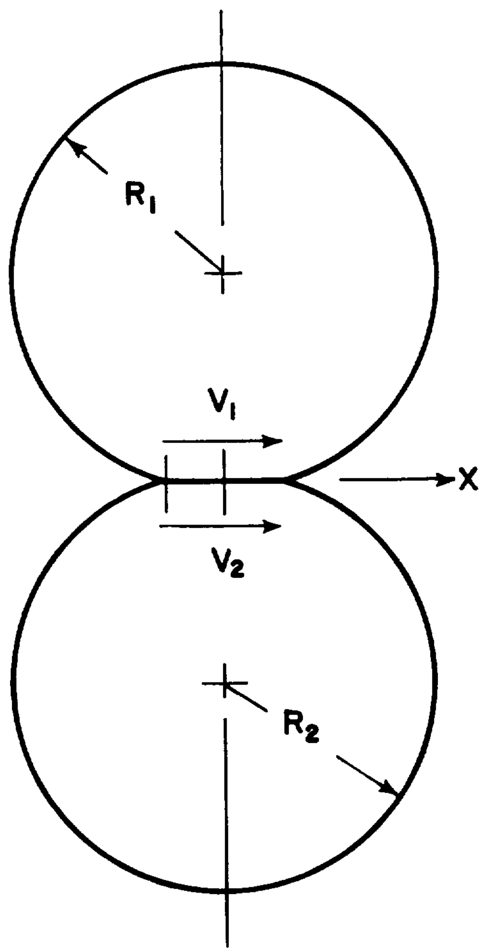


FIGURE 16. ILLUSTRATION OF DISKS IN ROLLING/SLIDING CONTACT

where

ν = Poisson's ratio,
E = Young's modulus,
τ = shear stress, and
2b = width of contact zone.

Normally, δ is known and Equation 2 and Equation 3 are used to determine the shear stress by a matrix technique (5). Kannel and Dow[5] present solutions for both solid cylinders and for cylinders containing a surface layer. The equations used in the layered film solutions are considerably more complicated than Equation 3 for a solid body. One difficulty associated with analyzing layered solids is in characterizing the layer thickness and modulus in a way that is useful.

In the report for Task 117 traction slip data were presented for a specific situation which simulated the HPOTP bearing. The conditions (in the absence of a surface layer) were as follows:

Max Hertz Pressure	P_H	1.9 GPa	(277,000 psi)
Width of Contact	2b	0.5 mm	(0.02 inch)
Modulus of Elasticity	E	200 GPa	(29 MPSI)
Poisson's Ratio	ν	0.3	
Relative Radius	R	7.6 mm	(0.3 inch)

Using these conditions the Battelle computer model ATCON was used to generate the traction slip curves of Figure 17. If the bearing load or the thickness of the coating is changed the traction curves will change.

It has been observed that the curves can be generalized by using the expressions:

$(\Delta v/v)(R/b)$, and

$\gamma(ho/h)$

which are apparently invarient under changing contact width (or pressure), radius, or layer thickness. Using the scale $(\Delta v/v)(R/b)$ in Figure 17 then allows for the curve to be used for any load or radius. Likewise

