

CARNEGIE INSTITUTE OF TECHNOLOGY
Department of Mechanical Engineering
Pittsburgh 13, Pennsylvania

FINAL REPORT

October 31, 1954

INVESTIGATION OF GALLING AND FRICTION
CHARACTERISTICS OF TITANIUM ALLOYS

TO

WATERTOWN ARSENAL
Watertown 72, Massachusetts

BY

EBER W. GAYLORD

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WAL REPORT NO. 401/65/37

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October 31, 1954

Carnegie Institute of Technology
Pittsburgh 13, Pa.

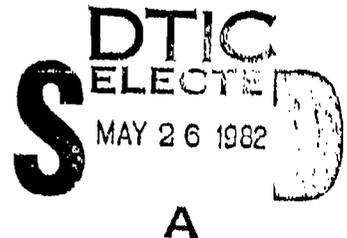
INVESTIGATION OF GALLING AND FRICTION
CHARACTERISTICS OF TITANIUM ALLOYS

BY

EBER W. GAYLORD

This work was performed under technical supervision of
Watertown Arsenal Laboratory

Contract No. DA-36-061-ORD-361
WAL REPORT NO. 401/65-37
Dept. of Army Project No. 593-08-021
Ordnance Research and Development Project No. TB4-15



Pittsburgh Ordnance District - 200 Fourth Avenue, Pittsburgh 22, Pa.

OBJECT

To study the galling and dry friction characteristics of titanium materials.

SUMMARY

The results of studies made to establish criteria for galling are presented. A method for measuring the interface temperature between two metals during dry rubbing is discussed. Results of rubbing tests of unalloyed, alloyed, and surface treated titanium specimens are given. The degree of improvement in friction and galling characteristics afforded by surface treatment is determined.

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CONCLUSIONS

1. The normal loads and speeds that cause galling of unalloyed titanium rubbing on unalloyed titanium do not depend significantly on the apparent contact area of the rubbing specimens, but with larger areas galling damage appears to progress at a slower rate.
2. When galling of a titanium slider block specimen rubbing on a steel plate occurs there is a significant increase in the amplitude of the fluctuations in normal load which may be detected by a piezo-electric crystal. Galling damage may increase in severity over a period of ten minutes or more.
3. Heavy galling of metallic surfaces in dry rubbing is accompanied by a large increase in surface roughness and an increase in the coefficient of friction which becomes more or less independent of load. When there is no galling the coefficient of friction is not reproducible and increases with time of rubbing.
4. When there is no galling a "dynamic thermocouple" formed by the junction of two dissimilar metals rubbing over each other may be used to get a fair estimate of the average interface temperature. A dynamic thermocouple will produce a randomly fluctuating component of voltage that increases to a much higher value when galling occurs.
5. The improvement in galling characteristics of titanium alloys afforded by surface coating and nitriding is significant.

I INTRODUCTION

This is the final report on the project INVESTIGATION OF GALLING AND FRICTION CHARACTERISTICS OF TITANIUM ALLOYS which is a continuation of the work done on the project GALLING AND SEIZING CHARACTERISTICS OF TITANIUM BASE ALLOYS (1), October 15, 1951 to June 30, 1953. This report covers the period from July 1, 1953 to September 1, 1954.

This project has, but is not necessarily limited to, the following objectives:

1. Determine the galling and friction characteristics of titanium and titanium alloys.
2. Establish satisfactory criteria for the galling of titanium materials.
3. Determine, quantitatively, factors affecting galling characteristics; such as load, speed, thermal effects, and time of rubbing.
4. Evaluate the degree of improvement in galling resistance afforded to titanium by various surface treatments to be suggested by Watertown Arsenal Laboratory. These may include nitriding carburizing, phosphating, oxidizing and electro-deposited coatings.

II APPARATUS

The test apparatus is essentially the same as that described in the final report of the previous contract (1), June 30, 1953. Modifications have made the testing machine adaptable to a greater range of loads, speeds, and types of tests.

A plate specimen is attached to a revolving face plate and is rubbed against a stationary test specimen, (see figures 1 and 2). The stationary test specimen is held by a loading arm so that it traces a circular path on the plate specimen. The loading arm contains an adapter that will hold both rod and slider block type specimens. A ring spring applies the normal load to the loading arm which is free to pivot about its base in the plane of the normal load. The normal load may be determined either by a dial indicator which measures the compression of the ring spring or by balancing the ring spring force with a weight and pulley system.

The entire normal load apparatus is attached to a platform which can oscillate in a plane parallel to the plate specimen. An arm which is attached to this platform rests on a strain ring equipped with SR-4 strain gages, and is attached to a dashpot for damping. The strain gauges make it possible to record the strain ring deflection, which is proportional to the tangential force on the rubbing specimen. This strain gauge reading may be continuously recorded on a direct inking oscillograph, observed on the screen of an oscilloscope, or indicated on the scale of a vacuum tube voltmeter. A set of known weights which are placed on the strain ring may be used for calibration. The loading apparatus has been designed to reduce transient effects and chattering. Relative rubbing speeds ranging from almost zero to 2000 feet per minute are available.

III GALLING CRITERIA

Part of the research consisted of studying phenomena that are related to galling during the dry rubbing of metallic surfaces. It would be desirable to have one or more methods that would consistently define galling damage and determine when it occurs.

Slider Blocks and Rod Tips

In the work done on the preceding contract, the specimens that were rubbed on the plate material were 1/16 inch diameter rod type. Because these showed some tendency to dig into the plate material unless the rod tip surfaces were very carefully prepared, it was decided to use slider block rubbing specimens. The slider block specimens (see figure 3), were held in place by steel jaws and rocked on a pivot through which the normal load was applied. The pivoting action insured good contact of the slider block surface against the plate surface. A chamfered leading edge and rounded corners prevented digging in. Rubbing tests of Ti 75-A slider blocks on Ti 75-A plates were made to find out what speeds and loads would produce visible galling damage of the slider blocks and plate surfaces. The test procedure was to operate at a constant rubbing speed and gradually increase the normal load at 15 minute intervals until galling occurred. On the previous contract a similar type of test had been run for a 1/16 inch diameter, Ti 75-A rod tip rubbing on a Ti 75-A plate surface. In figure 4, the results of the two tests are compared. The galling limit normal loads and speeds are similar for the slider block and the rod tip, but the surface area of slider blocks is 0.047 square inches whereas the surface area of the rod tip was only 0.003 square inches. Once galling begins, however, galling damage progresses at a more rapid rate with the rod tip than it does with the slider block.

Extended Time Galling Tests and Measurement of Variations in Normal Load

Ti 75-A unalloyed titanium slider blocks, with normal load being applied by a piezo-electric crystal, were rubbed against a steel plate at speeds of 10, 25 and 50 feet per minute and normal loads of 4, 8, 12, 16, and 20 ounces for a period of one hour for each load and speed. The arrangement of the piezo-electric crystal is shown in figure 3. The crystal develops a fluctuating voltage that depends on the fluctuations in the force that the slider block pivot exerts on the crystal. This voltage depends on the roughness of the two rubbing surfaces as well as on the magnitude of the average normal load, the rubbing speed, and the mechanical properties of the slider block holder system.

For a given amount of roughness or galling of the rubbing surfaces, light loads and low speeds produce considerably less voltage than do high loads and high speeds. However, for a given normal load and speed the crystal voltage gives a relative indication of the amount of galling damage that has taken place. The results shown in figures 5, 6, and 7, are significant in that they show a substantial increase in the voltage for a given load and speed as galling damage progresses, and that galling damage appears to increase in severity over a period of ten minutes or more.

Surface Roughness

A Brush Electronics Company "Surfindicator", Model BL-110, roughness indicator was used to see how surface roughness compared with galling damage. This instrument measured the average surface roughness of the slider blocks and plate specimens. Surfaces that were surface ground or polished with crocus cloth ranged in roughness between 4 and 7 micro-inches. After the specimens were rubbed, a visual change in the appearance of the surface could be observed when the roughness had increased by 3 to 4 micro-inches. Very heavy galling caused the surface roughness indicator to show a roughness increase of 20 micro-inches or more.

Coefficient of Friction

During many of the rubbing tests the coefficient of friction was measured. At the beginning of a rubbing test the coefficient of friction was rather low for the dry rubbing of metals. As rubbing continued in the absence of galling the coefficient of friction would gradually increase. (See figures 14, 16, 26, and 36.) When severe galling occurs the coefficient of friction increases to a much higher value (figures 13, 15 and 45), which seems to be more or less independent of the load. Figure 8 shows the frictional force for Ti 75-A rod tips rubbing on RC-55 Plates.* Over the range from about 1 lb. normal load to 10 lb. normal load, heavy galling occurred. In the range of 0 to 1 lb. normal load the coefficient of friction is quite random. In this range heavy galling does not take place. In the work done on the present contract the sensitivity of the friction load apparatus was increased so that more accurate measurements could be made in the range of normal loads where severe galling does not occur. It was found that the coefficient of friction was not constant or reproducible in this range. It is probable that in the absence of galling contaminants which serve as lubricants are always present on the rubbing surfaces no matter how carefully they are cleansed with carbon-tetrachloride. As the rubbing time increases some of the lubricant is worn away and the coefficient of friction increases. The increase in friction when heavy galling begins may be due to true metal to metal contact replacing contact between dry lubricated surfaces.

The Relationship Between Roughness, Coefficient of Friction and Galling

Figures 13, 15, 25, 35, and 45, show how the coefficient of friction and the increase in surface roughness vary with the normal load for steel. Ti 150-A, RC 130-A, RC-55, and RC 130-B sliders after rubbing on steel plates for 10 minutes at a speed of 100 feet per minute.

There is considerable correlation between the coefficient of friction and the increase in surface roughness. The condition of the surfaces after

* This work was done on Contract DA-36-061-ORD-112. Galling and Seizing Characteristics of Titanium and Titanium Base Alloys.

rubbing is arbitrarily classified in three types (see figures 9 and 10), which are:

1. No Galling. The plate and slider, except for some shininess, show no visual surface damage. The surface roughness increases by no more than 1 or 2 micro-inches and in some cases the surface may become smoother. The coefficient of friction is neither constant nor reproducible and seems to behave as though a dry lubricant were present between the rubbing surfaces.
2. Partial Galling. Visual damage occurs over parts of the rubbing surfaces but does not extend completely over the entire contact area. Scratches appear and portions of the rubbing surfaces alternately become roughened and then smooth out during rubbing. During much of the time the coefficient of friction will be sufficiently low to suggest the presence of some lubrication between the rubbing surfaces.
3. Total or Complete Galling. At the beginning of a test partial galling with small scratches or rough portions will appear on parts of the rubbing track. However, as rubbing continues they will not be smoothed out, but will spread over the entire area of the rubbing surfaces. When this happens the coefficient of friction will increase to a value that does not depend greatly on normal load or time of rubbing. Powdered metal appears on the plate and the plate and slider material wear away rapidly.

IV SLIDING FRICTION AND INTERFACE TEMPERATURE

An investigation was made of the relationship between friction and thermal effects at the interface of a pair of dry metallic surfaces in sliding contact with each other. The purpose of this study was two-fold. First to see if means could be found to gain a better understanding of how the frictional behavior of dry rubbing surfaces is related to the interface temperature and secondly, to establish a criterion for galling through the observation of thermal effects.

A complete report of this work is presented in Interim Report No. 2, "An Investigation of Sliding Friction and Interface Temperature Between Two Dry Metallic Surfaces (2)."

Dynamic Thermocouple

The use of a "dynamic thermocouple", formed by the junction of two dissimilar metals in sliding contact with each other, as a means of measuring the interface temperature was investigated. This type of thermocouple was compared with an ordinary "static thermocouple" formed by two dissimilar metals brought into intimate contact by means of pressure or fusion.

To evaluate the behavior of a dynamic thermocouple an experiment was performed. To reduce the number of variables in the test only one pair of dissimilar metals was used. Constantan and steel were selected because of their high thermoelectric properties. No titanium materials were tested; however, certain combinations of titanium and other metals will produce a thermal e.m.f.

In the test setup shown in figure 11 a constantan rod tip is rubbed against a steel plate to form a dynamic thermocouple. A fine wire rotating in a mercury bath is used to form the second moving contact. One normal load of 0.5 lb. was used. During rubbing the voltage output of the dynamic thermocouple, e_d was a randomly fluctuating voltage which was divided into two components by the circuit shown in figure 12. There was an alternating component of voltage, e'_d which was separated from e_d by an a-c amplifier and recorded on an oscillogram and a direct current or constant component \bar{e}_d which was separated from e_d by a filter and measured by a potentiometer.

The d-c component \bar{e}_d was investigated to see if it could be used as a measure of the interface temperature of the two metals sliding over each other. To do this a cone-shaped constantan rod was rubbed on a steel plate with the smaller end of the cone making contact with the steel plate. A "static thermocouple" was placed in the rod at a known distance back from the plate. During rubbing heat generated by friction caused a rise in the temperatures of the static thermocouple and the interface of the dynamic thermocouple. Both the dynamic thermocouple and static thermocouple voltages were measured. The temperature measured at the static thermocouple was used to calculate the time space averaged interface temperature at the dynamic thermocouple. This temperature was found to be in fair agreement with the temperature corresponding to the d-c component of the dynamic thermocouple voltage when no galling occurs.

The a-c voltage e'_d appeared to depend on load and rubbing speed and was observed for both dissimilar metals, constantan rubbing on steel, and for similar metals, steel on steel. This voltage shows promise as a criterion for galling because it becomes much higher when there is visible galling.

The dynamic thermocouple was used to obtain results, which are not yet conclusive, on the determination of the fractions of the heat generated by friction which go into the plate specimen and into the specimen which rubs on the plate, and on the effect of interface temperature on the coefficient of friction.

V SURFACE TREATED SPECIMENS

Slider block specimens of titanium and titanium alloys, Ti 150-A, RC-55, RC 130-A and RC 130-B, with four different types of surface treatments were received from Watertown Arsenal Laboratory. The surface treated materials were to be tested to determine their friction and galling and seizing characteristics. The degree of improvement in resistance to galling afforded by the surface treatments was to be determined.

Because of the number of specimens to be tested the variables in the tests were restricted to the normal load. All specimens were rubbed on C 1019 steel plates that were surface ground to a roughness of 5 to 7 micro-inches. The slider block specimens had a rubbing surface of about $3/16 \times 1/4$ inches with the corners chamfered and polished to prevent digging in. A rubbing speed of 100 feet per minute was chosen because it was thought to be high enough that galling would not be affected by small variations in rubbing speed. The specimens were rubbed for 10 minutes. Untreated specimens that will eventually gall at a given normal load will generally do so in this length of time, however, surface treated specimens that last ten minutes might fail over a longer rubbing period as the surface treatment wears away.

To find the degree of improvement in resistance to galling afforded by the surface treatments, untreated specimens were tested in the same manner as the treated ones. Steel on steel was also tested.

The four types of surface treatments are: Treatment A
Treatment B

Nitriding 16 hours nitrogen at 1600°F.

Nitriding 72 hours nitrogen at 1600°F. plus 16 hours partial pressure nitrogen at 1600°F.

and will be described in the order listed above.

Treatment A

Surface treatment

- (a) Fluoride Phosphate coated.
- (b) Heat treated, 5 hours at 800 F.
- (c) Molykote G lubricant

Specimens having this treatment have a dull black appearance which becomes shiny black after rubbing. A surface coated slider block specimen will leave a shiny black path on a steel plate indicating the presence of a dry lubricant which is rubbed off the slider and deposited on the plate track. As shown in table I, treatment A enables titanium and titanium alloys to withstand rubbing at much higher loads than the untreated specimens. In the case of RC 130-B no galling occurred at a normal load of 10 lb. Higher loads were not tried because the testing machine was not set up to apply higher loads. The results indicate that the rubbing surfaces were completely lubricated and there was no metal-to-metal contact until galling occurs. Galling seems to take place when the lubricant is rubbed off on a certain portion of the slider. When this happens there is galling and scratching in this area which quickly spreads over the entire rubbing area. The coefficient of friction rises to a value that corresponds to the galling of untreated specimens. The coating in treatment A is rather thin. A small amount of sanding with crocus cloth will wear it away to the extent that the slider blocks will gall at much lower loads.

The coefficient of friction before galling takes place is much larger than it would be for surfaces lubricated with a wet lubricant such as grease or oil. It varies considerably from test to test but is generally lower than it is for severe galling of the corresponding untreated specimens.

Treatment B

Surface Treatment

- (a) Fluoride Phosphate coated.
- (b) Treated with layer of Mo S₂ and phenolic resin.
- (c) Air dried 6 hours, cured 12 hours at 300°F.
- (d) Mo S₂ - Resin layer lapped to a thickness of 0.003"-0.004".

The specimens were received in the form of slider blocks which were cut from surface coated strips. The specimens showed a poor mechanical bond between the metal and the surface coating. The cutting had loosened some of the coatings so badly that they fell off. When tested none of the specimens galled at a normal load of 10 lbs. The coatings were much thicker than those for treatment A. It would probably take a much higher normal load or longer rubbing time to wear the coatings away and make the specimens gall. The

frictional characteristics are similar to those for treatment A when no galling takes place. Figure 56 shows the black smear which is deposited on the plate track. Figure 55 shows the condition of the slider block surface.

Nitrided Specimens 16 hours nitrogen at 600°F.

These specimens were received in the form of strips which were then cut into slider blocks. The metal had a golden yellow appearance and the surface was so hard that one cut on the surface would ruin a hacksaw blade. The surfaces of the specimens were badly deformed into a concave shape. In preparing the sliders the corners were chamfered, leaving the initial contact area as untreated metal. When tests were run this area would immediately gall, wear away, and leave two scratches on the two outside edges of the plate track. The treated portions of the surface would then come into contact with the plate and no further galling would take place. This was ruled out as being a failure of the surface treatment and the specimens were considered as having failed only if the galling spread over the treated portion of the contact surface. As shown in figure 58 these specimens left a black smear on the plate which may have acted as a lubricant. As shown in Table I none of the specimens galled at normal loads of less than 6 lbs. Some specimens did not gall at 10 lbs. No correlation was found between the galling loads for the treated alloys and the galling loads of the untreated alloys which are listed in Table I in the order of increasing resistance to galling. The coefficient of friction when no galling took place was much higher than it would be for wet lubricated surfaces but was lower than the coefficient of friction for untreated alloys. When galling takes place it begins on one portion of the contact area and spreads across the entire contact area. When the treated surface wears away completely the coefficient of friction rises to a value which corresponds to the coefficient of friction for the galling of untreated specimens.

Nitrided 72 hours Nitrogen at 1600 F. plus 16 hours partial pressure nitrogen at 1600 F.

The appearance and frictional characteristics of these specimens were similar to those for the previously described nitrided specimens. The scope of the tests was not sufficient to determine any significant difference between the two types of Nitriding.

VI PERSONNEL

The personnel who have worked on this project are Eber W. Gaylord, Frederick F. Ling, Yih-O Tu, Allen Selz, Latif Jilji, and Michael Rabins.

Professor D. W. Ver Planck and the late Professor Wayne S. McKee, have given valuable advice and criticism.

Respectfully Submitted,

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VII BIBLIOGRAPHY

1. "Galling and Seizing Characteristics of Titanium and Titanium-Base Alloys" by William C. Leone, Annual Report to Watertown Arsenal, July 1, 1953.
2. "An Investigation of Sliding Friction and Interface Temperature Between Two Dry Metallic Surfaces" by Frederick F. Ling. Interim Technical Report No. 2 to Watertown Arsenal, May 31, 1954.

TABLE I

Loads that cause galling for titanium alloys and surface treated titanium alloy slider blocks rubbing on steel plates.

Slider Block Material	Maximum Load for no Galling LB.	Load that causes total Galling LB.
Ti 150-A untreated	0.5	1.0
RC 130-A "	0.5	1.0
RC 55 "	0.5	1.5
Steel "	0.75	2.0
RC 130-B "	2.0	3.0
<u>Ti 150-A</u>		
Treatment A	*4	6
Treatment B		greater than 10
(Nitrided 16 Hrs. N ₂ at 1600°F.)		greater than 10
(Nitrided 72 Hrs. N ₂ at 1600°F. + 16 Hrs. N ₂ at Partial Pressure 1600°F.)		greater than 10
<u>RC 130-A</u>		
Treatment A	*4	6
Treatment B		greater than 10
(Nitrided 16 Hrs. N ₂ at 1600°F.)	*6	8
(Nitrided 72 Hrs. N ₂ at 1600°F. + 16 Hrs. N ₂ at Partial Pressure 1600°F.)	*8	10
<u>RC 55</u>		
Treatment A	*6	8
Treatment B		greater than 10
(Nitrided 16 Hrs. N ₂ at 1600°F.)	*8	10
(Nitrided 72 Hrs. N ₂ at 1600°F. + 72 Hrs. N ₂ at Partial Pressure 1600°F.)		greater than 10
<u>RC 130-B</u>		
Treatment A		greater than 10
Treatment B		greater than 10
(16 Hrs. N ₂ at 1600°F.)	*8	10
(16 Hrs. N ₂ at 1600°F. + 72 Hrs. N ₂ at Partial Pressure 1600°F.)	*8	10

* The material was not tested at loads in between loads for no galling and loads for total galling.

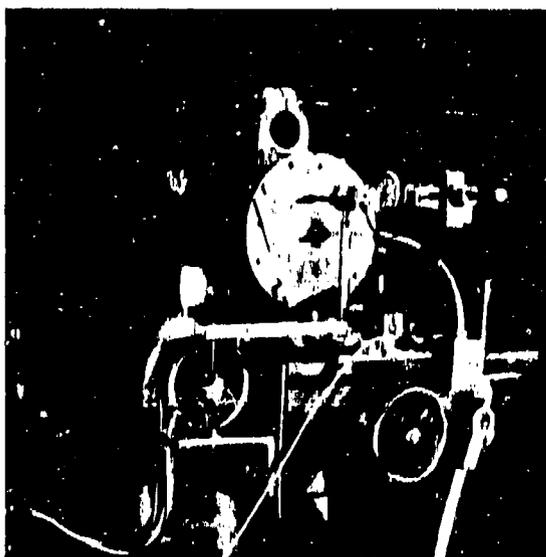


Figure 1 . Photograph of the Friction Apparatus

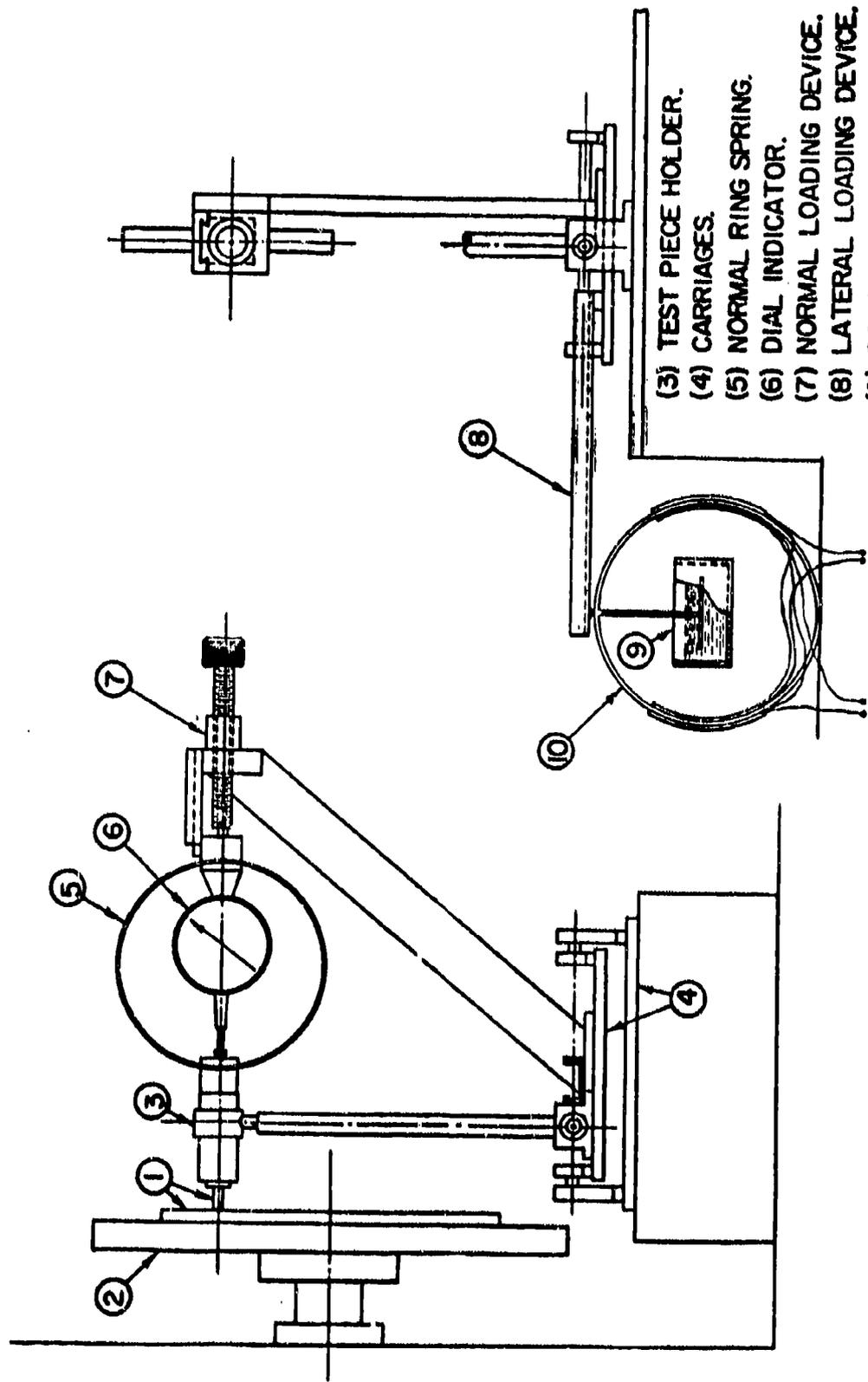


FIGURE 2 SCHEMATIC DRAWING OF TEST APPARATUS.

SLIDER BLOCK SPECIMAN HOLDER WITH PIEZOELECTRIC CRYSTAL

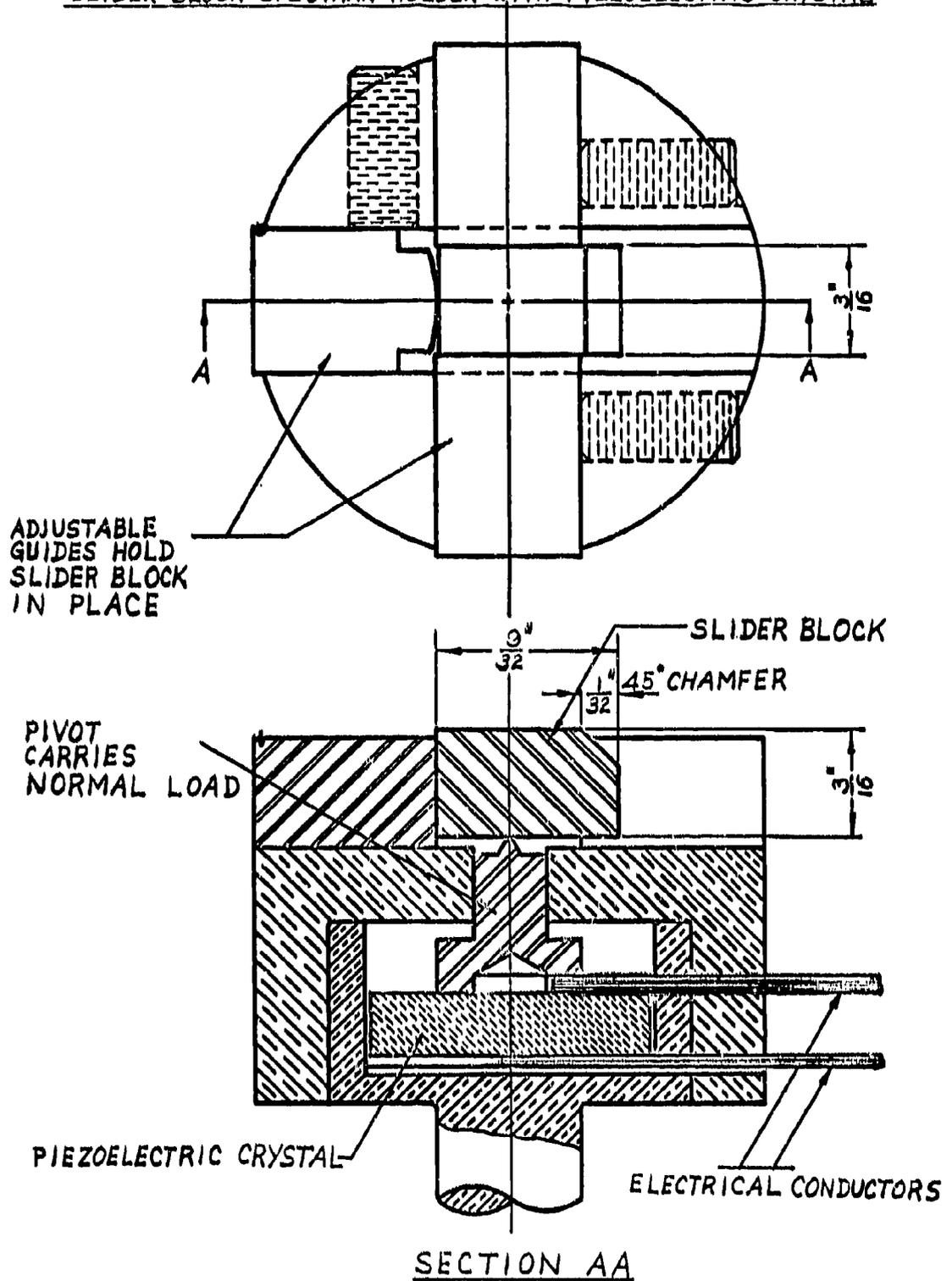


Figure 3 Diagram of Slider Holder with Piezoelectric Crystal

LOAD-SPEED GALLING LIMIT CURVE

—□— $\frac{3}{16}$ x $\frac{1}{4}$ UNALLOYED
TITANIUM SLIDER BLOCK VS.
UNALLOYED TITANIUM PLATE.
SEPT. 30, 1953.

---○--- $\frac{1}{16}$ DIA. UNALLOYED
TITANIUM ROD VS. UNALLOYED
TITANIUM PLATE.
MARCH 15, 1953.

