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Breakaway Friction and Dynamic Friction/Wear Measurements of Various Ceramic Materials from 25°C (75°F) to 650°C (1200°F)

D.J. Boes
Westinghouse Research Laboratory
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September, 1984

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-346

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16. Abstract

This report describes the results of a program designed to evaluate the breakaway friction and dynamic friction/wear characteristics of materials having potential for use as load bearing components in a high-performance high-temperature heavy duty diesel engine. Ten candidate materials were selected, six of which were evaluated under all possible material combinations as both stationary as well as moving breakaway specimens. The remaining materials were evaluated either in the static mode against themselves and all other materials, or against themselves only. Experiments were performed at five temperatures up to 650°C (1200°F) and unit pressures of 700 kPa (100 lb/in^2), 3500 kPa (500 lb/in^2), and 7000 kPa (1000 lb/in^2). Dynamic tests were performed under both rotating and oscillatory conditions at unit pressures up to 4.2×10^4 kPa (6000 lb/in^2) at 200 cycles/h (oscillatory) and 4060 kPa (590 lb/in^2) - 5000 rpm (rotating).

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BREAKAWAY FRICTION & DYNAMIC FRICTION-WEAR MEASUREMENTS OF VARIOUS CERAMIC MATERIALS FROM 25°C (75°F) to 650°C (1200°F)

D. J. Boes

ABSTRACT

This report describes the results of a program designed to evaluate the breakaway friction and dynamic friction/wear characteristics of materials having potential for use as load bearing components in a high-performance high-temperature heavy duty diesel engine. Ten candidate materials were selected, six of which were evaluated under all possible material combinations as both stationary as well as moving breakaway specimens. The remaining materials were evaluated either in the static mode against themselves and all other materials, or against themselves only. Experiments were performed at five temperatures up to 650°C (1200°F) and unit pressures of 700 kPa (100 lb/in^2), 3500 kPa (500 lb/in^2), and 7000 kPa (1000 lb/in^2). Dynamic tests were performed under both rotating and oscillatory conditions at unit pressures up to 4.2×10^4 kPa (6000 lb/in^2) at 200 cycles/h (oscillatory) and 4060 kPa (590 lb/in^2) - 5000 rpm (rotating).

Experimental results indicate that under dynamic conditions, four of the ten materials exhibited good to excellent friction/wear characteristics in various material combinations. These materials were: titanium carbide, silicon nitride, silicon carbide (reaction sintered), and Refel (SiC). At temperatures of 316°C (600°F) to 650°C (1200°F), breakaway friction coefficients for all of the various combinations tested were significantly higher than dynamic friction coefficients by a factor of three to four. For most material combinations, dynamic friction coefficients ranged from a low value of 0.11 to 0.35. Scanning electron microscope analyses suggest that material flow and mutual transfer is occurring in the contact areas.

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1. INTRODUCTION

This report describes the results of a twelve month program designed to investigate the friction and wear characteristics of materials considered as candidates for use as load bearing components in a high efficiency-heavy duty diesel engine. The program was conducted at the Westinghouse Research and Development Center and sponsored by the Department of Energy with the NASA Lewis Research Center acting as the monitoring agency.

The effort comprised two tasks. The first task involved the determination of the friction and wear characteristics of specific nitride, carbide, and oxide materials. These materials are believed to be suitable for use as load bearing components and seals in the high temperature environment associated with an uncooled and insulated diesel engine. Both breakaway (static) friction coefficients and dynamic friction/wear characteristics were determined on seven candidate materials.

The second task of the program was an evaluation of the friction/wear characteristics of two hard faced coatings and a porous metal body infiltrated with suitable solid lubricants.

Static friction measurements were performed over a 7000 kPa (1000 lb/in^2) pressure range at five temperatures ranging from room temperature to 650°C (1200°F). Dynamic friction/wear tests were performed under pressures up to 4.2×10^4 kPa (6000 lb/in^2) at temperatures of 316°C (600°F), 482°C (900°F), and 650°C (1200°F).

2. TEST EQUIPMENT DESCRIPTION

2.1 Dynamic Friction Measurements

Low-to-moderate speed dynamic torque measurements are performed on a modified Hohman Friction-Wear Test Apparatus. Figure 2.1 presents a schematic of this device, while Fig. 2.2 is a photograph of the unit with heaters removed.