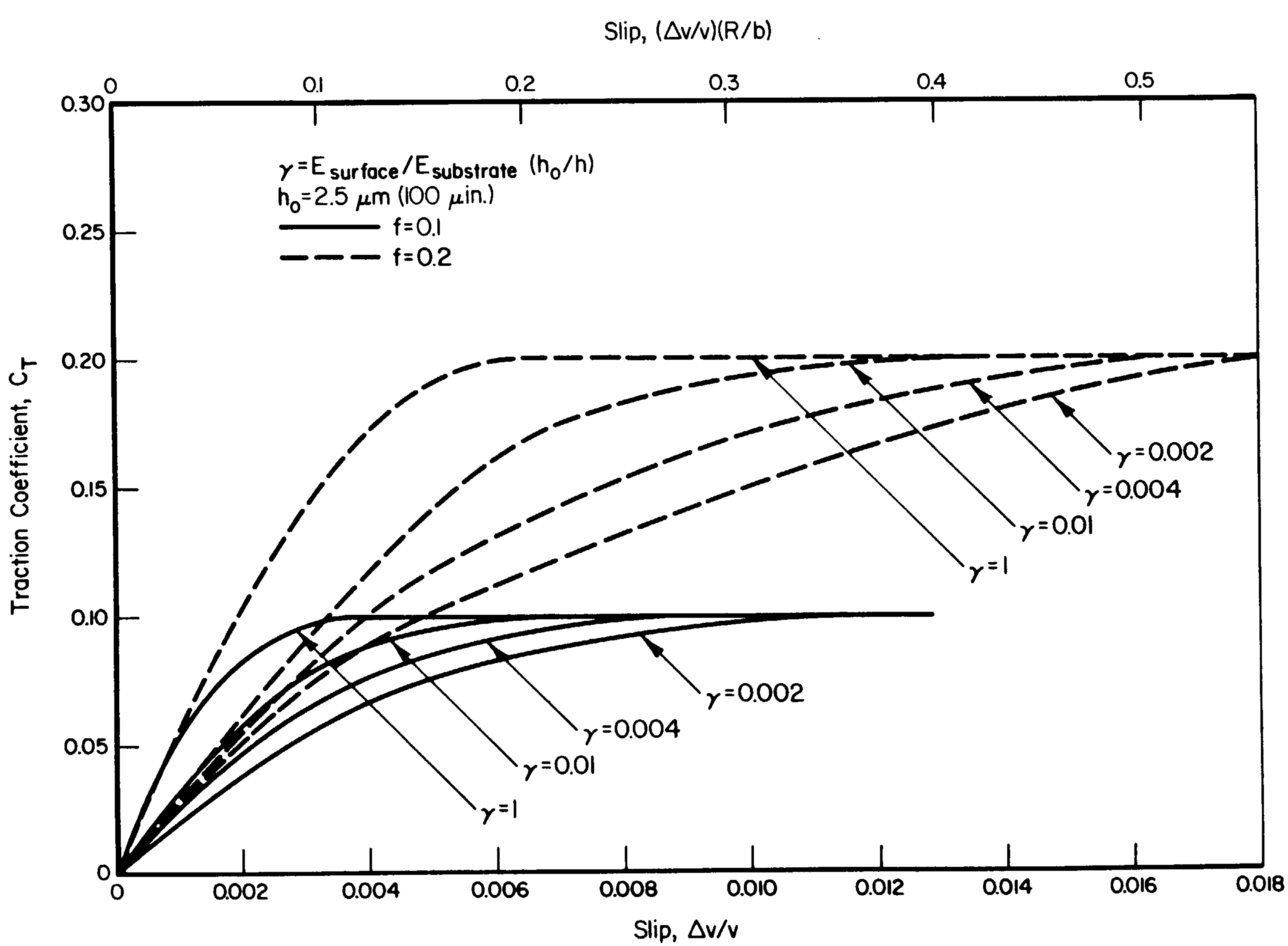


FIGURE 17. THEORETICAL TRACTION SLIP CURVES FOR VARIOUS COATINGS

TABLE 6. ESTIMATED VALUES OF TRACTION IN SLOPES FOR VARIOUS LOAD CONDITIONS

P_H GPa	γ	h (μm)	C_T v/Δv
1.9	>0.1	0	55
	0.01	2.5	33
	0.004	2.5	25.5
	0.002	2.5	19.5
0.85	>0.1	0	122
	0.01	2.5	74
	0.004	2.5	57
	0.002	2.5	43.5
0.85	>0.1	0	122
	0.01	1.25	~62
	0.004	1.25	43.5
	0.002	1.25	~38

Possible cage configurations are given in Figures 18 and 19. The design given in Figure 18 shows the cage to be made of Salox M except for stainless steel reinforcing rings. This configuration could have the structural strength required while still being basically a Salox M cage. The Salox M would be inherently exposed to the ball pocket and to the race-land guiding surface. The Salox M then would provide the good lubrication to all critical bearing components. Fabrication of this configuration would be straightforward. Material preparation would be a primary key to the success of the concept, such as material consistency and homogeneity. As an alternate to the bronze powder, bronze fibers (proposed by F. Dolan of NASA MSFC) may represent a method to increase the strength of the bronze-filled PTFE. Continuous bronze fibers may permit the construction of the cage directly from the bronze-filled PTFE.

The configuration of Figure 19 involves a set of cage (ball) pocket inserts in a stainless steel rib. This design will have excellent structural strength. Since each ball pocket is a separate configuration, inspection and quality control of the Salox M will be much easier than quality control for the design given in Figure 18. The Salox M insert "slugs" will be tapered such that centrifugal force will wedge them into the rib. The slug can extend beyond the O.D. of the cage to lubricate the land surface for an outer race guided bearing.

Either of the two concepts presented here have merit as cage designs. Both concepts should be subjected to a detailed design analysis, fabricated, and tested in a high speed bearing at cryogenic temperatures.