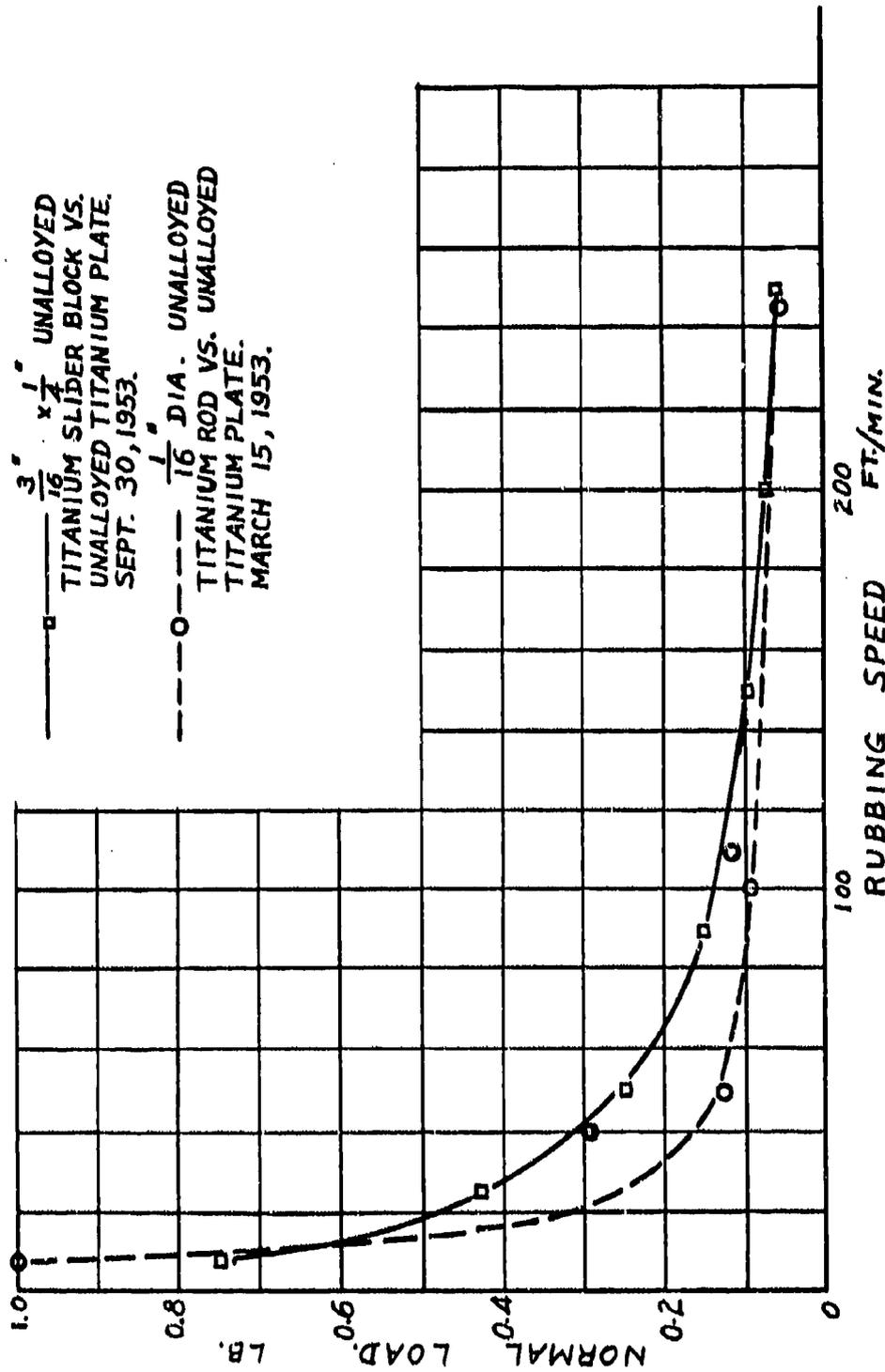


Figure 4 Load-Speed Galling Limit Curve

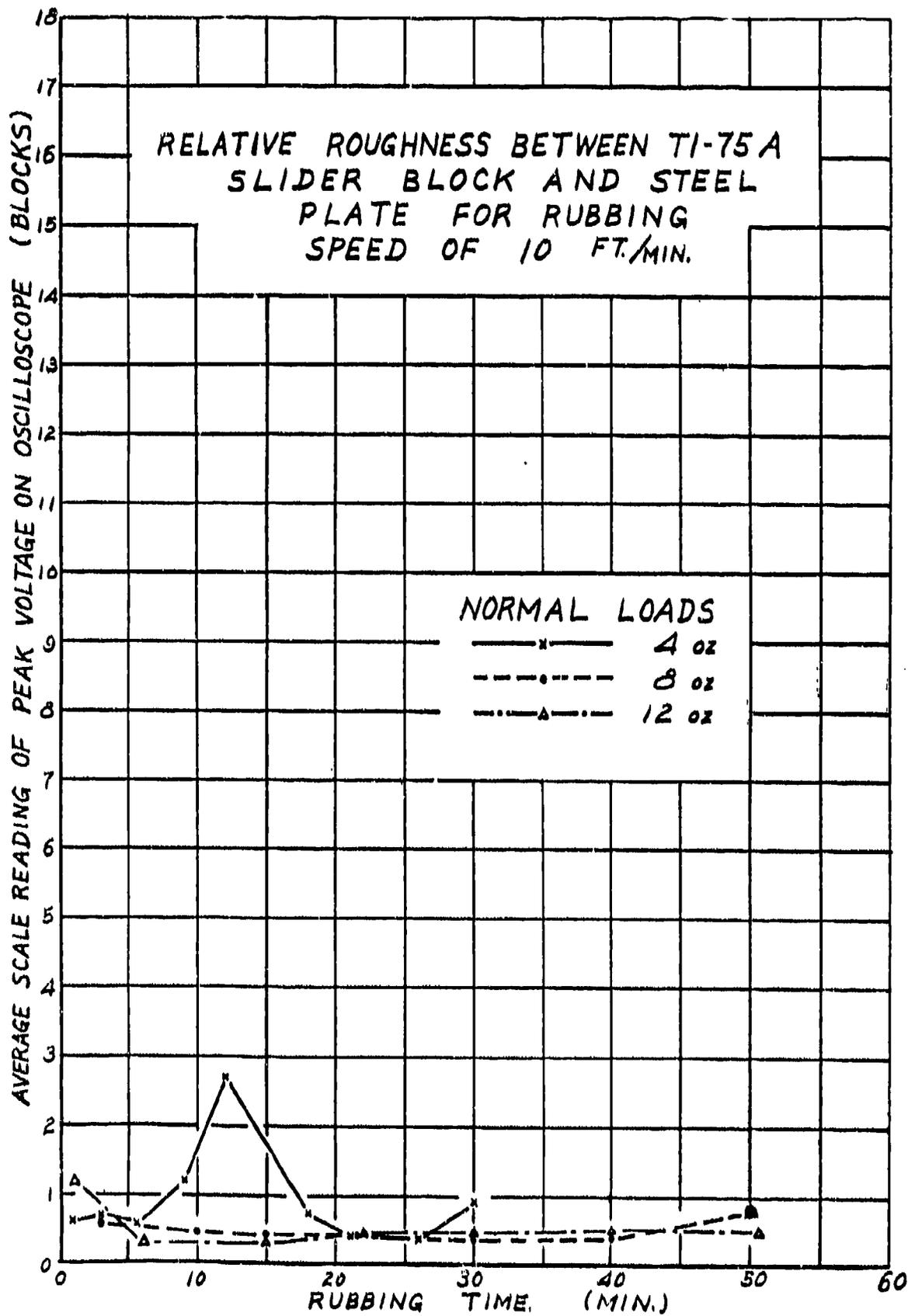


Figure 5

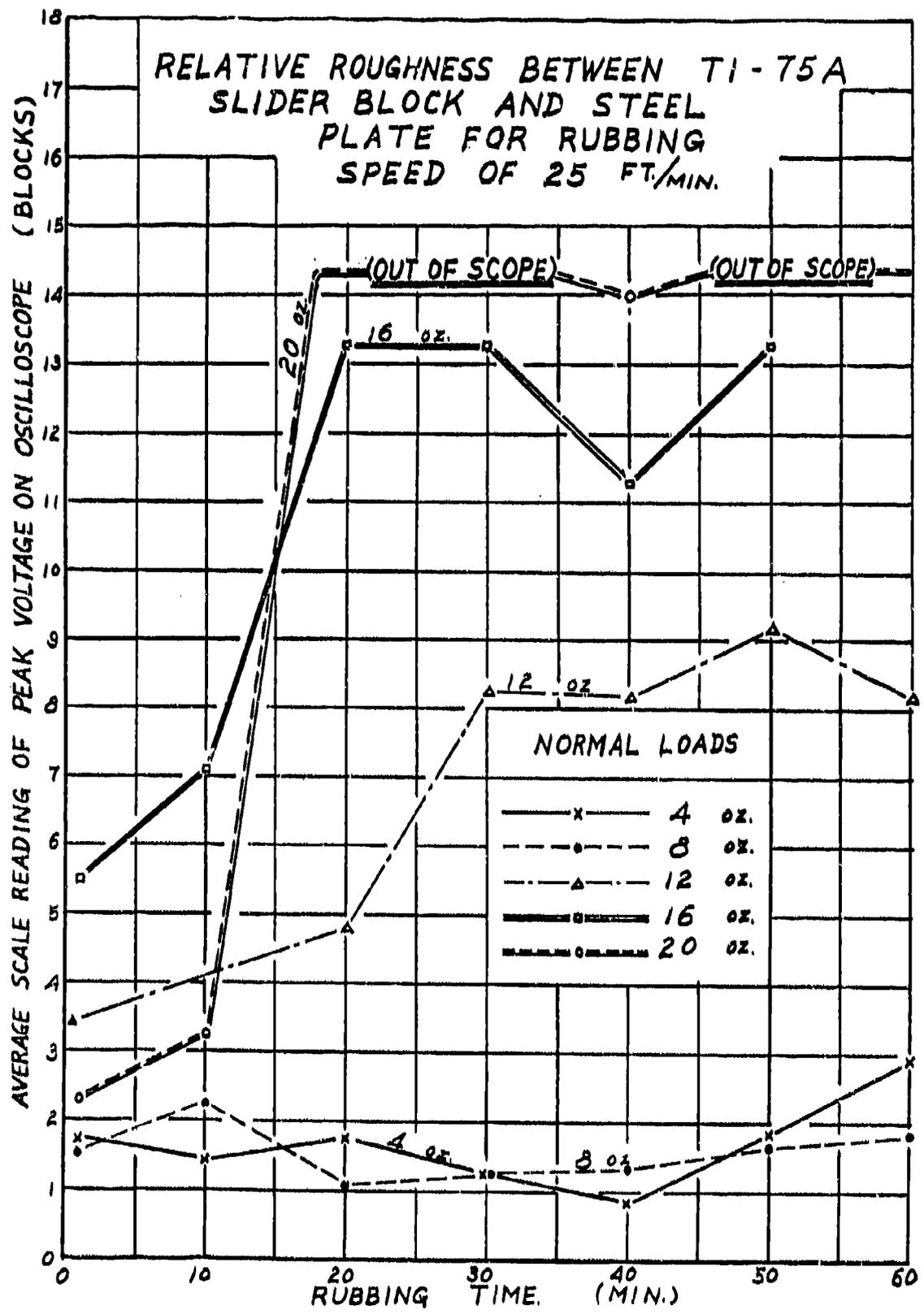


Figure 6

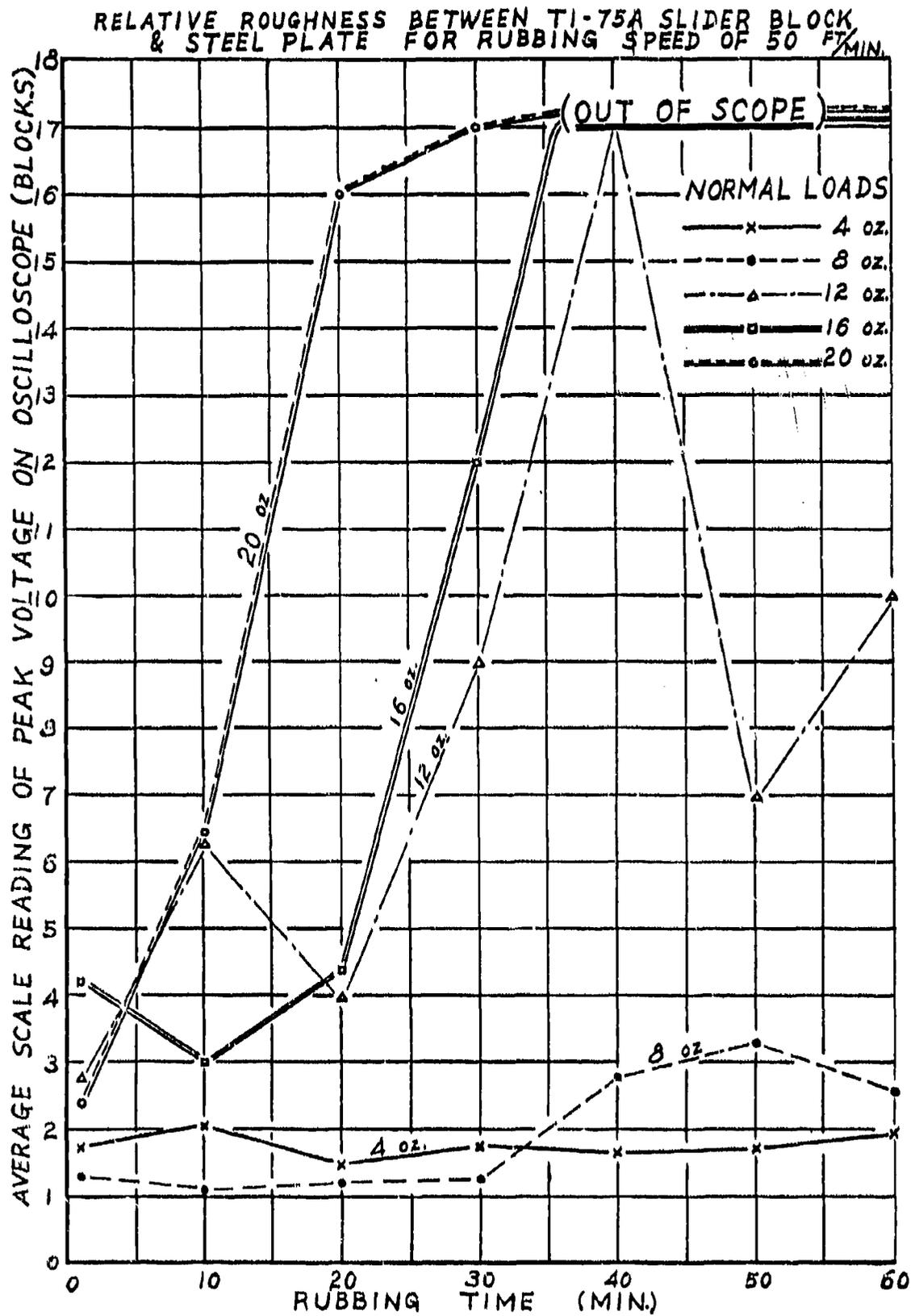


Figure 7

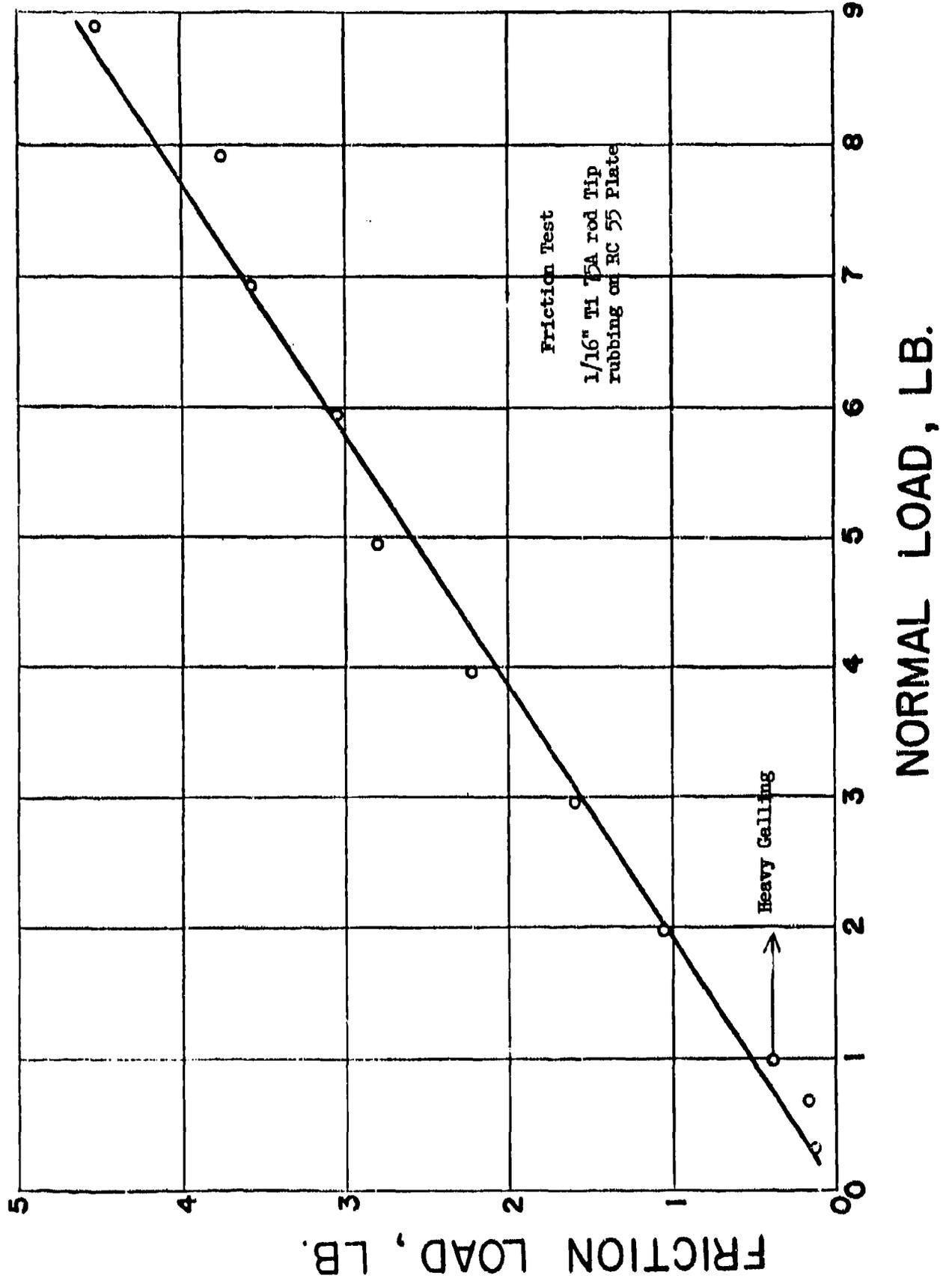


Figure 8

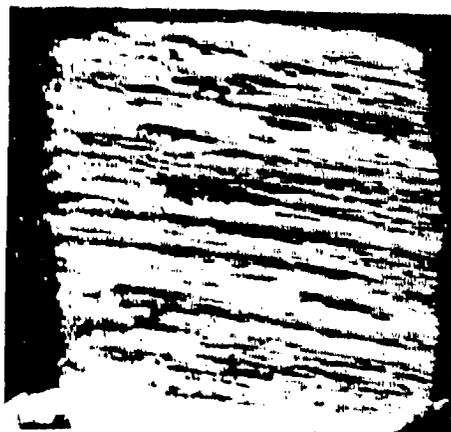
MICROPHOTOGRAPHS OF TITANIUM AND
TITANIUM ALLOY SLIDER BLOCKS (10X)



a. Some scratches - The bulk
of the surface is unchanged



b. Early stages of galling ,
Partially galled



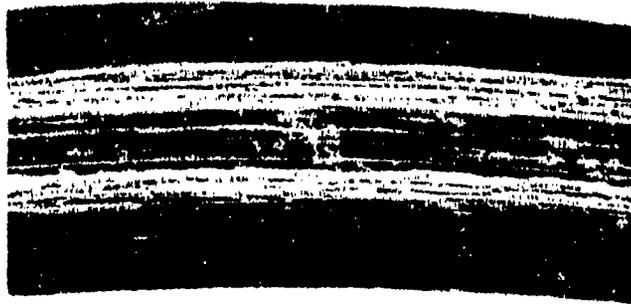
c. Completely galled

Figure 9

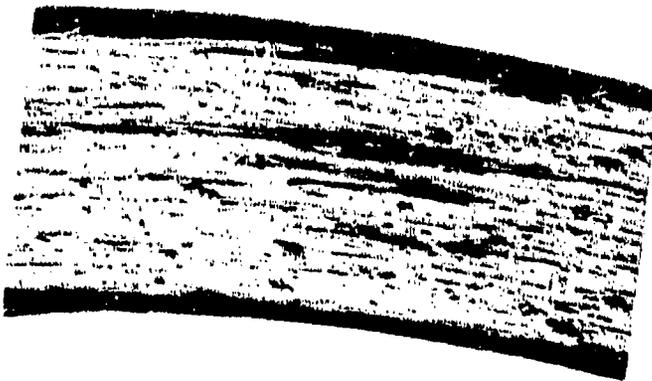
TYPICAL MICROPHOTOGRAPHS OF STEEL
PLATE TRACKS AFTER BEING RUBBED
WITH TITANIUM AND TITANIUM ALLOY
SLIDER BLOCK SPECIMENS. (8X)



a. Unused plate.



b. Partially galled plate track.



c. Completely galled plate track.

Figure 10

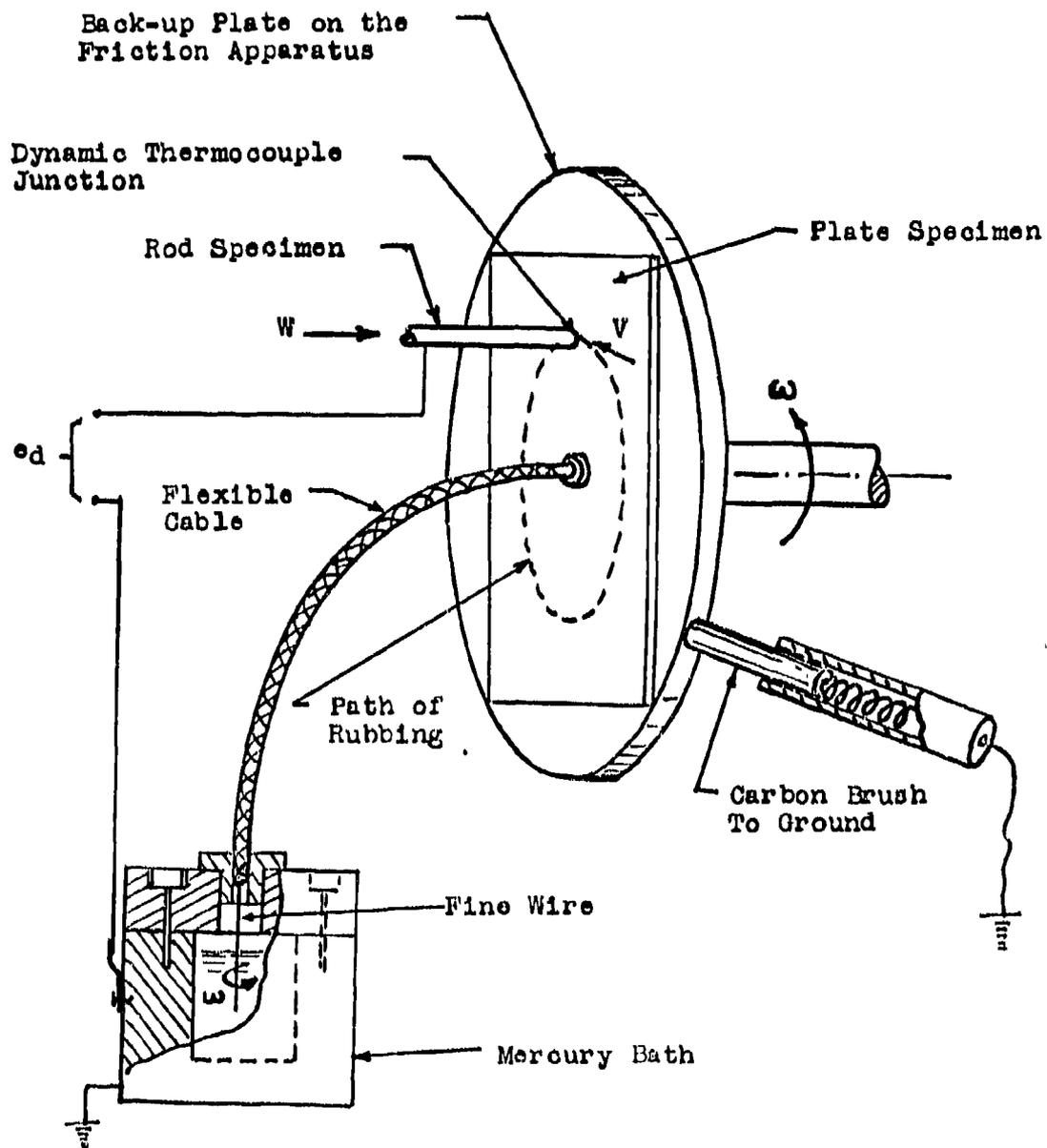


Figure 11 Schematic Diagram of Dynamic Thermocouple Set-up.

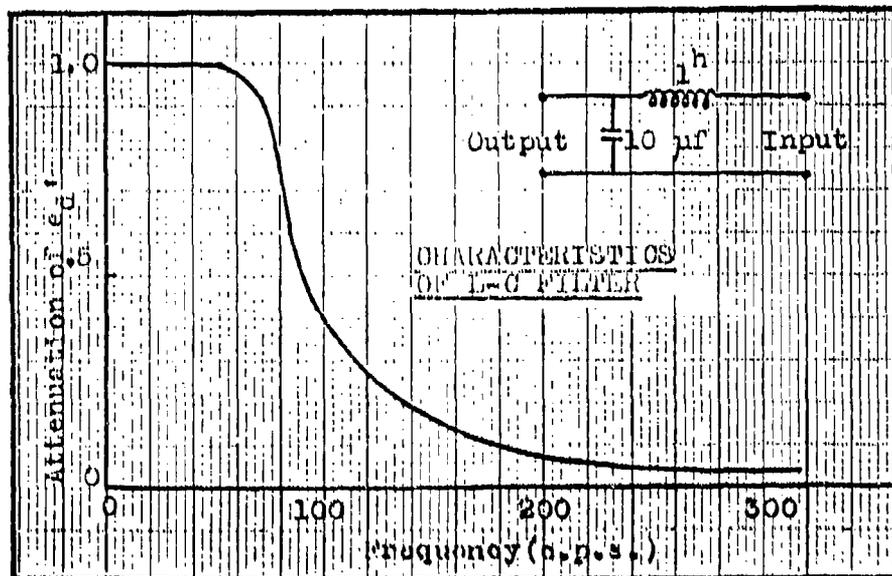
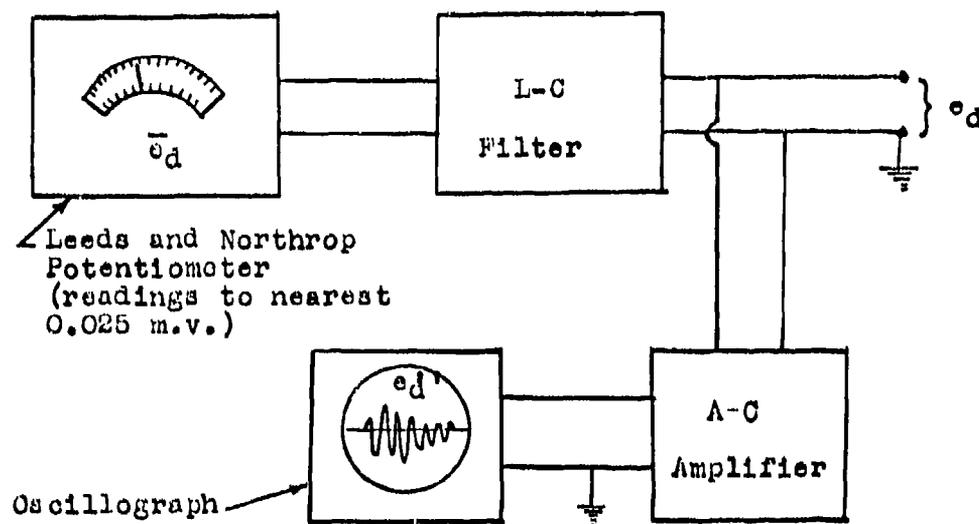


Figure 12 Schematic Diagram of Arrangement For Separating e_d into A-C and D-C Components.

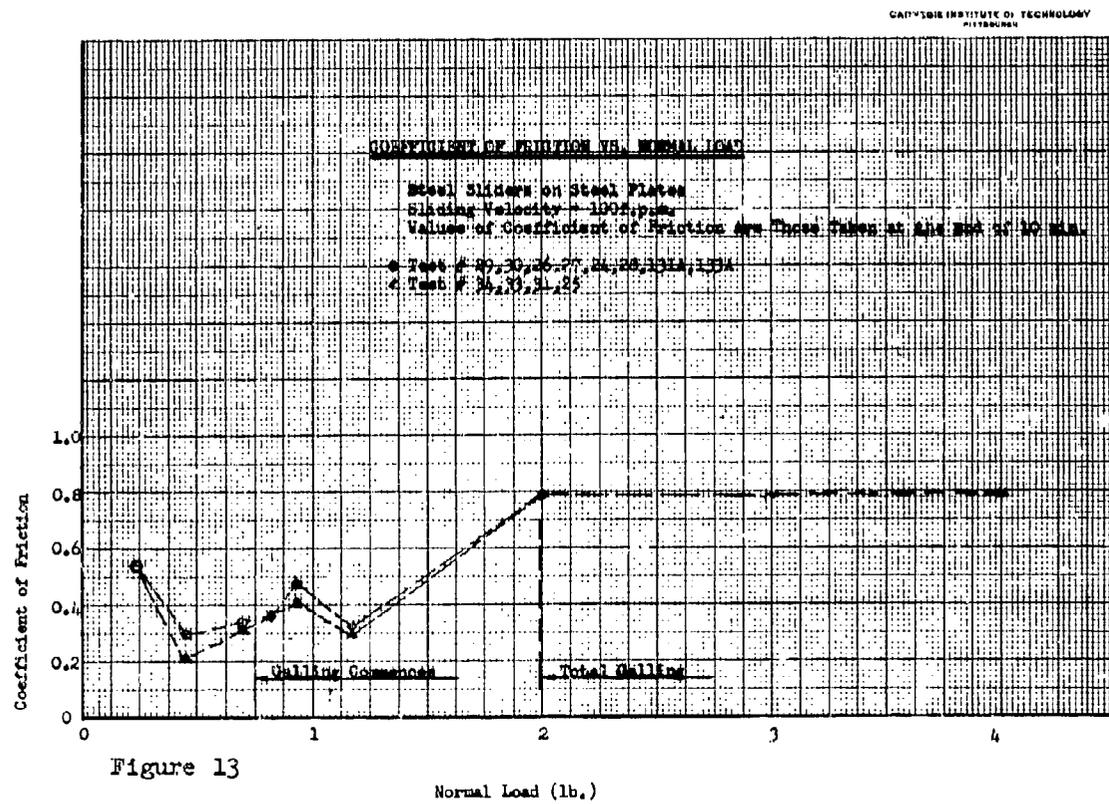
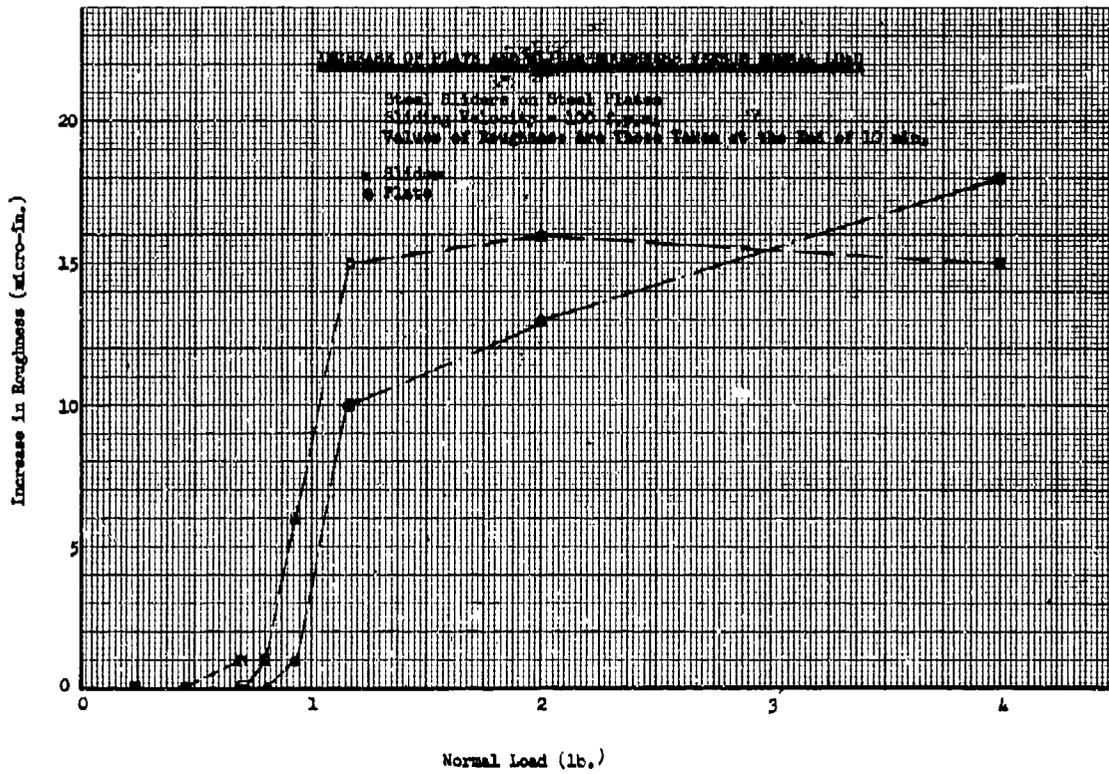


Figure 13

Normal Load (lb.)

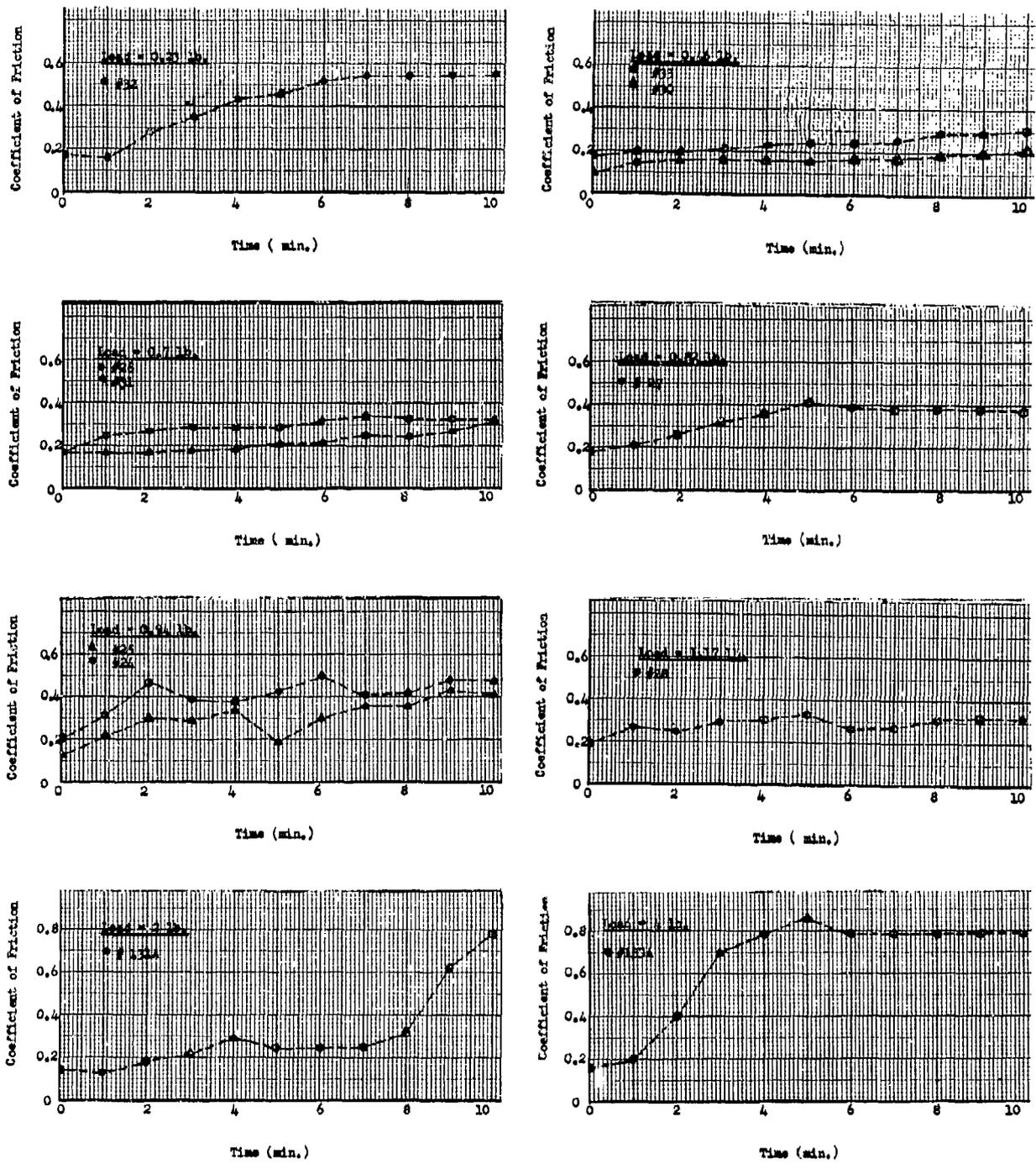


Figure 14

COEFFICIENT OF FRICTION VS. TIME OF RUBBING

Steel Sliders on Steel Plates
Sliding Velocity = 100 f.p.m.

