Friction and Galling Performance of NOREM 02 and NOREM 02A Alloys

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Friction and Galling Performance of NOREM 02 and NOREM 02A Alloys

TR-109655

Topical Report, December 1999

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CITATIONS

This report was prepared by

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This report describes research sponsored by EPRI, Southern Nuclear Operating Co., and UNICOM (ComEd).

The report is a corporate document that should be cited in the literature in the following manner:

Friction and Galling Performance of NOREM 02 and NOREM 02A Alloys, EPRI, Palo Alto, CA, Southern Nuclear Operating Co., Birmingham, Alabama, UNICOM (ComEd), Downers Grove, Illinois: 1999. TR-109655.

REPORT SUMMARY

To reduce plant radiation levels, EPRI has developed a series of iron-based hardfacing alloys known as NOREM. This report documents tests conducted to evaluate the friction and galling thresholds for NOREM 02 and 02A alloys to provide a basis for engineering evaluation of thrust requirements for gate valves in which these alloys are utilized.

Background

In 1994 EPRI completed the EPRI Motor Operated Valve (MOV) Performance Prediction Program to develop and validate methods for predicting the performance of motor-operated valves in nuclear power plants. These methods are currently applicable to gate valves with Stellite 6 seat and guide hardfacing material. Stellite 6 contains cobalt that, when activated, can result in elevated radiation levels in nuclear power plants. NOREM alloys have been developed as a potential replacement for Stellite 6 as a valve hardfacing material to reduce plant exposure levels. The frictional and galling threshold characteristics of NOREM are needed in order to evaluate the thrust requirements to operate gate valves with NOREM seats and/guides.

Objective

To determine the friction coefficients and galling thresholds for flat-on-flat, self-mated NOREM 02 and NOREM 02A for the expected range of water/steam temperatures, contact stresses, and loaded stroke lengths in nuclear valve service.

Approach

The project team conducted tests of NOREM in deionized water/steam in ambient and high-pressure test rigs. They thoroughly cleaned the test specimens prior to testing, and translated one specimen relative to the other in either a unidirectional or reciprocating motion for varying normal loads and stroke lengths. Testing continues until the friction coefficient stabilizes or until galling is observed.

Results

In general, the galling performance of the NOREM alloys was found to significantly dependent on temperature, contact stress and loaded stroke length.

Under room temperature conditions, both NOREM 02 and NOREM 02A exhibit acceptable (non-galling) performance at 10 ksi for loaded stroke lengths up to 3 inches.

For relatively short loaded stroke lengths, (< 0.5 inches) both NOREM 02 and NOREM02A exhibit non-galling behavior up to 550 degrees F.

Galling was observed for both NOREM alloys at10 ksi, 200 degrees F with a loaded stroke length of 3 inches. NOREM 02 was observed to exhibit galling behavior at 15 ksi, 200 degrees F and a loaded stroke length of 1.6 inches but not when tested at 10 ksi under these conditions.

EPRI Perspective

This test program is the first to evaluate the galling performance of NOREM alloys for loaded stroke lengths exceeding 0.5 inches. Loaded stroke length was found to strongly influence the potential for galling in these alloys.

These tests were conducted with extremely clean specimens. Accordingly, the conditions under which these tests were conducted may be more severe than those that would be expected in plant service where surface oxidation or potential impurities in the water may tend to mitigate galling.

EPRI Report TR-109343, “Compilation and Evaluation of NOREM Test Results: Implications for Valve Applications,” summarizes the existing database of NOREM performance information including the results of this test program. That report also provides guidance in the use of NOREM alloys in nuclear valve applications.

TR109655

Keywords

Valves
Valve Hardfacing

EXECUTIVE SUMMARY

This report documents the results of a series of sliding friction and wear tests performed on the iron-based hardfacing alloy known as NOREM. The tests were performed by Battelle, on behalf of the Electric Power Research Institute (EPRI). The purpose of the tests was to obtain coefficient of friction (COF) and galling threshold data to facilitate predictions of thrust requirements for gate valves with NOREM hardfacing on the seats and/or guides.

Two different compositions of NOREM, namely 02A – deposited from wire using the gas tungsten arc welding (GTAW) process, and 02 – deposited from a powder using the plasma transferred arc welding (PTAW) process, were investigated. In addition, limited tests were conducted on self-mated Stellite 6, and on Stellite 6 versus NOREM 02A.

A flat-on-flat contact geometry was used to simulate the contact conditions between the disk guide slot and body guide rail and the seating surfaces of gate valves, when the disk is in the untipped condition. Two different test rigs were used; one rig for ambient pressure conditions and one autoclave rig for high temperature and pressure conditions. Tests were conducted in de-ionized water on laboratory cleaned samples. Nominal contact stresses up to 15 ksi were evaluated. Conditions covered temperatures from room temperature up to 550°F, and stroke lengths ranging from 0.44” to 3”. The tests used specimens larger than those evaluated previously and making contact over large travel distances.

The principal observations are summarized below:

1. Both NOREM 02A deposited by gas tungsten arc welding (GTAW) and NOREM 02 deposited by plasma transferred arc welding (PTAW) exhibit acceptable (i.e., non-galling) behavior in flat-on-flat sliding friction and wear tests at nominal contact stresses of 10 ksi. Such testing was performed in deionized water at ambient temperature (70°F) where the loaded stroke length was 3 inches. A maximum COF of 0.57 was observed.

2. Both NOREM 02 and 02A exhibit non-galling behavior in flat-on-flat sliding friction and wear tests performed up to 15 ksi at temperatures up to 550°F provided the stroke length is less than ~0.5 inches. Maximum COF of 0.69 and 0.82 were observed at 15 ksi for self-mated NOREM 02, at 200°F and 550°F, respectively.

3. Galling of NOREM 02 and 02A was observed at stresses as low as 10 ksi in tests performed at 200°F where the stroke length was 3 inches. The peak traction coefficients during galling were 0.94 and 0.66, for NOREM 02A and NOREM 02, respectively. Galling of NOREM 02 was also observed after 70 reciprocating strokes at 15 ksi and 200°F where the stroke length was 1.6 inches. The maximum COF was 0.67.

4. After 25 strokes, there was no evidence of galling in NOREM 02 in tests performed at 550°F where the stroke length was 1.6 inches at stresses of 10 and 15 ksi, but the observed heavy scoring after testing at 15 ksi suggests the alloy is near its anti-galling limit. The maximum COF observed was 0.87.

5. Tests of NOREM 02A against Stellite 6 at 10 ksi and 200°F where the stroke length was 3 inches exhibited acceptable performance with a maximum COF of 0.57. When the contact stress was increased significantly to 40 ksi, galling of the NOREM 02A material was observed with a maximum traction coefficient of 0.57.

6. No galling was observed in the ambient rig for Stellite 6 at 10 ksi in either room temperature (maximum COF of 0.6) or 200°F (maximum COF of 0.46).

From the series of tests performed on the two types of NOREM alloys, it can be concluded that temperature, contact stress, and stroke length under loaded conditions play an important role in the frictional and galling behavior of NOREM alloys. The combination of intermediate temperatures and long stroke lengths appeared to be most conducive to the onset of galling. The results indicate that, for nominal contact stresses of 15 ksi, both NOREM 02A and NOREM 02 are not expected to gall in room temperature water. At elevated temperatures up to 550°F and at contact stresses up to 15 ksi, neither NOREM 02A nor NOREM 02 exhibited galling behavior for loaded stroke lengths less than or equal to 0.5 inch.

EPRI Report TR-109343 “Compilation and Evaluation of NOREM Test Results: Implications for Valve Applications” summarizes the existing database of NOREM performance information including the results of this test program. The report also provides guidance in the use of NOREM alloys in valve applications.

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1 INTRODUCTION

The Need for Friction Data

The Electric Power Research Institute (EPRI) has developed a methodology for predicting gate valve thrust requirements under flow and differential pressure conditions. Among the required inputs to the methodology are the tribological characteristics (friction coefficients and galling thresholds) of the hardfacing material found on the valve internal sliding surfaces. For a gate valve, these surfaces include the disk faces, seat rings, and guides. Friction and galling data has been previously obtained for Stellite® 6, and to a limited extent for other alloys[1].

Motivation for the NOREM Friction Test Program

Stellite 6 is a cobalt-based alloy, and has been used extensively for hardfacing valves because of its excellent friction, corrosion, and anti-galling properties. However, cobalt wear debris and corrosion products become radioactive when they pass through the core in the primary loop of reactors. In an effort to reduce plant radiation levels, a series of iron-based hardfacing alloys has been developed by EPRI to serve as a replacement for Stellite 6. This series of alloys is known as NOREM.

Early Work in the Development of NOREM

Several compositions of NOREM have had successful trials. In the late 1980s and early 1990s, tests were conducted in high temperature water by Atomic Energy Canada, Limited (AECL)[2] on a Velan 3-inch, 1500-lb class gate valve. In the first test, 2,000 repeated open-and-close cycles, in blocks of 500 between disassembly and inspection, were conducted in PWR chemistry (10 ppb O_2 and Boric Acid-treatment) at 572°F and 1875 psig. Subsequently, the valve disk was refurbished and 1000 cycles were run in BWR chemistry (100-300 ppb O_2 and room temperature pH of 5.5) at 570°F and 1450 psig. These tests were conducted in a 250 gpm flow system, with the inlet and outlet pressures being 1450 and 1340 psig, respectively. The hardfacing alloys in the AECL tests were designated NOREM 01 and NOREM 04, and were deposited from powder using the Plasma Transfer Arc weld (PTAW) process. No galling was observed in these valve tests.

® Stellite is a registered trademark of Deloro Stellite, Inc.

[1] EPRI TR-103119: MOV Friction Separate Effects Test Report, EPRI 103255: Gate Valve Design Effects Testing Results, July, 1994.

[2] These results are documented in EPRI Reports TR-100601: Endurance Tests of Valves with Cobalt-Free Hardfacing Alloys – PWR Phase Final Report, May, 1992, and TR-101847: Endurance Tests of Valves with Cobalt-Free Hardfacing Alloys – BWR Phase Final Report, January, 1993.

Subsequently, tests on a 1994 vintage of NOREM 02, deposited via PTAW by Anchor Darling Valve (ADV) Company, were conducted in room temperature (RT) water and under 600°F dry steam at Rensselaer Polytechnic Institute (RPI)[3]. The test rig at RPI used a snub-nosed bullet sample contact geometry, with a reciprocating 0.5 inch stroke and 15 ksi nominal contact stress. Tap water was used for these tests. No galling was reported in these reciprocating tests with a short stroke length.

In 1996 and 1997, successful trials at room temperature of both NOREM 02 and NOREM 02A were completed at EPRI's NDE center in Charlotte, NC, using a rotating pin-on-block galling test (ASTM G-98). For these tests, a 0.375" diameter pin and an approximate ± 80° rotation were used resulting in a loaded stroke length at the pin circumference of less than 0.5 inch. The tests were conducted in RT air and in RT water. The PTAW process was used for the NOREM 02 samples and the manual gas tungsten arc weld (GTAW) process was used for the NOREM 02A samples. In these rotating pin-on-block tests, no galling was observed up to 60 ksi, and the performance of NOREM alloys was comparable to that of Stellite 6[4].

The results from all of the earlier studies were considered successful in that no galling was observed.

NOREM Data for the EPRI Gate Valve Methodology (MOVPPM)

As a result of these earlier successes, a program to obtain the tribological properties of NOREM for use in the MOVPPM was initiated in the fall of 1997. Tests were to be performed using Battelle's ambient and autoclave test rigs. These rigs were used to develop the Stellite 6 data for the MOVPPM in 1992 and 1993. The same procedures and test protocols that were used in Battelle's earlier studies were to be followed for the NOREM testing. Since the Stellite 6 laboratory data obtained in Battelle's rigs had subsequently been validated in the Valve Separate Design Effects Program[5] and in flow loop tests at Wyle Labs, it was intended that the Battelle NOREM data would be used in the MOVPPM.

Material Selection

Since the sponsoring utilities had a strong interest in weld repair or in-situ replacement of valve trim, the alloy chosen for the current program was NOREM 02A. NOREM 02A contains a relatively low weight percent nitrogen (on the order of 0.03%), which facilitates weld deposition using the GTAW process. During the development of the NOREM alloys, it was determined that the nitrogen level had a strong influence on both the weldability (enhanced with low nitrogen), and on the galling resistance (enhanced with high nitrogen)[6]. As such, a balance between the two was sought for the final composition specification. The level of nitrogen contained in the NOREM 02 (PTAW) tested in this program was 0.17 weight percent. Chemical compositions of NOREM 02 and NOREM 02A are detailed in Table 3-1.

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[3] W.A. Knecht, Paper 3C-73, Proceedings of the 4th NRC/ASME symposium on valve and pump testing, July, 1996.

[4] EPRI TR-105816, NOREM™ Applications Guide, November, 1995.

[5] EPRI TR-103255, Gate Valve Design Effects Testing Results, July, 1994.

[6] EPRI TR-107231, NOREM™ Arc Welding Guidelines, page 5-14, December, 1996.

It should be noted that the versions of NOREM 01 and 04 previously tested by AECL contained 0.1 and 0.23 weight percent nitrogen, respectively. Valve tests conducted with both NOREM 01 and 04 alloys were considered successful, and the higher nitrogen version, NOREM 04, was reported to have performed the best[7].

Work Covered in this Report

This report presents the results of two series of tribological tests performed on NOREM alloys. The first series focused on NOREM 02A, while the second focused on NOREM 02. The origin and evolution of the test matrices are described in the Results Section. A description of the experimental methods follows.

[7] Personal communication with I. Inglis of AECL, June, 1999.

2
DESCRIPTION OF FRICTION TEST RIGS

Ambient Friction Rig

The ambient friction rig is illustrated in Figures 2-1 and 2-2. The normal load was applied using a pneumatic bladder. The bladder was fixed to the underside of a movable crosshead, and the normal force was transmitted through a 5,000 pound capacity load cell to the top of a freely pivoting cantilever beam via a spherical contact.

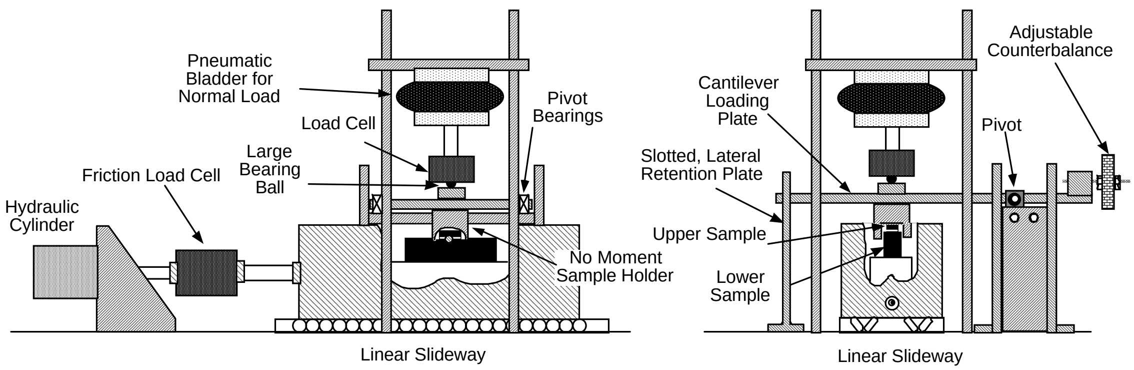

Figure 2-1
Schematics of the ambient friction test rig

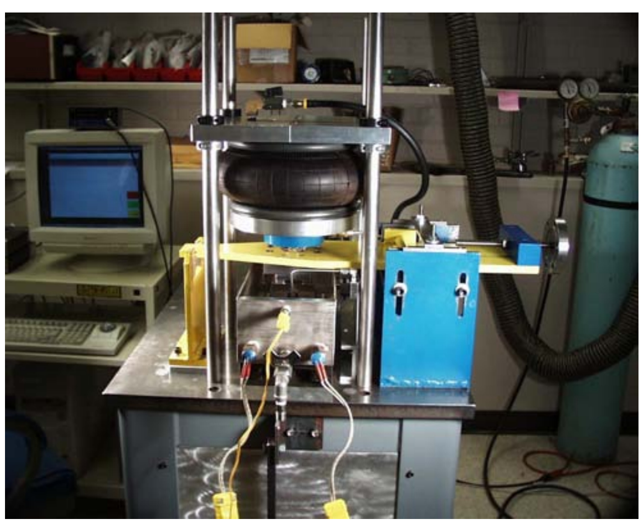

Figure 2-2
Photographs of the ambient friction test rig

For testing a flat-on-flat interface, the upper sample was held in a specially designed, pivoting "no-moment" holder that was attached to the underside of the cantilever beam (Figure 2-3). The lower portion of this sample-holder is free to pivot along an axis transverse to the sliding direction. As such, when the friction interface is at the level of the pivot point (pin center) of the no-moment holder, any over-turning or under-turning moment is eliminated. The proper position of the interface was monitored by measuring the distance between the friction face and the holder base.

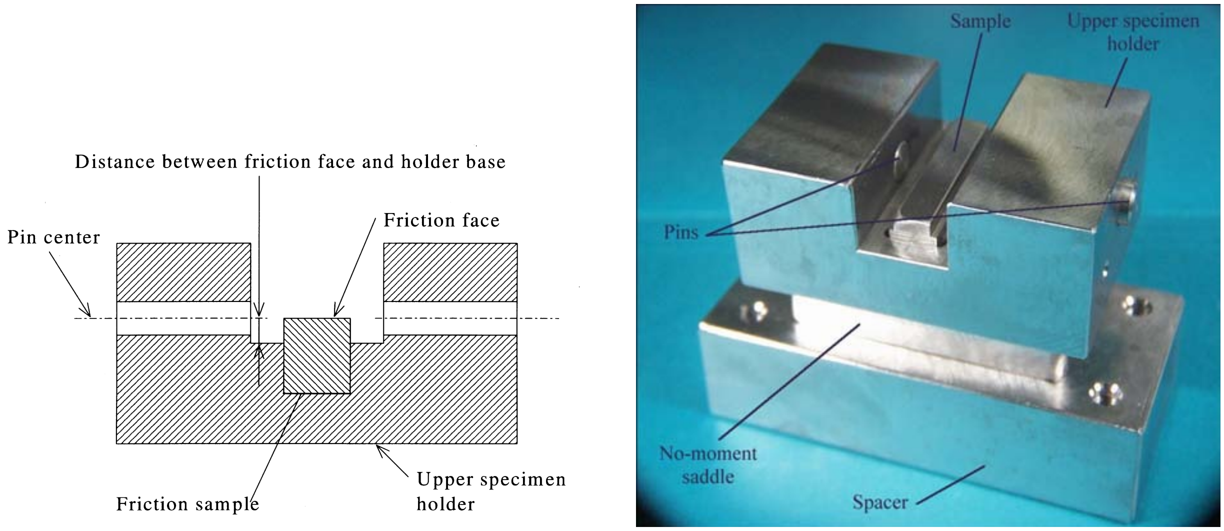

Figure 2-3
Schematic drawing and photograph of a specially designed no-moment holder

The lower sample holder was held within a pocket in a plate that was mounted in the base of a watertight, aluminum box. This entire lower box assembly was mounted to a crossed-roller bearing-supported slide table, and was pushed or pulled with a horizontal hydraulic cylinder that was attached to a second 5,000 pound capacity load cell used to monitor the friction load.

The fluid medium was kept above the sample interface during testing. For warm or boiling water tests, the temperature was maintained using a thermocouple-fed temperature controller and two immersion rod-type resistance heaters. Water from the test chamber was circulated through a peristaltic pump and directed through nozzles at each end of the lower sample surface to help clear any debris that might be generated during sliding.

A piece of compliant gasket material, typically a single piece of Teflon or Velumoid, approximately 0.020" thick, was used behind the upper sample, along with a 0.005" thick strip below the lower sample to accommodate any rotation required along the longitudinal sample axis to maintain a flat contact geometry. The uniformity of the contact stress was measured and maximized prior to each test using pressure sensitive film (Fuji Pressurex/Prescale®).

The speed of a stroke was approximately 18 inches per minute for all tests. The stroke length was set using moveable proximity sensors whose output was tied to the hydraulic valve signal input. Both load cell signals were taken from their respective conditioners (amplifiers) and run through an analog to digital (A/D) conversion using LabTech Notebook data acquisition software. For test series 1, a data acquisition rate of 10 HZ was used and the data were plotted as one second averages in the summary plots. Some breakaway friction data was collected at 100 Hz. In test series 2, 32 Hz was used for all tests. In both test series, the data for each stroke were plotted on the computer monitor, and written to a file for subsequent reduction and documentation.

In test series 1, friction tests were run consecutively as reciprocating strokes, with a one-second dwell period between strokes (unless indicated otherwise in Tables 4-1a and 4-1b). In test series 2, friction tests were performed separately, as unidirectional strokes, unless indicated otherwise in Table 4-2. Each stroke in test series 2 was separated by a minimum dwell time of one minute.

Autoclave Rig Friction Rig

In the autoclave friction rig, shown schematically in Figure 2-4, internal space limitations prohibit the use of a no-moment holder. Instead, a sandwich composed of two inner samples and two outer samples is used. The inner samples were mounted in a sample carrier bar that was attached to the pull rod via a pin and clevis assembly. The outer samples were mounted in fixed holders (hardened steel “window frames”) in two rigid beams. The geometry of the interfaces was designed to minimize the overturning moment by having a height of only 0.020 inches of the outer sample sticking above the reaction point at the upper edge of the window frame. This configuration limits the end-to-end variation in load across a sample to less than 6 percent for a COF of 0.7.

The normal load is applied to the sandwich by pressurizing a small stainless steel bellows, using a high temperature heat transfer fluid as the hydraulic medium. A calibration of the bellows to determine the relationship between pressure (or output voltage of a pressure transducer) and normal load is conducted with a button load cell and special fixture before and after running of the autoclave test series. Shims of Teflon sheet of appropriate thickness are used behind each sample to provide the compliance required to maintain a flat contact geometry. The uniformity of the contact stress was documented prior to each test using pressure sensitive film.

The pulling load was directly measured with a load cell outside of the autoclave. The tare contributions from the seal friction and the expulsion force on the pull rod (which varies with the internal autoclave pressure) were directly measured during the initial portion of the stroke. A slot in the sample carrier bar provides free travel of the clevis pin on the end of the pull rod for 0.75 inches. During this free travel, no pulling force is applied to the samples and the force measured at the load cell is due only to the tare, which is measured and subtracted out during data reduction.

Both the pulling load cell signal and the bellows pressure signal were taken from their respective conditioners (amplifiers) and run through an analog to digital (A/D) conversion using LabTech Notebook software at a data acquisition rate of 32 Hz. In addition, the voltage signal from the LVDT, corresponding to the position of the pullrod, was also collected. The data for each stroke were plotted on the computer monitor, and were written to a file for subsequent processing. Since there were two sample interfaces, the measured friction was the average of the two. Each individual, unidirectional stroke was separated by approximately one to two minutes.

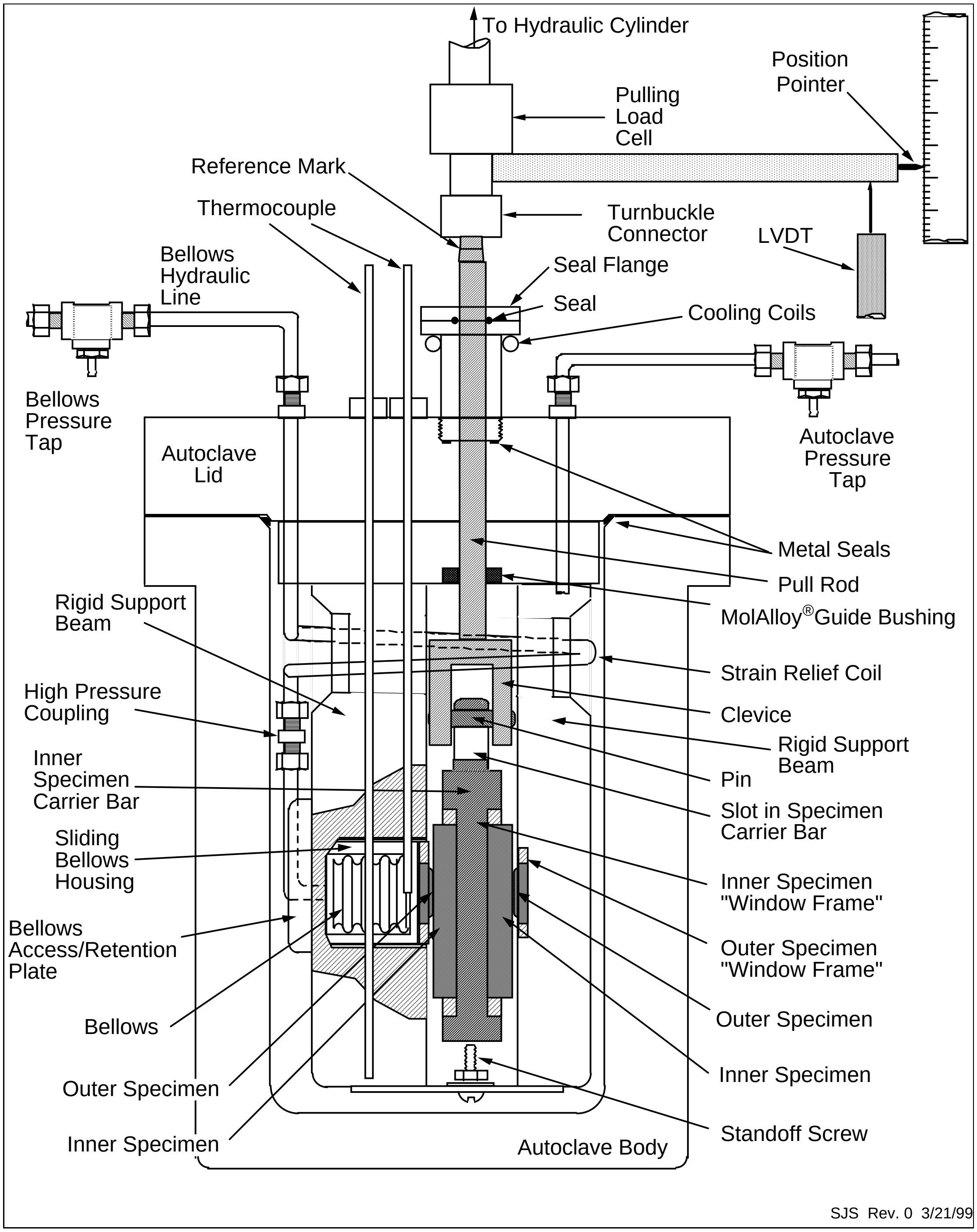

Figure 2-4
Schematic of Autoclave friction test rig

3
COMPOSITION AND PREPARATION OF TEST SPECIMENS

Weld Deposition

The NOREM 02A samples were prepared by Commonwealth Edison, using the manual gas tungsten arc welding (GTAW) process. Weld rod of 0.125-inch diameter was used with a heat input of between 25 and 45 KJ/in under argon shield gas flow of 20-35 cu. ft/hr. The base material was 1.5” x 1.0” A36 carbon steel bar stock, approximately 30 inches long. A minimum of three weld passes was used to obtain a hardfacing thickness of at least 0.125 inches (after machining). Typical as-deposited thicknesses were 0.200 inches. The microstructure is shown in Figure 3-1. Compositional and hardness measurements were obtained as a function of hardfacing thickness (height above the carbon steel). The results indicated minimum dilution to a depth of 0.08 inches, as shown in Figure 3-2. Typical values are given in Table 3-1.

Table 3-1
Characteristics of NOREM 02A (GTAW) and NOREM 02 (PTAW)

Material	Fe	Cr	Si	Mn	Ni	Mo	C	S	P	Co	B	N	O	HRC
NOREM 02A (GTAW)	Bal	24.1	2.9	4.1	3.9	1.9	1.24	<0.01	0.02	<0.05	0.002	0.027	0.018	36
NOREM 02 (PTAW)	Bal	24.2	3.3	4.2	4.1	1.9	1.2	<0.01	0.02	0.06	0.001	0.17	0.035	38

Compositions given in weight percent. HRC = Rockwell “C” Hardness

The NOREM 02 samples were prepared by Anchor Darling, using their standard commercial plasma transfer arc (PTA) process. The microstructure of the as-deposited alloy is also shown in Figure 3-1. Results of compositional analysis are also given in Table 3-1. Depth profile characteristics were not measured for these deposits.

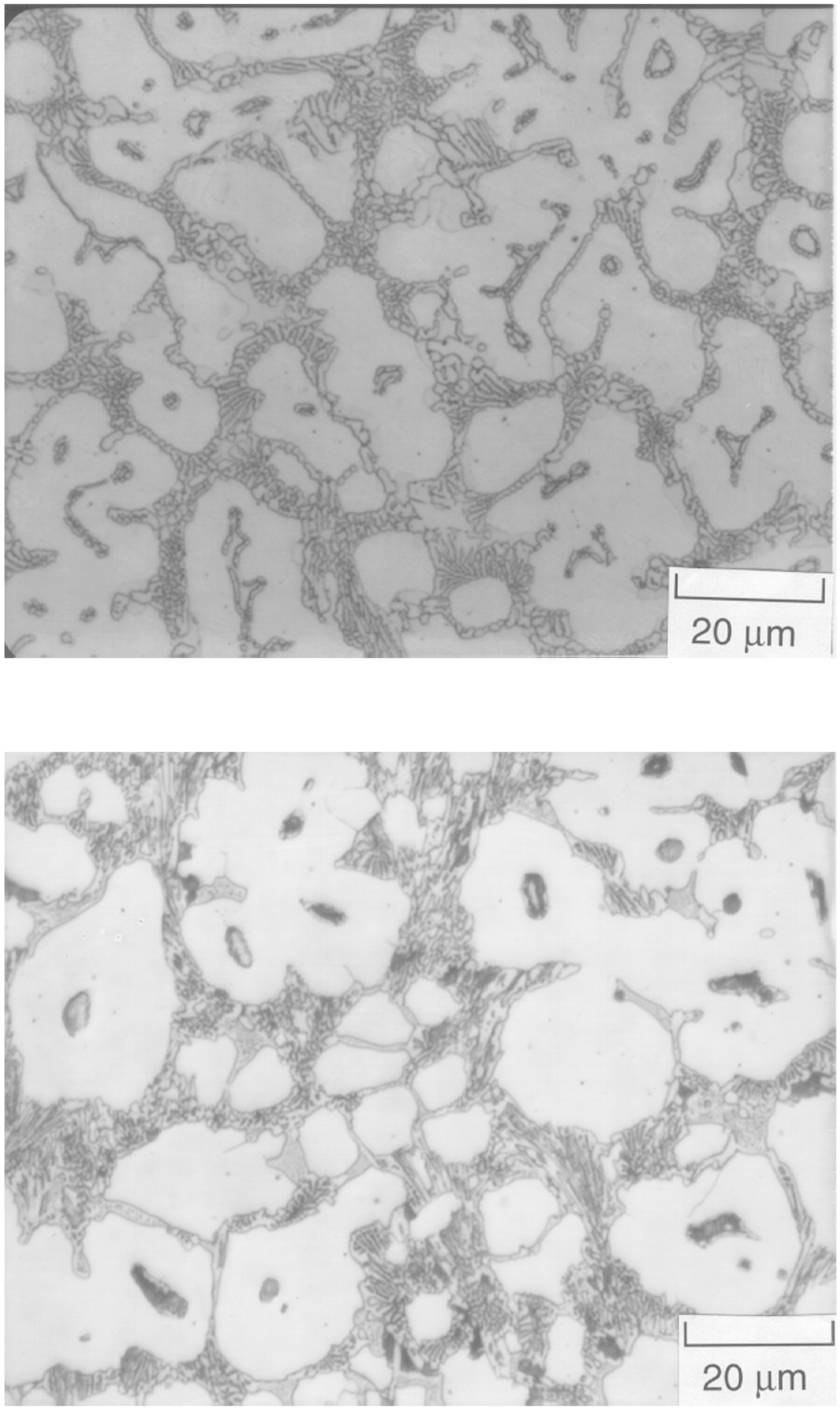

Figure 3-1
Microstructures of NOREM. Top: Alloy 02A, GTAW deposit. Bottom: Alloy 02, PTA deposit. 1000x, 50 % Nitric Etch

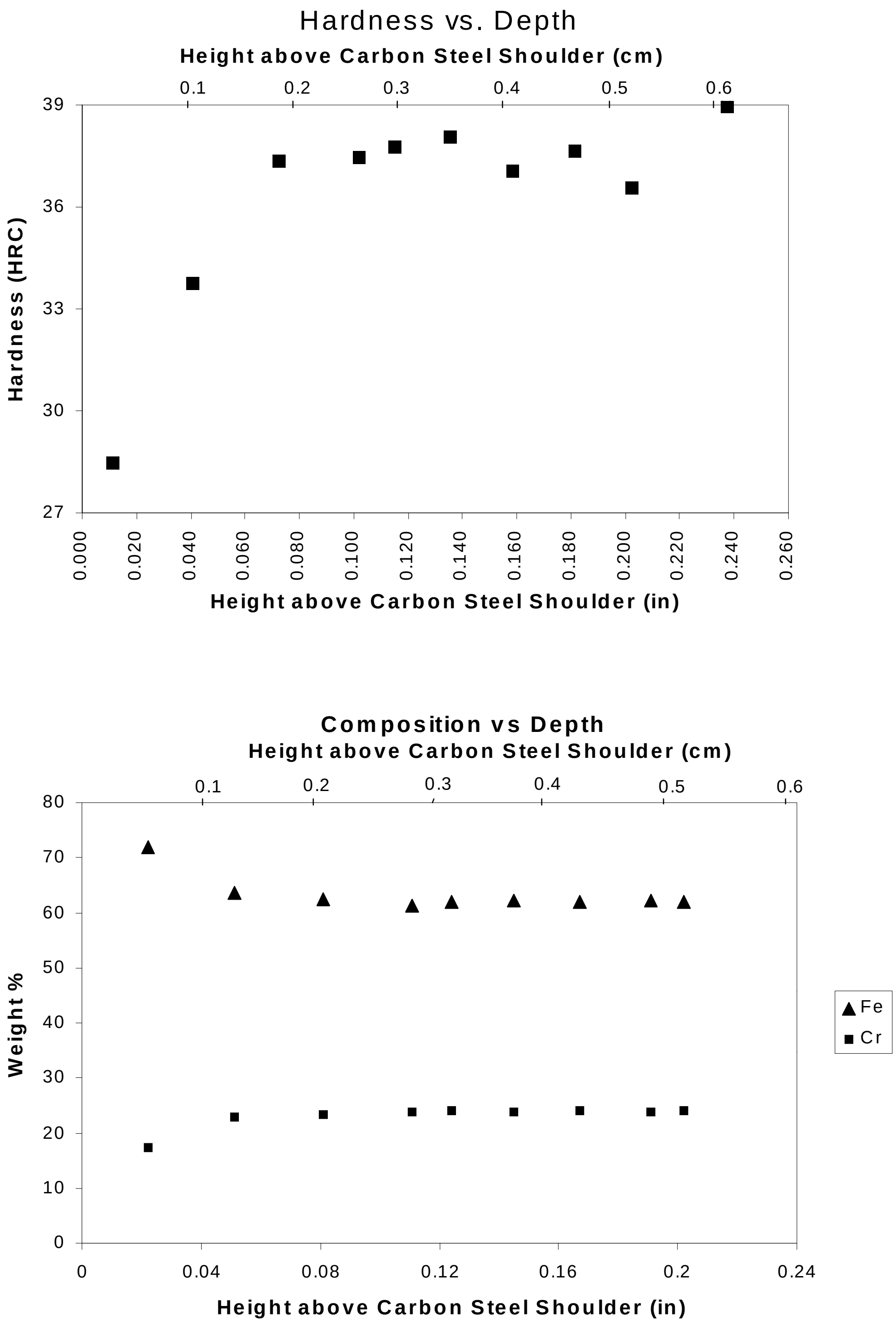

Figure 3-2
Hardness and composition of selected elements as a function of depth for NOREM 02A, GTAW deposit

Test Samples

Friction test samples and characterization samples were prepared by Battelle. All machining was performed using carbide-tipped cutting tools and either dry, or using a water-soluble coolant. For the ambient tests on NOREM 02A in Test Series 1, friction test surfaces were ground dry, using an Al_2O_3 wheel, to a transverse roughness on the order of 5 to 15 µin R_a. Hand lapping was performed on the NOREM 02A samples for Test 23, and for all of the NOREM 02 samples. For the NOREM 02 test series, a fixture was used to maintain flatness and samples were lapped on SiC metallographic paper down to 400 grit. Edges were hand stoned to ensure no edge stresses resulted from burrs or machining deformation. A “toboggan” end, of approximately 0.025” to 0.050” radius, was put on both leading and trailing edges of the smaller samples to eliminate any potential digging in due to the flat-on-flat contact geometry. The lapping typically provided a surface roughness of 5 to 10 µin R_a. Longitudinal and transverse roughness measurements (both R_a and R_q) were made on each of the samples prior to testing. For all samples in test series 2, transverse surface profiles were also recorded to document the sample flatness. Final contact footprint sizes are shown in Table 3-2.

Photographic documentation of representative samples in their pre-test condition is presented in Figures 3-3 and 3-4.

Table 3-2
Contact footprint dimensions for friction test samples

Test Series 1				Tests Series 2			
Ambient Rig		Autoclave Rig		Ambient Rig		Autoclave Rig	
Stress (ksi)	Footprint (inches)	Stress (ksi)	Footprint (inches)	Stress (ksi)	Footprint (inches)	Stress (ksi)	Footprint (inches)
2, 10	0.4 x 1.0	10	0.25 x 1.0	10	1.05 x 0.222	10	1.05 x 0.222
40	0.2 x 0.625	15	0.2 x 0.9	15	0.9 x 0.222	15	0.9 x 0.222

Prior to testing, all machined or refinished samples were cleaned in a series of ultrasonic baths. The sequence consisted of an anionic detergent solution, acetone, and isopropyl alcohol, finally followed by a rinse in de-ionized (DI) water. The samples were then hot air dried, stored in desiccators, and handled only with clean gloves prior to testing.

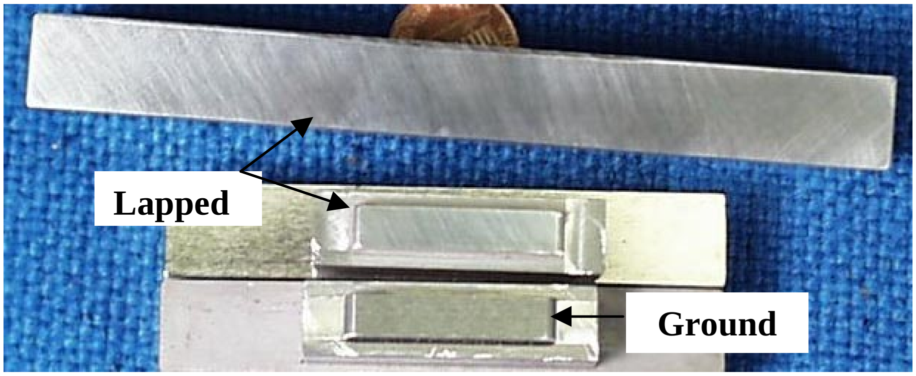

Figure 3-3
Flat-on-Flat Ambient Test Samples. The larger sample is the moving lower sample (0.5" x 4.5"). Two upper samples are shown, lapped and ground

Figure 3-4
Lapped Flat-on-Flat Autoclave Test Samples. The larger samples are the moving inner samples (1" x 3")

4 RESULTS

Test Series 1

Initial Tests in Battelle's Test Rigs

The preliminary RT friction work at EPRI's NDE Center on NOREM 02A did not indicate any tendency for galling. However, the ASTM G-98 test used is designed for screening purposes and does not necessarily simulate field conditions[8]. Testing was performed only at RT, and the geometry of the contact interface (rotating pin-on-block) differs from the flat-on-flat translating contact of gate valves. A new program was initiated between EPRI and Battelle to test NOREM alloys with large flat-on-flat samples over a greater range of loaded stroke lengths.

A summary of the first series of tests performed in the ambient rig is presented in Table 4-1A. Selected "COF versus stroke" and/or "COF versus time" plots are included in Appendix A. Photographic documentation of the sample surfaces after testing is presented in Figures 4-1 through 4-3. Initial tests of NOREM 02A and Stellite 6 using Battelle's ambient rig at RT (Tests 1, 2, 3, 5, 7 and 17) agreed with previous EPRI data: no galling was observed at RT. Above 120°F, galling was observed for NOREM 02A at a nominal contact stress of 10 ksi[9] using a 3-inch stroke length (Tests 6 and 21). As these results were unexpected, the test matrix and test procedures were modified in an effort to understand the galling observations. To begin with, dwell times between strokes were increased up to 60 seconds to minimize potential heat buildup at the interface with repeated stroking (Tests 10, 13 and 21). Galling was still observed above RT with increased dwell times. Similarly, changes in surface finish method, from unidirectional grinding to multidirectional lapping, appeared to have no beneficial effect (Tests 4, 23 and 22, 24). The combination of NOREM 02A and Stellite 6 at 10 ksi in RT and 200°F water (Tests 17, 15 and 16) produced very favorable results in terms of both low coefficient of friction (COF) and anti-galling performance. However, at 40 ksi in 200°F water (Test 18), significant material disruption of the surface (galling) of the NOREM 02A occurred. Tests of self-mated Stellite 6 at RT and 200°F (Tests 7 and 9) produced results that were comparable to earlier studies, both in terms of the absence of galling and COF levels.

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[8] Section 5.5 of G-98 states that, "This test method should not be used for quantitative or final design purposes since many environmental factors influence the galling performance of materials in service. Lubrication, alignment, stiffness and geometry are only some of the factors that can affect how materials perform. This test method has proven valuable in screening materials for prototypical testing that more closely simulates actual service conditions."

[9] Note that all normal stresses given are the nominal contact stress, defined by the normal load divided by the apparent area of contact.

Tests on NOREM 02

A limited number of tests were conducted on NOREM 02 during Test Series 1: ambient pressure rig tests 20, 22, and 24 (Table 4-1A) and autoclave rig tests AC 4-8 (Table 4-1B). The RT ambient test (Test 20) showed normal sliding behavior with a maximum COF of 0.57. The 200°F tests with a 3-inch stroke length (Tests 22, 24) resulted in galling. The first autoclave test (AC4) simulated conditions of a gate valve tested by Electricité de France[10] (EdF). Fifty unidirectional 0.44-inch strokes were performed at 550°F at 15.6 ksi. Consistent with the results of the EdF gate valve test, heavy scoring, but no galling, was observed. Similarly, no galling was observed after 19 strokes at 15 ksi following unidirectional 1.6-inch[11], 3 ksi and 10 ksi strokes (Test AC5). Finally, a 10 ksi test at 200°F, following a single stroke at 1.5 ksi, was performed, and no galling was observed after 25 strokes. This result differed from results of comparable stress and temperature tests conducted in the ambient rig (Test 22). The differences between the two tests were the unidirectional versus reciprocating strokes, the 1.6-inch stroke versus the 3-inch stroke, and the single low stress stroke (hereafter referred to as the "preconditioning stroke") performed prior to the high stress strokes versus no preconditioning stroke. Based on these observations, a new test matrix was developed and new testing procedures were implemented for the second series of tests.

[10] EPRI TR-109345, Monitoring Performance of Valves with NOREM Hardfacing, November, 1998.
[11] Note that Battelle's autoclave friction test rig is limited to a maximum stroke length of 1.6 inches for a 1.1 inch sample. Strokes are performed unidirectionally, with unloading between strokes.

Table 4-1A
Test Series 1 - Ambient Rig

Test #	Stationary Specimen Material	Moving Specimen Material	% N	Water Temp. (°F)	Nominal Contact Stress (ksi)	Dwell Time (sec)	Stroke Length (in)	Total No. of Strokes	Max. COF	Galled?	Post Test Surface Condition
1	02A	02A	0.027	RT	2	1	3	150	0.46	No	Light Scoring
2	02A	02A	0.027	RT	10	1	3	201	0.5	No	Light Scoring
3	02A	02A	0.027	RT	10	1	3	150	0.47	No	Light Scoring
5	02A	02A	0.027	RT	10	1	3	150	0.49	No	Light Scoring
4	02A	02A	0.027	200	10	1	3	3	0.94	Yes	Significant Material Disruption
23	02A†	02A†	0.027	200	10	1	3(0.9)*	1	0.76	Yes	Significant Material Disruption
13	02A	02A	0.027	200	10	30	3	47	0.8	Yes	Significant Material Disruption
10	02A	02A	0.027	200	10	30	0.5	250	0.69	No	Scoring
21	02A	02A	0.027	120	10	60	3(1.5)*	1	0.72	Yes	Significant Material Disruption
6	02A	02A	0.027	70-140‡	10	1	3	138	0.95	Yes	Significant Material Disruption
7	St 6	St 6	-	RT	10	1	3	279	0.6	No	Light Scoring
9	St 6	St 6	-	200	10	1	2.5	150	0.46	No	Light Scoring
17	St 6	02A	0.027	RT	10	1	3	200	0.57	No	Light Scoring
16	St 6	02A	0.027	200	10	1	3	150	0.52	No	Scoring
15	St 6	02A	0.027	200	10	30	3	150	0.5	No	Scoring
18	St 6	02A	0.027	200	40	60	3	1	0.57	Yes	Significant Material Disruption
20	02	02	0.17	RT	10	60	3	158	0.57	No	Light Scoring
22	02	02	0.17	200	10	60	3(2.1)*	4	1.1	Yes	Significant Material Disruption
24	02†	02†	0.17	200	10	60	3(1.7)*	1	0.66	Yes	Significant Material Disruption

02A = NOREM 02A (GTAW deposit), St 6 = Stellite® 6, 02 = NOREM 02 (PTA deposit)
All tests reciprocating, where more than one stroke was accomplished.
* - Parentheses indicate estimated distance of travel when galling initiated.
† - Indicates sample surface finished by hand lapping. All other samples were finished by surface grinding.
‡ - Test temperature was increased during the test. Galling occurred on the 138th stroke, when the temperature reached 140°F.

Table 4-1B
Test Series 1 - Autoclave Rig

Test #	Stationary Specimen Material	Moving Specimen Material	% N	Water Temp. (°F)	Nominal Contact Stress (ksi)	Dwell Time (sec)	Stroke Length (in)	Total No. of Strokes	Max. COF	Galled?	Post Test Surface Condition
AC4	02†	02†	0.17	550	15.6	>60	0.44	50	0.82	No	Scoring
AC5	02†	02†	0.17	550	10	>60	1.6	1	0.86	No	Not Examined (preconditioning stroke for test AC6)
AC6	02†	02†	0.17	550	15	>60	1.6	19	0.87	No	Scoring / Some small Pullouts
AC7	02†	02†	0.17	200	1.5	>60	1.6	1	0.71	No	Not Examined (preconditioning stroke for test AC8)
AC8	02†	02†	0.17	200	10	>60	1.6	25	0.64	No	Scoring / Some small Pullouts

02A = NOREM 02A (GTAW deposit), St 6 = Stellite® 6, 02 = NOREM 02 (PTA deposit)
All tests are unidirectional.
† = All samples in this series were finished by hand lapping.

The larger sample is the moving lower sample, and is 4.5 inches long by 0.5 inches wide.

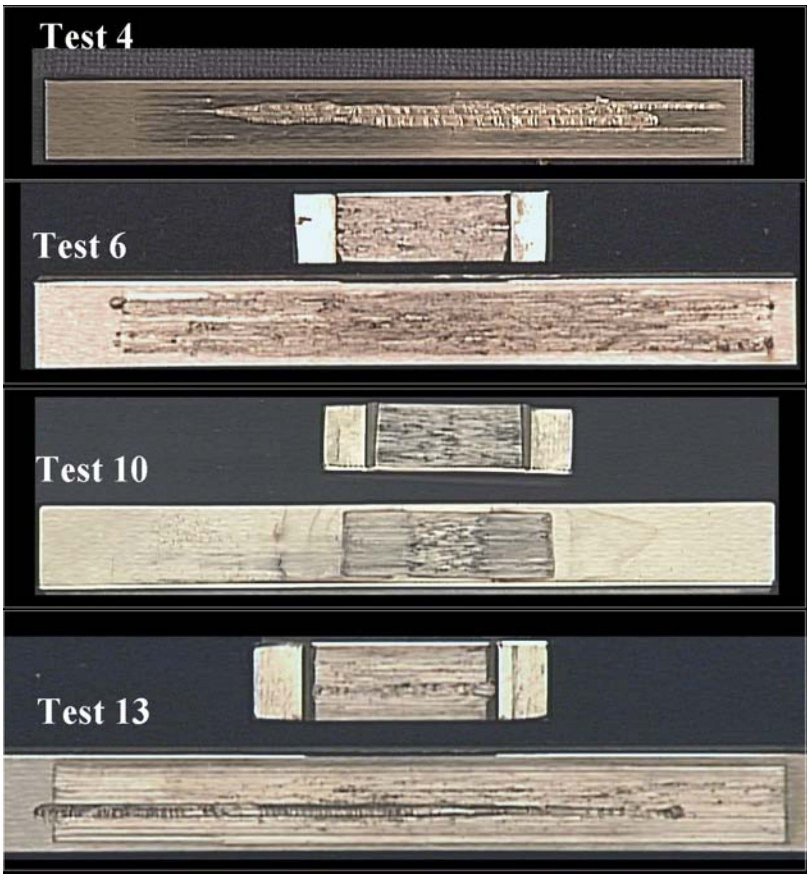

Figure 4-1
Photographs of samples after Ambient Series 1 Tests 4, 6, 10 and 13. See Table 4-1A for conditions

The larger sample is the moving lower sample, and is 4.5 inches long by 0.5 inches wide.

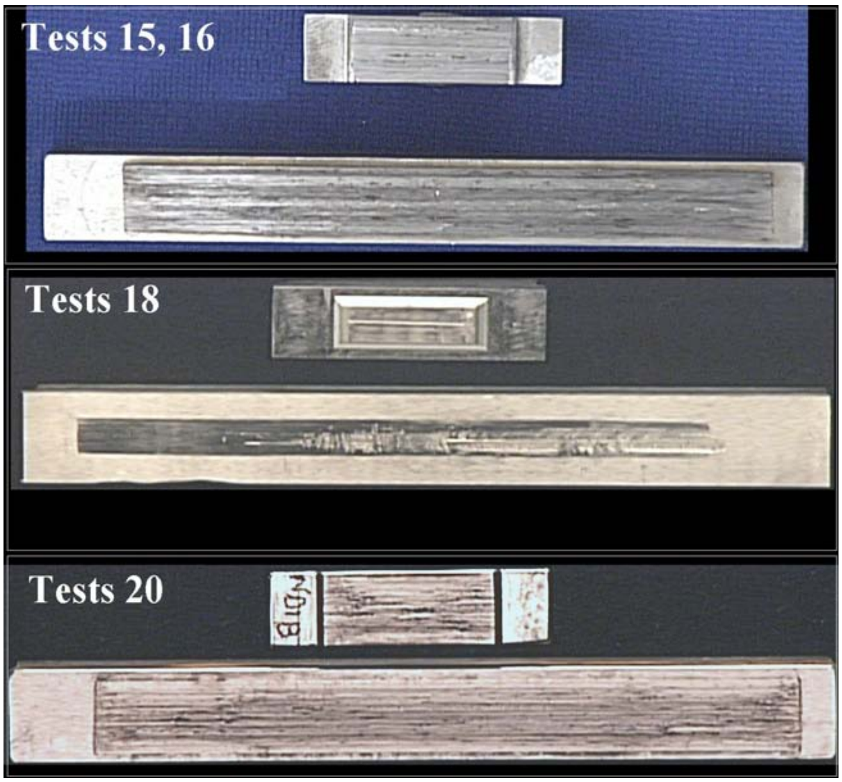

Figure 4-2
Photographs of samples after Ambient Series 1 Tests 15, 16, 18 and 20. See Table 4-1A for conditions

The larger sample is the moving lower sample, and is 4.5 inches long by 0.5 inches wide.

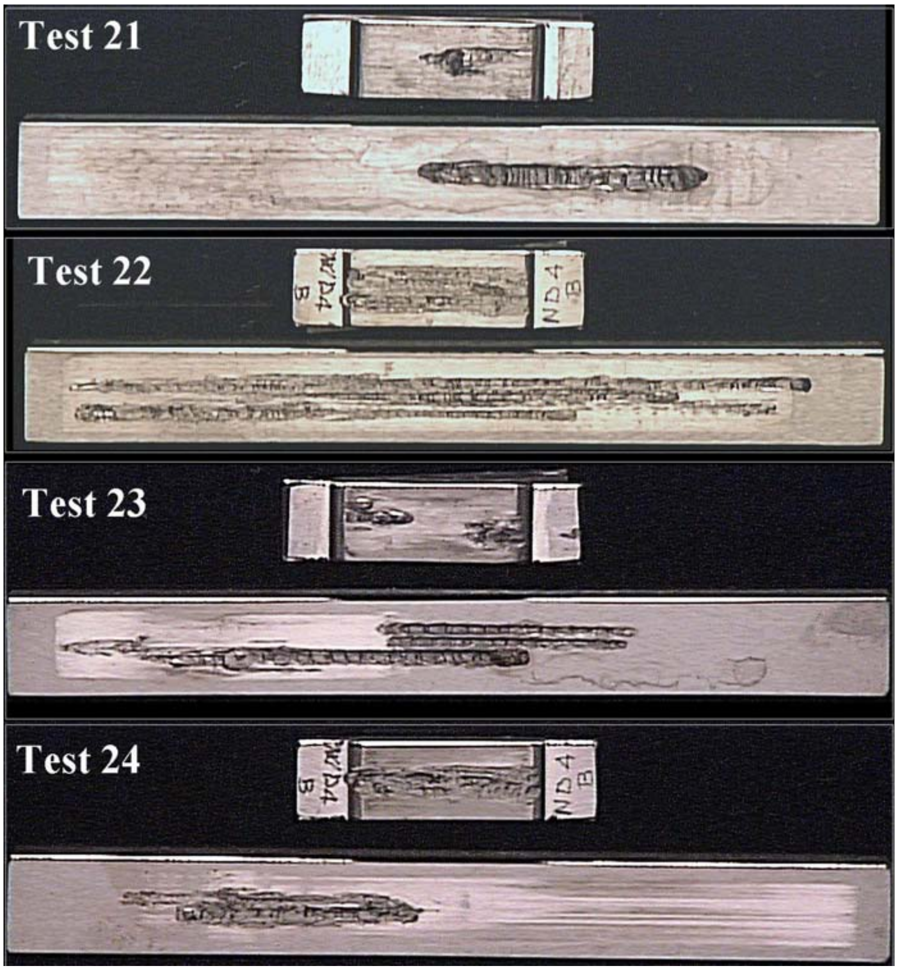

Figure 4-3
Photographs of samples after Ambient Series 1 Tests 21, 22, 23 and 24. See Table 4-1A for conditions

Test Series 2

For all the tests in Series 2, pressure sensitive tape was used to ensure that uniform loading, to the extent possible, was achieved between the test specimens. The aim of these tests was to evaluate the effect of stroke length and preconditioning on the galling propensity of NOREM 02. A summary of the results of the tests performed in both the ambient and the autoclave rigs is presented in Table 4-2. Selected "COF versus stroke" and "COF versus time" plots are included in Appendix B. Photographic documentation of the sample surfaces after testing is presented in Figures 4-4 through 4-14. With the exception of Tests AM6&7, no galling was observed for stroke lengths of 1.6 inches, irrespective of testing temperature. Galling of NOREM 02 was observed after approximately 70 1.6-inch reciprocating strokes. Galling occurred in both 200°F tests with a 3-inch stroke (Tests AM3&4, AM5), regardless of the implementation of a preconditioning stroke.

The 550ºF tests at 15 ksi nominal contact stress conducted in the autoclave rig (stroke length limited to 1.6 inches) did not gall, though surface scoring was moderately heavy and at least one heavy plow was found on the samples after the test. This indicates that, although galling did not occur during the duration of the test, the potential for galling was high. Factors contributing to galling are listed in the Discussion Section.