The unit is comprised of a rotating test disc [(3.49 cm dia × 0.95 cm thick) - (1.375 in. dia × 0.375 in. thick)], mounted and locked to a drive spindle, which rubs against a 1.9 cm × 1.27 cm × 0.63 cm (0.75 in. × 0.50 in. × 0.25 in.) stationary block supported in a rotating shoe. The shoe is mounted on a torque bearing support whose axis is in line with that of the rotating shaft. Load is applied through a system of parallelogram linkage bars to the rub block. Friction force is determined by the use of strain gages mounted on the torque bearing support which measure the tendency of the load shoes to rotate with the disc. Prior to each test, the specimens are degreased in alcohol and air dried. After weighing the block to 1×10^{-4} g, the specimens are installed in the apparatus and the experiment performed. The surface finish of all contact surfaces was ~ 4 rms.

2.2 Static Friction Measurements

Static, or breakaway, friction measurements were performed on the test rig shown in schematic in Figure 2.3. The unit was designed to drive a vertical shaft linearly at a surface velocity ranging from 0.008 cm/min to 0.15 cm/min (0.003 in/min to 0.060 inch/min). A 1/4 hp variable speed drive, gear reducers, and rack and pinion are employed to provide shaft motion. The shaft is supported in a housing equipped with linear-type ball bearings. Drive motor reversing capability provides for shaft motion in both the upward and the downward direction. Attached at right angles to the top of the drive shaft is an arm to which is locked a 1.27 cm × 1.27 cm × 2.54 cm (1/2 in. × 1/2 in. × 1 in.) test specimen. The static specimen [1.27 cm dia (1/2 in dia)] is loaded against the moving specimen's 1.27 cm × 2.54 cm (1/2 in. × 1 in.) face by means of a dead-weight load. The pellet end is machined to a taper configuration terminating in a 0.33 cm (1/8 in.) diameter flat. The pellet is held firmly in a collar attached, in turn, to a second vertical shaft located in a housing equipped with a pair of linear-type ball bearings identical to those used on the main drive shaft. A gimbal bearing locates the nose of the pellet with respect to the center line of the moving specimen while preventing motion in any other plane. As shown in Figure 2.3 the shaft holding the stationary pellet is supported on a flexible, 0.25 cm (0.1 inch) thick steel beam to which has been bonded a strain gauge. Thus, as the central shaft is driven downward at a given rate of speed, the righthand shaft is free to follow this motion due to the interlock generated by loading the pellet against the metal specimen. This movement results in a deflection of the strain gauge beam, thereby providing a direct reading of force. When the restoring force exerted by the beam reaches a value equivalent to the static frictional forces inherent to the material couple, relative motion between these two components is initiated. Surface finish of contact surfaces was ~4 rms. Figure 2.4 is a photograph of this apparatus.

2.3 Reciprocating Friction/Wear Test Apparatus

The test apparatus consists of a pad assembly, ball screw jack, load ram, drive motor, heaters, reversing and safety over-ride control, oven cover plates, sensing strain gages, and recording potentiometer.

The two test plates and two test blocks are located in the pad assembly as noted in Figure 2.5. The stationary plates are held in plate holders -- one upper and one lower. The moving blocks are held in the yoke of the pad assembly. The hydraulic load ram, mounted on the top of the apparatus, imposes a vertical load on the four surfaces of the plate-block combination. The adjustable reversing control regulates the stroke of the test apparatus, while an electronic reversing circuit is used to control dwell time as well as stroke length. A safety override control is set to stop the test apparatus in the event of a malfunction of the reversing control. An enclosed test chamber is provided by installing transite cover plates over the testing area, thus allowing operation in either air, inert gas, or steam at temperatures up to 538°C (1000°F). The dimensions of the driven specimens are 3.8 cm × 1.9 cm × 0.95 cm (1-1/2 in. × 3/4 in. × 3/8 in. thick). Stationary cubes [0.95 cm (3/8 in.)] are loaded against the 3.8 cm × 1.9 cm (1-1/2 in. x 3/4 in.) face of the driven specimens. The surface finish of all contact surfaces was ~ 4 rms. Figure 2.6 presents a photograph of this test device. Fig. 2.7 presents schematics of the test specimens used in the breakaway and dynamic friction/wear tests.