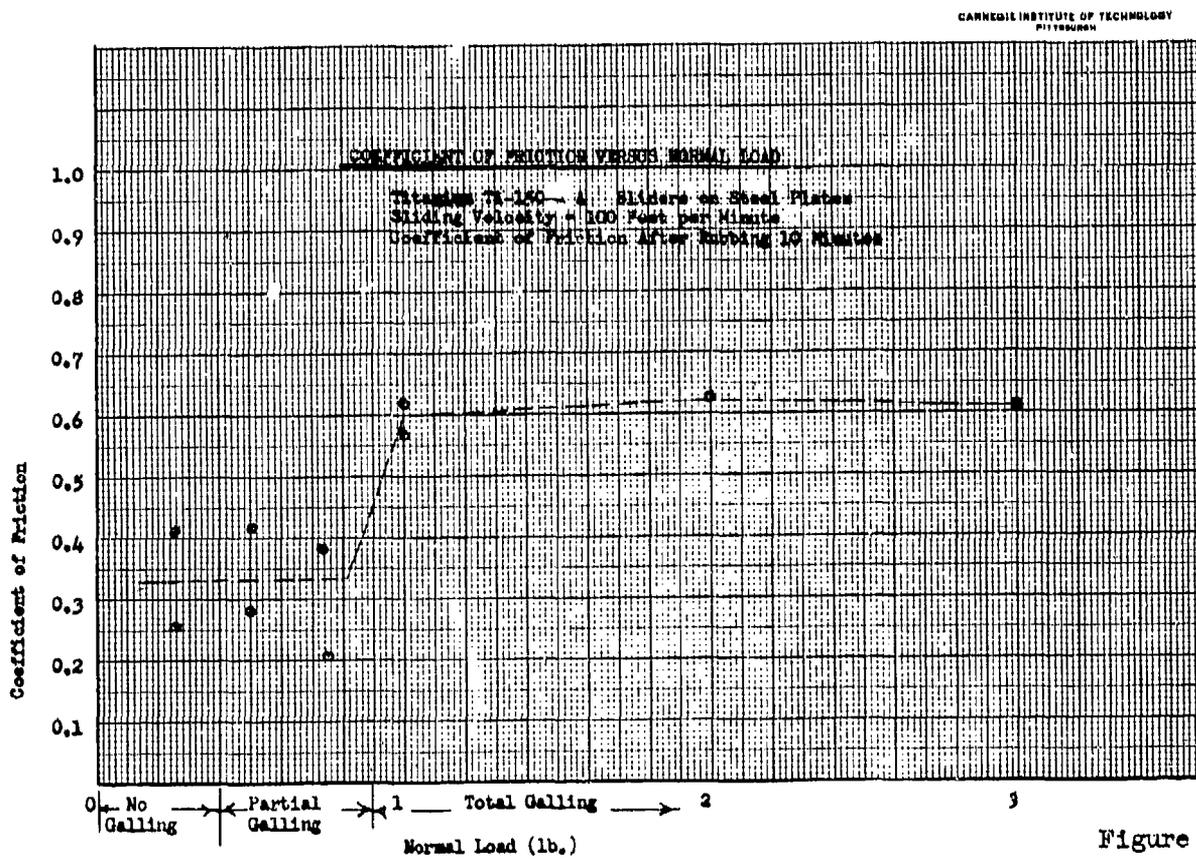
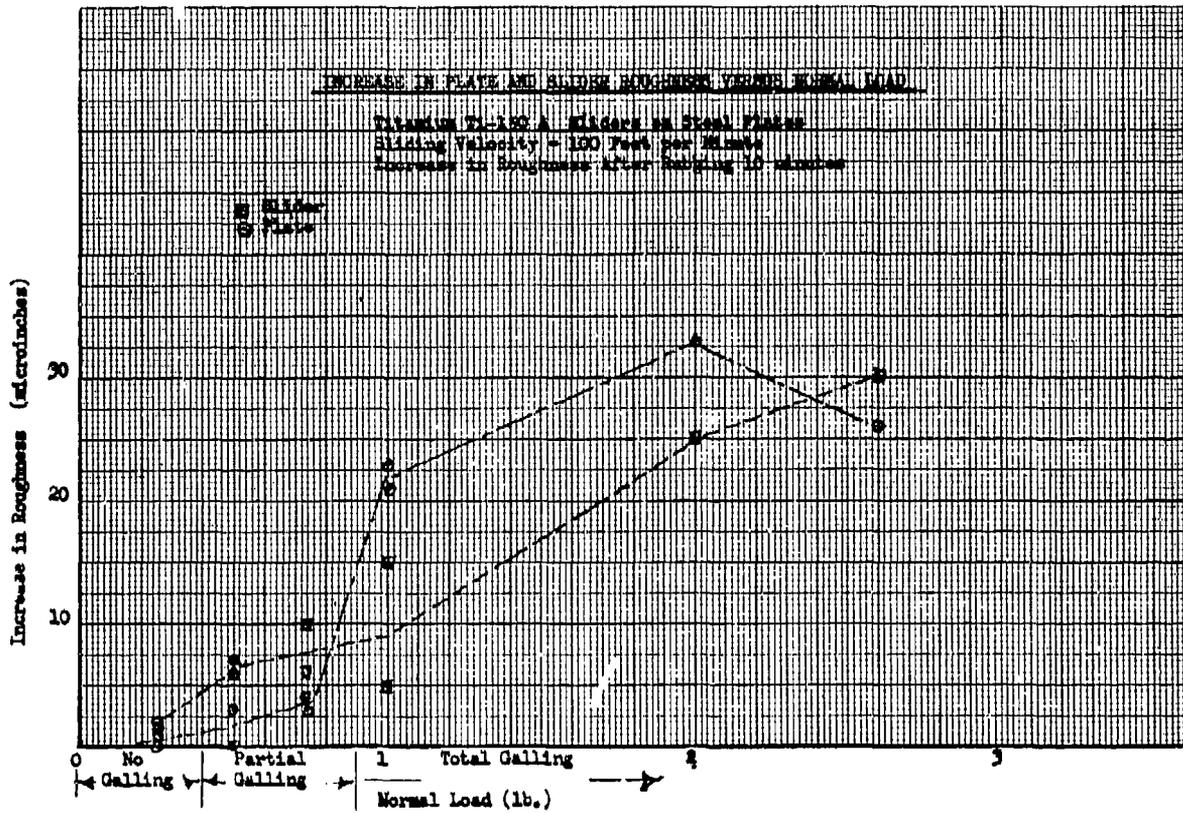


Figure 15

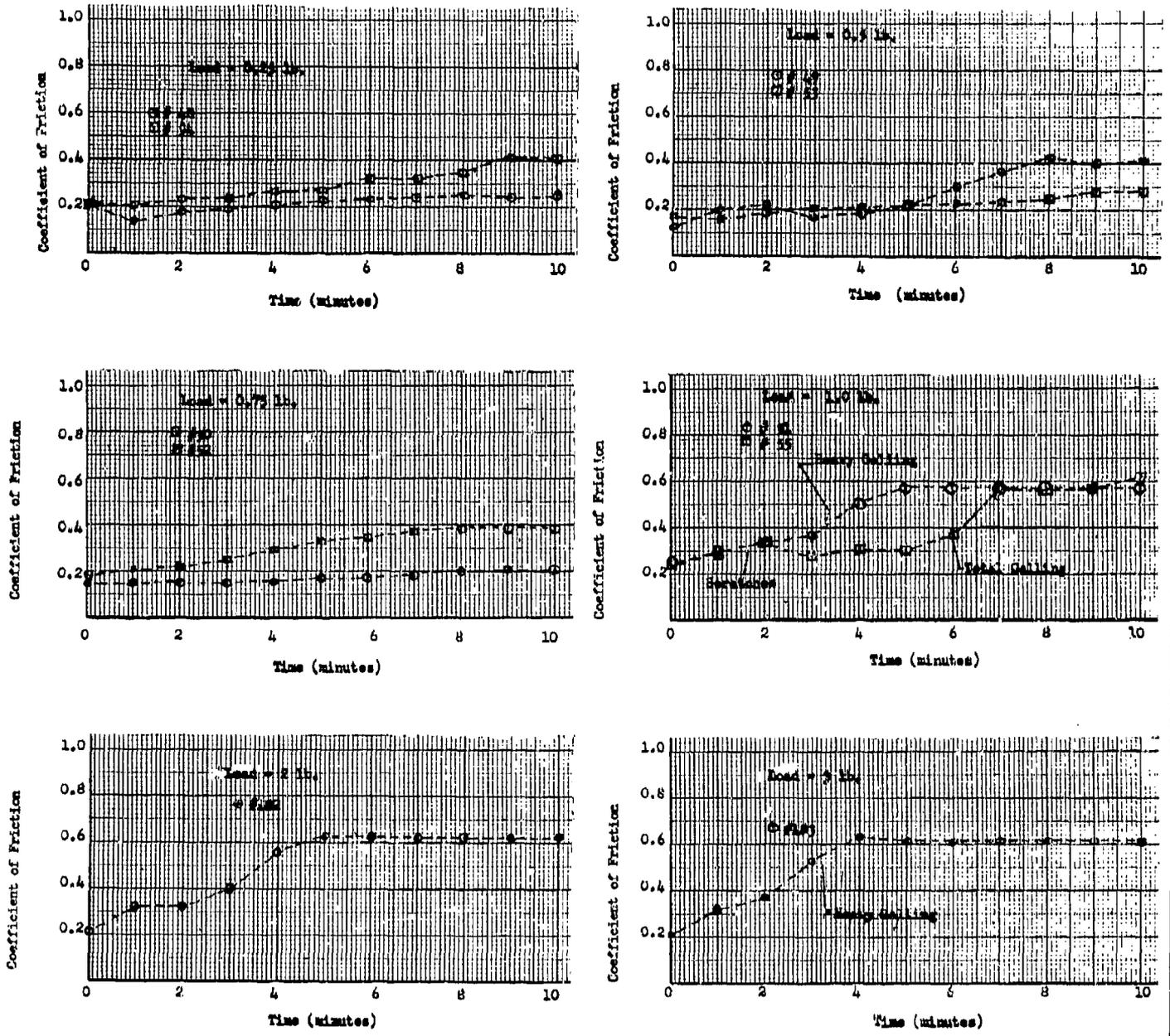


Figure 16

COEFFICIENT OF FRICTION VERSUS TIME OF RUBBING

Titanium TI-150A Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

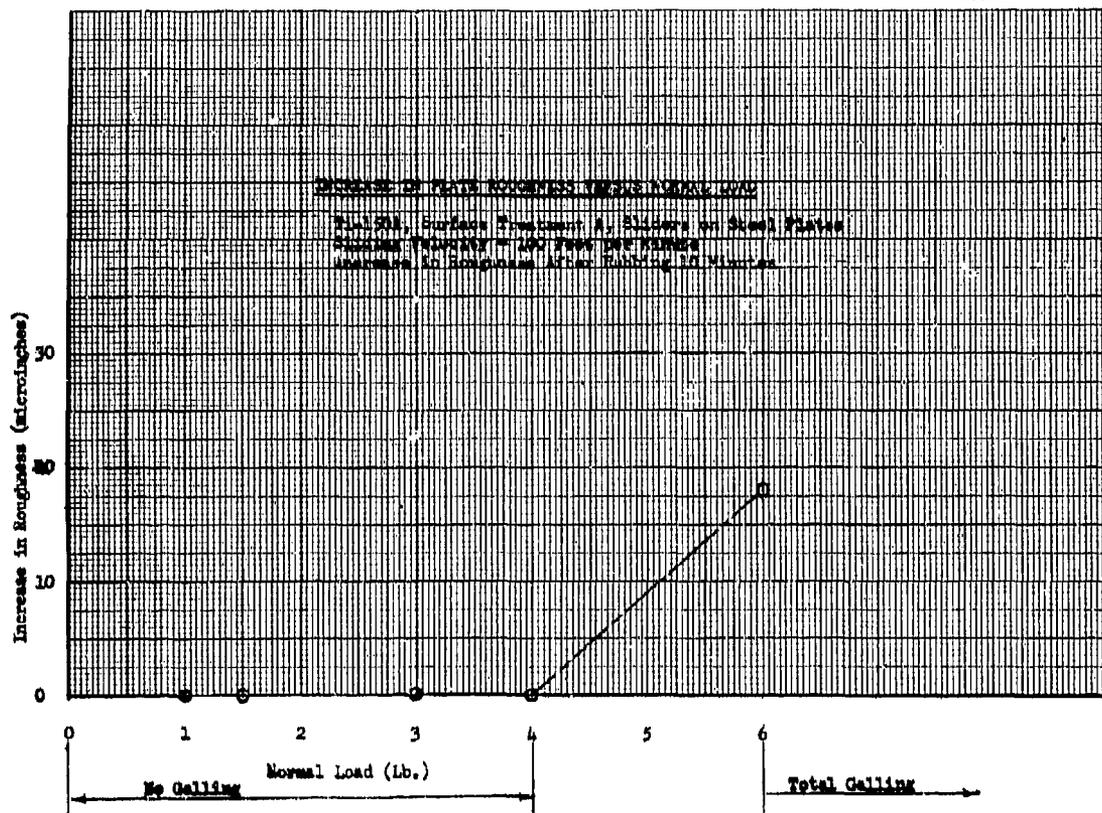
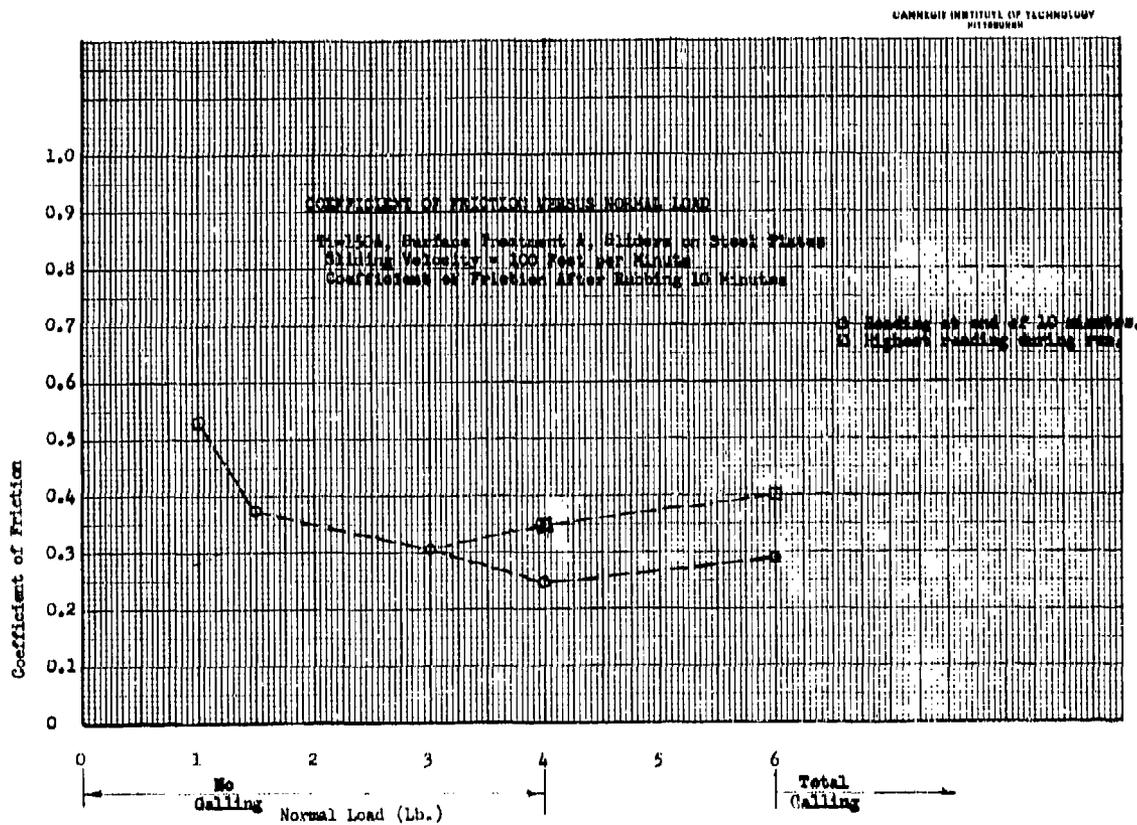


Figure 17



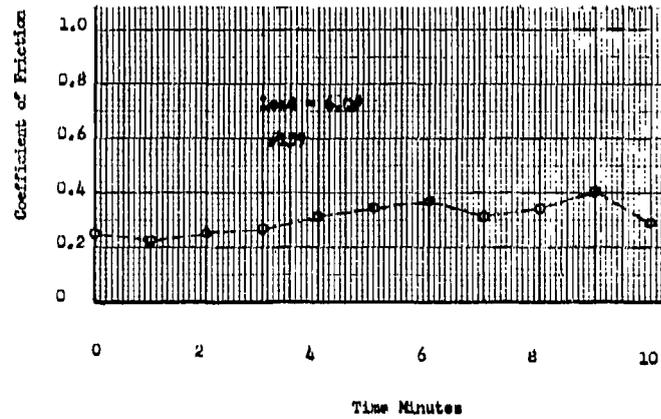
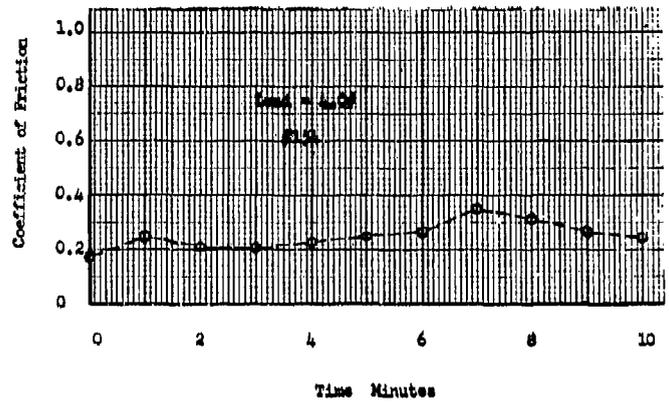
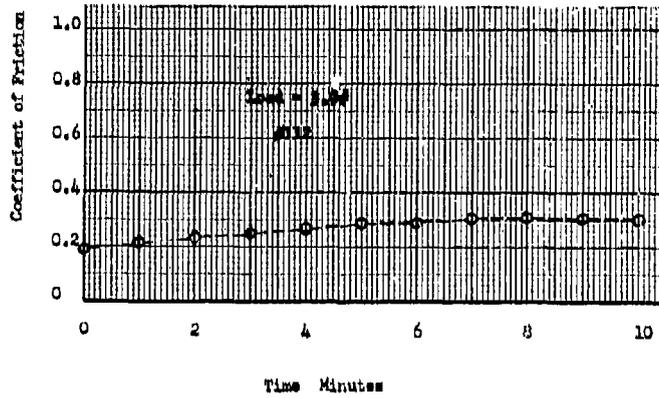
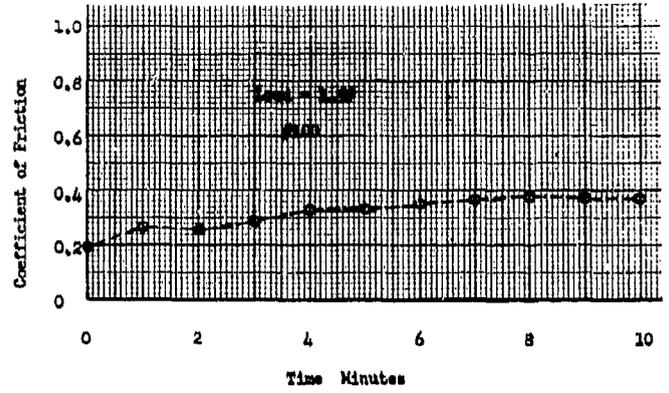
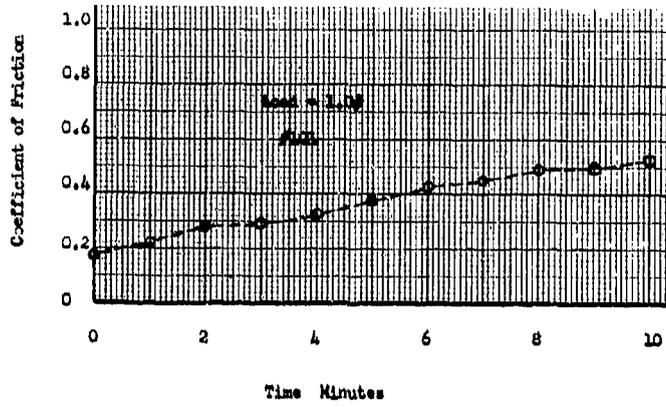


Figure 18

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium TI-150A, Surface Treatment A,
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

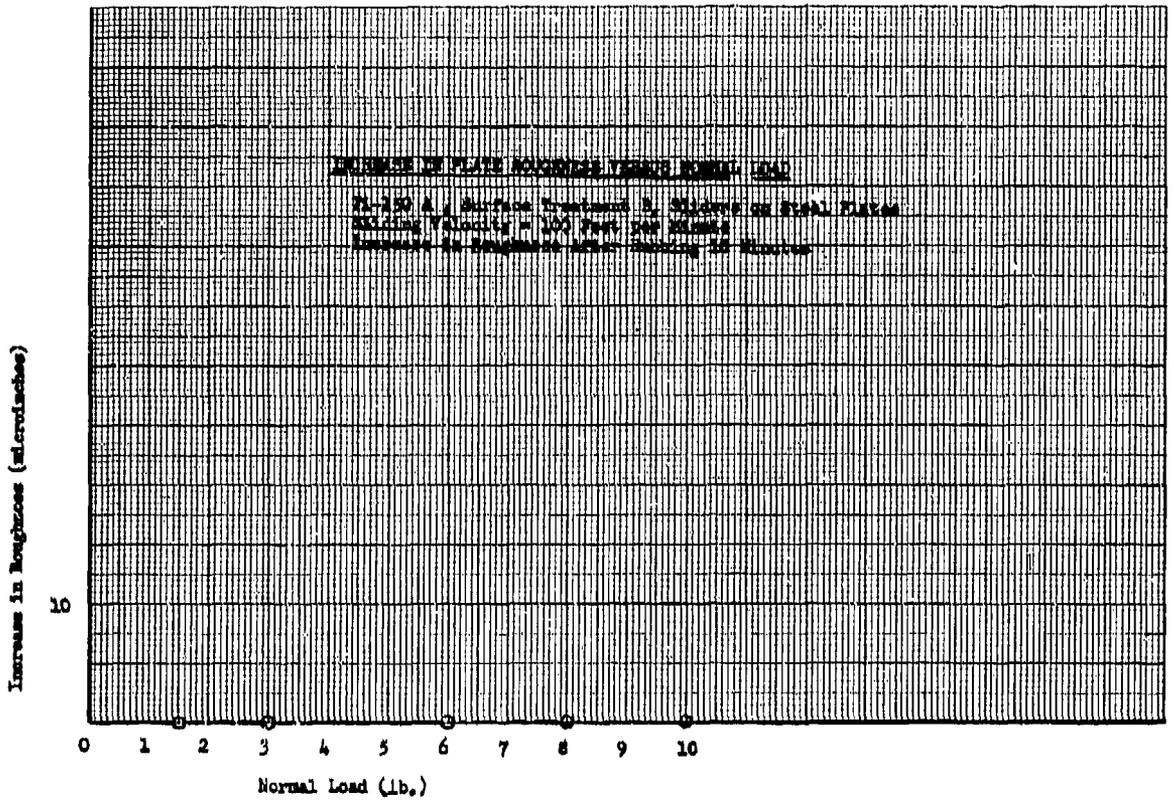
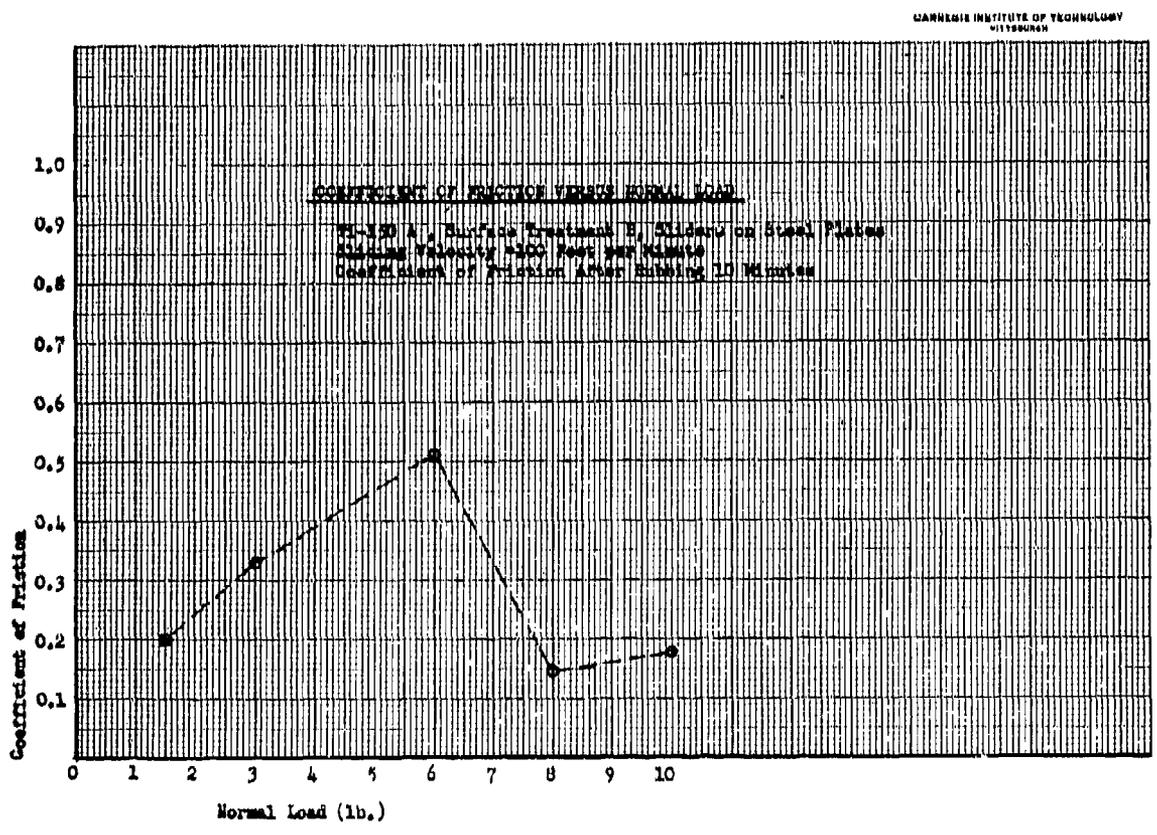
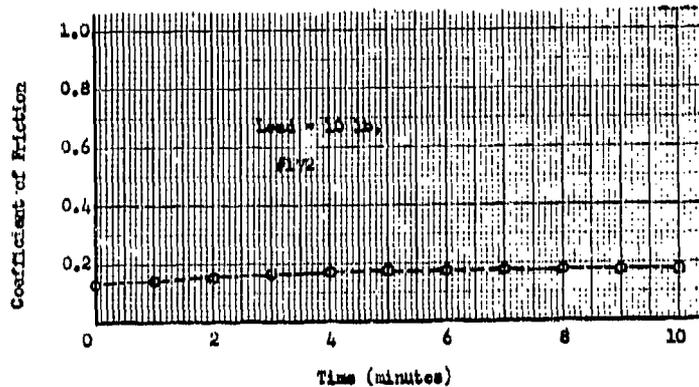
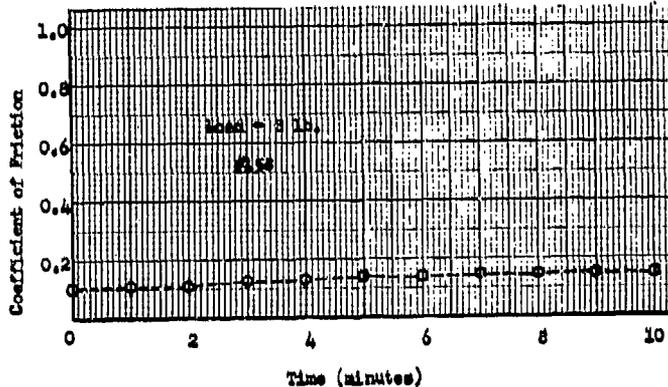
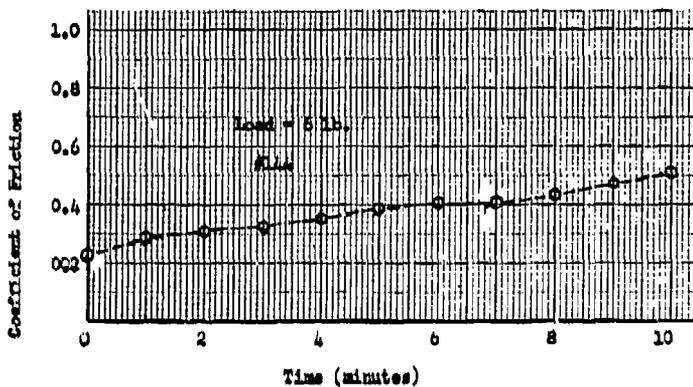
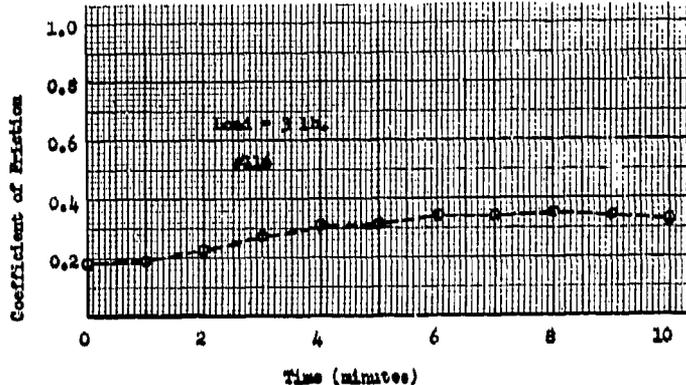
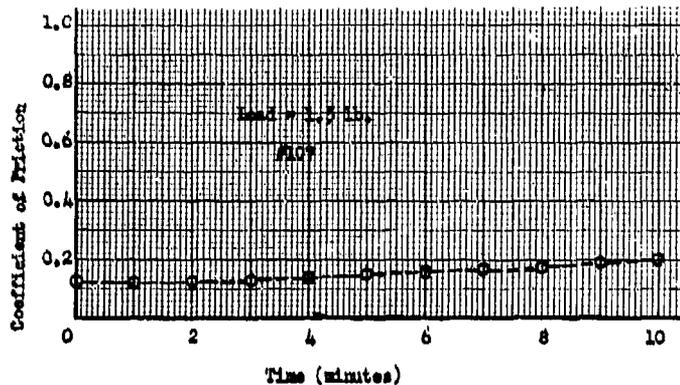


Figure 19





COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium TI-150A, Surface Treatment B,
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

Figure 20

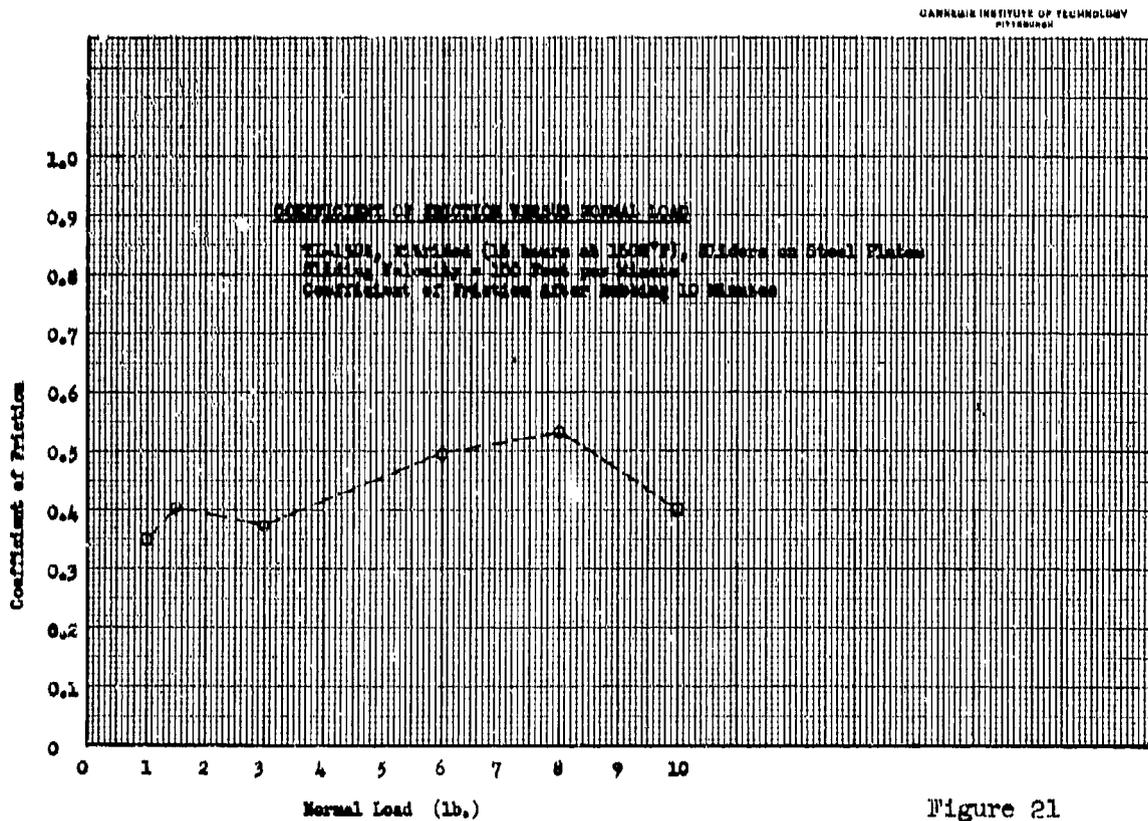
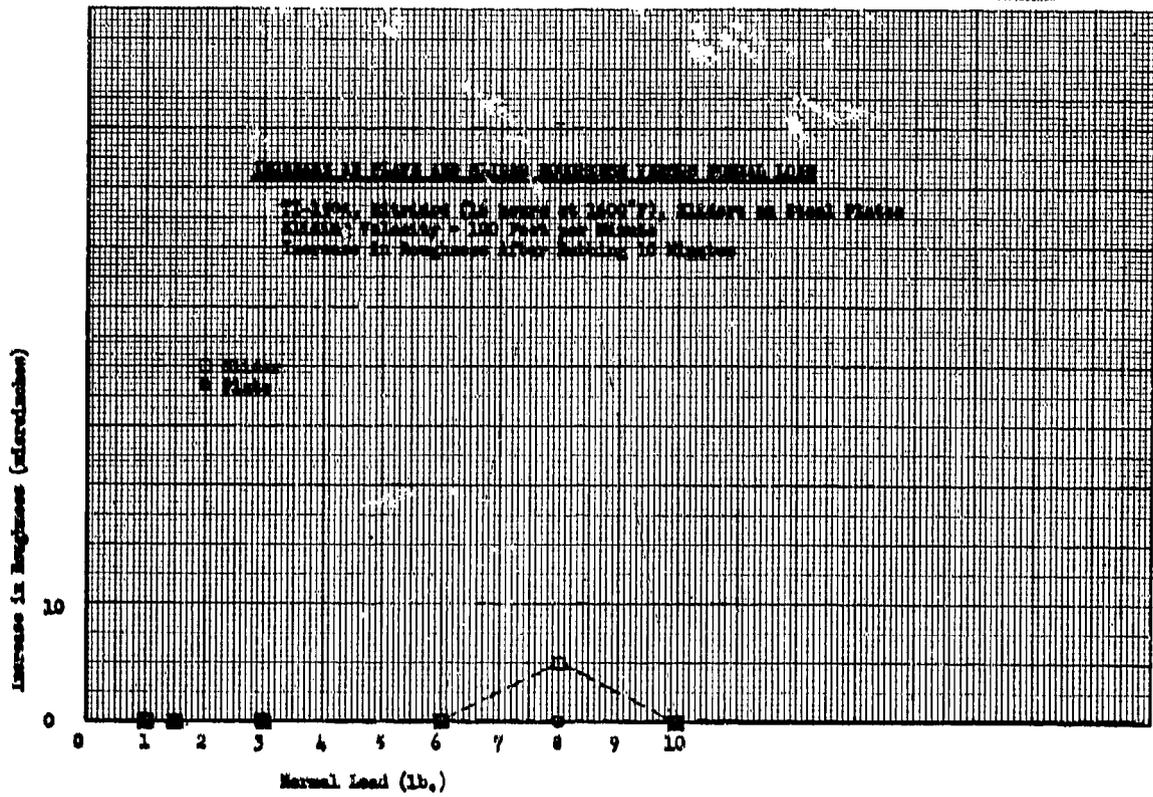