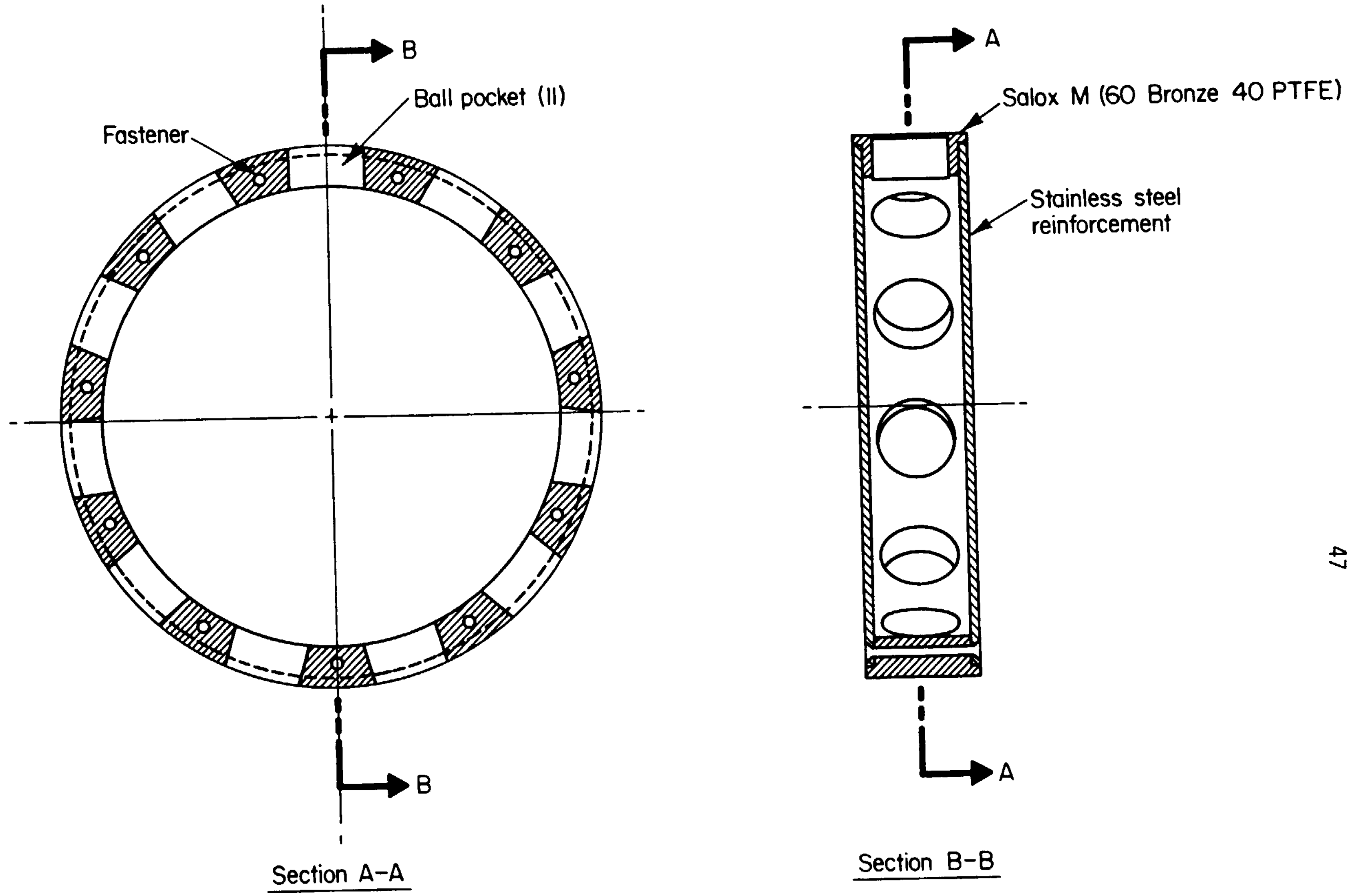


FIGURE 18. POSSIBLE SALOX M CAGE CONFIGURATION USING STAINLESS STEEL REINFORCING RINGS

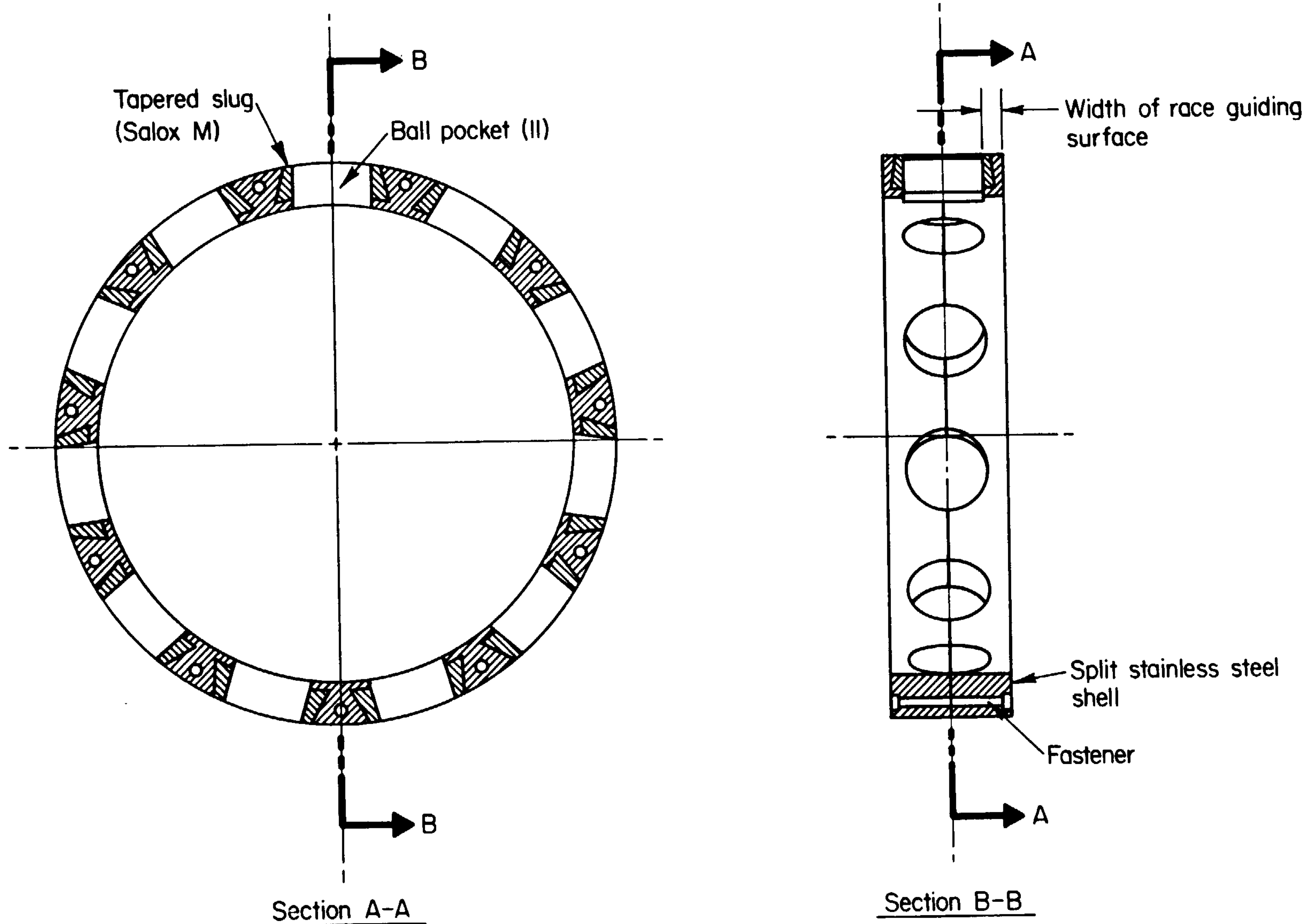


FIGURE 19. POSSIBLE CAGE CONFIGURATION USING SALOX M BALL POCKET INSERTS

MEASURING AND CALCULATING UNITS

The measurements and calculations were performed in English units with the exception of selected sample weighings and the application of loads in terms of grams force. Therefore, most of the SI units presented in this report were converted from English units. Data on which this report is based are located in Battelle Laboratory Record Book No. 41438.

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(2) Barber, S., Dufrane, K. F., Kannel, J. W., Merriman, T. L., Rosenfield, A. R., "Bearing Materials Studies for Space Shuttle Main Engine (SSME) Cryogenic Turbopump Application", task report submitted to NASA-Marshall Space Flight center, May 15, 1985.

(3) Steijn, R. P., "The Sliding Surface of Polytetrafluoroethylene: An Investigation With the Electron Microscope", Wear, 12 (1968) 193-212.

(4) Rabinowicz, E., "Friction and Wear of Materials", John Wiley and Son, 1965.

(5) Kannel, J. W., and Dow, T. A., "Analysis of Traction Forces in a Precision Traction Drive, Trans ASME (J.O.L.T.), June 1986, pp. 403-411.

APPENDIX A

Slip-Traction Curves for Various
Experimental Conditions Investigated

SLIP-TRACTION CURVES FOR VARIOUS EXPERIMENTAL CONDITIONS INVESTIGATED

Slip-traction curves featured in Figure 14 were collected by using the rolling disk apparatus shown in Figure 13. To generate individual data points, a speed difference between the upper crowned disk and the lower test disk was selected and the rotating disks were brought into loaded contact. The resulting traction force was measured with a traction load cell.

The figures shown in this appendix show data points collected for the various experimental conditions. Slopes for the slip-traction curves listed in Table 5 have been taken from these curves. All experiments were conducted under cryogenic conditions.