3. EXPERIMENTAL RESULTS

3.1 Candidate Material Selection

Table 3.1 lists the materials and coatings selected for study in this program. The group includes two hardface coatings, one solid lubricant-filled composite, and six ceramic materials. Table 3.2 presents some of the more pertinent physical properties of the ceramics and composite material. The materials and coatings were selected based on their potential ability to exhibit physical and chemical properties compatible with the anticipated operating environment of a high temperature heavy duty diesel engine. The properties include:

- o Oxidation resistance at temperatures to 816°C (1500°F)
- o Reasonable machinability or workability
- o High impact strength and elastic modulus
- o Excellent thermal shock resistance
- o High resistance to galling and wear under sliding conditions
- o Acceptable static and dynamic friction coefficients

3.2 Test Conditions

3.2.1 Breakaway Friction Measurement

- o Environment: Air
- o Temperature: Room Temperature to 650°C (1200°F) (tests were run at 93°C (200°F) increments from 316°C to 650°C (600°F to 1200°F)
- o Load: 700-3500 and 7000 kPa (100, 500, and 1000 psi) at each test temperature
- o Speed of moving specimen relative to stationary: 0.076 cm/min. (0.030 in/min.)

Experiments under each combination of test condition were performed in duplicate and the average reported. Test temperature was achieved by subjecting the material combination to the flame of a propane torch. Experiments on the six ceramics studied evaluated each in both the static as well as the moving mode against each of the other materials.

3.2.2 Dynamic Friction/Wear Measurements (Rotary)

Following are the test conditions employed in the dynamic tests.

- o Environment: Air
- o Temperature: 316°C, 482°C, 650°C (600°F, 900°F, 1200°F)
- o Speed: 2400 rpm to 5000 rpm
- o Load 700 kPa to ~ 2800 kPa (100 lb/in^2 to ~ 400 lb/in^2)
- o Test Duration: 30 minutes

Friction force measurements were monitored continuously and weight measurements of the test piece made to the nearest 0.1 mg.

3.2.3 Dynamic Friction/Wear Measurements (Oscillatory)

Those material combinations exhibiting superior performance as compared to the overall group were evaluated under significantly higher load bearing pressures than in either the rotary or the breakaway studies. The experiments were performed at 538°C (1000°F) under pressures ranging from 7000 kPa (1000 lb/in^2) to 4.2×10^3 kPa (6000 lb/in^2). The oscillatory tests were performed at a rate of 3-1/2 cycles/min for as many as 1000 cycles. All load bearing surfaces were lapped to a 4 rms surface finish.

Test parameters continuously monitored during both static and dynamic testing were temperature, friction coefficient, and load. Subsequent to test completion, weight loss measurements were determined. Profilometer traces were taken of wear surfaces in some cases.

In those cases of particular interest, the wear surfaces were microscopically analyzed by scanning electron microscopy (SEM) and emission dispersive X-ray analysis (EDX).

3.3 Breakaway Friction Coefficient Test Results

3.3.1 Ceramic Materials

As mentioned previously, breakaway friction coefficient measurements on six of the ceramic materials selected were performed in both the static as well as the moving mode against each of the other materials, as well as itself. The results of these tests are presented in tabular form in Tables 3.3 through 3.7. Each table presents the average breakaway friction coefficient at progressively higher temperatures over the 25°C (75°F) to 650°C (1200°F) range. In addition, each table presents data obtained under three bearing pressures 700 kPa (100 lbs/in^2) - 3500 kPa (500 lbs/in^2) - 7000 kPa (1000 lbs/in^2).

In attempting to analyze these data, the writer found it quite difficult to establish specific trends and/or differences among the six ceramics being screened at five temperatures and three bearing pressures. For this reason, the data were also arranged in bar graph form, presenting a given stationary material loaded against each ceramic at the five temperatures under investigation. These bar graphs are included in this report as Appendix I.

The following general comments are made regarding breakaway data obtained from 25°C (75°F) to 650°C (1200°F). While exceptions to these observations exist, they are not excessive and may be related to normal scatter.

(a) In three of the six materials studied, similar combinations; i.e., B_4C vs. B_4C, exhibit higher breakaway friction coefficients than when operating against a dissimilar material. The three exceptions to this observation are SiC, Refel, and K-162B.