Figure 21

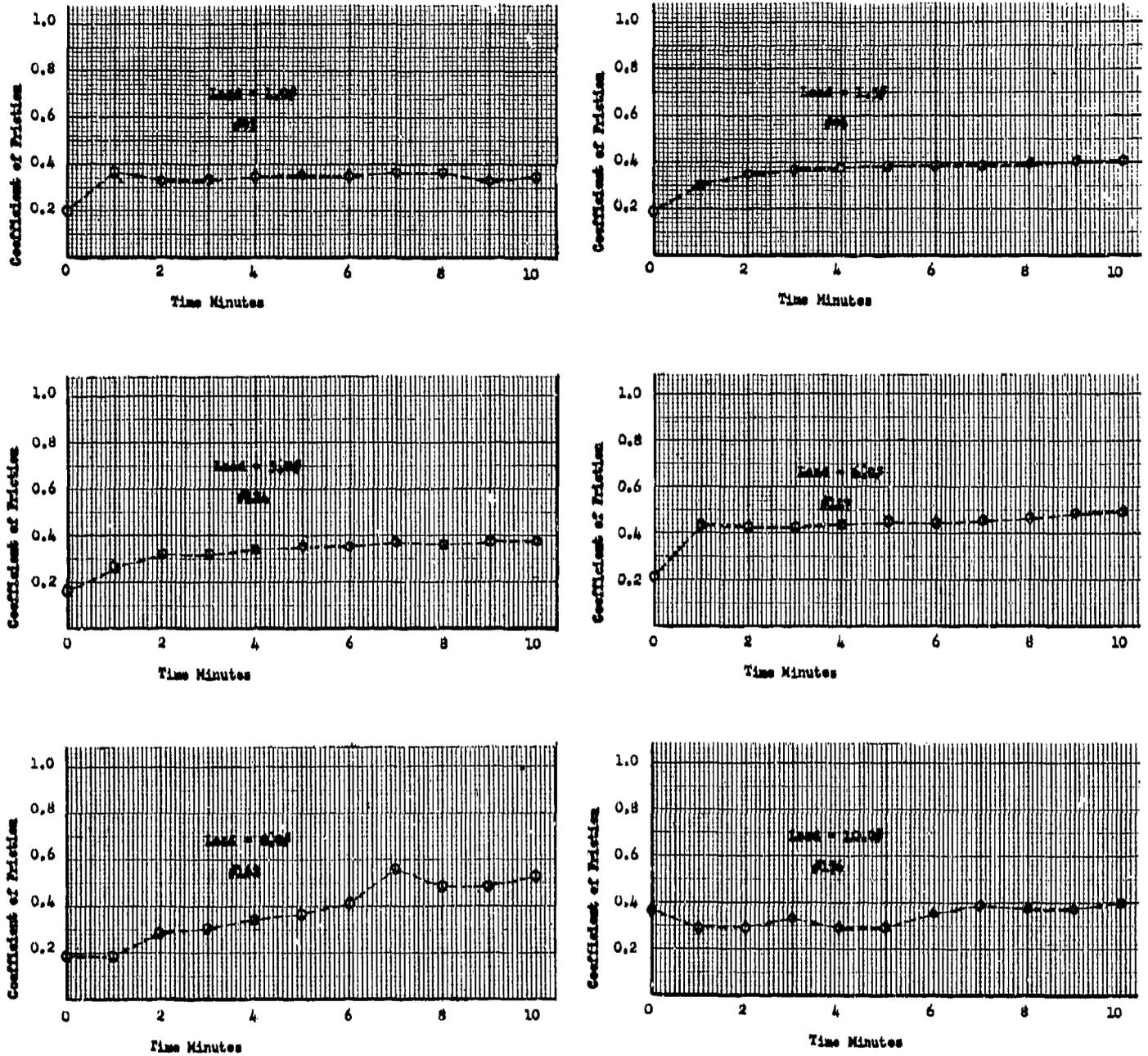


Figure 22

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium TI-150A, Nitrided (16 hrs. @ 1600°F),
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

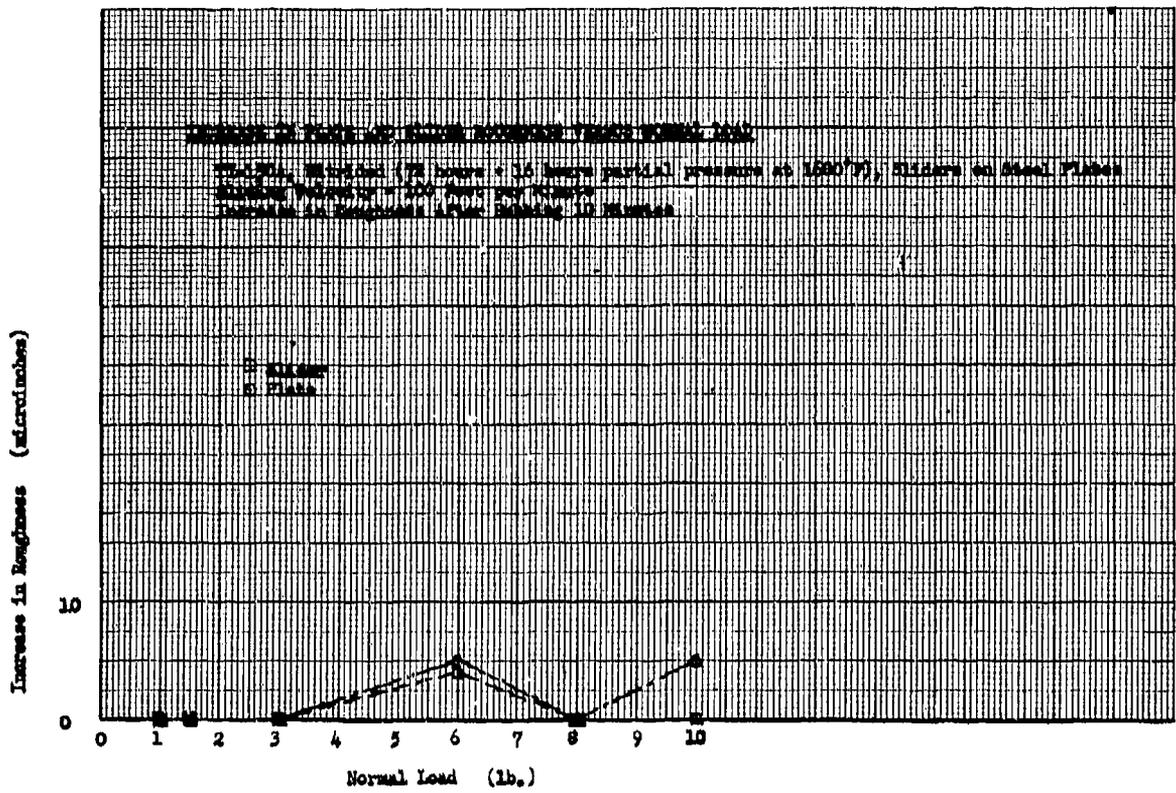
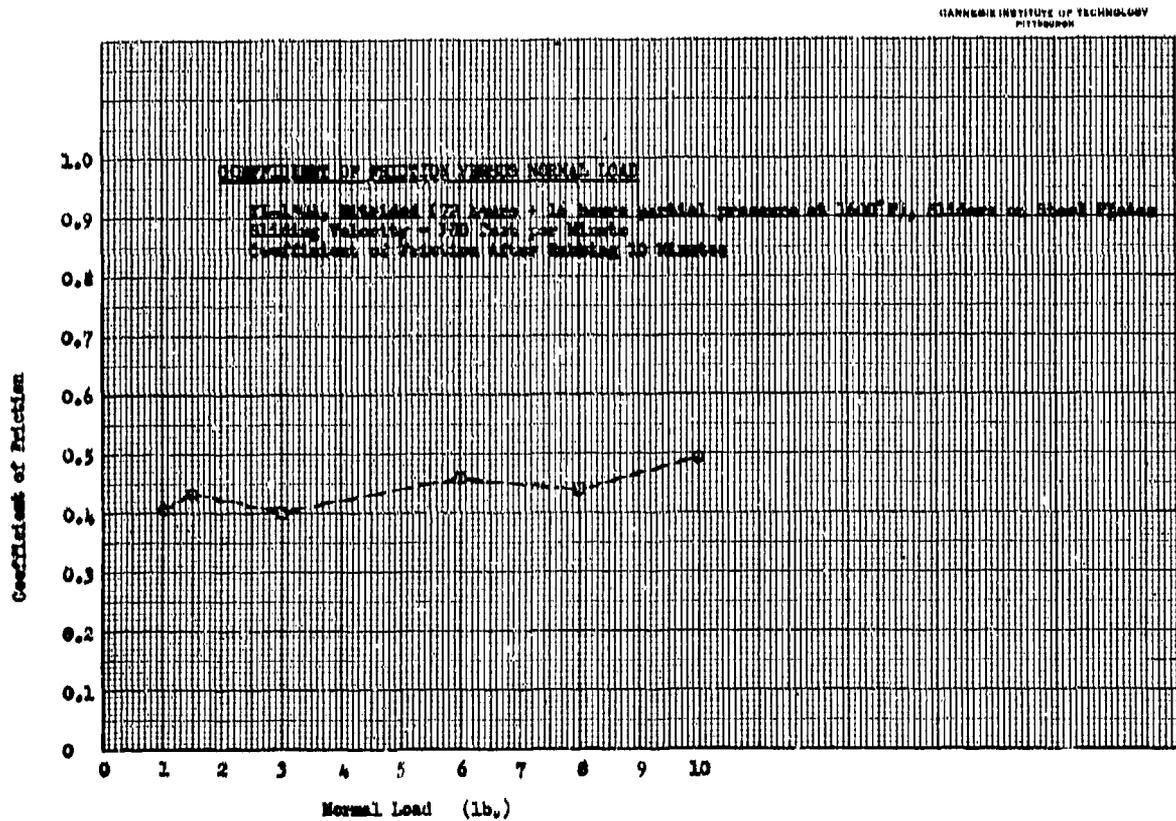


Figure 23



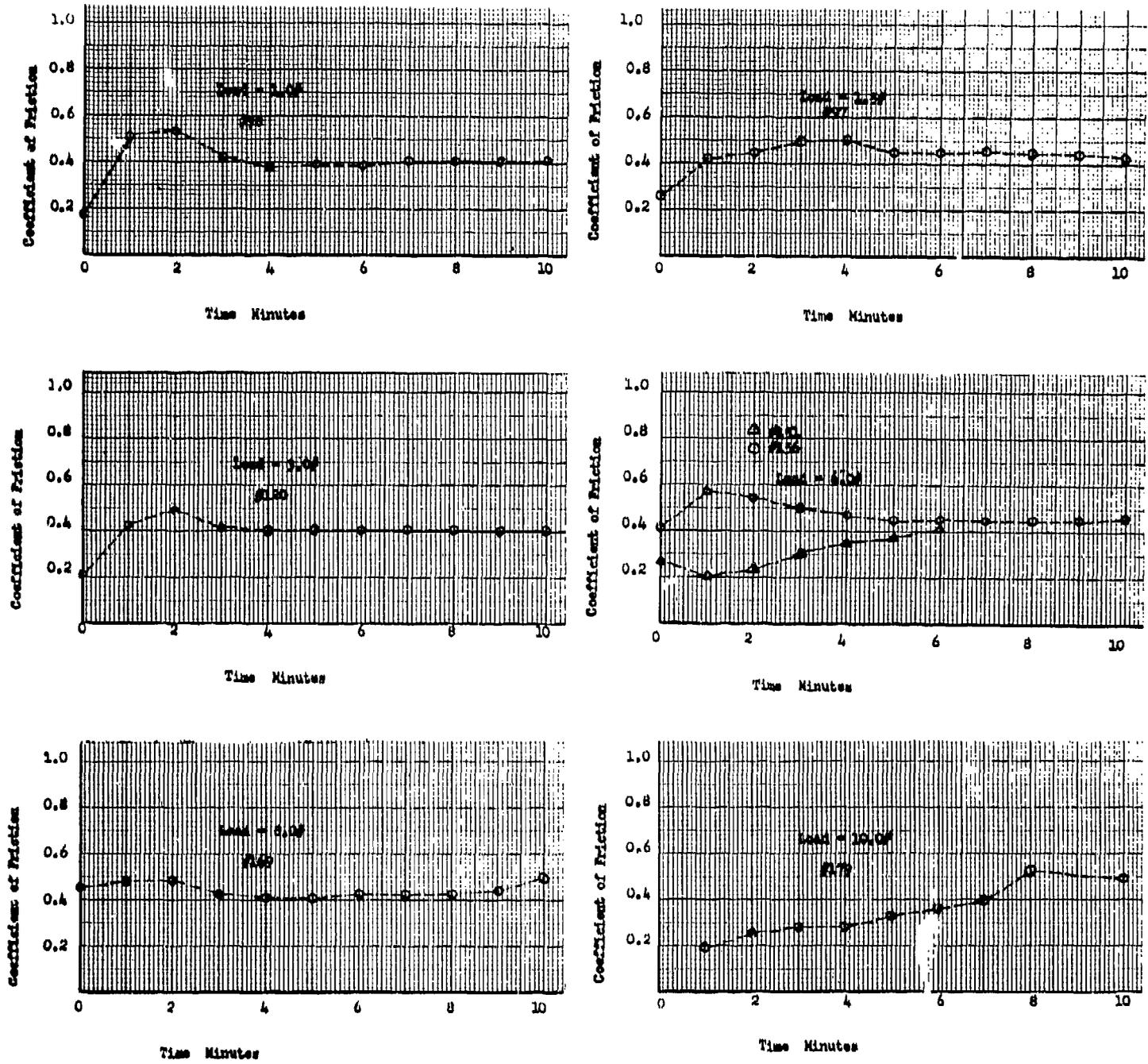


Figure 24

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium TI-150A, Nitrided (72 hrs. + 16 hrs.
 Partial Pressure @ 1600°F), Sliders on
 Steel Plates
 Sliding Velocity: 100 Feet per Minute

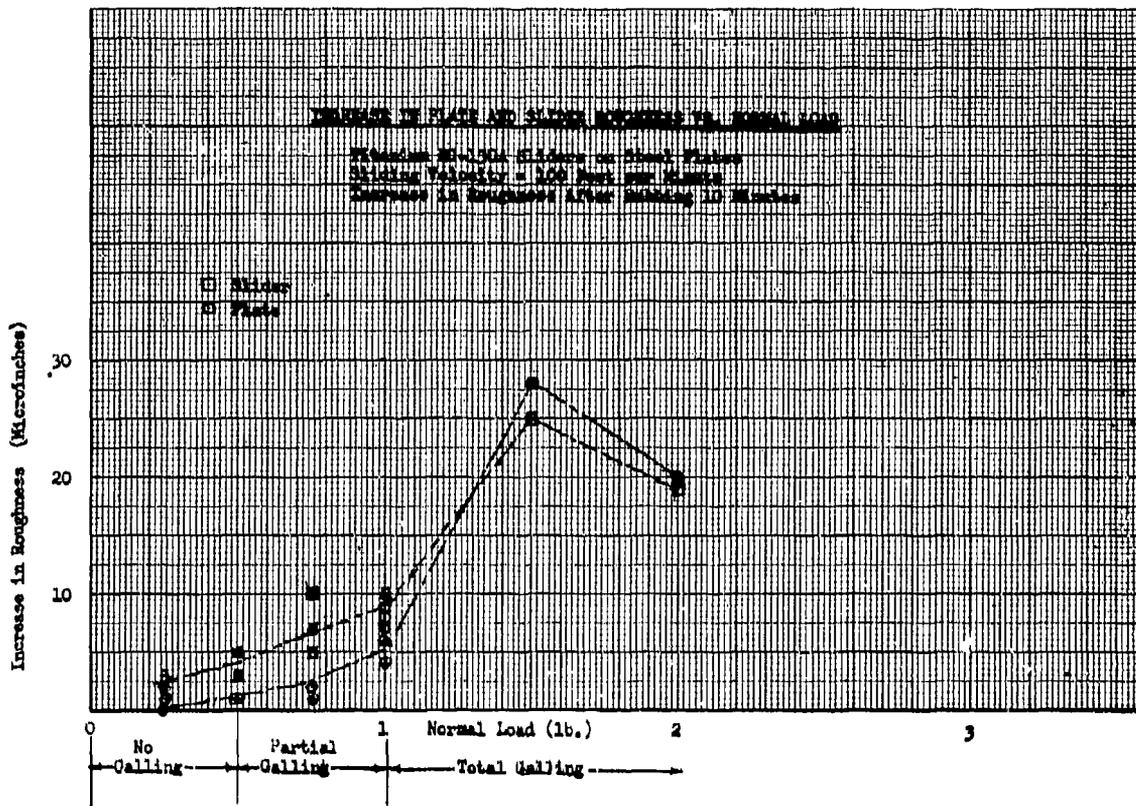
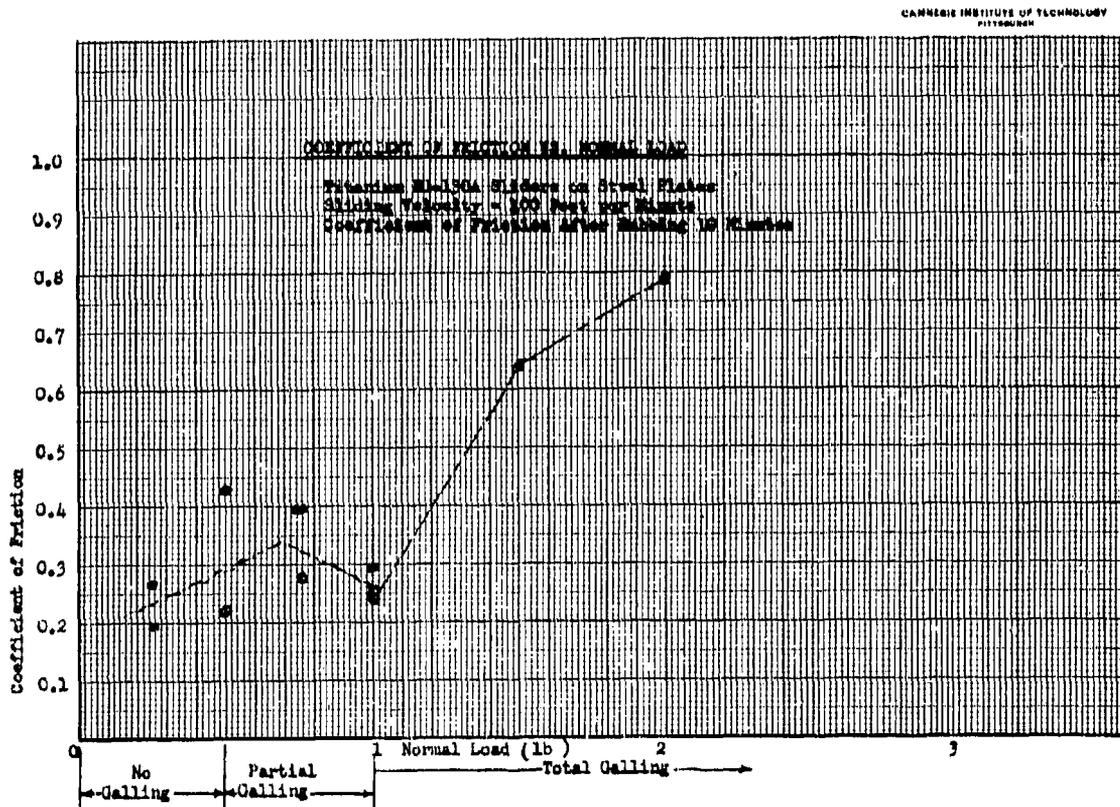


Figure 25



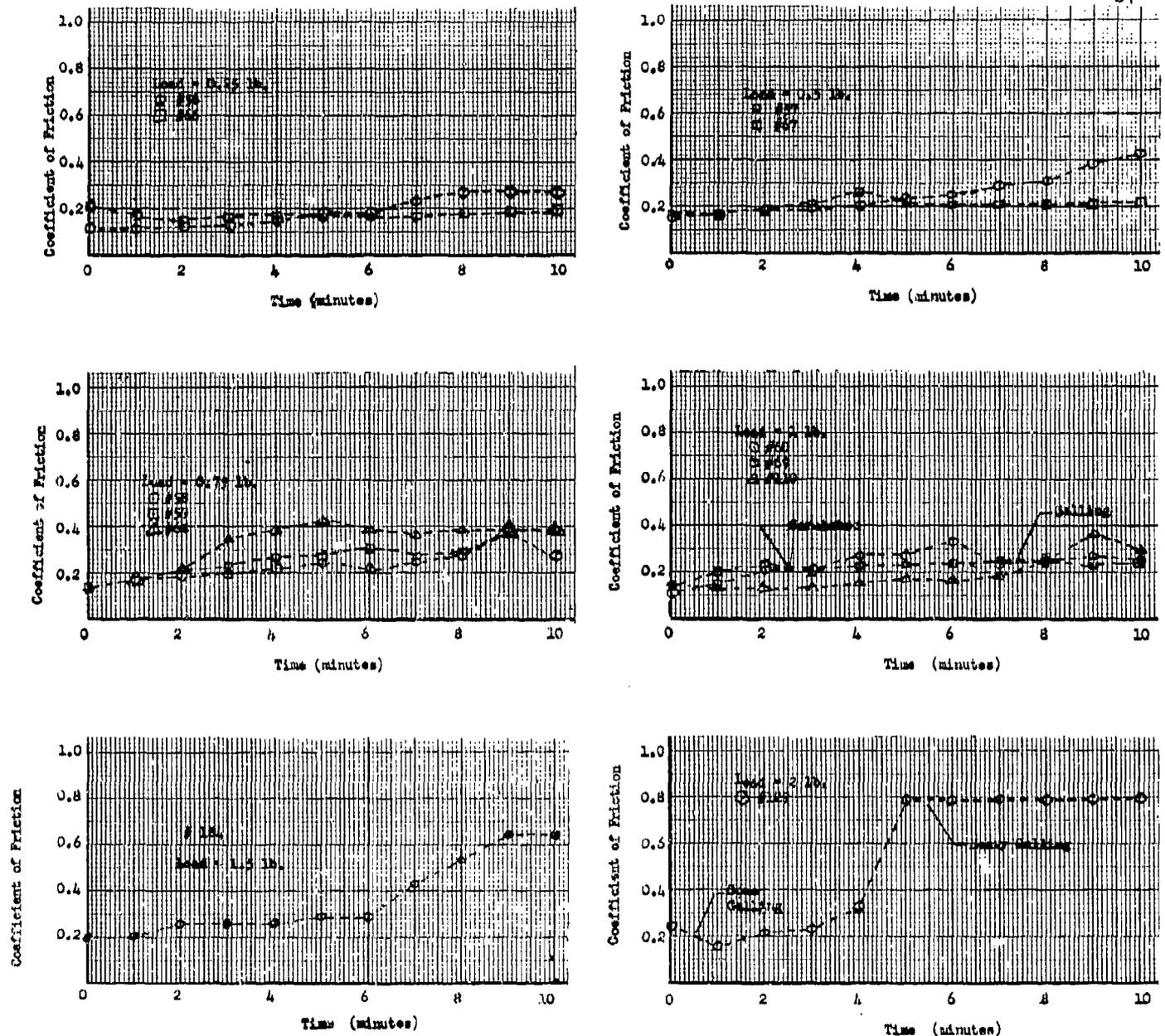


Figure 26

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130A Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

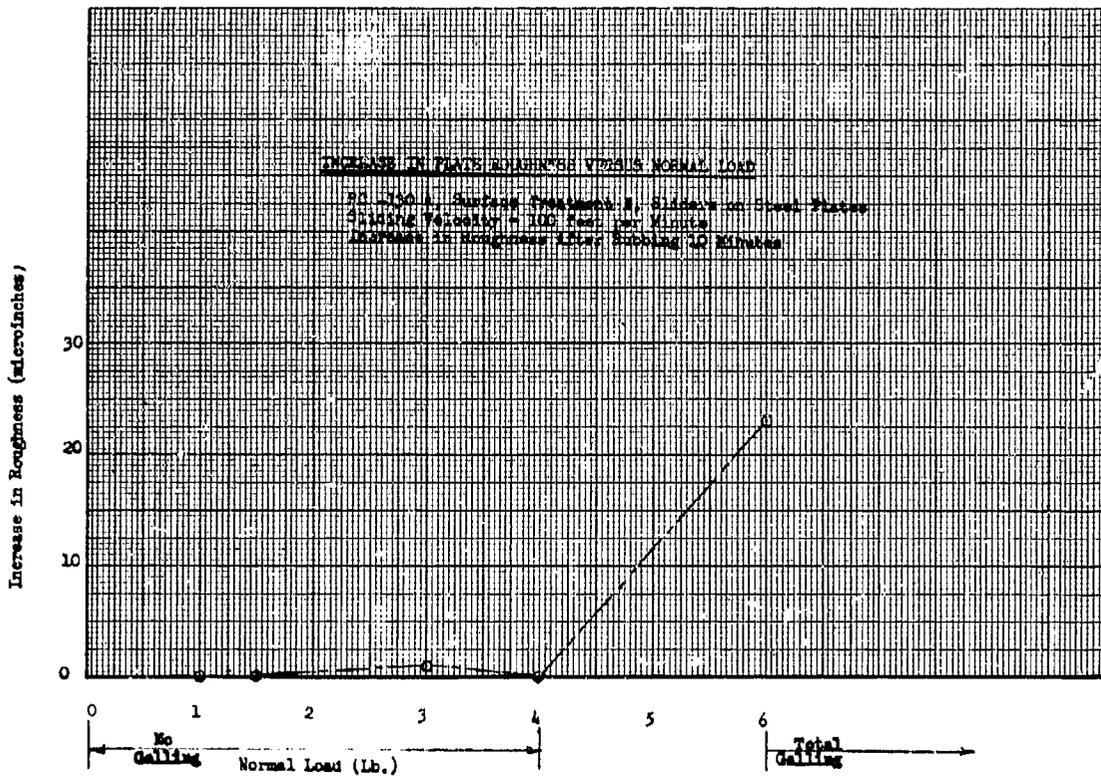
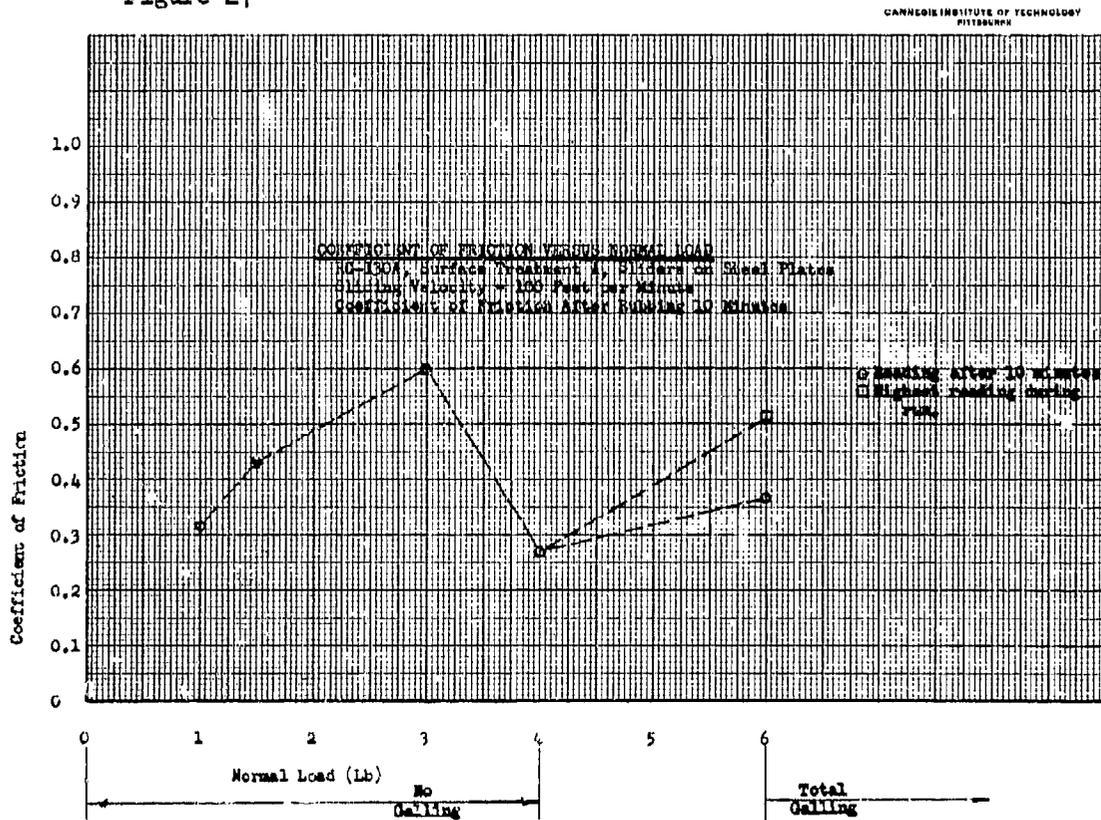
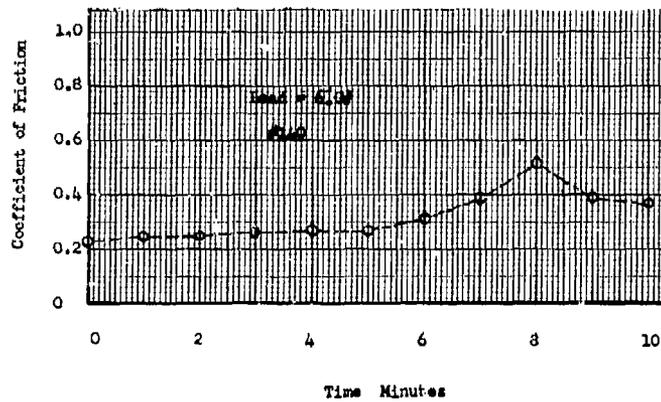
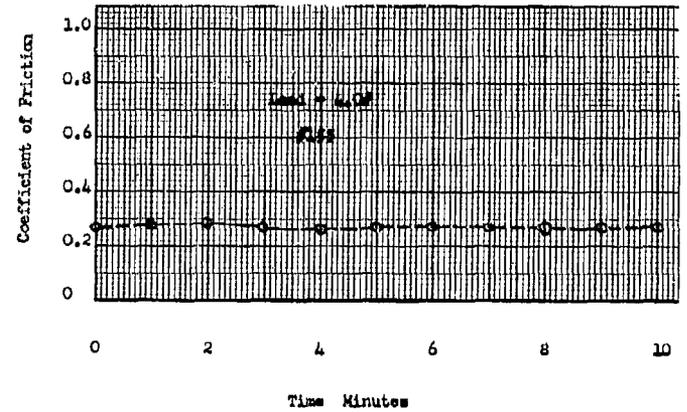
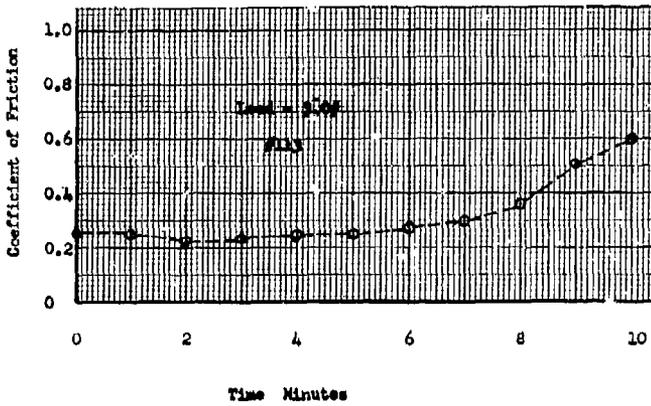
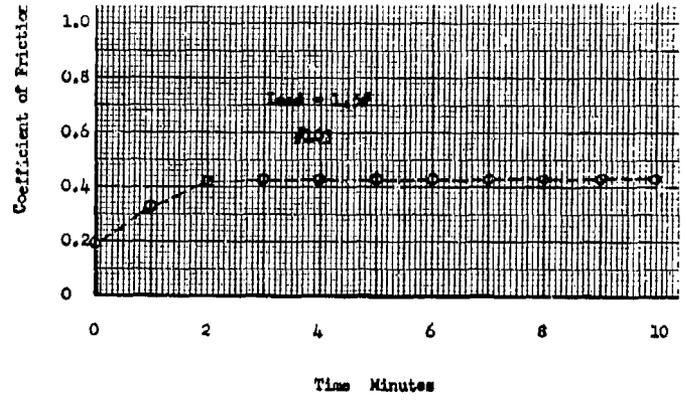
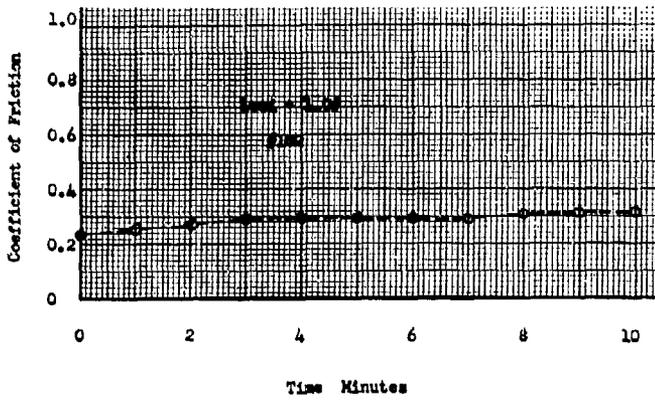