Table 4-2
Test Series 2: NOREM 02 PTA (0.17 wt % Nitrogen)

Test ID	Water Temp. (°F)	Nominal Contact Stress (ksi)	Maximum Stress (Based on Fuji Film Average Ratio)	Dwell Time (sec)	Stroke Length (in)	Total No. of Strokes	Max. COF	Post Test Surface Condition
Ambient Rig Tests								
AM0A	200	1.5		>60	1.6	1	0.38	
AM0B	200	10	21	>60	1.6	25	0.51	Scoring/ Light Pullouts
AM1	200	1.5		>60	1.6	1	0.40	
AM2	200	15	31	>60	1.6	25	0.61	Scoring/ Light Pullouts
AM3	200	1.5		>60	3	1	0.21	
AM4	200	15	31	>60	3	25	0.64	Significant Material Disruption
AM5	200	15	31	>60	3	25	0.66	Significant Material Disruption
AM6	200	1.5		>60	1.6	1	0.24	
AM7	200	15	31	>60	1.6	120	0.67	Significant Material Disruption
AM8	200	1.5	3.1	>60	3	25	0.5	Very Light Scoring
Autoclave Rig Tests								
AUTOA	199	1.4		>60	1.6	1	0.53	
AUTOB	199	10	20	>60	1.6	25	0.61	Scoring/ Light Pullouts
AUTOC	205	3		>60	1.6	1	0.54	
AUTOD	205	10	20	>60	1.6	25	0.65	Scoring/ Light Pullouts
AUT1	550	1.5		>60	1.6	1	0.67	
AUT2	550	15	29	>60	1.6	25	0.74	Scoring/ Light Pullouts
AUT3	550	1.5		>60	1.6	1	0.88	
AUT4	550	15	29	>60	1.6	25	0.85	Heavy Scoring/Pullouts/ 1 Plow
AUT6	550	15	29	>60	1.6	25	0.84	Heavy Scoring/Pullouts/ 1 Plow

The larger sample is the moving lower sample, and is 0.5 inches wide

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AM0A	1.5	200	1.6	1 (uni)
AM0B	10	200	1.6	25 (unidirectional)

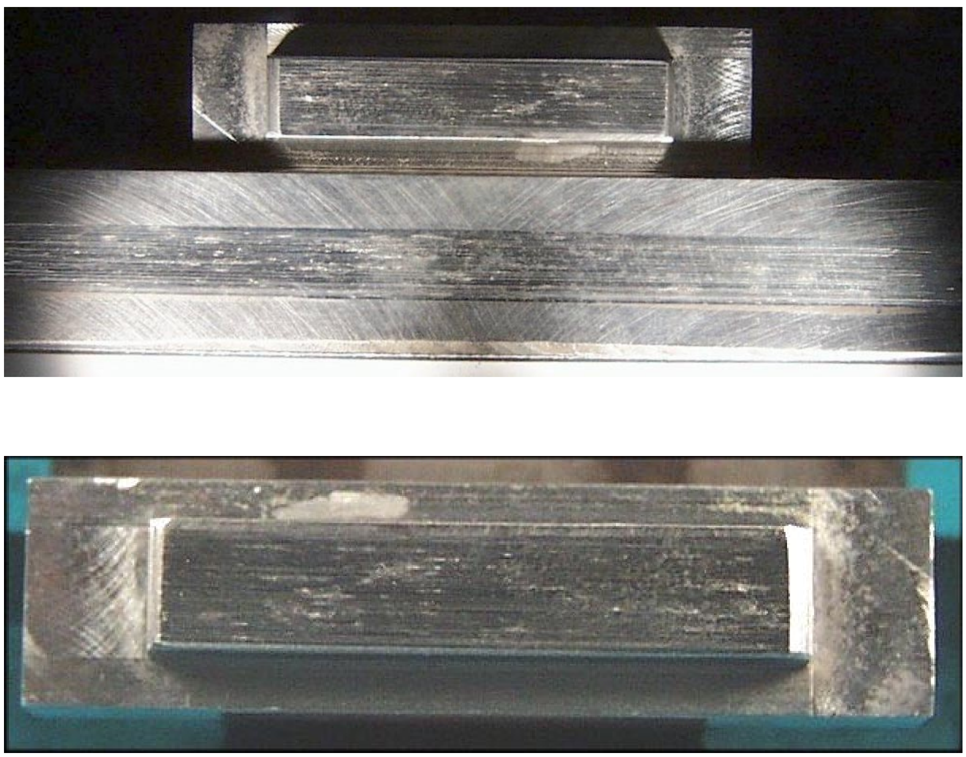

Figure 4-4
Photographs of samples after Ambient Series 2 Test AM0

The larger sample is the moving lower sample, and is 0.5 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AM1	1.5	200	1.6	1 (uni)
AM2	15	200	1.6	25 (unidirectional)

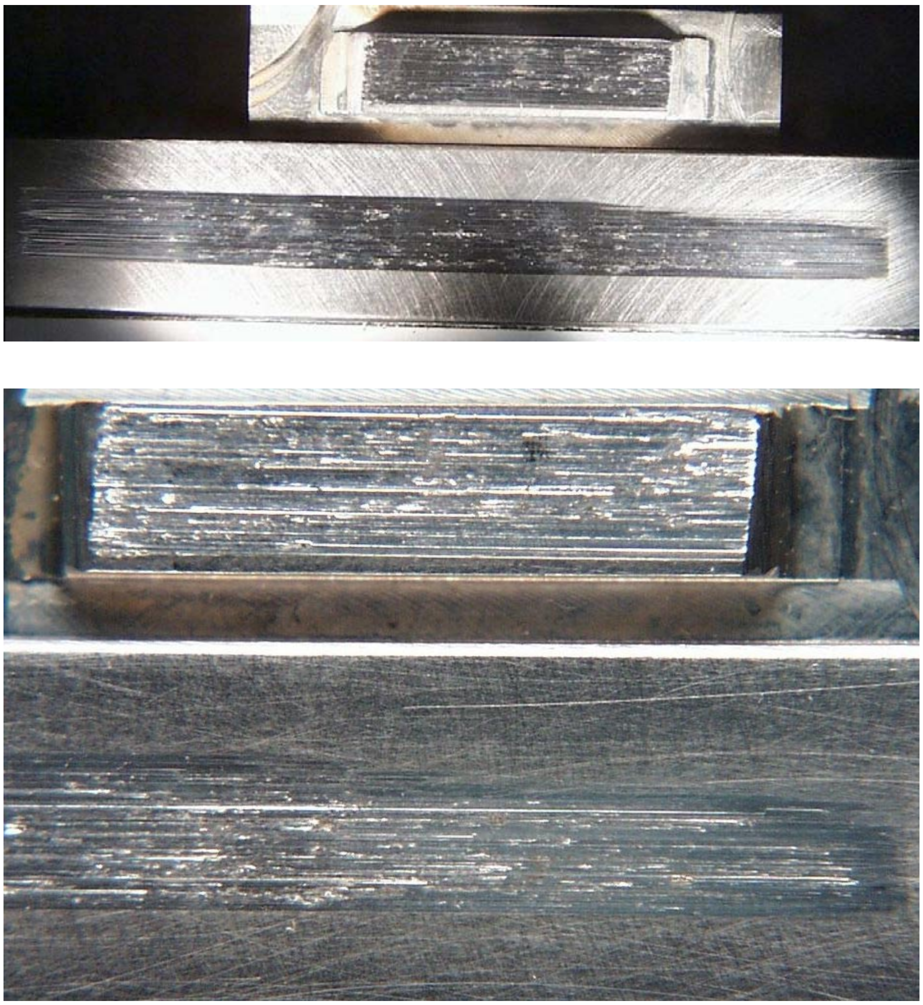

Figure 4-5
Photographs of samples after Ambient Series 2 Tests AM1 and AM2

The larger sample is the moving lower sample, and is 0.5 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AM3	1.5	200	3	1 (uni)
AM4	15	200	3	25 (unidirectional)

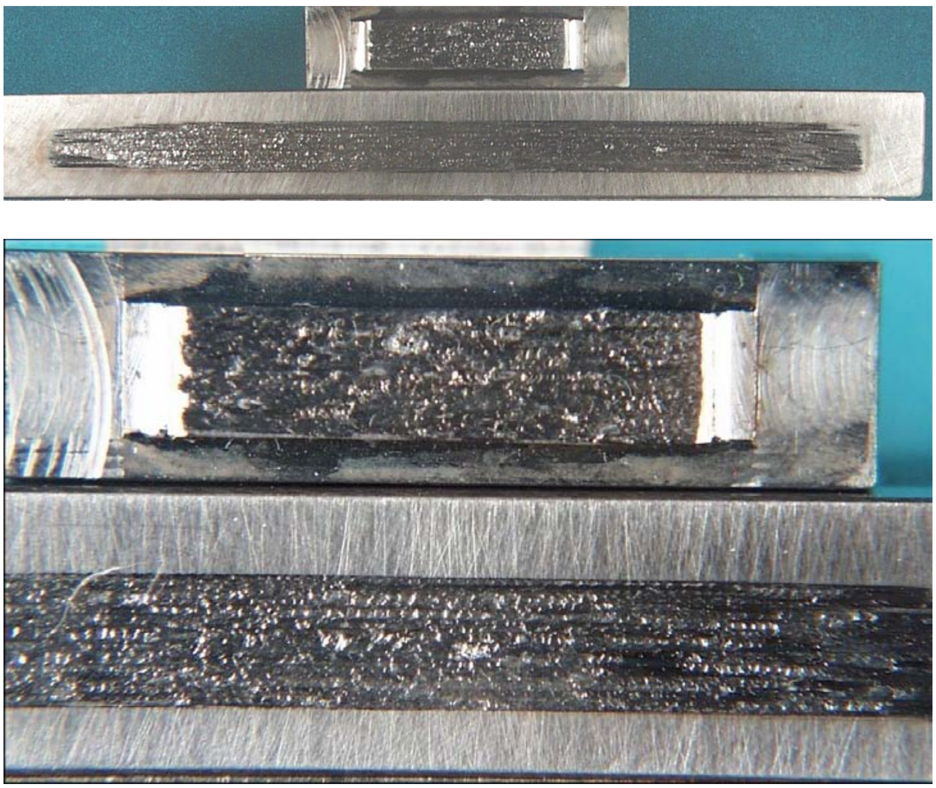

Figure 4-6
Photographs of samples after Ambient Series 2 Tests AM3 and AM4

The larger sample is the moving lower sample, and is 0.5 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AM5	15	200	3	25 (unidirectional)

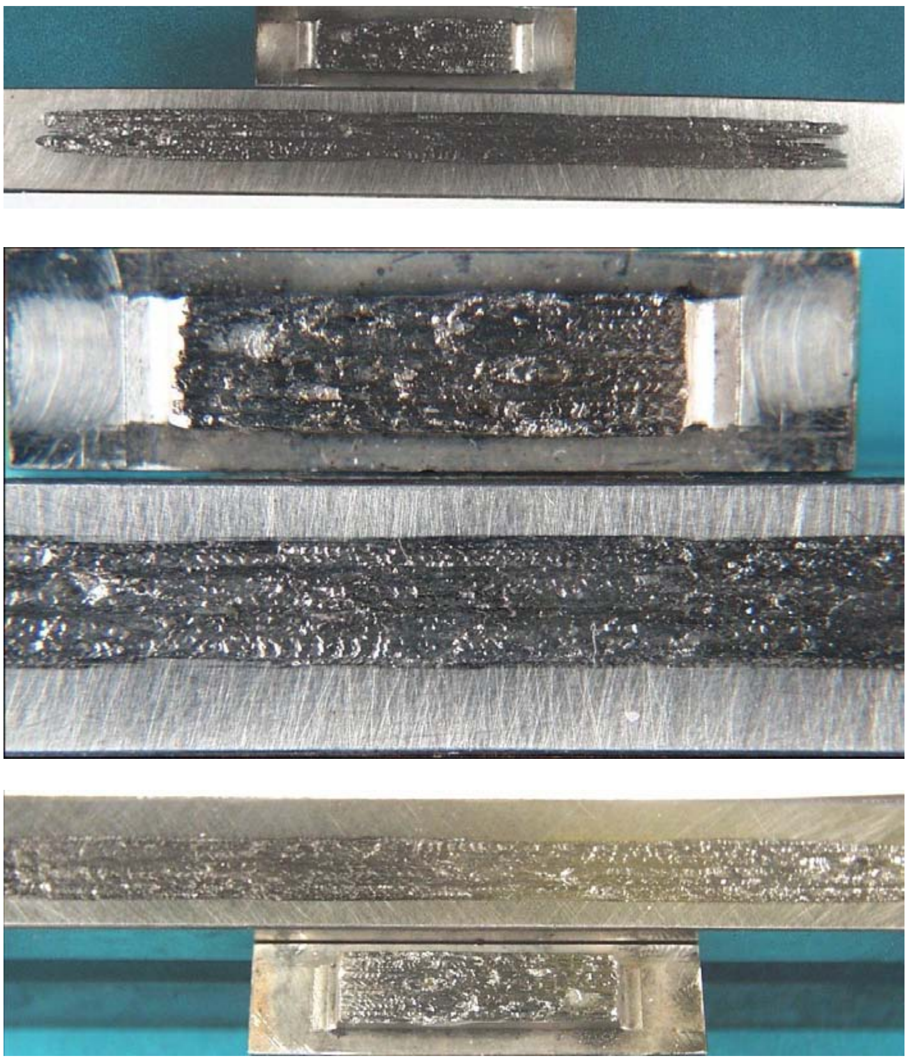

Figure 4-7
Photographs of samples after Ambient Series 2 Test AM5

The larger sample is the moving lower sample, and is 0.5 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AM6	1.5	200	1.6	1
AM7	15	200	1.6	120 (bidirectional)

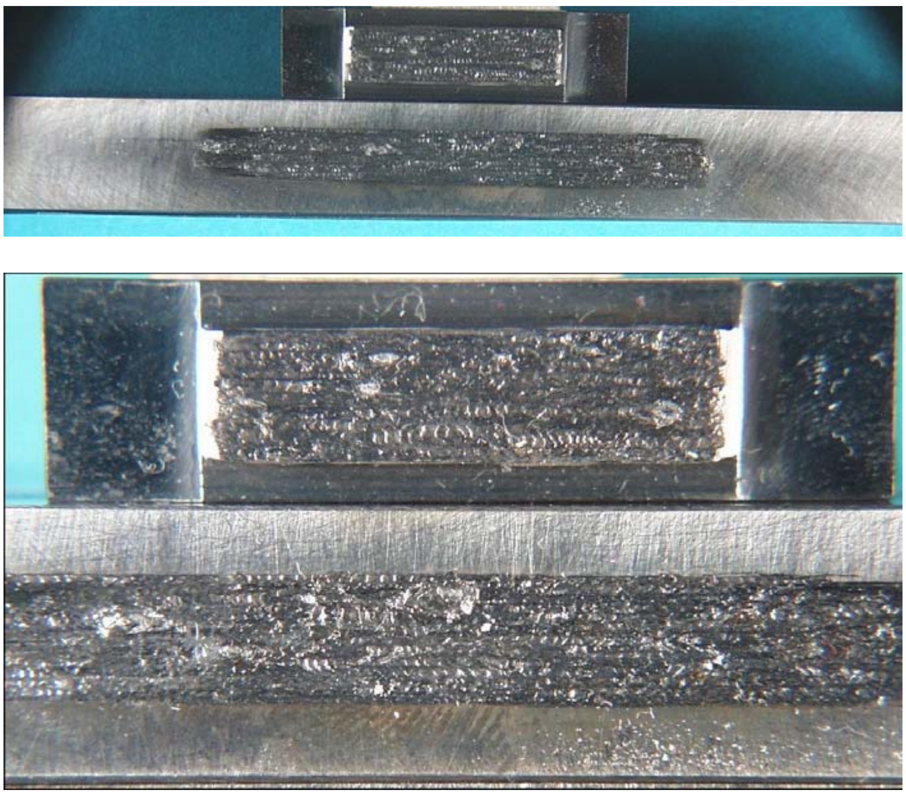

Figure 4-8
Photographs of samples after Ambient Series 2 Tests AM6 and AM7

The larger sample is the moving lower sample.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AM8	1.5	200	3	25 (unidirectional)

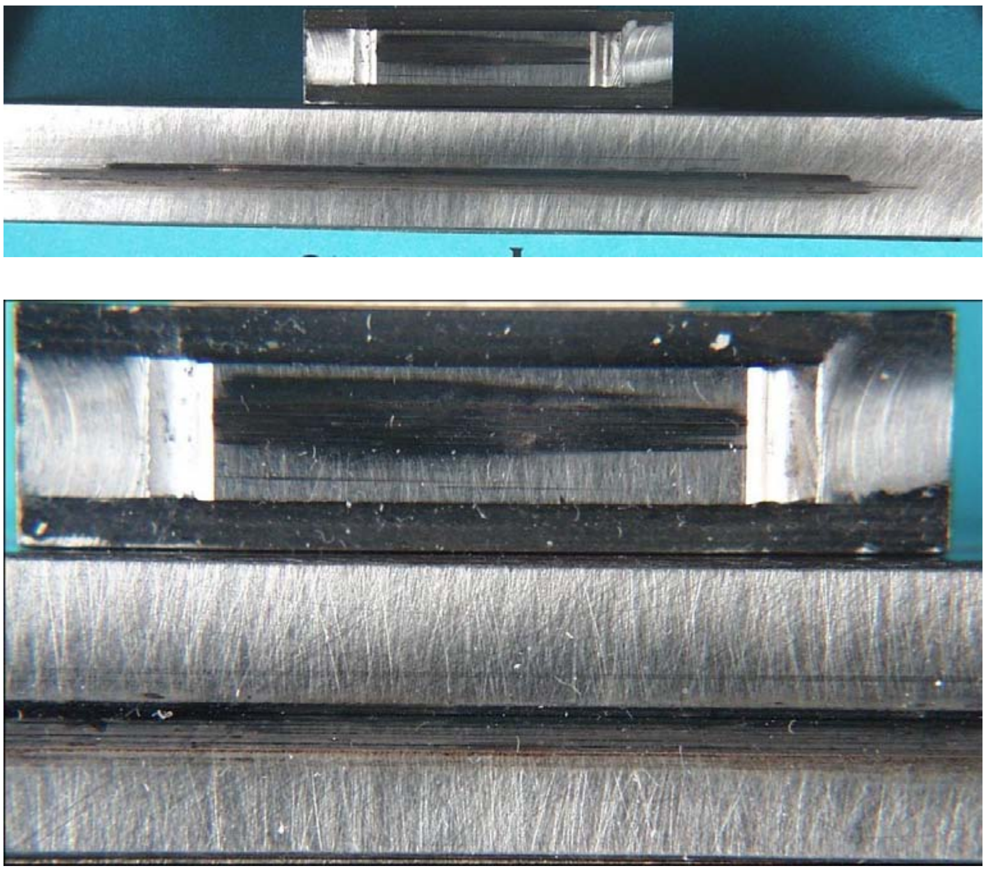

Figure 4-9
Photographs of samples after Ambient Series 2 Test AM8

The larger samples are the moving inner samples, and are 0.995 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AUT0A	~1.5	199	1.6	1
AUT0B	10	199	1.6	25 (unidirectional)

Figure 4-10
Photographs of samples after Autoclave Series 2 Test AUT0 (A and B)

The larger samples are the moving inner samples, and are 0.995 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AUT0C	~1.5	205	1.6	1
AUT0D	10	205	1.6	25 (unidirectional)

Figure 4-11
Photographs of samples after Autoclave Series 2 Test AUT0 (repeat: C and D)

The larger samples are the moving inner samples, and are 0.995 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AUT1	~1.5	200	1.6	1
AUT2	15	200	1.6	25 (unidirectional)

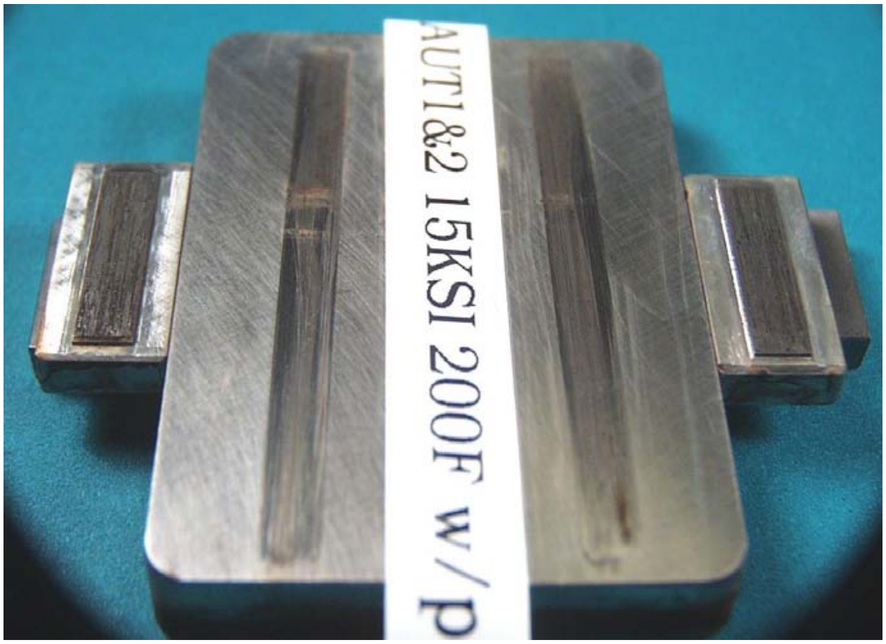

Figure 4-12
Photographs of samples after Autoclave Series 2 Tests AUT1 and AUT2

The larger samples are the moving inner samples, and are 0.995 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AUT3	~1.5	550	1.6	1
AUT4	15	550	1.6	25 (unidirectional)

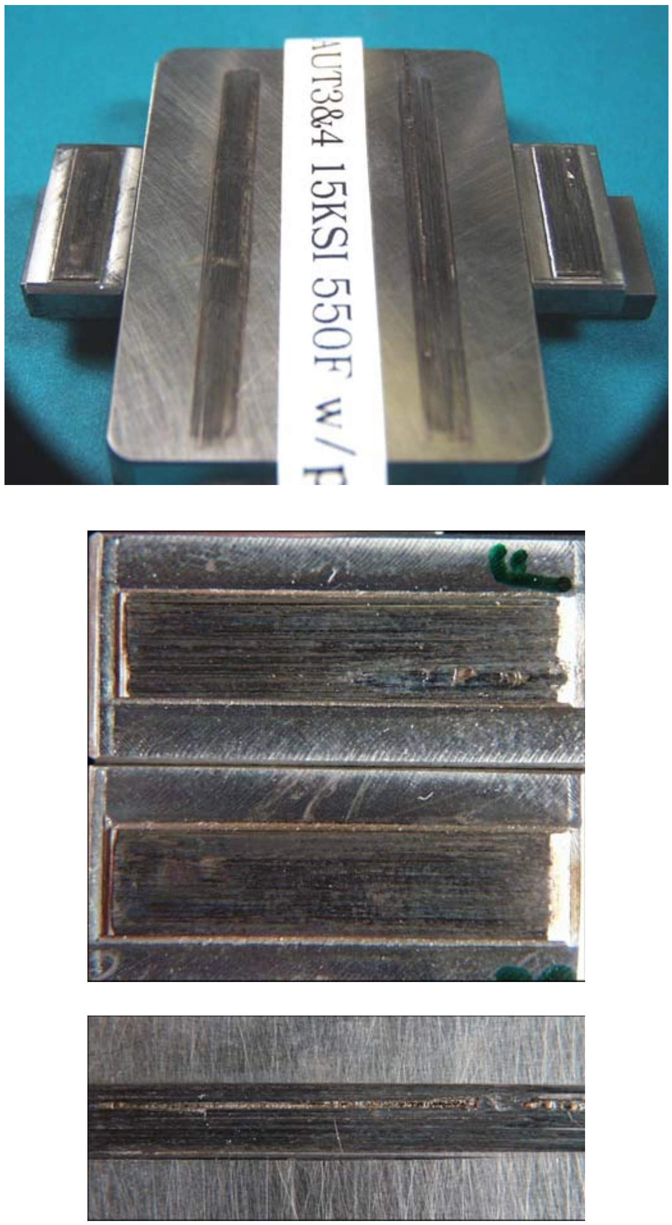

Figure 4-13
Photographs of samples after Autoclave Series 2 Tests AUT3 and AUT4

The larger samples are the moving inner samples, and are 0.995 inches wide.

Test ID	Nom. Stress (ksi)	Water Temperature (°F)	Stroke Length (in)	No. of Strokes
AUT6	15	550	1.6	25

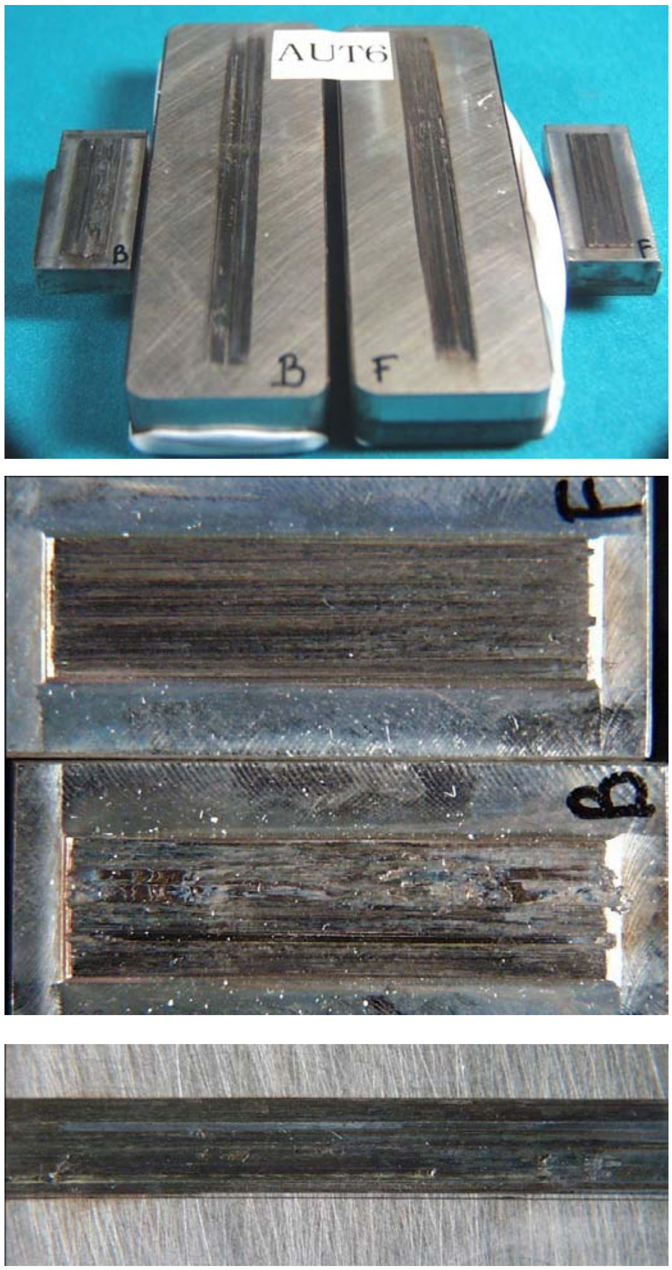

Figure 4-14
Photographs of samples after Autoclave Series 2 Test AUT6

5
DISCUSSION

Effect of Structure and Alloy Composition

The properties of a material are determined by the material's microstructure and composition. The microstructure, in turn, is determined by the composition and the processing of the material. Weld-deposited NOREM has a dendritic iron-chromium matrix with a carbide network. The properties related to friction, wear, and galling resistance are more than simple material properties, and are those of a system. The system is comprised of both sliding components as well as the layers of oxide films, contaminants, and debris trapped between them. In addition, the microstructure of the material in the near surface region evolves during sliding, and may differ drastically from the initial microstructure[12]. The starting microstructures for both versions of NOREM tested in this program were shown in Figure 3-1. Detailed analyses of these microstructures and of the evolution of the sub-surface structure during testing were beyond the scope of this program. Nevertheless, some comments can be made regarding alloy composition.

In this program, the effect of alloy composition was explored to the extent that two different chemical compositions and weld methods were tested. A number of studies have been undertaken in which the beneficial effect of nitrogen on wear resistance of steels has been observed[13], though the precise mechanism is still under debate. There was possible evidence of the beneficial effects of nitrogen in that the sliding distance before galling was longer for the NOREM 02 (0.17 wt. % nitrogen) than for the NOREM 02A (0.027 wt. % nitrogen). 1.7 inches versus 0.9 inches, respectively. However the dwell times and sample surface finish methods for these tests (23 and 24) were not the same. In addition to the nitrogen content, the percentage of silicon was slightly higher in the 02 alloy than in the 02A (3.3 versus 2.9 wt. %). Silicon is also reported to have a beneficial effect on wear and galling resistance[14], though in this case it is thought to be through the effect of the surface oxide (see following discussion on galling). Definitive benefits of these alloying elements for NOREM would require additional studies using specific compositional variations. No such studies were possible within the scope of this work.

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[12] D.A. Rigney, "Microstructural Evolution during Sliding", Proc. ASM Symp. On Wear of Engineering Materials, Ed. J. Hawk, Indianapolis, IN , pp. 3-12, September, 1997.

[13] For example, J.A. Hawk, et al., "Effect of Nitrogen Alloying on the Microstructure and Abrasive Wear of Stainless Steels", J. Mater. Eng. and Perf., v. 3, pp. 259-272, April, 1994.

[14] J.H. Magee, "Silicon Beefs Up Stainless Steel", Machine Design, v. 62, no. 22, pp. 60-64, October 25, 1990.

Sample Alignment Procedures

There was concern that the contact stress imposed in the test rigs was much higher than that defined by the normal load divided by the nominal contact area. It is well known that alignment of test samples is highly difficult, yet critical, in flat-on-flat configurations. Misalignment can result in concentrated loading, hence much higher stresses than originally intended. Prior to all tests in Series 1, aluminum foil was placed between the samples. The resulting imprint of the foil, or sample footprint, allowed us to observe and optimize the uniformity of the stress in the contact region. For Series 2, a pressure sensitive film (Fuji Prescale/Pressurex®) was used to optimize the uniformity of the stress in the contact region. This second method has better resolution than the aluminum foil method. In addition, samples used in the Series 2 were hand lapped using a custom-built fixture to hold the sample surfaces flat against the metallographic paper. Both these techniques lead to a more uniform contact between the samples.

Contact Stress

Nominal versus Maximum Contact Stress

A series of experiments was conducted to investigate the distribution of contact stresses at the interface of the two specimens compared with the nominal contact stress. The nominal contact stress is defined as the applied normal load divided by the nominal area of contact, as shown in the upper portion of Figure 5-1.

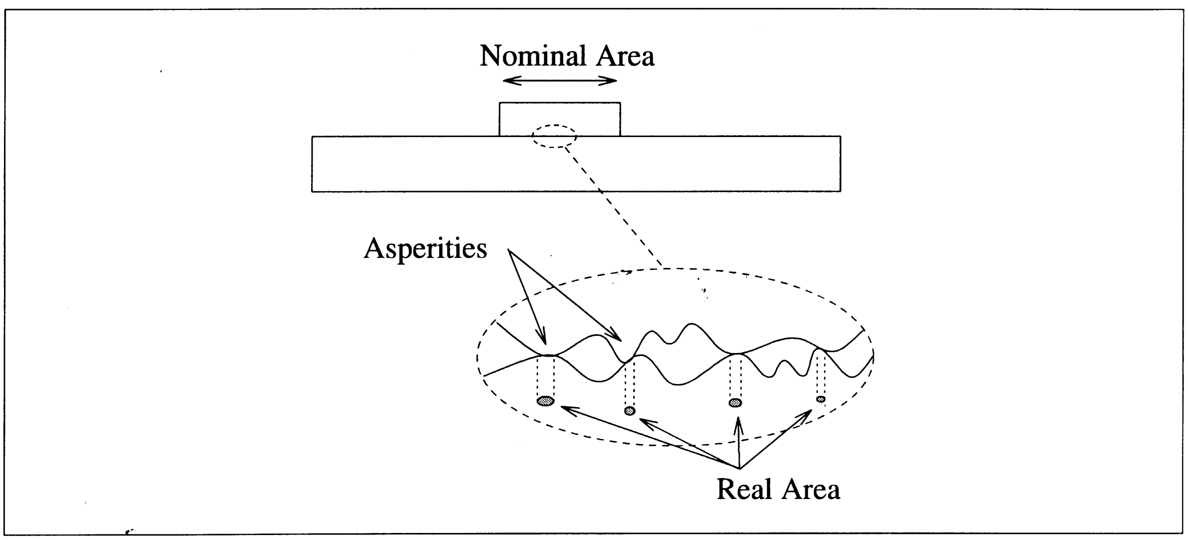


Figure 5-1
Nominal and real contact areas at the interface between two flat specimens[15]

[15] Adapted from E. Rabinowicz, Friction and Wear of Materials, 2nd Ed., J. Wiley and Sons, 1995.

Fuji Prescale/Pressurex® film was placed at the interface between two samples as they were loaded. The pressure-sensitive film contains a layer of microcapsules which collapse under load. Upon rupture, the microcapsules react with the film substrate, producing a color image of the contact area. The density of the image is proportional to the applied load, within the working range of the film utilized. No change in color means that the stress was below the threshold pressure of the film, and complete saturation indicates that the upper limit of the film was exceeded. Fuji film with the highest pressure range available, i.e. 7.1 ksi to 18.5 ksi, was used. The footprints obtained were sent out for analysis to Sensor Products, Inc. (NJ). Example maps of the contact stresses at the interface are shown in Figure 5-2. Edge effects can be seen in the longitudinal direction, as the stresses near the ends are higher than that in the center of the footprint. Flatness of the sample can also be identified with Fuji film. The two maps shown in Figure 5-2 were obtained with samples of identical nominal contact area, though the length and width dimensions were different. The footprint in the left-side image also shows evidence of transverse crowning of the sample, resulting from hand lapping without a fixture. Profilometric transverse profiles, as shown in Figure 5-3, also indicate crowning.

The Fuji film could not be used to measure loads under incipient motion as the microcapsules are designed and calibrated for use under normal load only.

The maximum contact stress compared with the nominal contact stress for the sample footprints sent to SPI is indicated in Table 5-1. Typical ratios of the max-to-nom contact stresses, as evidenced by Fuji film experiments, were approximately equal to 2. Theoretical analyses of the stress distribution in a flat-on-flat contact using two different modeling techniques (finite element and boundary element) also indicated stress concentrations at the ends. Results of the latter for a block on a flat surface are shown in Figures 5-4 and 5-5, indicating higher stresses near the ends of the block. When two non-rigid elements of different lateral dimensions are loaded against each other, the larger element tends to provide a higher resistance to deflection near the edges of the smaller element, resulting in higher local contact stresses. Since the lower ambient specimen is much longer than the upper specimen, stresses tend to be higher at the ends of the upper specimen.

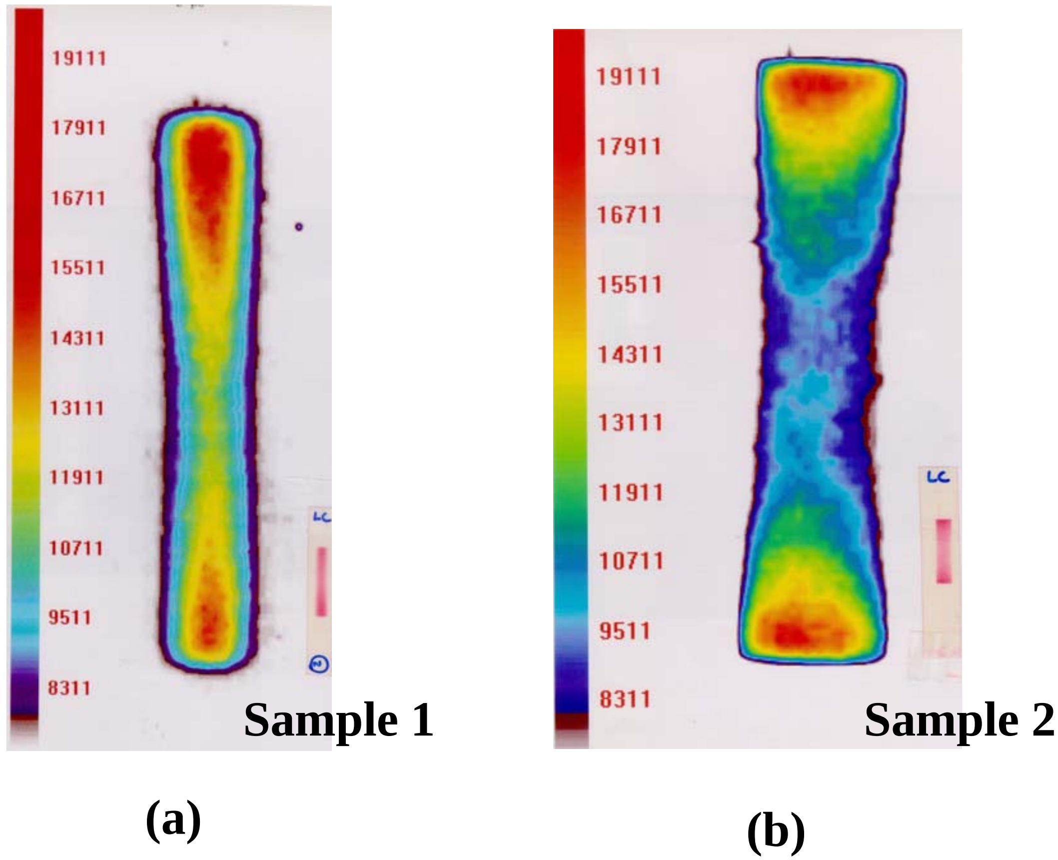
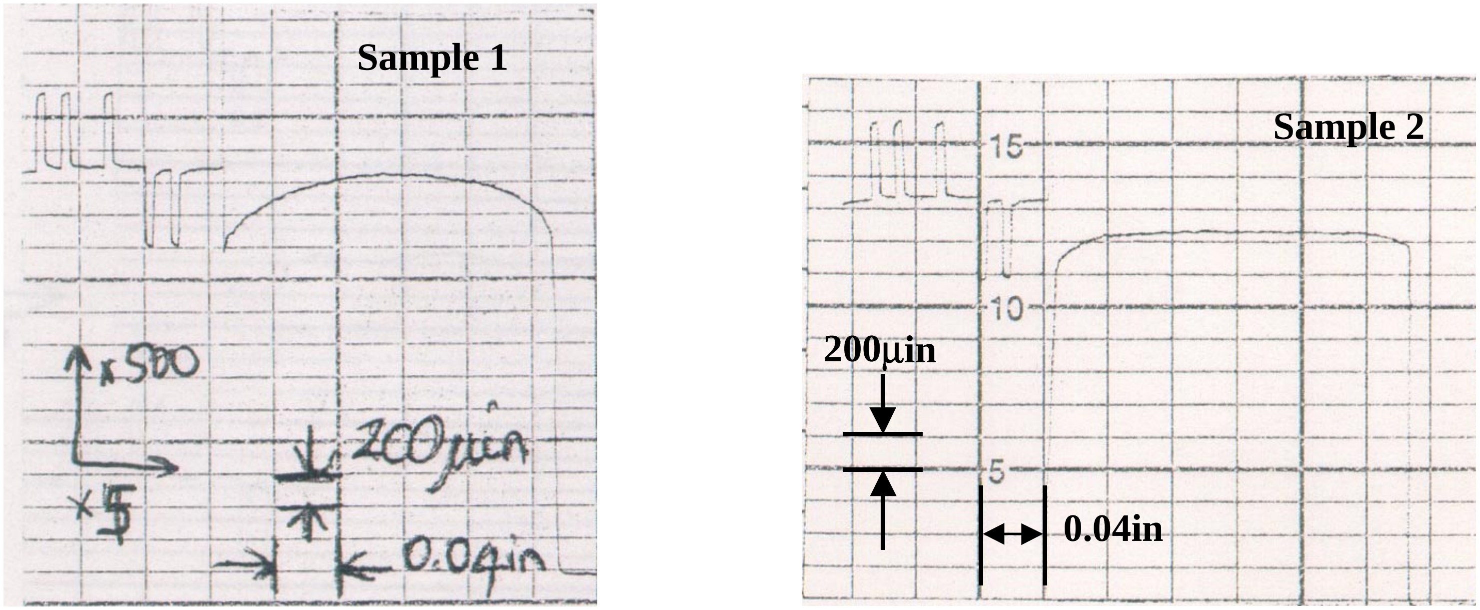


Figure 5-2
Pressure sensitive film analyses showing contact stress distribution (in psi) for flat-on-flat samples under nominal normal loading: (a) Sample 1:8 ksi, showing the presence of a transverse crown as a result of lapping without using a fixture; (b) Sample 2:10 ksi, for a sample lapped with the custom-built fixture. The pressure sensitive film footprints are shown to the right of the contact stress distribution maps



(a) (b)

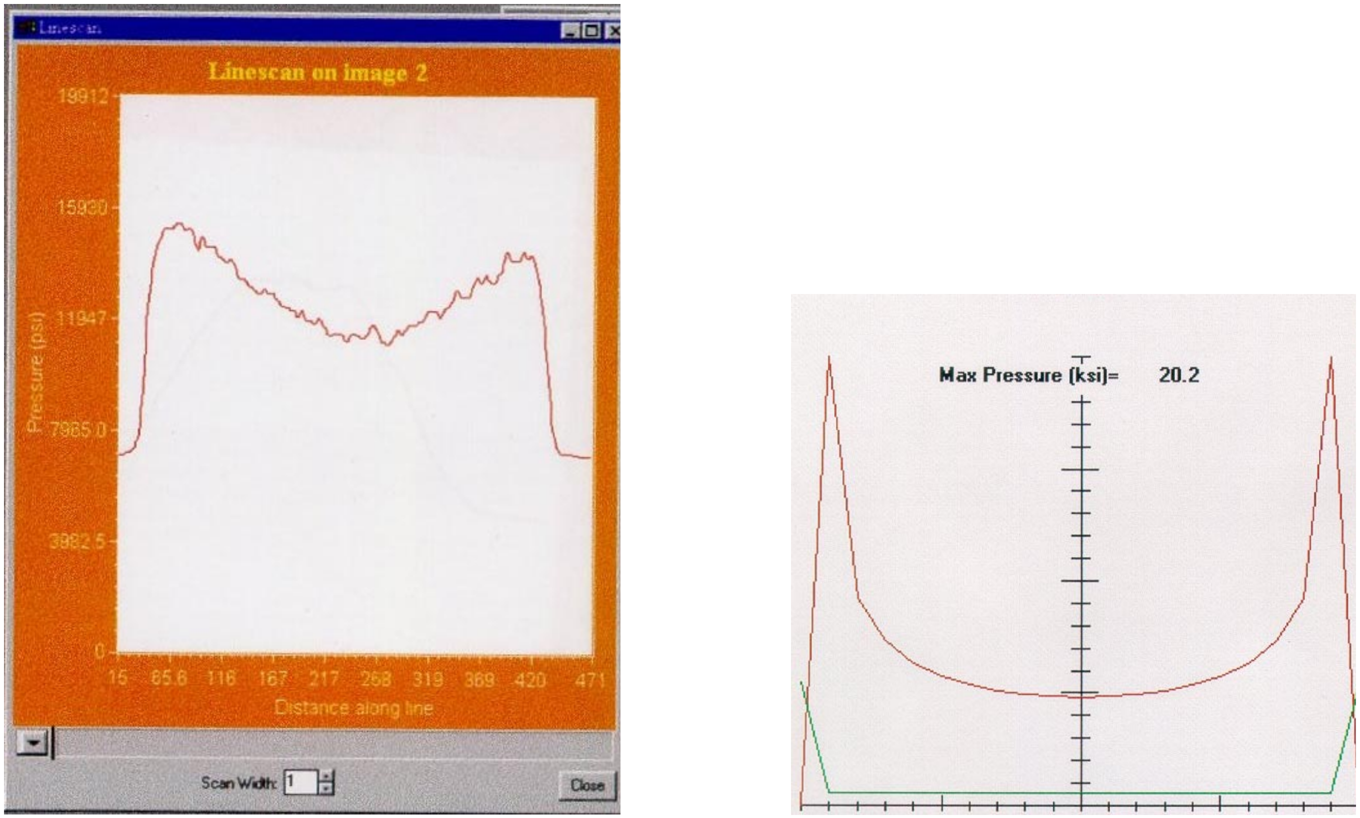
Figure 5-3
Transverse surface profiles of the upper samples as tested with Fuji film in Figure 5-2, showing the excessive curvature for Sample 1(a)

Table 5-1
Results of Pressure Sensitive Film Contact Stress Measurements.

	Nominal Applied Contact Stress (ksi)	Maximum Measured* Contact Stress (ksi)	Max-to-Nom ratio	Average Max-to-Nom ratio
Ambient	6	13.5	2.3	2.1
	8	15.5	2.0	
	8	17.2	2.1	
	10	19.1	2.0	
	10	19.0	2.0	
	15	19.9†	1.3†	
Autoclave	8	16.5	2.1	1.9
	8	16.1	2.0	
	10	18.1	1.9	
	10	18.9	1.9	
	10	17.3	1.8	
	10	17.9	1.8	

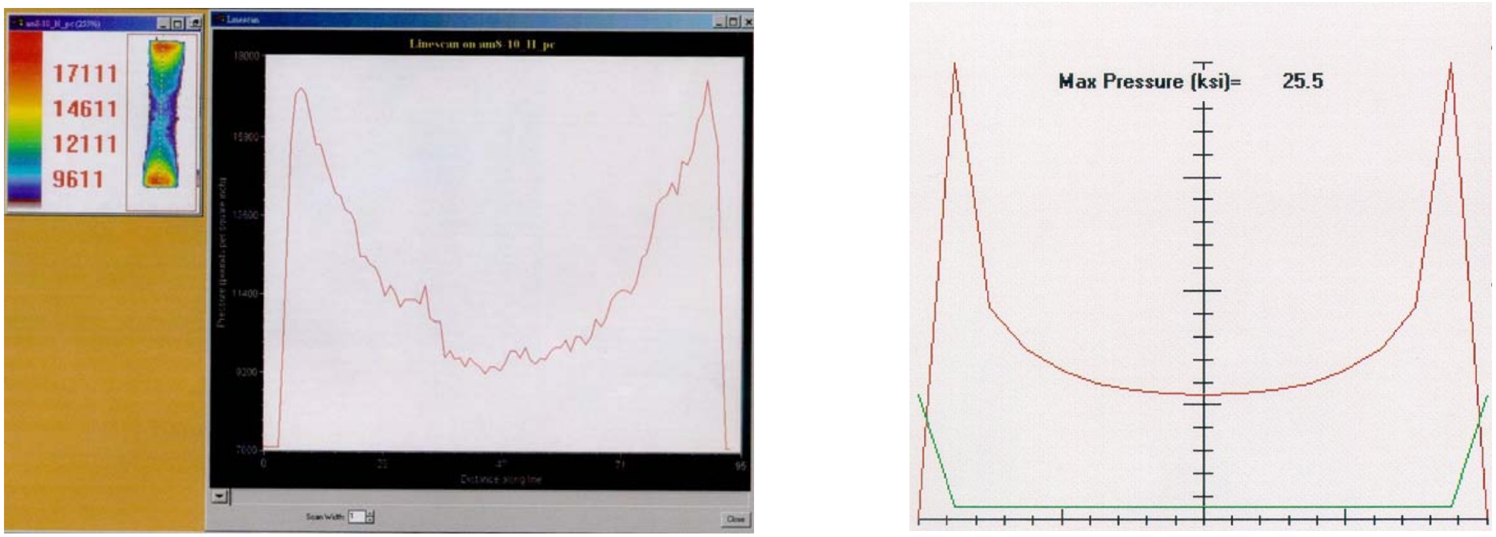
* Values reported by SPI from analyses of footprints.

† Film saturated, data not included in average.



Pressure Film Analysis **Boundary Element Model**

Figure 5-4
Edge Effects in the longitudinal direction for Sample 1 under 8 ksi nominal stress, as determined (a) experimentally with the line scan extracted from pressure sensitive film analysis (Figure 5-2(a)); and (b) theoretically using the boundary element technique



Pressure Film Analysis **Boundary Element Model**

Figure 5-5
Edge Effects in the longitudinal direction for Sample 2 under 10 ksi nominal stress, as determined (a) experimentally with the line scan extracted from pressure sensitive film analysis (Figure 5-2(b)); and (b) theoretically using the boundary element technique

Microscopic Contact Stresses

When two materials are loaded against one another, the weaker material supports the total load over the *real* contact area. The real contact area is defined by the contacts formed at asperities as shown in the lower portion of Figure 5-1. This contact area is many times smaller than the apparent area. The stress at the asperity contacts is constant, and is considered to be equal to the yield strength of the weaker material. As the load increases, the number of asperities in contact increases, resulting in a larger total real area of contact. However, the stress at any of the asperity contacts will still be equal to the local yield strength of the weaker material.

In the case of the current NOREM investigation, because both samples were of the same material, the local maximum contact stress at the asperities is expected to be the local yield strength of NOREM.

As such, local stresses at the asperities might be considerably higher than the nominal contact stress or even any increased stress due to local macroscopic contact geometry (edge effects). At these local stresses, welded junctions or raised prows can form during sliding and could result in galling initiation.

Comments on Friction

The two main contributions to high friction levels during flat-on-flat, unlubricated sliding are **plowing** and **adhesion**. **Plowing** refers to the resistance of a softer material to plastic (or elastic) deformation when an asperity, or some other protrusion, of a harder material is dragged across it. The result is often a series of furrows left behind in the softer material. In addition, a raised prow is formed in front of the contact during sliding. **Adhesion** refers to the resistance associated with the breaking of atomic level bonds that are formed when two materials are brought into sufficiently close proximity, typically at asperity contacts. The type and strength of bonds can vary from electrostatic to full metallic bonds (formed in “cold welded” junctions.) These latter bonds are essentially grain boundaries, and stresses on the order of the material shear strength are required to break them. As such, very small fractions of the contact area can dictate friction. With the austenitic matrix structure of NOREM, in unlubricated sliding, breaking these adhesive bonds could lead to severe surface damage. Surface contamination (wear debris or films) can also play a significant role, much in the way lubrication does. For example, oxygen films or some other contaminant can, in some cases, decrease adhesion and hence, friction.

Independent of the friction mechanisms, the COF is a mathematical definition. The COF represents the constant of proportionality between the force required to overcome the tangential resistance to sliding between two objects in motion relative to each other, and the force pressing the two objects together. The term “traction coefficient” is preferred when behavior other than smooth or normal sliding takes place, such as during galling when material is being removed and significant plastic deformation and damage is occurring. However, the mathematical definition is the same in both cases.

Comments on Galling

Although commonly used by engineers, galling is a term that is not generally favored by tribologists since it has no precise definition and cannot be readily predicted. Mechanistically, some contact phenomenon leads to severe damage of the surfaces in contact during sliding. Often, transfer of material from one surface to another, and possibly back, is observed. In lubricated contacts, the phenomenon is often referred to as “scuffing”, and is associated with a breakdown of the lubricant film, followed by the onset of adhesive wear. In unlubricated sliding contacts, either local junctions are formed, or an elastic/plastic prow is formed. High friction can also be a result of prow formation. There is a rise in local stress under the prow leading to either shearing of the material within the prow or junction interface, or, if it is sufficiently strong, shearing of some subsurface material. If the depth to which the imposed shear stress can be resisted is large, but a decreasing gradient of material strength or a local region of weaker material is present, the depth of damage is increased. The region of weaker material can be one in which fatigue has taken place or exhaustion of work hardening has occurred. Once material is ripped from the surface and is trapped in the interface, local stress concentrations are developed which further induce damage. The process is usually irreversible.

Galling is Influenced by Many Factors

1. **Cleanliness of surfaces –** Any contaminant that inhibits the adhesion of surfaces will increase galling resistance. Such “contaminants” include oxides, adsorbed hydrocarbons from the atmosphere, lubricants (including skin oils, residual machining lubricants, and deliberately applied oils, greases, soaps, or waxes), and wear debris. Clean surfaces of a material that either does not oxidize, or forms a very thin oxide, often readily gall.

2. **Material Compatibility –** Self-mated materials are more likely to form adhesive junctions than dissimilar materials. Rabinowicz[16] developed a compatibility ranking of materials based on their binary phase diagrams. The materials least likely to undergo adhesive wear, were materials that form two liquid phases (completely incompatible). The materials most likely to undergo adhesive wear were identical metals, followed by those with solid solubility greater than one percent.

3. **Surface Roughness –** The smoother and flatter a surface, the fewer locations are available to act as “sinks” for built-up prows or growing junctions. An analogy to consider is that of a special bull dozer trying to remove a few inches of dirt along a straight path. If the blade is infinitely wide and tall, and the ground over which it is moving is flat, none of the dirt can escape around, over, or beneath the blade. At some point the capacity of the machine to continue pushing the pile of dirt (i.e. the prow) will be exceeded, and the bull dozer’s forward progress will cease. However, if holes, crevices, or other depressions in the path allow dirt from the pile to be displaced, or if dirt can move around the edges of the blade, then the machine capacity will likely be sufficient to continue to make forward progress. The roughness of two surfaces in sliding contact is beneficial since it forms “sinks” for material build-up, which can decrease the propensity, or even inhibit galling.

[16] “Wear Coefficients”, in Wear Control Handbook, M.B. Peterson and W.O. Winer, Eds., ASME, pp. 491, 1980.

4. **Contact Size and Geometry –** Similar to the surface roughness effect, small area sliding contacts of a hemispherical geometry against a flat plate will often show a reduced galling tendency compared to that of a large flat contact. This is because material junctions or prows cannot grow to a critical size before they either escape out the back or to the sides of the contact. Prow growth is also minimized with shorter sliding distances.

5. **Thermal Considerations –** Heat can also increase the potential for galling initiation. In lubricated sliding, the breakdown of protective boundary lubricant films (leading to subsequent scuffing) is a thermally activated process. Through heat generation, test conditions such as stroke speed, elevated temperatures of the environment and long loaded stroke lengths potentially favor galling initiation.

6. **Strength, Ductility, and Structure of the Surface and Subsurface Layers –** The tangential forces resulting from the surface contact between two bodies in relative sliding motion under normal load penetrate to some depth below the surface. As long as the subsurface material is strong enough to resist these shear forces, it will remain intact. As such, it is not clear whether materials with high work hardening rates are beneficial or not. The propensity for galling depends on the imposed contact stress, the transmitted shear stress gradient, and the strength profile of the subsurface material. Additionally, significant volume fractions of hard and brittle second phases, such as carbides and borides, or structures that have limited ductility, such as martensite or intermetallic compounds, can contribute to galling resistance. The anti-galling mechanism is thought to be through the fracture of small junctions prior to transmission of stress deeper into the base material. Conversely, materials with high stacking fault energy (SFE), in which cross-slip of dislocations is relatively easy, tend to show lower work hardening rates. The SFE of austenitic stainless steels is considered high. The matrix phase of NOREM is essentially an austenitic stainless steel, although the work hardening characteristics of this phase have not been specifically measured. It is expected that significant plastic deformation can be accommodated locally in the matrix phase, between the carbide network, leading to large strain buildup at adhesive junctions or plastically deformed prows. This can result in an increased tendency to gall. In contrast, materials with limited dislocation cross-slip (low SFE), or those with strongly anisotropic preferred slip planes (materials possessing a hexagonal close packed structure with a high c/a ratio), tend to be resistant to galling, again due to fracture of junctions before significant strain can be built up.

There are clearly many factors that contribute to galling. The properties of the matrix phase of NOREM (high ductility, presumably high SFE, very thin native oxide), and the conditions of the tests performed in this study (large loaded sliding distances, flat contact area, elevated temperature, laboratory cleaned samples) tend to increase the potential for galling initiation. The previous work on NOREM performed at other laboratories did not impose similarly stringent conditions of cleanliness and sliding distance on the samples. As such, the results of this investigation are not in conflict with the results found in the earlier investigations.

6
SUMMARY OF PRINCIPAL OBSERVATIONS

Sliding wear tests were performed on the iron-base NOREM hardfacing alloy in two (ambient and autoclave rigs) friction and wear test rigs using specimens larger than those evaluated previously and making contact over large travel distances. The results show:

1. Both NOREM 02A deposited by gas tungsten arc welding (GTAW) and NOREM 02 deposited by plasma transferred arc welding (PTAW) exhibit acceptable (i.e., non-galling) behavior in flat-on-flat sliding friction and wear tests at nominal contact stresses of 10 ksi. Such testing was performed in deionized water at ambient temperature (70°F) where the loaded stroke length was 3 inches.

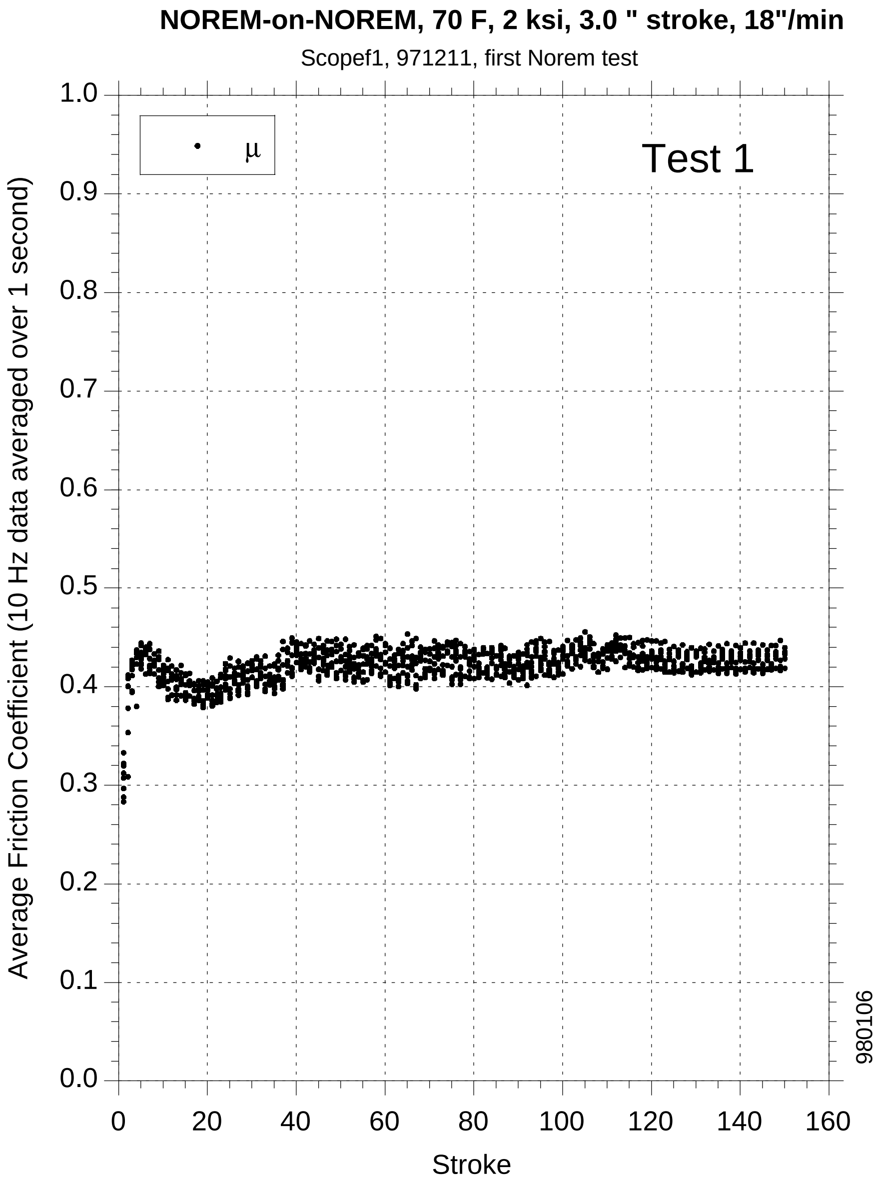
2. Both NOREM 02 and 02A exhibit non-galling behavior in flat-on-flat sliding friction and wear tests performed up to 15 ksi at temperatures up to 550°F provided the stroke length is less than ~0.5 inches.

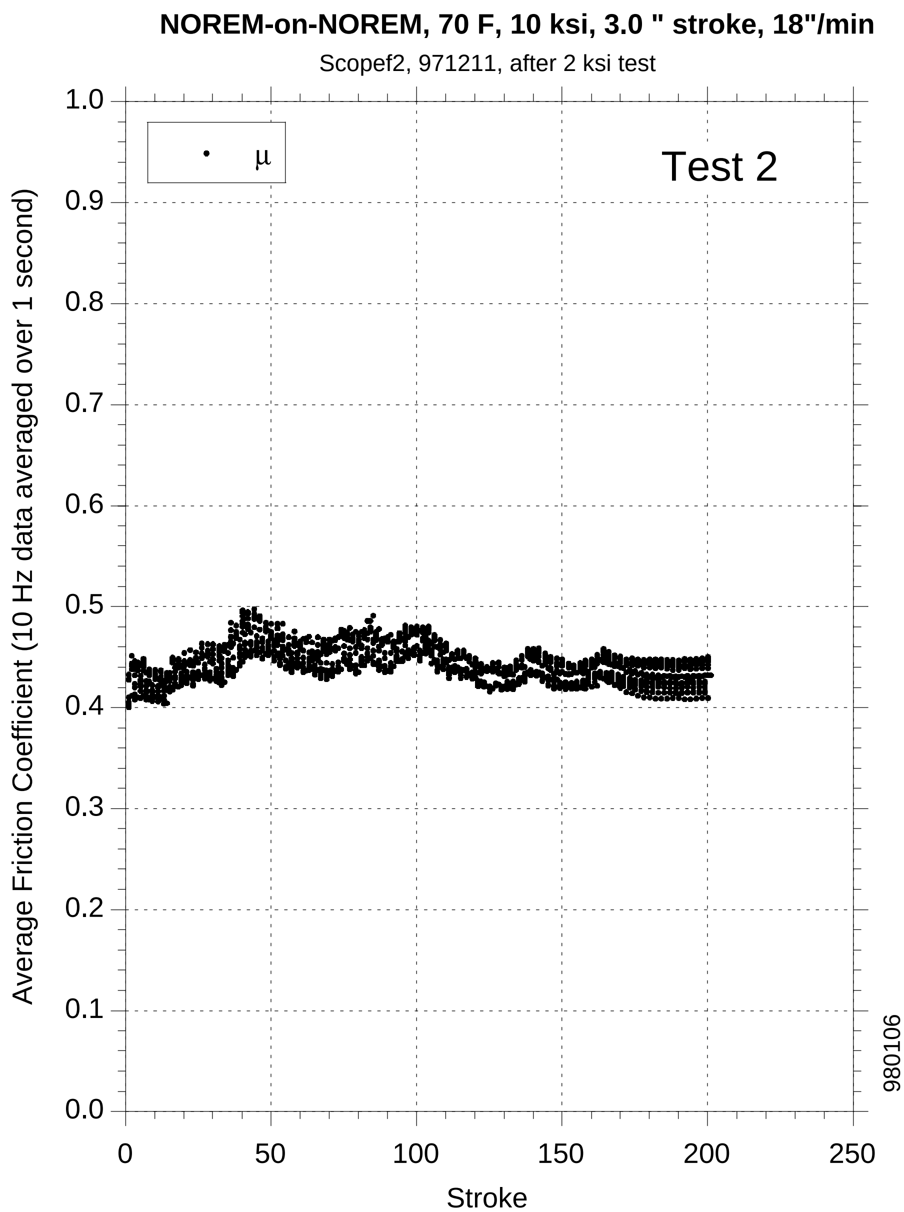
3. Galling of NOREM 02 and 02A was observed at stresses as low as 10 ksi in tests performed at 200°F where the stroke length was 3 inches. Galling of NOREM 02 was also observed after 70 strokes at 15 ksi and 200°F where the stroke length was 1.6 inches.

4. After 25 strokes, there was no evidence of galling in NOREM 02 in tests performed at 550°F where the stroke length was 1.6 inches at stresses of 10 and 15 ksi, but the observed heavy scoring after testing at 15 ksi suggests the alloy is near its anti-galling limit.

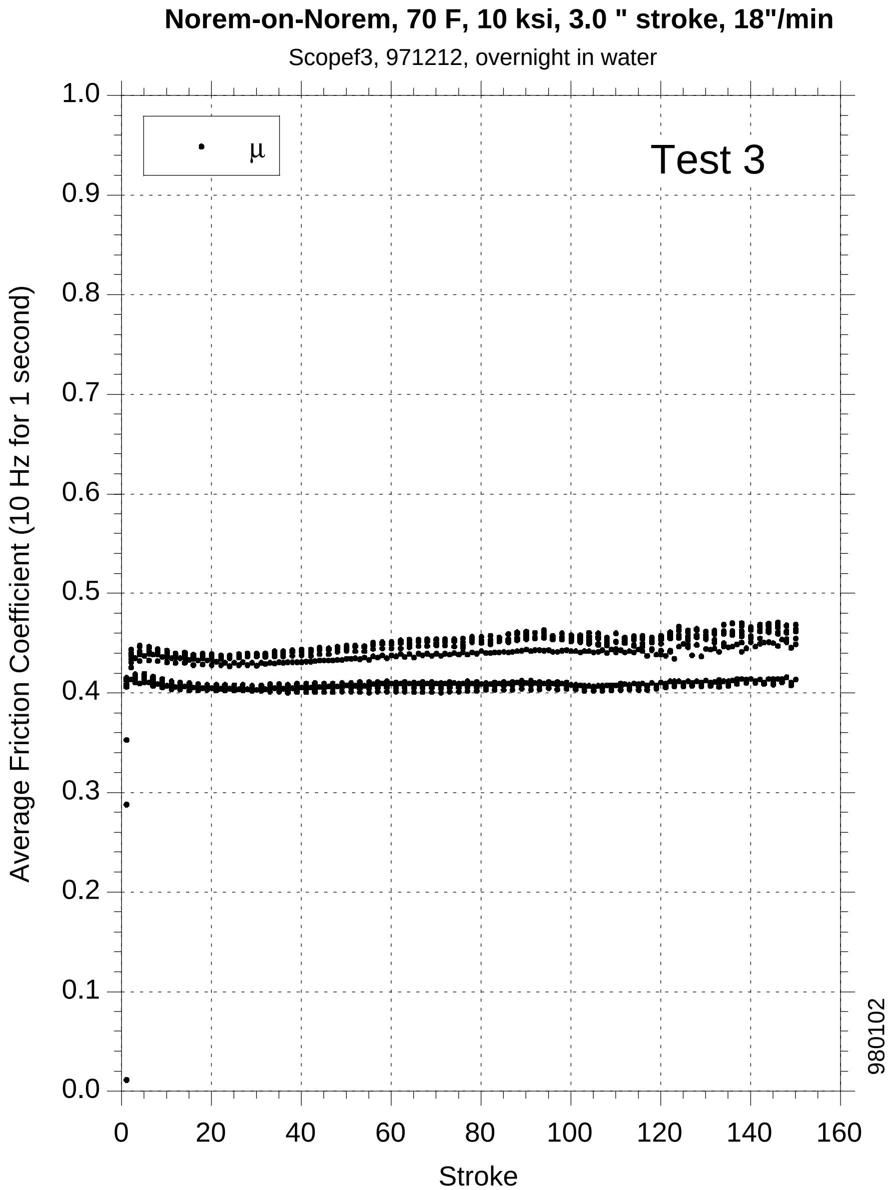
5. Tests of NOREM 02A against Stellite 6 at 10 ksi and 200°F where the stroke length was 3 inches exhibited acceptable performance. When the contact stress was increased significantly to 40 ksi, galling of the NOREM 02A material was observed.