(b) Al_2O_3 exhibits high friction coefficients when operating against all materials except SiC and Refel.

(c) In general, the four most promising materials studied (K-162B, SiC, Refel, and Si_3N_4) exhibit decreasing breakaway friction coefficients with increasing bearing pressures at elevated temperatures.

(d) Unlike elevated temperature runs, breakaway friction coefficients at room temperatures did not exhibit an inverse relationship with pressure. In general, however, friction coefficients were significantly lower at room temperature than those measured at the elevated temperatures. In most cases, breakaway friction coefficients at room temperature ranged from 0.3 to 0.5, while at temperatures of 316°C (600°F) and higher, friction coefficients in the 0.5 to 0.8 range were common.

(e) Refel and SiC appear to exhibit lower friction coefficients when paired against dissimilar combinations than the other materials studied.

(f) Boron carbide oxidizes significantly at 650°C (1200°F).

3.3.2 Composite & Coatings

Table 3.8 presents the breakaway friction coefficients measured on the chromium carbide hardfaced coating as well as AmCerMet, the fluoride eutectic infiltrated Tribaloy 700. The experiments were performed over the same temperature and bearing pressure ranges employed for ceramics. These two materials, however, were evaluated in only the moving mode against the static ceramics and themselves, as opposed to both the moving and the static mode, as was the case with the ceramics.

As shown in Table 3.8, both the chromium carbide hardface coating and the AmCerMet composite exhibited unusually high breakaway friction coefficients in the temperature range of 316°C (600°F) to 650°C (1200°F). At room temperature, however, breakaway friction coefficients for both materials against the ceramic candidates were relatively low

(0.3 - ~0.6). As was found with the ceramic combinations, breakaway friction coefficients exhibited an inverse relationship with unit loading. In addition, friction coefficients increased with temperature.

Tables 3.9 and 3.10 present breakaway friction coefficients for the Chemical Vapor Deposited (CVD) titanium nitride hardfaced coating vs. itself and the Westinghouse (W) transformation toughened zirconia, respectively. The titanium nitride CVD coating was deposited on a titanium carbide (K-162B) substrate. Because of delivery and time availability problems, these two materials were evaluated only against themselves.

The results of breakaway experiments on these two materials again illustrate an inverse relationship between friction coefficient and bearing pressure, particularly in the case of titanium nitride. It will also be noted that zirconium oxide exhibited quite high friction coefficients under all test conditions except that of room temperature. It should also be pointed out that, through discussions with Westinghouse R&D ceramicists, it has been learned that transformation toughened zirconia loses its attractive fracture toughness characteristics as temperatures exceed ~316°C (~600°F).

3.4 Dynamic Friction-Wear Measurements

3.4.1 Rotary Motion

A series of forty dynamic friction-wear experiments were performed on a variety of material combinations during this program. Table 3.11 presents data summarizing operating conditions and test results. The first four tests were of an exploratory nature performed to establish minimum operating speed and load bearing pressures. The tests were performed on a Si_3N_4-Si_3N_4 material combination over a 25°C (75°F) to 427°C (800°F) temperature range. In retrospect, this was a poor selection for screening purposes, since later work demonstrated that a number of material combinations exhibited far better performance characteristics. These first four tests, however, did indicate that (a) a different material combination should be selected, and (b) bearing pressure and speed should be reduced - at least for the next test series.

Runs #5 through #9, therefore, employed a K-162B rotor operating against a Si_3N_4 stationary block. Runs #5 and #6 were performed at 316°C (600°F) under a reduced load of 0.57 kg (1.25 lb) at speeds of 2400 and 5000 rpm, respectively. Both tests operated smoothly, with block wear after 30 minutes of operation remaining below 1 mg. For this reason, Runs #7 and #8 were performed at the same two speeds as the two previous tests, but at a face load three times greater than previously. Stationary block wear again was below 1 mg, and operation during the test was quite smooth. Figure 3.1 presents photographs of the rotor and block from Run #7 after testing at 5000 rpm and 316°C (600°F) under a bearing pressure of 700 kPa (100 lb/in^2). Wear tracks are highly polished and, as will be discussed later in this report, quite smooth over most of the contact area.