Figure 27





COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Figure 28

Titanium RC-130A, Surface Treatment A,
Sliders on Steel Plates
Sliding Velocity: 100 Feet per Minute

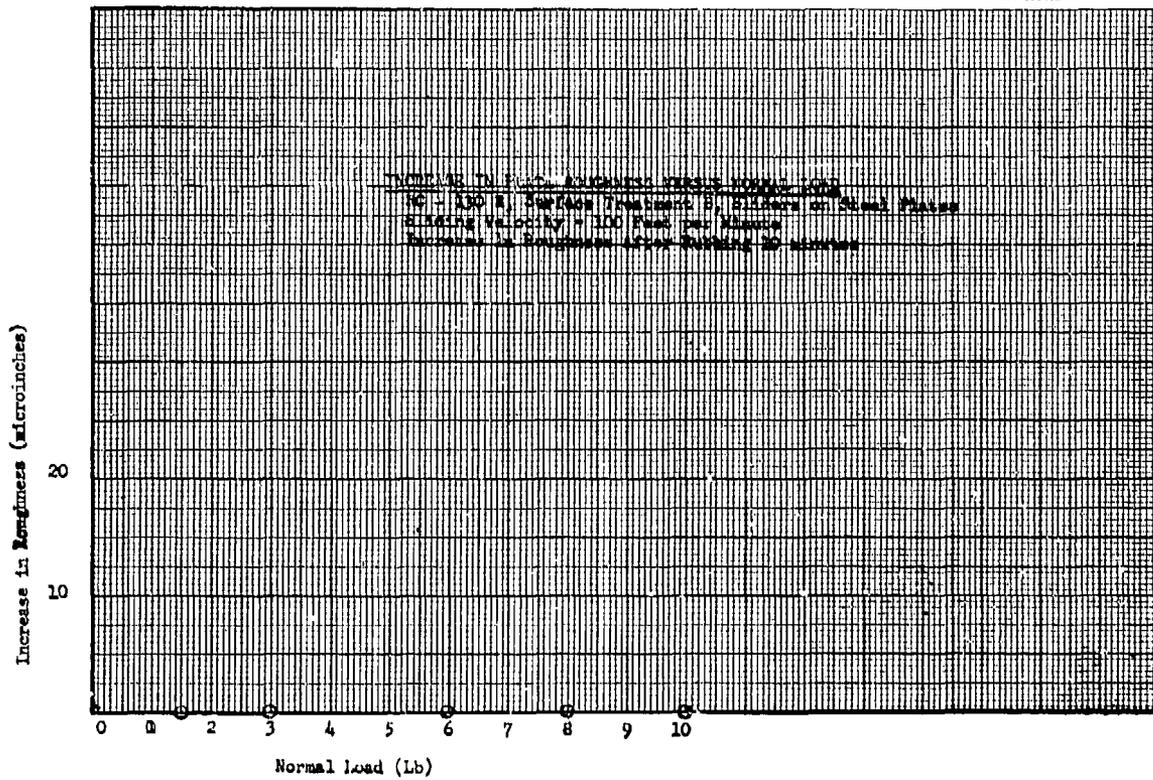
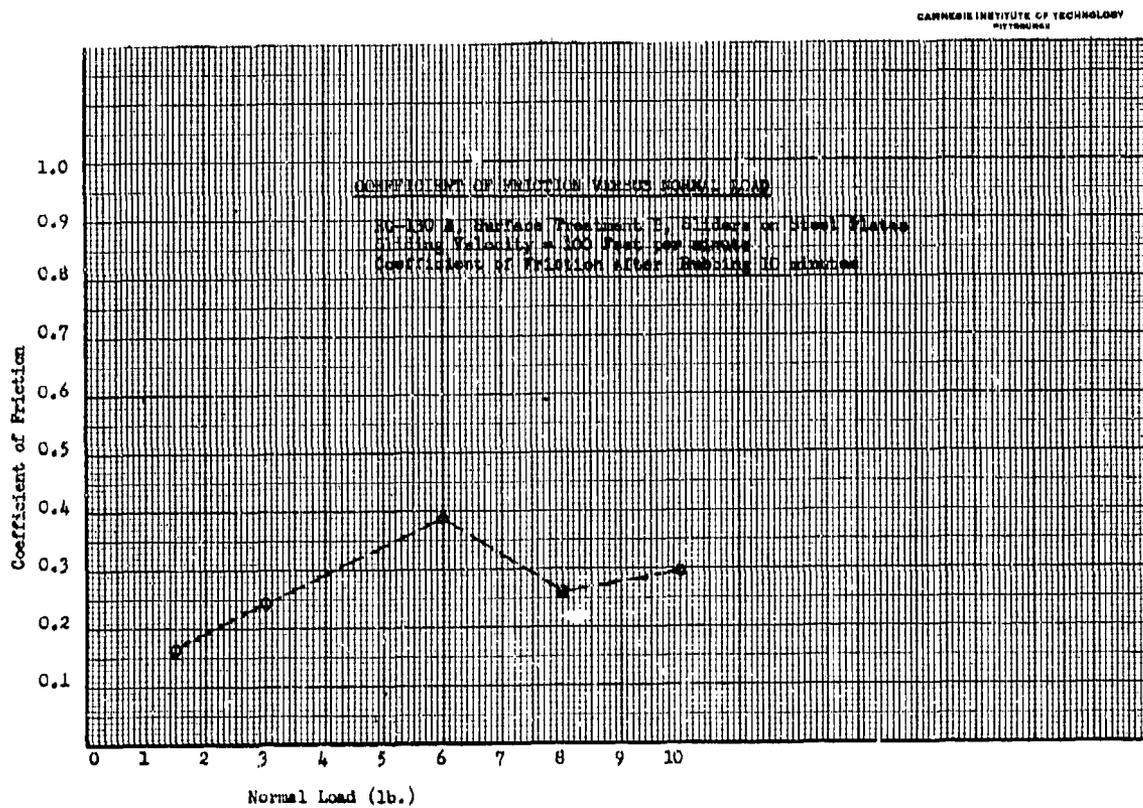


Figure 29



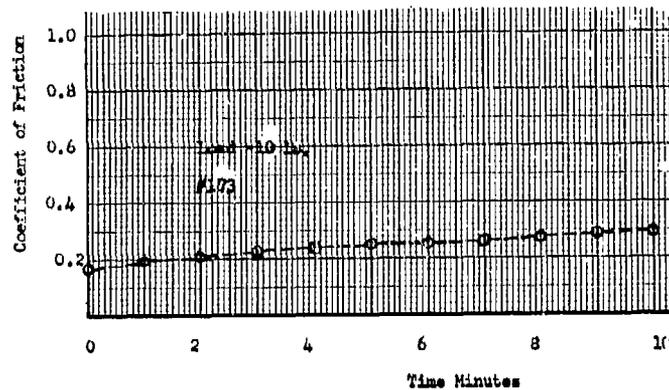
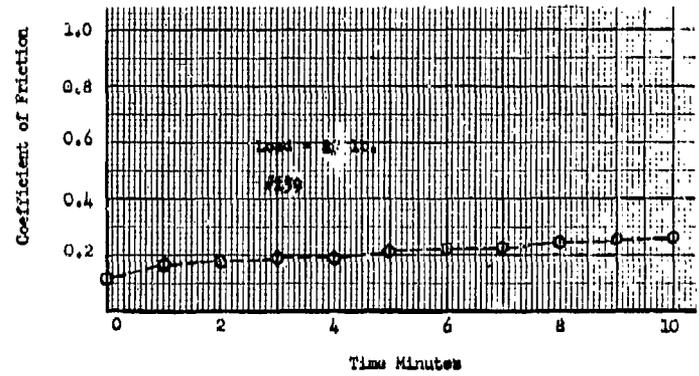
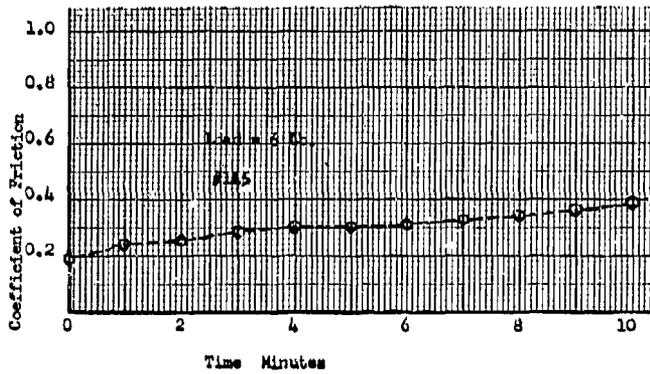
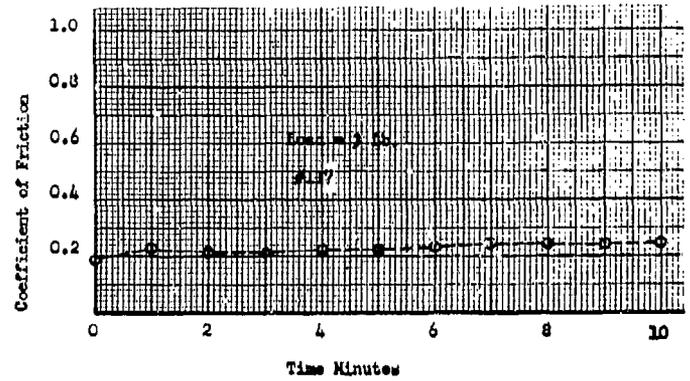
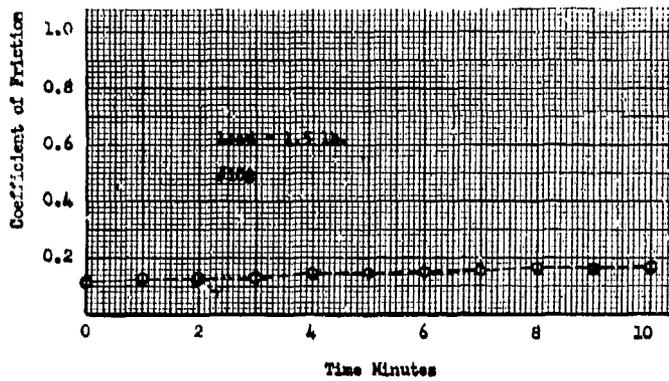


Figure 30

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130A, Surface Treatment B,
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

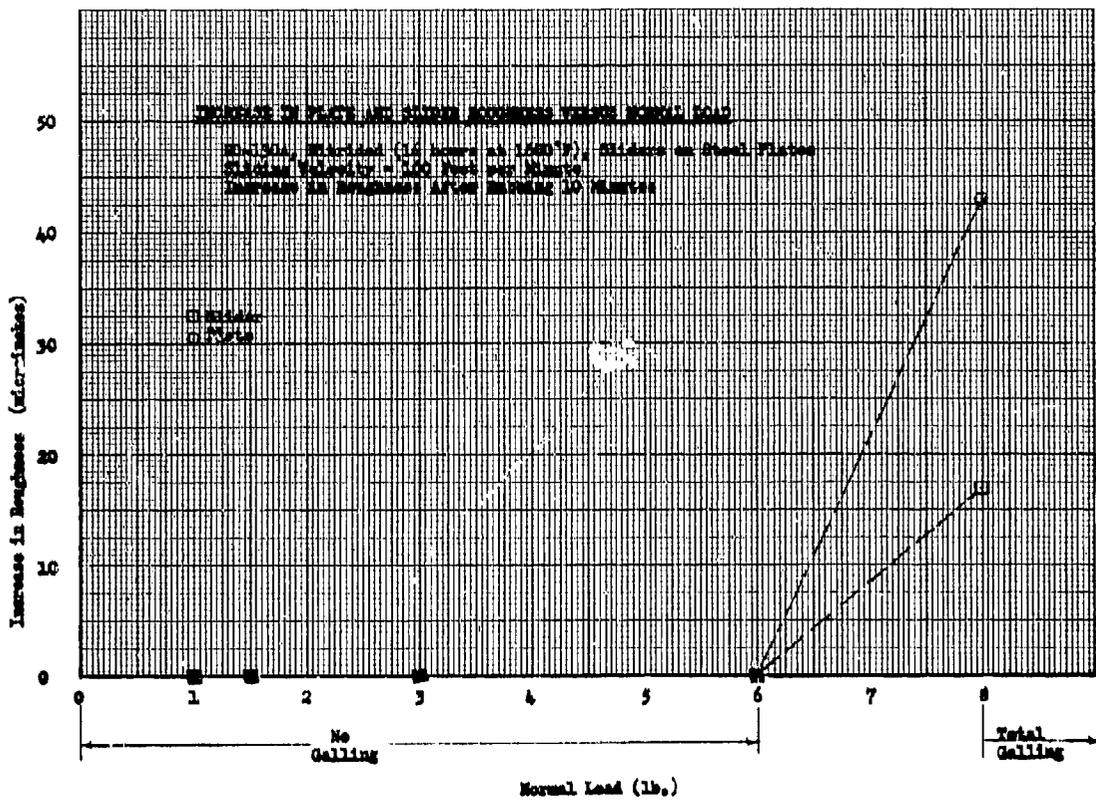
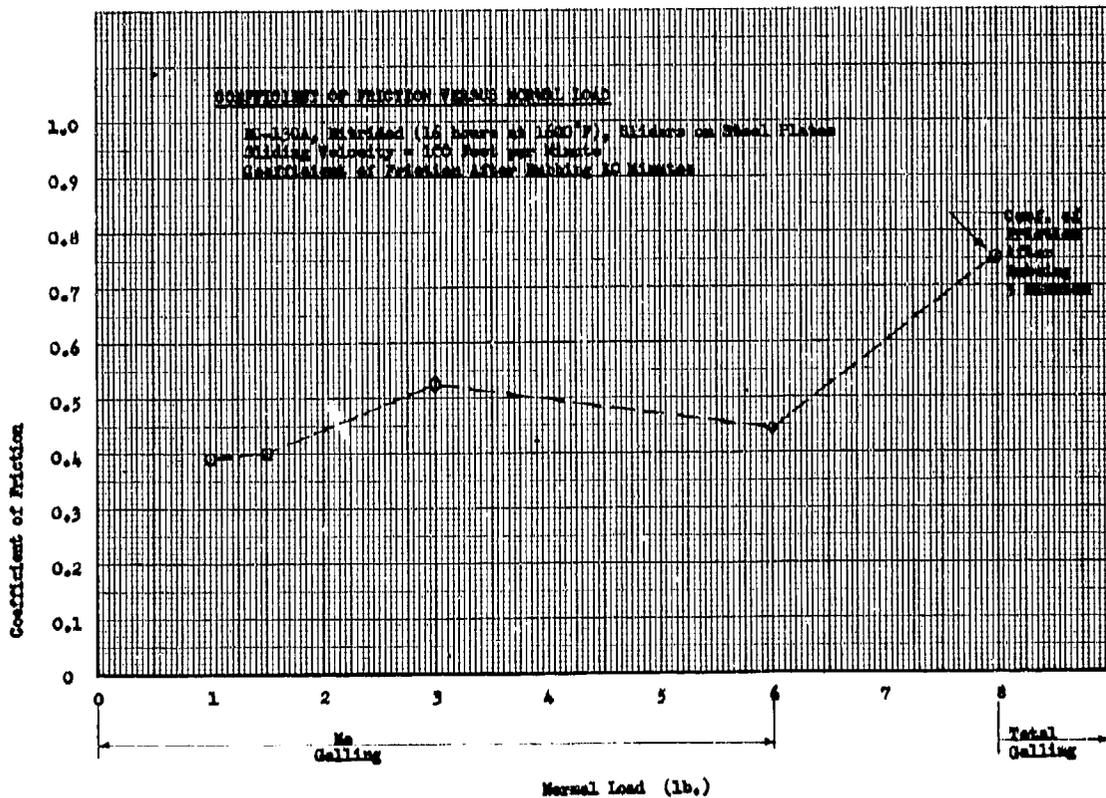


Figure 31



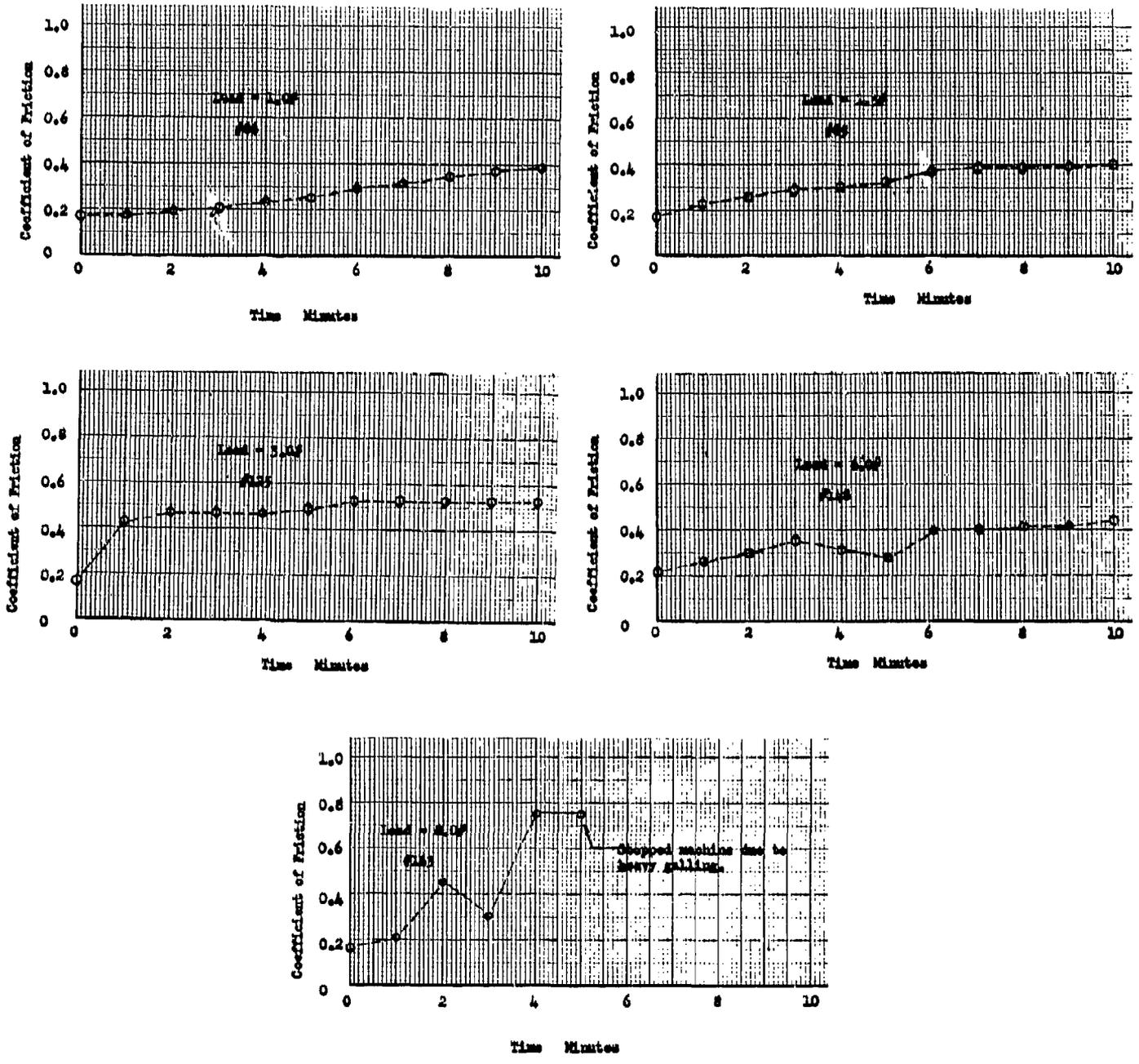


Figure 32

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130A, Nitrided (16 hrs. @ 1600° F),
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

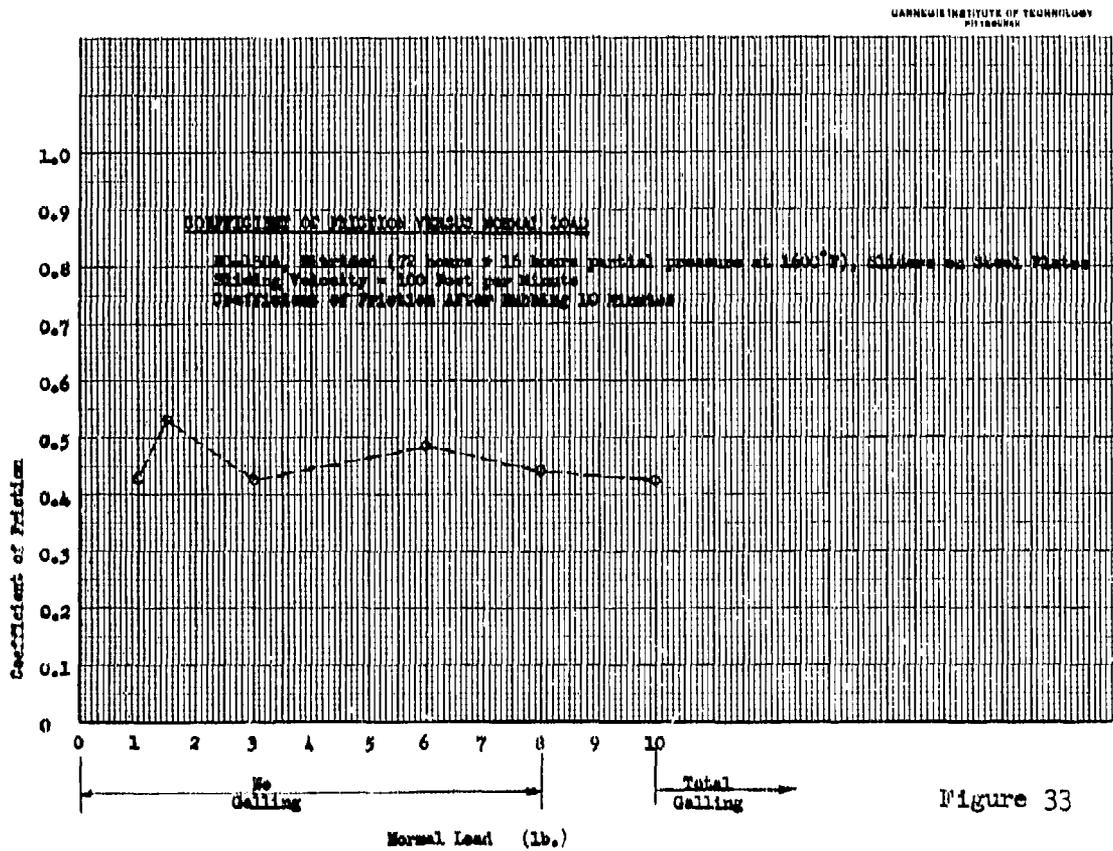
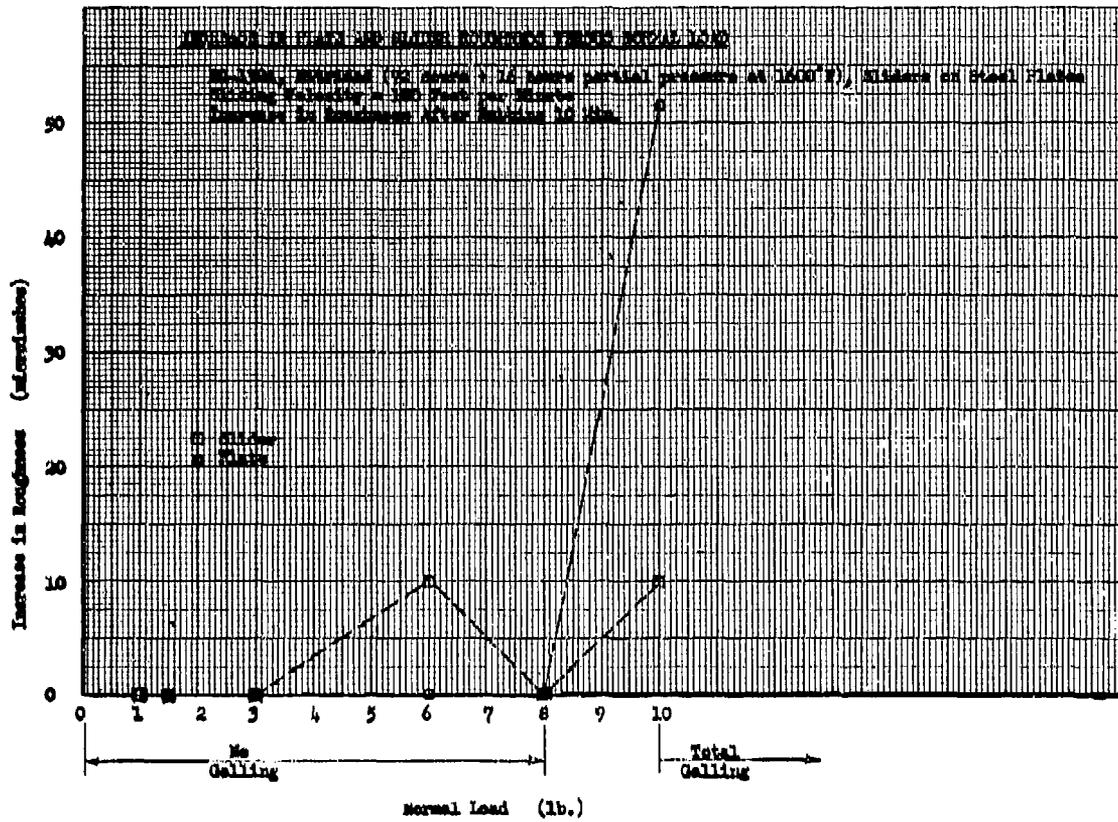


Figure 33

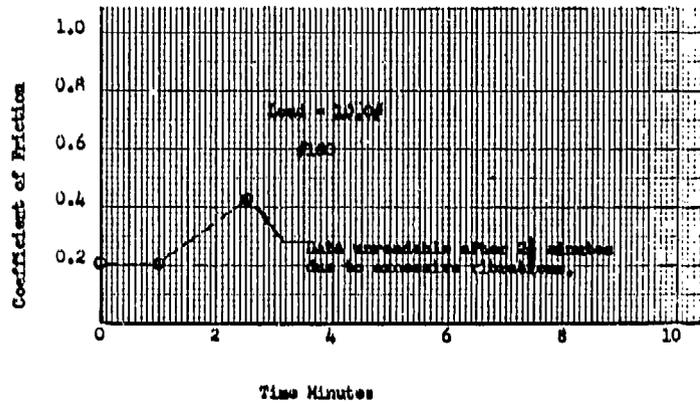
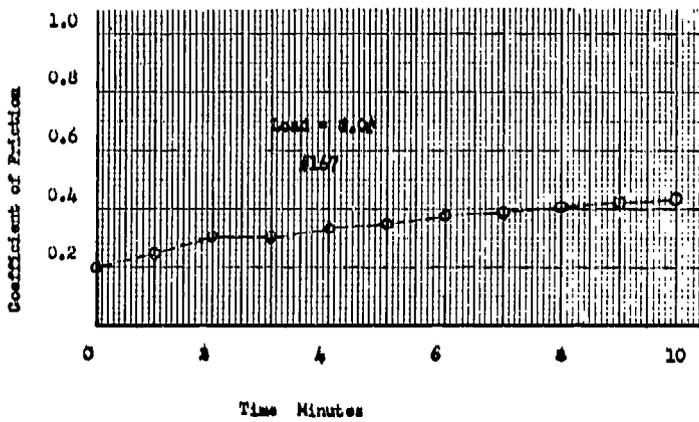
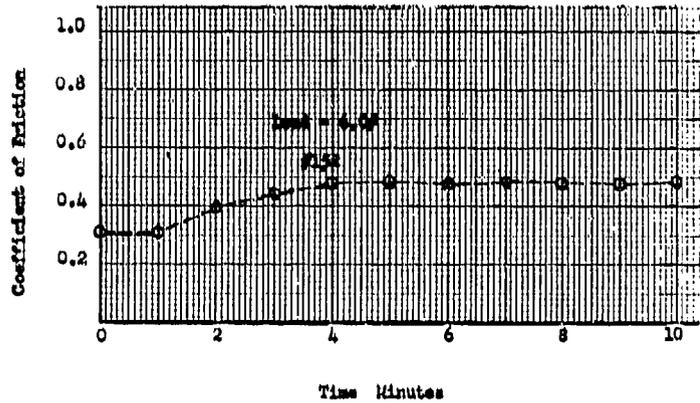
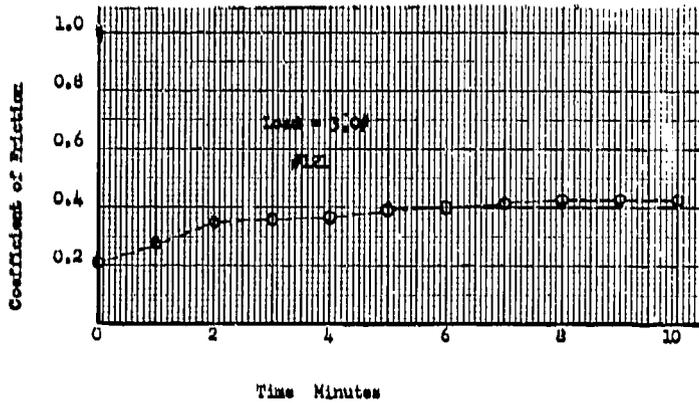
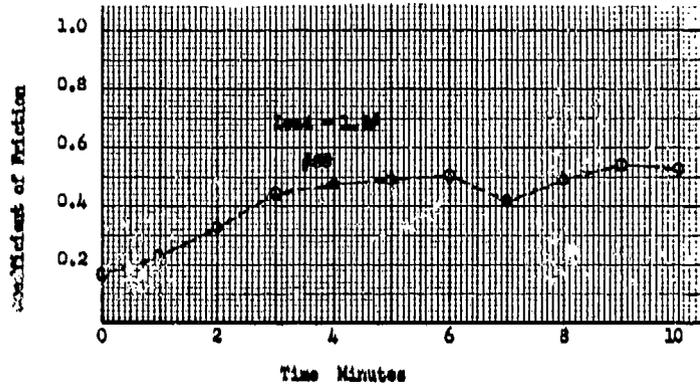
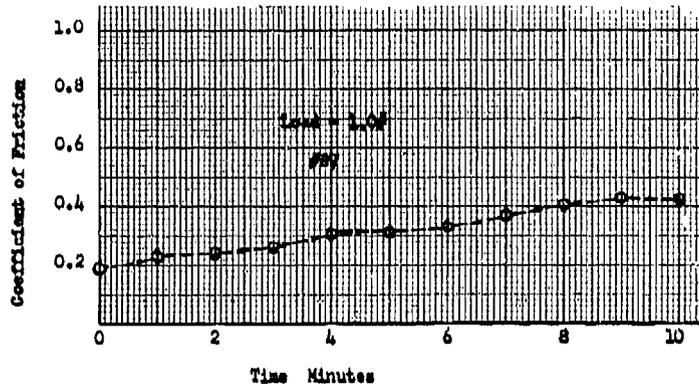


Figure 34

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130A, Nitrided (72 hrs. + 16 hrs.
Partial Pressure @ 1600°F), Sliders on
Steel Plates
Sliding Velocity: 100 Feet per Minute