A
SELECTED "COF VERSUS STROKE" AND/OR "COF VERSUS TIME" PLOTS: TEST SERIES 1

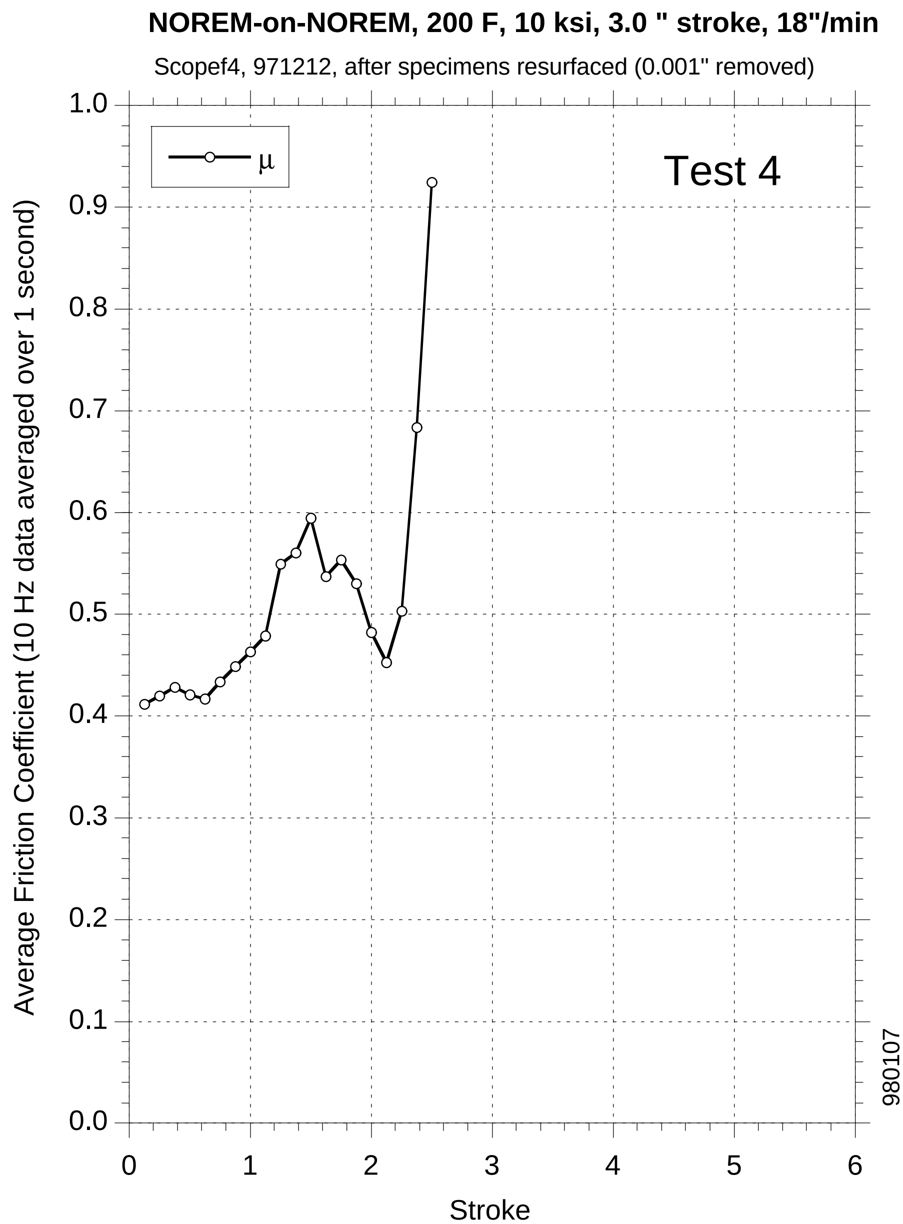

NOREM-on-NOREM, 70 F, 2 ksi, 3.0 " stroke, 18"/min
Scopef1, 971211, first Norem test
μ
Test 1
Average Friction Coefficient (10 Hz data averaged over 1 second)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
160
Stroke
980106

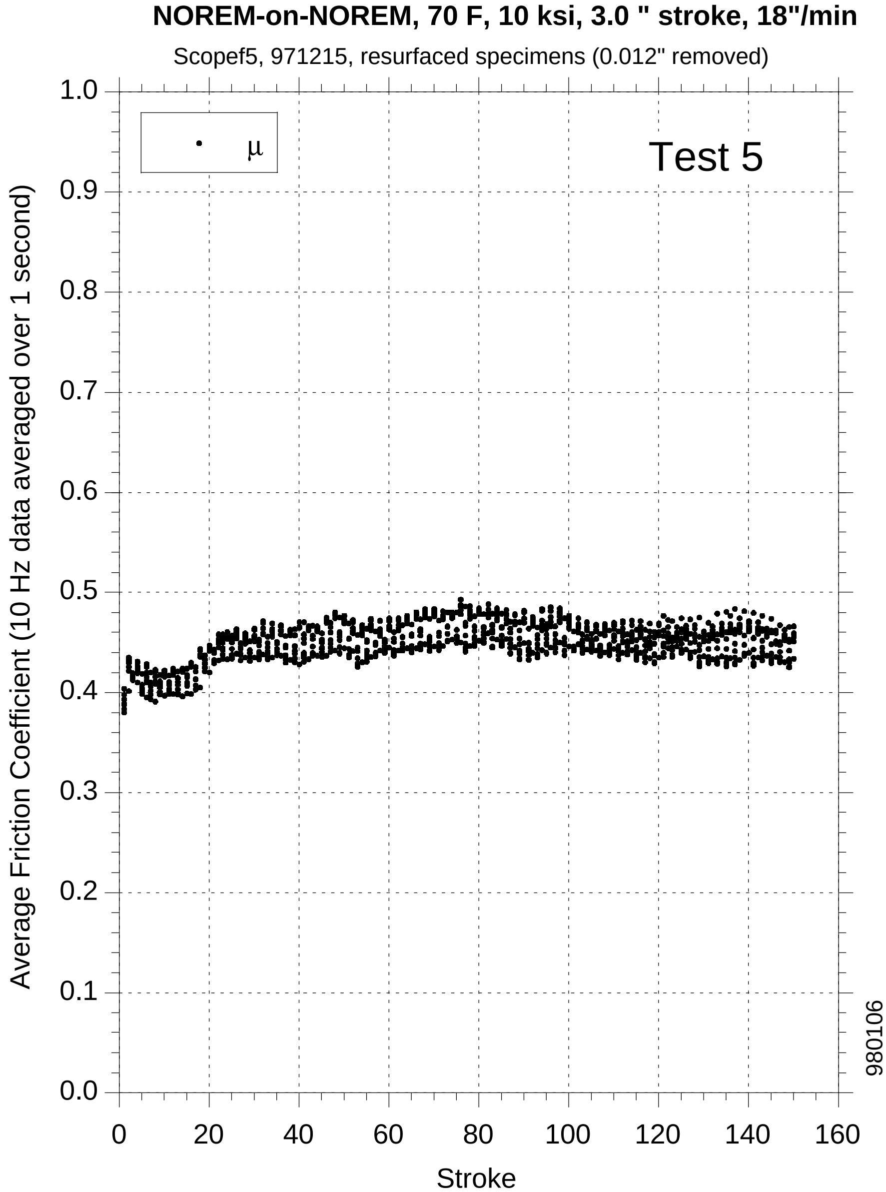


NOREM-on-NOREM, 70 F, 10 ksi, 3.0 " stroke, 18"/min
Scopef2, 971211, after 2 ksi test
μ
Test 2
Average Friction Coefficient (10 Hz data averaged over 1 second)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
200
250
Stroke
980106

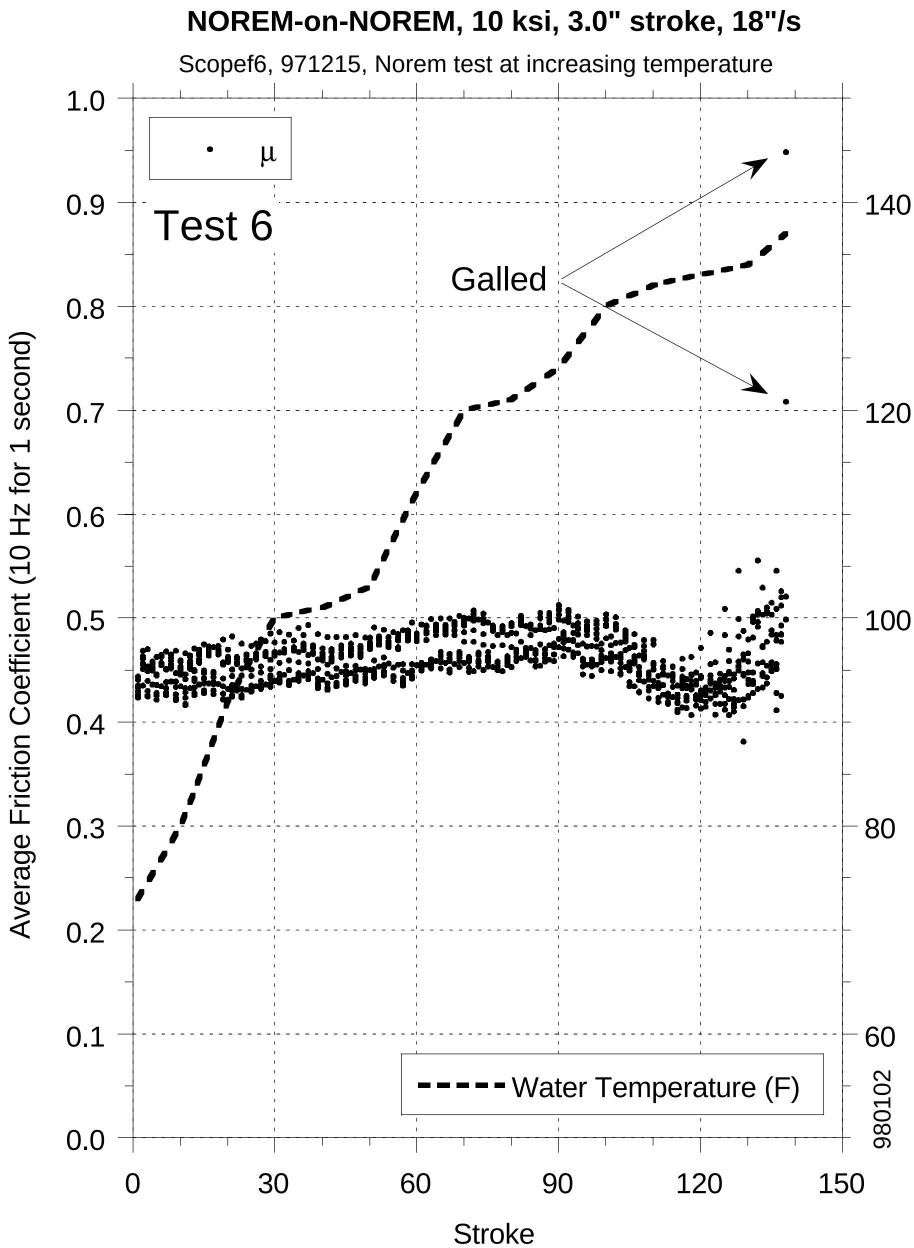

Norem-on-Norem, 70 F, 10 ksi, 3.0 " stroke, 18"/min
Scopef3, 971212, overnight in water
μ
Test 3
Average Friction Coefficient (10 Hz for 1 second)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
20
40
60
80
100
120
140
160
Stroke
980102

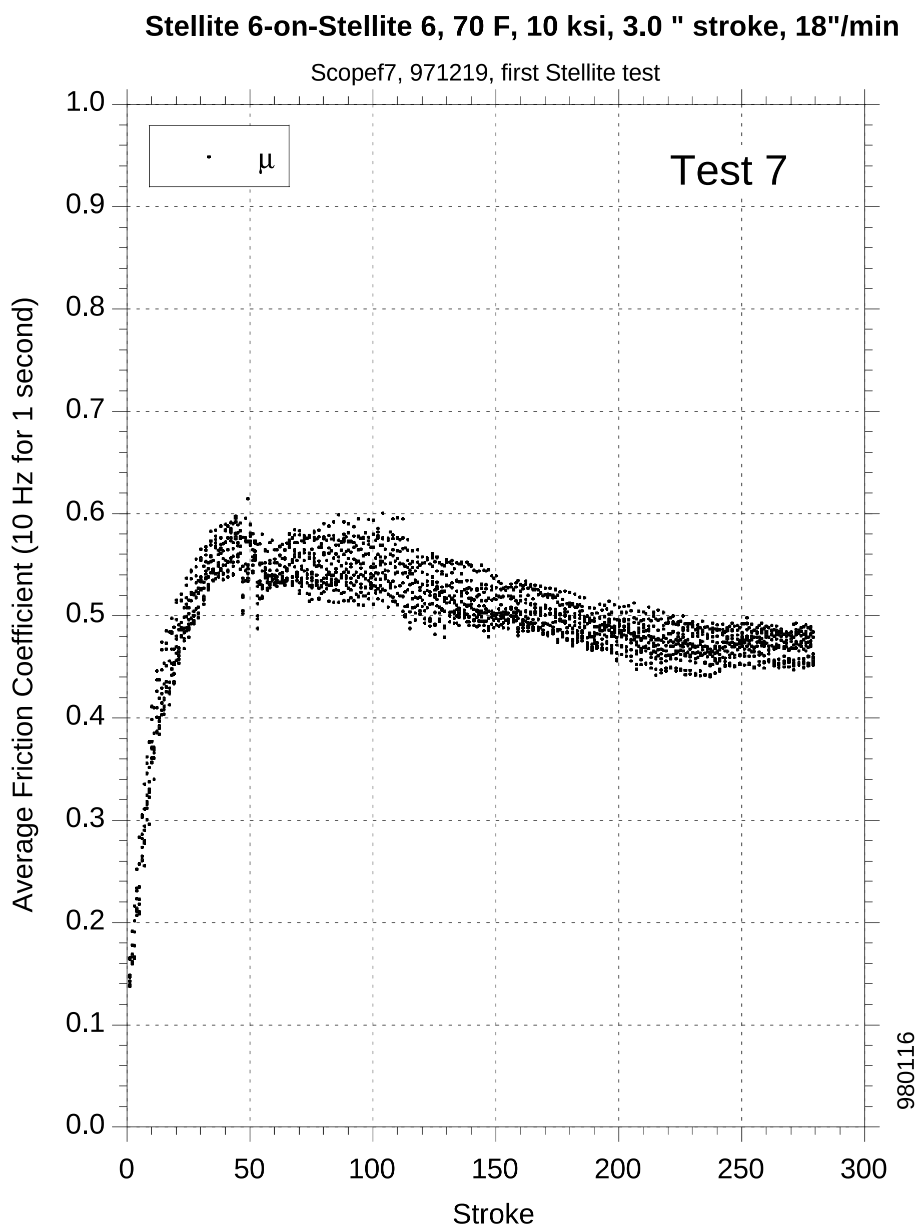
Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1



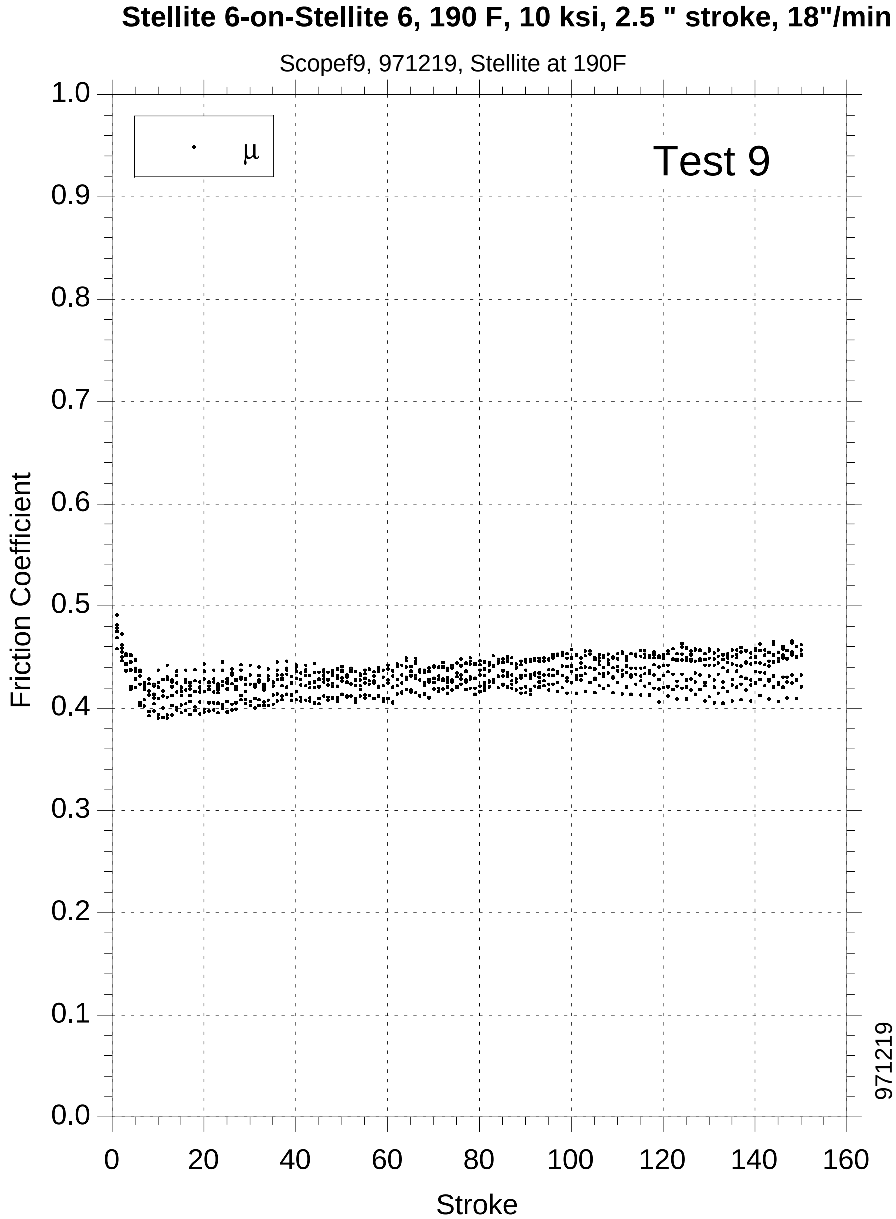

NOREM-on-NOREM, 70 F, 10 ksi, 3.0 " stroke, 18"/min
Scopef5, 971215, resurfaced specimens (0.012" removed)
μ
Test 5
Average Friction Coefficient (10 Hz data averaged over 1 second)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
160
Stroke
980106

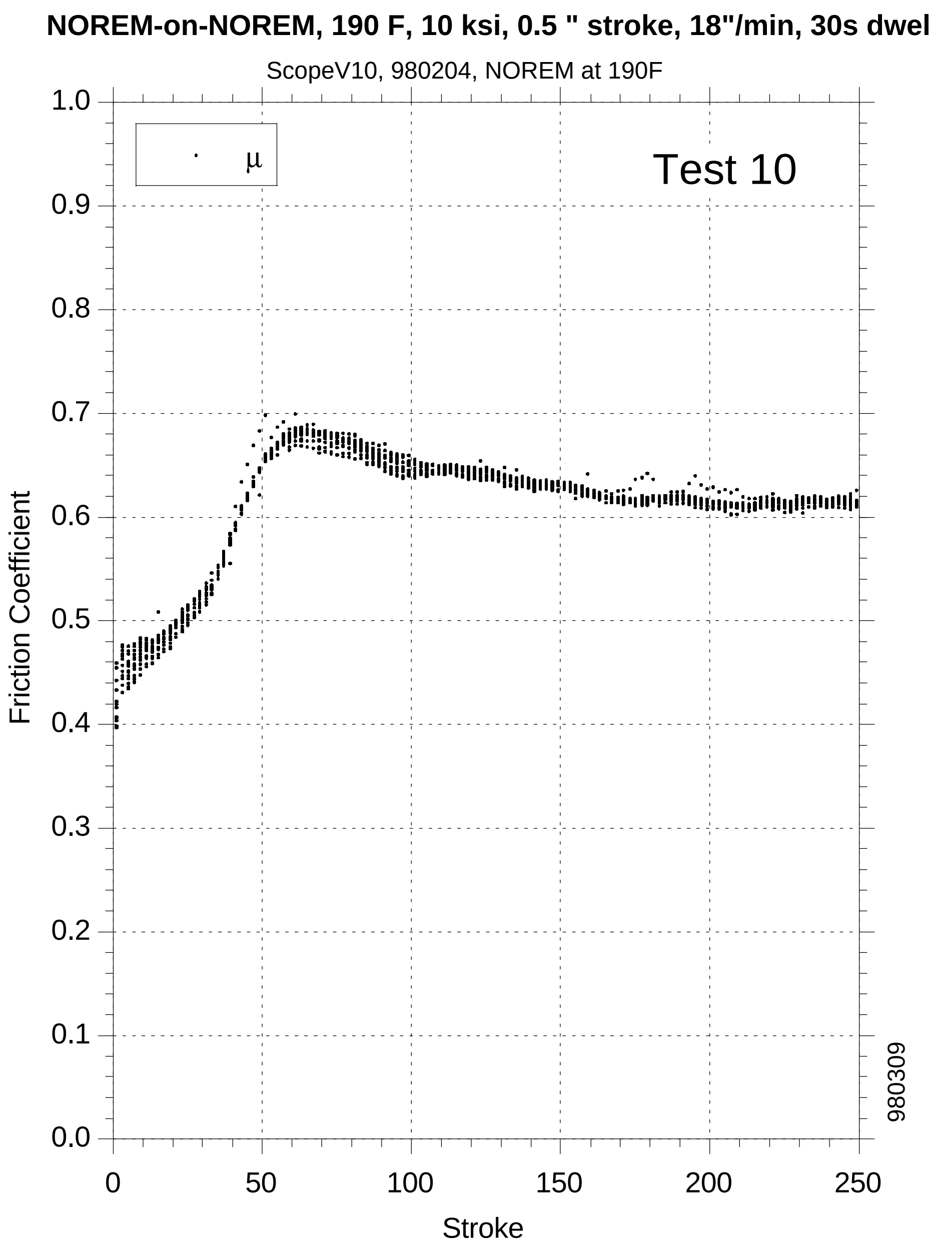
Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1



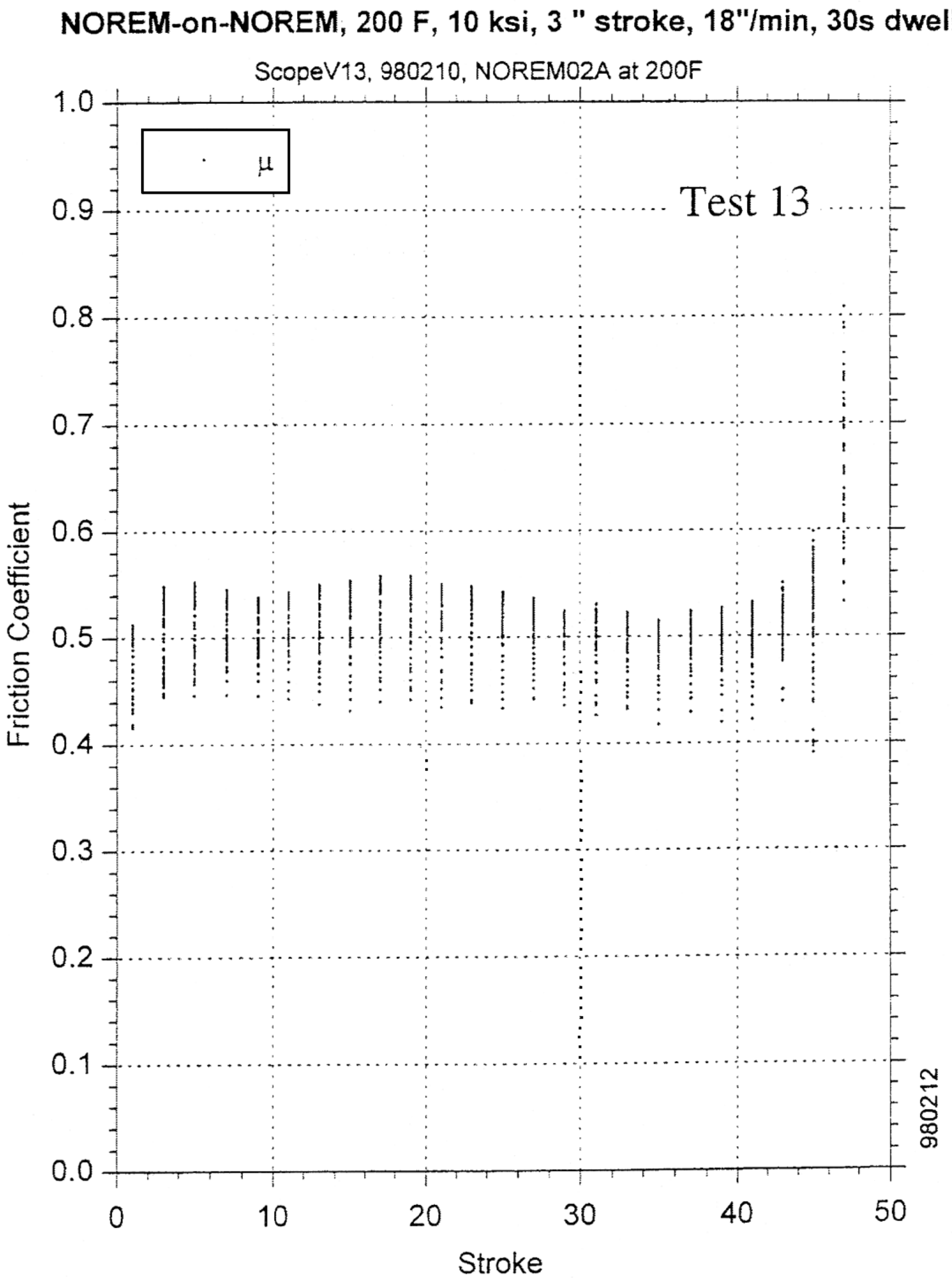

Stellite 6-on-Stellite 6, 70 F, 10 ksi, 3.0 " stroke, 18"/min
Scopef7, 971219, first Stellite test
μ
Test 7
Average Friction Coefficient (10 Hz for 1 second)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
200
250
300
Stroke
980116

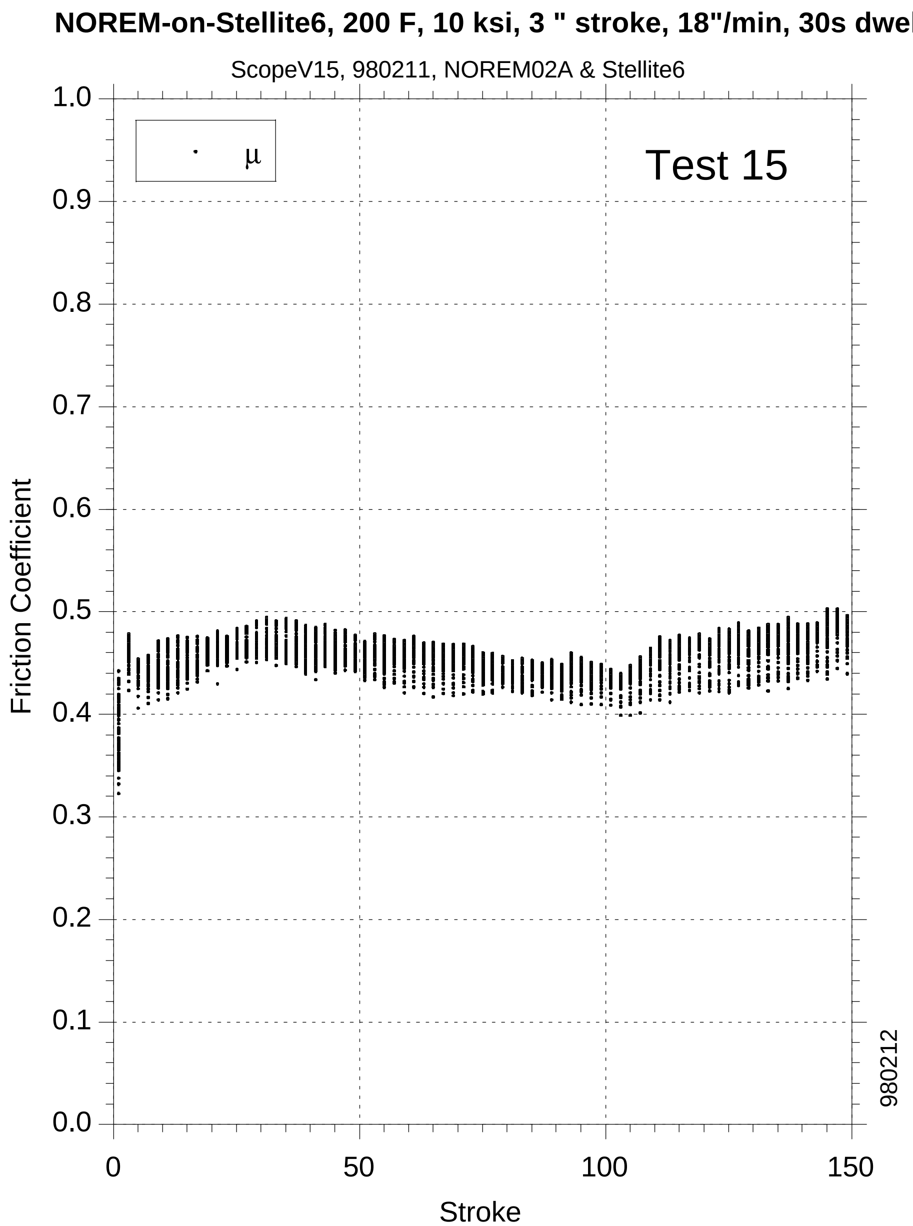
Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1

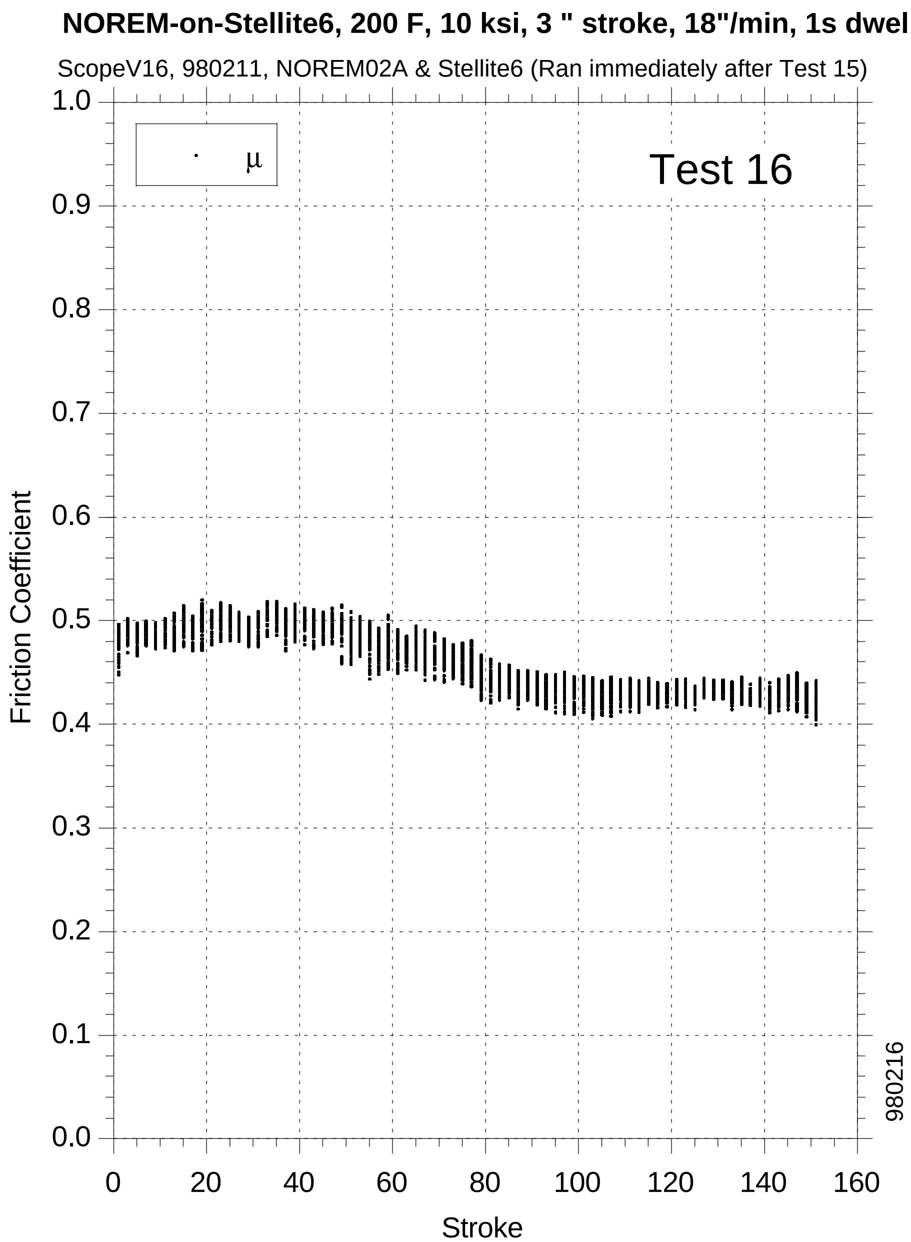


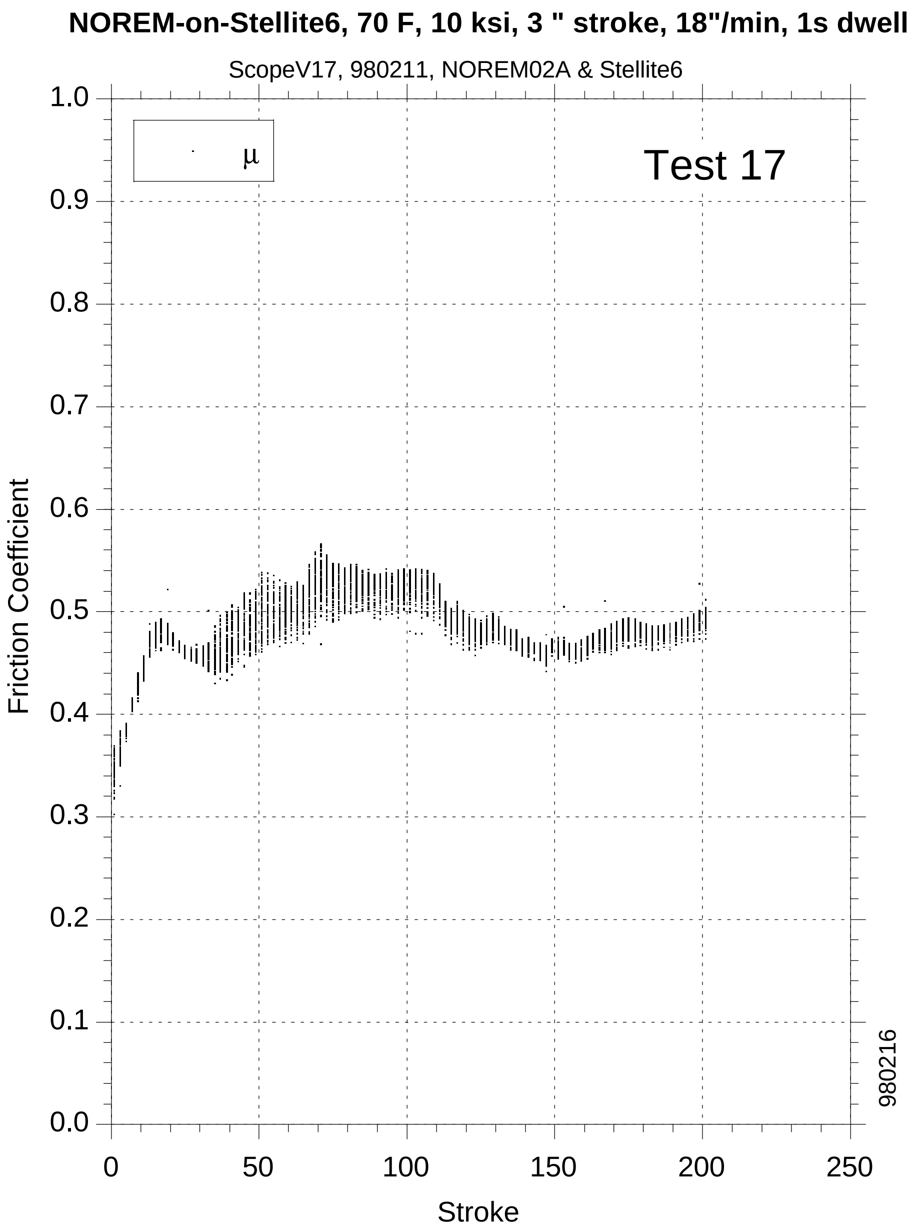

NOREM-on-NOREM, 190 F, 10 ksi, 0.5 " stroke, 18"/min, 30s dwel
ScopeV10, 980204, NOREM at 190F
μ
Test 10
Friction Coefficient
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
200
250
Stroke
980309

Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1

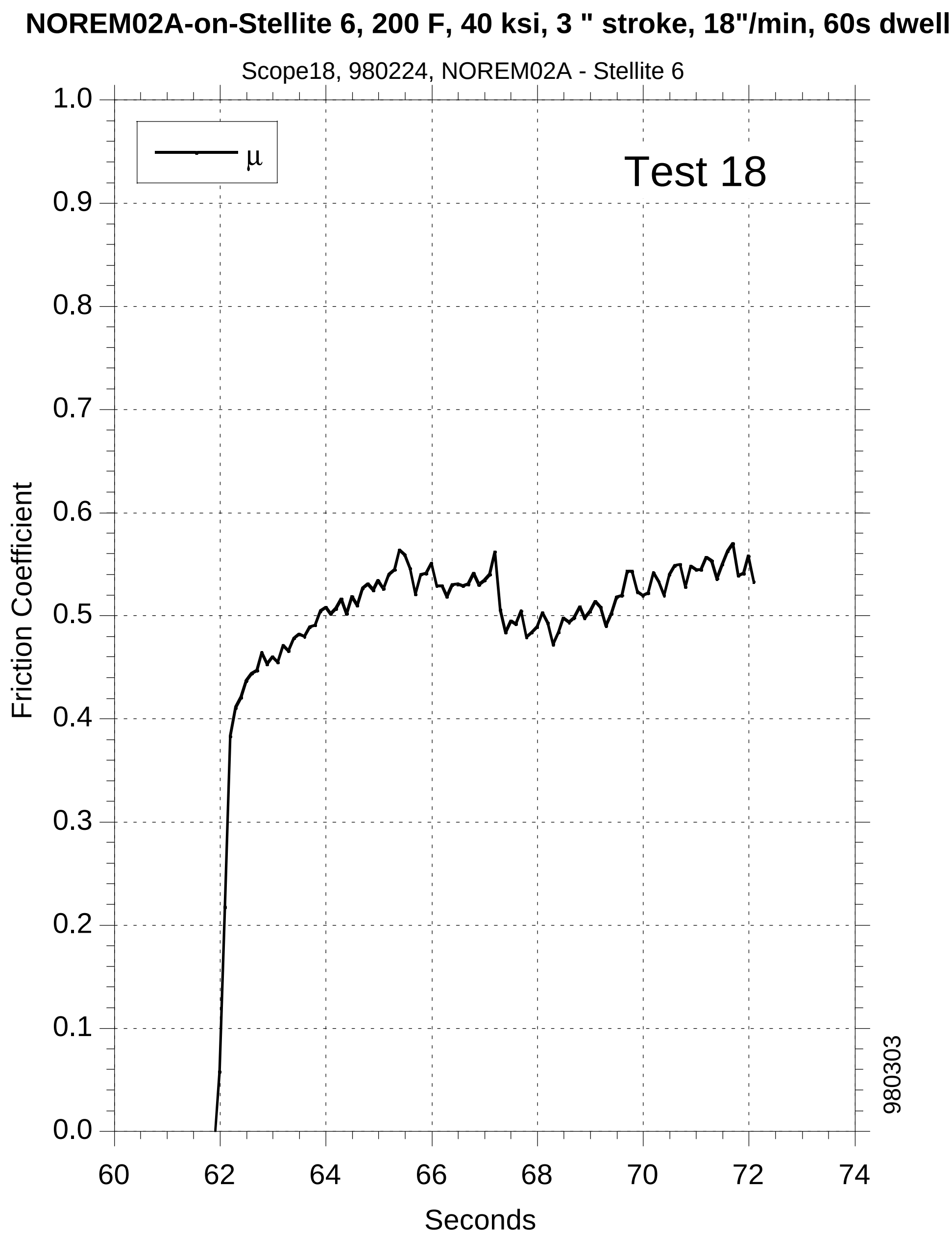


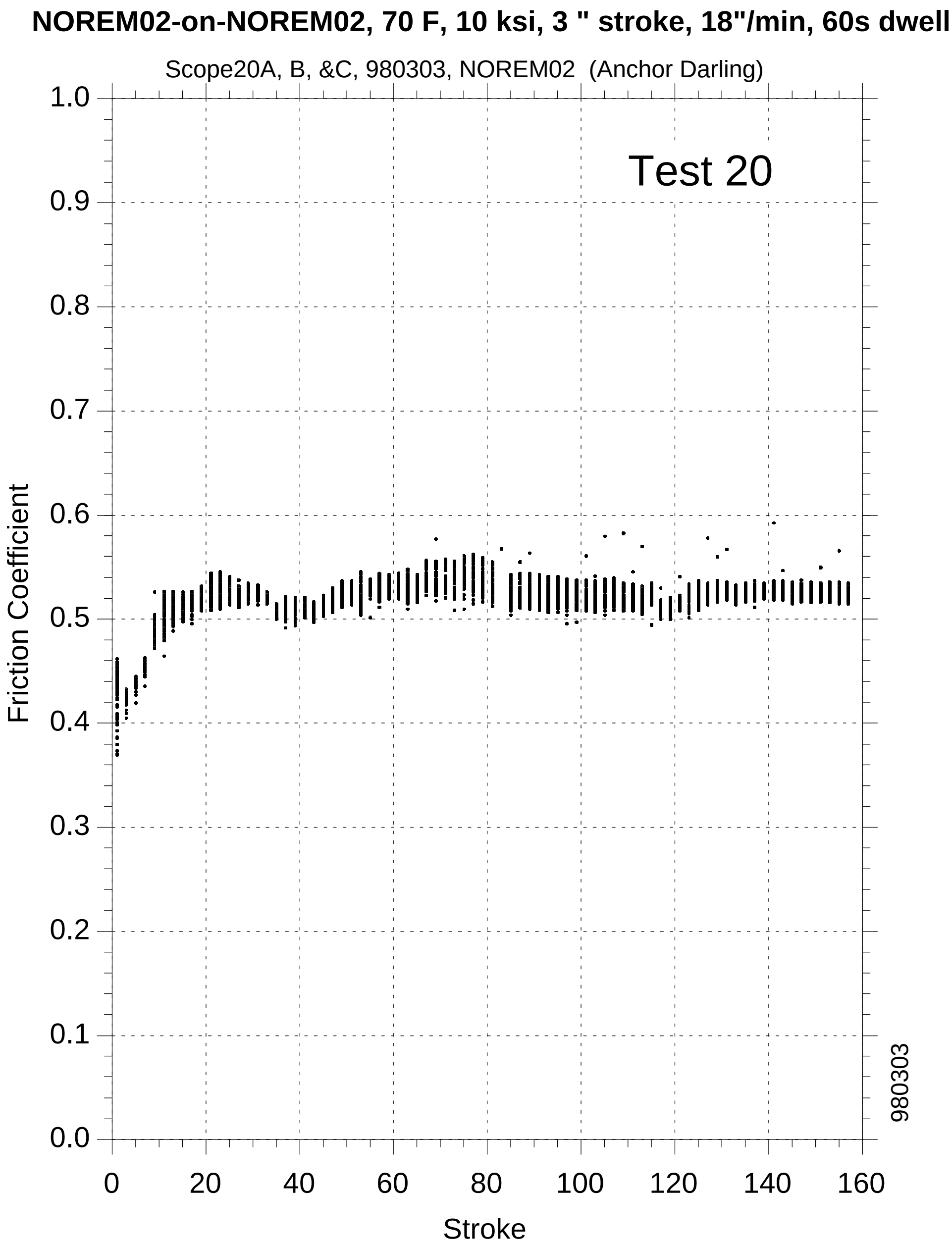

NOREM-on-Stellite6, 200 F, 10 ksi, 3 " stroke, 18"/min, 30s dwell
ScopeV15, 980211, NOREM02A & Stellite6
μ
Test 15
Friction Coefficient
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
Stroke
980212


NOREM-on-Stellite6, 200 F, 10 ksi, 3 " stroke, 18"/min, 1s dwell
ScopeV16, 980211, NOREM02A & Stellite6 (Ran immediately after Test 15)
μ
Test 16
Friction Coefficient
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
20
40
60
80
100
120
140
160
Stroke
980216

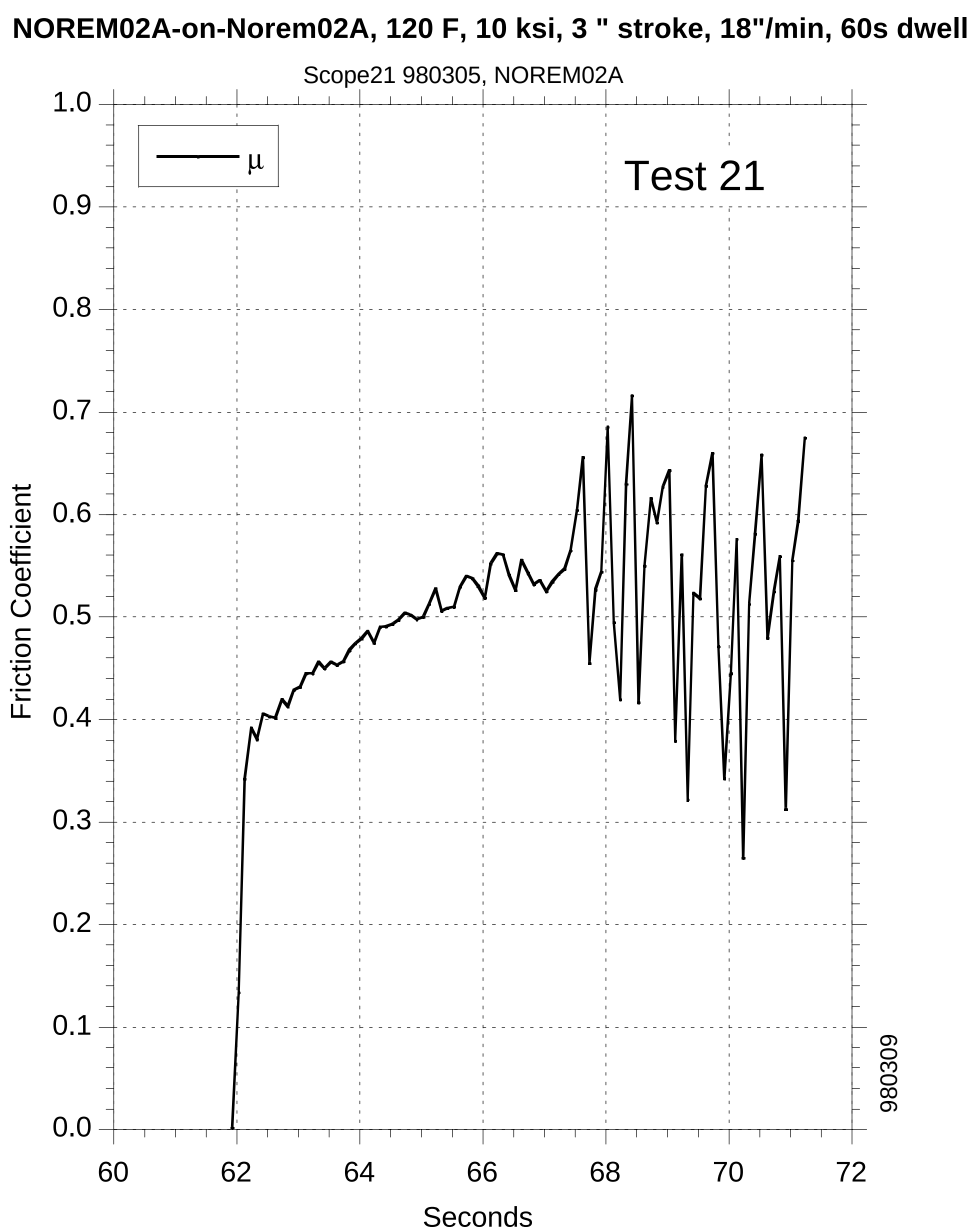

NOREM-on-Stellite6, 70 F, 10 ksi, 3 " stroke, 18"/min, 1s dwell
ScopeV17, 980211, NOREM02A & Stellite6
μ
Test 17
Friction Coefficient
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
200
250
Stroke
980216

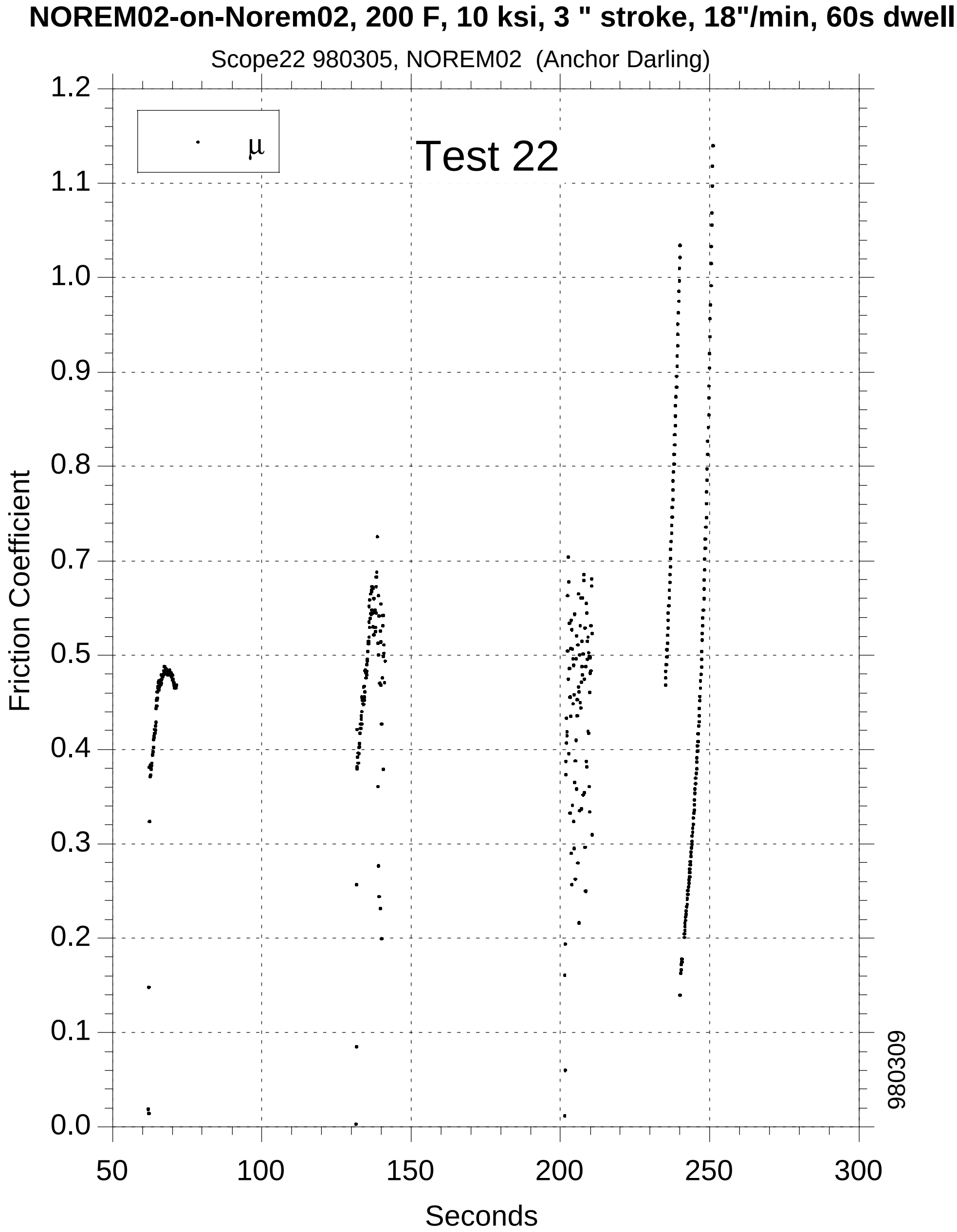
Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1



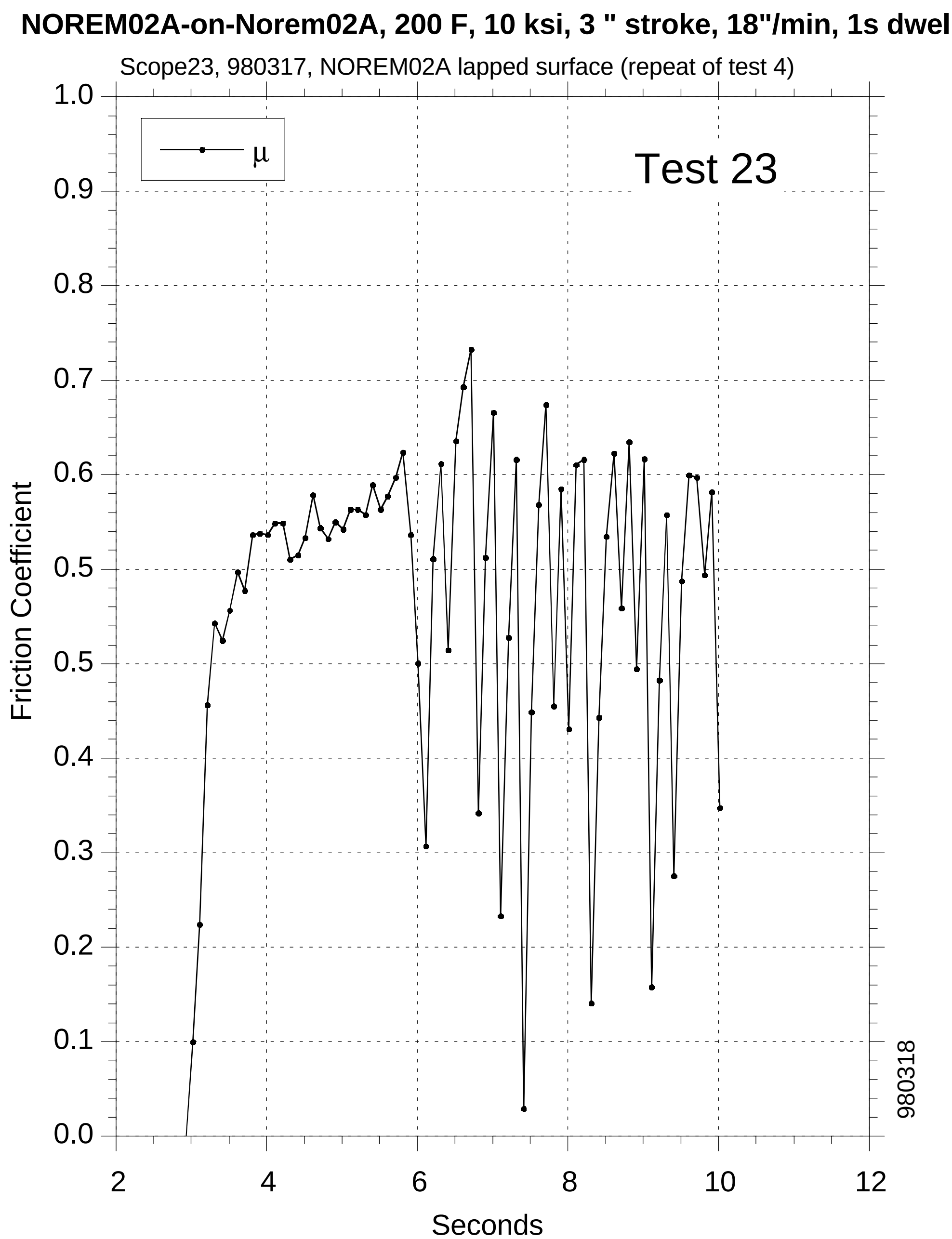

NOREM02-on-NOREM02, 70 F, 10 ksi, 3 " stroke, 18"/min, 60s dwell
Scope20A, B, &C, 980303, NOREM02 (Anchor Darling)
Test 20
Friction Coefficient
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
160
Stroke
980303

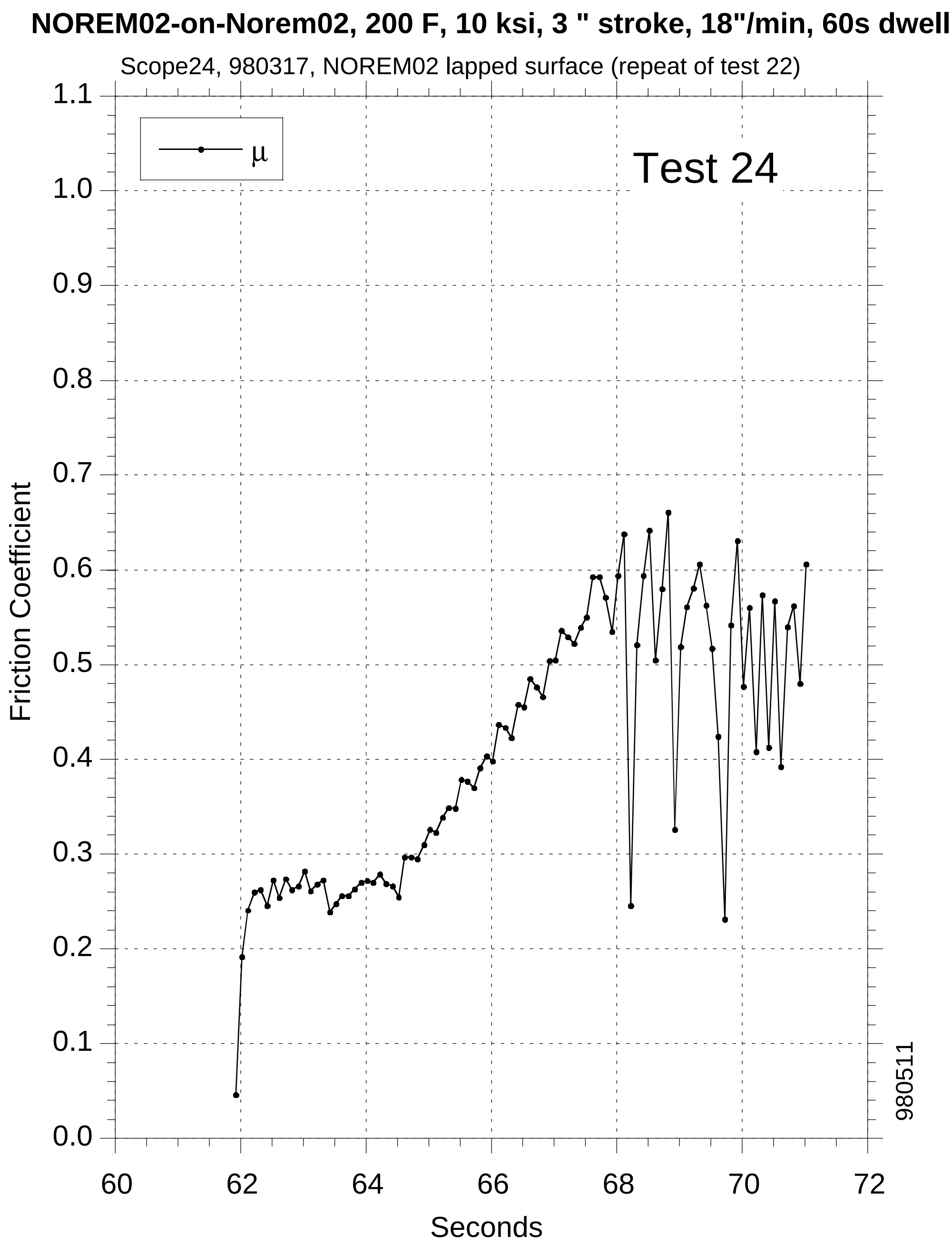
Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1



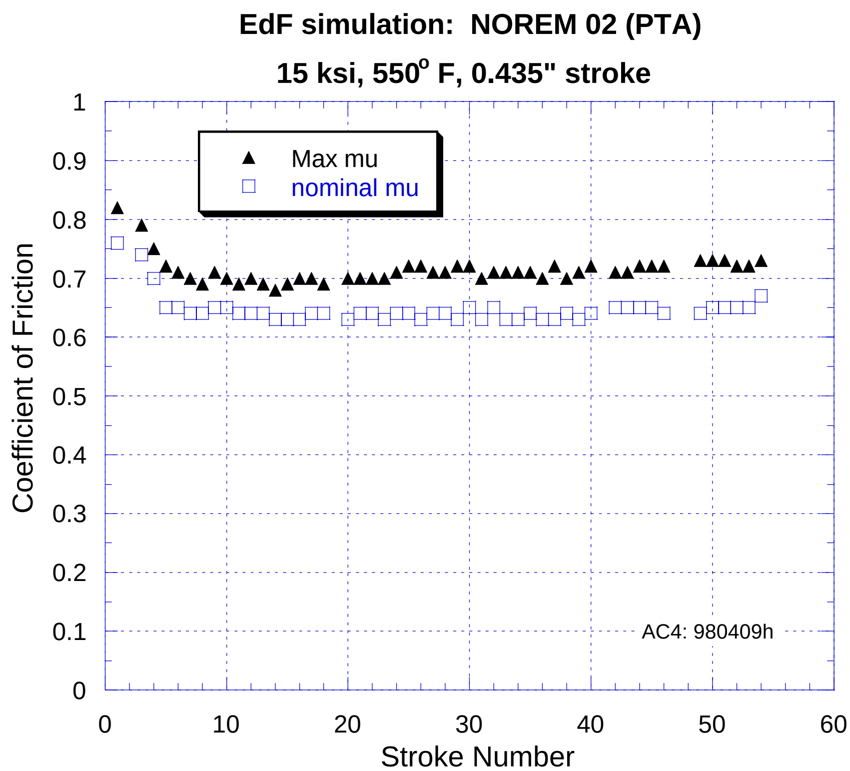

NOREM02-on-Norem02, 200 F, 10 ksi, 3 " stroke, 18"/min, 60s dwell
Scope22 980305, NOREM02 (Anchor Darling)
μ
Test 22
Friction Coefficient
0.0
0.1
0.2
0.3
0.4
0.5
0.7
0.8
0.9
1.0
1.1
1.2
50
100
150
200
250
300
Seconds
980309

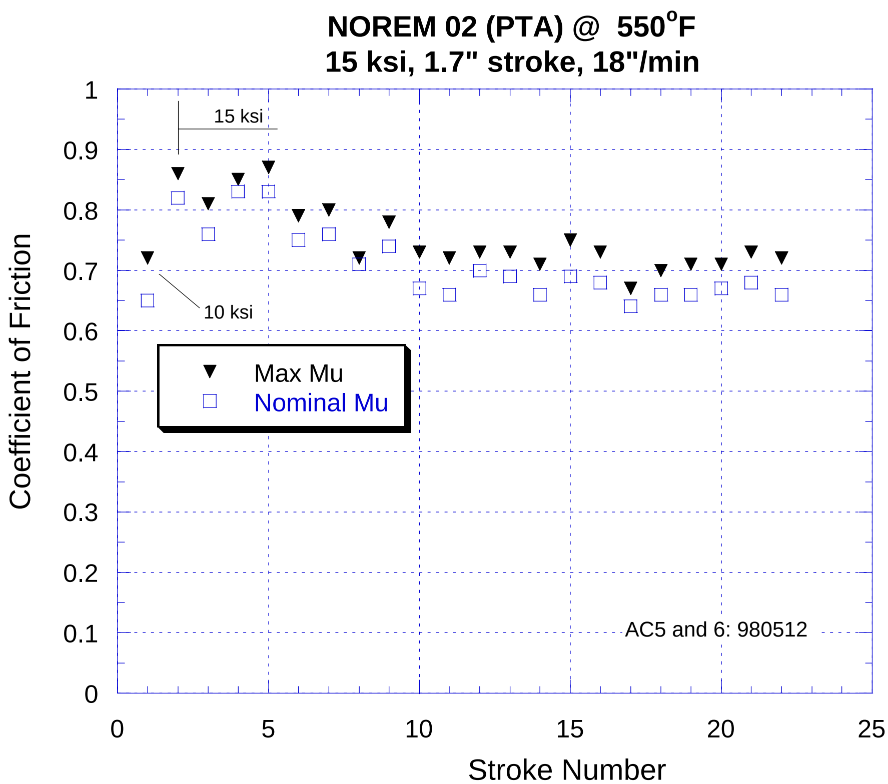
Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1



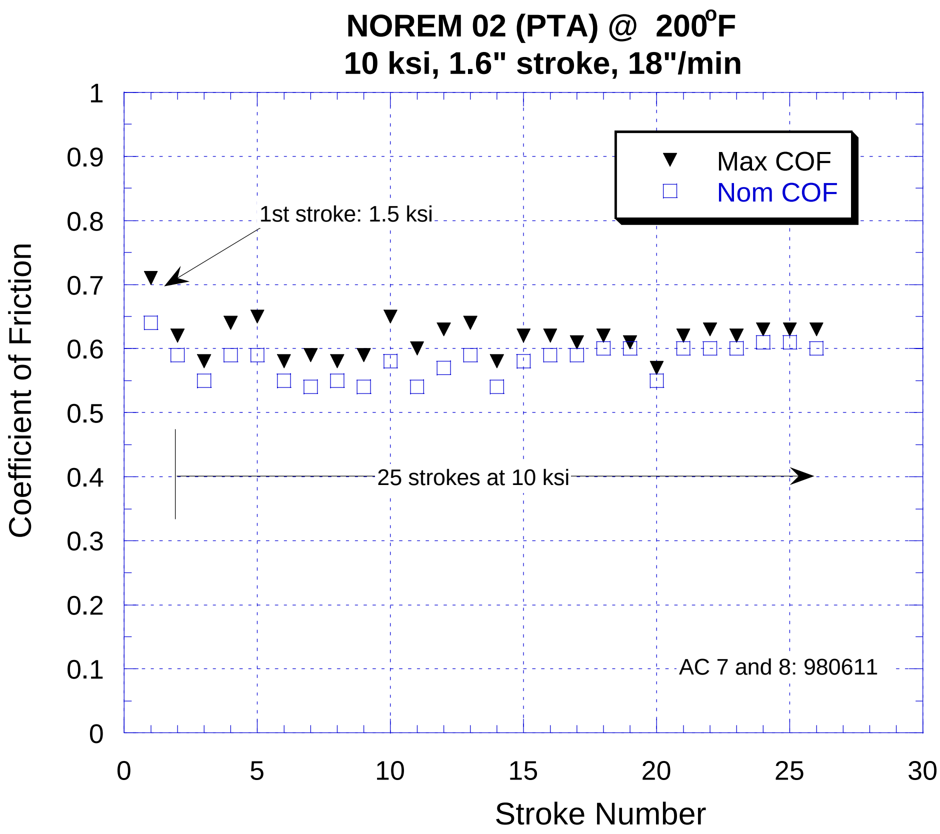

NOREM02-on-Norem02, 200 F, 10 ksi, 3 " stroke, 18"/min, 60s dwell
Scope24, 980317, NOREM02 lapped surface (repeat of test 22)
μ
Test 24
Friction Coefficient
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
60
62
64
66
68
70
72
Seconds
980511

Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1




NOREM 02 (PTA) @ 550°F
15 ksi, 1.7" stroke, 18"/min
Coefficient of Friction
Stroke Number
15 ksi
10 ksi
Max Mu
Nominal Mu
AC5 and 6: 980512
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25

Selected "COF Versus Stroke" and/or "COF Versus Time" Plots: Test Series 1



B
SELECTED "COF VERSUS STROKE" AND/OR "COF VERSUS TIME" PLOTS: TEST SERIES 2

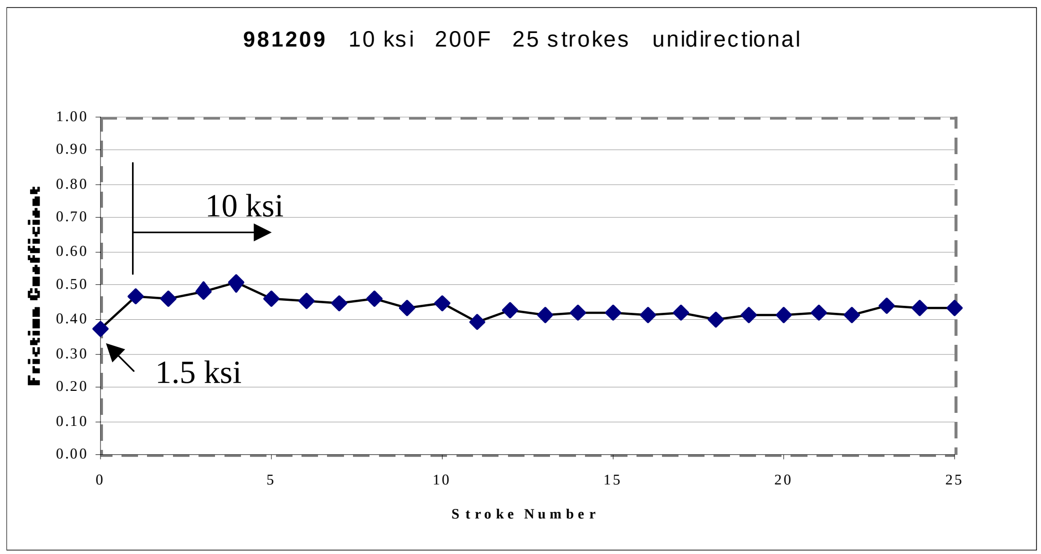
AM0 A: 1 Preconditioning Stroke at 1.5 ksi
&
AM0 B: 25 Strokes at 10 ksi

200°F

1.6" Stroke Length

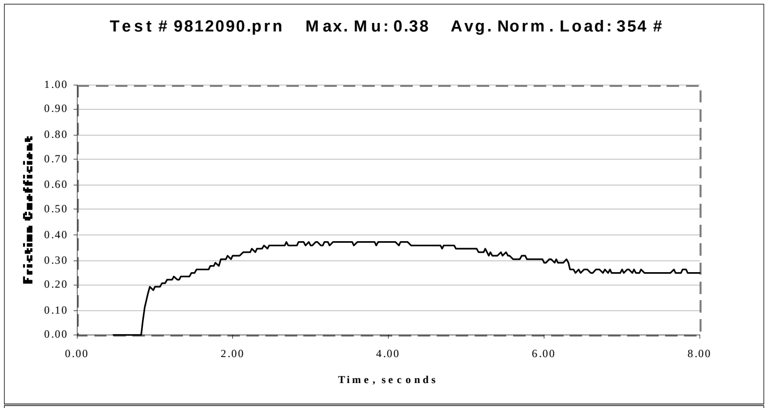
AM0 12/09/98 Norem 02 200F 10ksi 25 strokes/uni

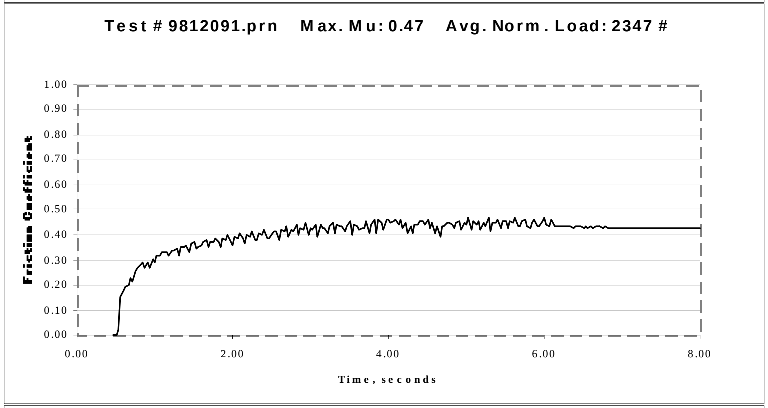
	Max. Mu:	Avg. Norm. Load:
9812090.prn	0.38	354
9812091.prn	0.47	2347
9812092.prn	0.47	2355
9812093.prn	0.49	2345
9812094.prn	0.51	2351
9812095.prn	0.47	2348
9812096.prn	0.46	2349
9812097.prn	0.45	2350
9812098.prn	0.47	2352
9812099.prn	0.44	2350
98120910.prn	0.45	2352
98120911.prn	0.39	2350
98120912.prn	0.43	2351
98120913.prn	0.42	2350
98120914.prn	0.42	2351
98120915.prn	0.42	2354
89120916.prn	0.42	2350
98120917.prn	0.42	2348
98120918.prn	0.40	2356
98120919.prn	0.42	2352
98120920.prn	0.42	2352
98120921.prn	0.42	2351
98120922.prn	0.42	2356
98120923.prn	0.44	2354
98120924.prn	0.44	2354
98120925.prn	0.44	2353

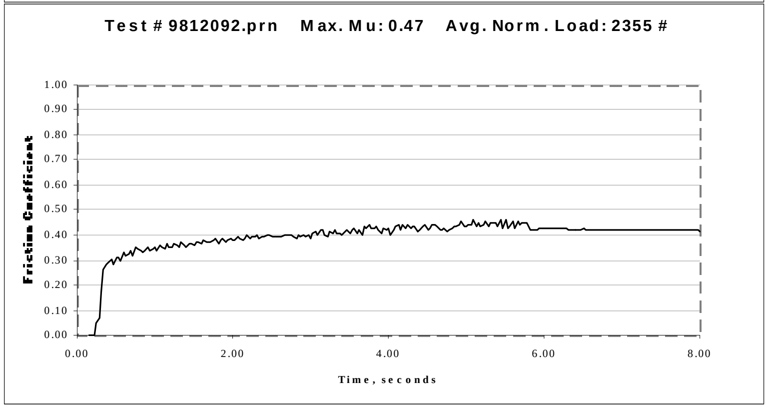


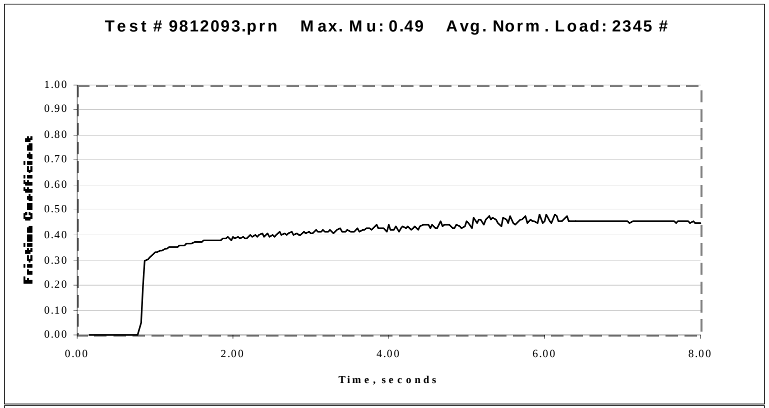
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

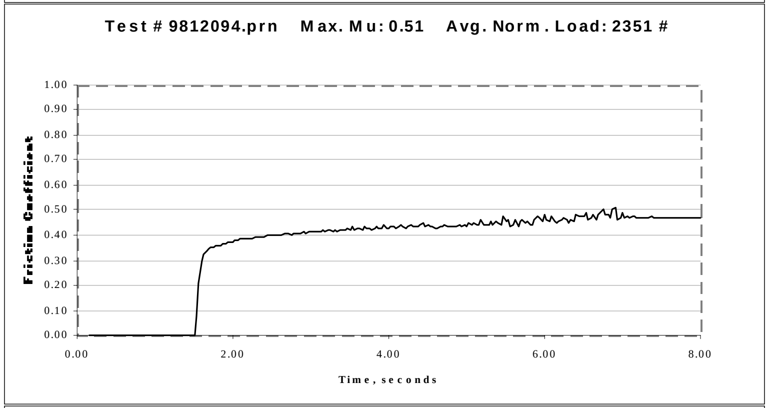
AM0 12/09/98 Norem 02 200F 10ksi 25 strokes/uni

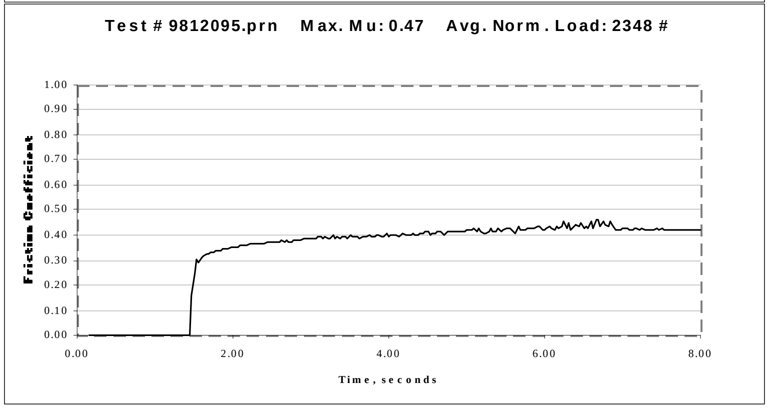




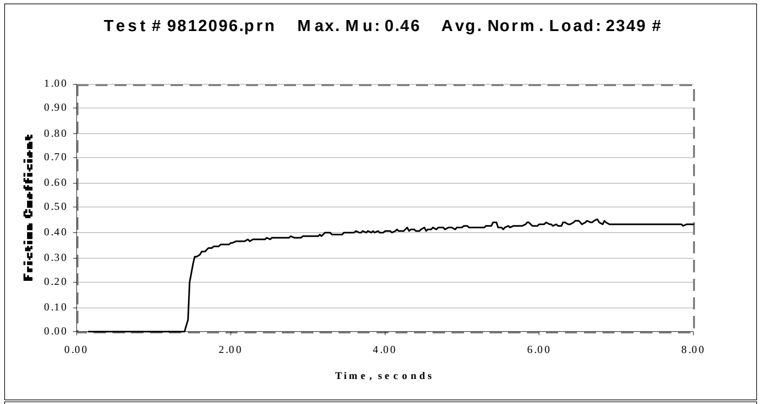


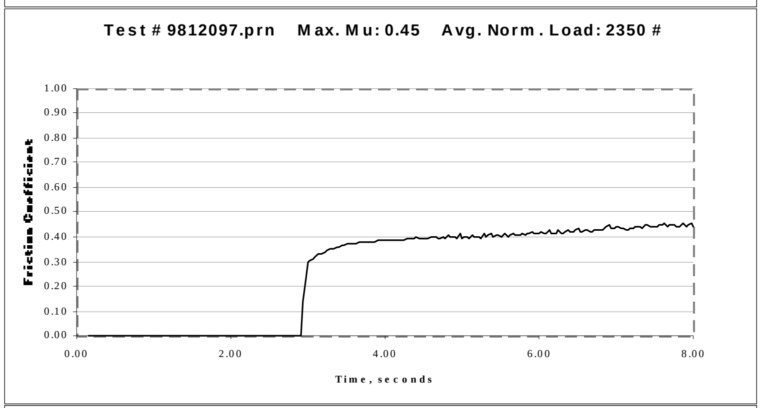


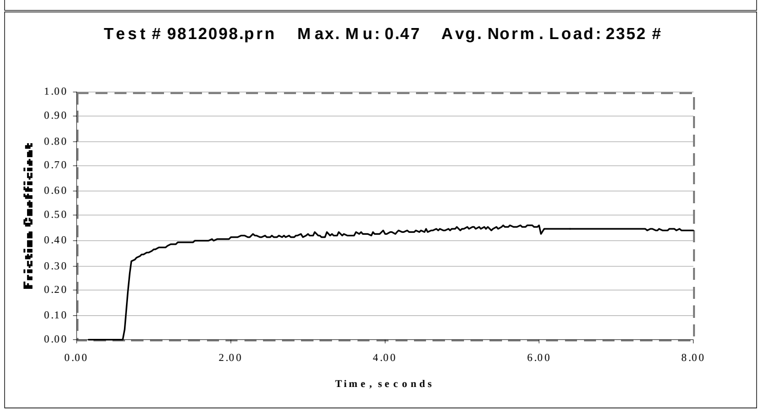


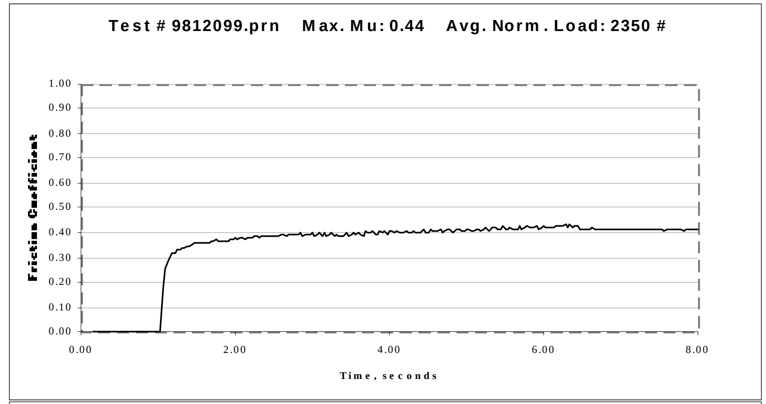


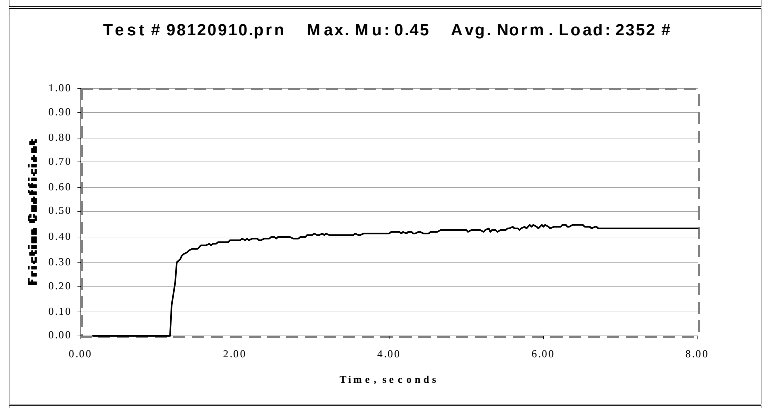
AM0 12/09/98 Norem 02 200F 10ksi 25 strokes/uni

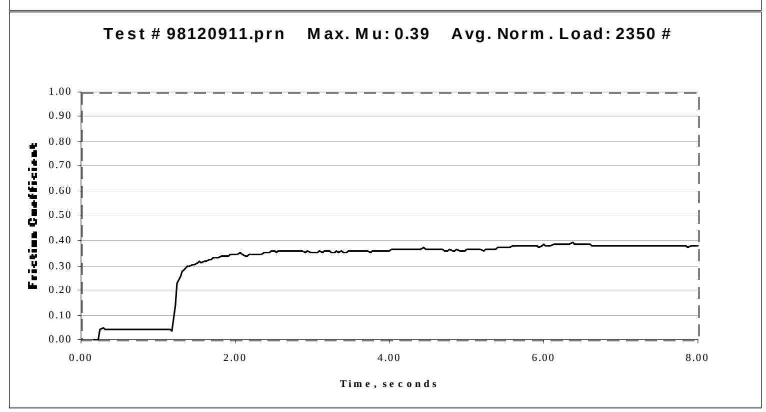






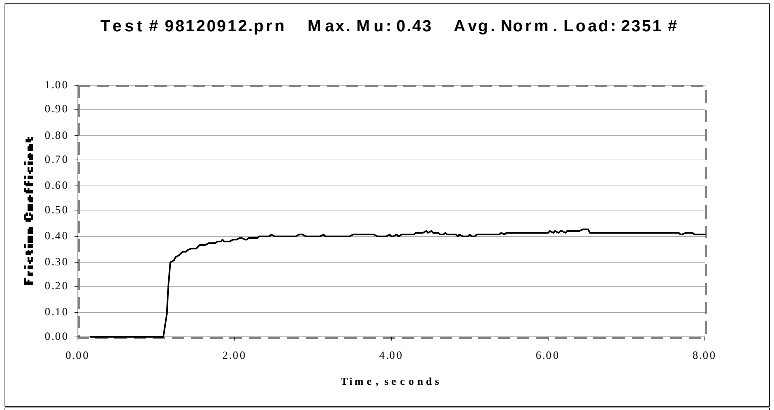


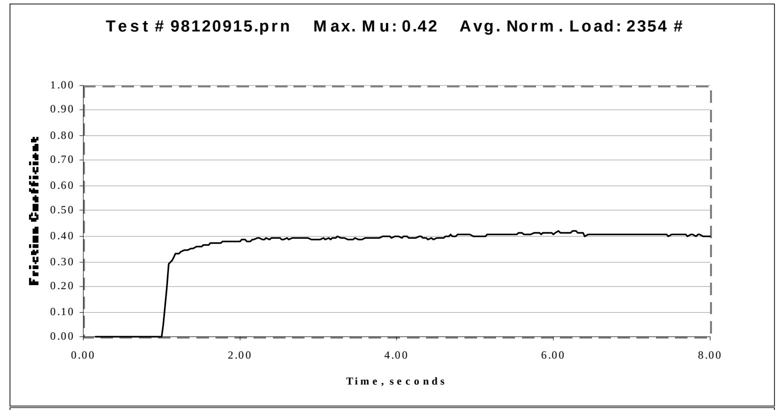


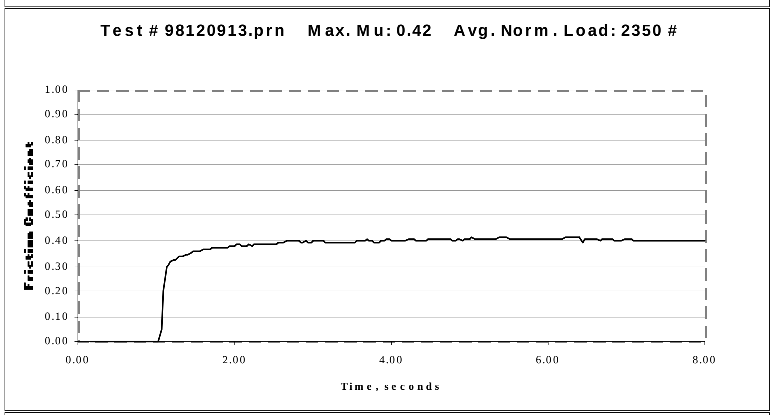


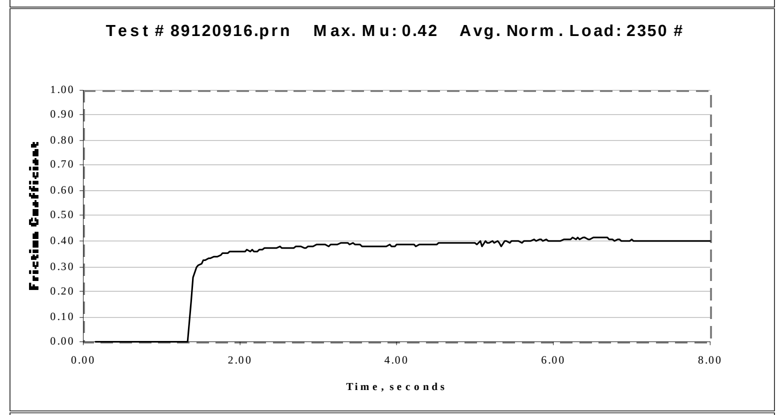
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

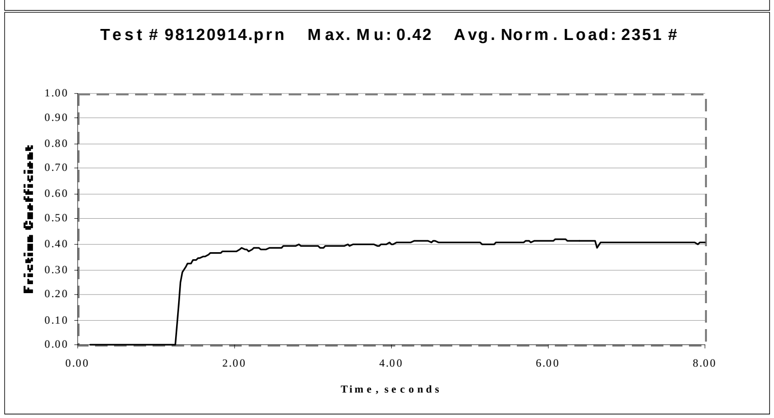
AM0 12/09/98 Norem 02 200F 10ksi 25 strokes/uni

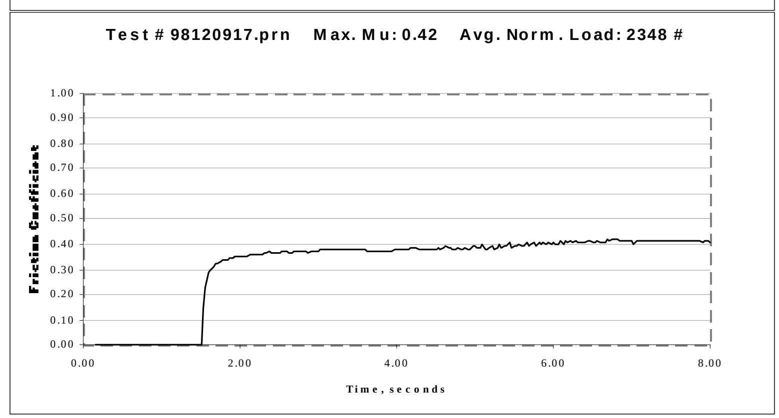




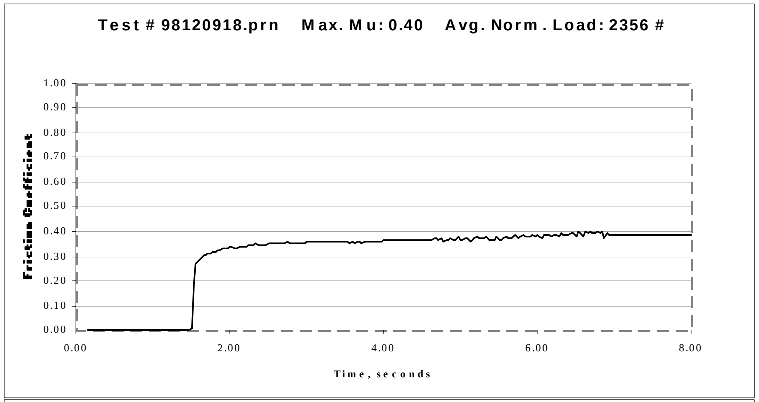


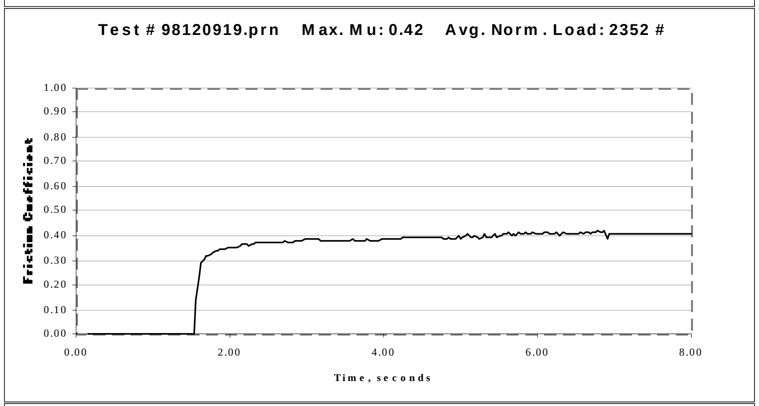


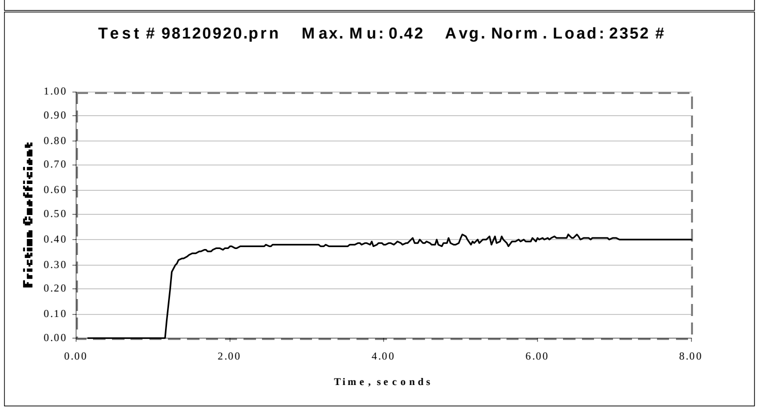


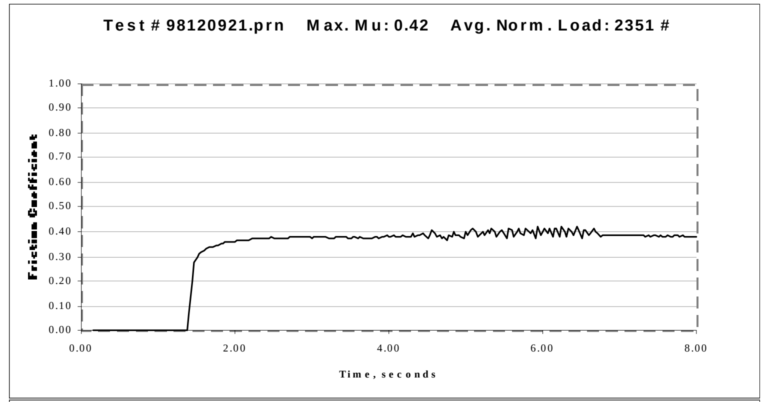


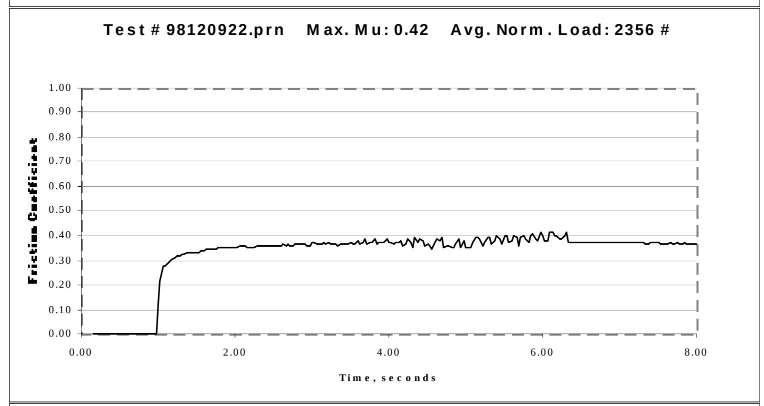
AM0 12/09/98 Norem 02 200F 10ksi 25 strokes/uni

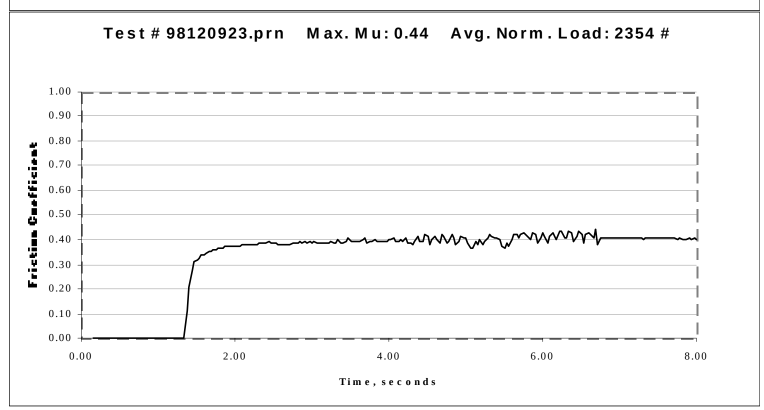






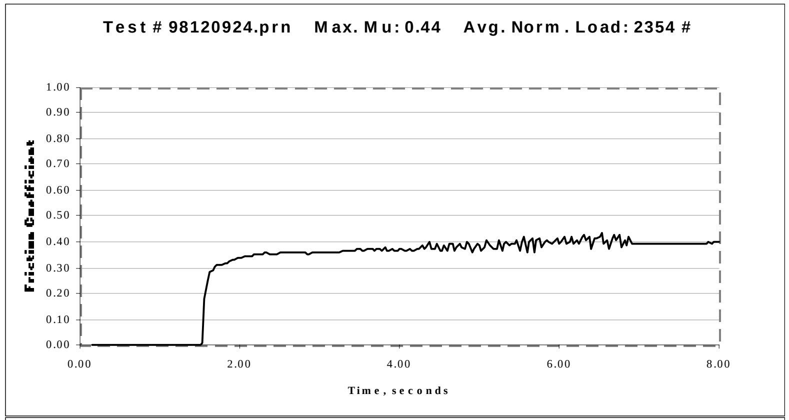


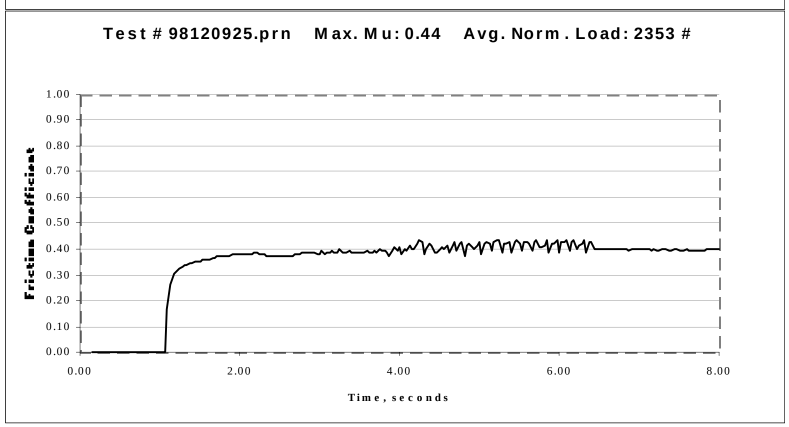




Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

AM0 12/09/98 Norem 02 200F 10ksi 25 strokes/uni





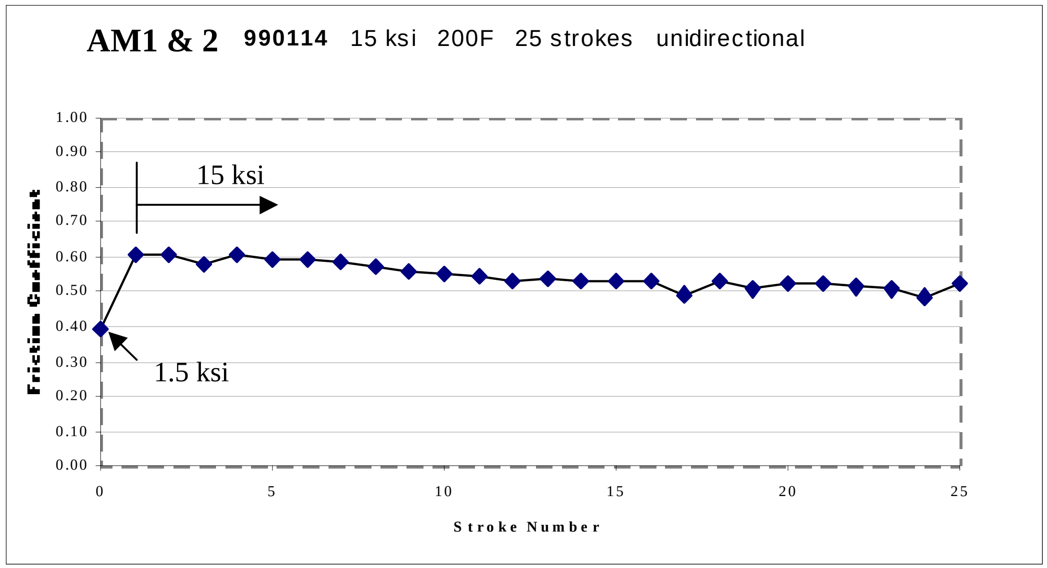
AM1: 1 Preconditioning Stroke at 1.5 ksi
&
AM2: 25 Strokes at 15 ksi

200°F

1.6" Stroke Length

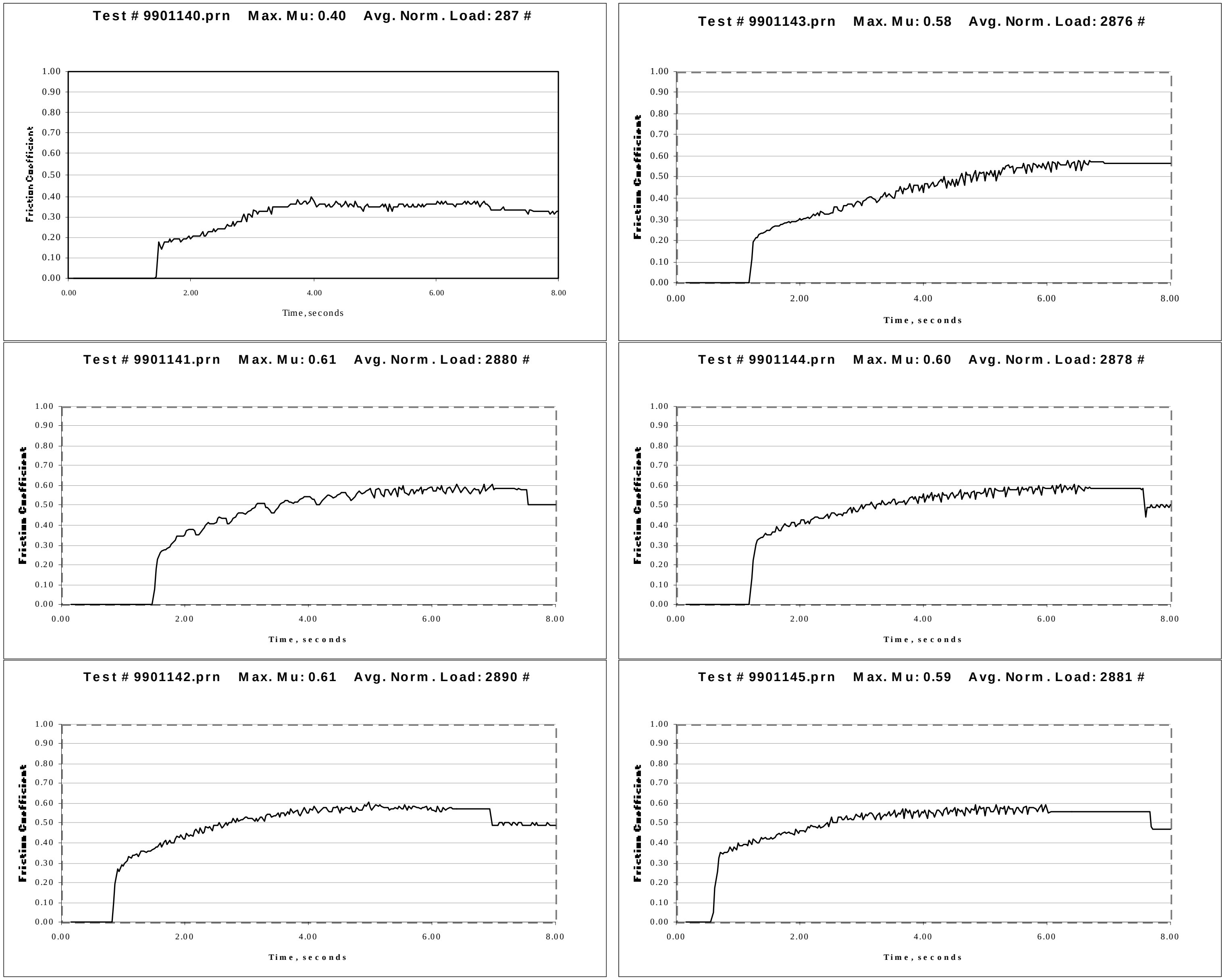
AM1and2 01/14/99 Norem 02 200F 15ksi 25 strokes/uni

	Max. Mu:	Avg. Norm. Load:
9901140.prn	0.40	286
9901141.prn	0.61	2880
9901142.prn	0.61	2890
9901143.prn	0.58	2876
9901144.prn	0.60	2878
9901145.prn	0.59	2881
9901146.prn	0.59	2880
9901147.prn	0.58	2885
9901148.prn	0.57	2889
9901149.prn	0.56	2889
99011410.prn	0.55	2886
99011411.prn	0.54	2881
99011412.prn	0.52	2886
99011413.prn	0.53	2883
99011414.prn	0.53	2883
99011415.prn	0.53	2882
99011416.prn	0.53	2883
99011417.prn	0.49	2880
99011418.prn	0.53	2879
99011419.prn	0.51	2880
99011420.prn	0.52	2880
99011421.prn	0.52	2880
99011422.prn	0.52	2879
99011423.prn	0.51	2881
99011424.prn	0.49	2885
99011425.prn	0.52	2880

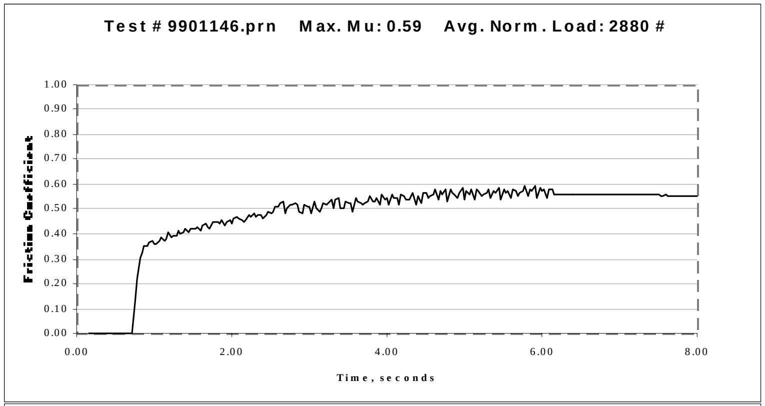


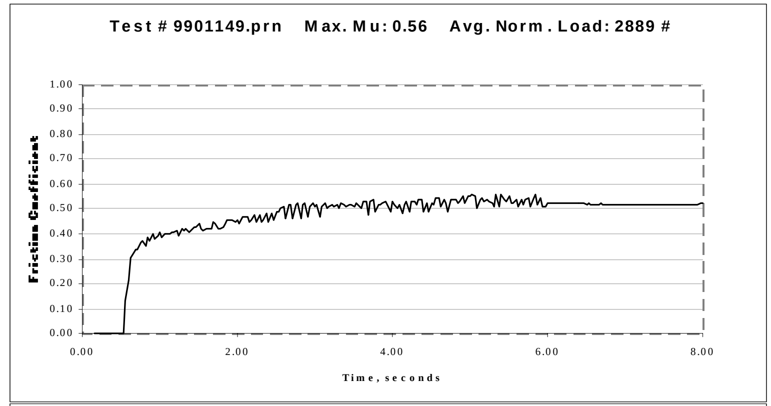
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

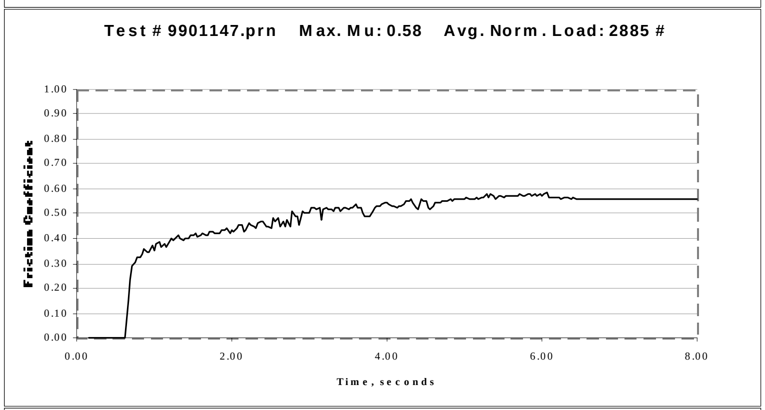
AM1and2 01/14/99 Norem 02 200F 15ksi 25 strokes/uni

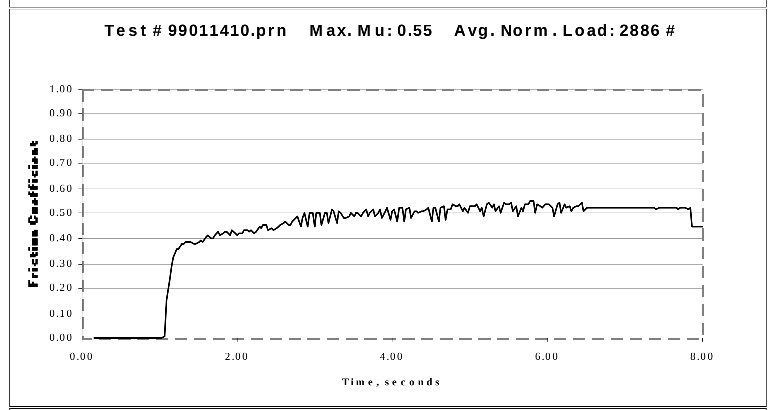


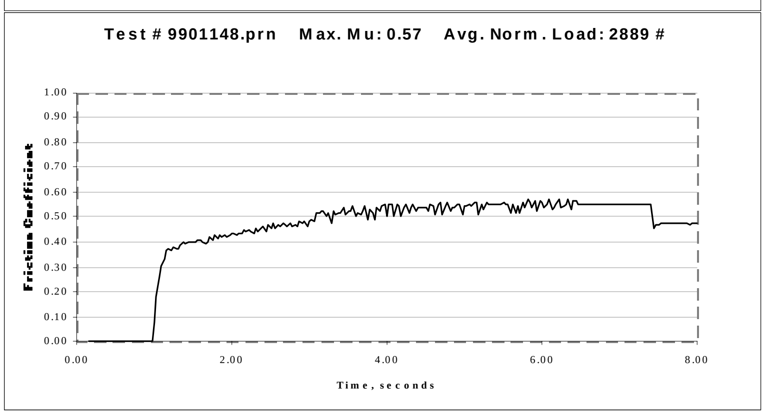
AM1and2 01/14/99 Norem 02 200F 15ksi 25 strokes/uni

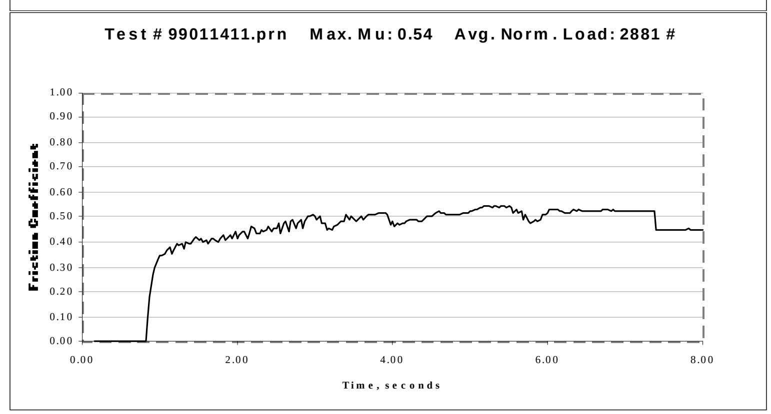






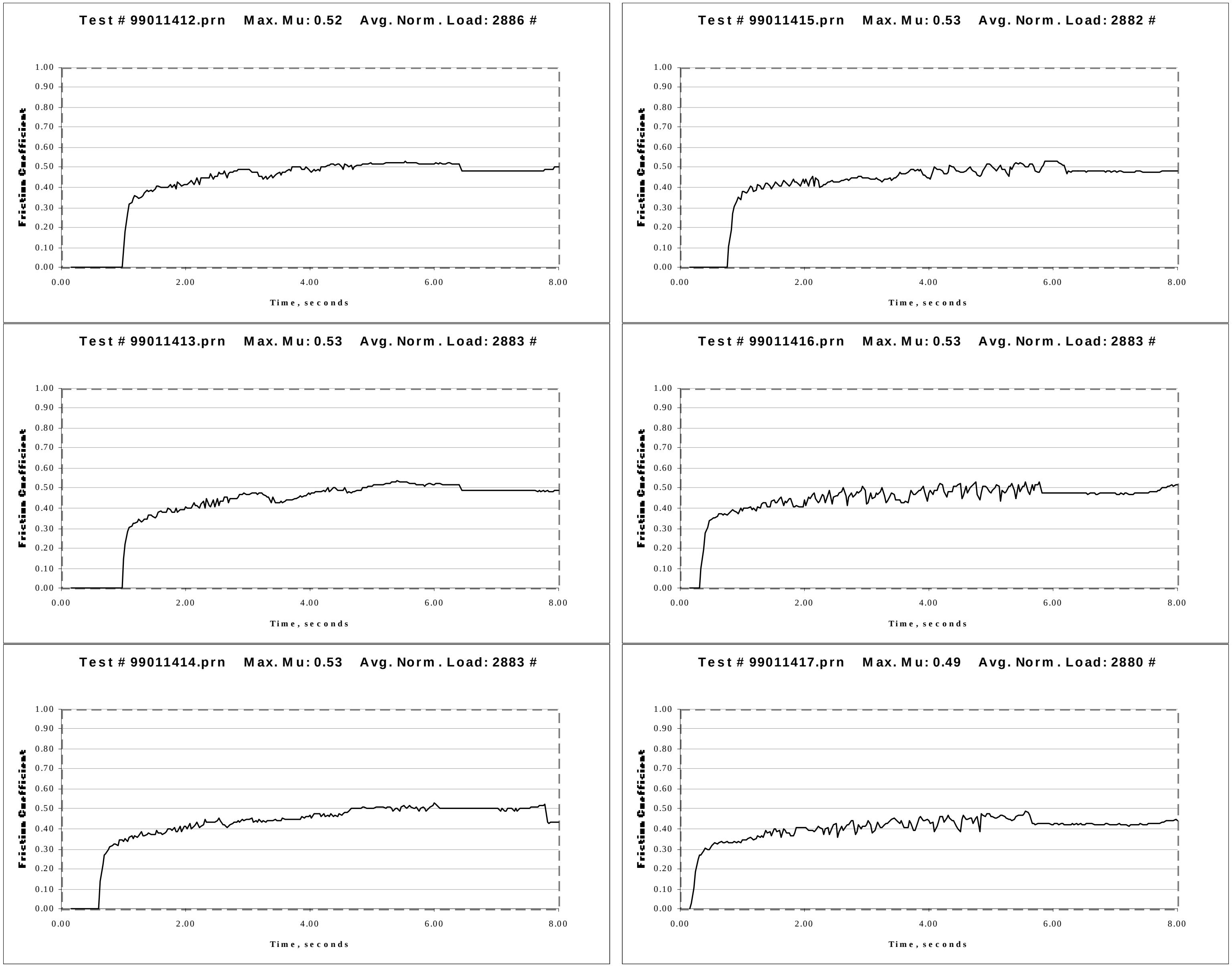




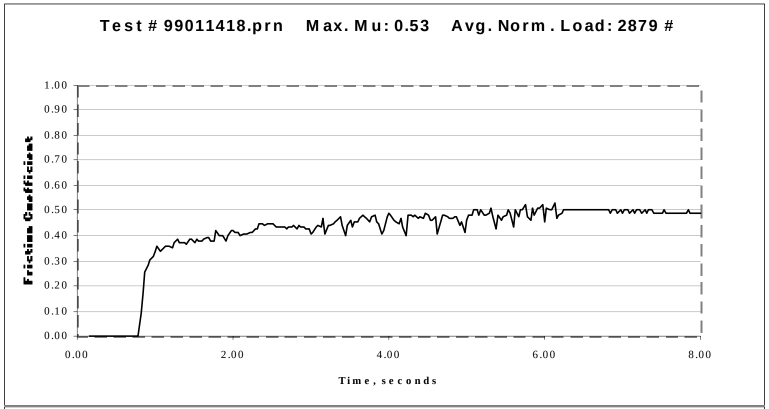


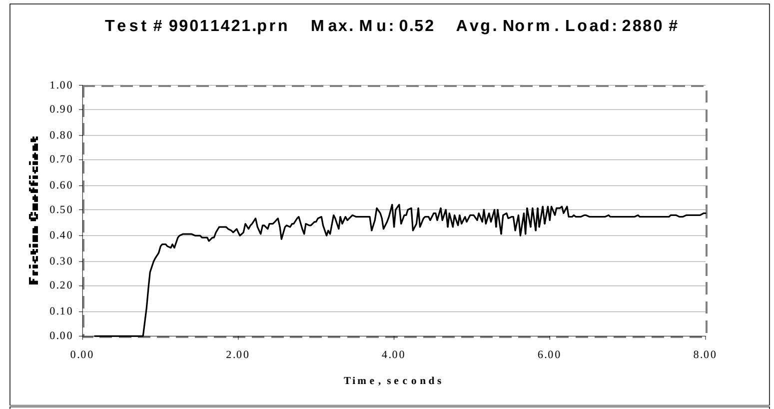
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

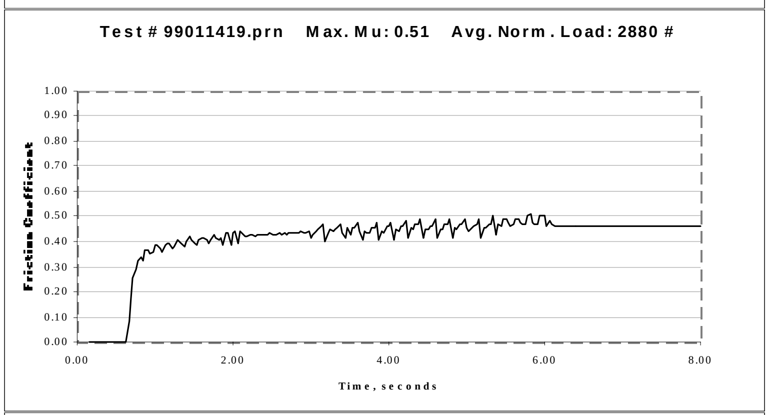
AM1and2 01/14/99 Norem 02 200F 15ksi 25 strokes/uni

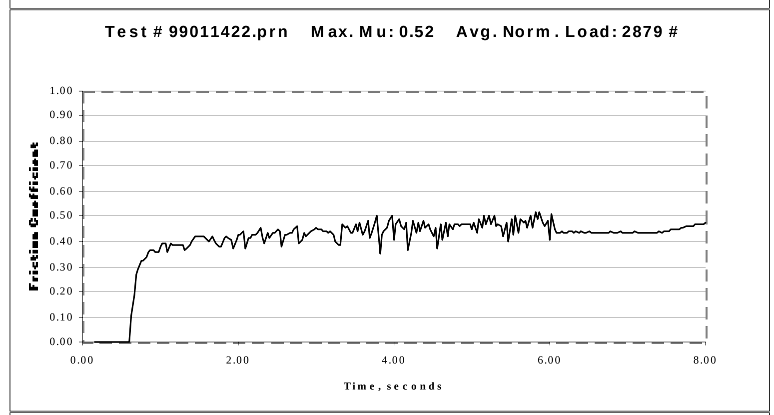


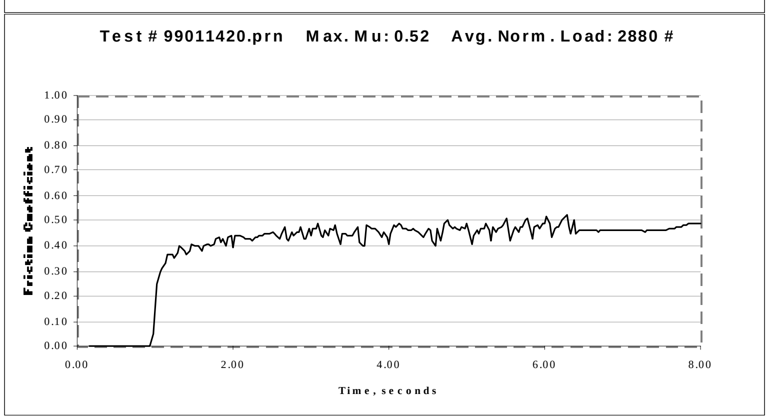
AM1and2 01/14/99 Norem 02 200F 15ksi 25 strokes/uni

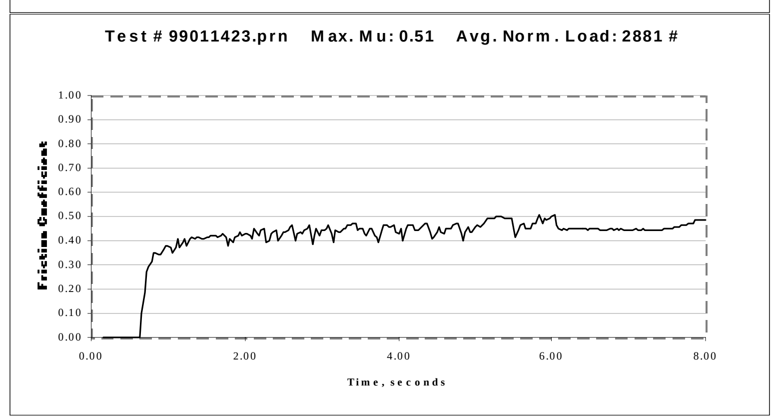






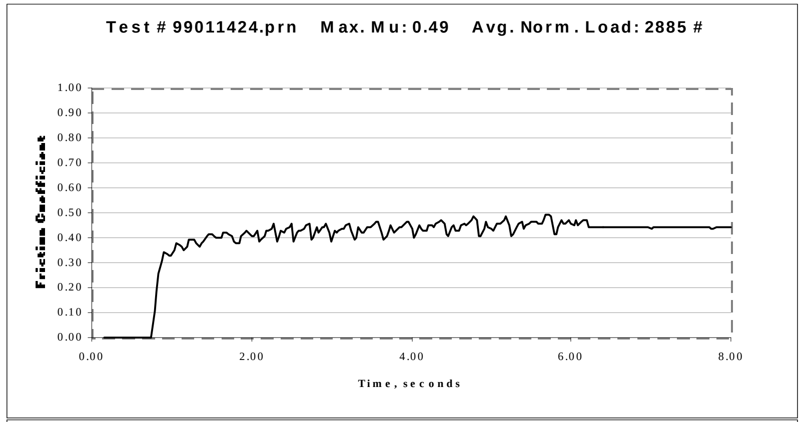


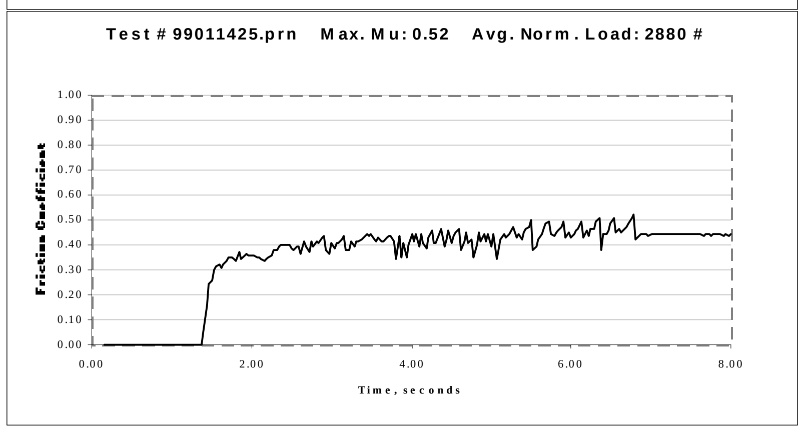




Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

AM1and2 01/14/99 Norem 02 200F 15ksi 25 strokes/uni





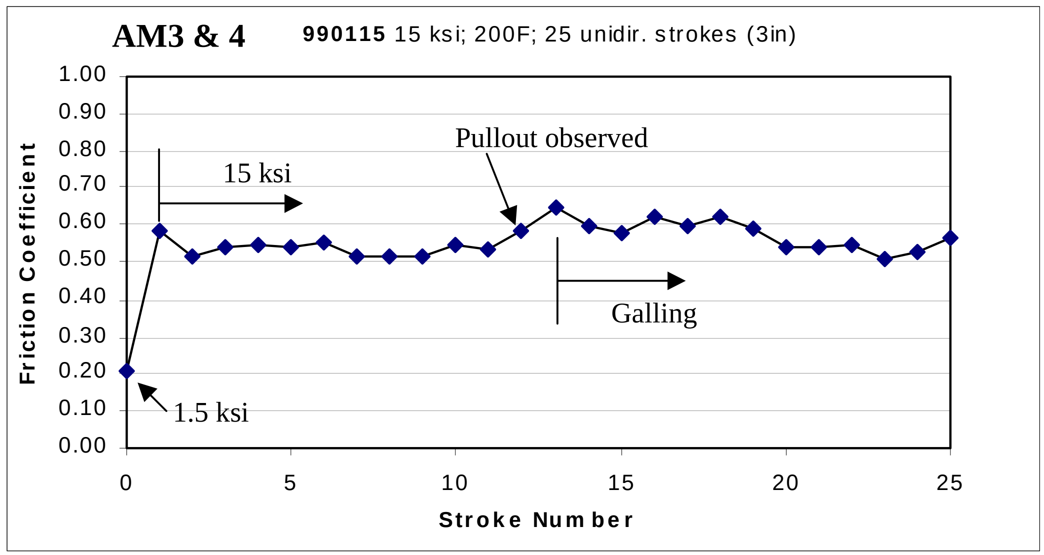
AM3: 1 Preconditioning Stroke at 1.5 ksi
&
AM4: 25 Strokes at 15 ksi

200° F

3" Stroke Length

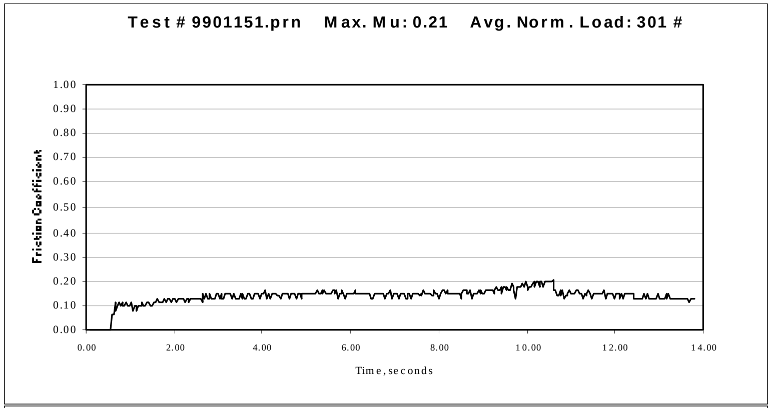
AM3and4 01/15/99 Norem 02 200F 15ksi 25 strokes/uni 3inches

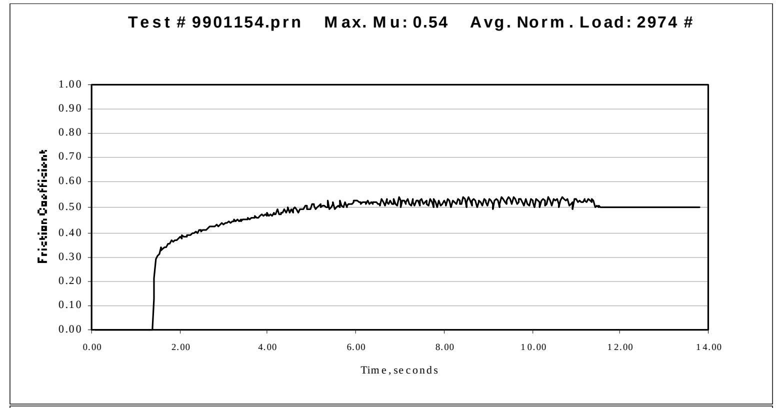
	Max. Mu:	Avg. Norm. Load:
9901151.prn	0.21	301
9901152.prn	0.58	2950
9901153.prn	0.51	2972
9901154.prn	0.54	2974
9901155.prn	0.55	2971
9901156.prn	0.54	2974
9901167.prn	0.55	2977
9901158.prn	0.51	2969
9901159.prn	0.51	2972
99011510.prn	0.51	2965
99011511.prn	0.54	2963
99011512.prn	0.53	2971
99011513.prn	0.58	2970
99011514.prn	0.64	2969
99011515.prn	0.59	2970
99011516.prn	0.58	2969
99011517.prn	0.62	2962
99011518.prn	0.59	2966
99011519.prn	0.62	2969
99011520.prn	0.59	2966
99011521.prn	0.54	2966
99011522.prn	0.54	2965
99011523.prn	0.54	2969
99011524.prn	0.51	2969
99011525.prn	0.52	2968
99011526.prn	0.56	2969

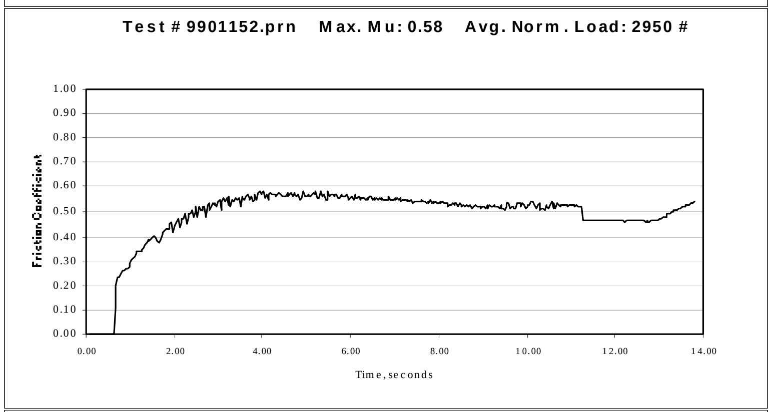


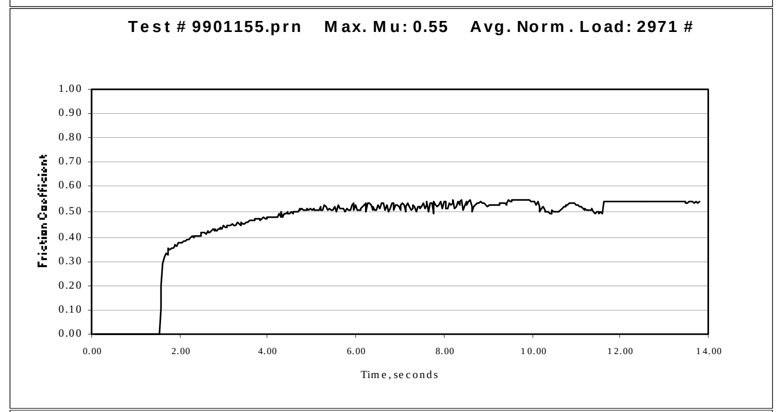
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