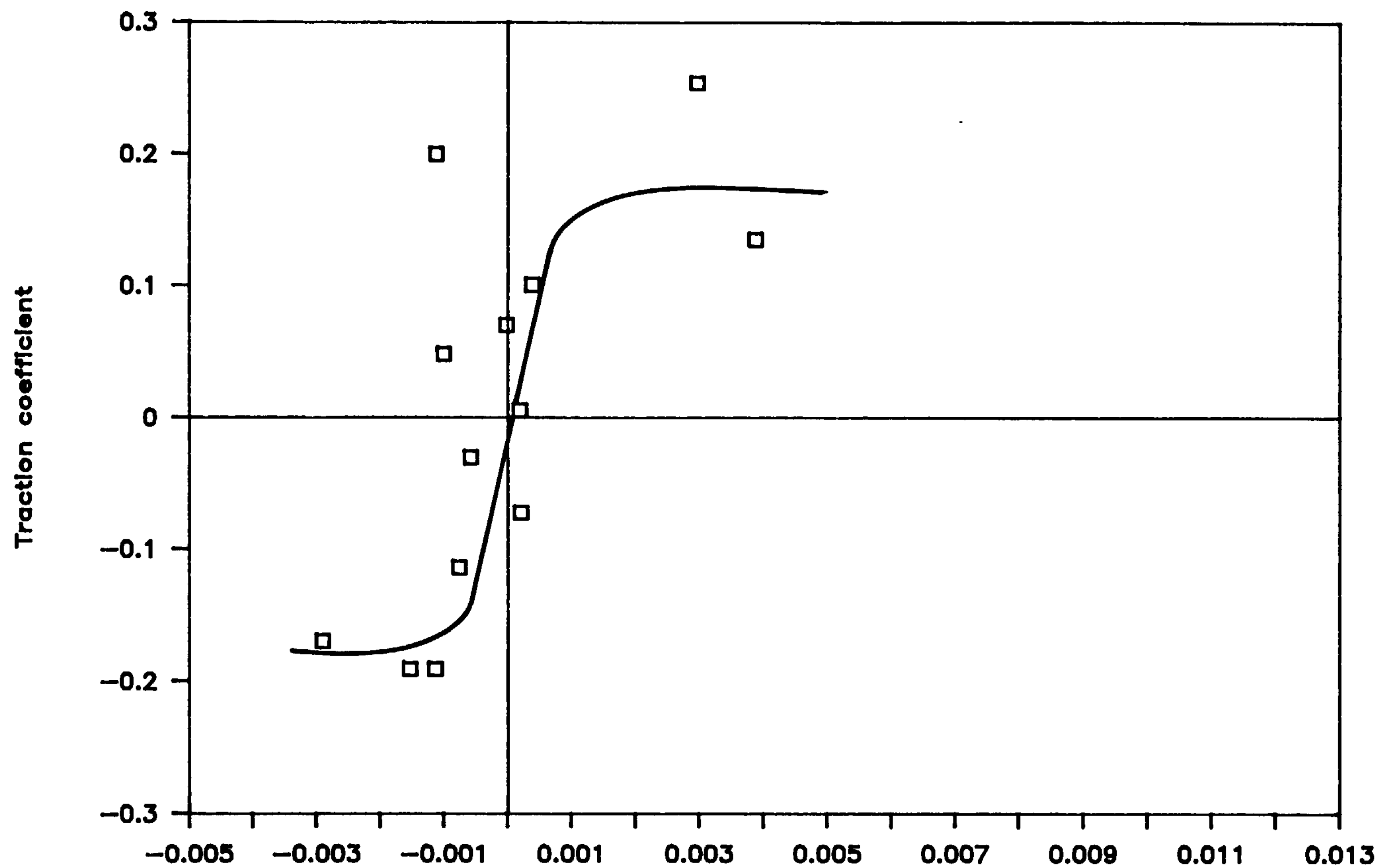

FIGURE A-1. SLIP-TRACTION CHARACTERISTICS OF UNCOATED 440C, 1207 MPa (175 ksi) PEAK HERTZIAN CONTACT STRESS

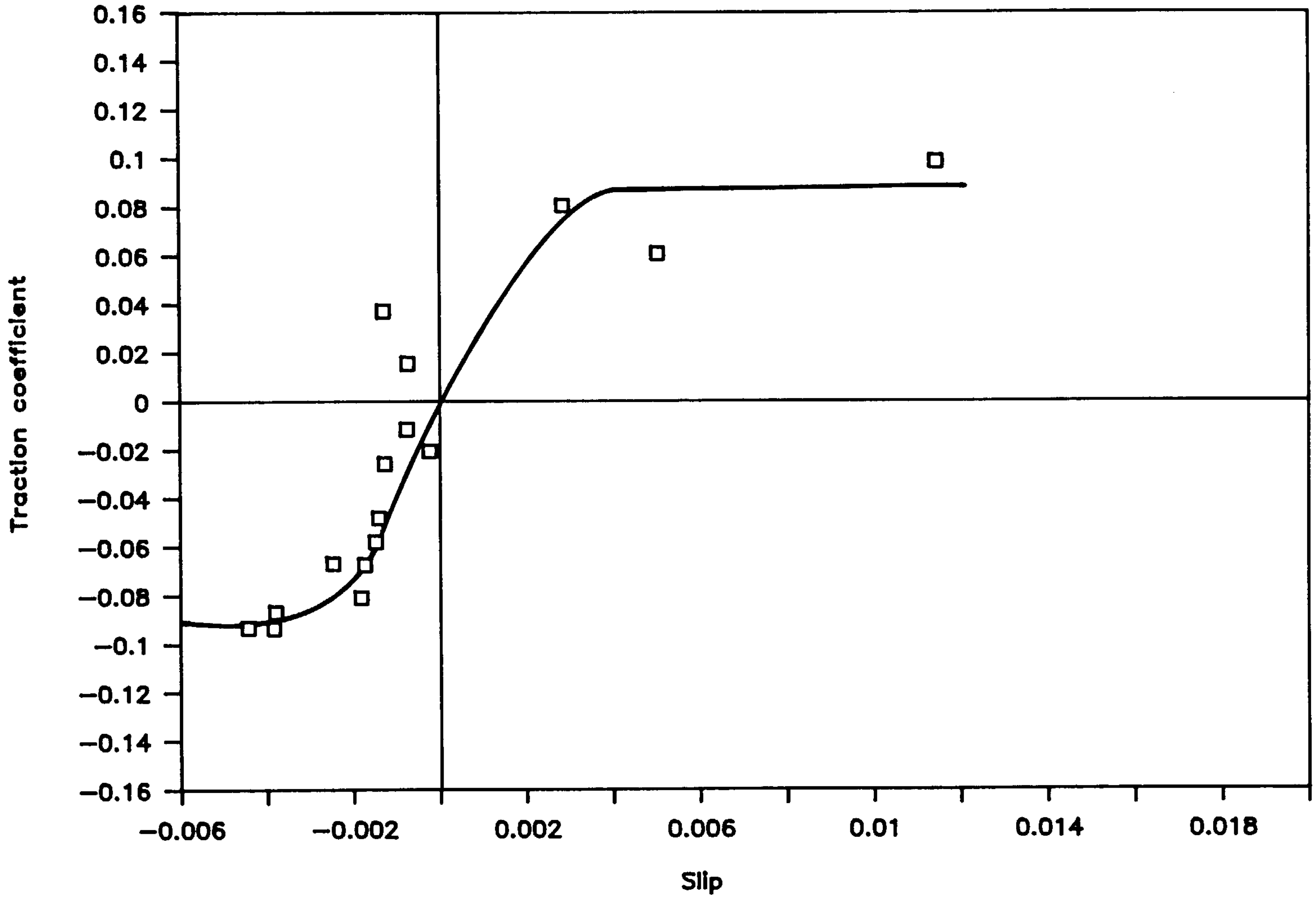

FIGURE A-2. SLIP-TRACTION CHARACTERISTICS OF FILM ON 440C TEST RING