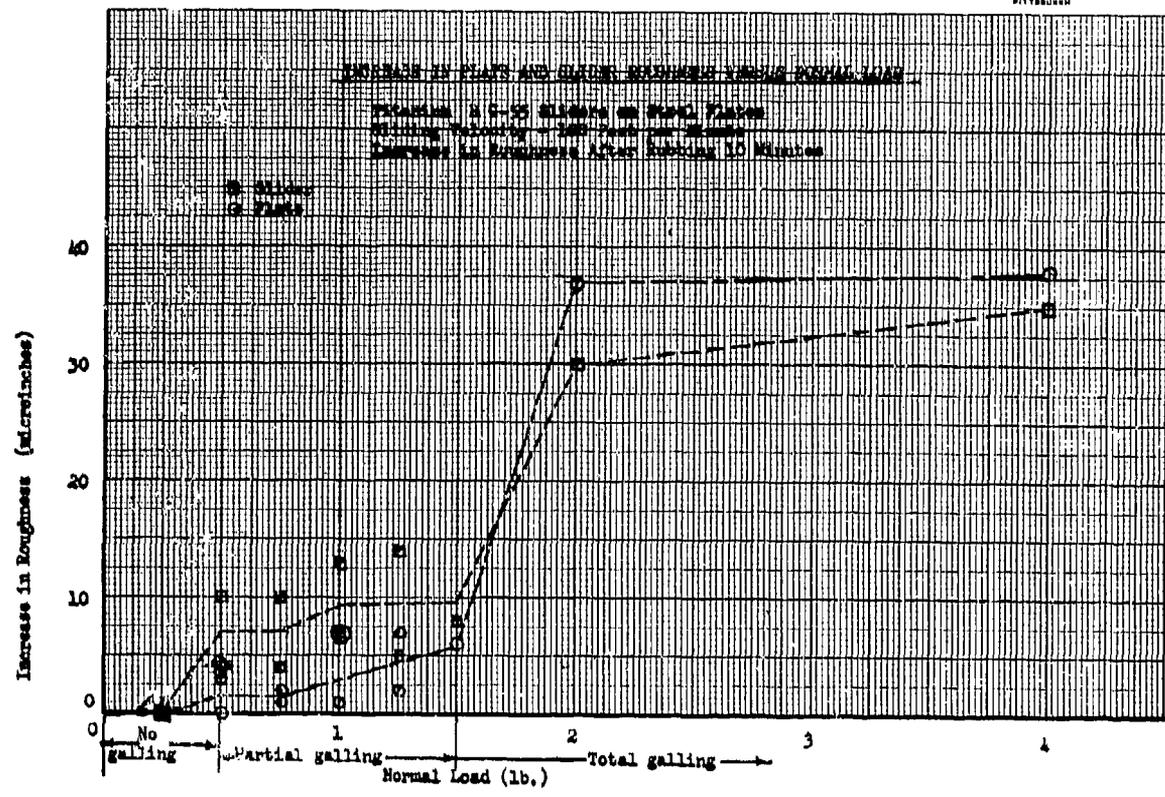
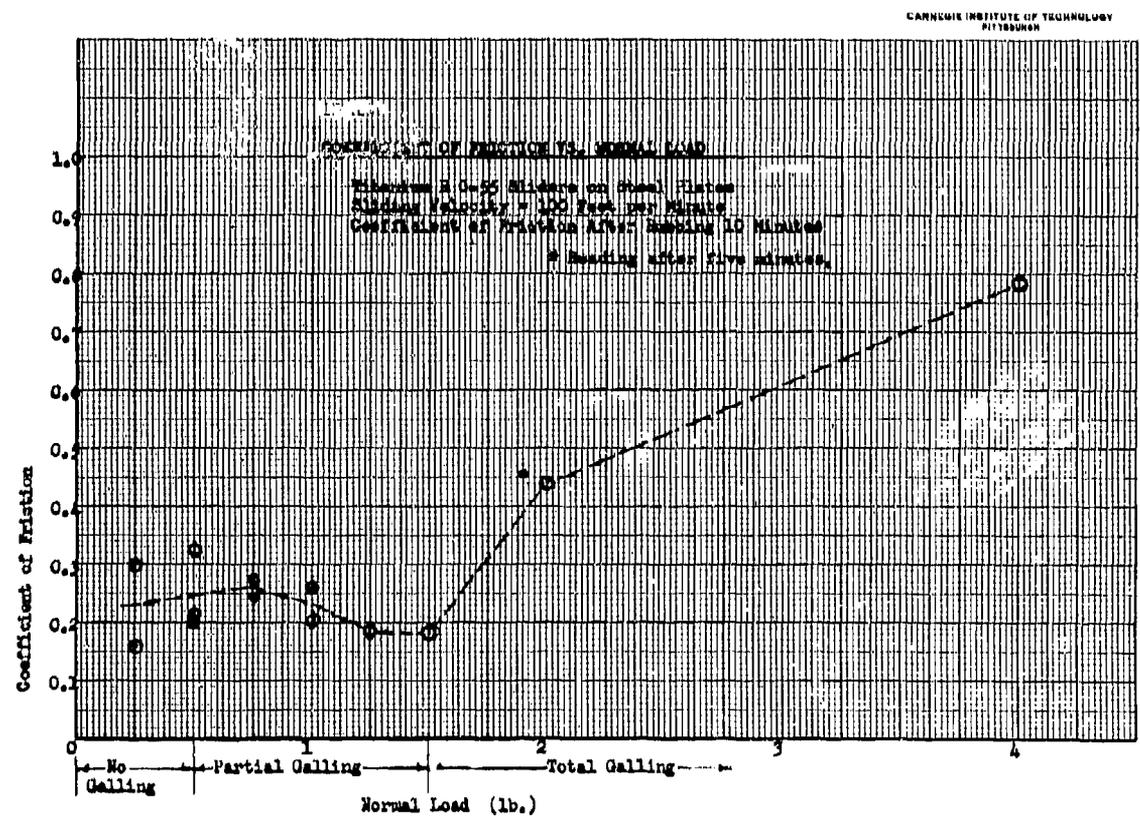
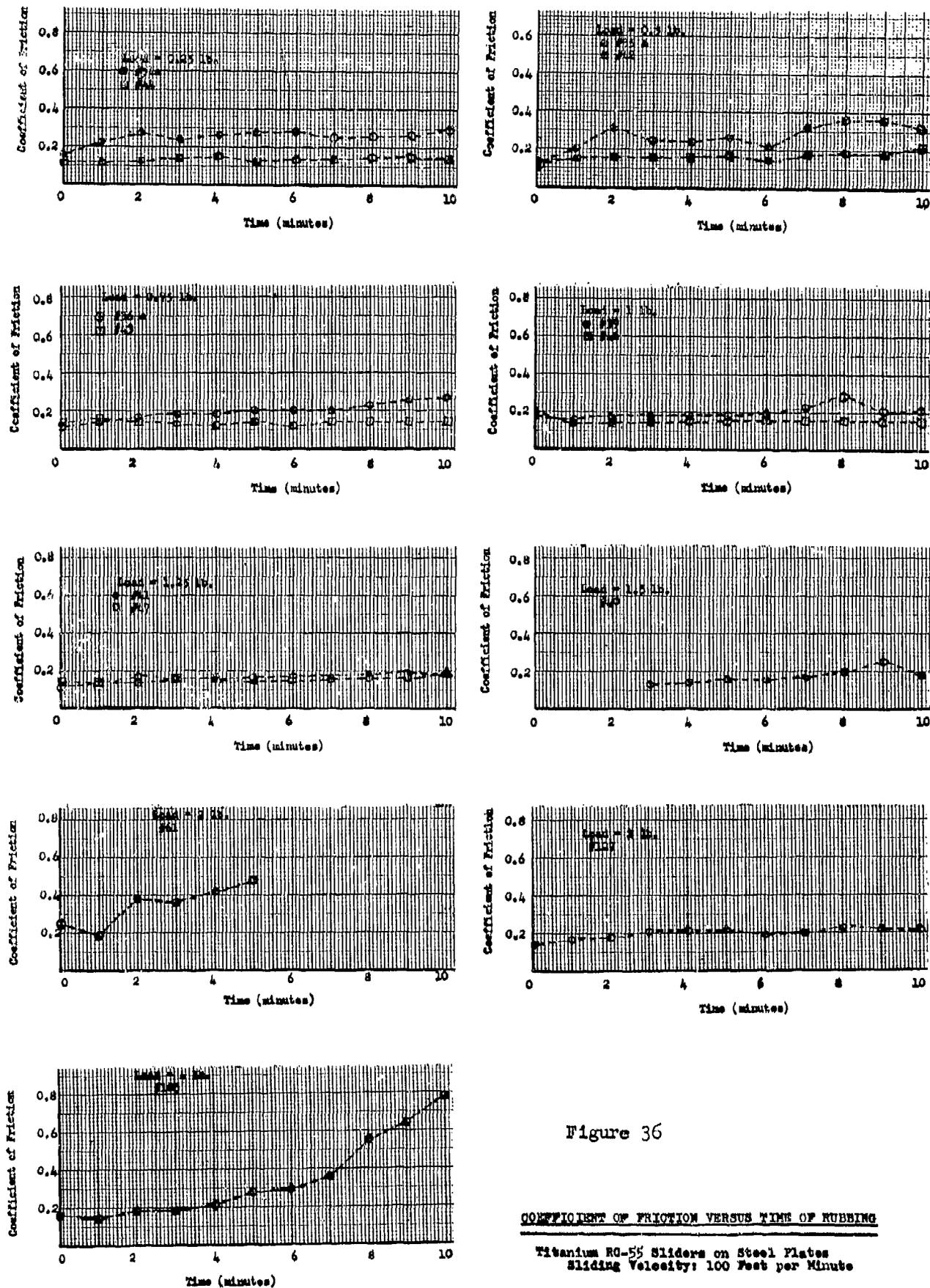


Figure 35





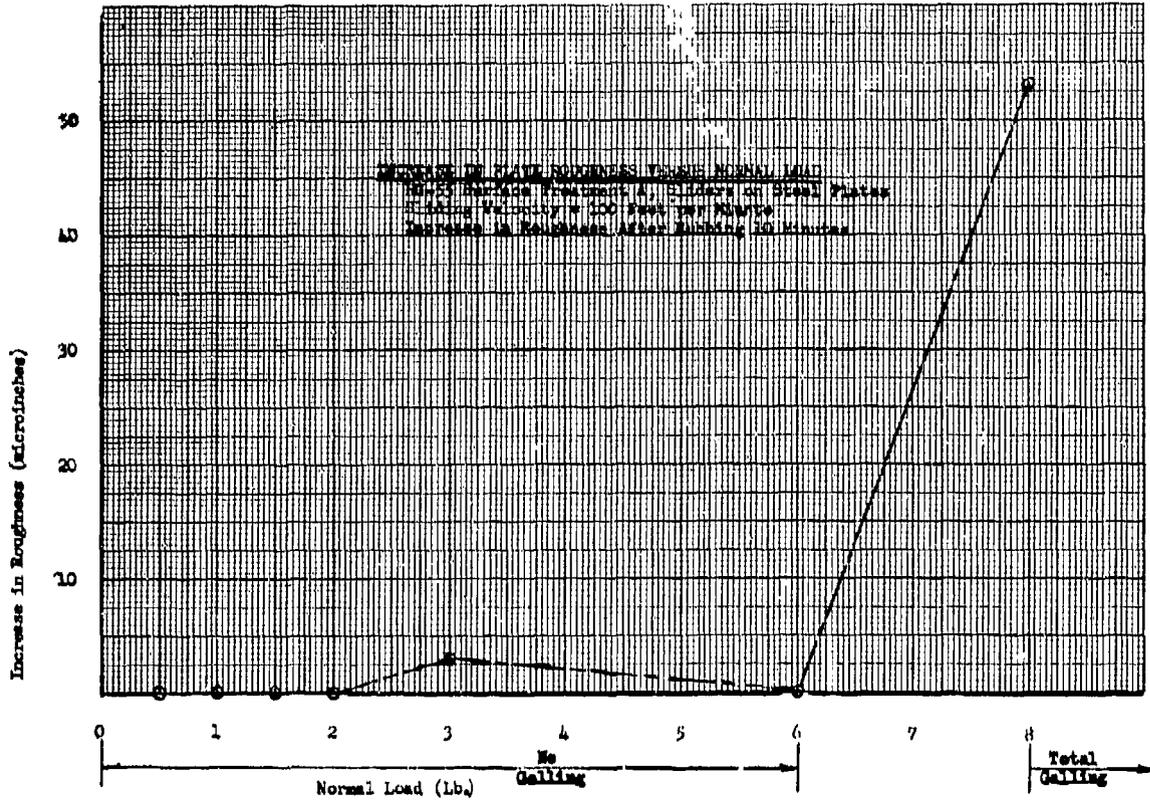
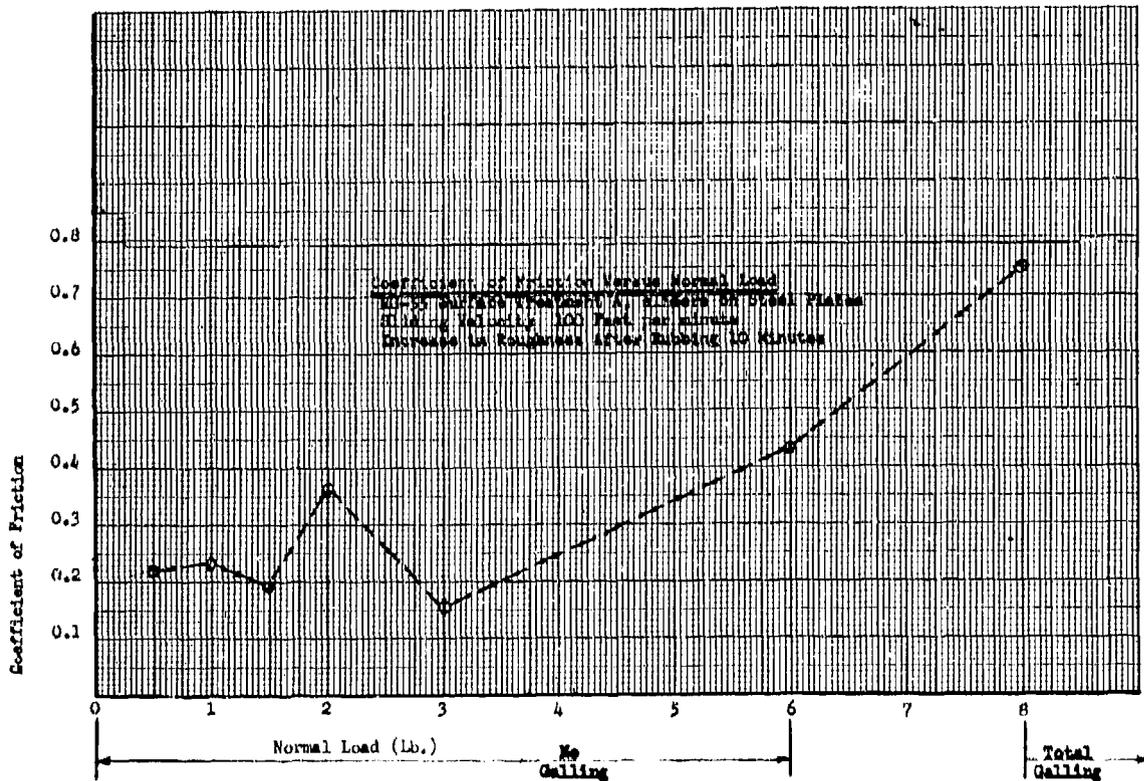


Figure 37



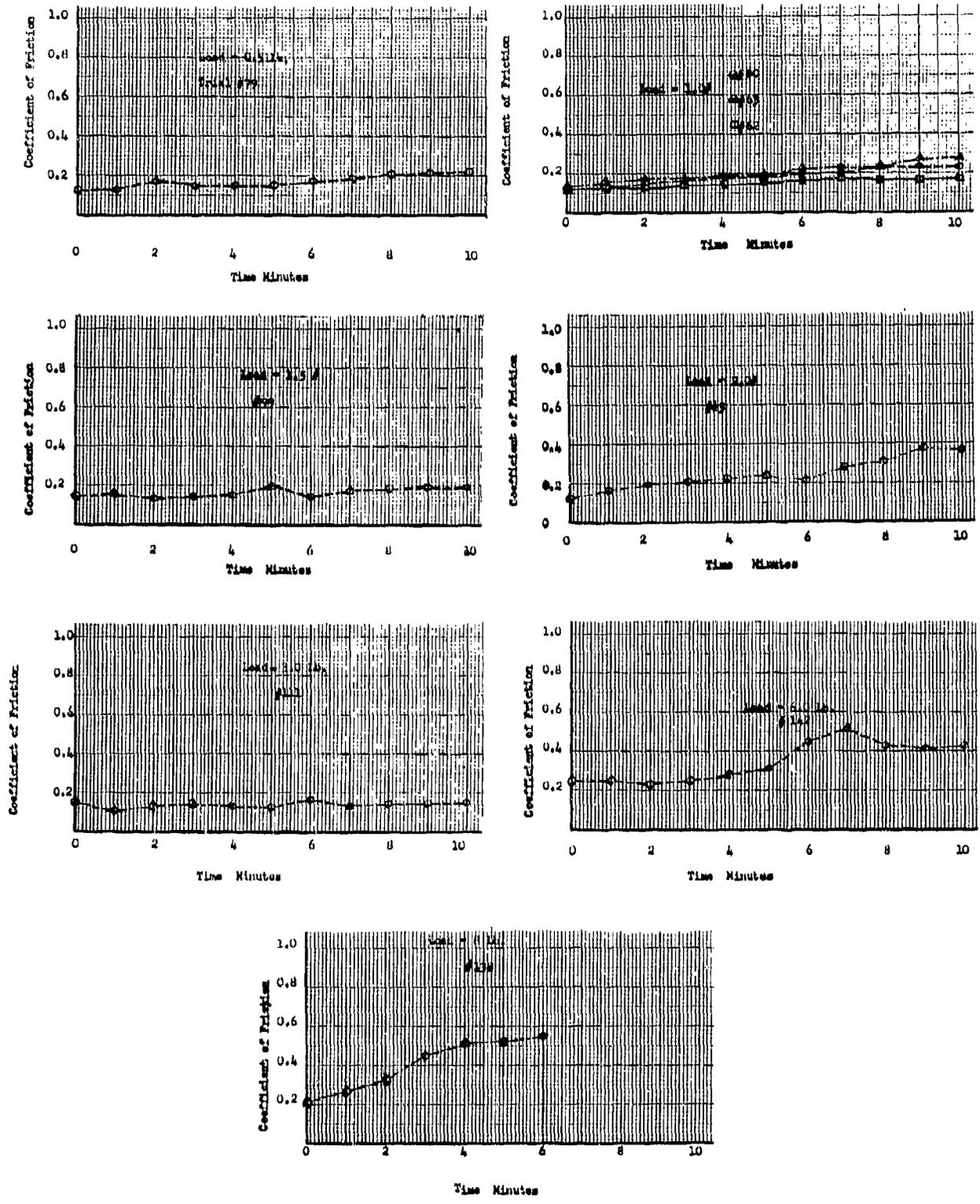


Figure 38

COEFFICIENT OF FRICTION VERSUS RUBBING TIME
 Titanium RC-55, Surface Treatment A,
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

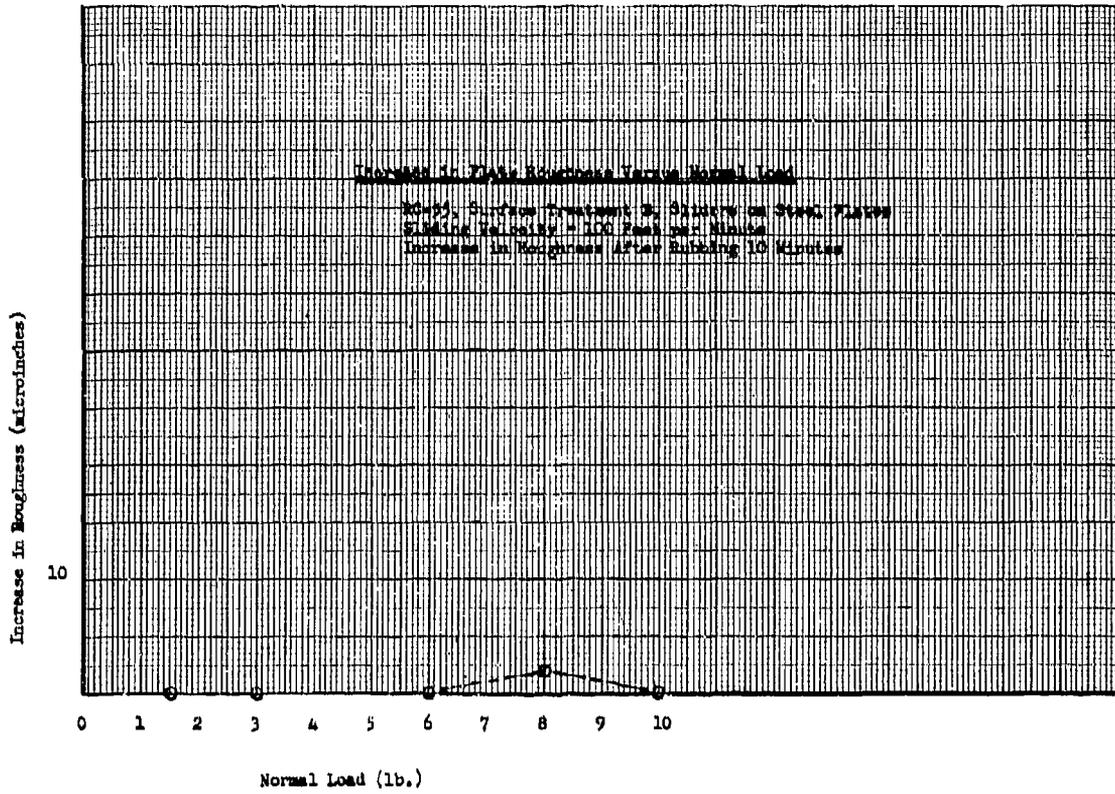
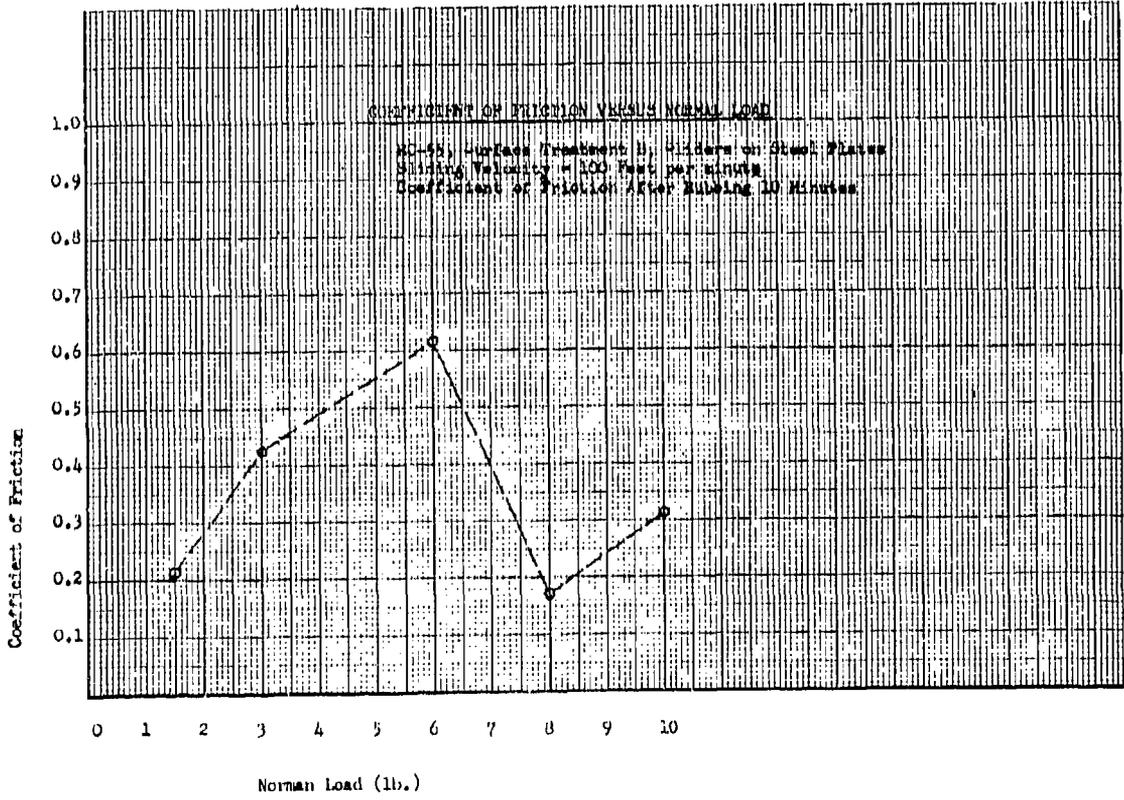
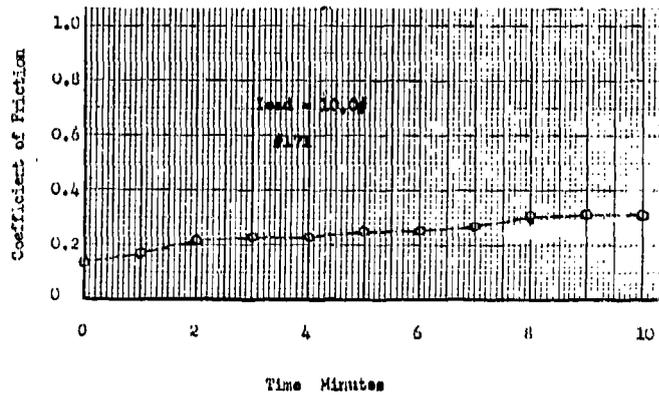
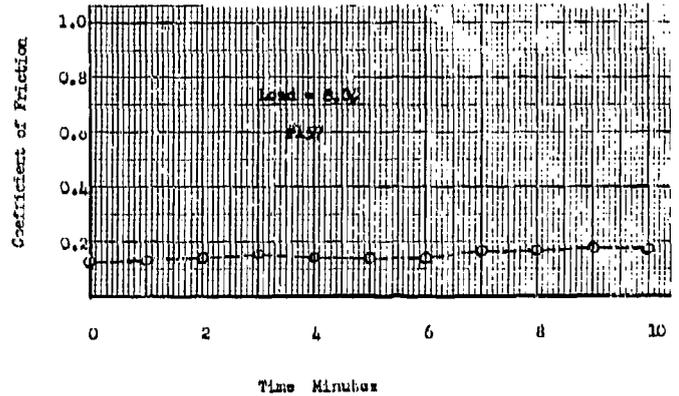
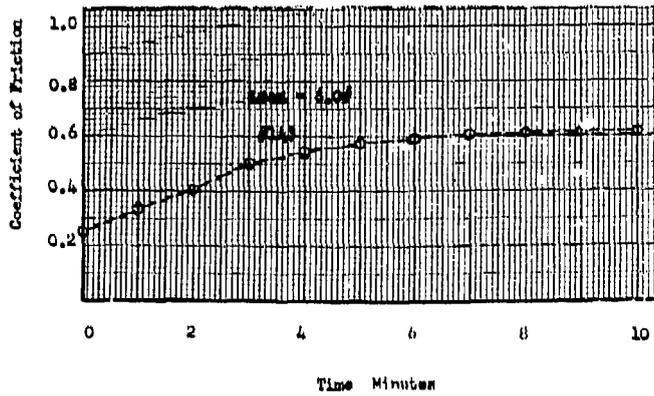
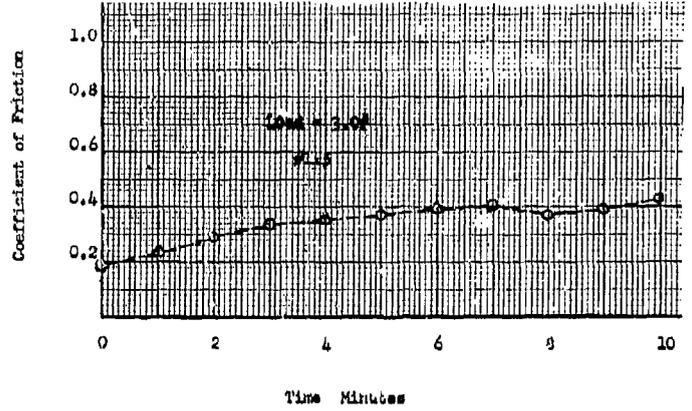
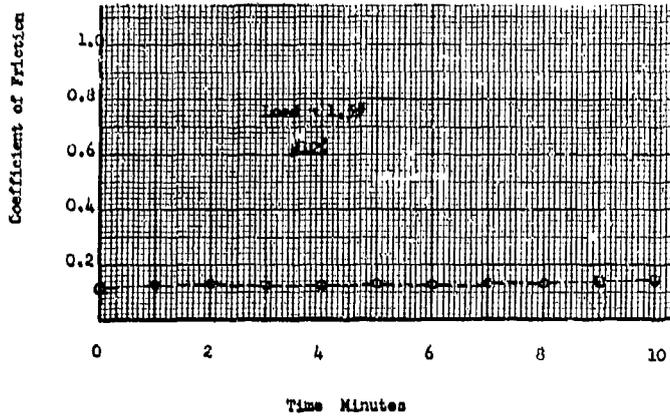


Figure 39





COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium 20-45, Surface Treatment B,
Sliders on Steel Plates
Sliding Velocity: 100 Feet per Minute

Figure 40

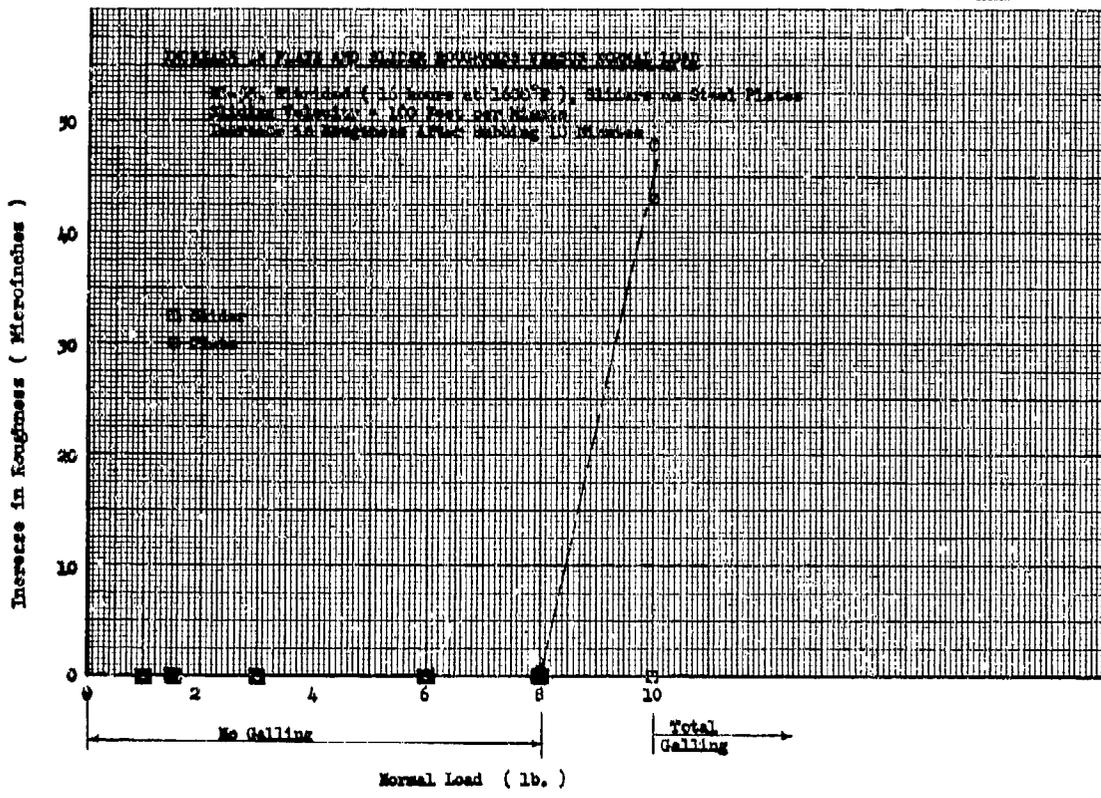
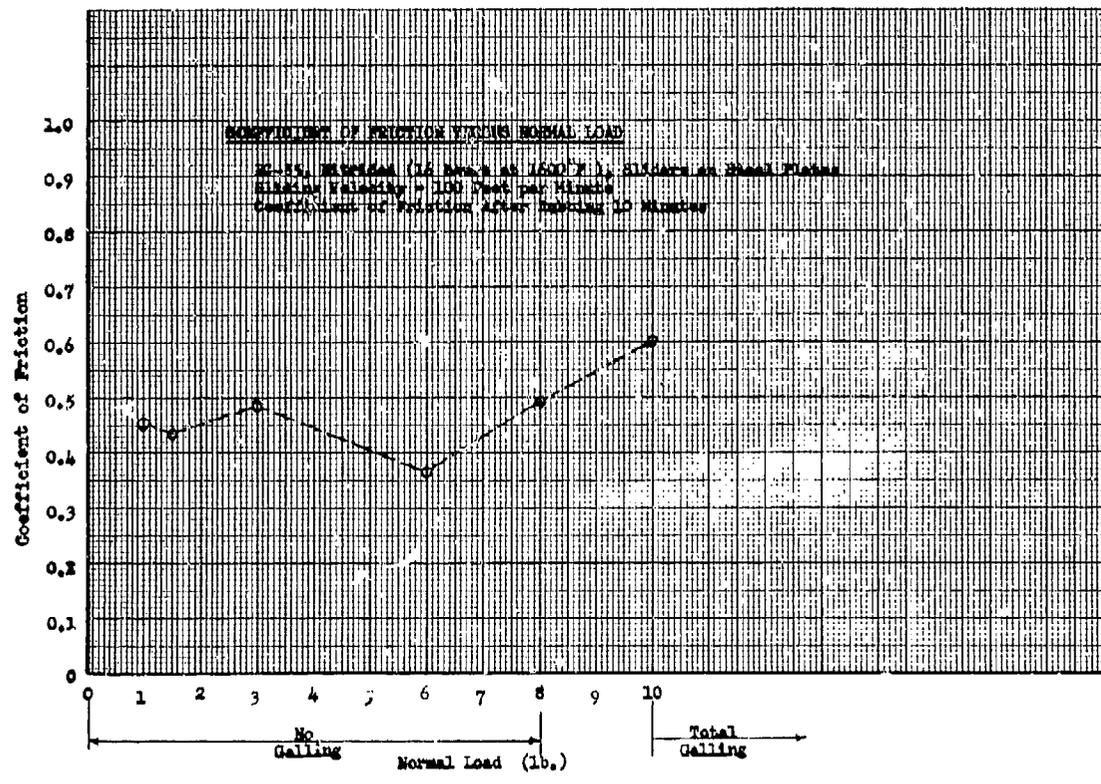