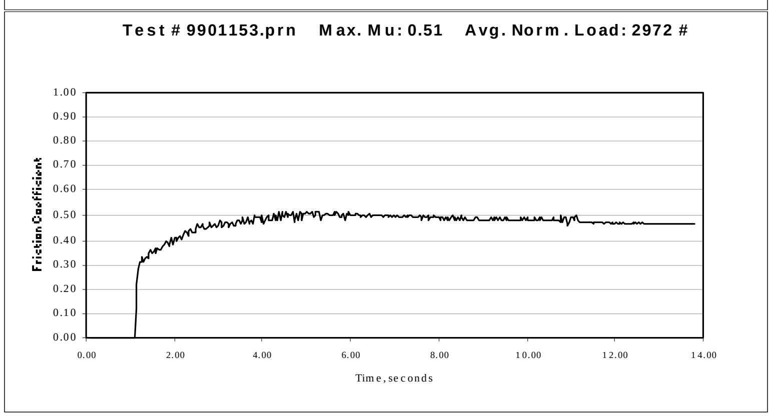
AM3and4 01/15/99 Norem 02 200F 15ksi 25 strokes/uni 3inches

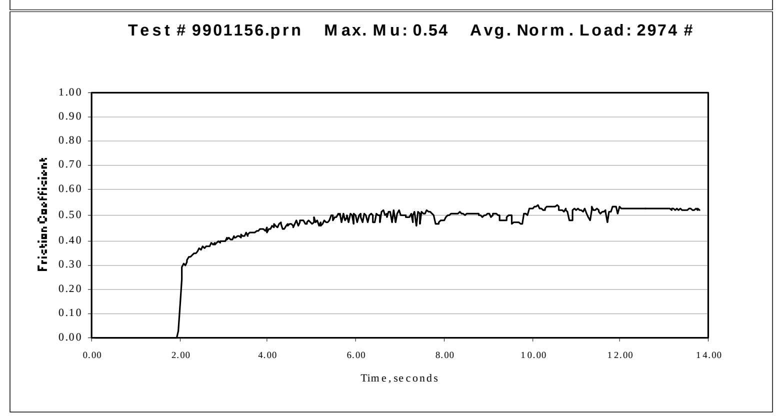




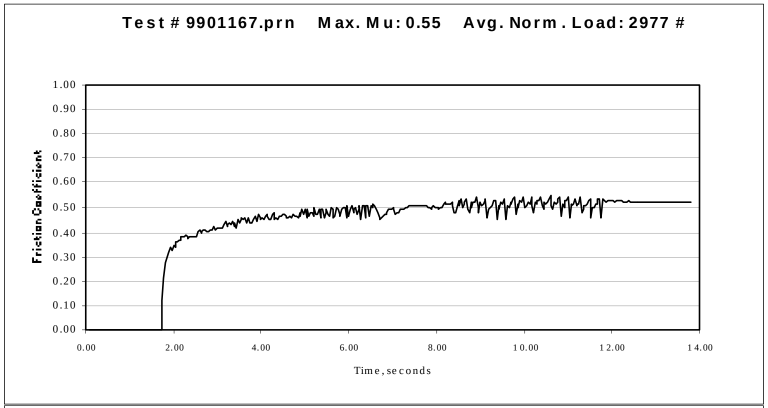


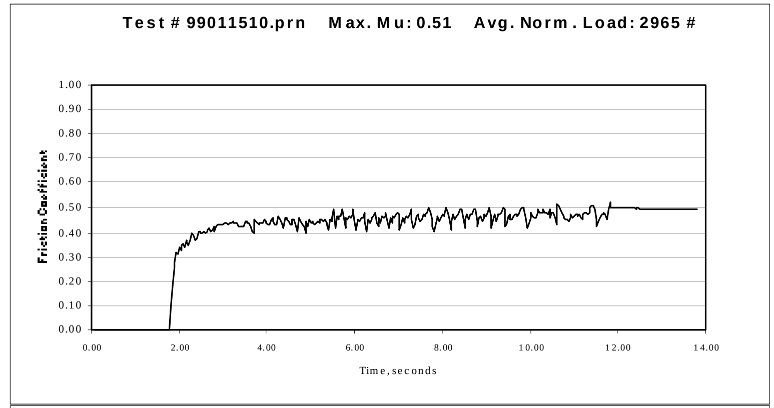


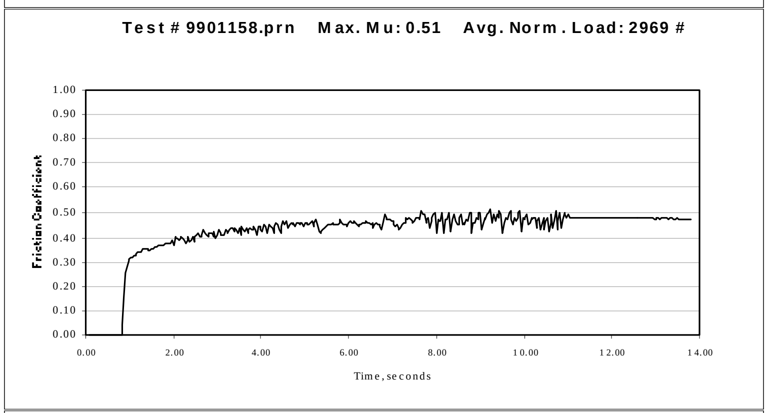


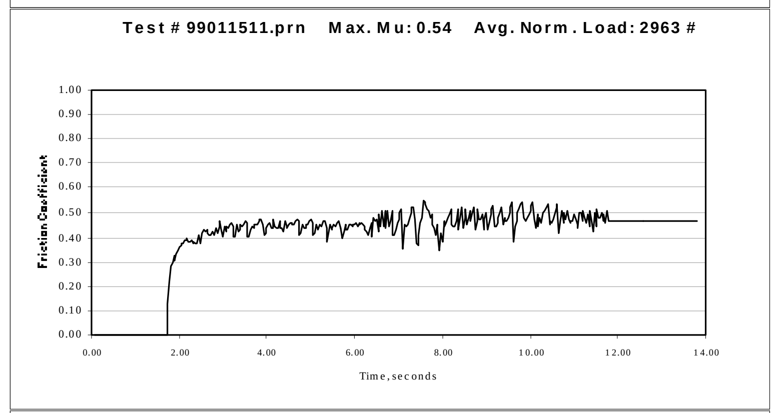


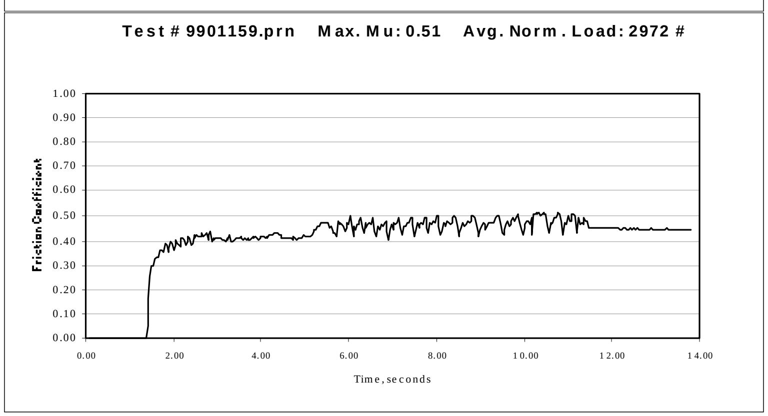
AM3and4 01/15/99 Norem 02 200F 15ksi 25 strokes/uni 3inches

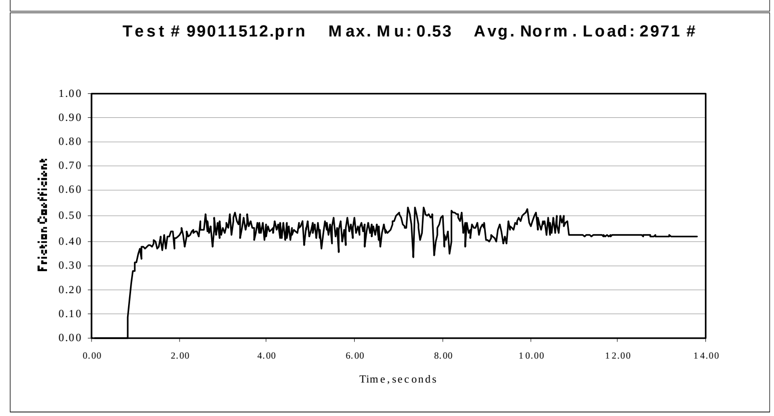






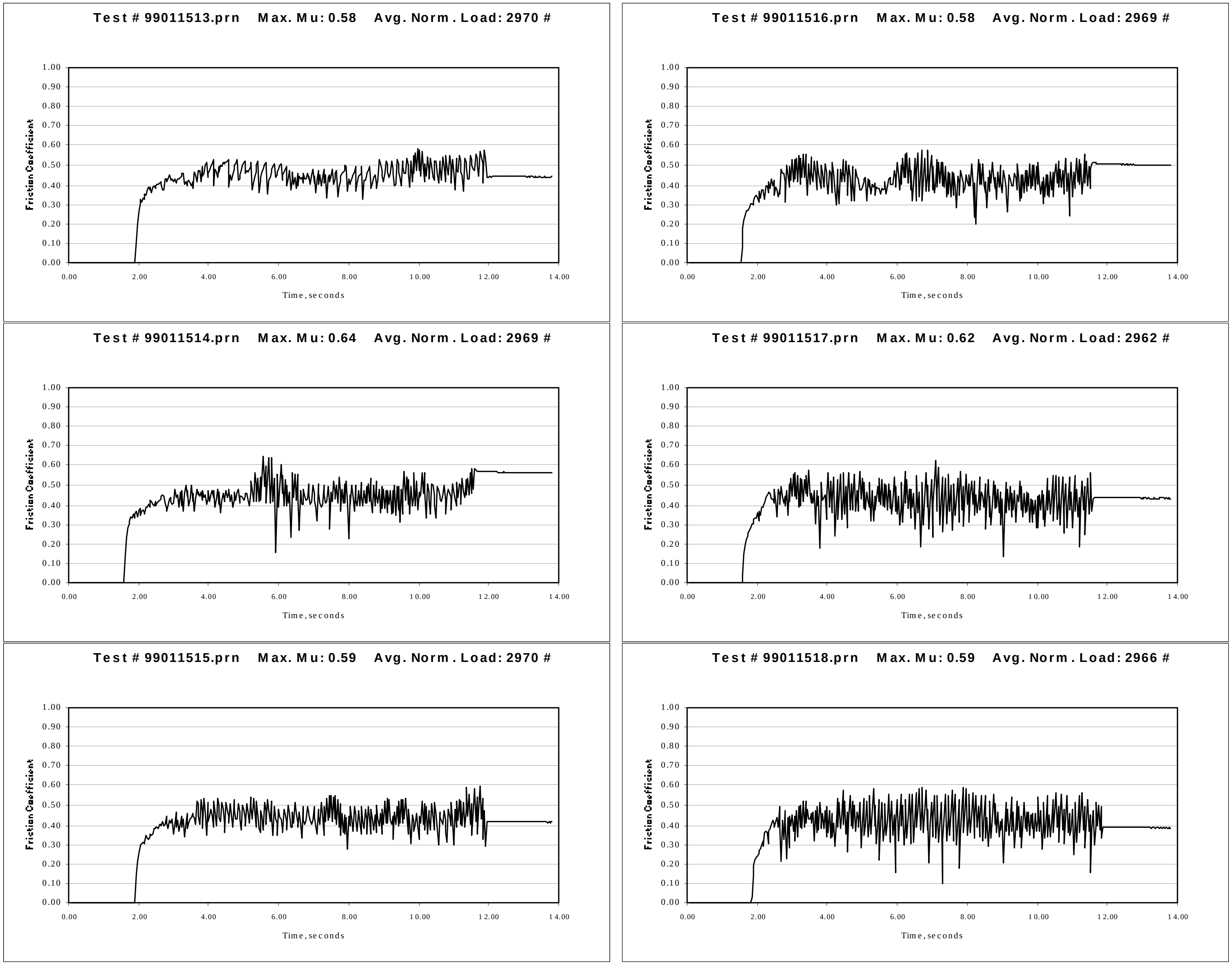




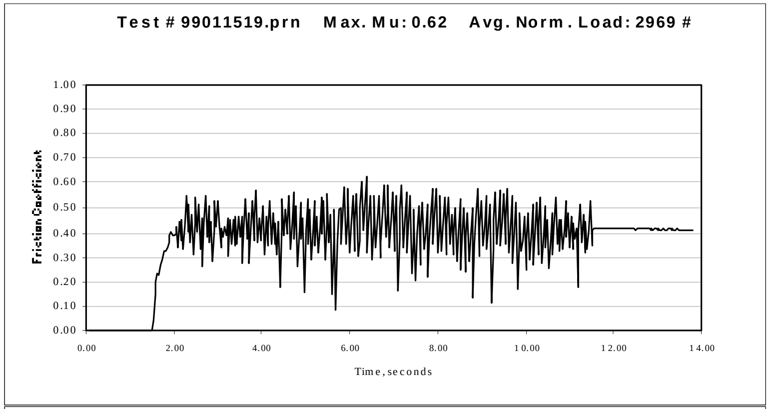


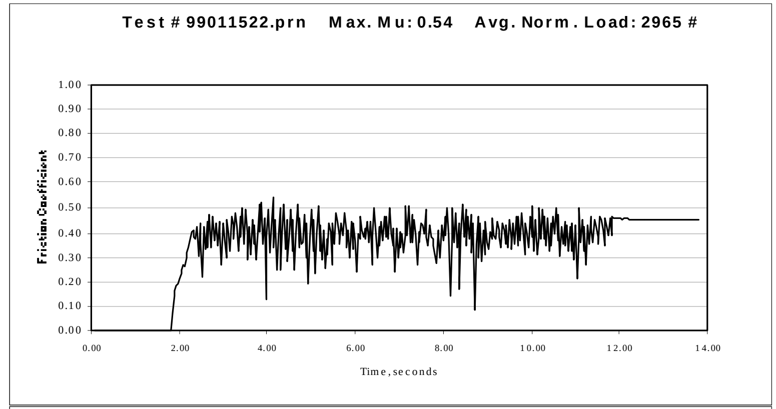
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

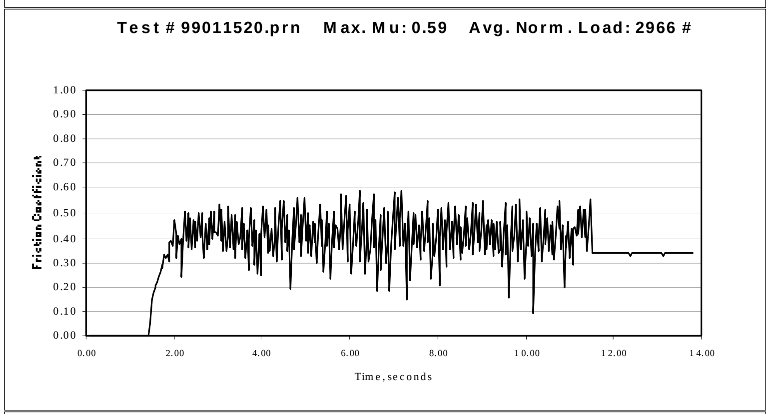
AM3and4 01/15/99 Norem 02 200F 15ksi 25 strokes/uni 3inches

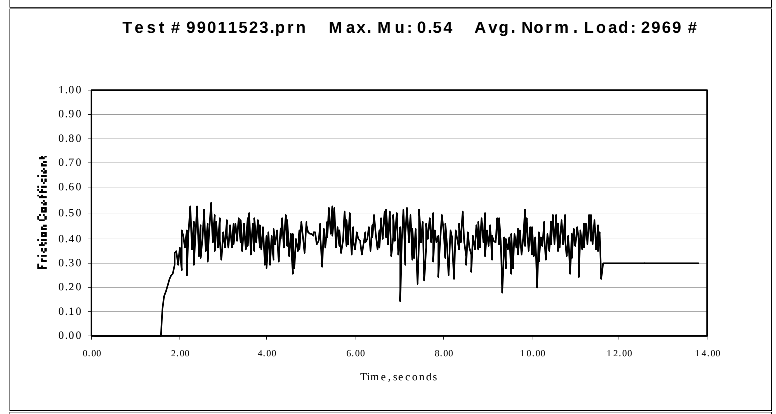


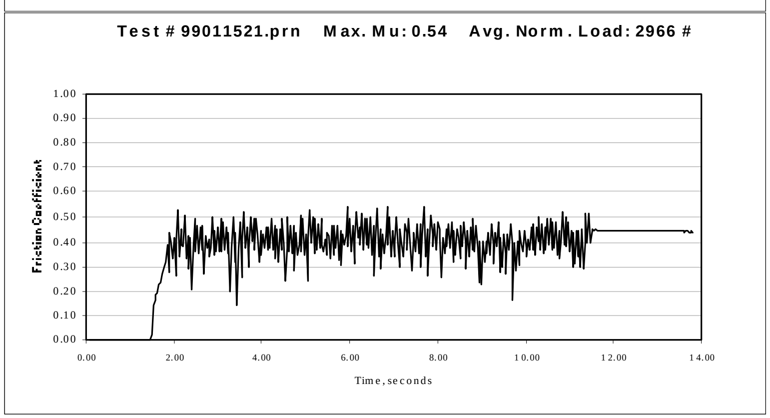
AM3and4 01/15/99 Norem 02 200F 15ksi 25 strokes/uni 3inches

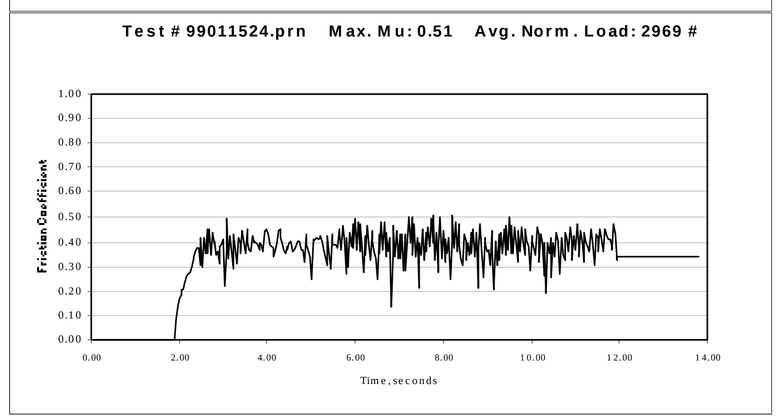






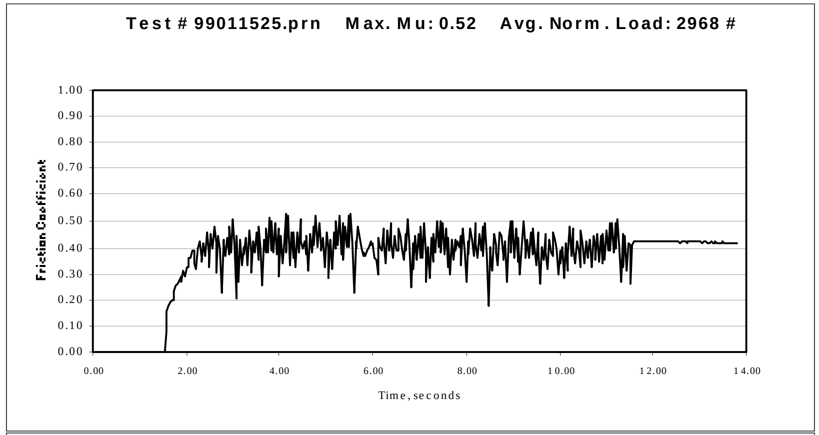


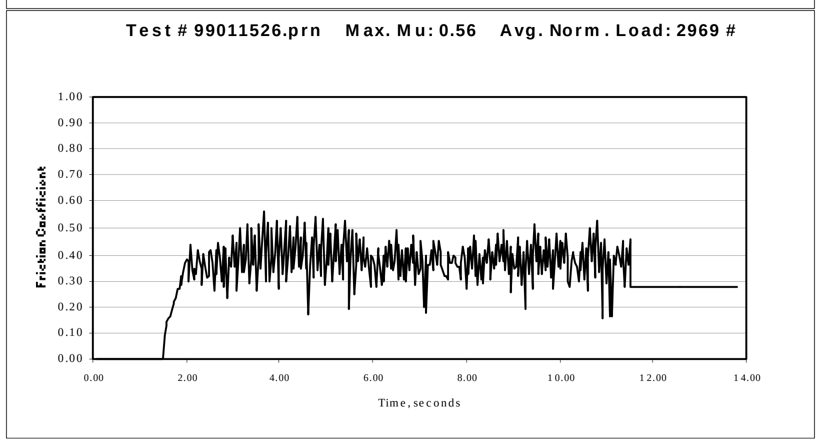




Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

AM3and4 01/15/99 Norem 02 200F 15ksi 25 strokes/uni 3inches





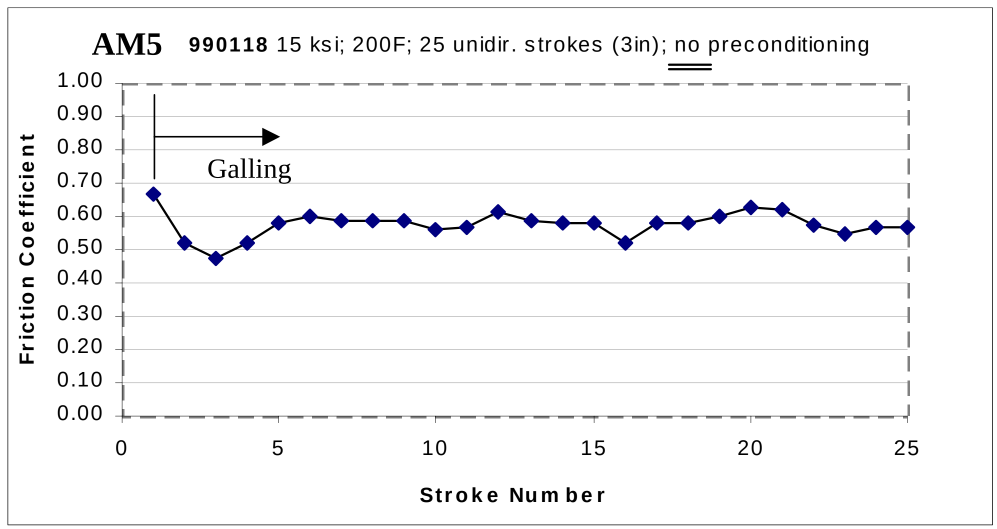
AM5: 25 Strokes at 15 ksi
(No Preconditioning)

200°F

3" Stroke Length

AM5 01/18/99 Norem 02 200F 15ksi 25 strokes/uni 3inches no preconditioning stroke

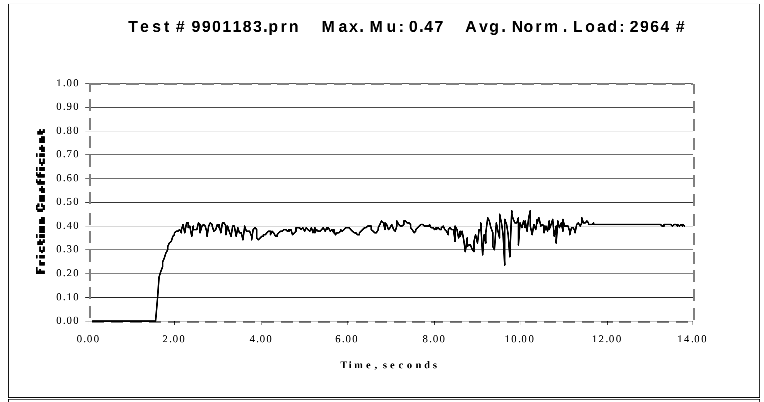
	Max. Mu:	Avg. Norm. Load:
9901181.prn	0.66	2967
9901182.prn	0.52	2965
9901183.prn	0.47	2964
9901184.prn	0.52	2962
9901185.prn	0.58	2966
9901186.prn	0.60	2970
9901187.prn	0.58	2969
9901188.prn	0.58	2966
9901189.prn	0.59	2964
99011810.prn	0.56	2963
99011811.prn	0.56	2962
99011812.prn	0.61	2963
99011814.prn	0.58	2964
99011815.prn	0.58	2962
99011816.prn	0.58	2963
99011817.prn	0.52	2961
99011818.prn	0.58	2963
99011819.prn	0.58	2962
99011820.prn	0.60	2965
99011821.prn	0.62	2963
99011822.prn	0.62	2963
99011823.prn	0.57	2968
99011824.prn	0.54	2964
99011825.prn	0.57	2964
99011826.prn	0.56	2963

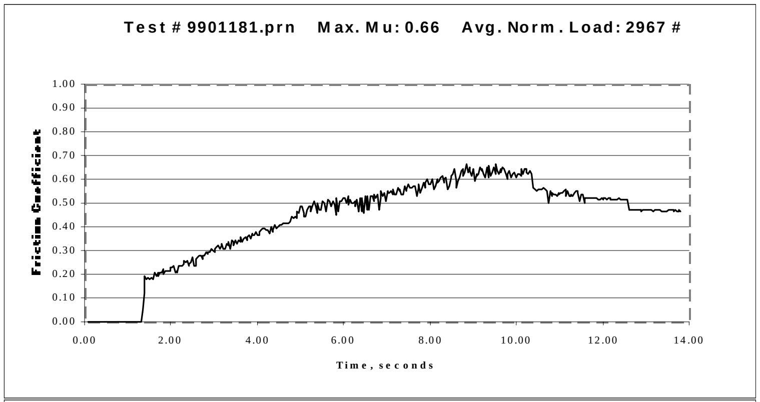


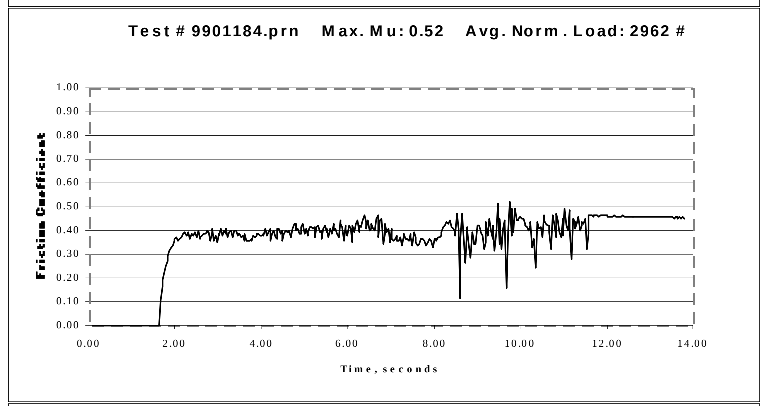
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

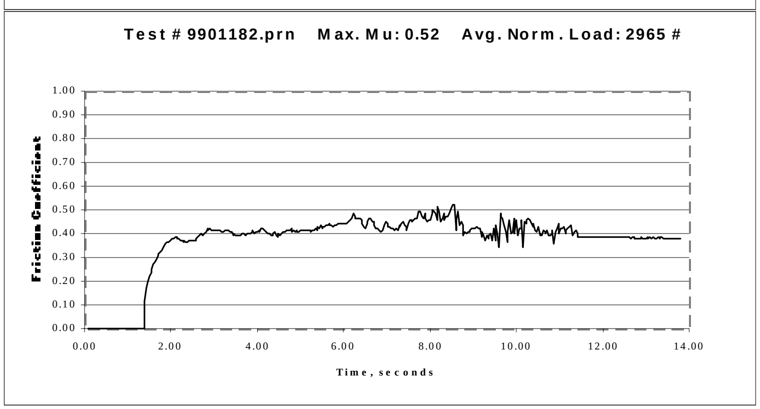
AM5 01/18/99 Norem 02 200F 15ksi 25 strokes/uni 3inches no preconditioning stroke

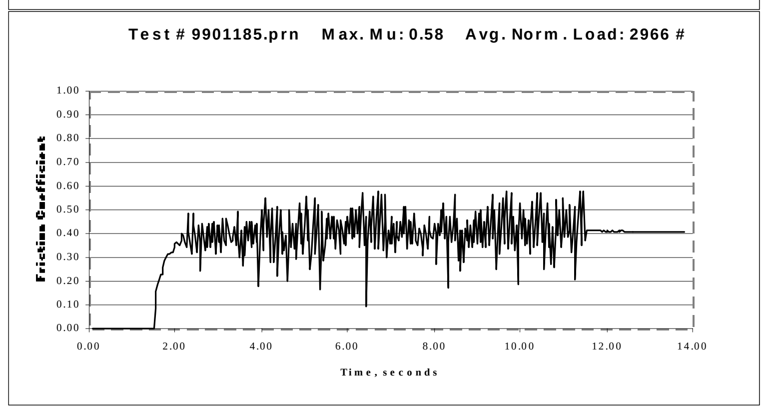
No preconditioning stroke



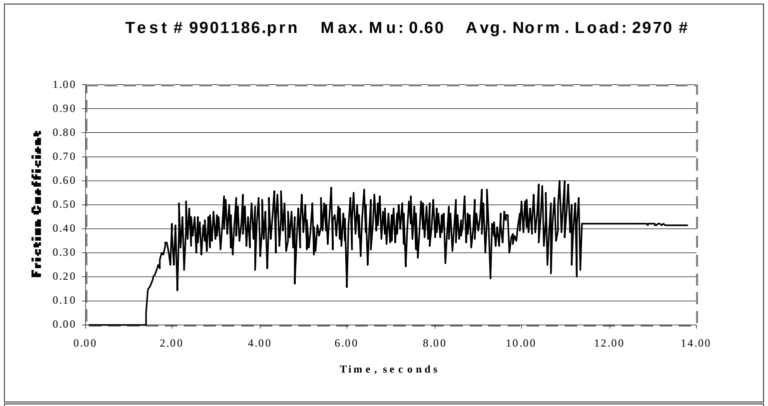


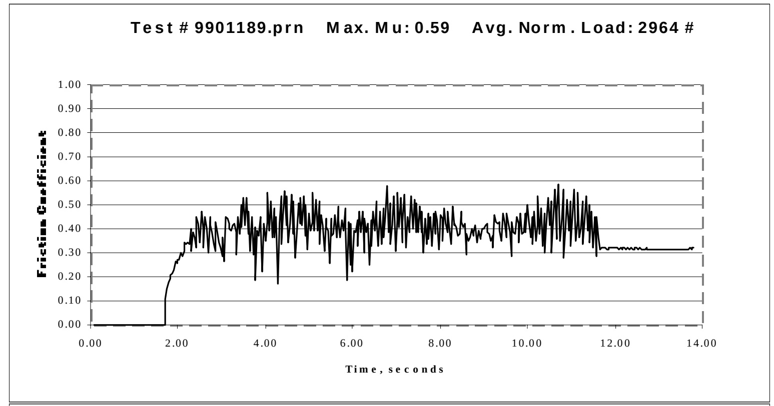


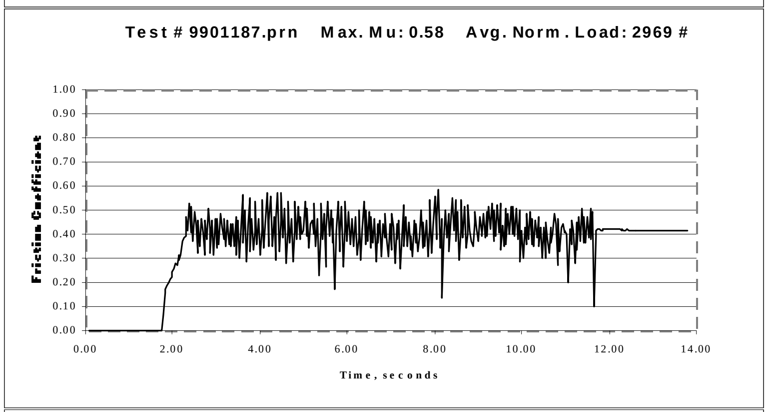


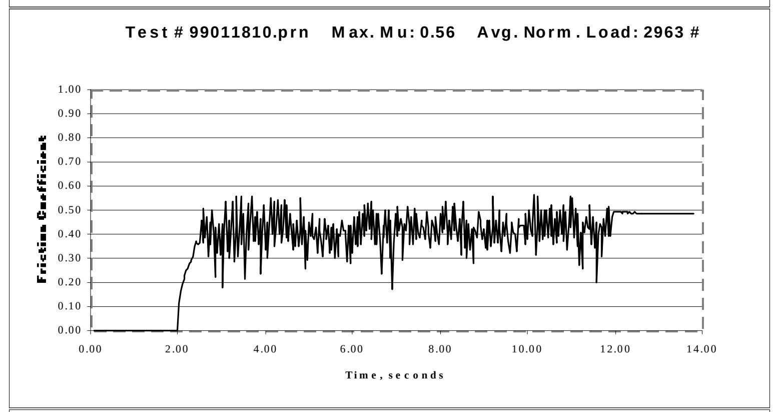


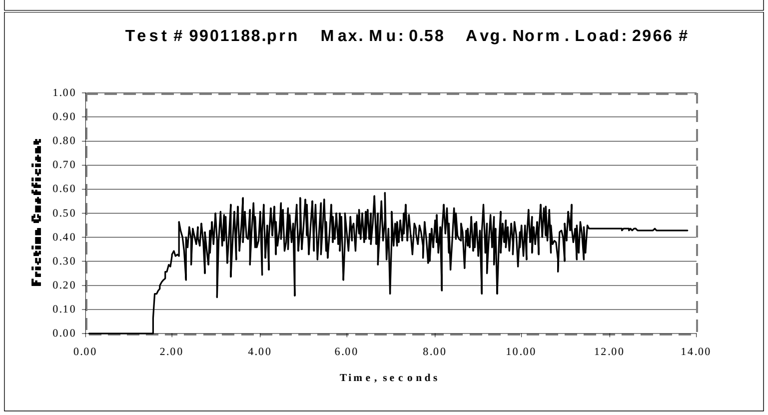
AM5 01/18/99 Norem 02 200F 15ksi 25 strokes/uni 3inches no preconditioning stroke

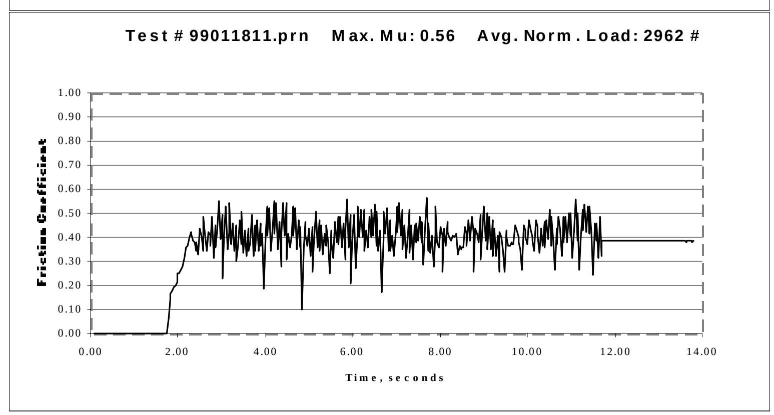






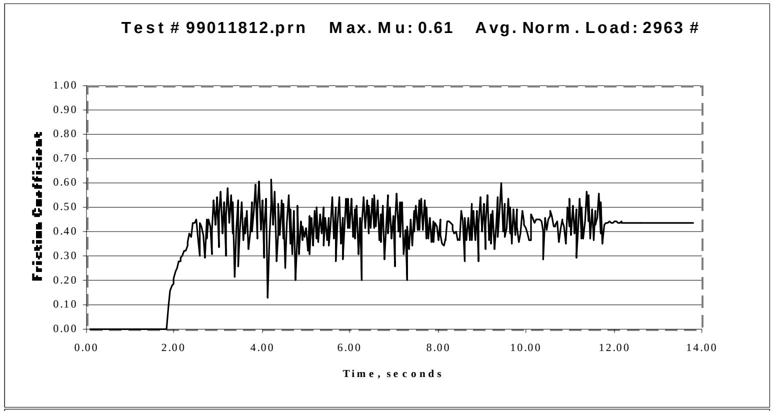


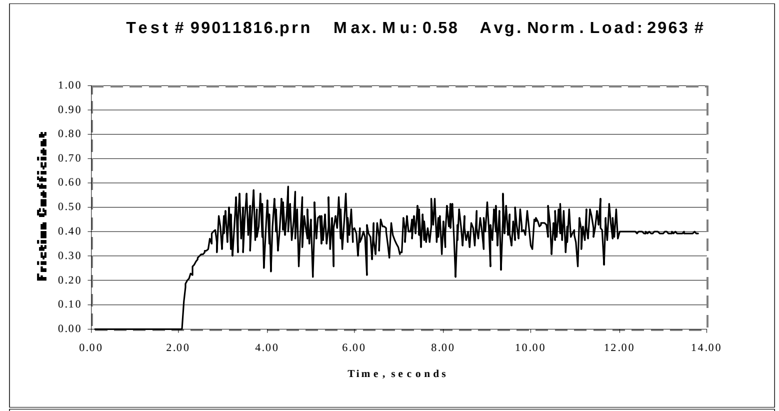


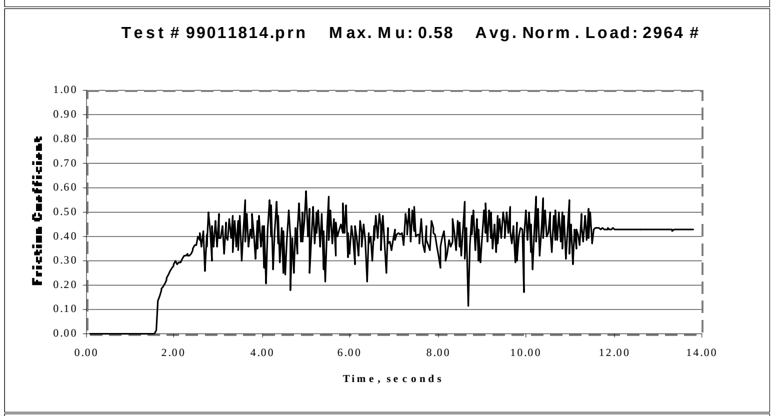


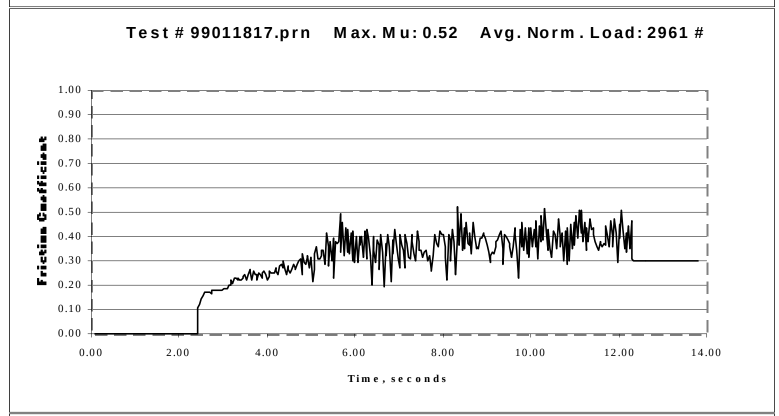
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

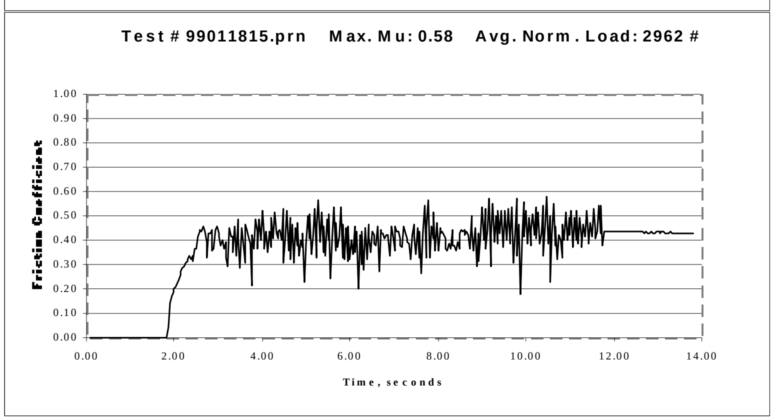
AM5 01/18/99 Norem 02 200F 15ksi 25 strokes/uni 3inches no preconditioning stroke

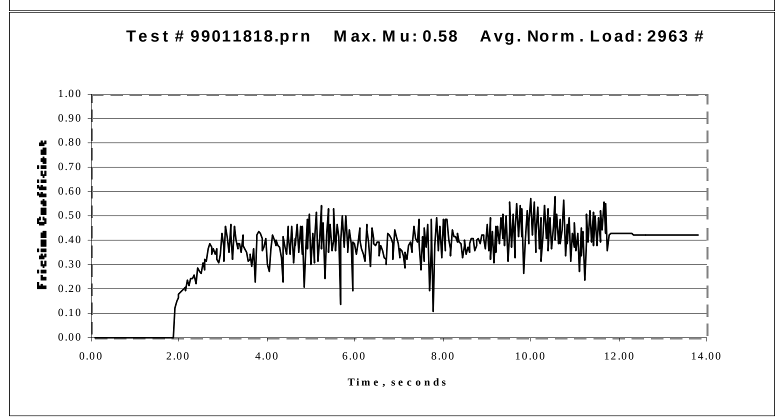




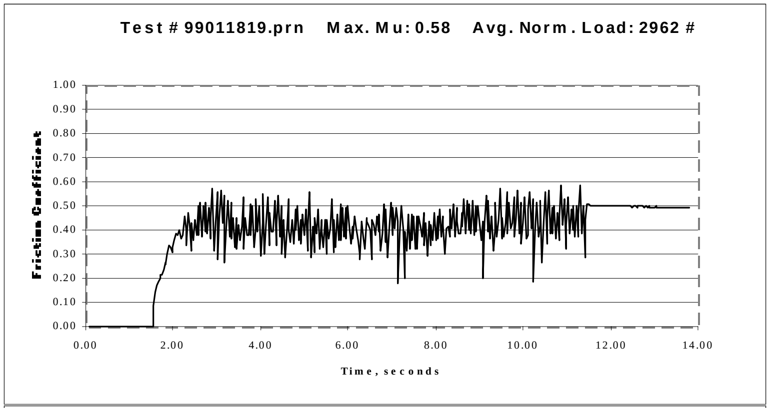


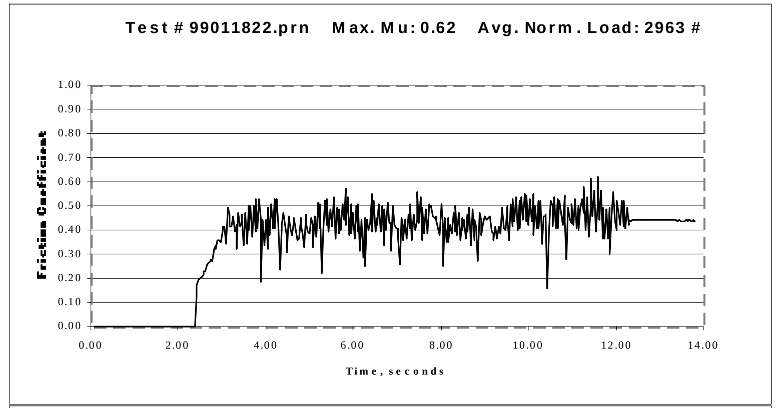


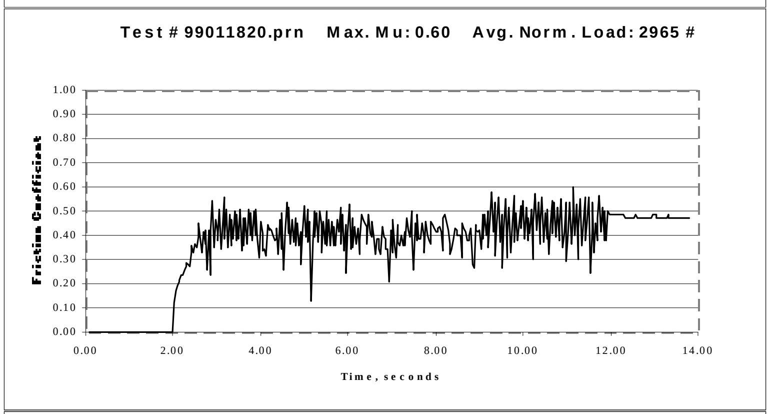


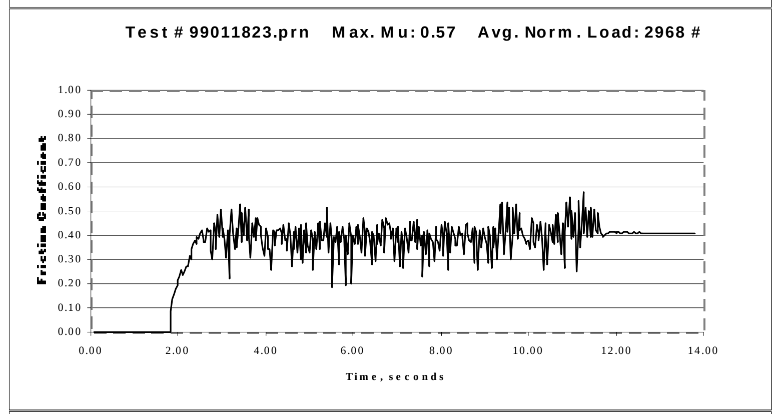


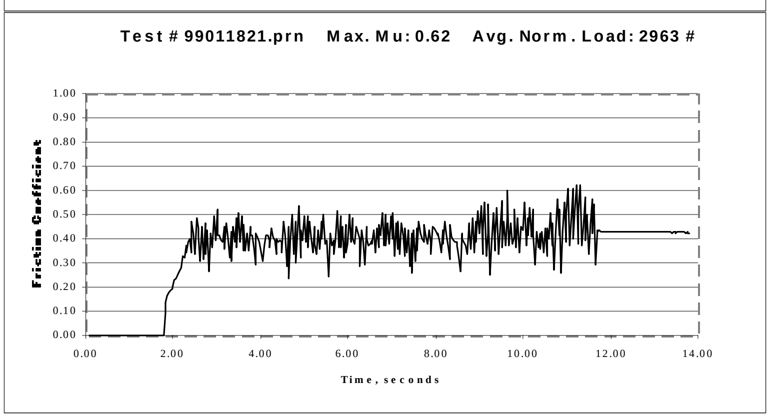
AM5 01/18/99 Norem 02 200F 15ksi 25 strokes/uni 3inches no preconditioning stroke

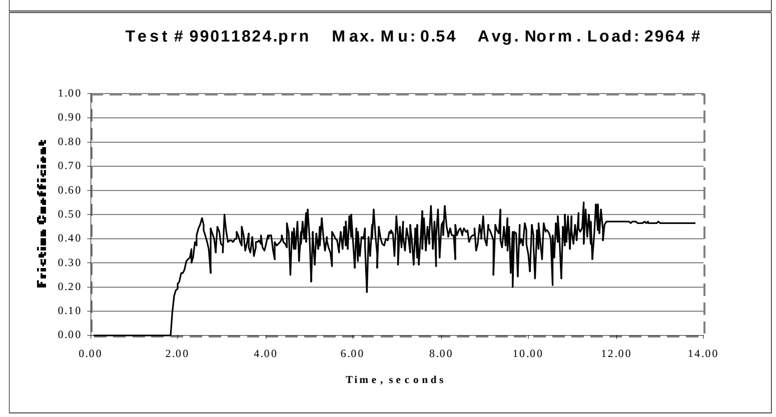






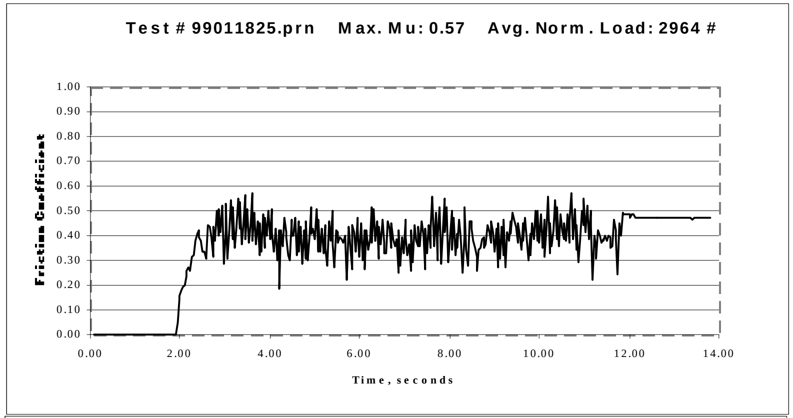


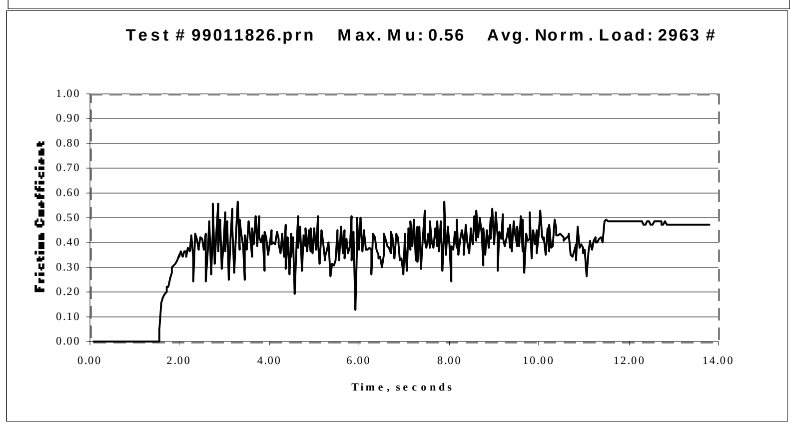




Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

AM5 01/18/99 Norem 02 200F 15ksi 25 strokes/uni 3inches no preconditioning stroke



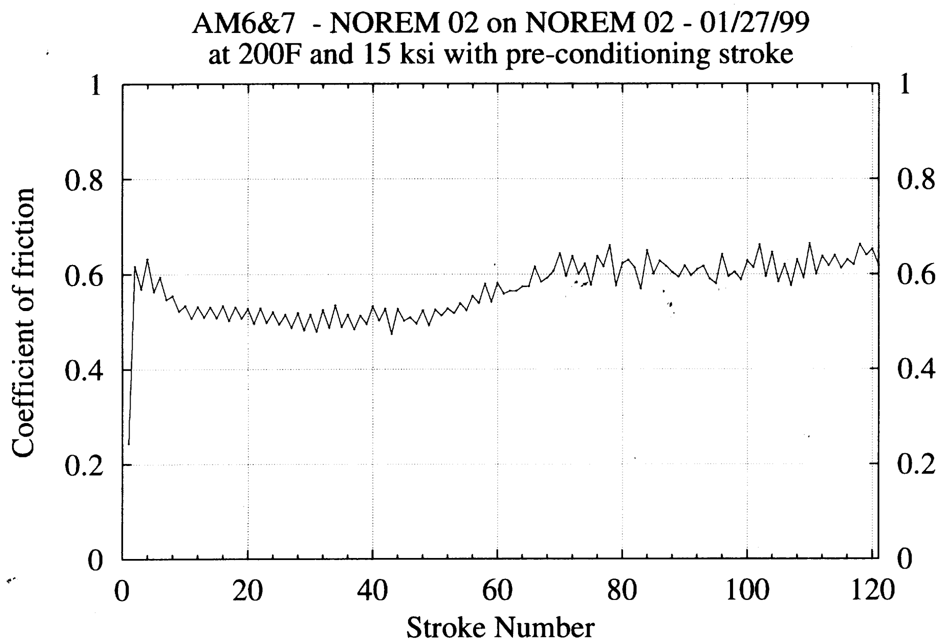


AM6: 1 Preconditioning Stroke at 1.5 ksi
&
AM7: 120 Strokes at 15 ksi

200° F

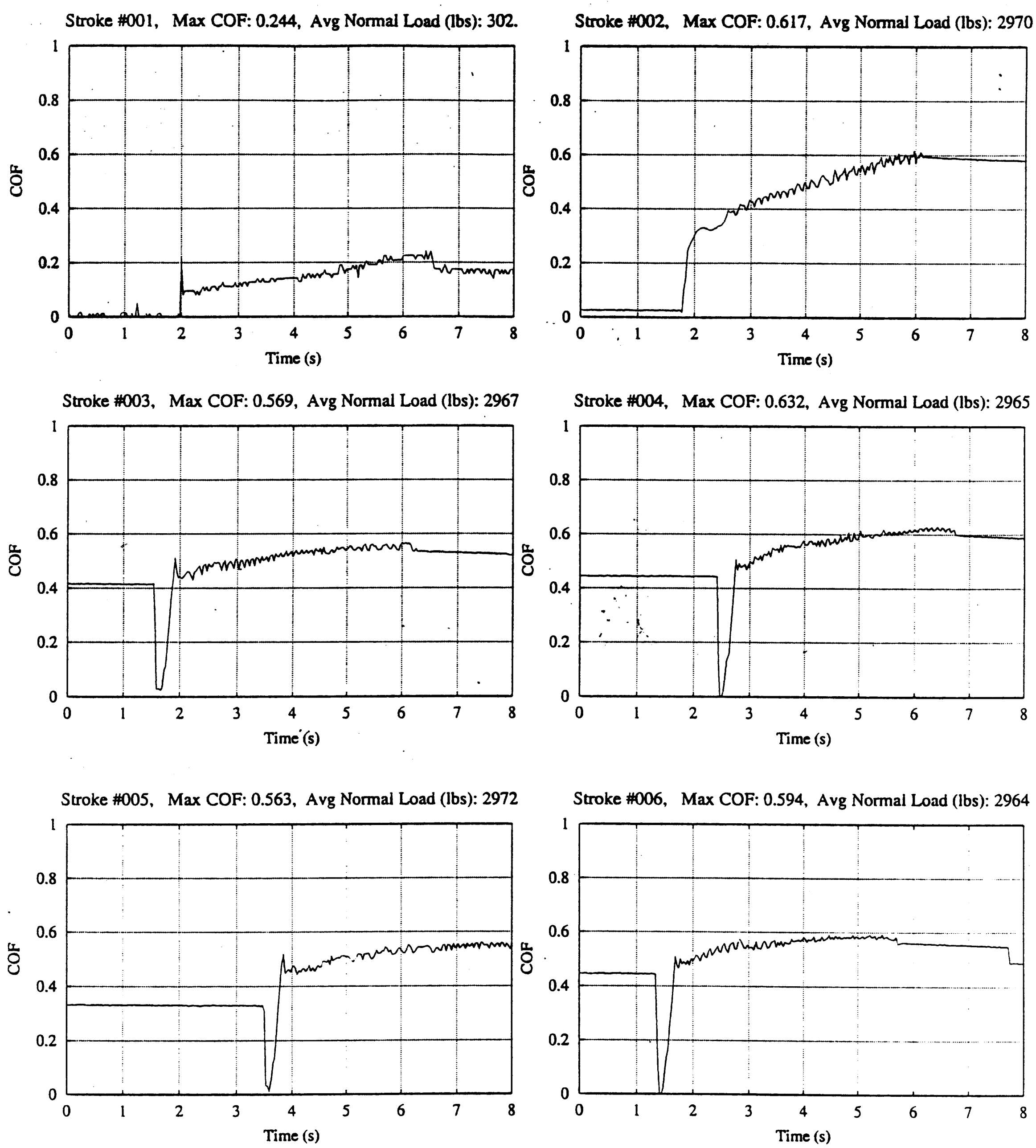
1.6" Stroke Length

Reciprocating



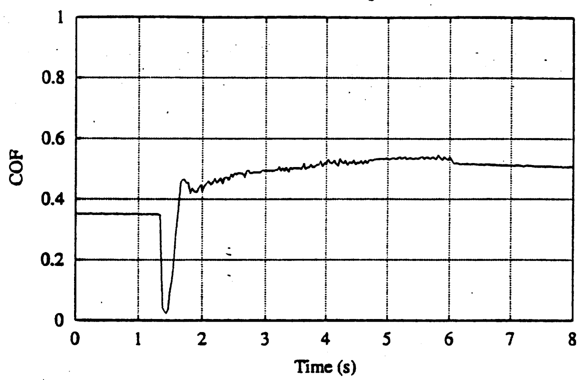
AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in

Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

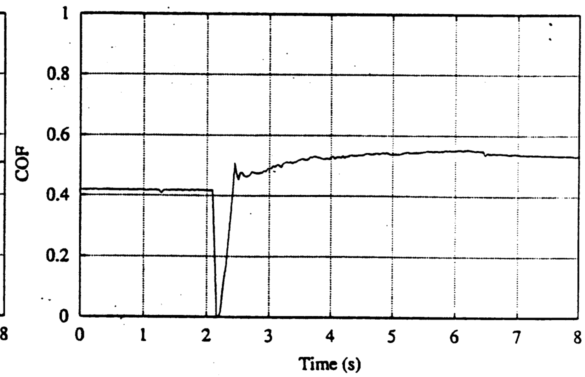


AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in

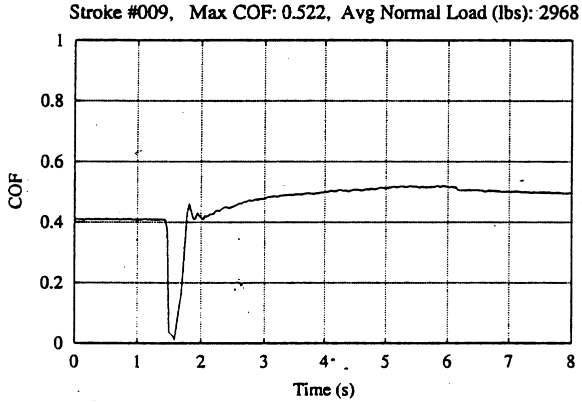
Stroke #007, Max COF: 0.547, Avg Normal Load (lbs): 2969



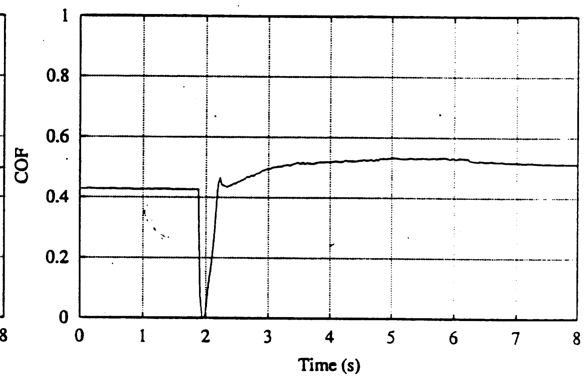
Stroke #008, Max COF: 0.555, Avg Normal Load (lbs): 2966



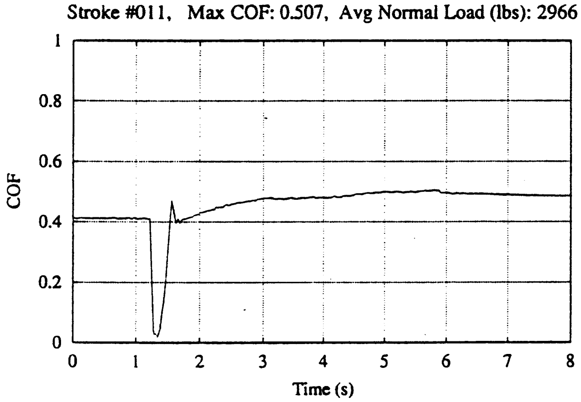
Stroke #009, Max COF: 0.522, Avg Normal Load (lbs): 2968



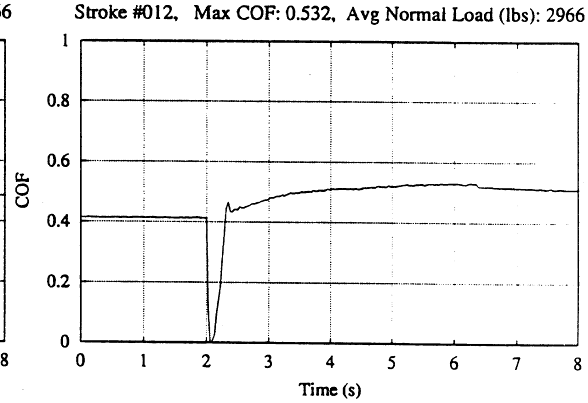
Stroke #010, Max COF: 0.534, Avg Normal Load (lbs): 2966



Stroke #011, Max COF: 0.507, Avg Normal Load (lbs): 2966

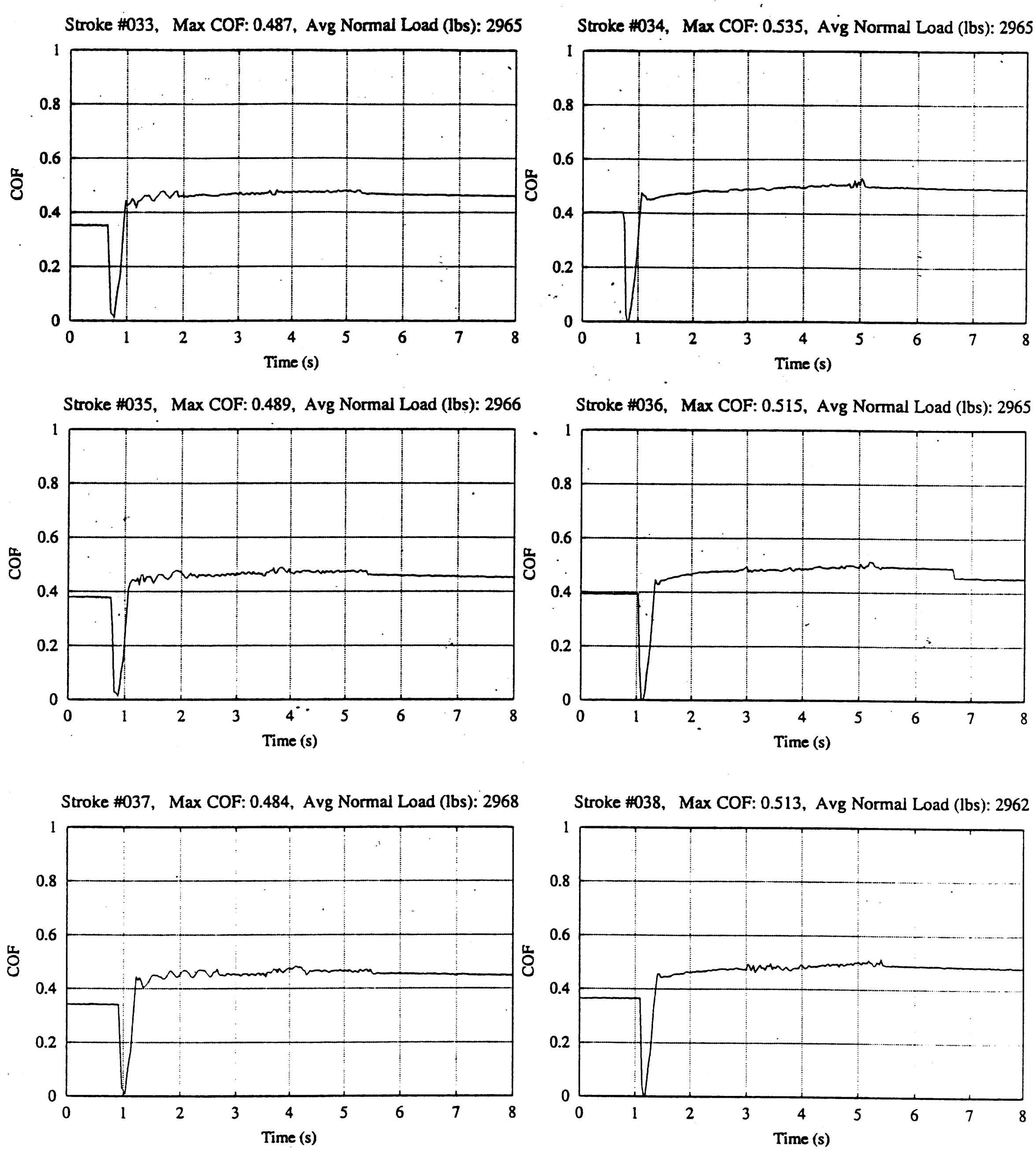


Stroke #012, Max COF: 0.532, Avg Normal Load (lbs): 2966



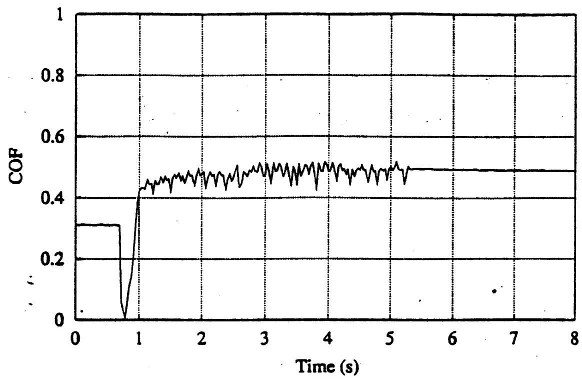
AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in

Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

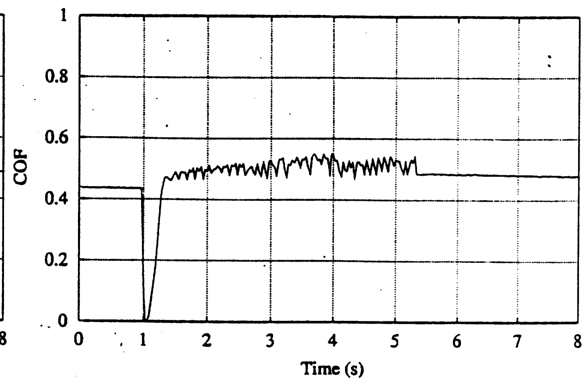


AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in

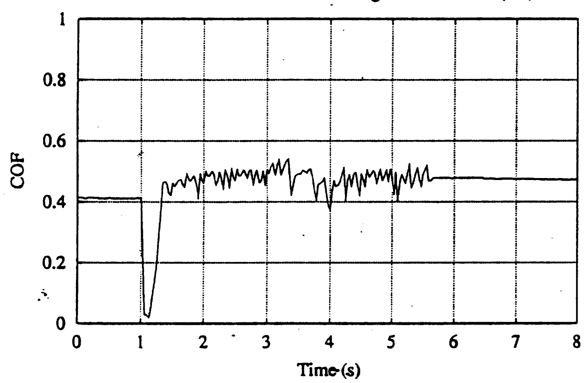
Stroke #055, Max COF: 0.524, Avg Normal Load (lbs): 2960



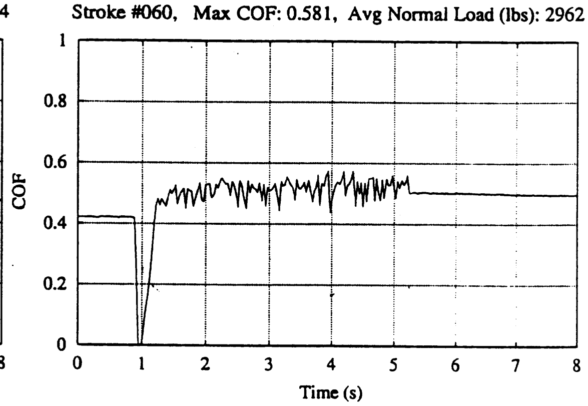
Stroke #056, Max COF: 0.554, Avg Normal Load (lbs): 2960



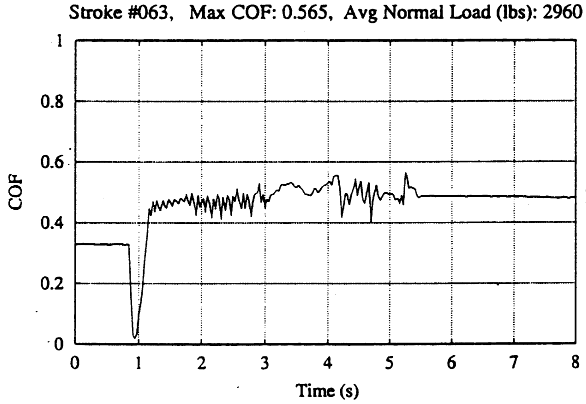
Stroke #059, Max COF: 0.542, Avg Normal Load (lbs): 2964



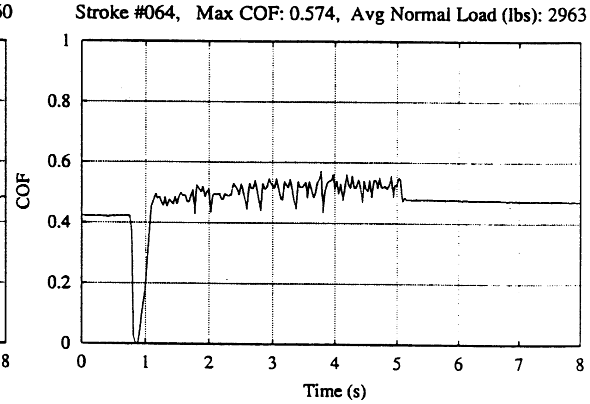
Stroke #060, Max COF: 0.581, Avg Normal Load (lbs): 2962



Stroke #063, Max COF: 0.565, Avg Normal Load (lbs): 2960

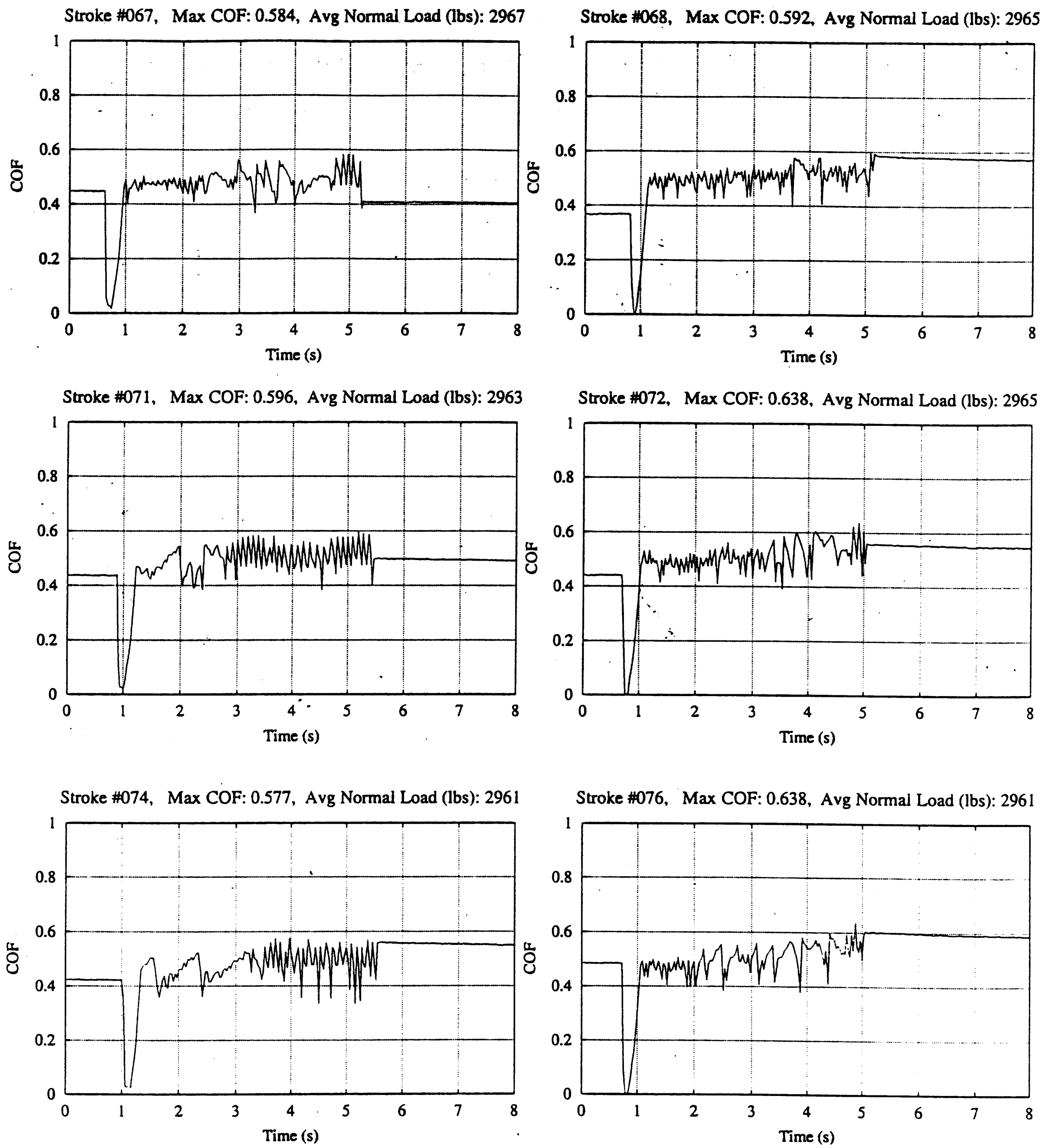


Stroke #064, Max COF: 0.574, Avg Normal Load (lbs): 2963

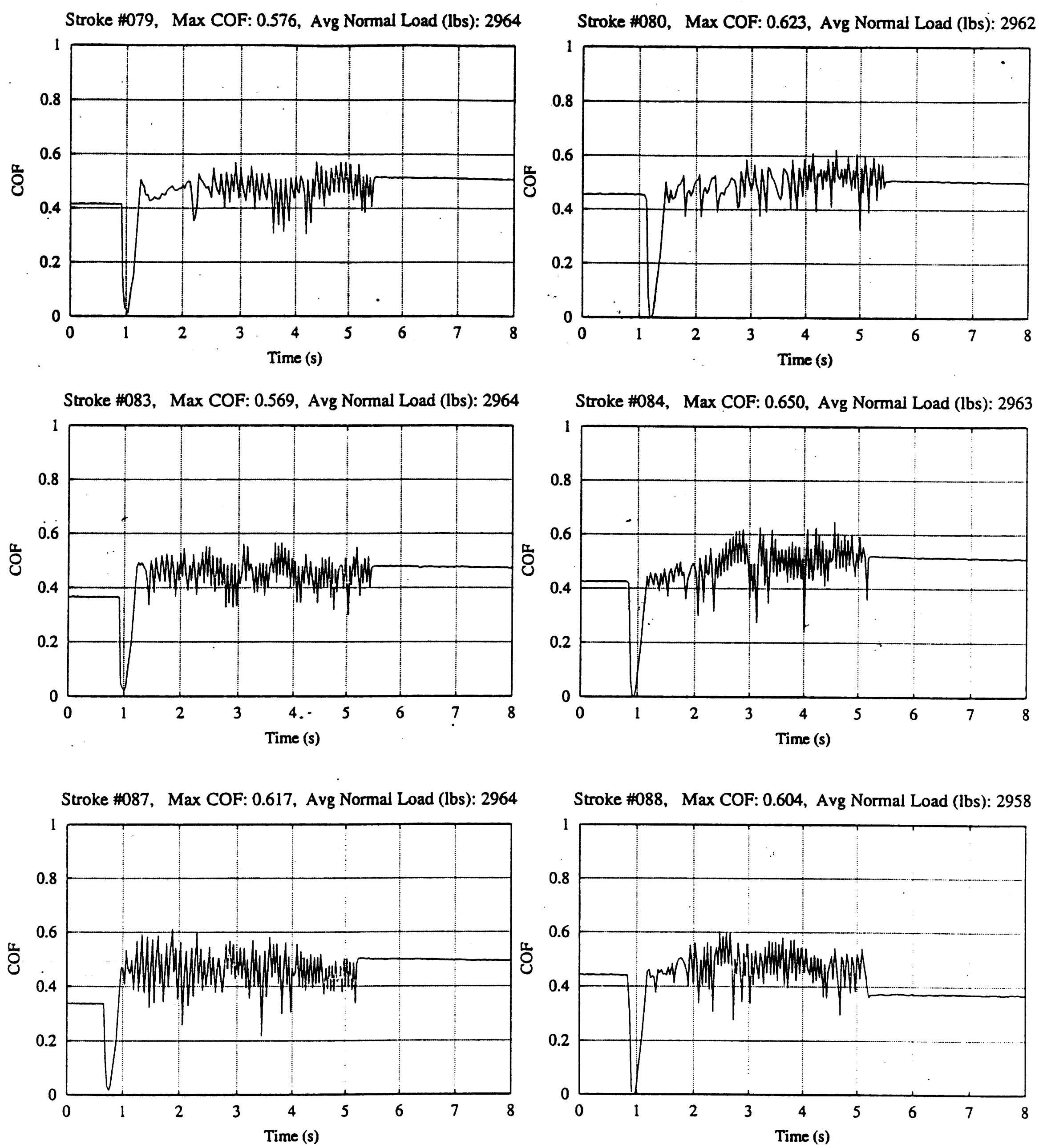


AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in

Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

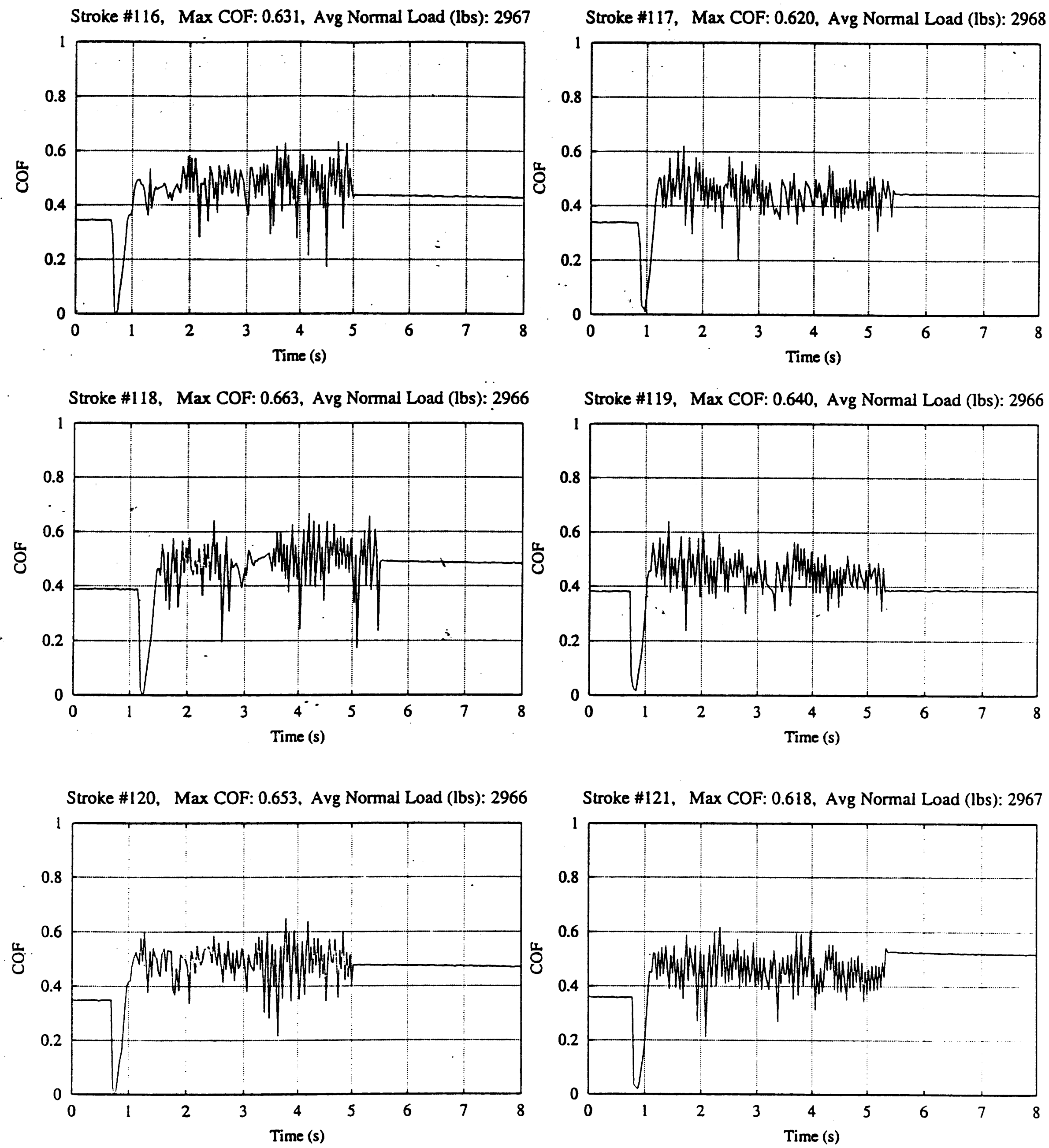


AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in



AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in

Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2



AM6&7 01/27/99 Norem 02 200F 15ksi rec. 1.6in

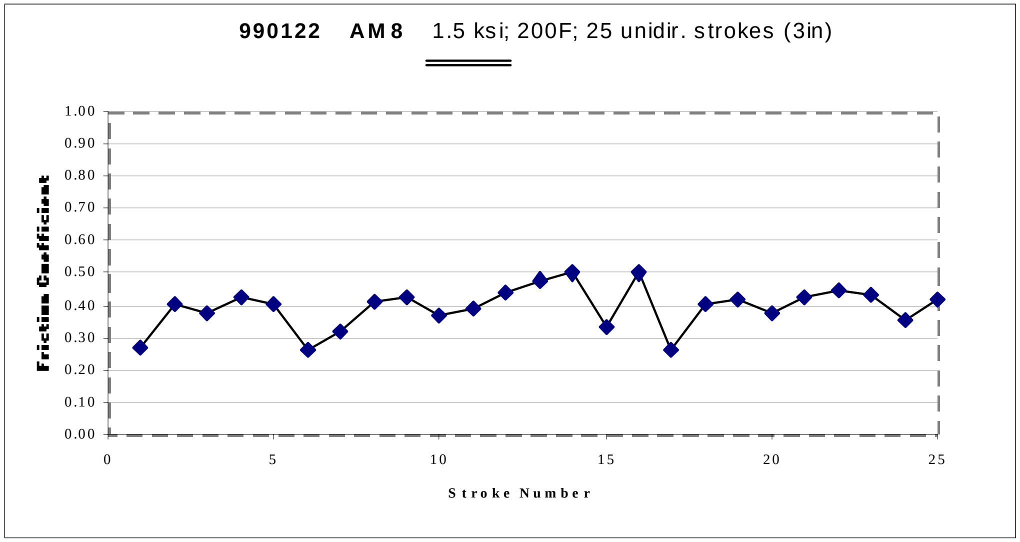
AM8: 25 Strokes at 1.5 ksi

200°F

3" Stroke Length

AM8 01/22/99 Norem 02 200F 1.5ksi 25 strokes/uni 3inches

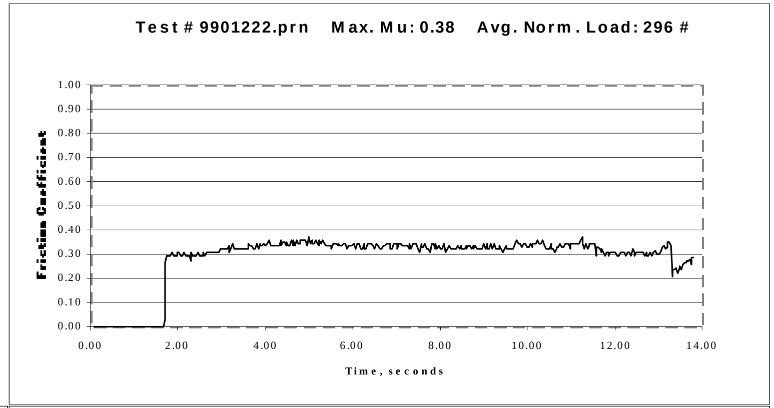
	Max. Mu:	Avg. Norm. Load:
9901220.prn	0.27	296
9901221.prn	0.40	296
9901222.prn	0.38	296
9901223.prn	0.43	299
9901224.prn	0.41	298
9901225.prn	0.27	301
9901226.prn	0.32	298
9901227.prn	0.42	302
9901228.prn	0.43	304
9901229.prn	0.37	302
99012210.prn	0.39	301
99012211.prn	0.45	300
99012212.prn	0.48	303
99012213.prn	0.50	303
99012214.prn	0.34	300
99012215.prn	0.50	299
99012216.prn	0.27	296
99012217.prn	0.41	299
99012218.prn	0.42	299
99012219.prn	0.38	300
99012220.prn	0.43	298
99012221.prn	0.45	303
99012222.prn	0.43	302
99012223.prn	0.35	300
99012224.prn	0.42	305

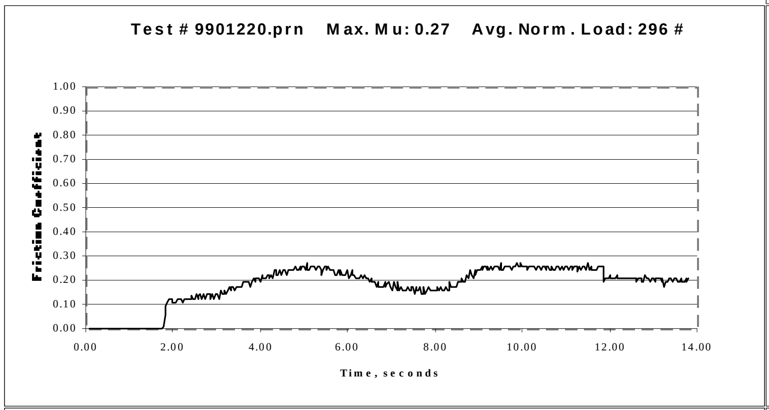


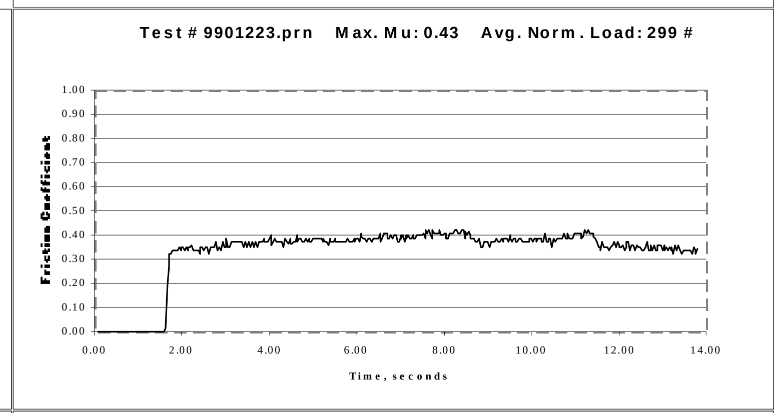
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

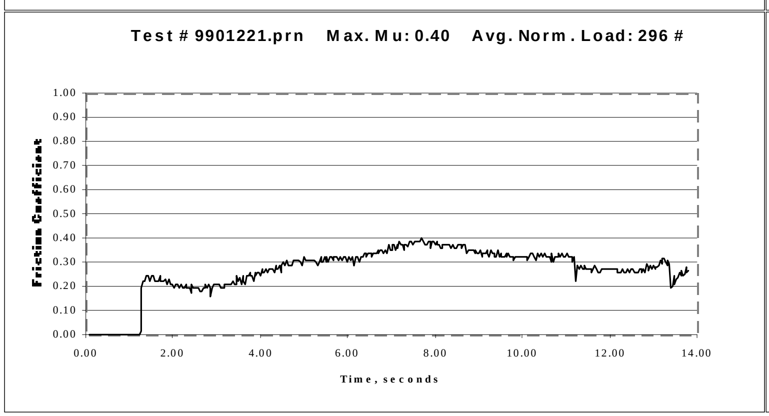
AM8 01/22/99 Norem 02 200F 1.5ksi 25 strokes/uni 3inches

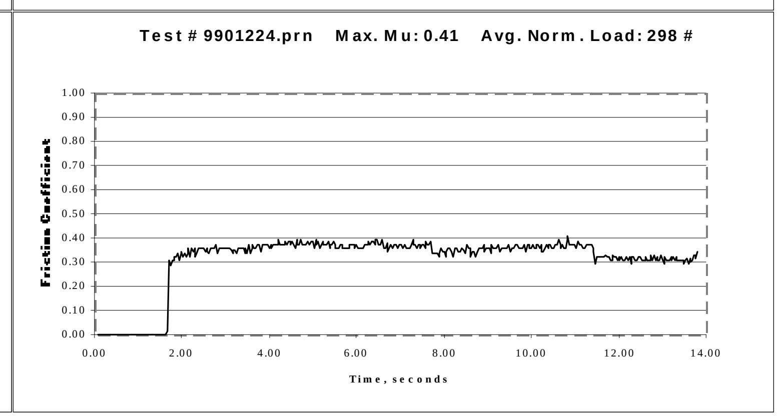
No preconditioning stroke



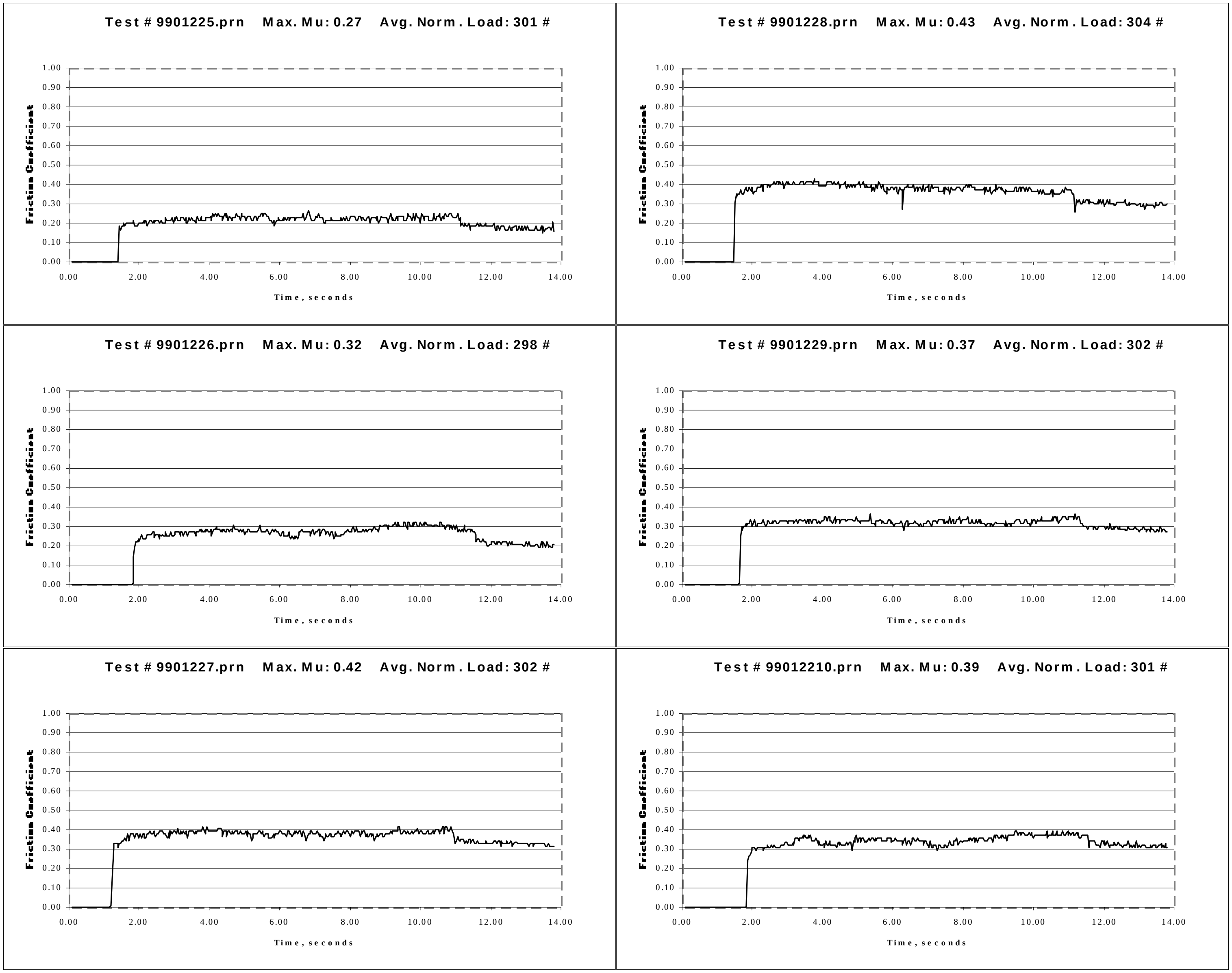






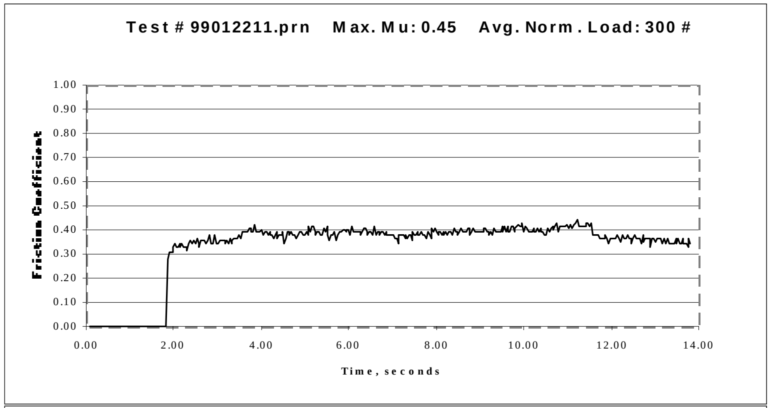


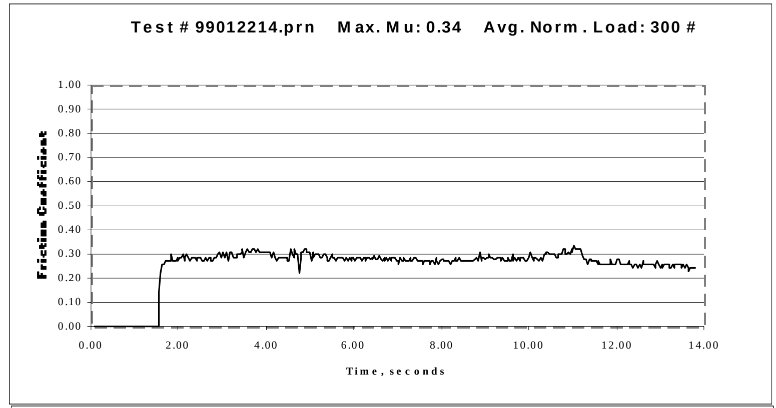
AM8 01/22/99 Norem 02 200F 1.5ksi 25 strokes/uni 3inches

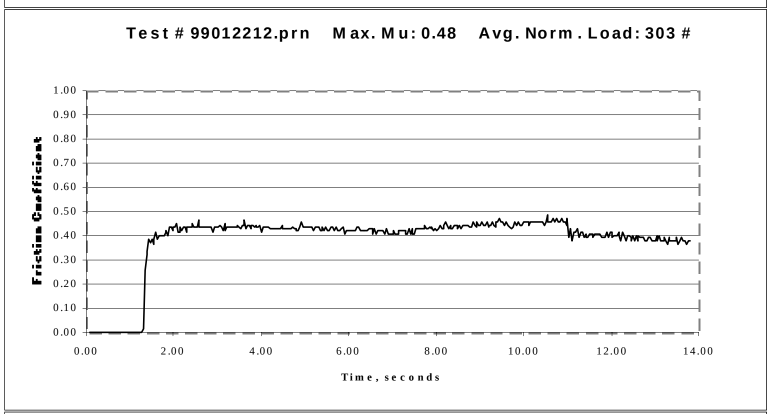


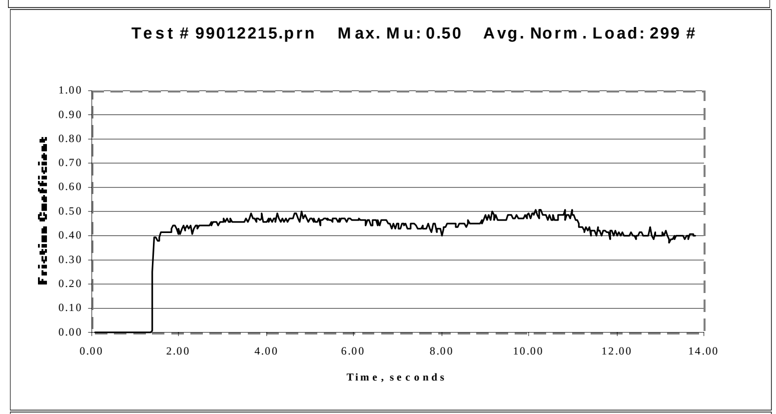
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

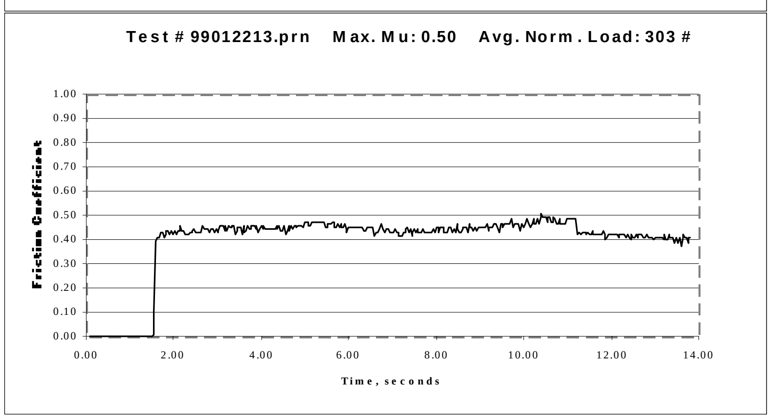
AM8 01/22/99 Norem 02 200F 1.5ksi 25 strokes/uni 3inches

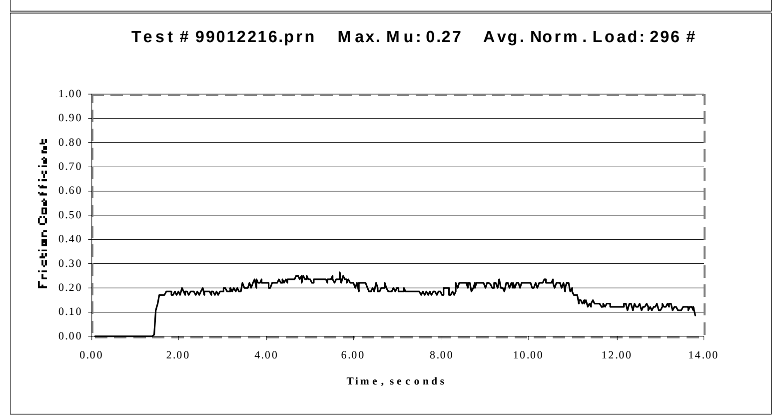




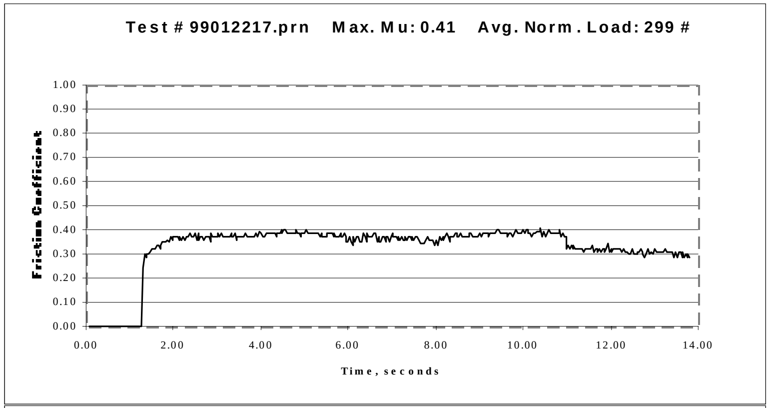


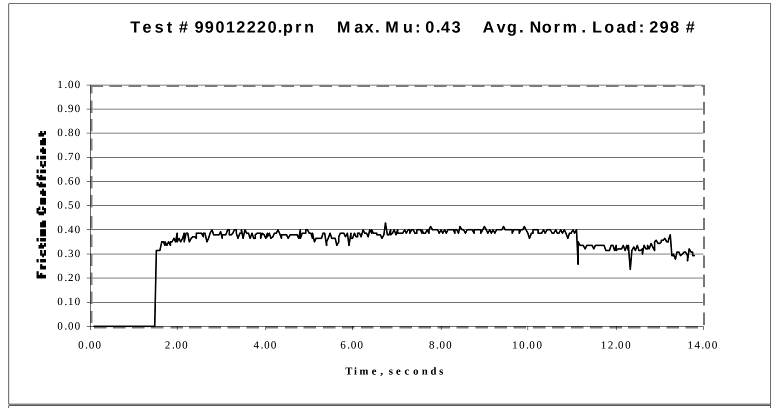


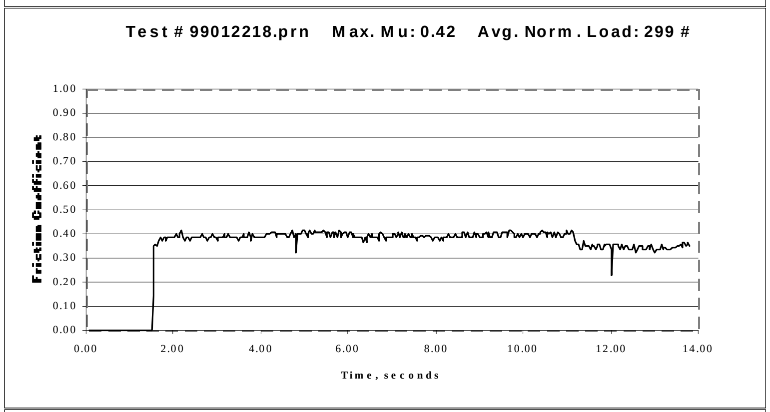


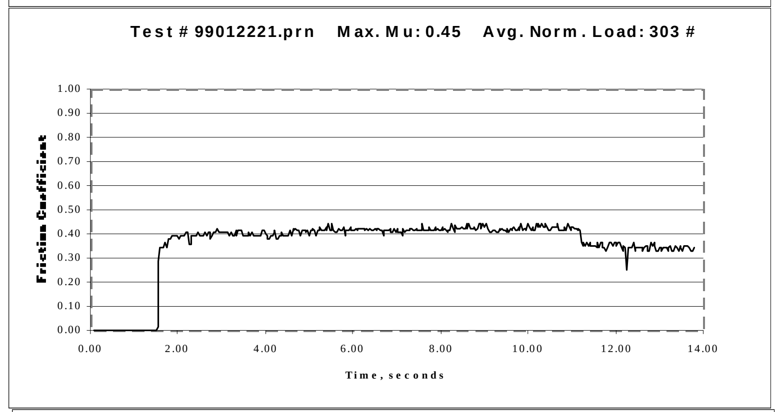


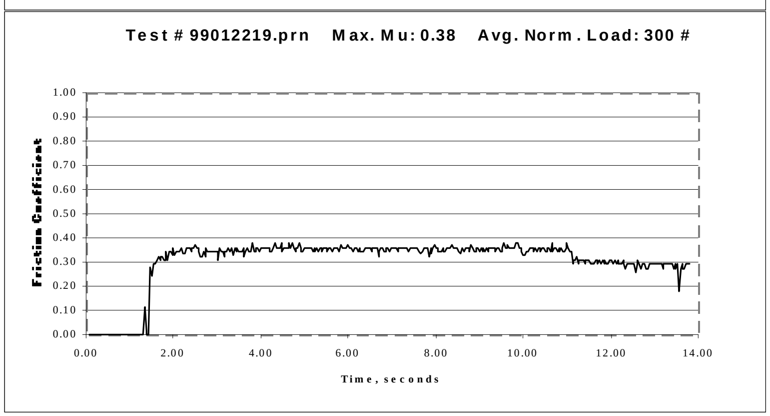
AM8 01/22/99 Norem 02 200F 1.5ksi 25 strokes/uni 3inches

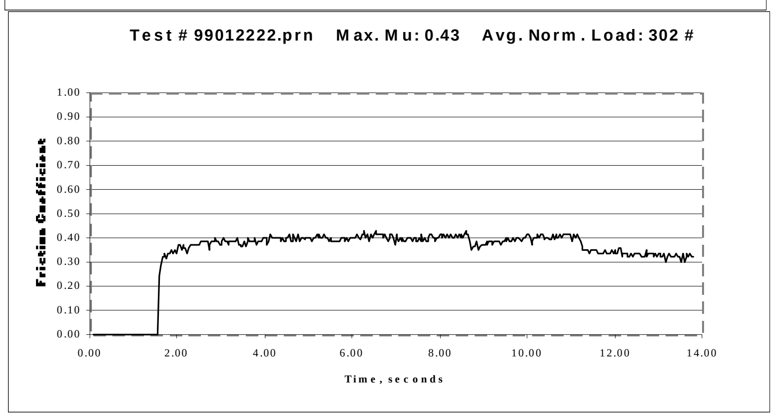






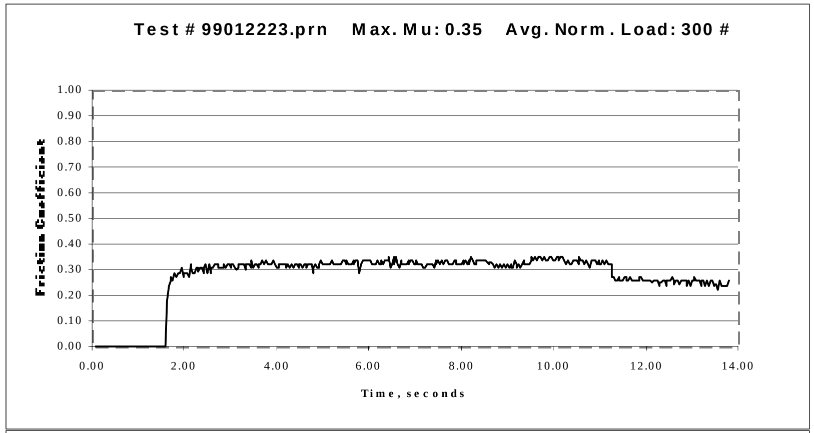


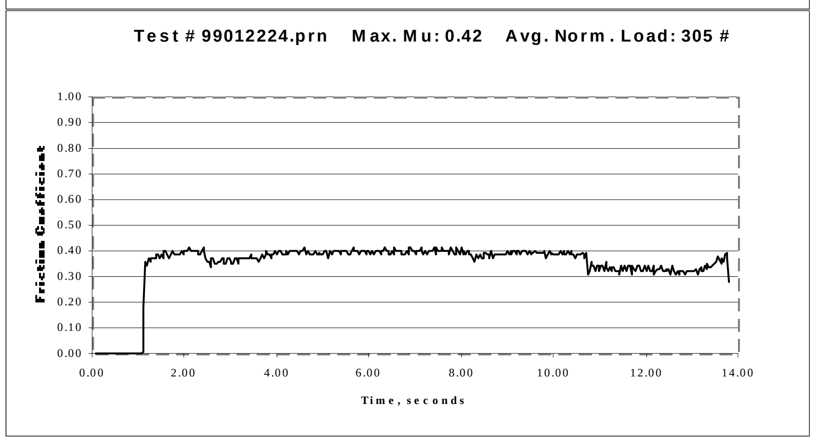




Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

AM8 01/22/99 Norem 02 200F 1.5ksi 25 strokes/uni 3inches



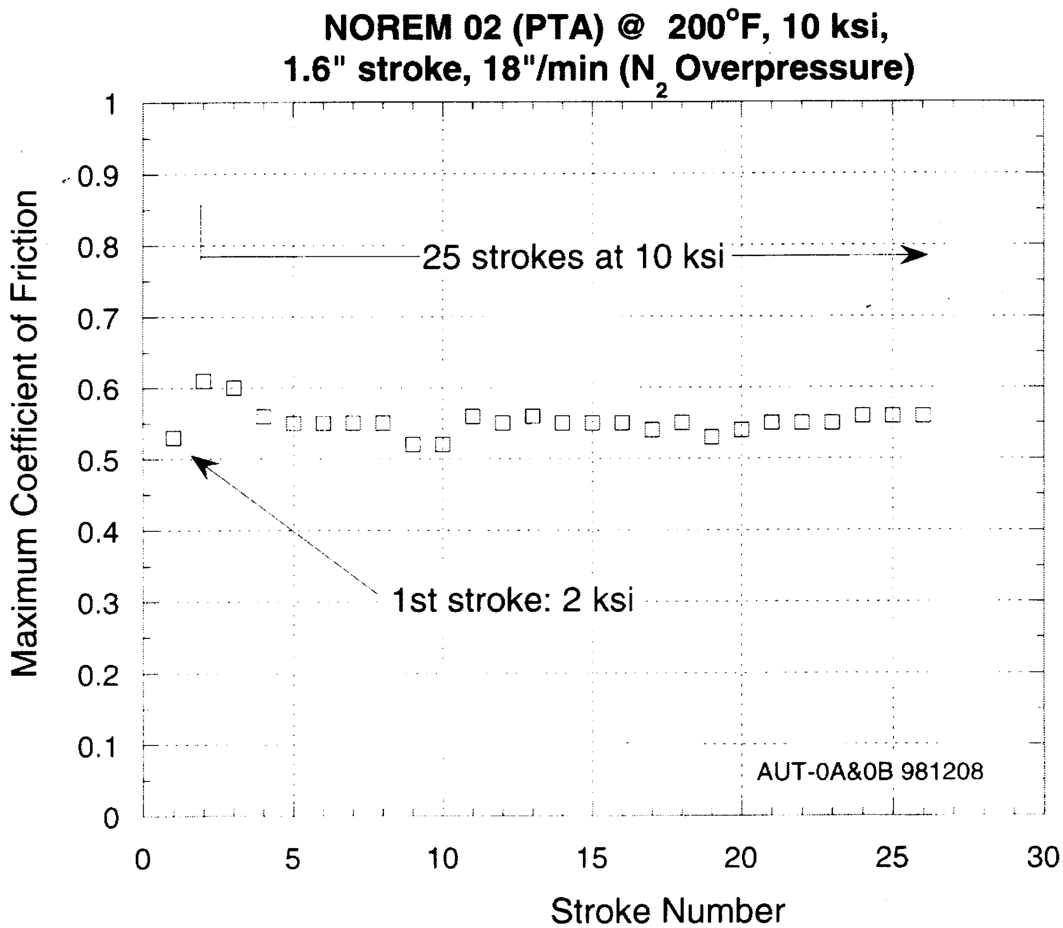


AUT0 A: 1 Preconditioning Stroke at 2 ksi
&
AUT0 B: 25 Strokes at 10 ksi

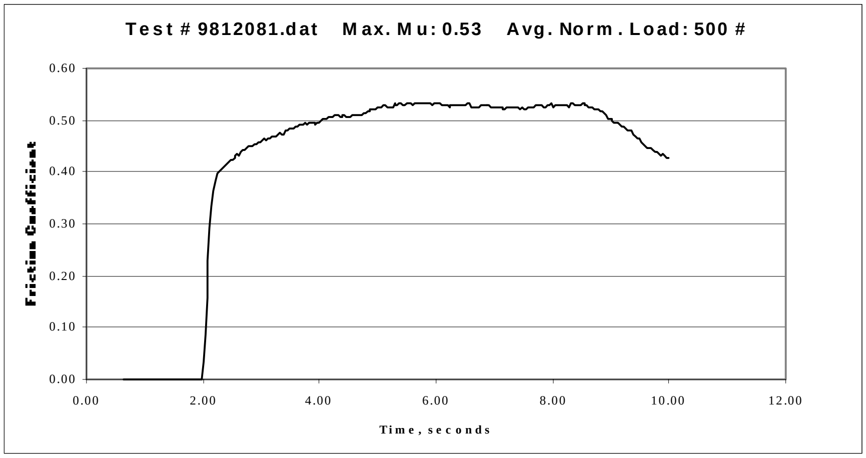
200°F

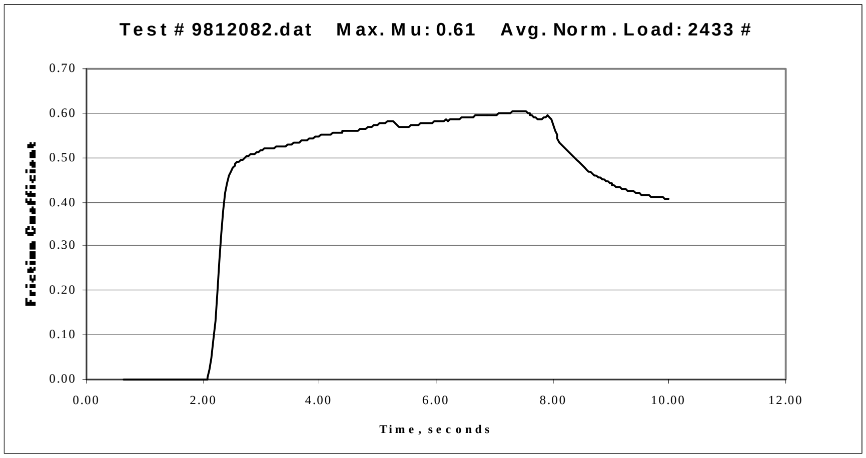
Overpressure with N_2

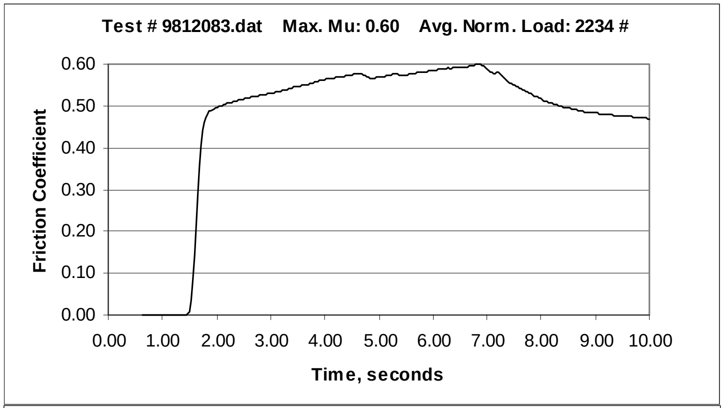
1.6" Stroke Length

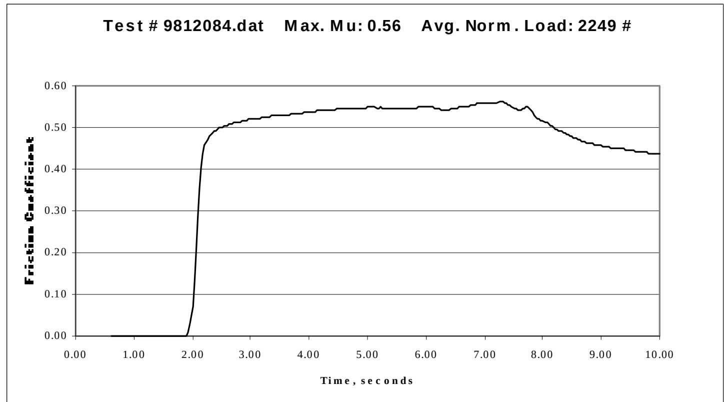

NOREM 02 (PTA) @ 200°F, 10 ksi,
1.6" stroke, 18"/min (N2 Overpressure)
Maximum Coefficient of Friction
Stroke Number
25 strokes at 10 ksi
1st stroke: 2 ksi
AUT-0A&0B 981208
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30

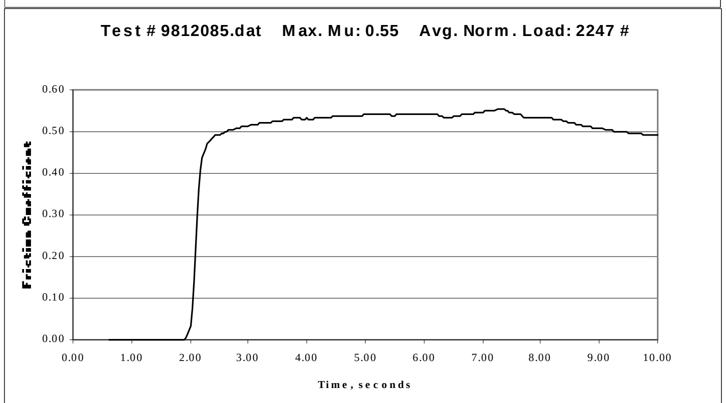
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

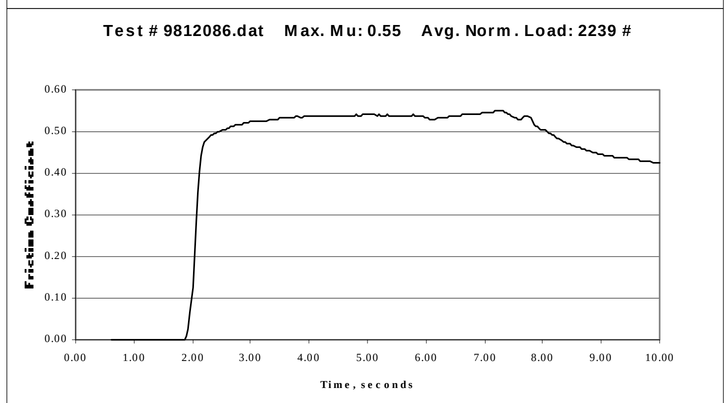


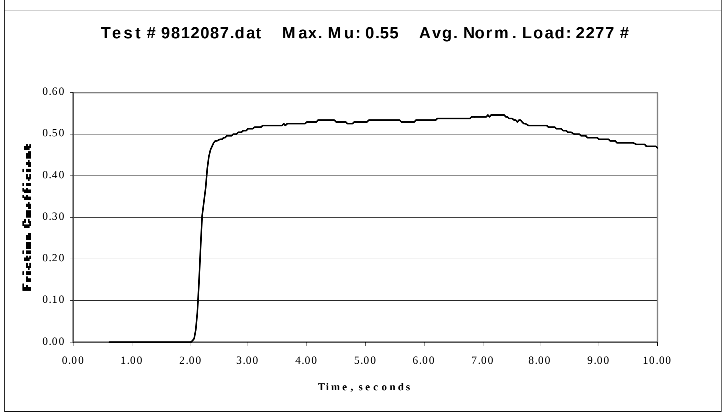


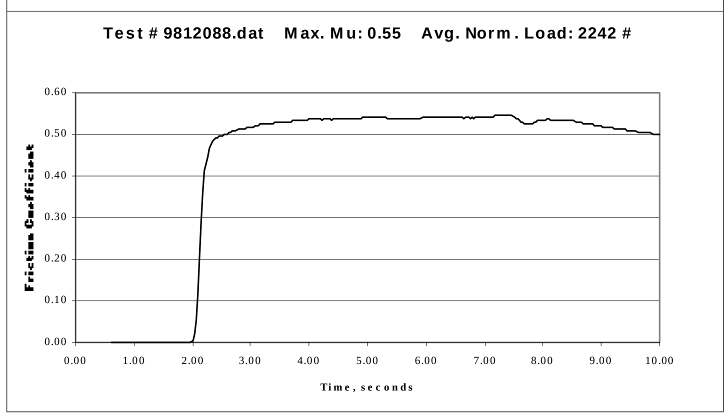

Test # 9812083.dat Max. Mu: 0.60 Avg. Norm. Load: 2234 #
Friction Coefficient
Time, seconds


Test # 9812084.dat Max. Mu: 0.56 Avg. Norm. Load: 2249 #
Friction Coefficient
Time, seconds

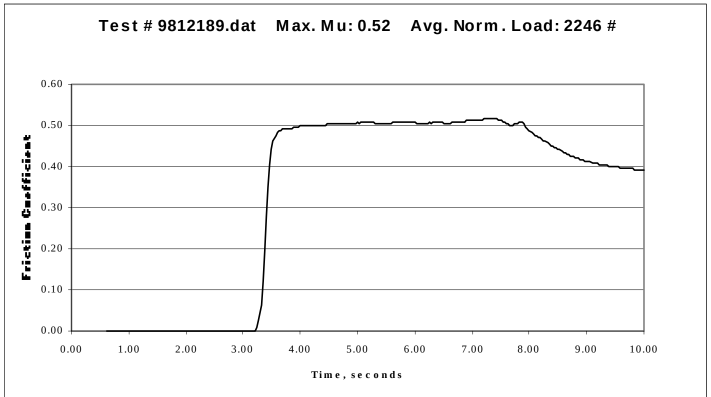

Test # 9812085.dat Max. Mu: 0.55 Avg. Norm. Load: 2247 #
Friction Coefficient
Time, seconds

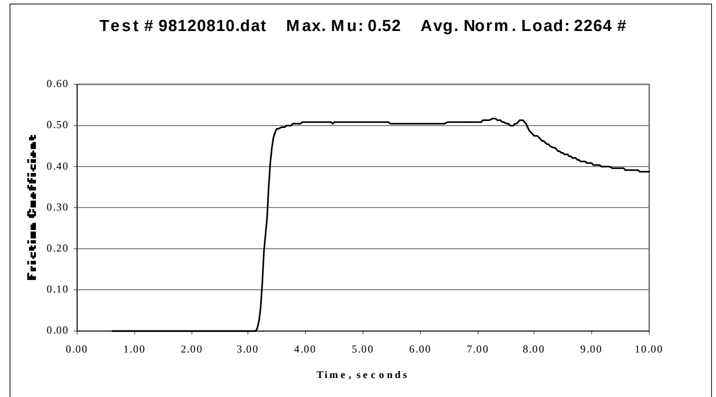

Test # 9812086.dat Max. Mu: 0.55 Avg. Norm. Load: 2239 #
Friction Coefficient
Time, seconds

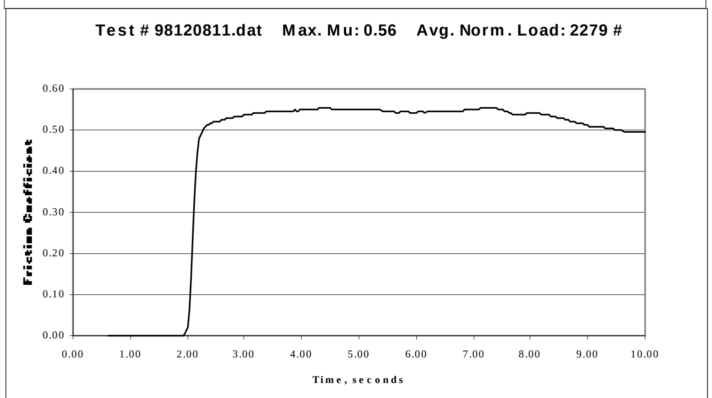

Test # 9812087.dat Max. Mu: 0.55 Avg. Norm. Load: 2277 #
Friction Coefficient
Time, seconds

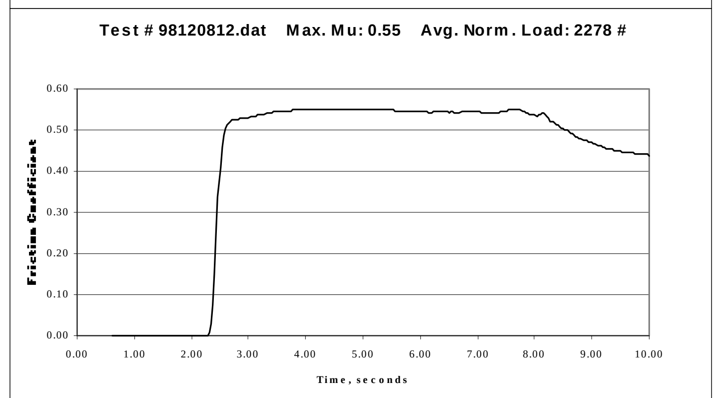

Test # 9812088.dat Max. Mu: 0.55 Avg. Norm. Load: 2242 #
Friction Coefficient
Time, seconds

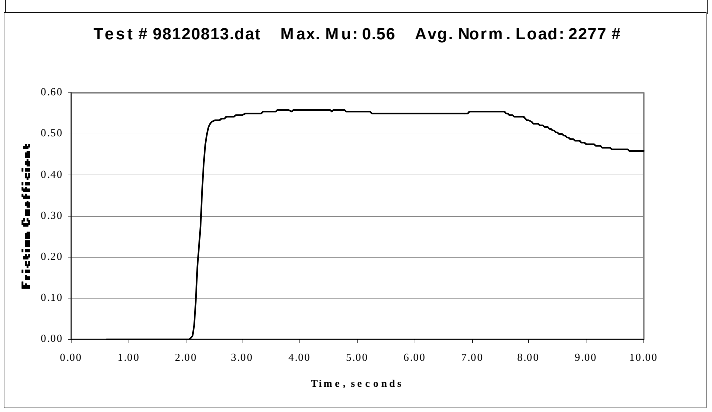
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