SALOX M (60 PTFE-40 BRONZE), 1030 MPa (150 ksi) PEAK HERTZIAN CONTACT STRESS

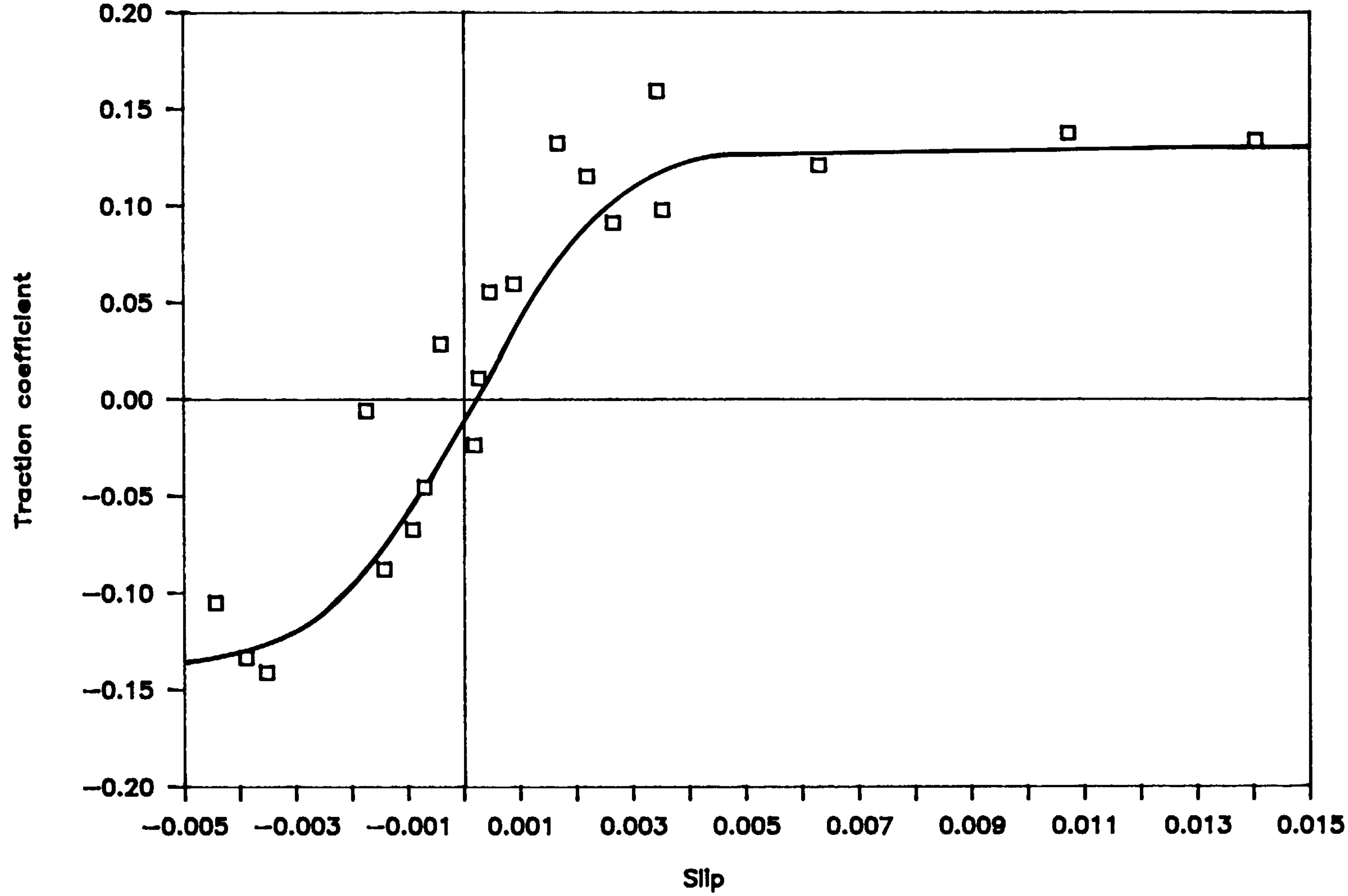

FIGURE A-3. SLIP-TRACTION CHARACTERISTICS OF FILM FORMED ON 440C TEST RING, 40 PTFE-60 BRONZE, 862 MPa (125 ksi) PEAK HERTZIAN CONTACT STRESS