Figure 41



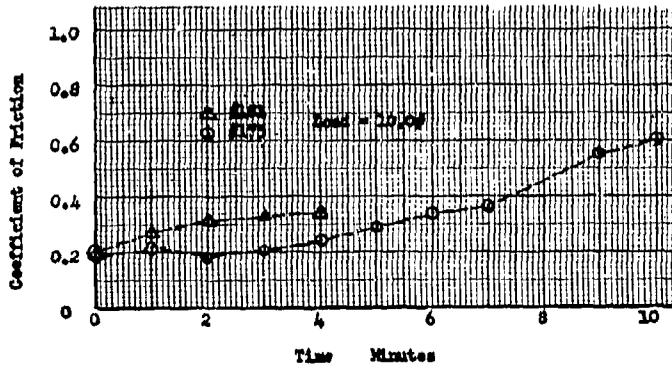
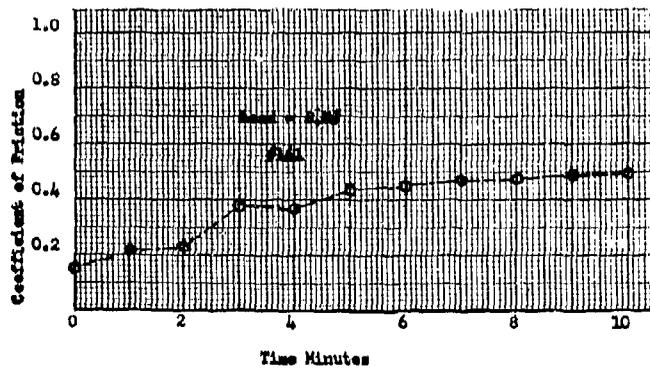
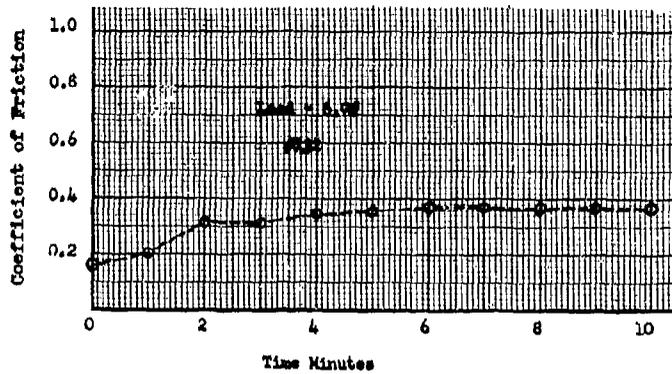
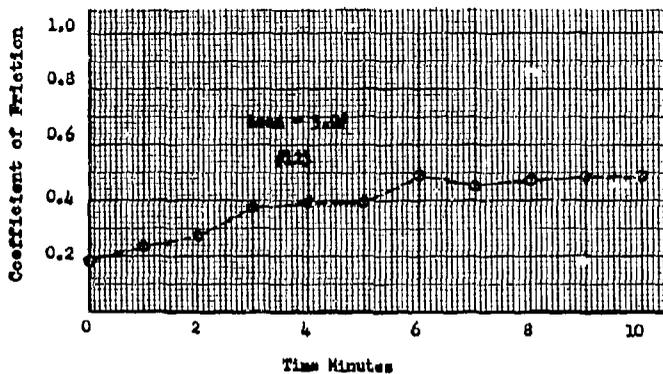
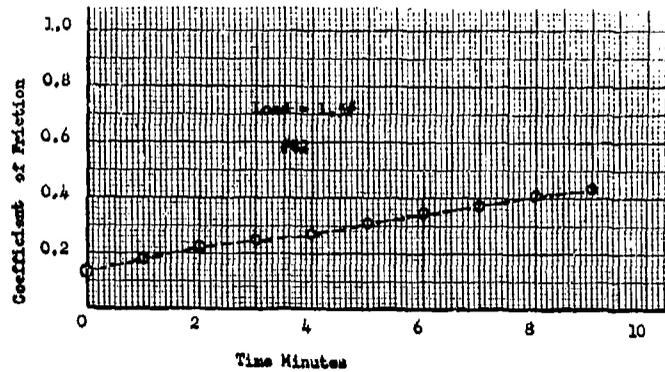
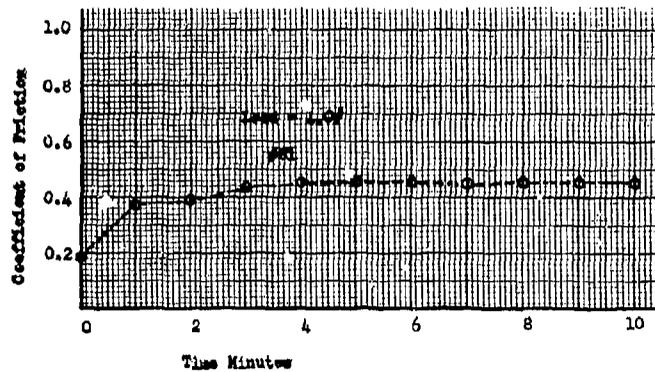


Figure 42

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-55, Nitrided (16 hrs. @ 1600°F),
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

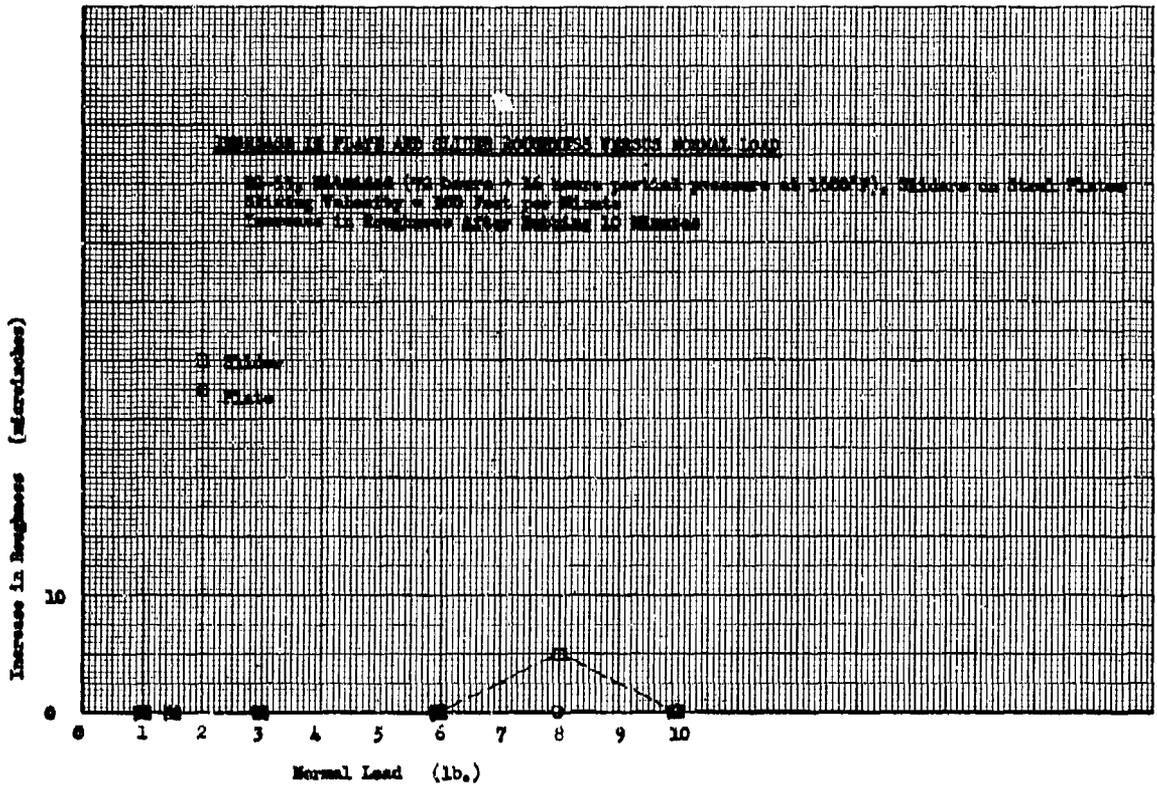
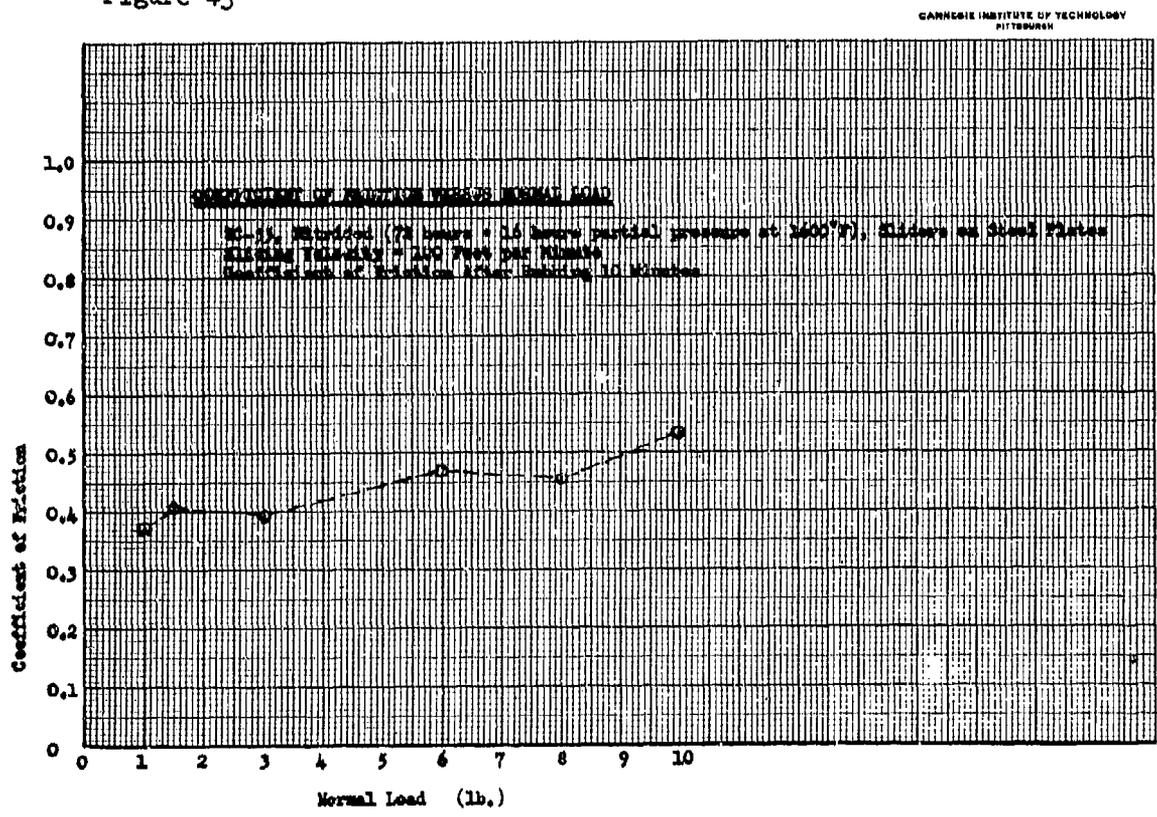


Figure 43



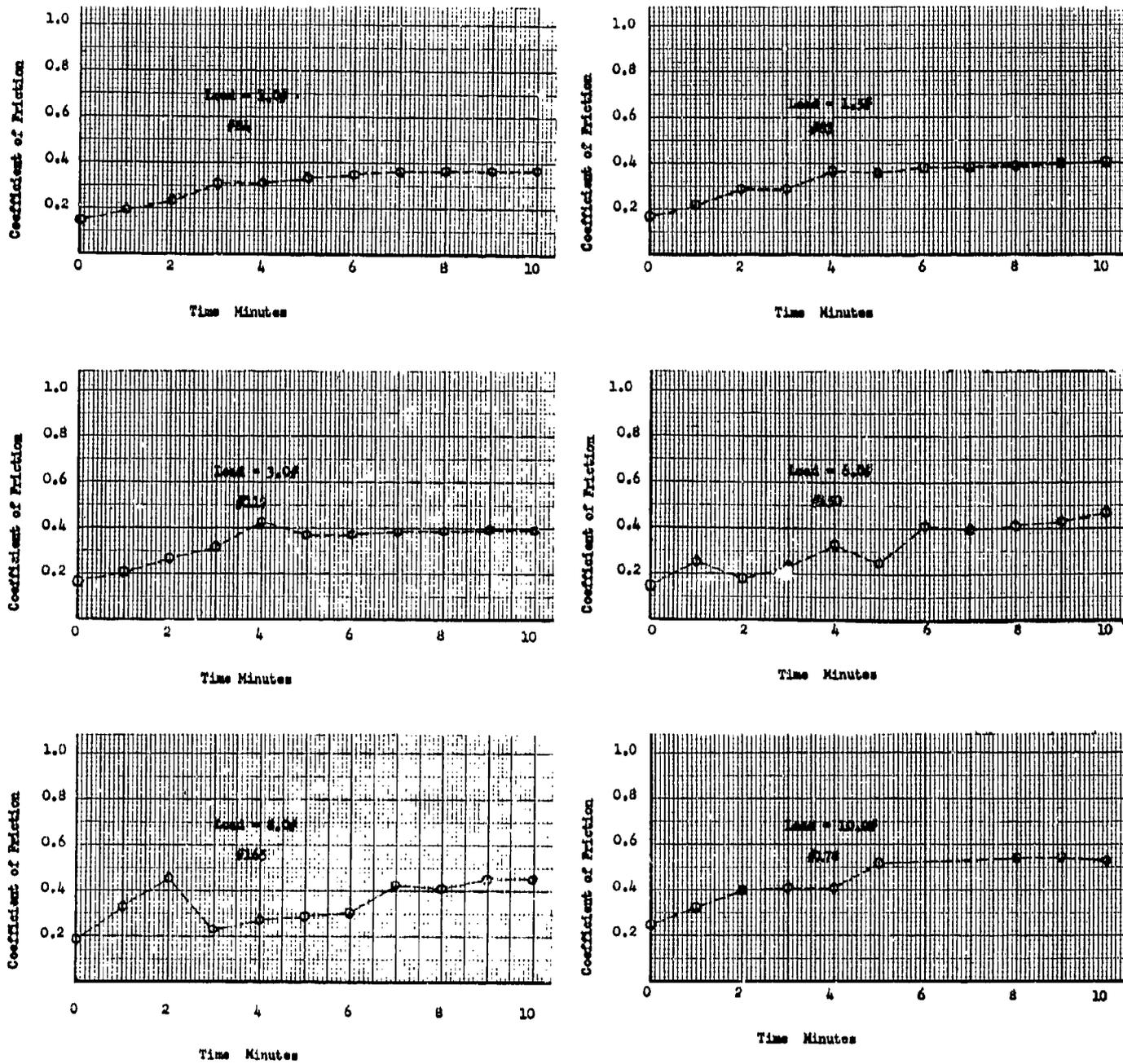


Figure 44

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-55, Nitrided (72 hrs. + 16 hrs.
 Partial Pressure @ 1600°F), Sliders on
 Steel Plates
 Sliding Velocity: 100 Feet per Minute

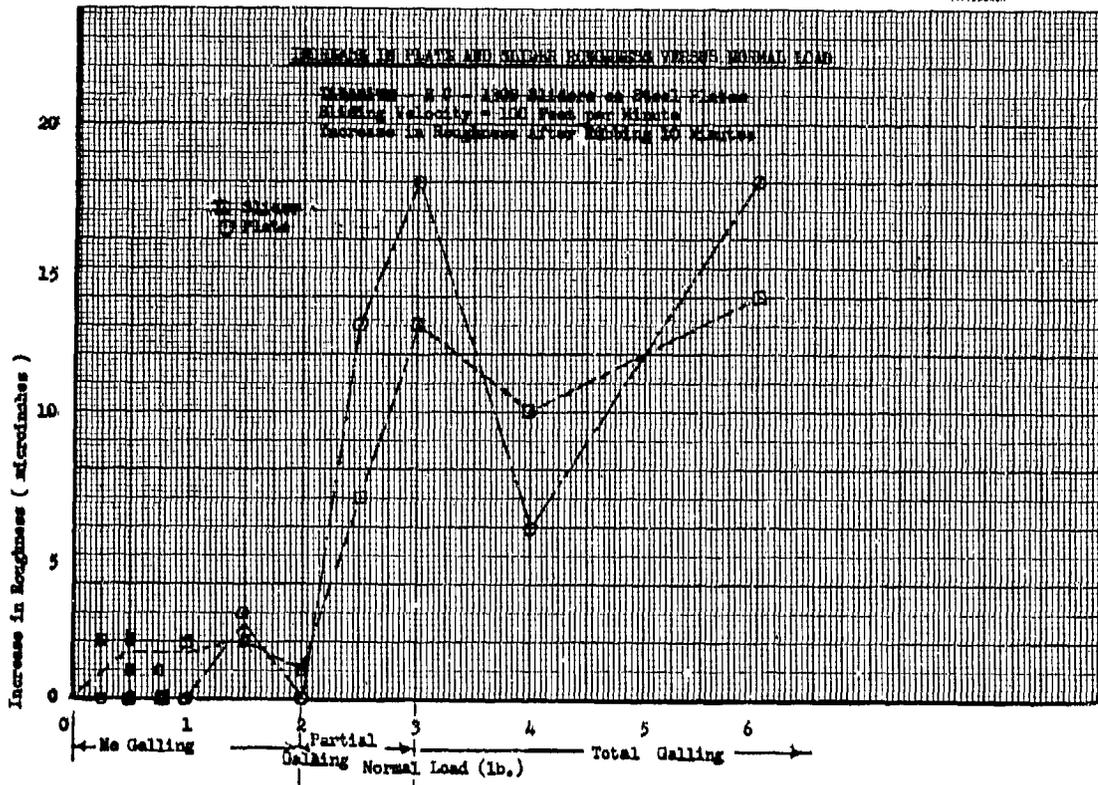
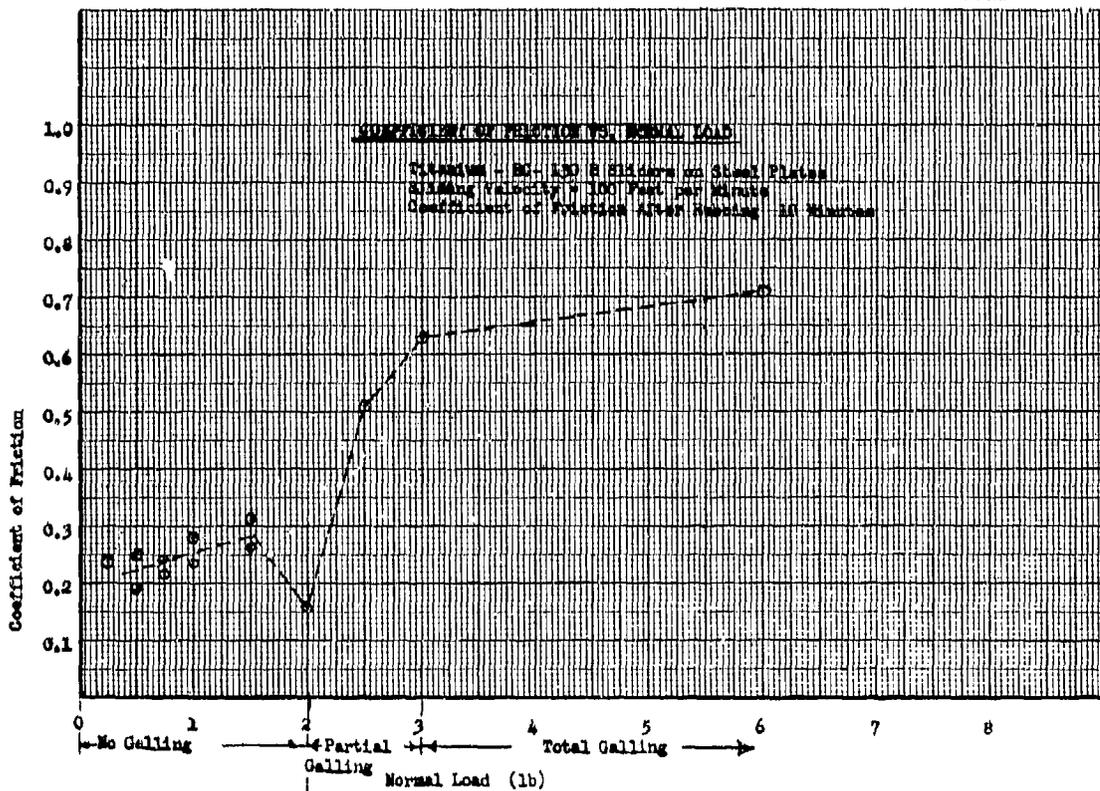


Figure 45



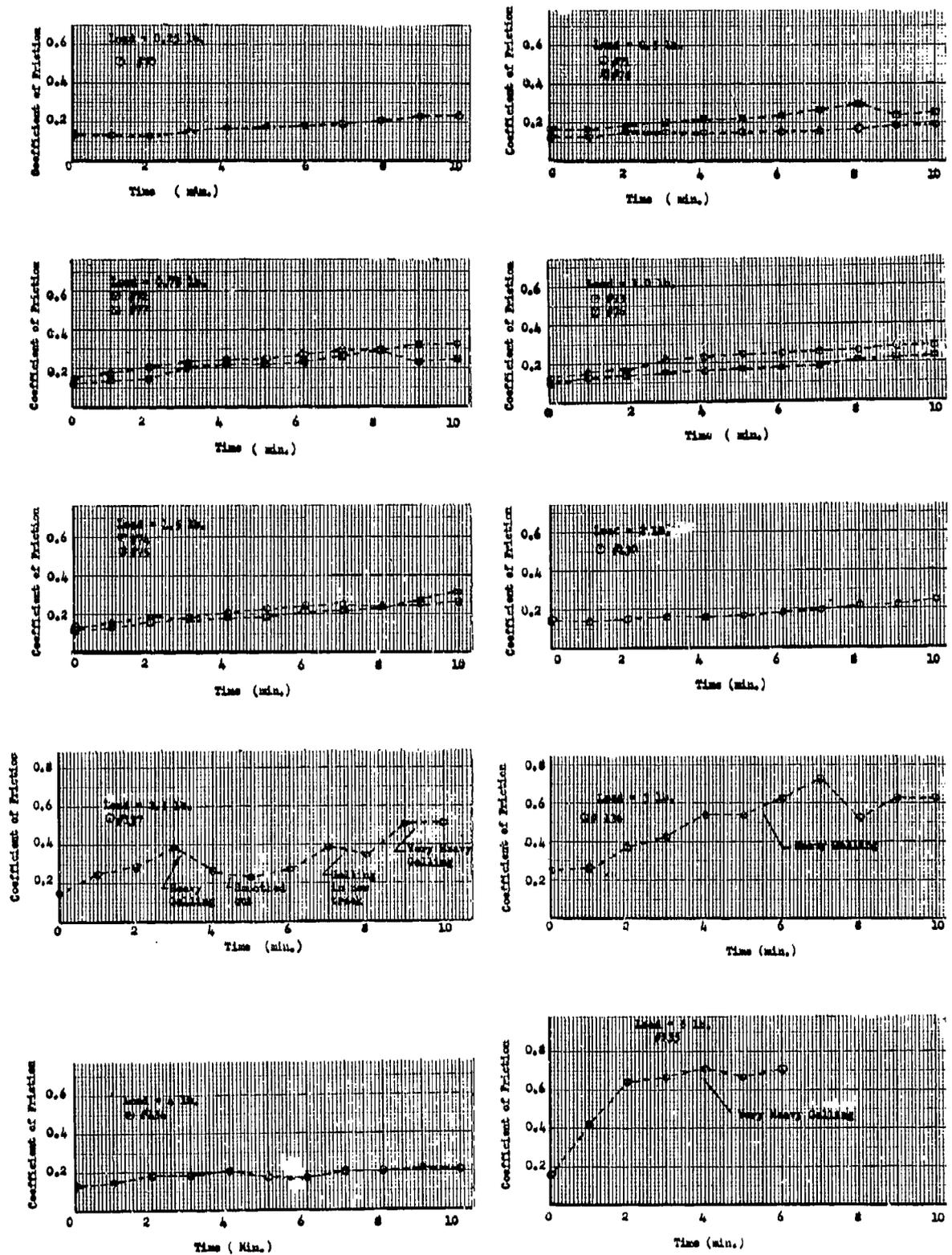


Figure 46

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130B Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

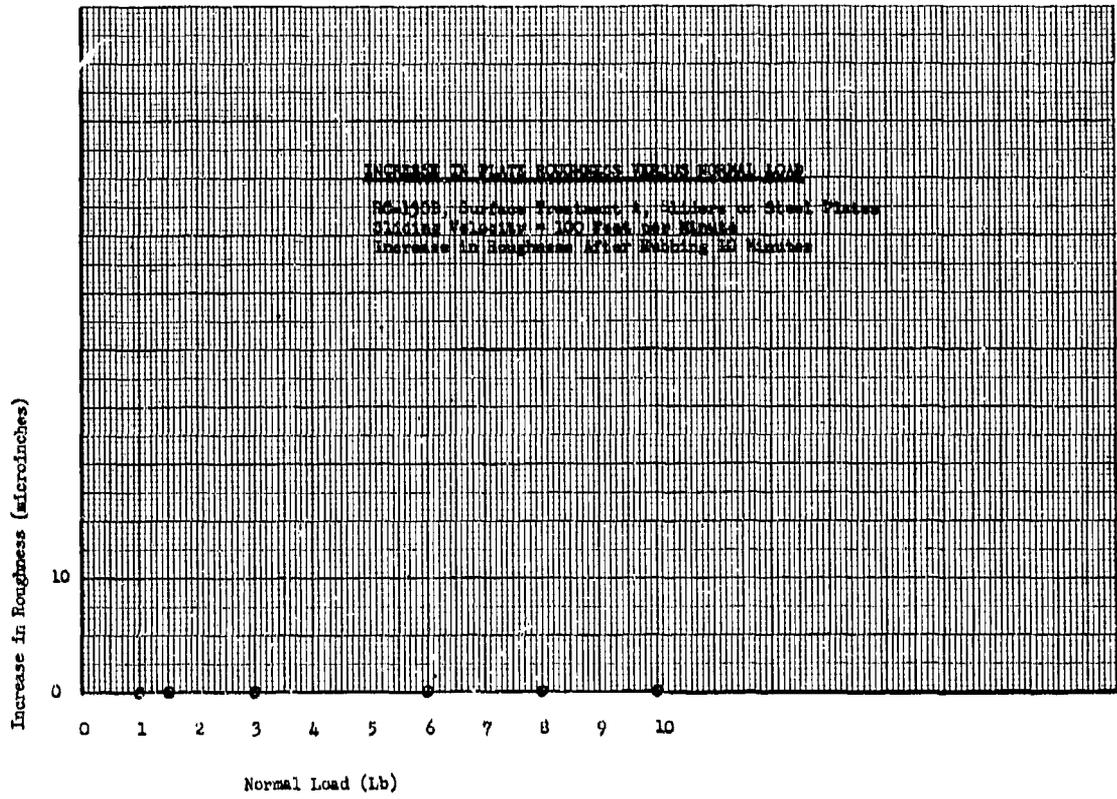
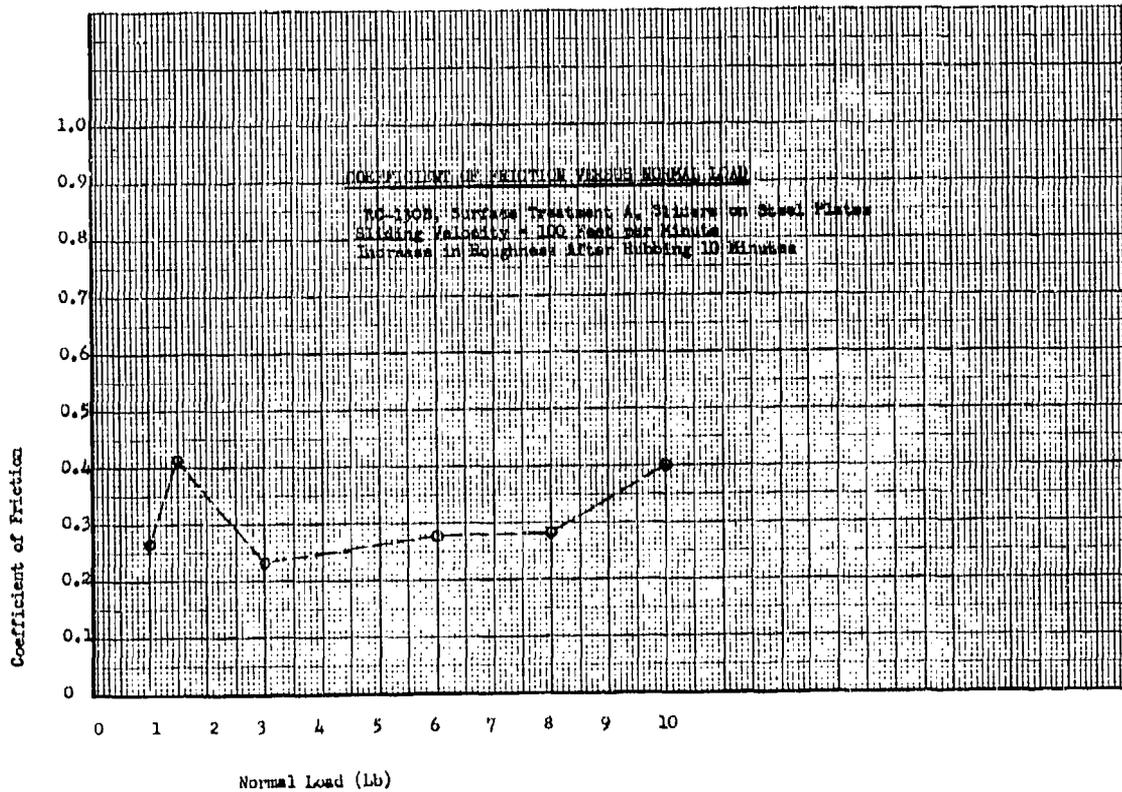


Figure 47



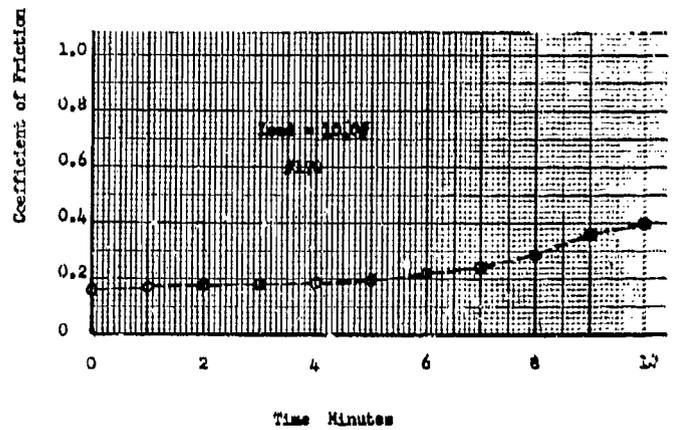
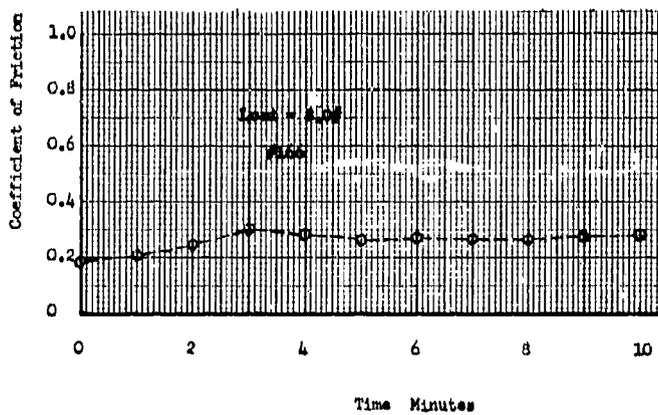
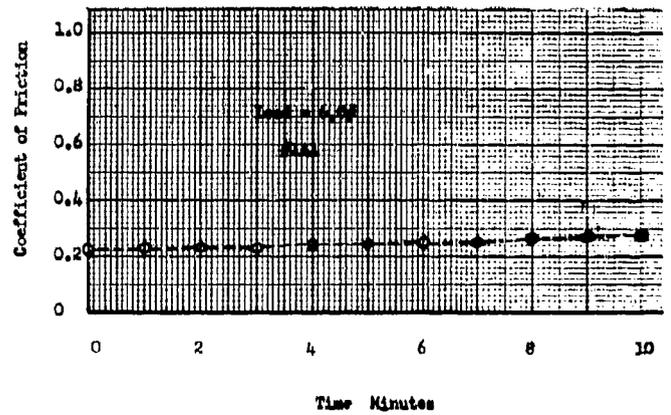
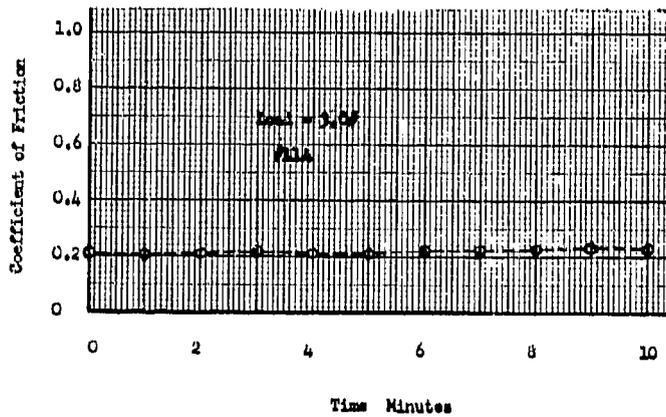
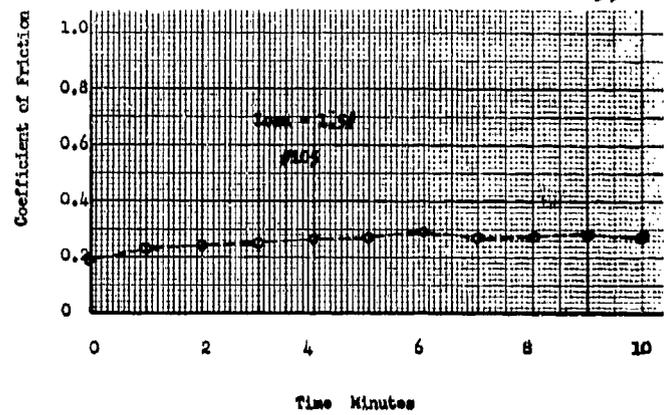
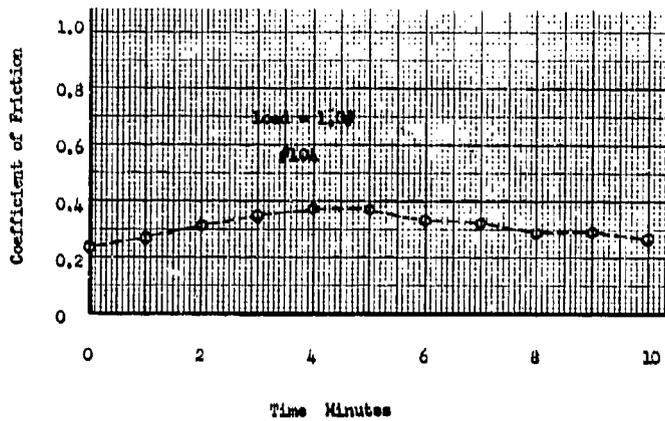


Figure 48

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130B, Surface Treatment A,
Sliders on Steel Plates
Sliding Velocity: 100 Feet per Minute