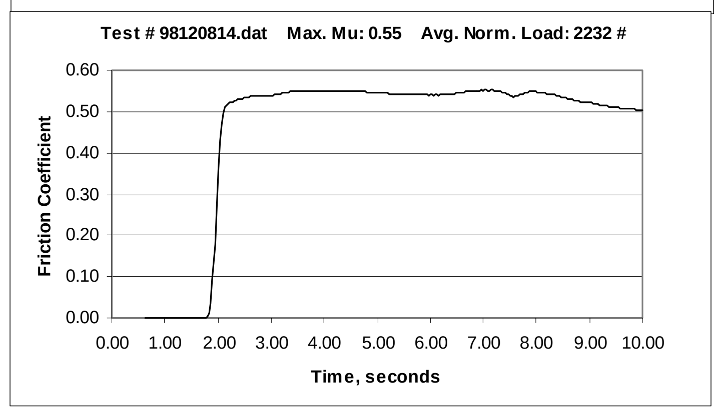


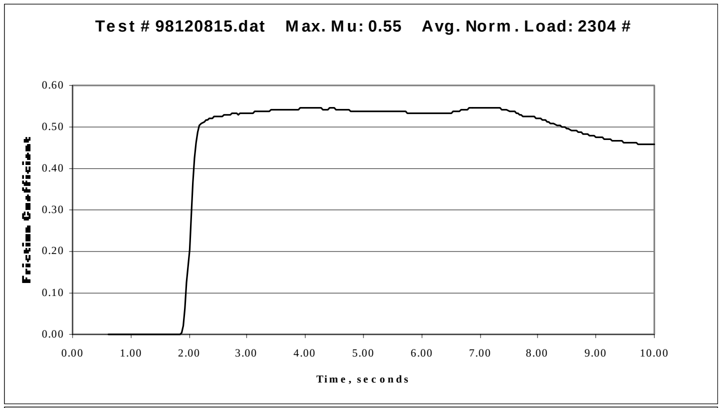


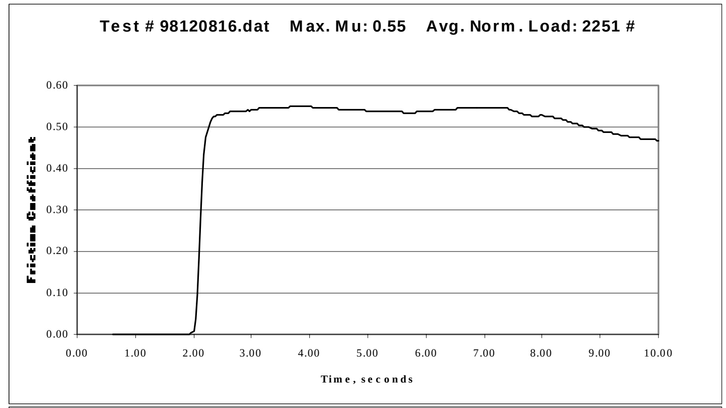


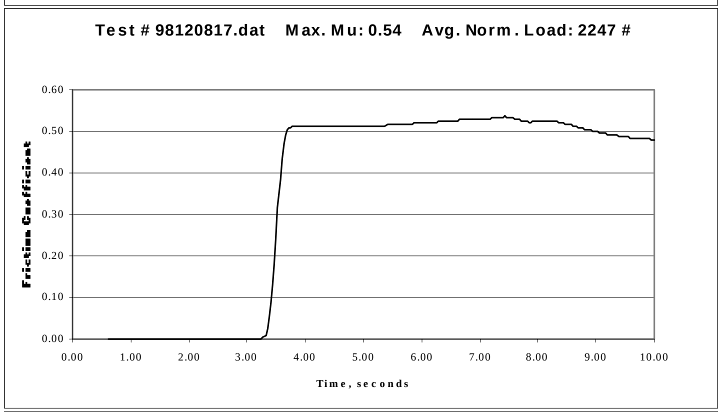


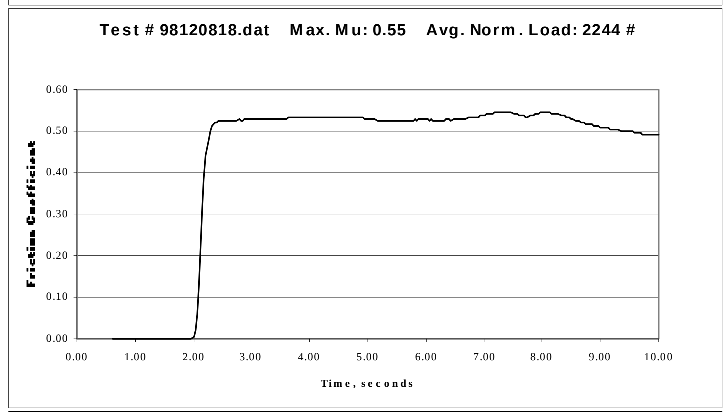


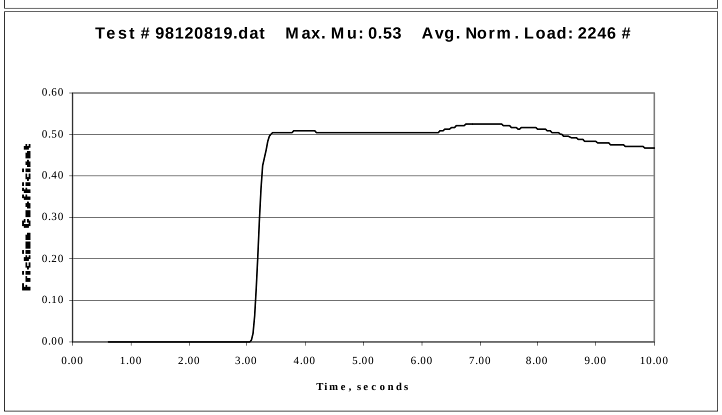


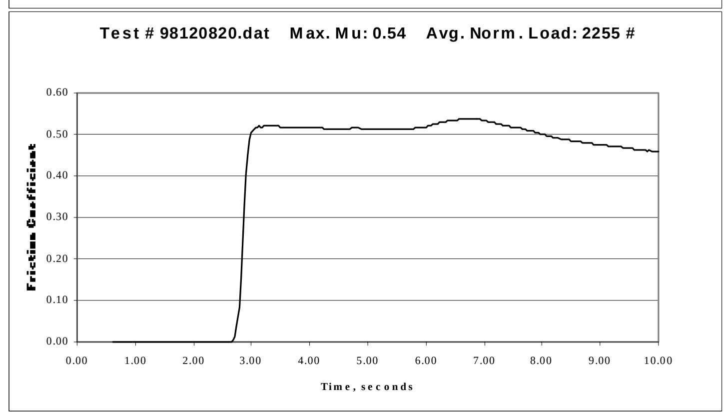

Test # 98120815.dat Max. Mu: 0.55 Avg. Norm. Load: 2304 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 98120816.dat Max. Mu: 0.55 Avg. Norm. Load: 2251 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

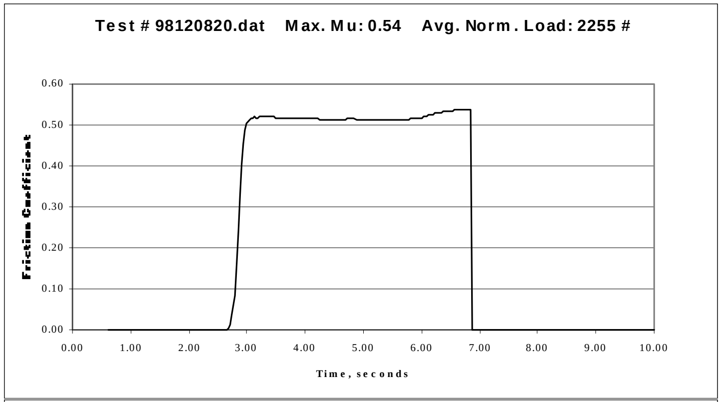

Test # 98120817.dat Max. Mu: 0.54 Avg. Norm. Load: 2247 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

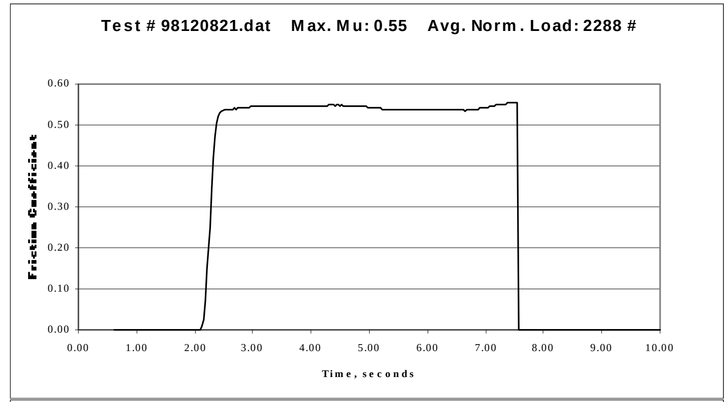

Test # 98120818.dat Max. Mu: 0.55 Avg. Norm. Load: 2244 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

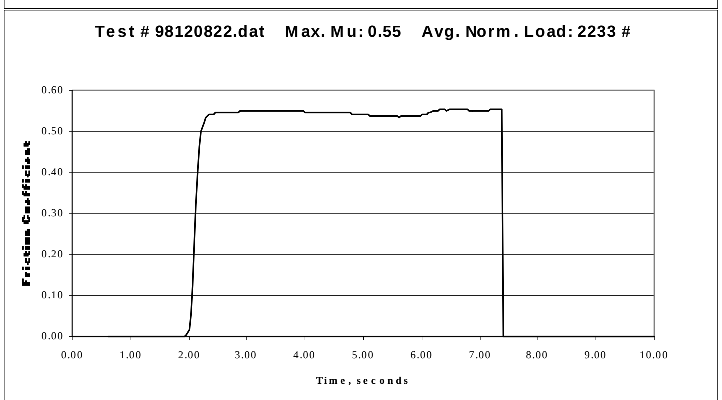

Test # 98120819.dat Max. Mu: 0.53 Avg. Norm. Load: 2246 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

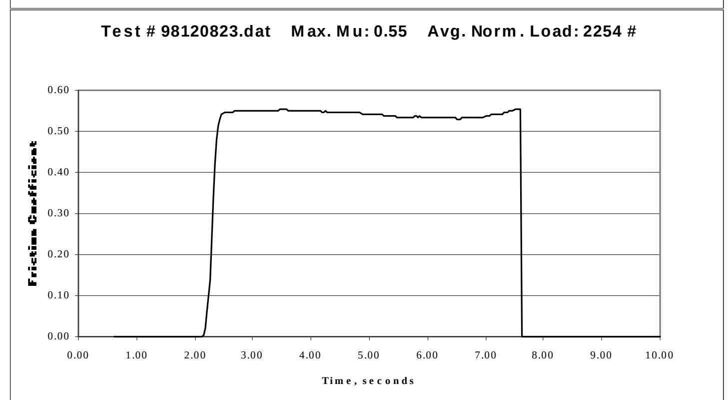

Test # 98120820.dat Max. Mu: 0.54 Avg. Norm. Load: 2255 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

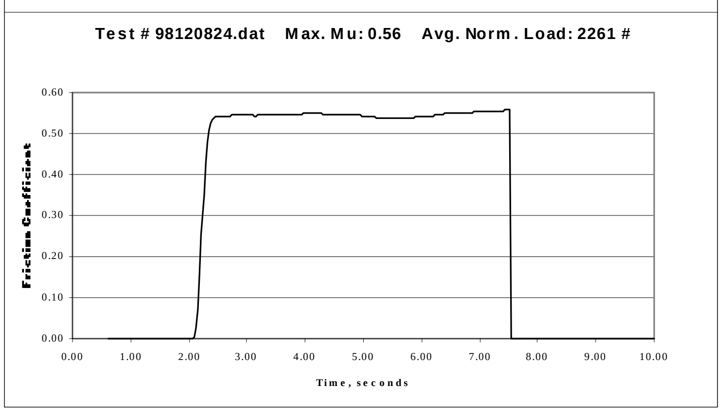
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

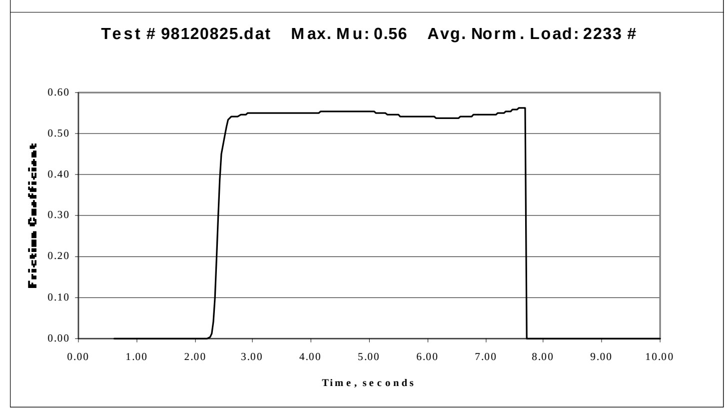


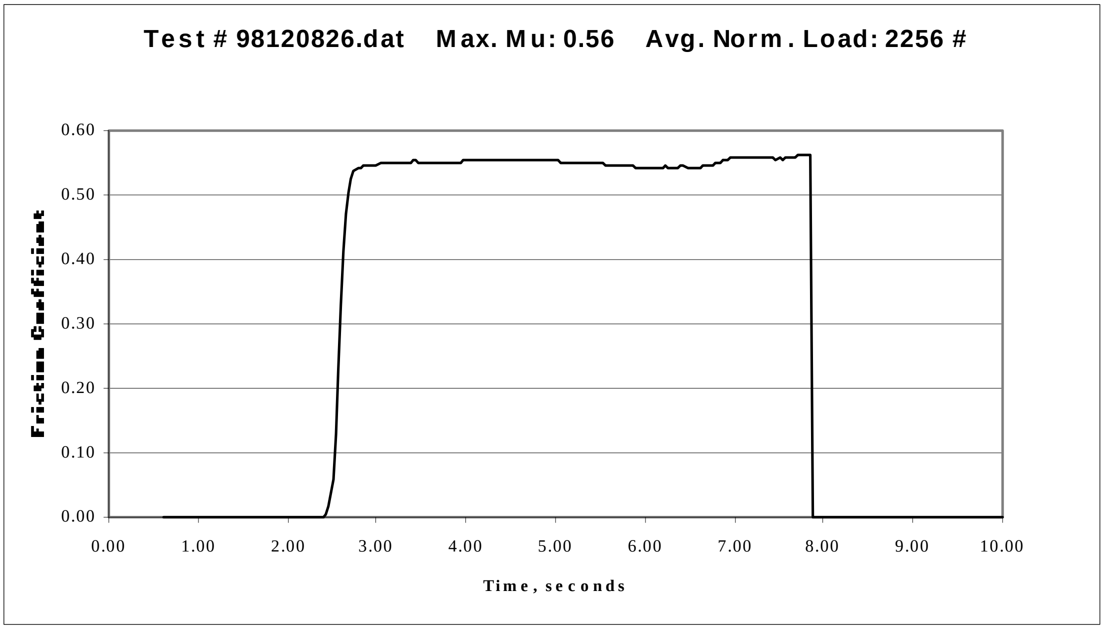










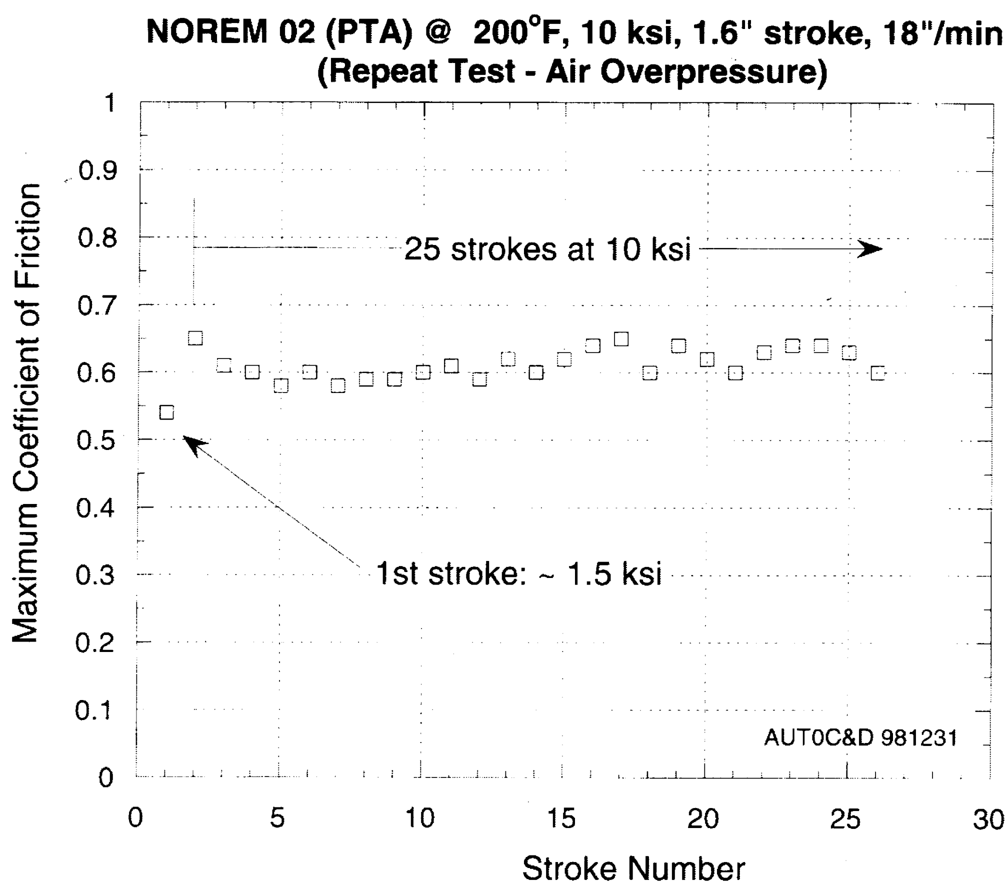

Test # 98120826.dat Max. Mu: 0.56 Avg. Norm. Load: 2256 #
Friction Coefficient
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Time, seconds

AUT0 C: 1 Preconditioning Stroke at 1.5 ksi
&
AUT0 D: 25 Strokes at 10 ksi

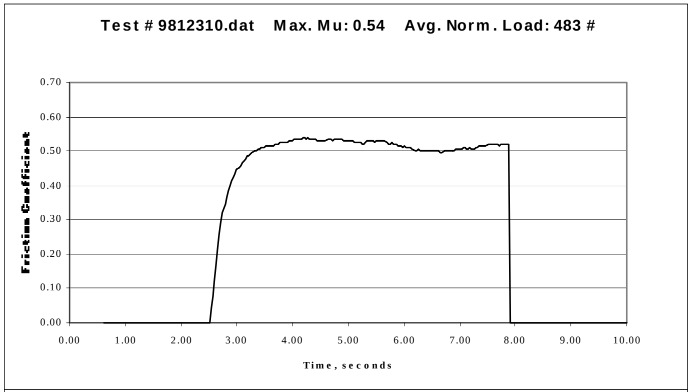
200°F

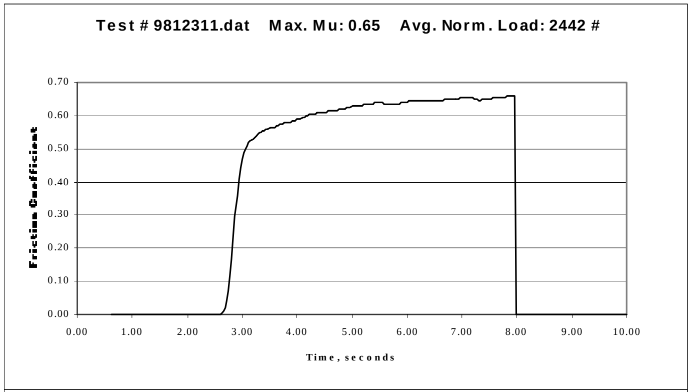
Overpressure with Air

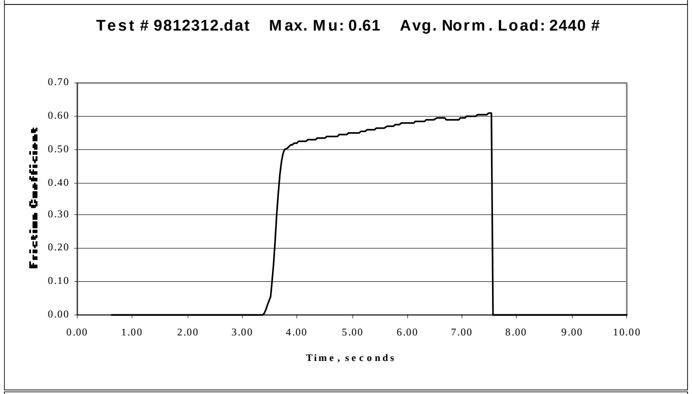
1.6" Stroke Length

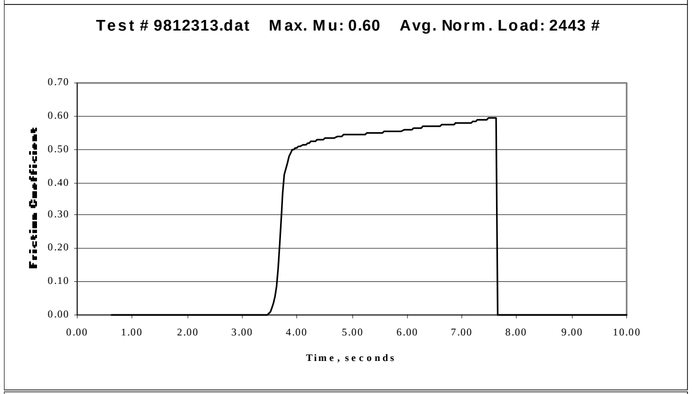

NOREM 02 (PTA) @ 200°F, 10 ksi, 1.6" stroke, 18"/min
(Repeat Test - Air Overpressure)
Maximum Coefficient of Friction
Stroke Number
25 strokes at 10 ksi
1st stroke: ~ 1.5 ksi
AUT0C&D 981231
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
5
10
15
20
25
30

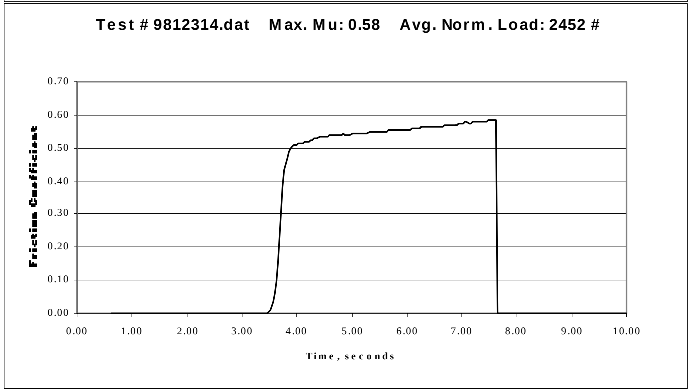
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

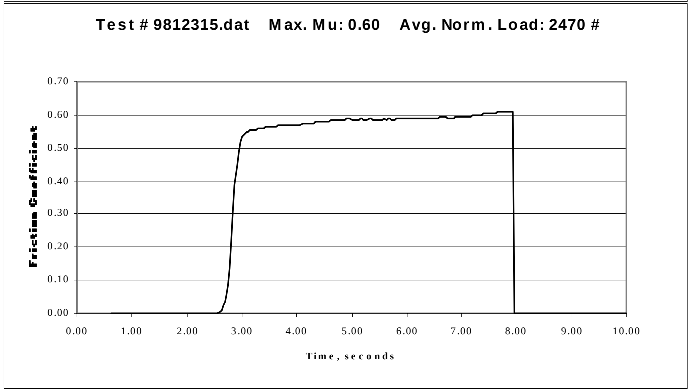


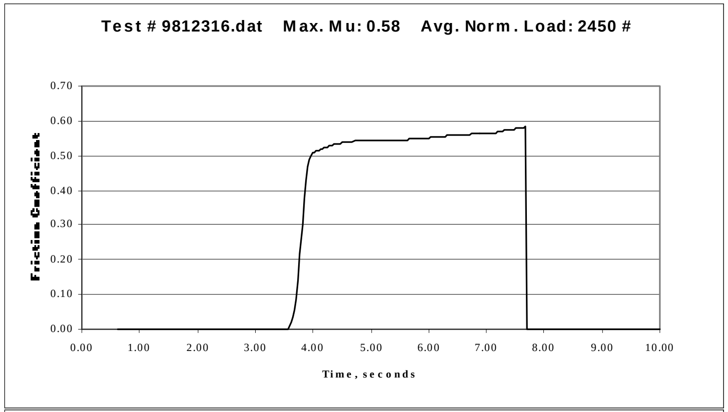


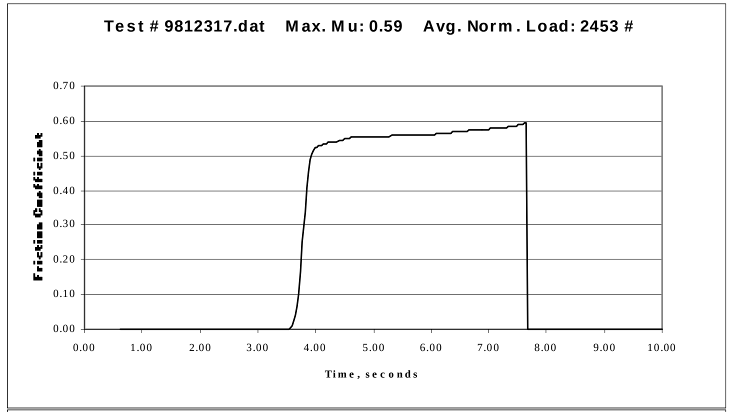


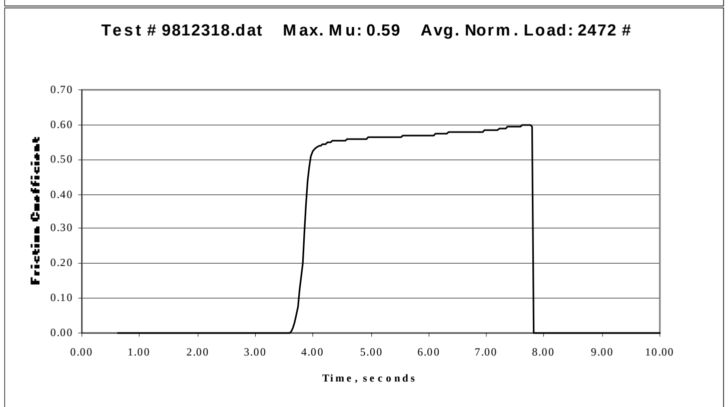


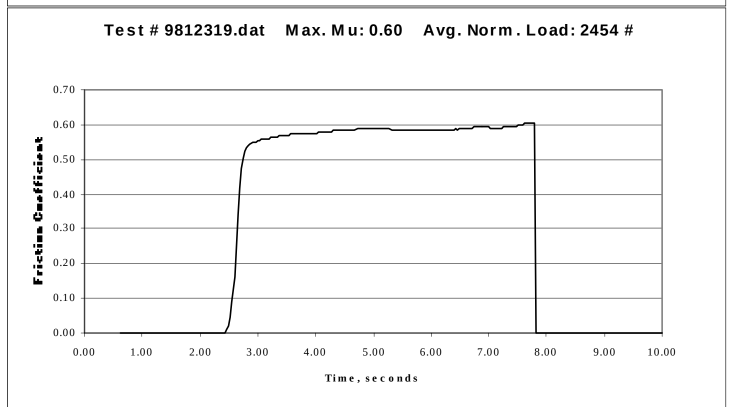


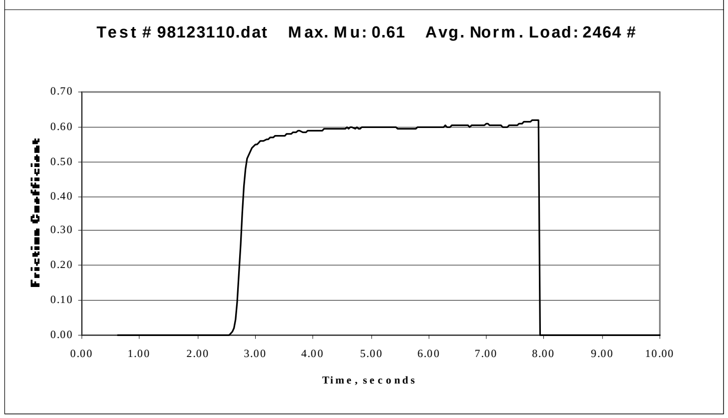


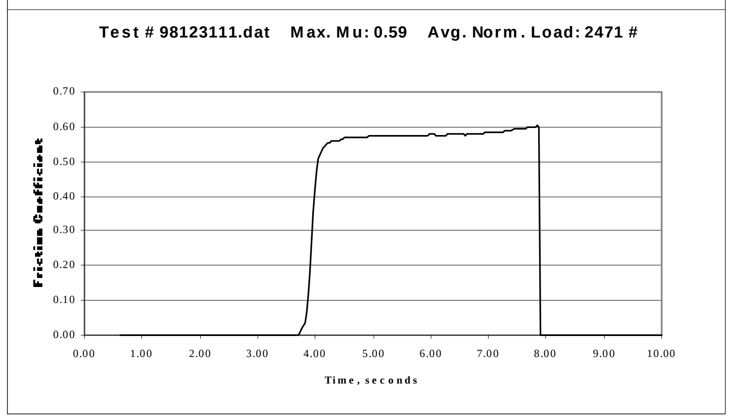

Test # 9812316.dat Max. Mu: 0.58 Avg. Norm. Load: 2450 #
Friction Coefficient
Time, seconds


Test # 9812317.dat Max. Mu: 0.59 Avg. Norm. Load: 2453 #
Friction Coefficient
Time, seconds

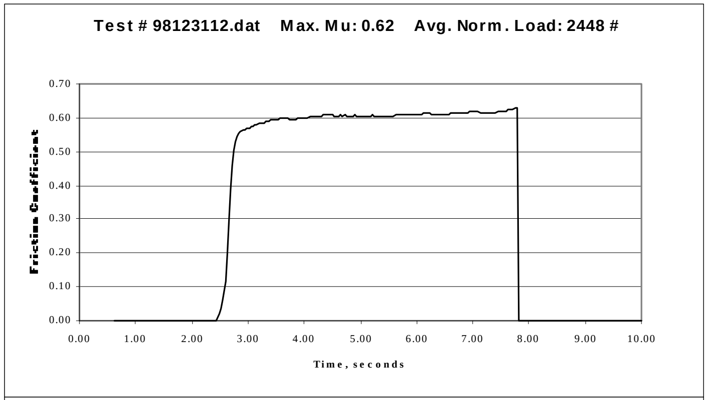

Test # 9812318.dat Max. Mu: 0.59 Avg. Norm. Load: 2472 #
Friction Coefficient
Time, seconds

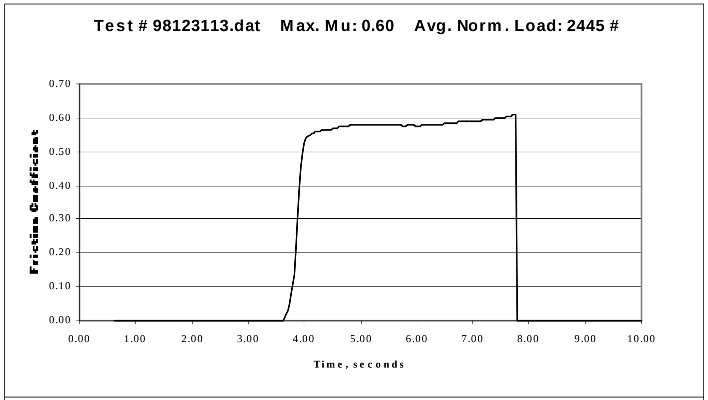

Test # 9812319.dat Max. Mu: 0.60 Avg. Norm. Load: 2454 #
Friction Coefficient
Time, seconds

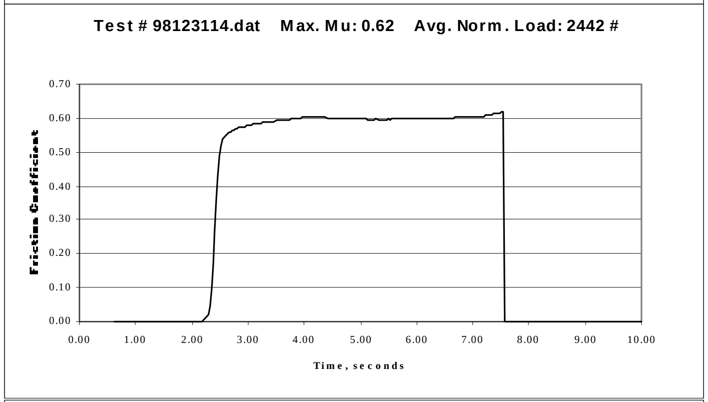

Test # 98123110.dat Max. Mu: 0.61 Avg. Norm. Load: 2464 #
Friction Coefficient
Time, seconds

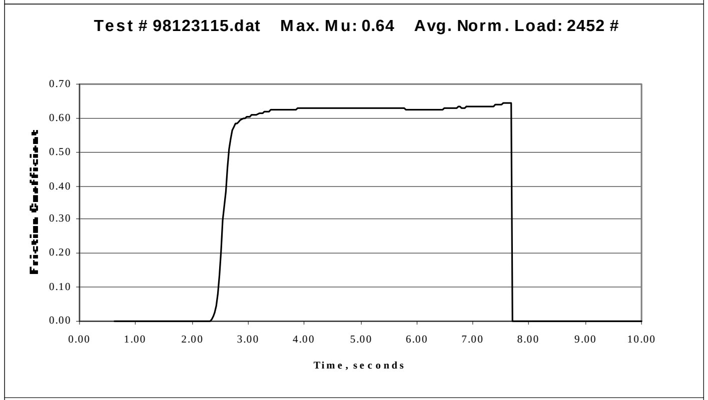

Test # 98123111.dat Max. Mu: 0.59 Avg. Norm. Load: 2471 #
Friction Coefficient
Time, seconds

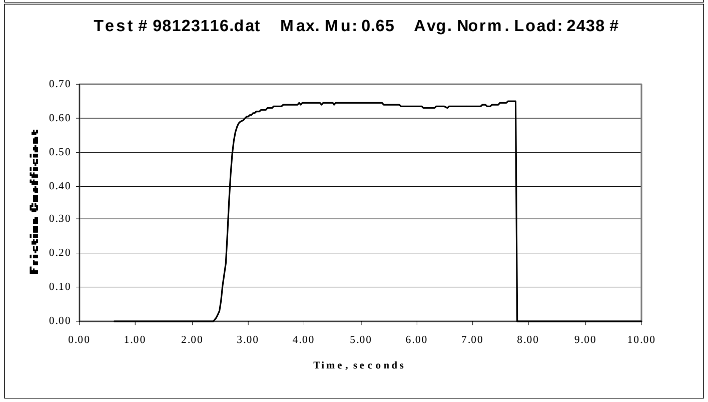
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

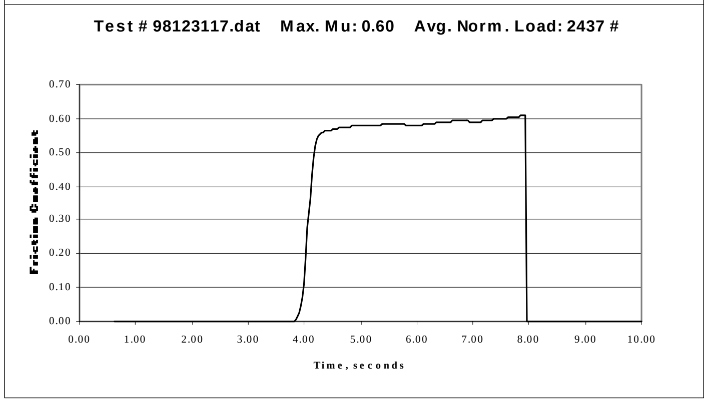


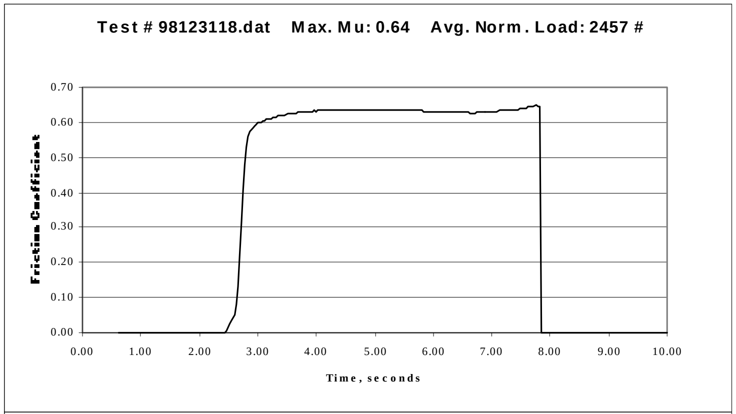


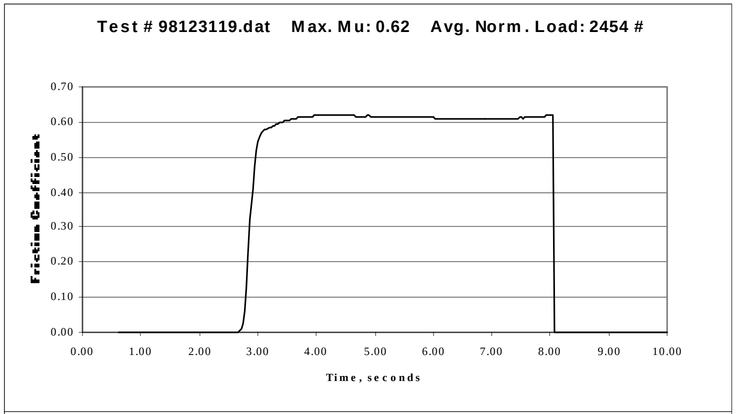


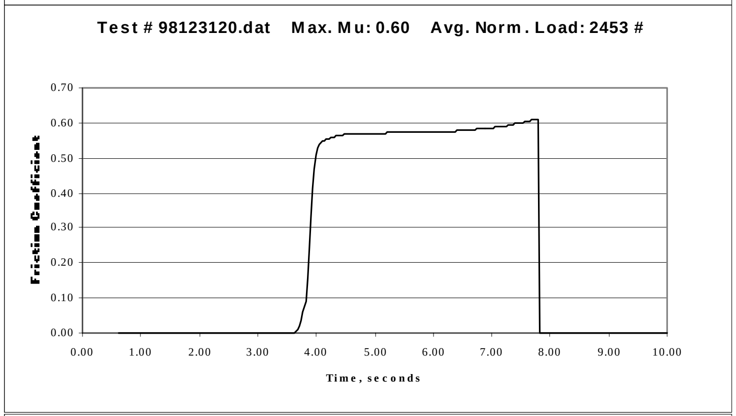


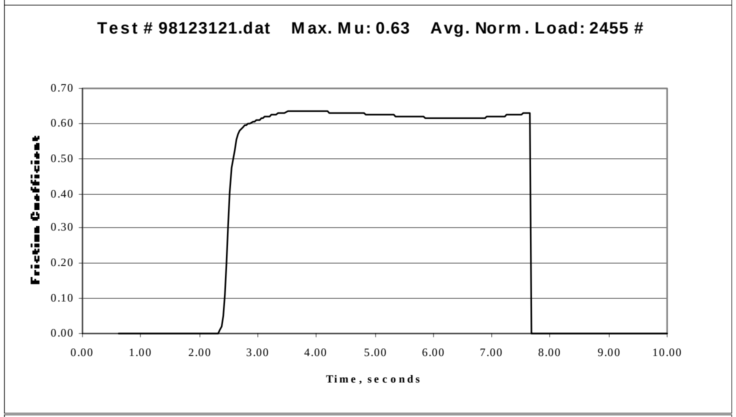


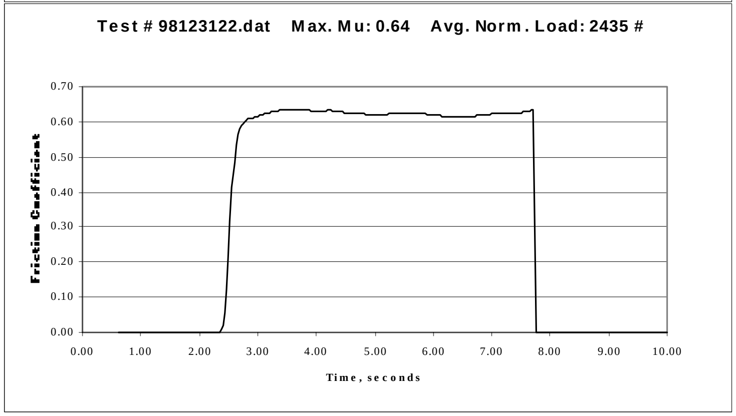


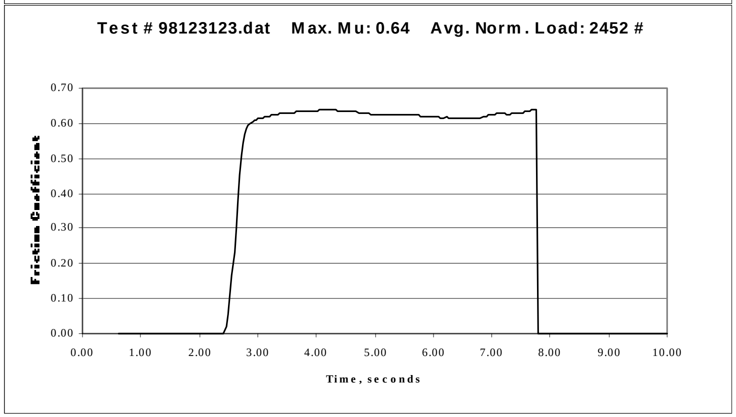

Test # 98123118.dat Max. Mu: 0.64 Avg. Norm. Load: 2457 #
Friction Coefficient
Time, seconds


Test # 98123119.dat Max. Mu: 0.62 Avg. Norm. Load: 2454 #
Friction Coefficient
Time, seconds

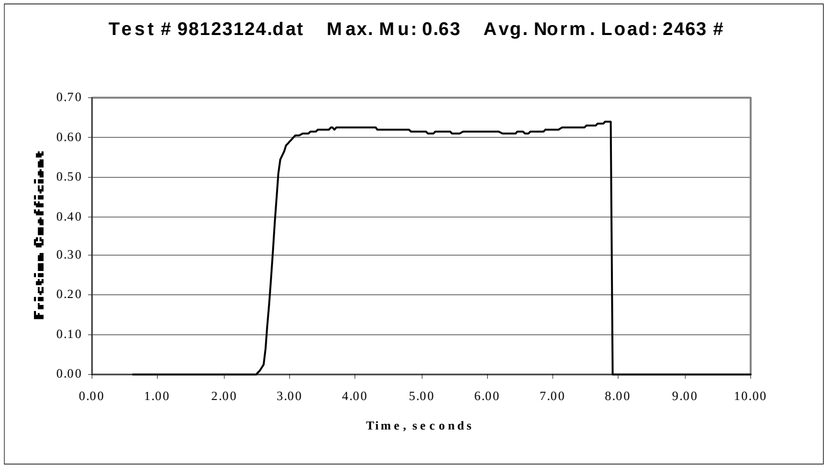

Test # 98123120.dat Max. Mu: 0.60 Avg. Norm. Load: 2453 #
Friction Coefficient
Time, seconds

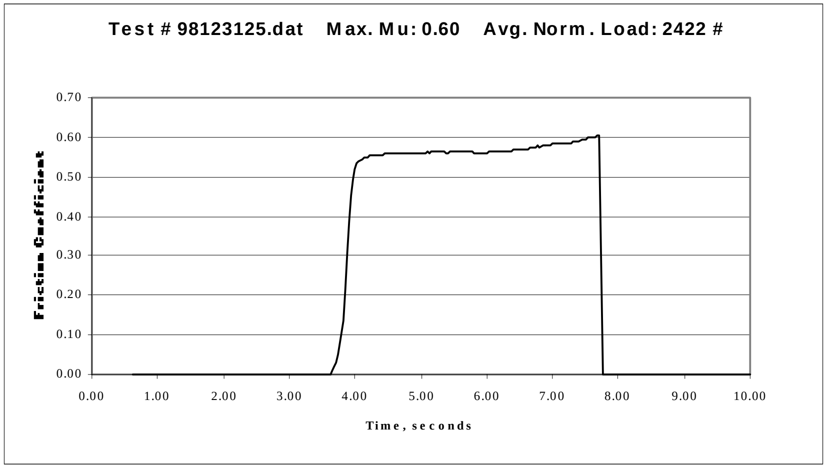

Test # 98123121.dat Max. Mu: 0.63 Avg. Norm. Load: 2455 #
Friction Coefficient
Time, seconds

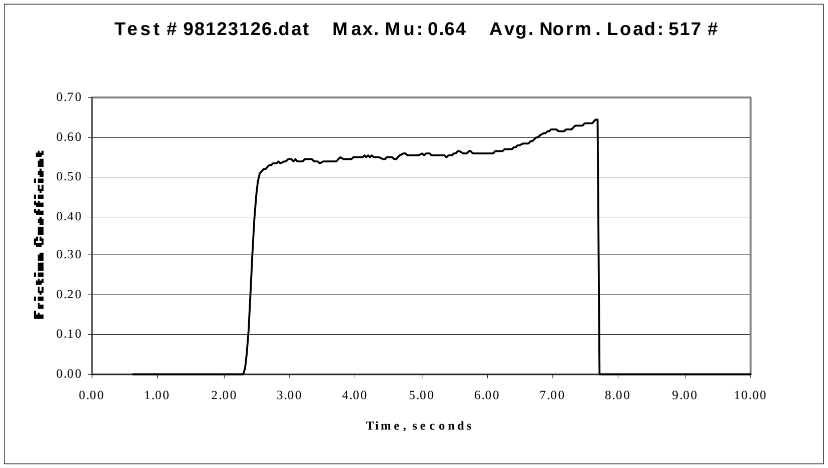

Test # 98123122.dat Max. Mu: 0.64 Avg. Norm. Load: 2435 #
Friction Coefficient
Time, seconds


Test # 98123123.dat Max. Mu: 0.64 Avg. Norm. Load: 2452 #
Friction Coefficient
Time, seconds

Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2



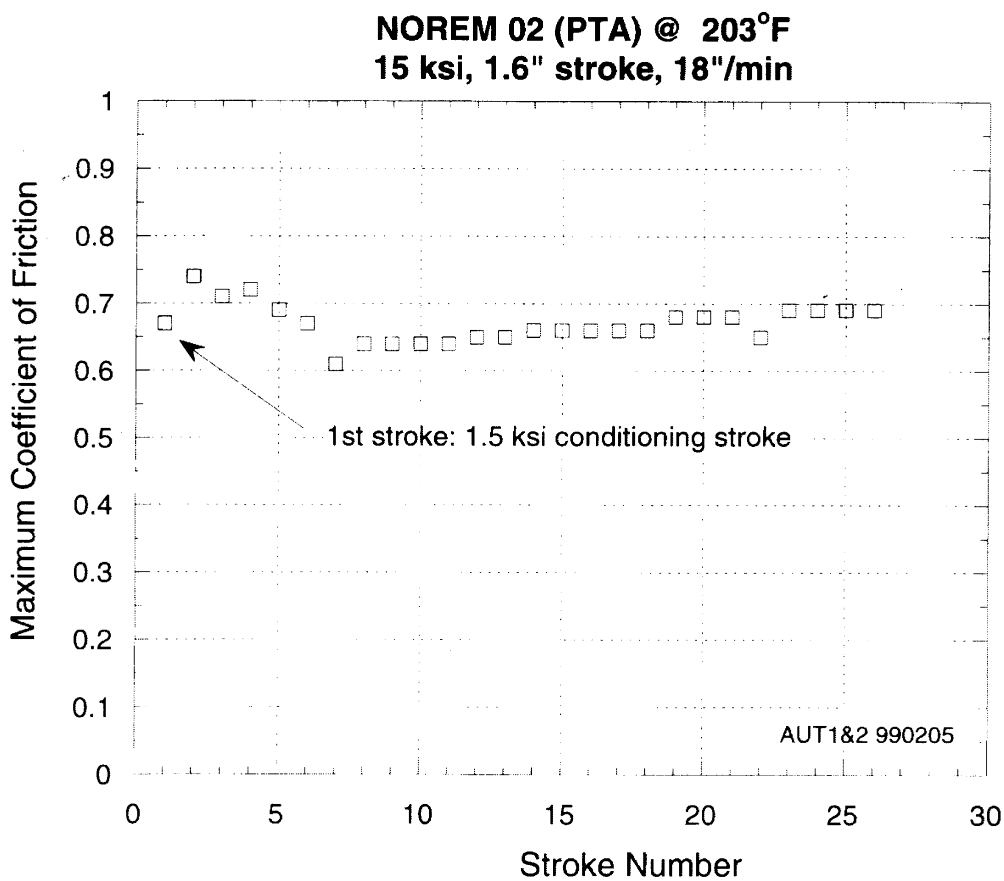




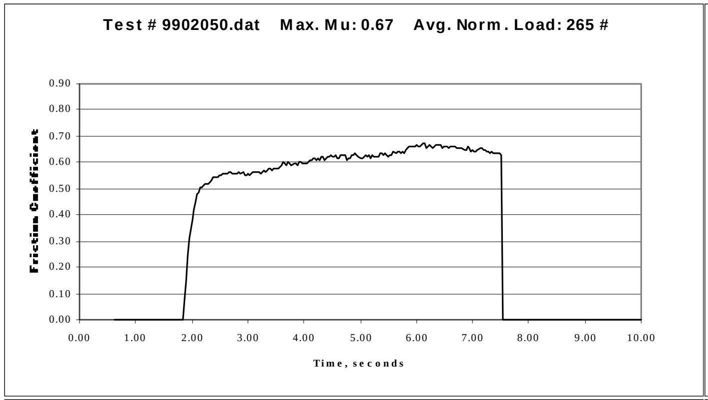
AUT1: 1 Preconditioning Stroke at 1.5 ksi
&
AUT2: 25 Strokes at 15 ksi

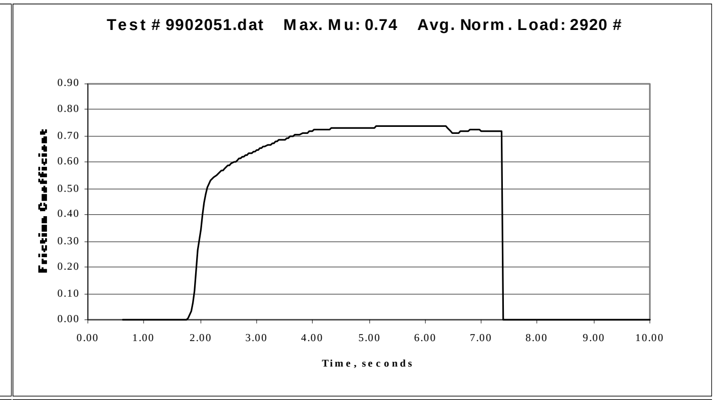
200°F

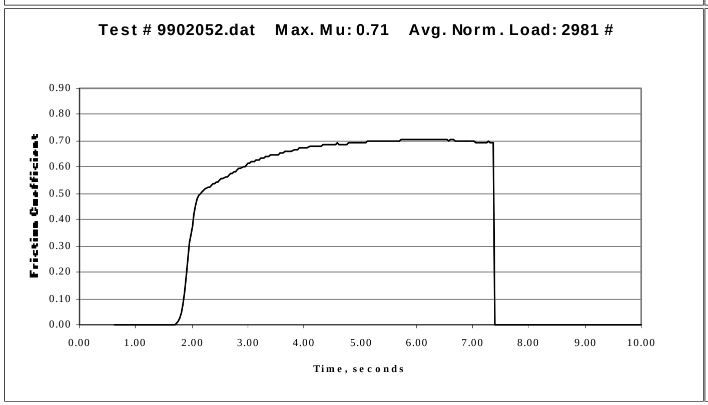
1.6" Stroke Length

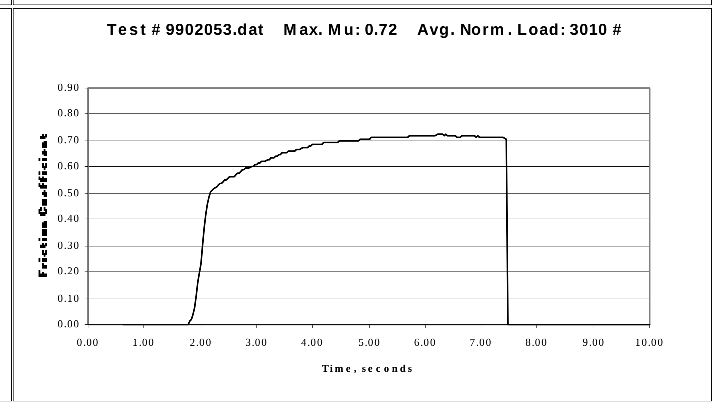

NOREM 02 (PTA) @ 203°F
15 ksi, 1.6" stroke, 18"/min
Maximum Coefficient of Friction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
Stroke Number
1st stroke: 1.5 ksi conditioning stroke
AUT1&2 990205

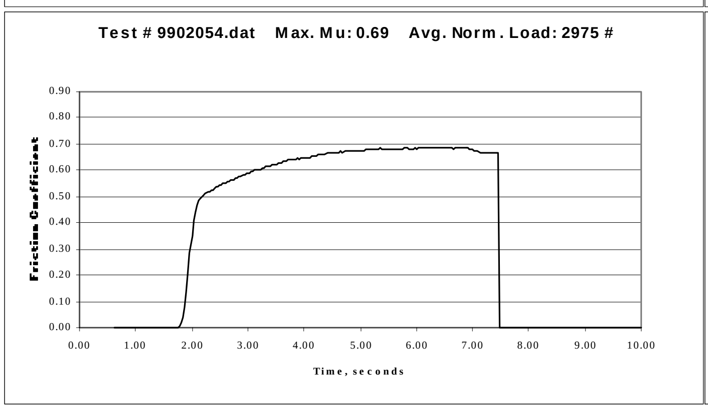
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

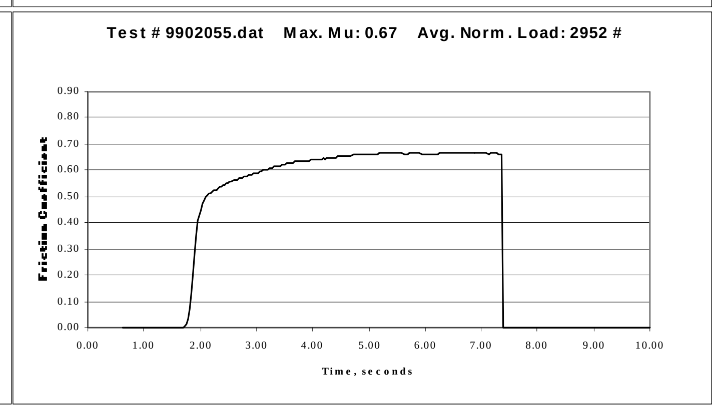


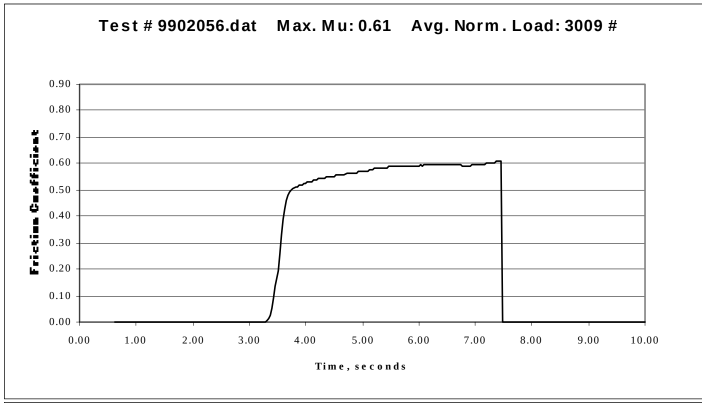


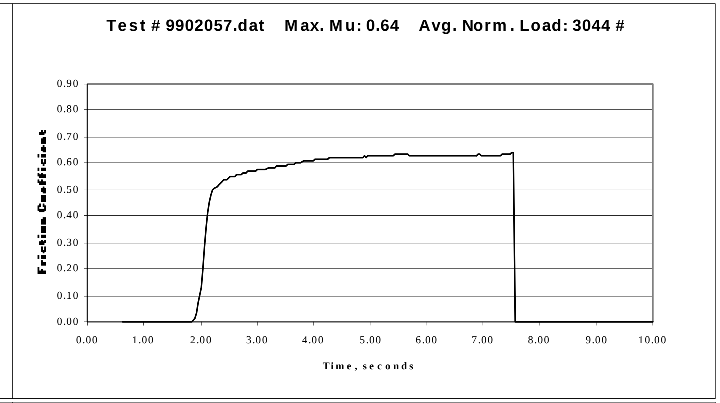


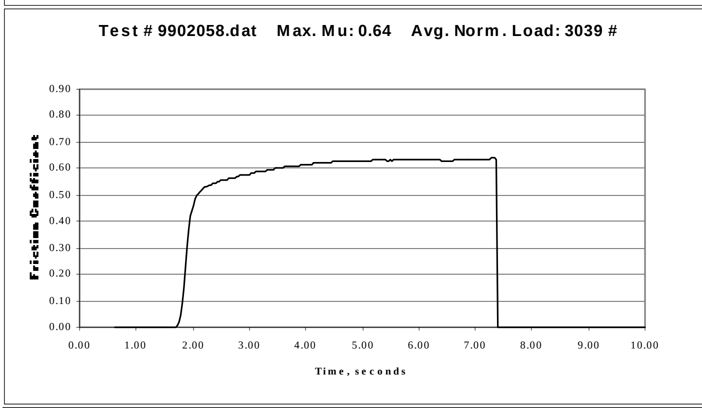


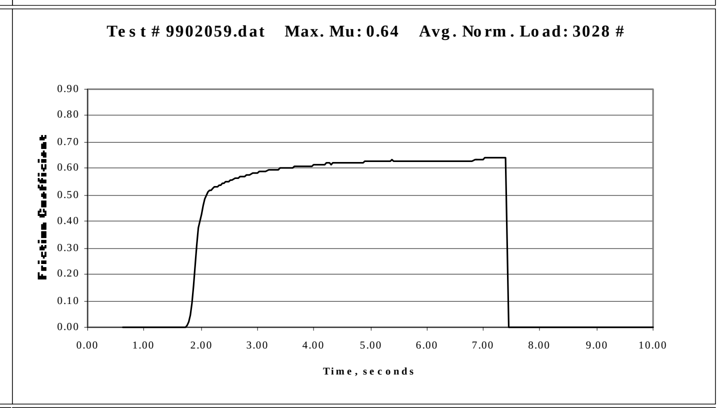


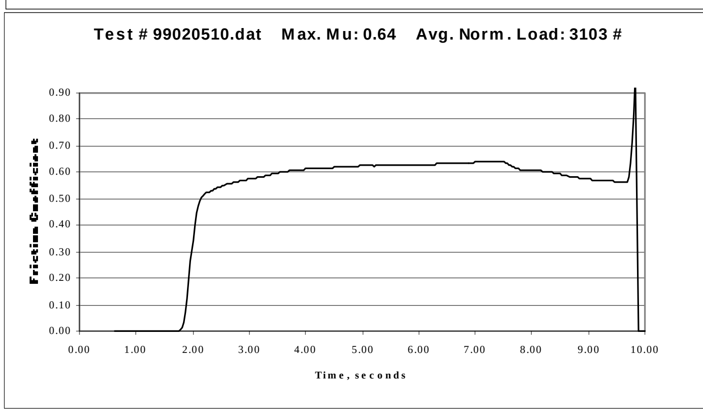


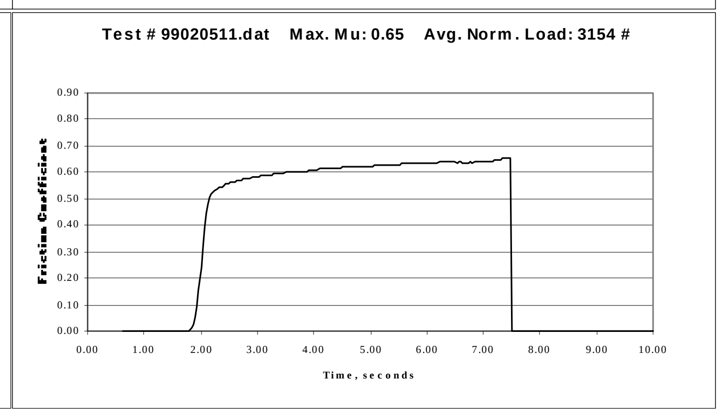

Test # 9902056.dat Max. Mu: 0.61 Avg. Norm. Load: 3009 #
Friction Coefficient
Time, seconds


Test # 9902057.dat Max. Mu: 0.64 Avg. Norm. Load: 3044 #
Friction Coefficient
Time, seconds

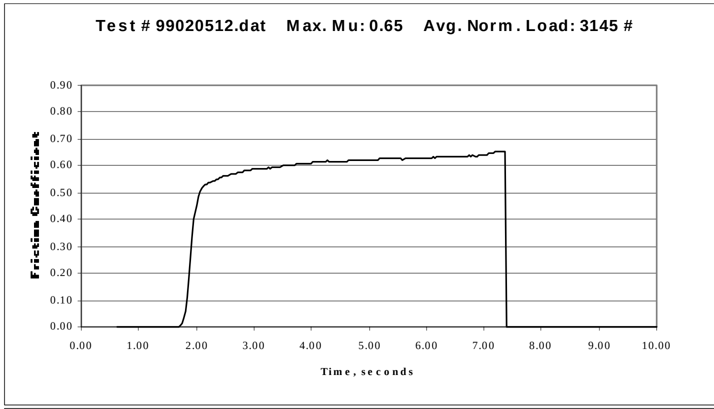

Test # 9902058.dat Max. Mu: 0.64 Avg. Norm. Load: 3039 #
Friction Coefficient
Time, seconds

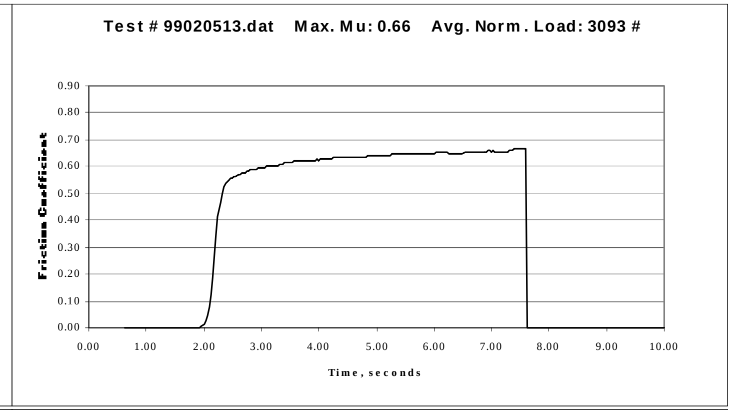

Test # 9902059.dat Max. Mu: 0.64 Avg. Norm. Load: 3028 #
Friction Coefficient
Time, seconds

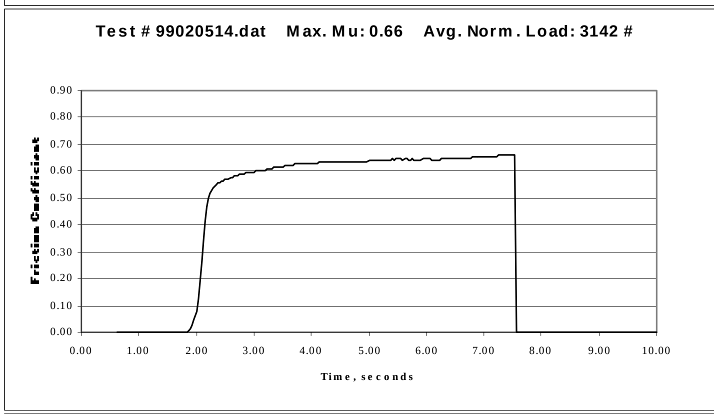

Test # 99020510.dat Max. Mu: 0.64 Avg. Norm. Load: 3103 #
Friction Coefficient
Time, seconds

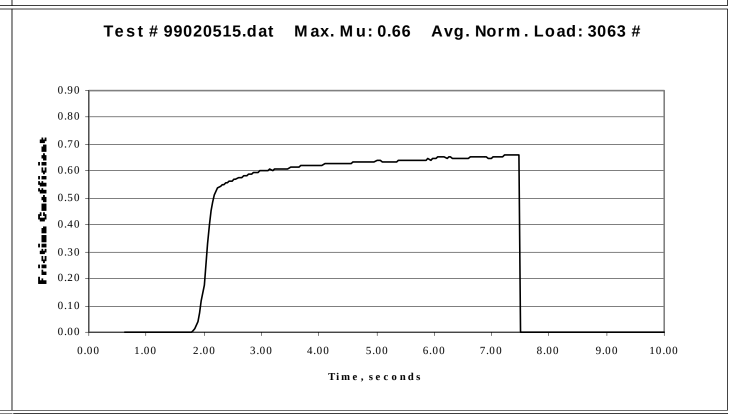

Test # 99020511.dat Max. Mu: 0.65 Avg. Norm. Load: 3154 #
Friction Coefficient
Time, seconds

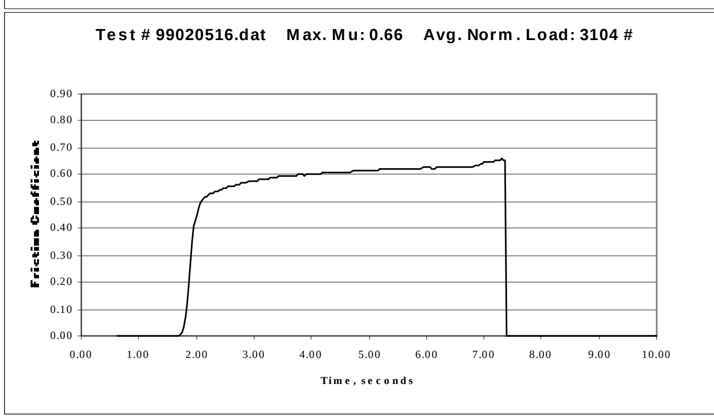
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