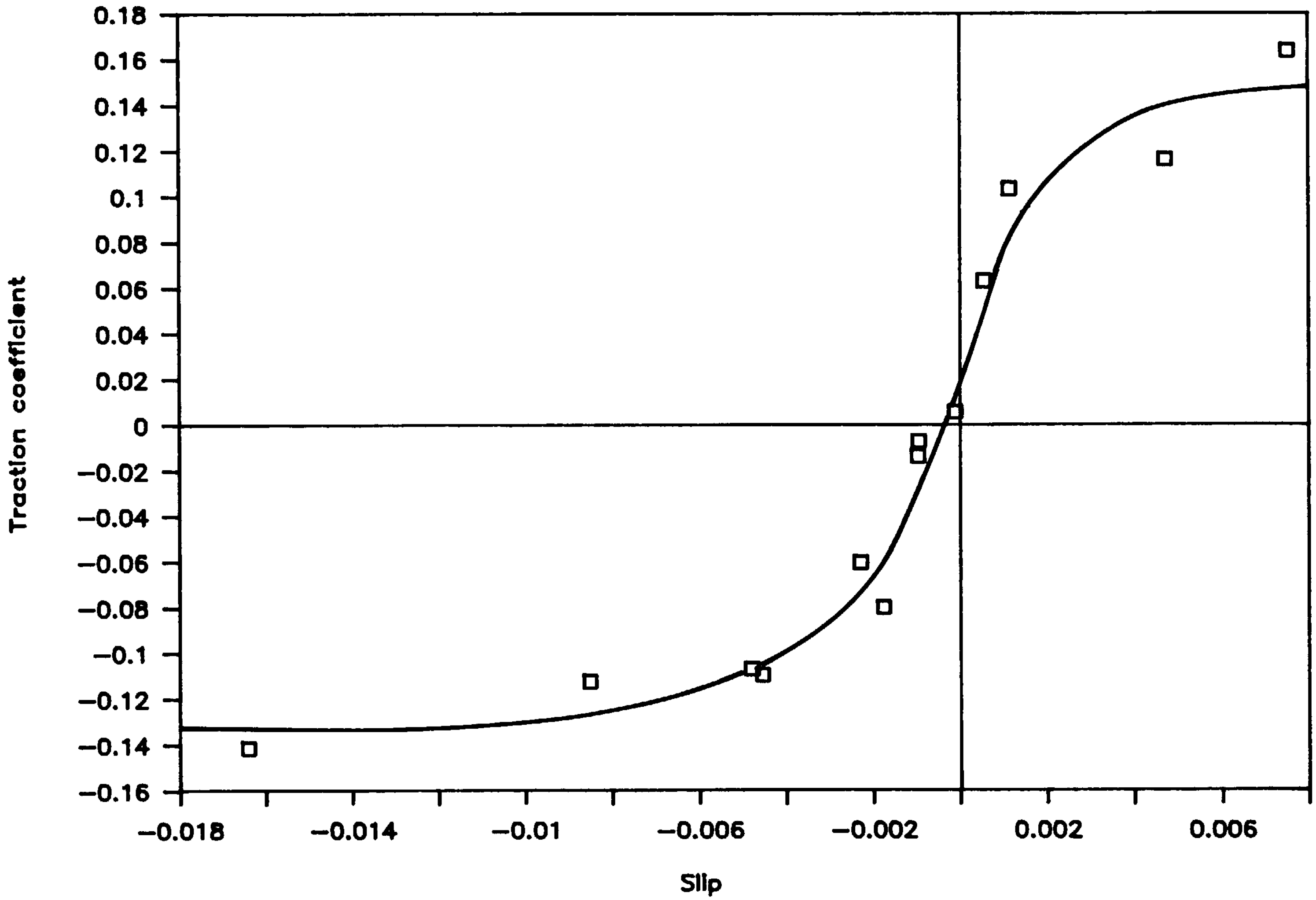

FIGURE A-4. SLIP-TRACTION CHARACTERISTICS OF FILM FORMED ON GROUND 440C TEST RING, 40 PTFE-60 BRONZE; 862 MPa (125 ksi) PEAK HERTZIAN STRESS

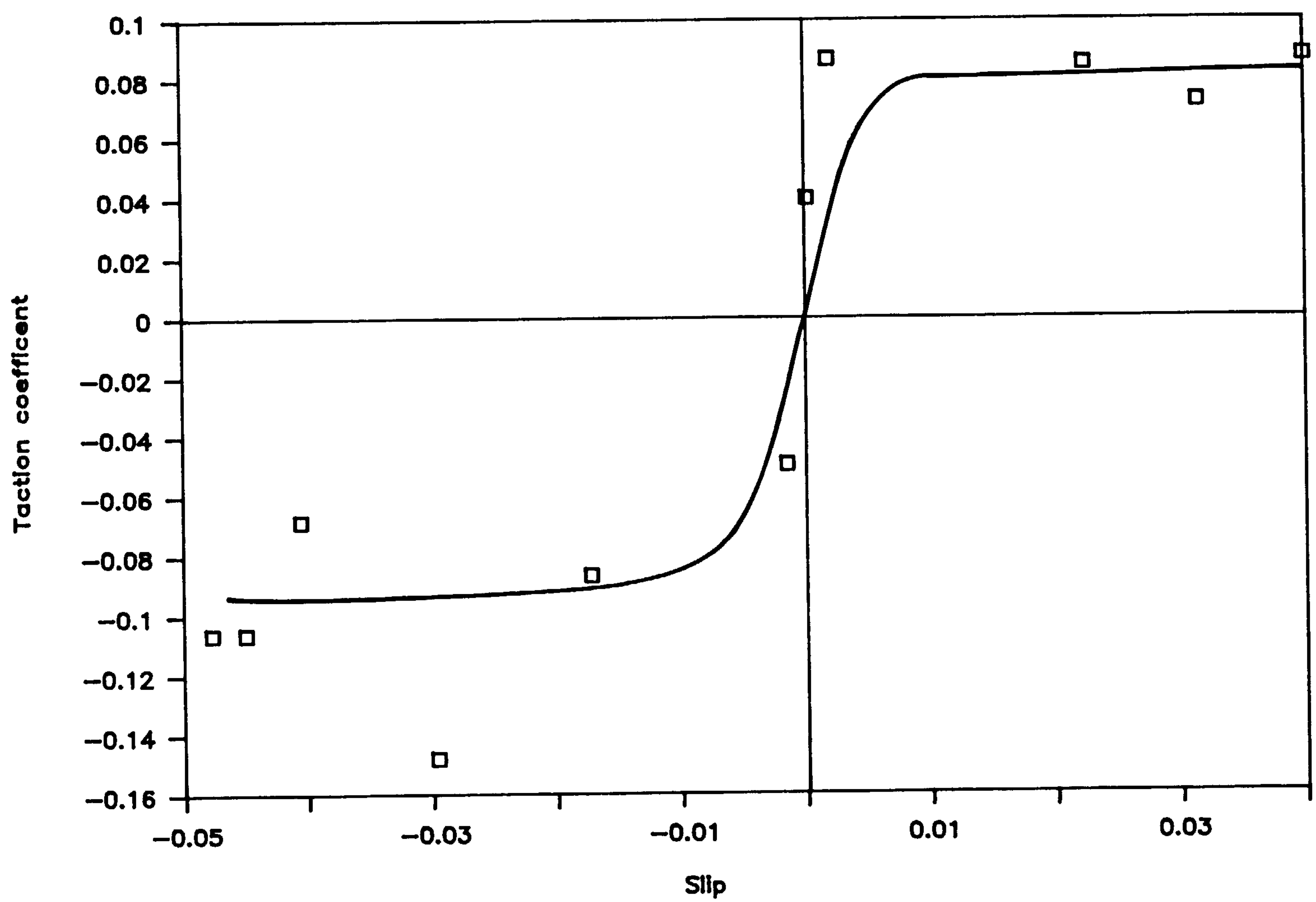

FIGURE A-5. SLIP-TRACTION CHARACTERISTICS OF FILM ON MoS_2-COATED 440C TEST RING, 60 PTFE-40 BRONZE, 1030 MPa (150 ksi) PEAK HERTZIAN CONTACT STRESS