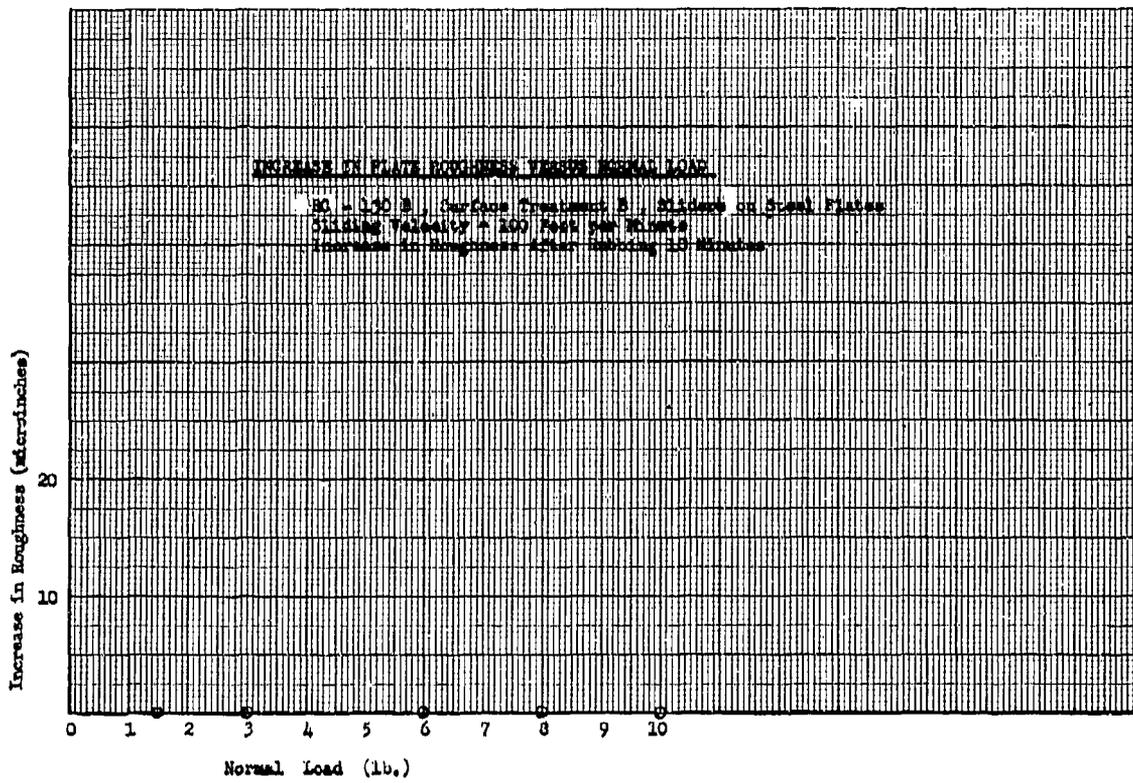
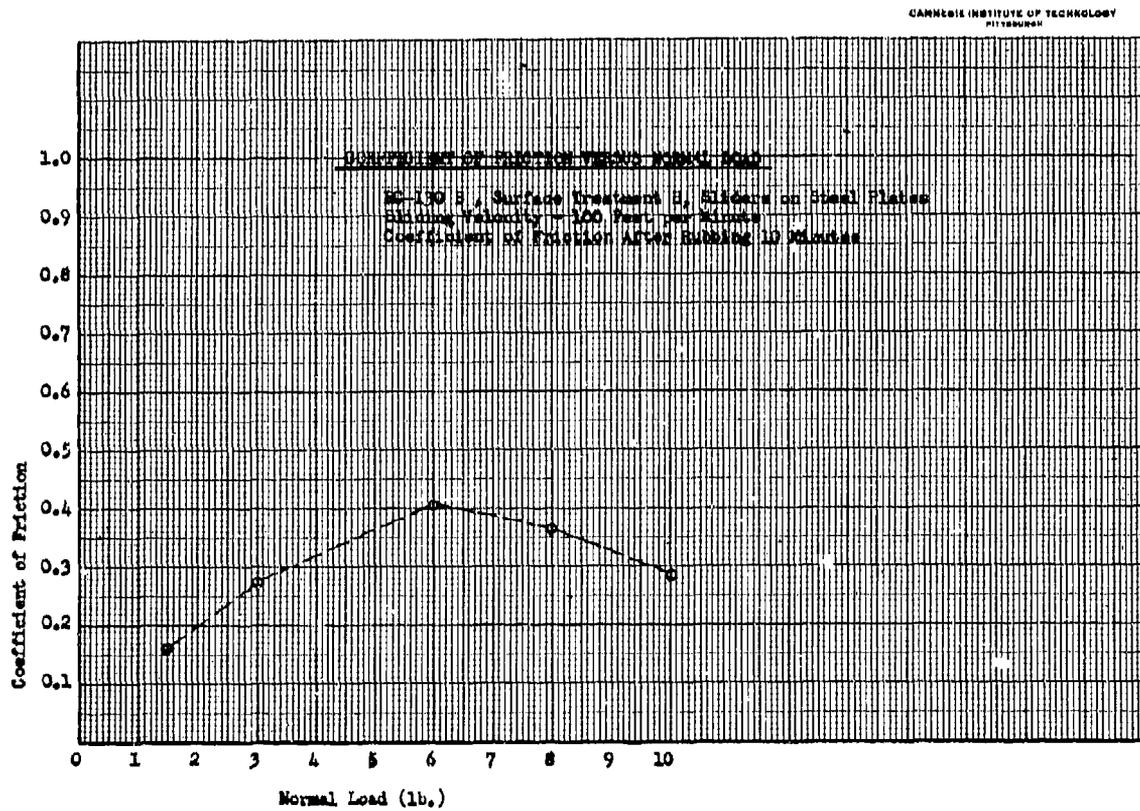


Figure 49



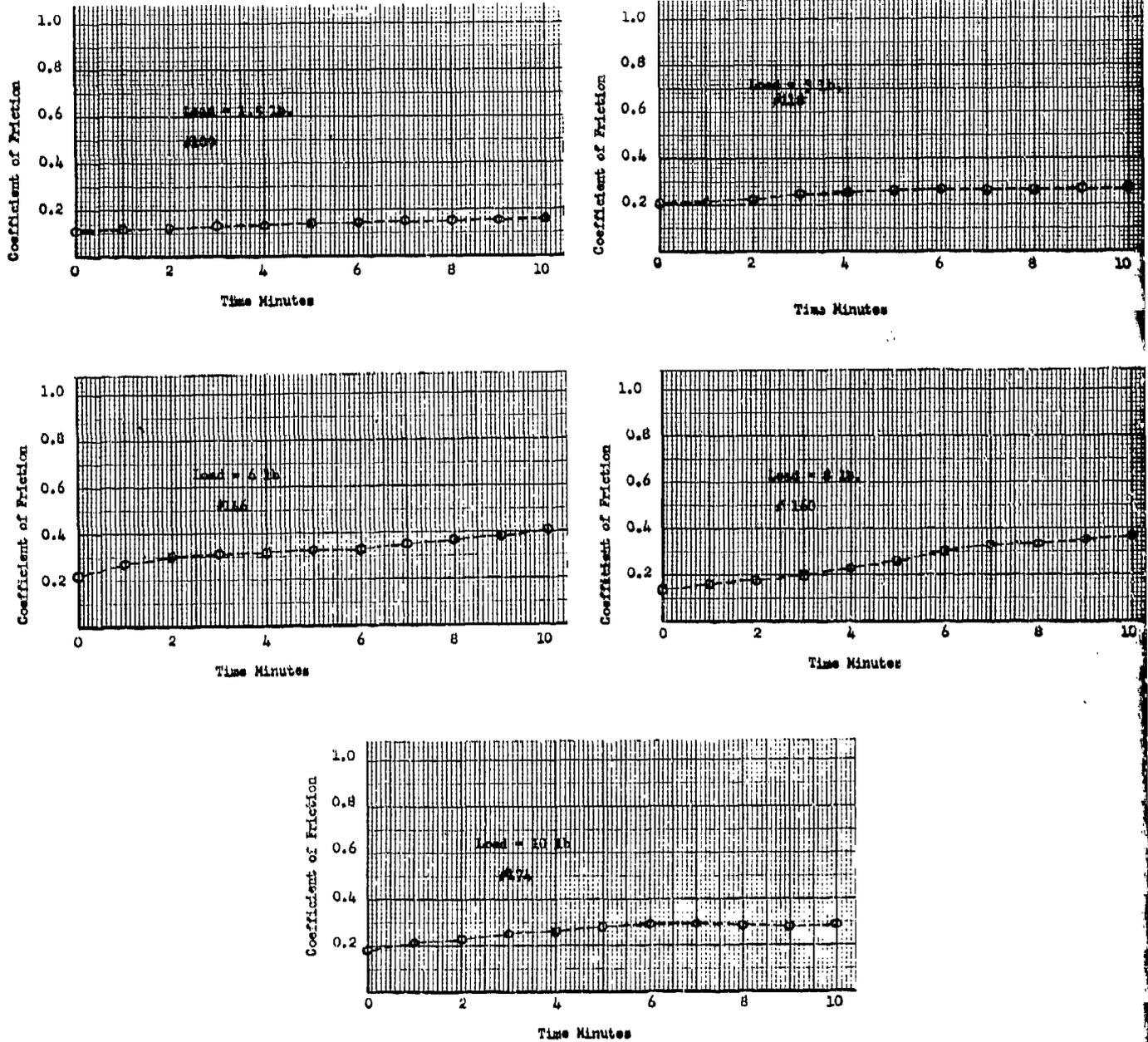


Figure 50

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130B, Surface Treatment B,
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet Per Minute

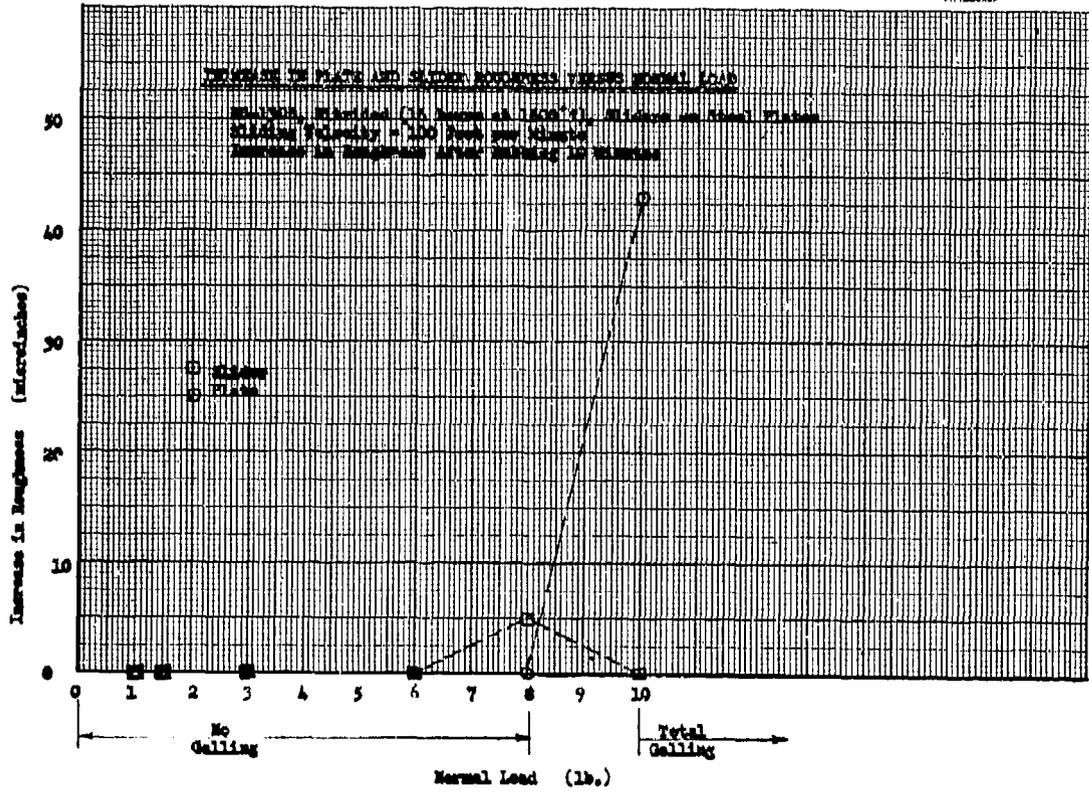
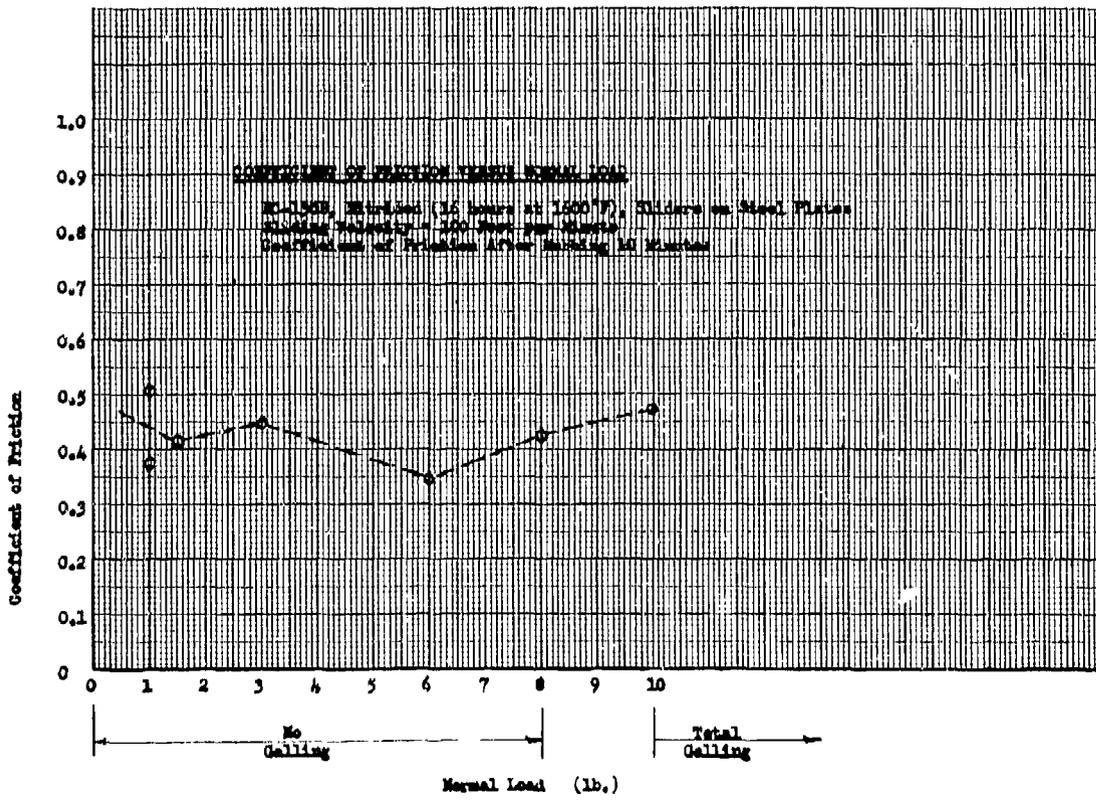


Figure 51



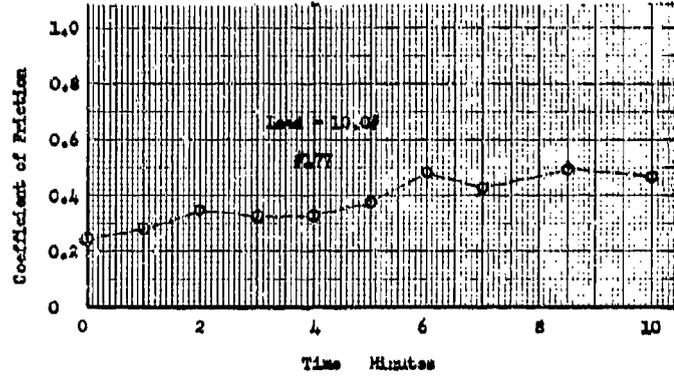
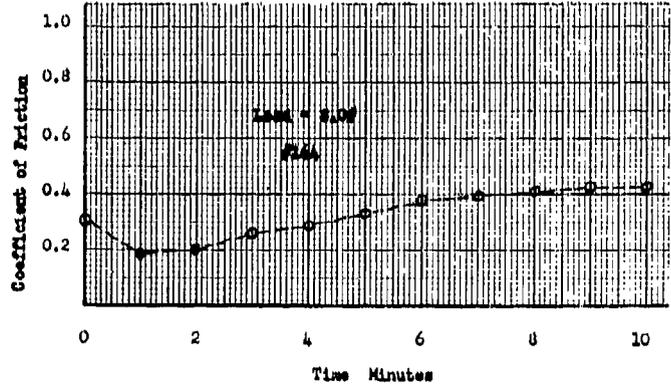
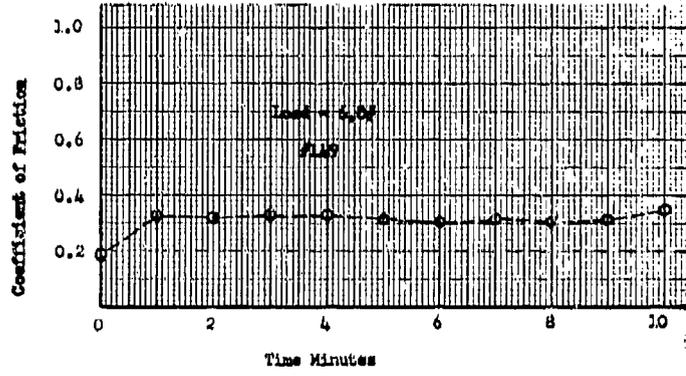
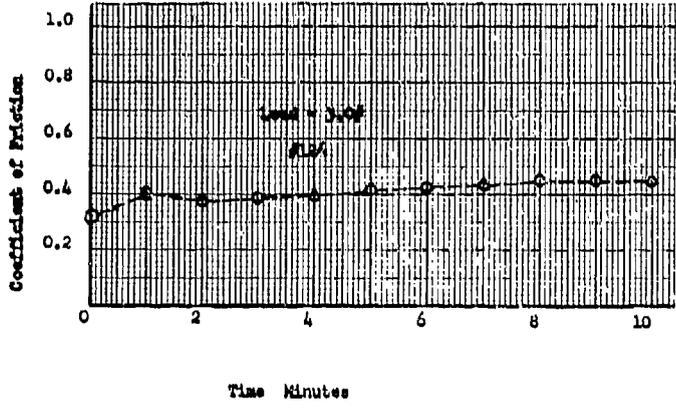
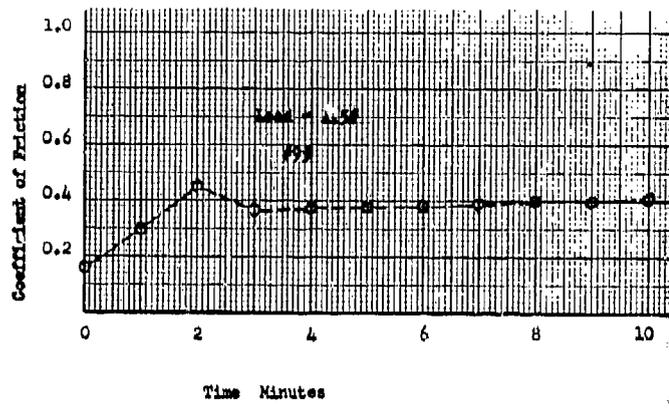
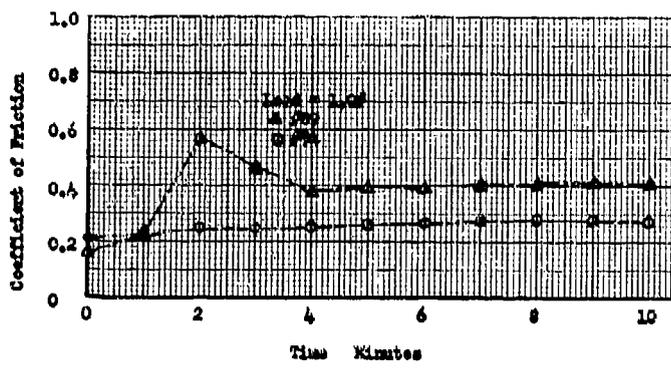


Figure 52

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130B, Nitrided (16 hrs. @ 1600° F),
 Sliders on Steel Plates
 Sliding Velocity: 100 Feet per Minute

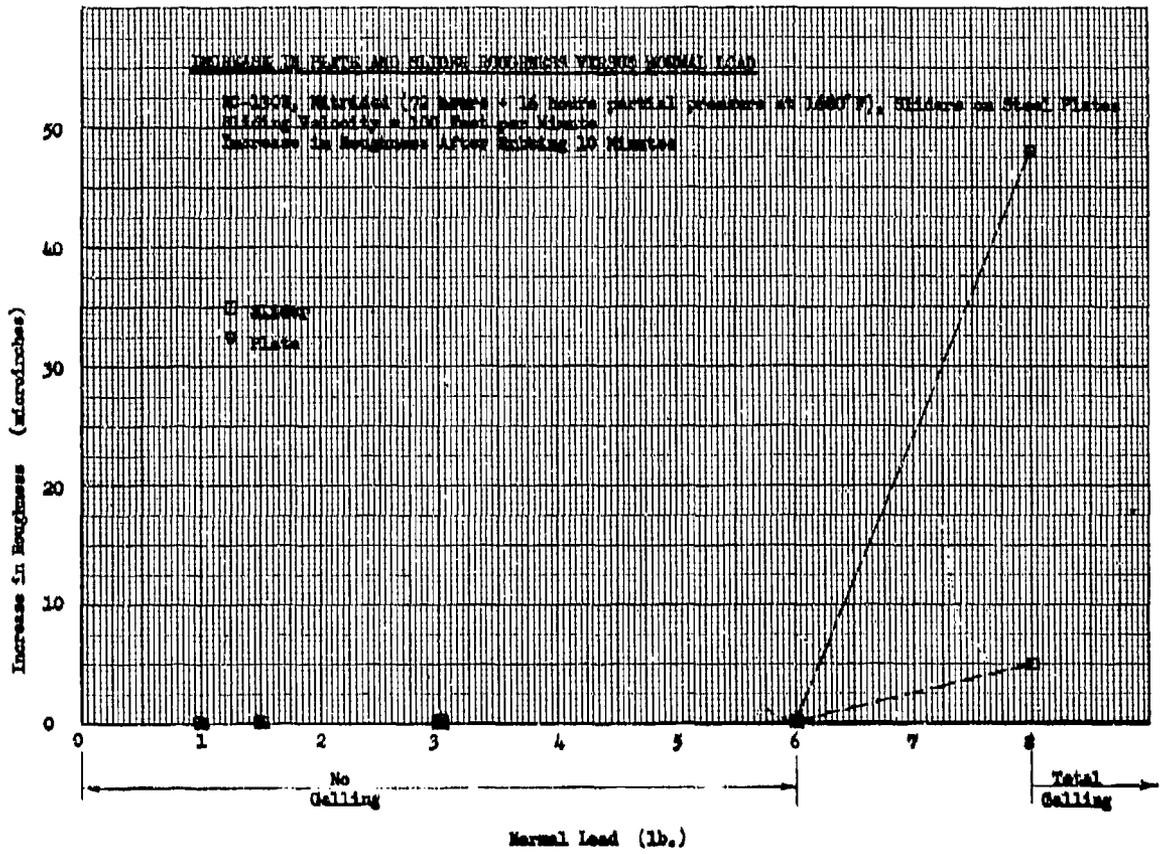
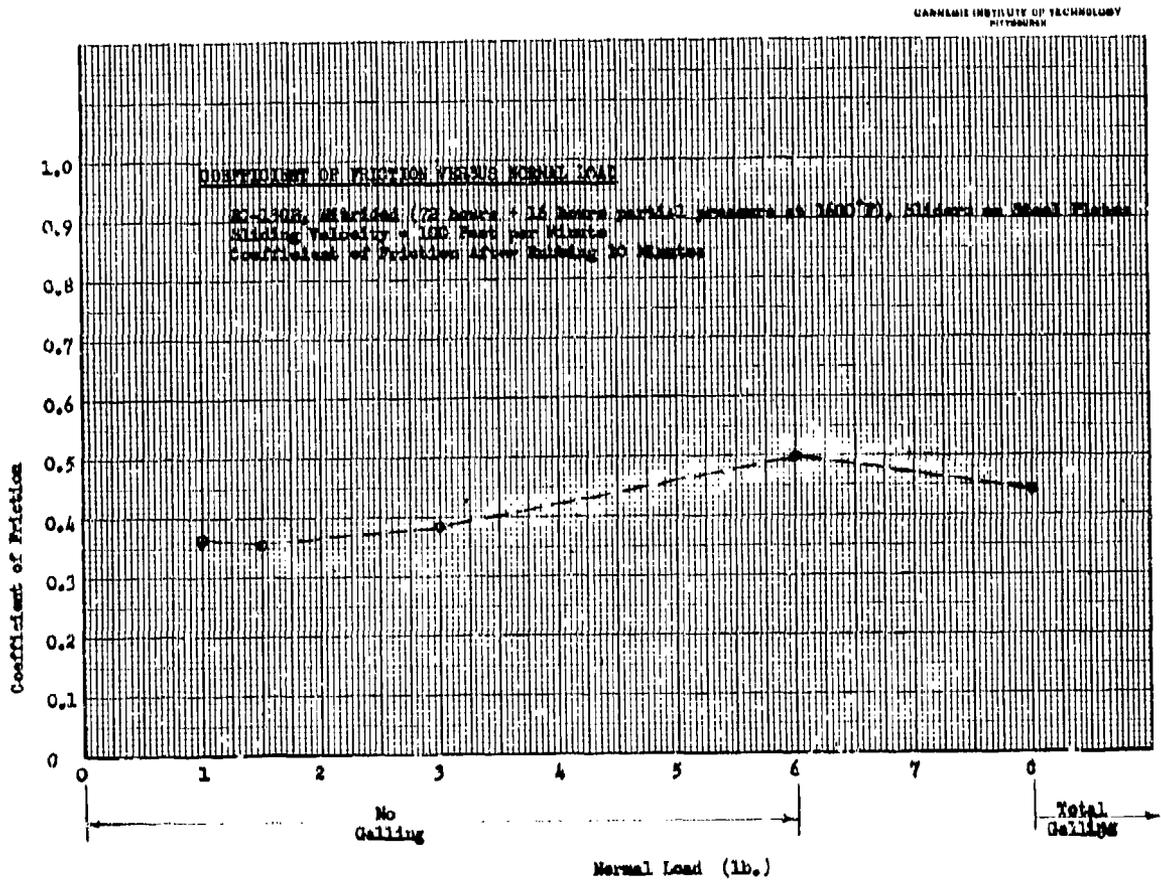


Figure 53



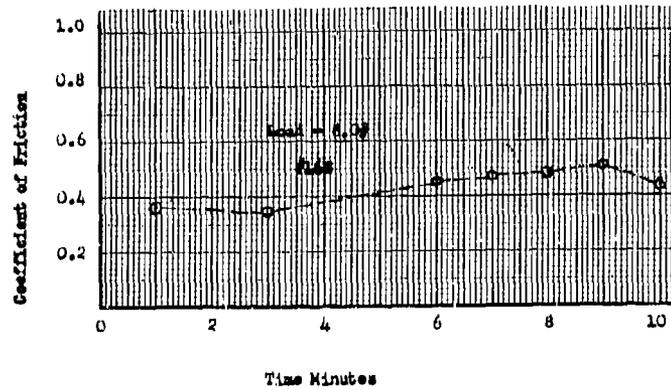
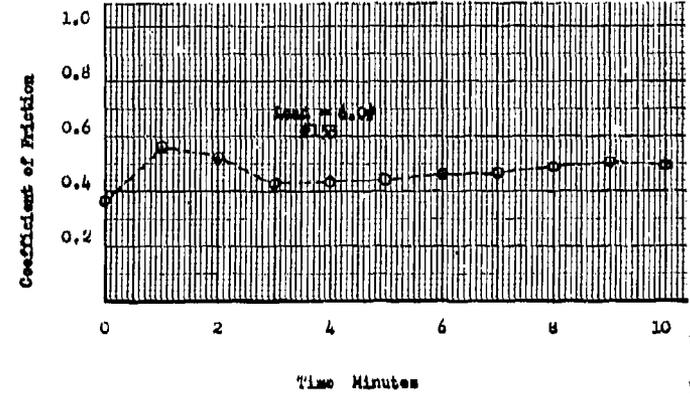
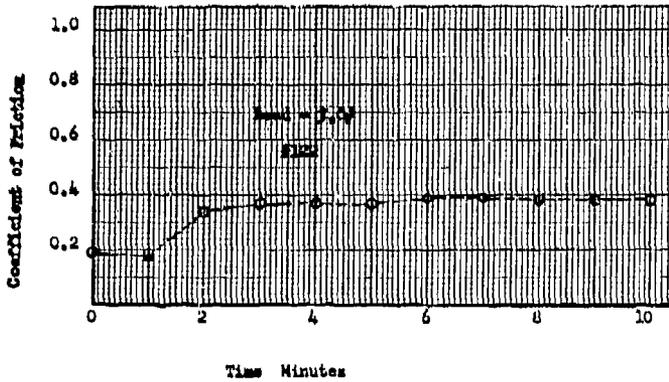
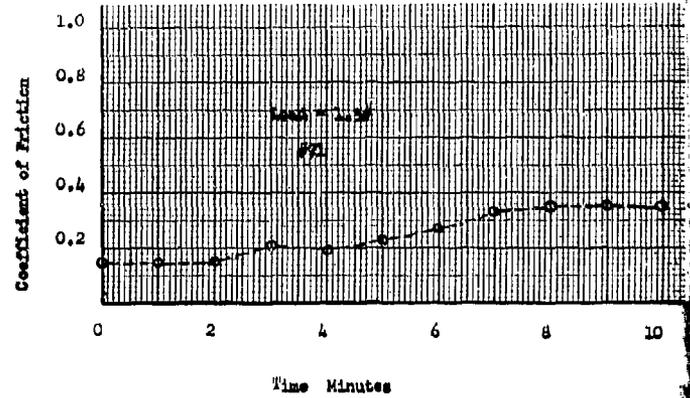
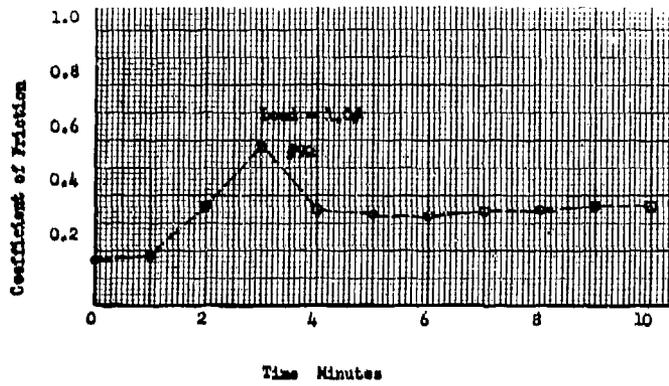


Figure 54

COEFFICIENT OF FRICTION VERSUS RUBBING TIME

Titanium RC-130B, Nitrided (72 hrs. + 16 hrs.
 Partial Pressure @ 1600°F), Sliders on
 Steel Plates
 Sliding Velocity: 100 Feet per Minute

TYPICAL MICROPHOTOGRAPHS OF TITANIUM AND TITANIUM ALLOY SLIDER BLOCKS WITH SURFACE TREATMENTS A AND B . (10X)



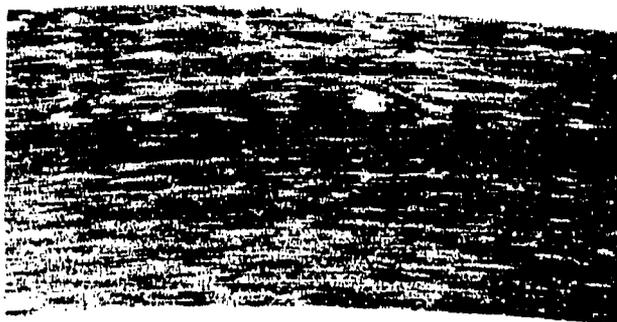
a. After rubbing on steel at very light loads. (No change)



b. After rubbing at higher loads shiny black grease like areas appear , represented by light areas on the photograph.

Figure 55

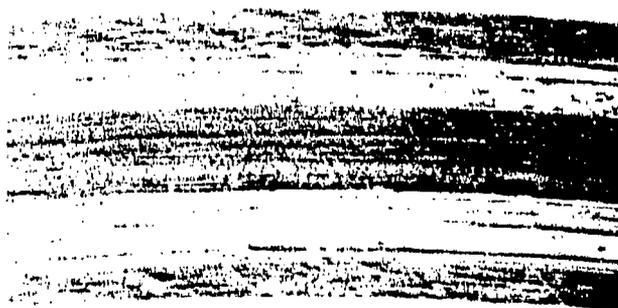
TYPICAL STEEL PLATE TRACKS AFTER
BEING RUBBED BY TITANIUM SLIDER
BLOCK SPECIMENS HAVING SURFACE
TREATMENT B



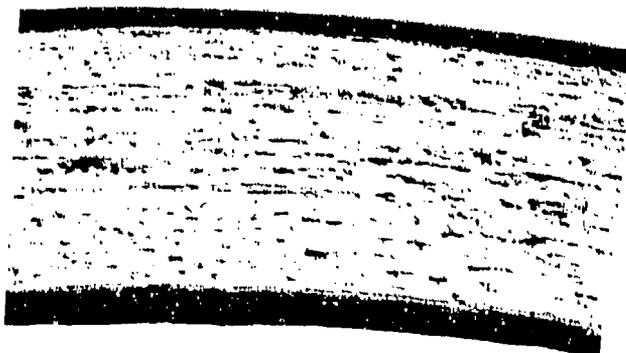
a. Unused plate



b. The plate is slightly galled at the edges with some smearing of a black grease like lubricant.



c. The center of the plate track is completely smeared with the lubricant.



d. A completely galled plate track.

Figure 56

MICROPHOTOGRAPHS OF TITANIUM AND
TITANIUM ALLOY SLIDER BLOCKS WITH
NITRIDED SURFACES (10X)



a. After rubbing at very light loads. - The white marks are actually a shiny black, grease like lubricant. The bulk of the surface is unchanged.



b. After rubbing at higher loads the shiny black lubricant appears along the top and bottom edges.



c. After rubbing at still higher loads the entire surface is smeared with the black lubricant.

Figure 57

TYPICAL MICROPHOTOGRAPHS OF STEEL
PLATE TRACKS AFTER BEING RUBBED
WITH NITRIDED TITANIUM AND TITANIUM
ALLOY SLIDER BLOCK SPECIMENS
(8X)



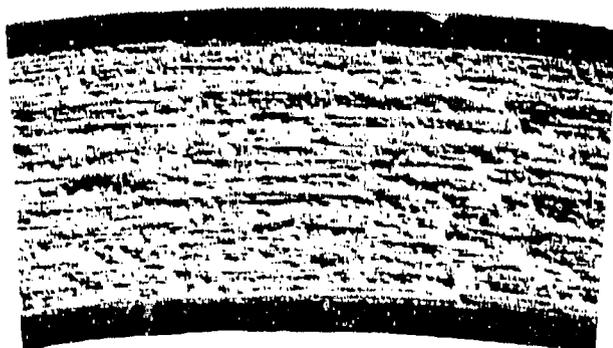
a. Unused plate.



b. Galling on the edges.



c. The center of the track is
plated with a shiny black
lubricant.



d. Completely galled plate track.

Figure 58

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