Run #9, the final test in this sequence, was again performed at 5000 rpm, but at a face loading of 1.7 kg (3.75 lbs) and a temperature of 650°C (1200°F). Test performance under these conditions proved excellent in the writer's opinion, with operation smooth and block wear < 1 mg. An average friction coefficient of 0.19 was measured over the 30 minute test duration.

At this point in the program, it was decided to perform subsequent screening tests on various material combinations at a speed of 5000 rpm, a face load of 1.7 kg (3.75 lbs), and at progressively higher temperatures of 316°C (600°F), 482°C (900°F), and 650°C (1200°F). Runs #10 through #30 are the results of these experiments. Runs #10-#12 employed a K-162B rotor operating against a SiC block. Test results were considered good to excellent, with friction coefficient ranging between 0.19 and 0.26 and block wear holding at 1 mg or less.

Runs #13 through #18 were performed on a B_4C/B_4C couple at 316°C (600°F), a Si_3N_4/Si_3N_4 couple at all three temperature levels, and a Si_3N_4/Refel couple at 316°C (600°F) and 482°C (900°F). All tests were operated at 5000 rpm and a 1.7 kg (3.75 lb) block face load. In all six experiments, either rotor or block chipping or cracking occurred accompanied by extremely rough operation. At this point, it was decided to (a) return to K-162B as the stationary block mating surfaces (the best performing material at this point), and (b) reduce operating speed from 5000 rpm to 2400 rpm. The remaining tests in this series (Run #19 through #27) were run at this operating speed under a 1.7 kg (3.75 lb) block face load at temperatures of 316°C (600°F), 482°C (900°F), and 650°C (1200°F). The material combinations studied were Si_3N_4/K-162B, SiC/K-162B, and K-162B vs itself. In general, all tests performed well, with friction coefficients falling in the 0.11 to 0.26 range and weight loss ranging between 0.4 and 1.5 mg. The final three tests in this sequence were performed on an Am Cer Met/Am Cer Met couple under the same operating conditions employed in the previous nine experiments. As noted in Table 3.11, friction coefficients were quite low (0.17 to 0.21) at the three test temperatures. Wear, however, was quite high at 316°C (600°F), and the stationary block actually gained considerable weight at 482°C (900°F) and 650°C (1200°F) due to material build-up at the edges of the wear scar.

The final sequence of tests in this series (Runs #31 to #40) included experiments on various combinations of the four materials selected as the most promising of the original ten as well as one test each on two materials obtained late in the program. The four most promising materials selected were: K-162B, Si_3N_4, SiC, and Refel. All but one test were performed at 5000 rpm in a temperature range of 593°C (1100°F) - 650°C (1200°F). Load and test duration were varied.

Run #31 incorporated a K-162B rotor operating against a Si_3N_4 block. Although this test was terminated after only 16 minutes of operation, scanning electron microscopic photographs (SEM) and electron dispersive X-ray analyses (EDX) were performed on the Si_3N_4 stationary block. Figure 3.2 presents SEM photographs of the block's wear track edge. The upper figure clearly illustrates the extremely smooth, polished condition in the contact area (left side in photo), strongly suggesting that these materials - despite their high melting points - are in at least a semi-fluid state in the load zone. Higher magnification SEM (500X) in lower photograph supports this hypothesis, showing wear material beyond the wear track edge which gives the appearance of having been "splashed" onto the non-contact, as-ground surface. Figure 3.3 presents high magnification SEM views (500X and 2000X) of wear material transferred from the K-162B rotor, while Figure 3.4 presents EDX analyses of the areas identified in the SEM view. Spot #1 - Figure 3.3 is shown to contain some silicon, but substantially higher concentrations of those elements comprising the K-162B rotor. The major element present at Spot #2 is silicon, with minor traces of K-162B. Finally, Spot #3 is that of the actual Si_3N_4 surface.

Runs #32 and #33 were performed using a K-162B rotor operating against SiC obtained from two different sources; namely Norton Co. and Pure Carbon, respectively. Test results were found to be practically identical, except for a slightly higher friction coefficient observed with Refel. Figures 3.5 and 3.6 are composites presenting SEM and EDX views of the Refel block's wear track from Run #33. Again, the SEM photographs illustrate the very smooth, fluid-type nature of the transfer film (Spot #1 - Figure 3.5d). It is not, however, continuous, as proven from EDX analyses of Spots #1 and #2 (Figure 3.5b), which show only silicon present in those areas.