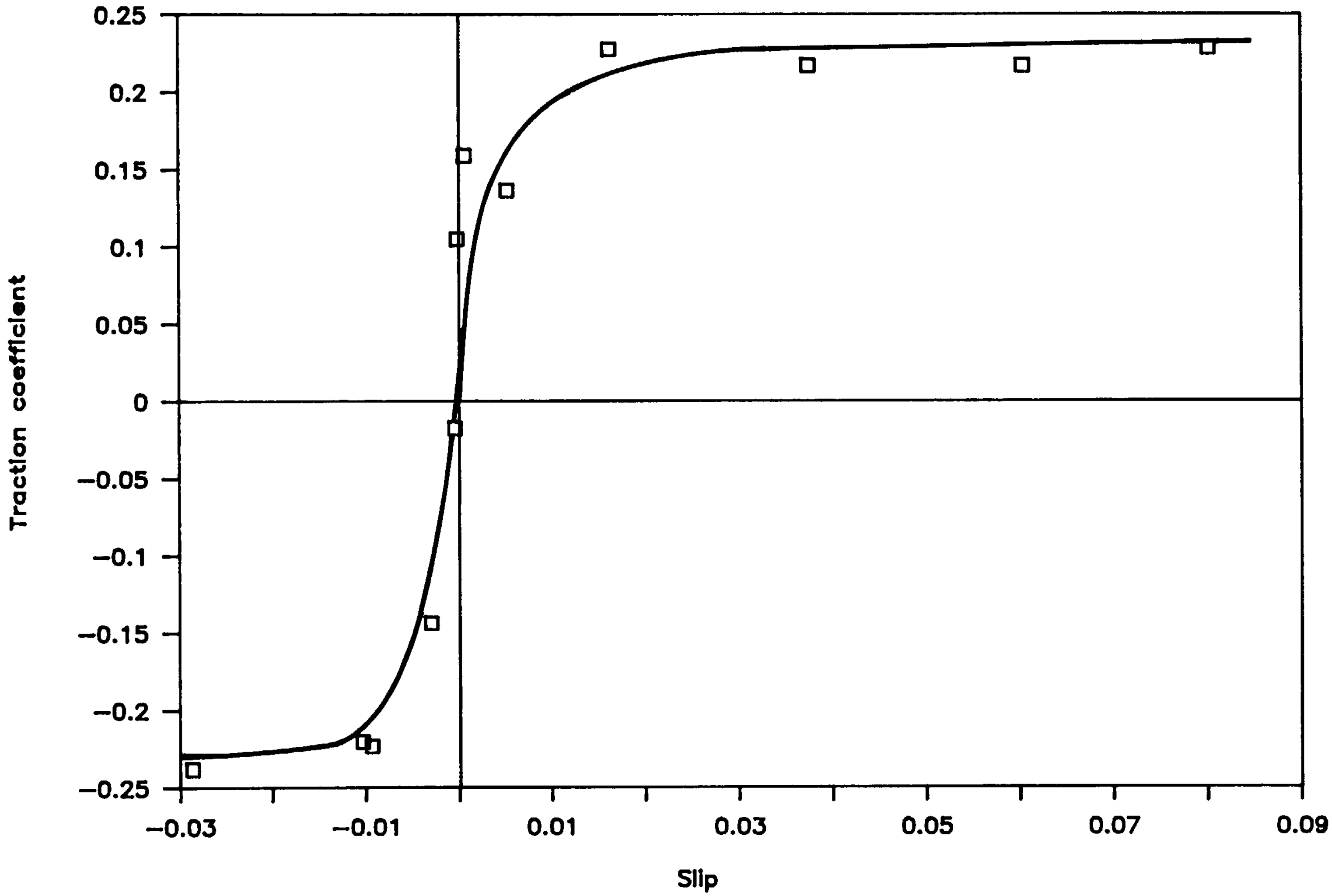

FIGURE A-6. SLIP-TRACTION CHARACTERISTICS OF FILM ON TiN-COATED 440C TEST RING, 60 PTFE-40 BRONZE; 1030 MPa (150 ksi) PEAK HERTZIAN CONTACT STRESS