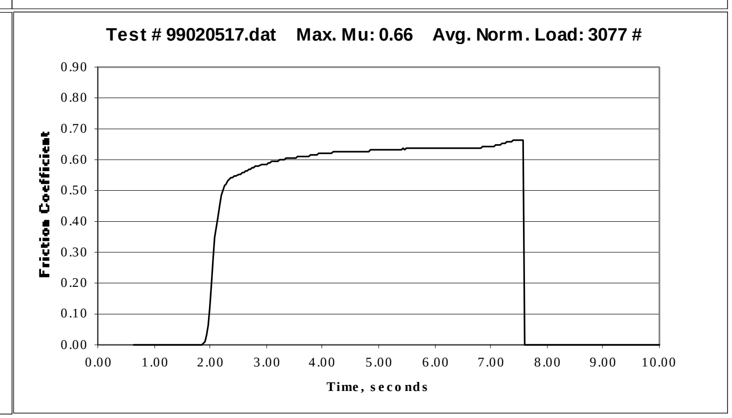


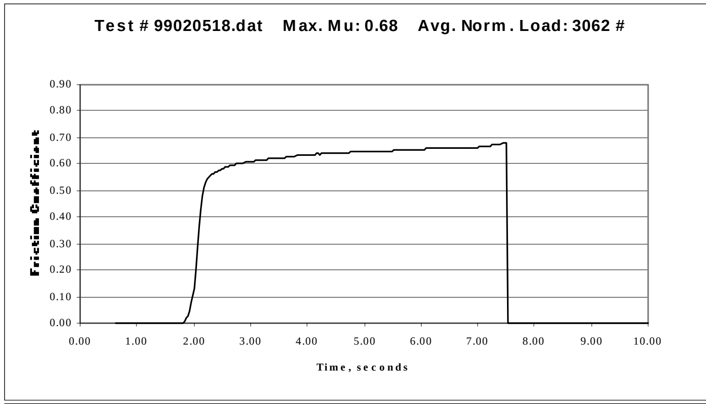


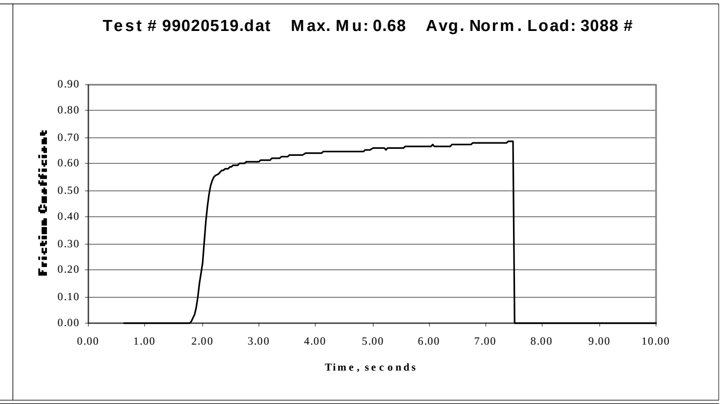


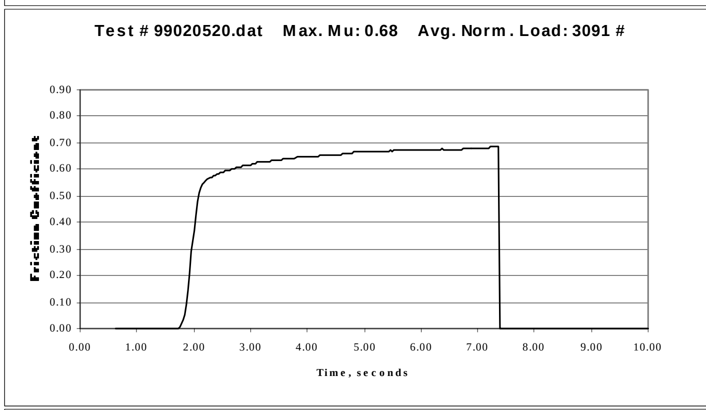


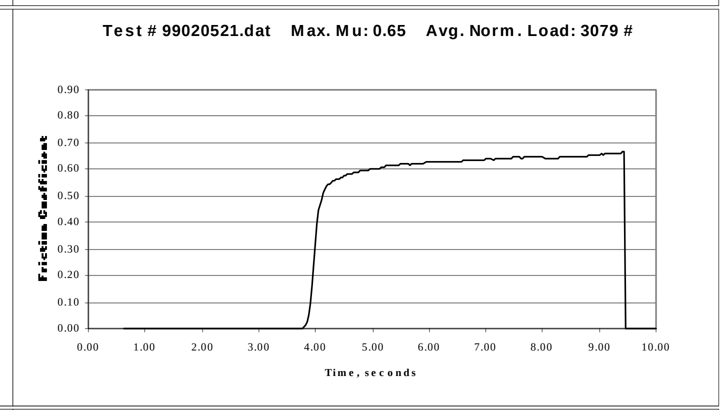


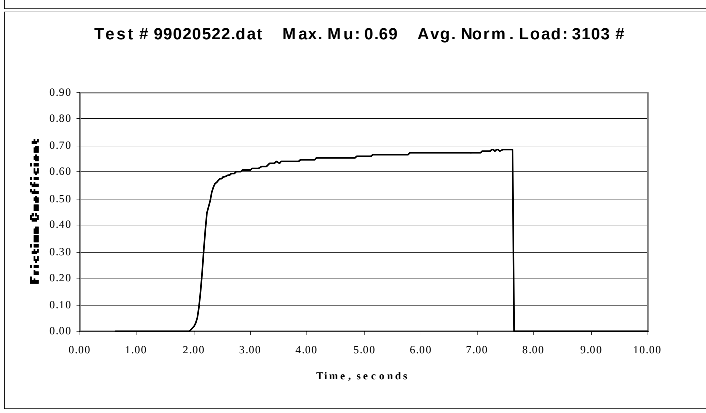


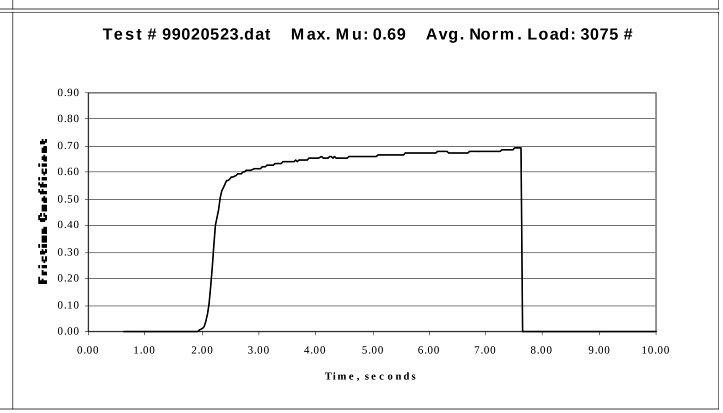

Test # 99020518.dat Max. Mu: 0.68 Avg. Norm. Load: 3062 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99020519.dat Max. Mu: 0.68 Avg. Norm. Load: 3088 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

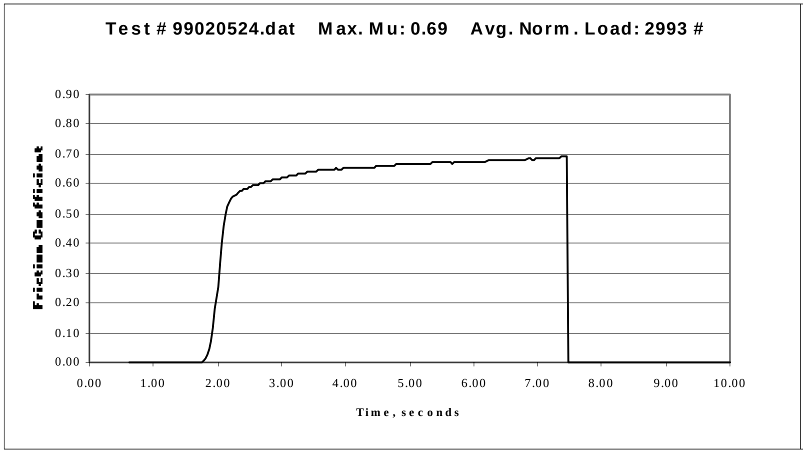

Test # 99020520.dat Max. Mu: 0.68 Avg. Norm. Load: 3091 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

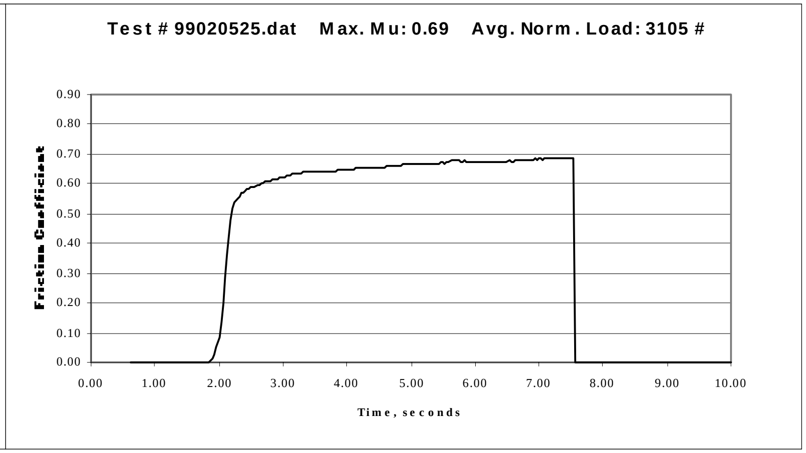

Test # 99020521.dat Max. Mu: 0.65 Avg. Norm. Load: 3079 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99020522.dat Max. Mu: 0.69 Avg. Norm. Load: 3103 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99020523.dat Max. Mu: 0.69 Avg. Norm. Load: 3075 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

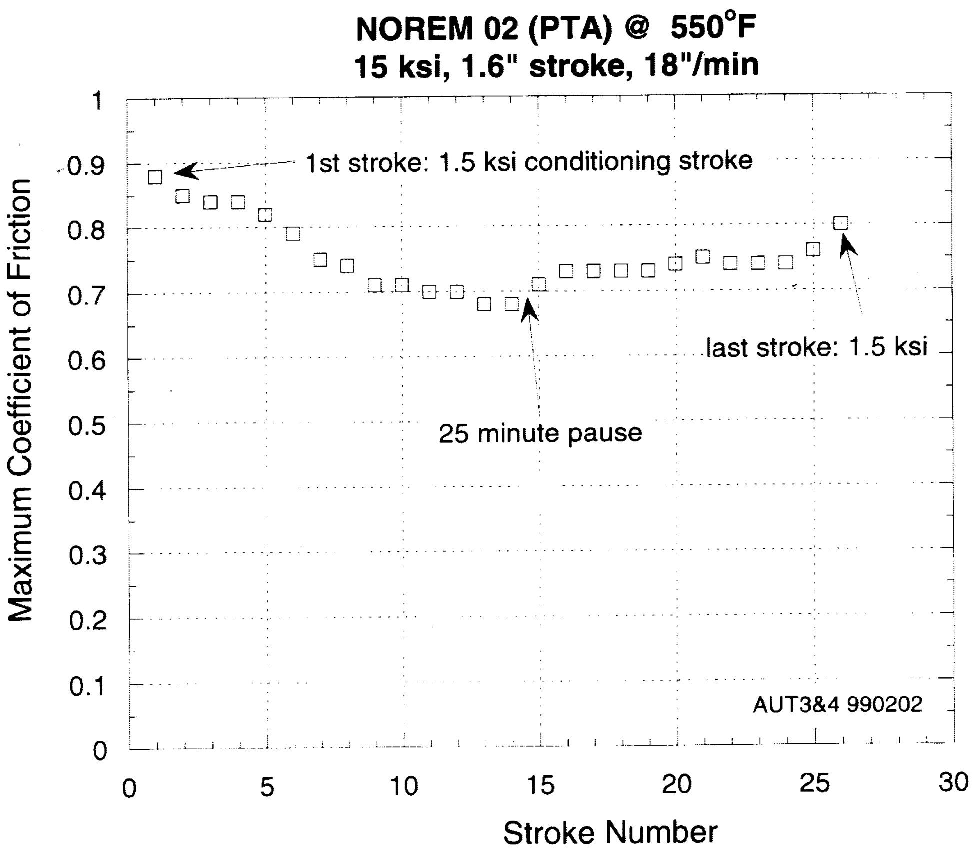




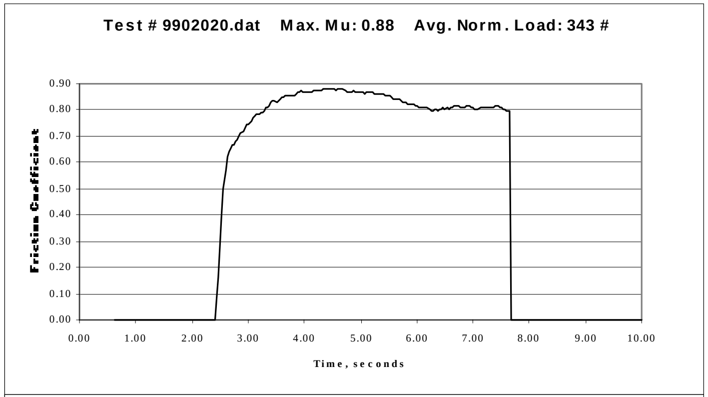
AUT3: 1 Preconditioning Stroke at 1.5 ksi
&
AUT4: 25 Strokes at 15 ksi

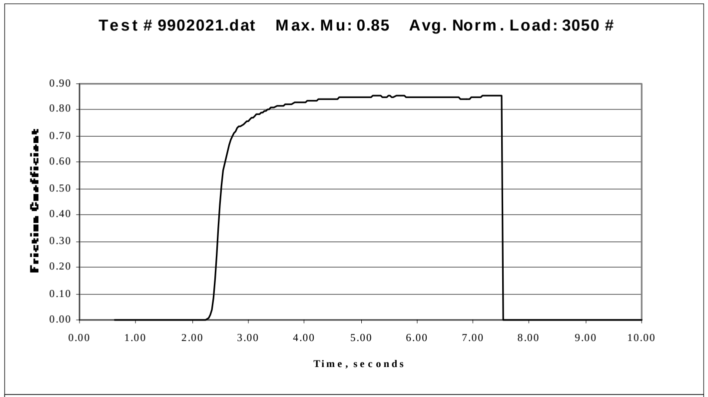
550°F

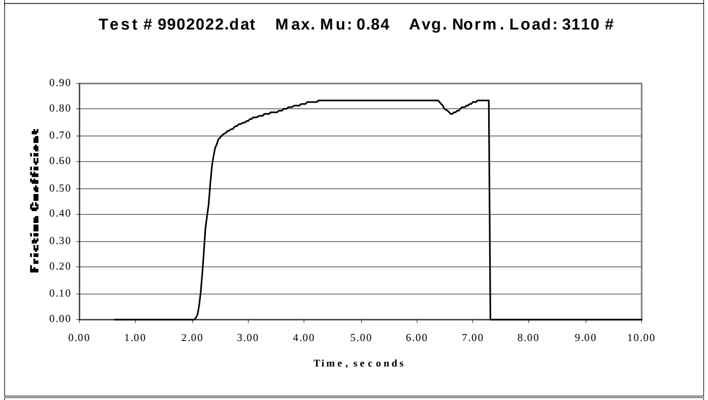
1.6" Stroke Length

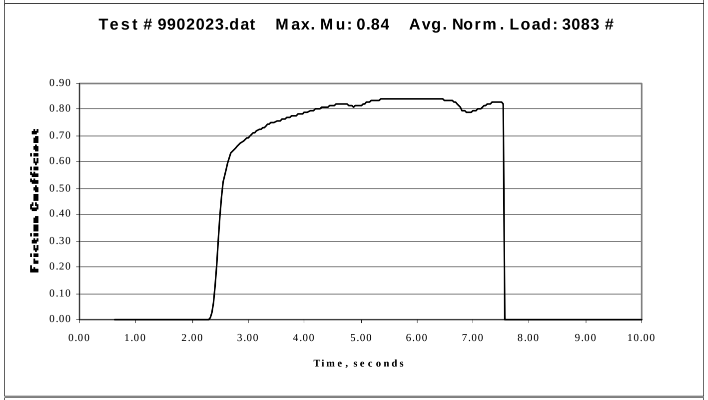

NOREM 02 (PTA) @ 550°F
15 ksi, 1.6" stroke, 18"/min
Maximum Coefficient of Friction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
Stroke Number
1st stroke: 1.5 ksi conditioning stroke
last stroke: 1.5 ksi
25 minute pause
AUT3&4 990202

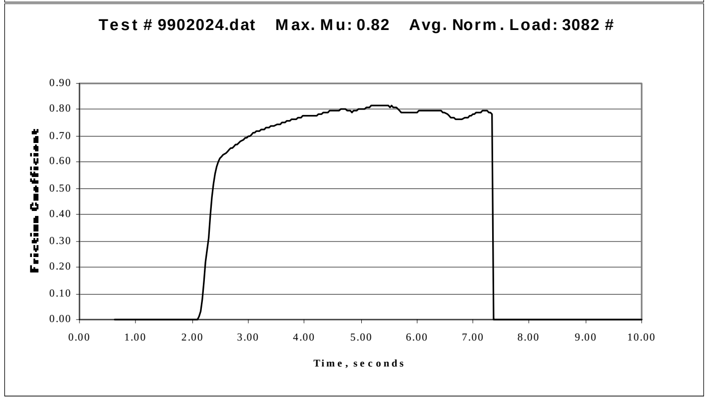
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

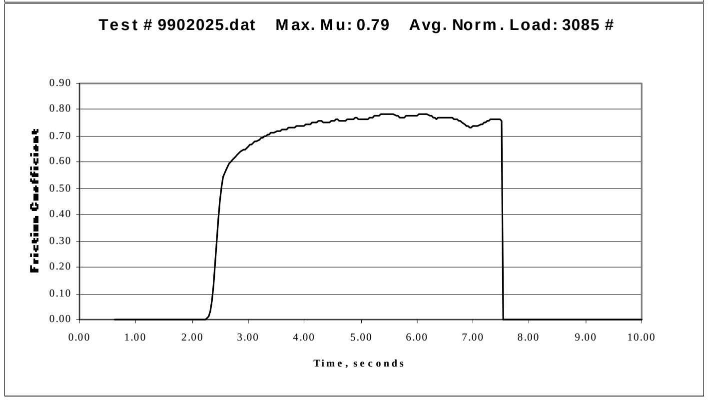




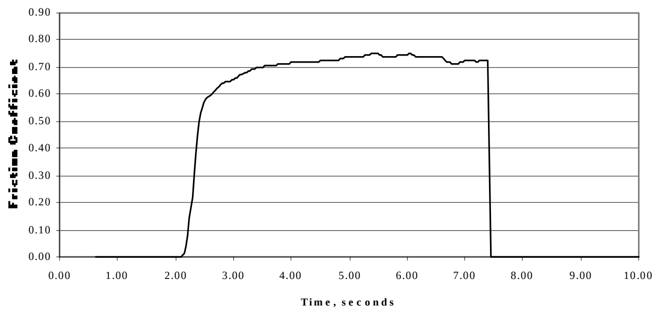




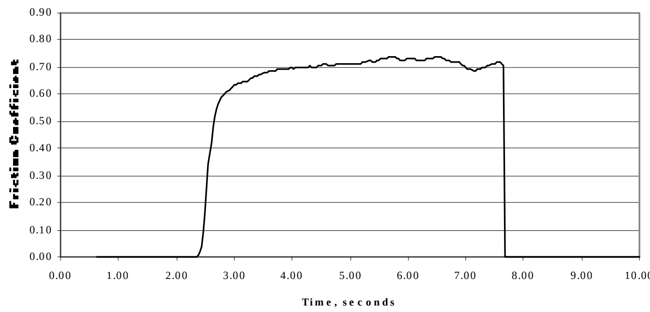




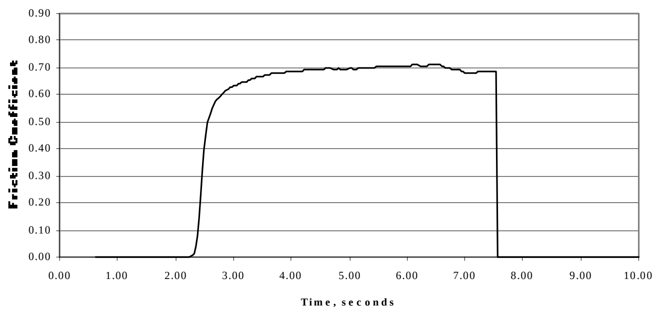
Test # 9902026.dat   Max. Mu: 0.75   Avg. Norm. Load: 3087 #



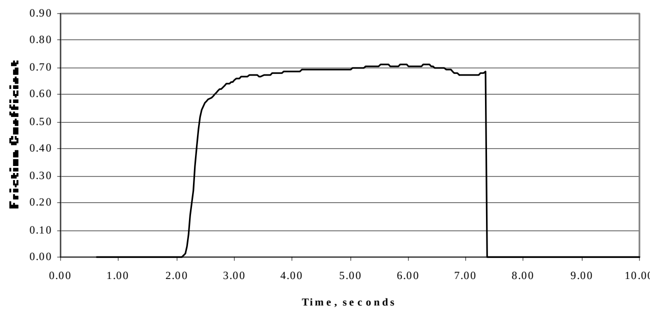
Test # 9902027.dat   Max. Mu: 0.74   Avg. Norm. Load: 3141 #



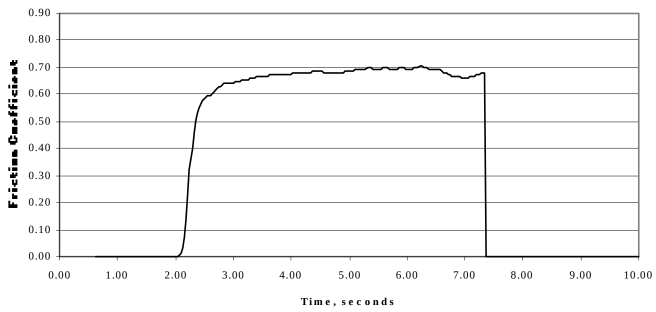
Test # 9902028.dat   Max. Mu: 0.71   Avg. Norm. Load: 3073 #



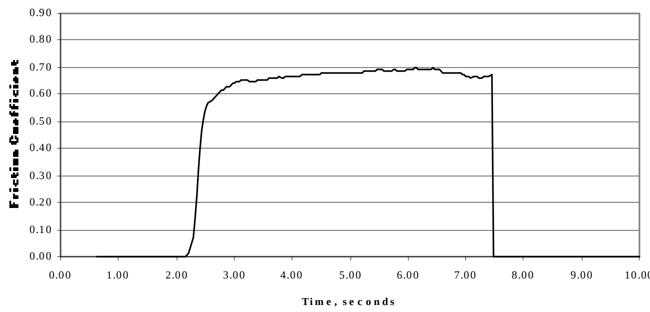
Test # 9902029.dat   Max. Mu: 0.71   Avg. Norm. Load: 3118 #



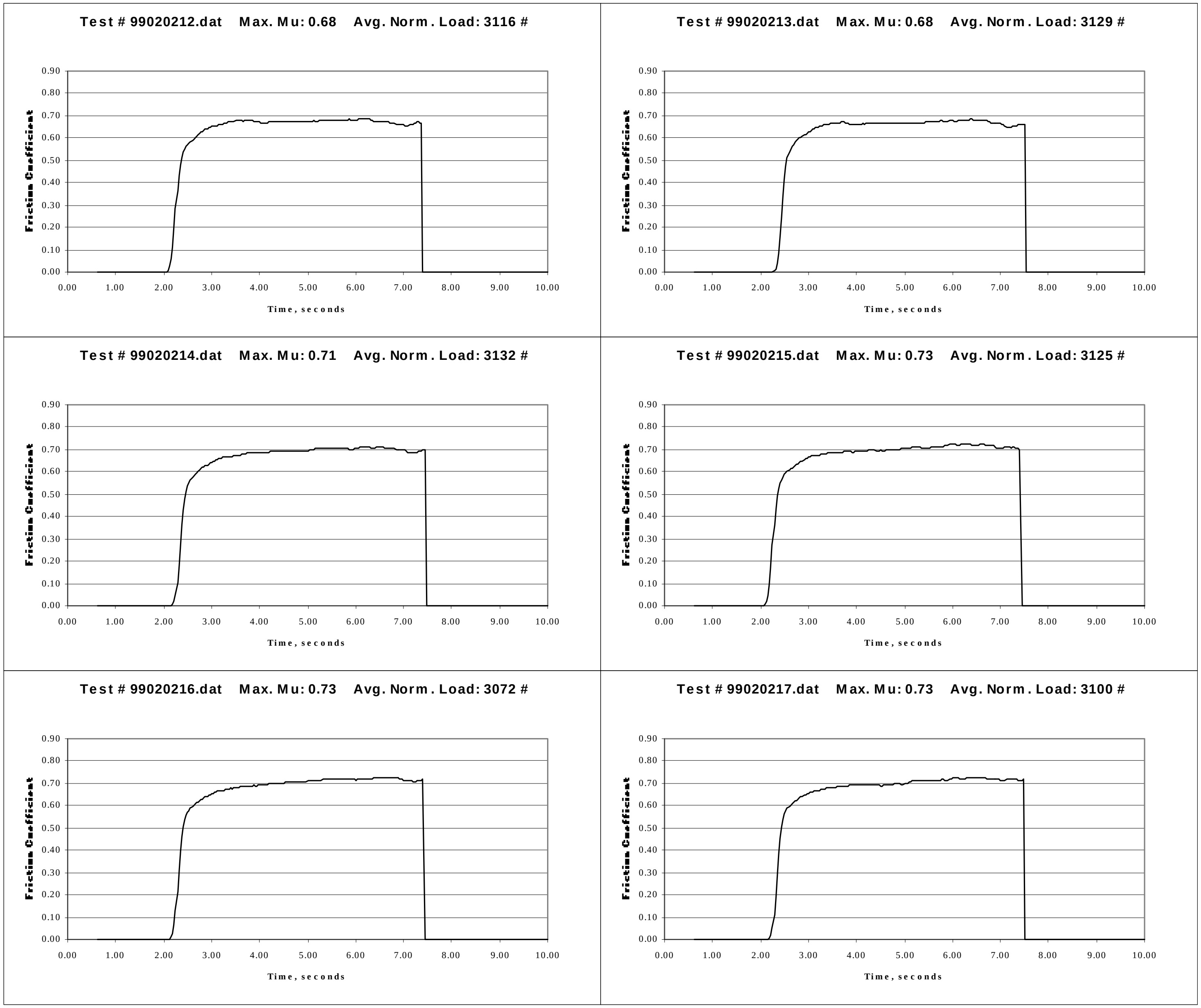
Test # 99020210.dat   Max. Mu: 0.70   Avg. Norm. Load: 3089 #

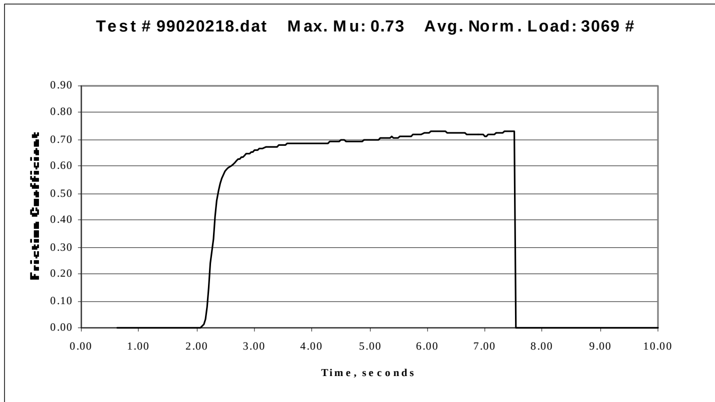


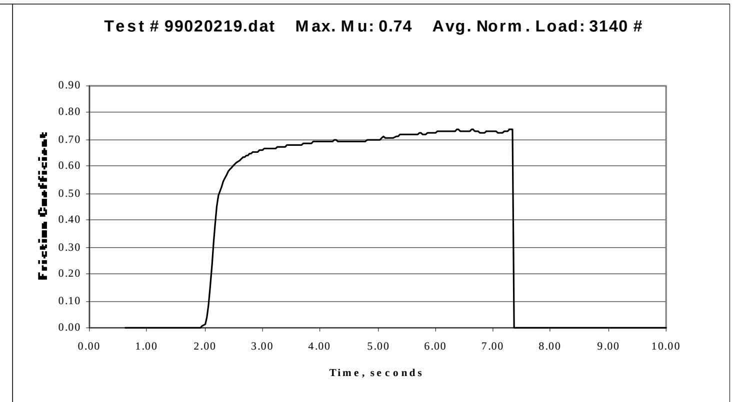
Test # 99020211.dat   Max. Mu: 0.70   Avg. Norm. Load: 3131 #

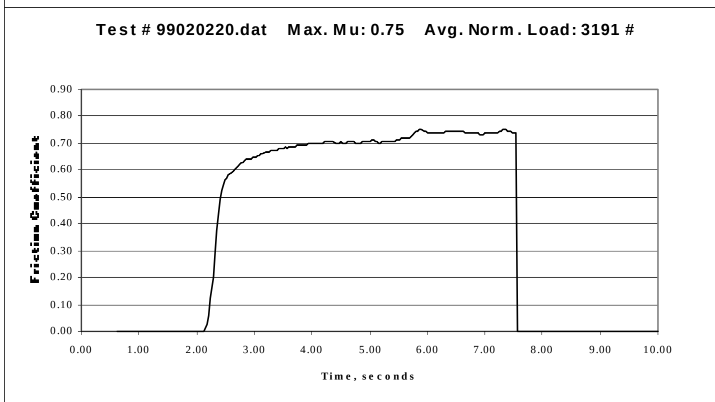


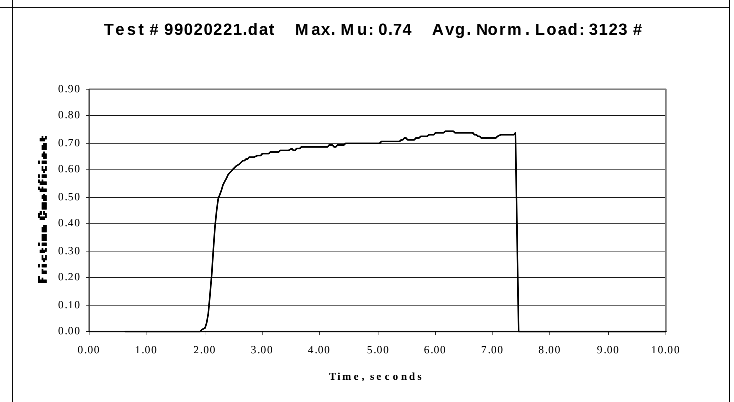
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

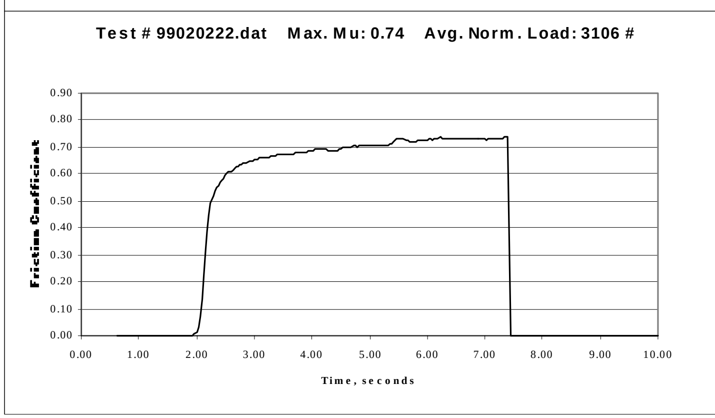


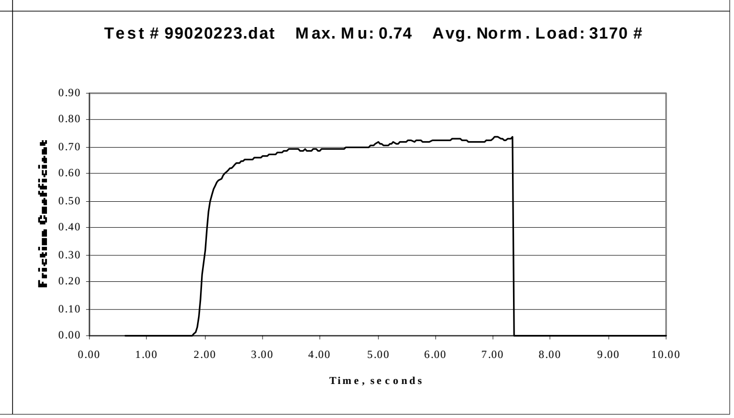

Test # 99020218.dat Max. Mu: 0.73 Avg. Norm. Load: 3069 #
Friction Coefficient
Time, seconds


Test # 99020219.dat Max. Mu: 0.74 Avg. Norm. Load: 3140 #
Friction Coefficient
Time, seconds

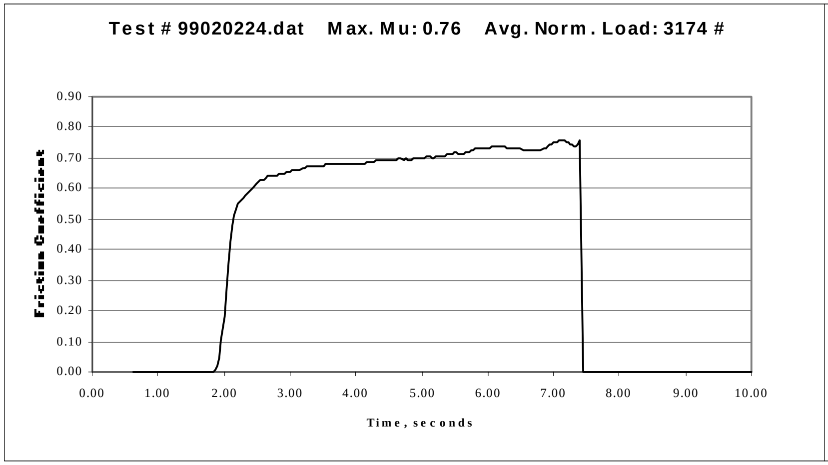

Test # 99020220.dat Max. Mu: 0.75 Avg. Norm. Load: 3191 #
Friction Coefficient
Time, seconds

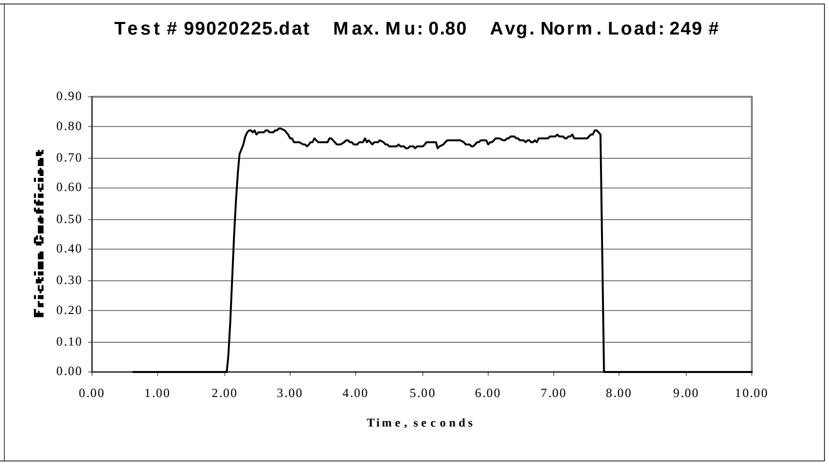

Test # 99020221.dat Max. Mu: 0.74 Avg. Norm. Load: 3123 #
Friction Coefficient
Time, seconds


Test # 99020222.dat Max. Mu: 0.74 Avg. Norm. Load: 3106 #
Friction Coefficient
Time, seconds


Test # 99020223.dat Max. Mu: 0.74 Avg. Norm. Load: 3170 #
Friction Coefficient
Time, seconds

Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

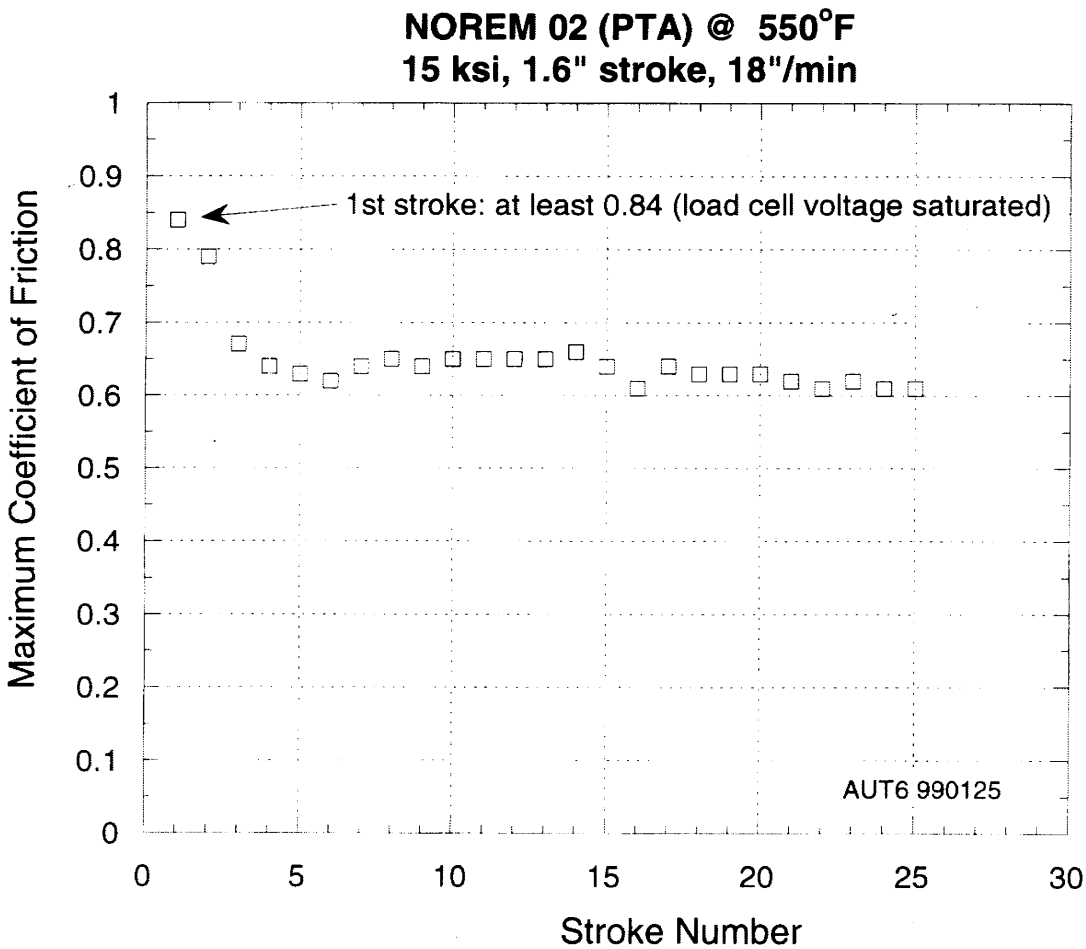




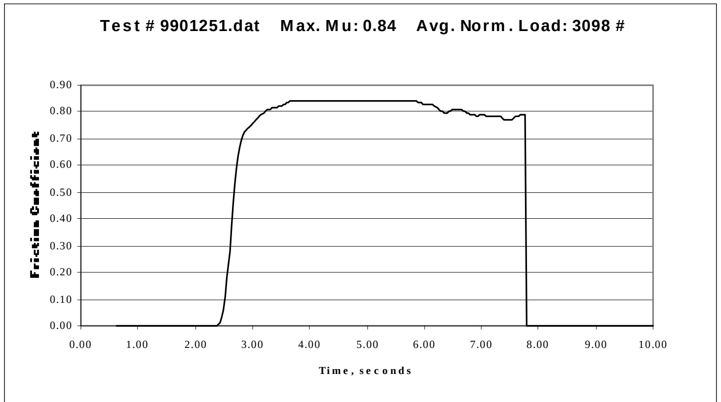
AUT6:25 Strokes at 15 ksi
(No Preconditioning Stroke)

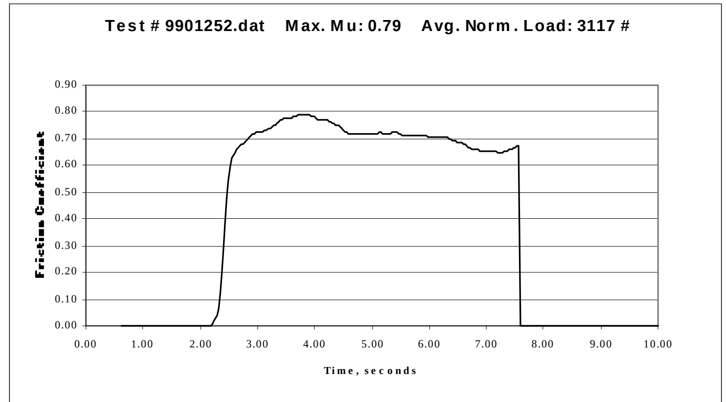
550°F

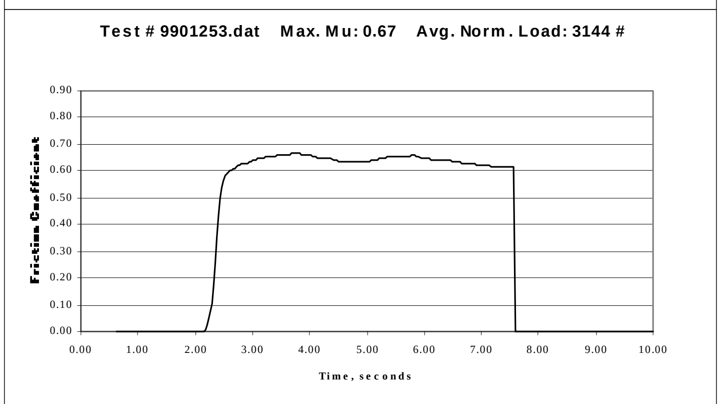
1.6" Stroke Length

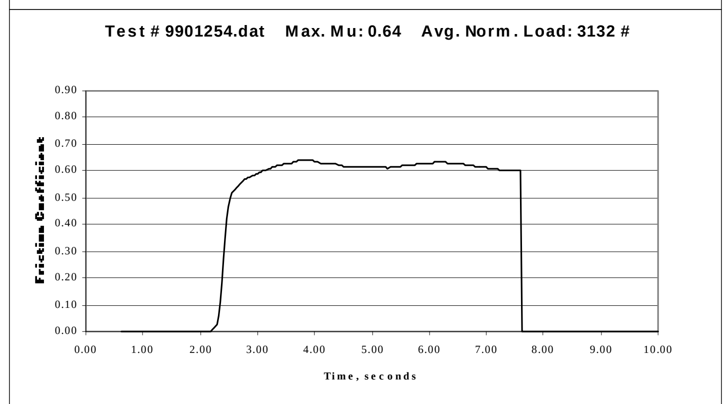

NOREM 02 (PTA) @ 550°F
15 ksi, 1.6" stroke, 18"/min
1st stroke: at least 0.84 (load cell voltage saturated)
AUT6 990125
Maximum Coefficient of Friction
Stroke Number
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30

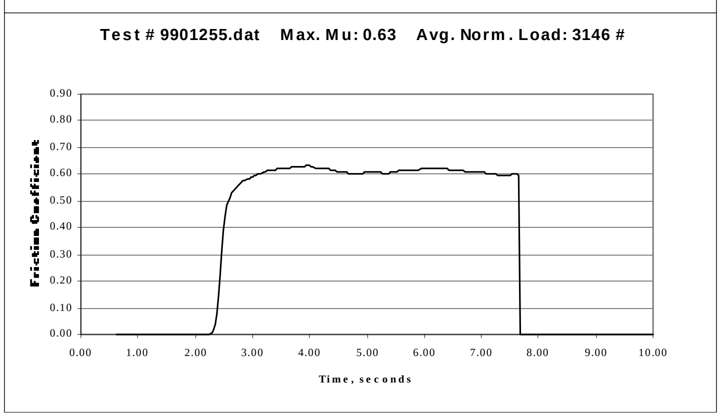
Selected “COF versus Stroke” and/or “COF versus Time” Plots: Test Series 2

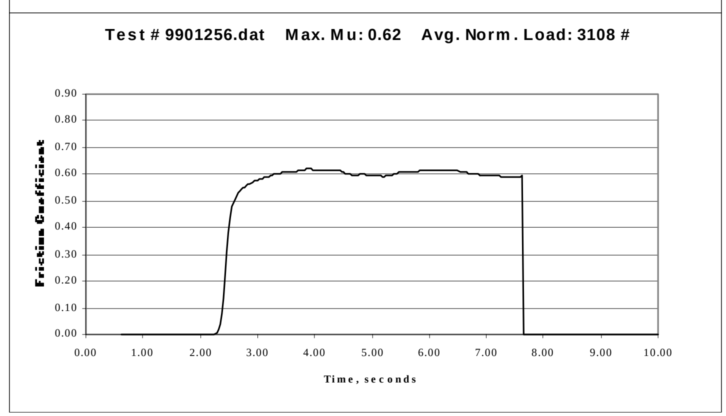


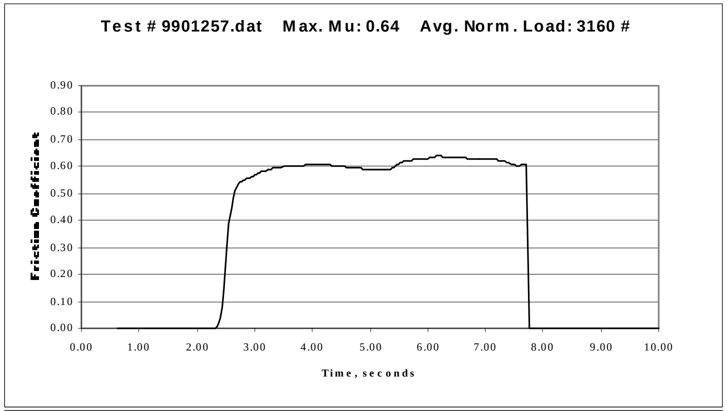


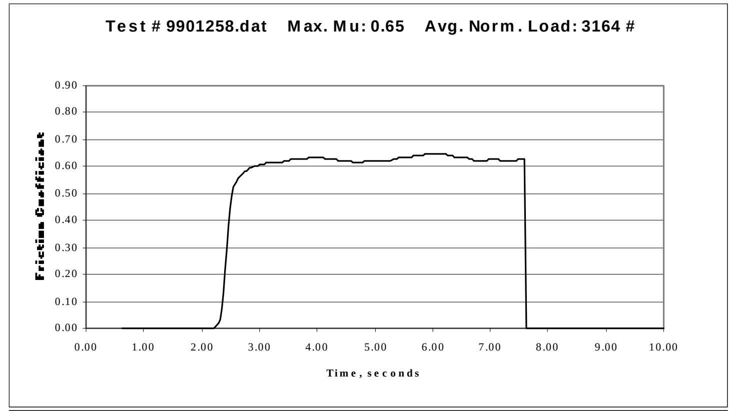


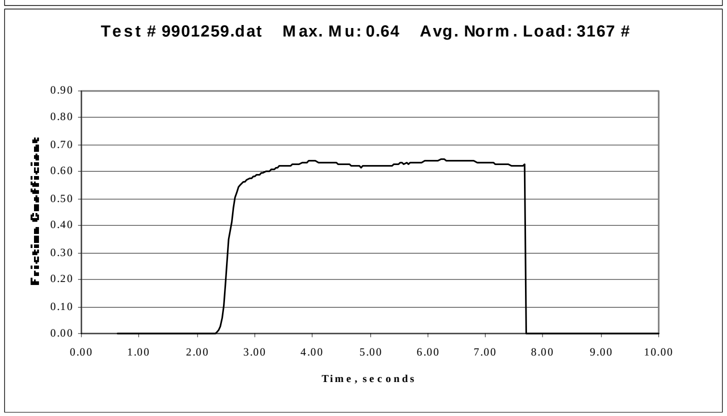


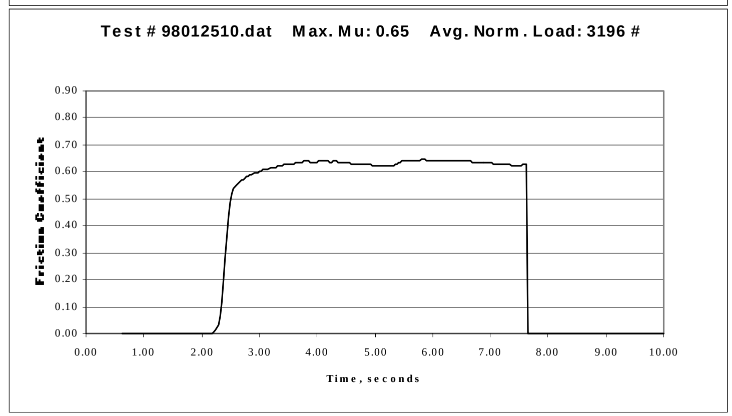


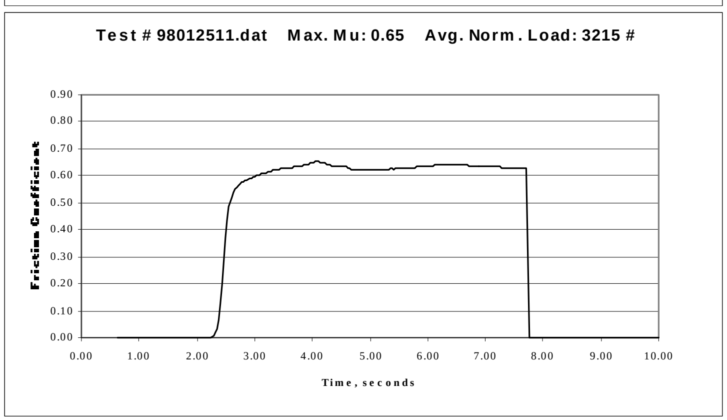


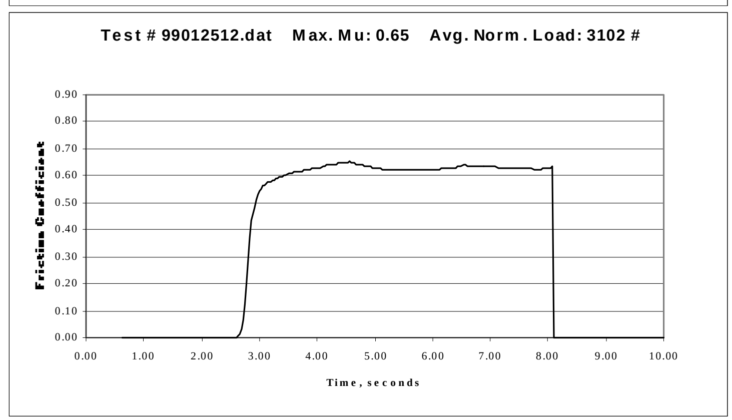

Test # 9901257.dat Max. Mu: 0.64 Avg. Norm. Load: 3160 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 9901258.dat Max. Mu: 0.65 Avg. Norm. Load: 3164 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

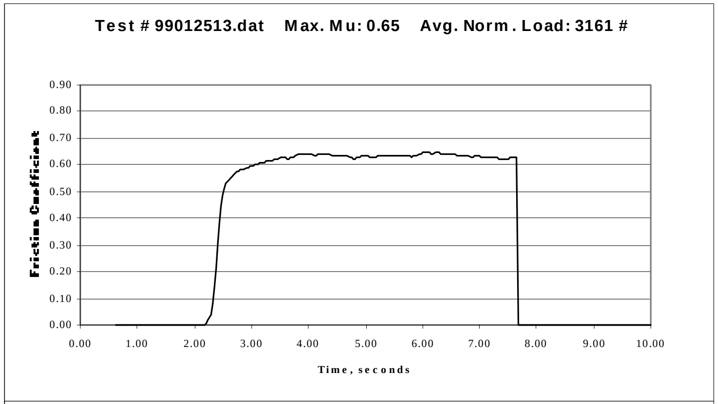

Test # 9901259.dat Max. Mu: 0.64 Avg. Norm. Load: 3167 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

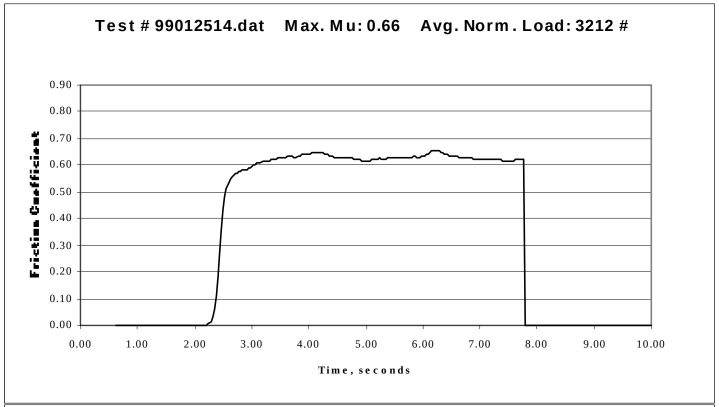

Test # 98012510.dat Max. Mu: 0.65 Avg. Norm. Load: 3196 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

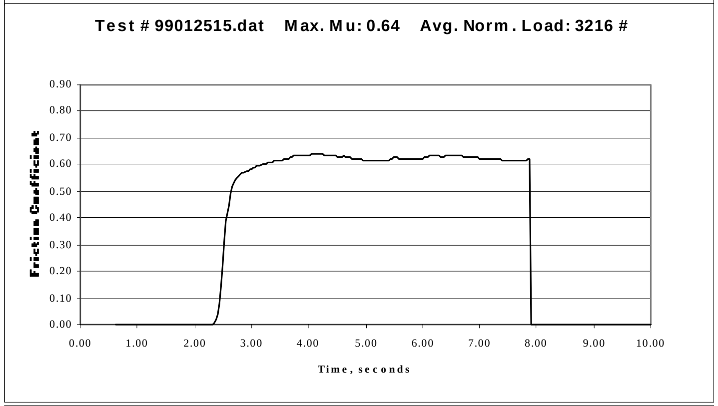

Test # 98012511.dat Max. Mu: 0.65 Avg. Norm. Load: 3215 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

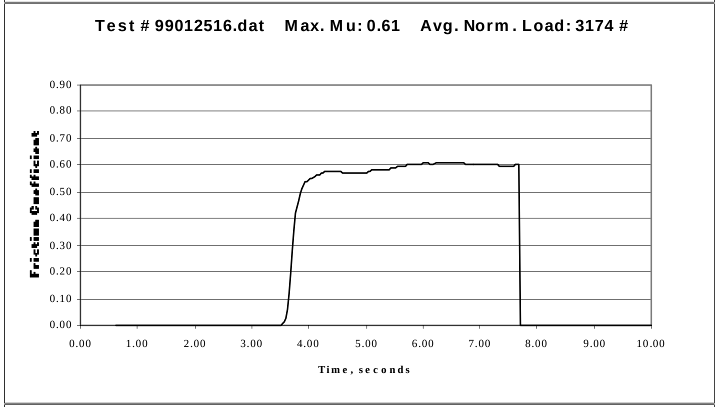

Test # 99012512.dat Max. Mu: 0.65 Avg. Norm. Load: 3102 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

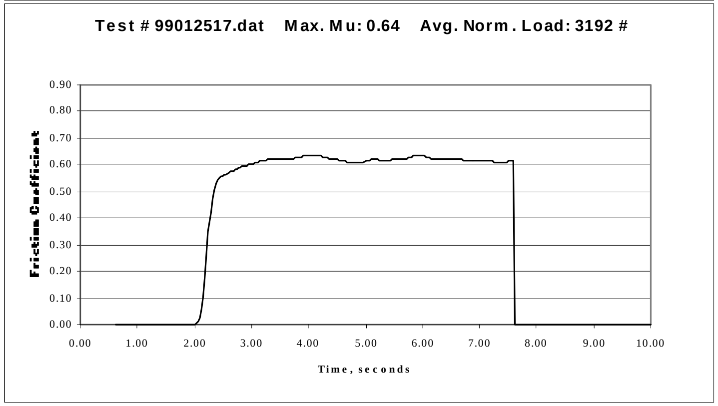
Selected "COF versus Stroke" and/or "COF versus Time" Plots: Test Series 2

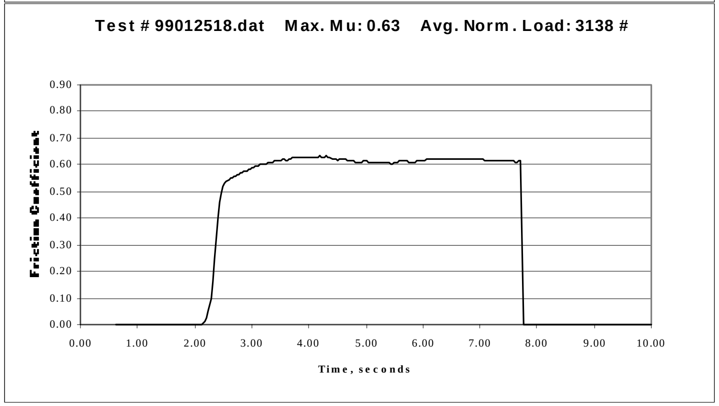


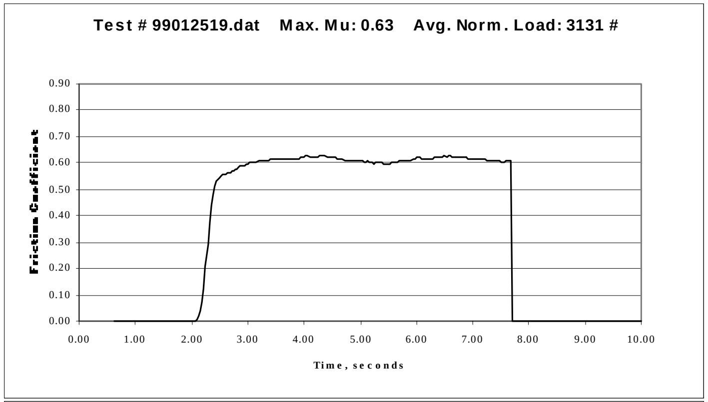


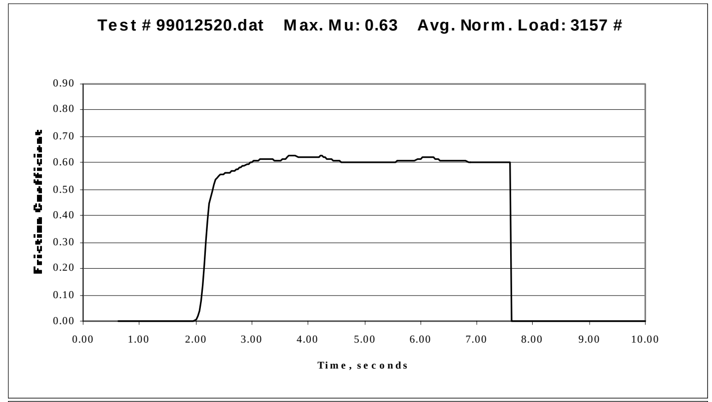


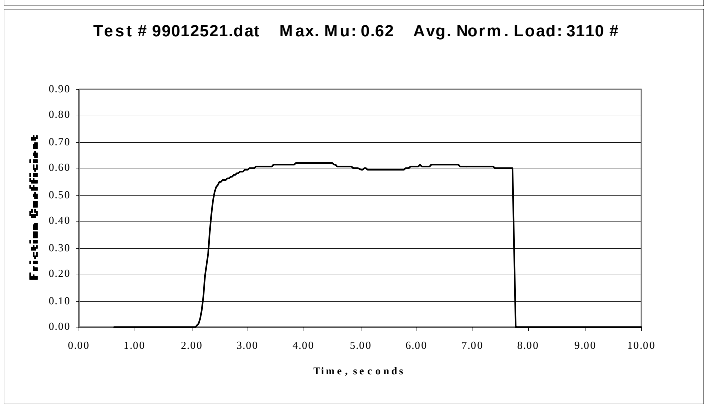


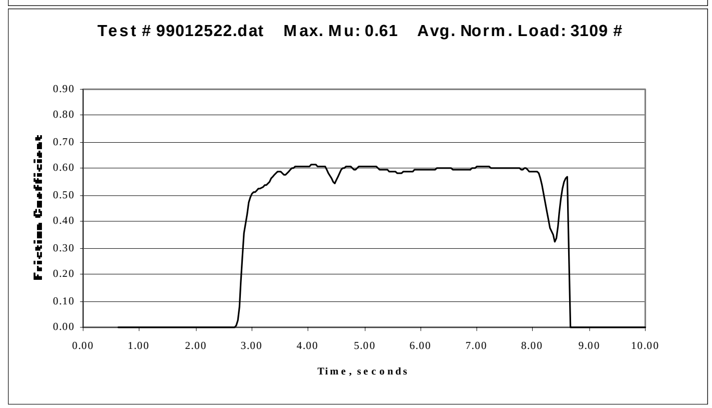


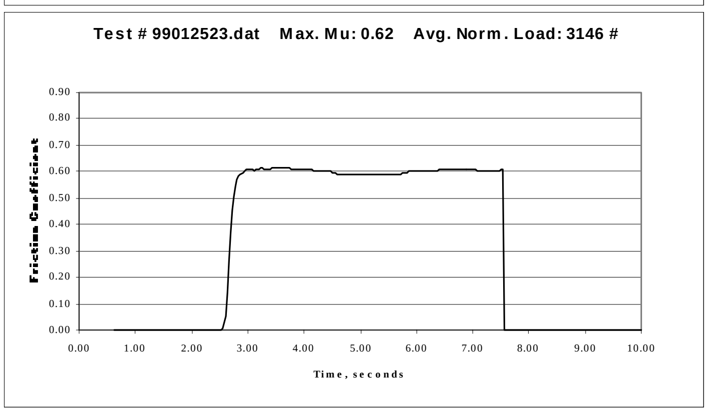


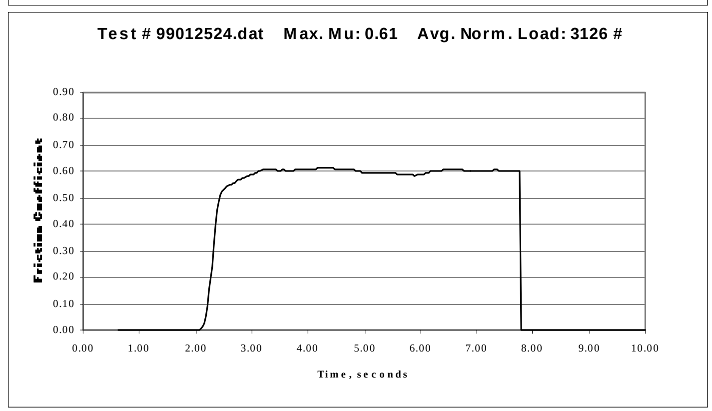

Test # 99012519.dat Max. Mu: 0.63 Avg. Norm. Load: 3131 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99012520.dat Max. Mu: 0.63 Avg. Norm. Load: 3157 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99012521.dat Max. Mu: 0.62 Avg. Norm. Load: 3110 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99012522.dat Max. Mu: 0.61 Avg. Norm. Load: 3109 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99012523.dat Max. Mu: 0.62 Avg. Norm. Load: 3146 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds


Test # 99012524.dat Max. Mu: 0.61 Avg. Norm. Load: 3126 #
Friction Coefficient
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00
Time, seconds

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