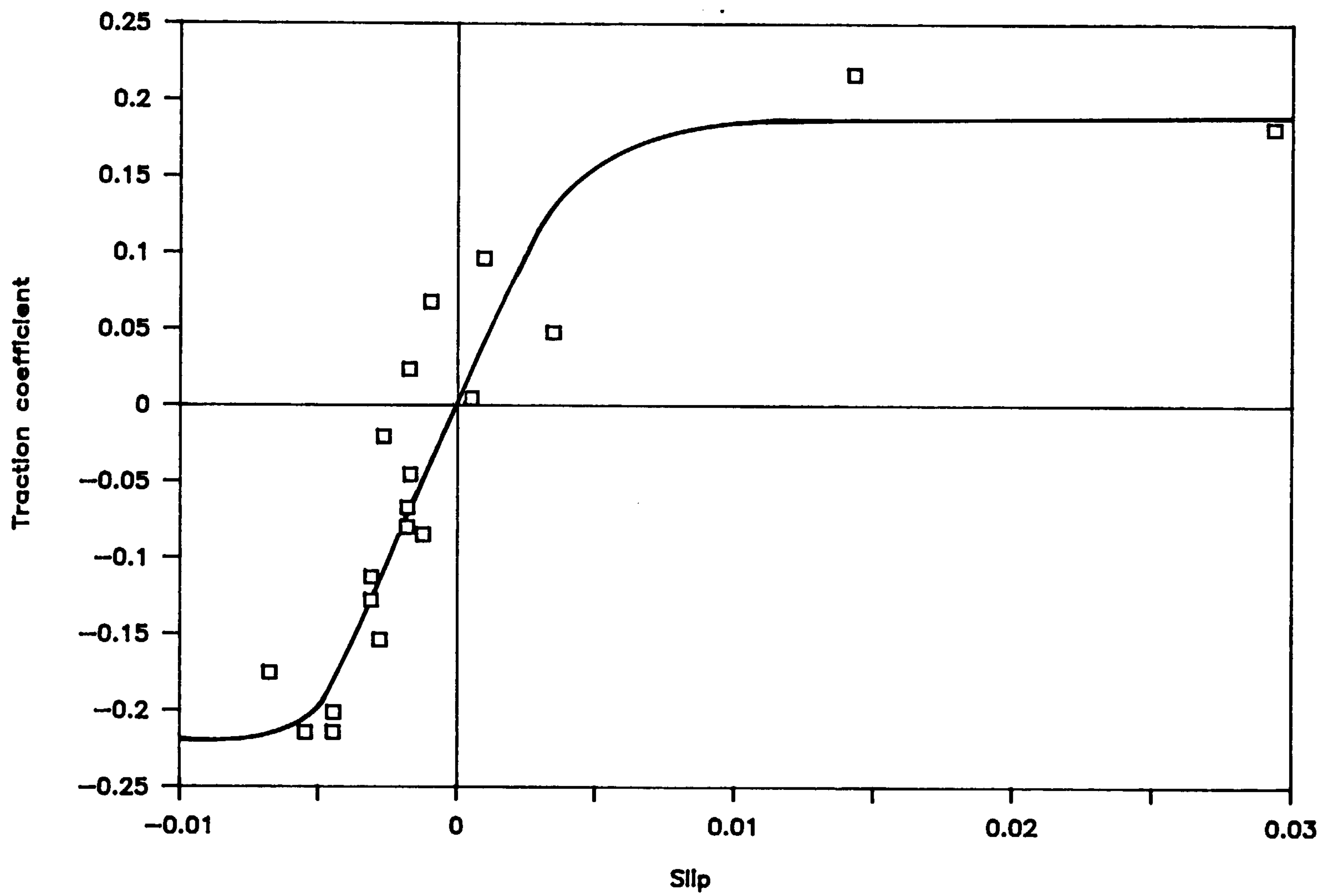

FIGURE A-7. SLIP-TRACTION CHARACTERISTICS OF FILM GENERATED ON 440C TEST DISK, ARMALON, 862 MPa (125 ksi) PEAK HERTZIAN CONTACT STRESS

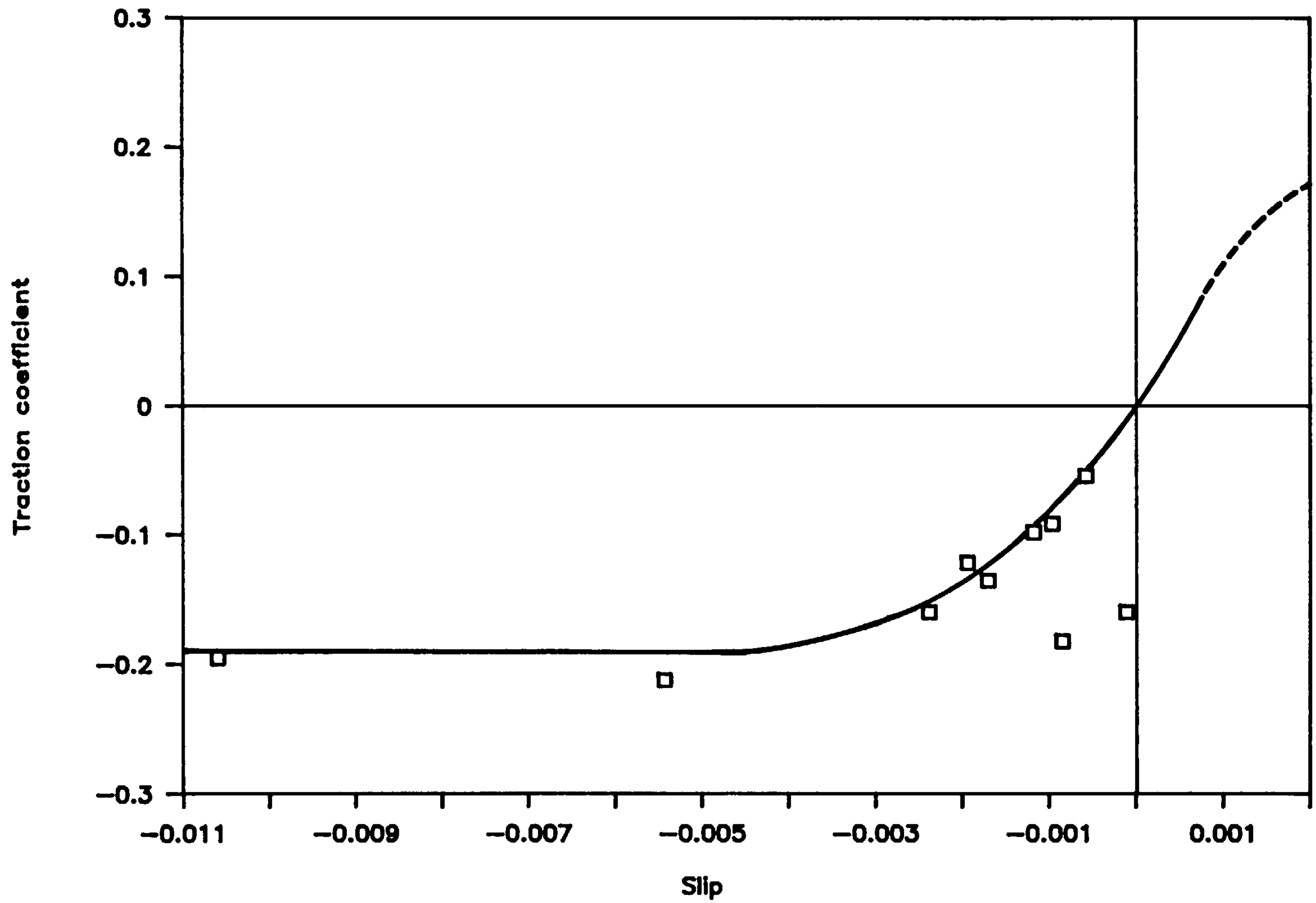

FIGURE A-8. SLIP-TRACTION CHARACTERISTICS OF FILM ON 440C TEST RING, 2068 MPa (300 ksi) PEAK HERTZIAN CONTACT STRESS

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