Figures 3.7 through 3.12 present the SEM views and EDX analyses performed on stationary block wear tracks from Runs #34 through 36. In Runs #34 and #35, K-162B was used as the block rather than the rotor. Si_3N_4 and SiC, respectively, were employed as rotors. In Run #36, a K-162B rotor was operated against an LC-1C hard faced coating (chromium carbide).

In comparing results from the Si_3N_4 and SiC tests (Runs #34 and #35), the Si_3N_4/K-162B pair appears to be superior to the SiC/K-162B pair. Silicon carbide exhibited both a higher friction coefficient and higher wear and scar width than did Si_3N_4.

In the case of the Si_3N_4 test, SEM views (Figure 3.7a) again reveal the familiar smooth wear track. EDX analyses of this wear track, however, (Figure 3.7b and Figure 3.8) reveal that it is primarily smeared K-162B and contains only small traces of silicon nitride. This observation suggests that in a material combination containing K-162B as one of its members, it is the K-162B - not the Si_3N_4 or SiC - that is doing the majority of the flowing, or smearing during operation. For example, when K-162B is employed as the rotor, a considerable amount of it is found on the mating block. However, when the reverse is the case and the Si_3N_4 or SiC is used as the rotor against K-162B, little of the silicon is found in the block wear track, the primary constituent being K-162B.

Figures 3.9 and 3.10 present the SEM and EDX results from the SiC rotor - K-162B block combination (Run #35). Again, EDX analyses show that K-162B is the primary constituent in the wear track film. In that area of the track where the film has been plucked out (Area #1 - Figure 3.9b), no silicon is found, but only those elements comprising K-162B. Area #2, Figure 3.9b, as well as Spots #1 and #2, Figure 3.9a, however, contain both K-162B constituents as well as silicon.

Figures 3.11 and 3.12 present the SEM and EDX results of Run #36. In this experiment, a K-162B rotor was operated against an LC-1C (chromium carbide) hardface coating deposited on a 304 stainless steel substrate. The test was performed at an ambient temperature of 593°C (1100°F) and a speed of 5000 rpm. Operating performance was quite smooth, with an average friction coefficient of 0.19 being measured. EDX analyses performed on Spots #1 and 2 (Figure 3.11d), again strongly indicate that the K-162B rotor material is transferring to the LC-1C hard-face surface. The elemental analysis of the surface beneath the film (Spot #1, Photo #5 - Figure 3.12), finds only chromium with a small amount of nickel. Analysis of the film itself (Spot #2, Photo #5 - Figure 3.12), reveals heavy concentrations of K-162B constituents. Identical results are found in the EDX analyses of Spots #1 and #2, (Figure 3.11b). While the substrate reveals only chromium and nickel (Area #2, Photo 8, Figure 3.12), the film itself contains high concentrations of K-162B constituents. A net weight gain of 1.5 mg on the LC-1C stationary block supports this observation.

Run #37 was performed on the K-162B rotor/SiC block combination employed in Run #32 under identical conditions of speed, temperature, and load (5000 rpm - 650°C (1200°F) - 1.7 kg (3.75 lb) face load). The difference between these tests was that Run #37 was operated for a period of 120 min rather than 30 min as was the case in Run #32. It will be noted that little difference was observed in either the friction coefficient or the total wear. In fact, if one compares the wear rate of the SiC block from those two tests, it is found that the wear rate of the longer duration test is approximately 50% lower than the shorter duration test. The data indicate that subsequent to a brief run-in period, the wear rate of at least this particular material combination decreases significantly.

Run #38 was performed on a K-162B rotor-SiC block combination under identical conditions of temperature, speed, and test duration as Run #32, but at double the face loading 3.4 kg vs. 1.7 kg (7.50 lb vs. 3.75 lb). Except for a slight increase in friction coefficient, test results were practically identical, indicating that some of these material combinations are capable of carrying significantly higher unit bearing pressures than were investigated in this portion of the program. This observation is supported from the high pressure-oscillatory test results reported in the following section.

The final two runs performed in this series involved a transformation toughened zirconia rotor operating against itself and a titanium nitride chemical vapor deposited hardface coated rotor operating against itself. In both cases, test results were disappointing. Severe cracking and chipping of both the zirconia rotor and block occurred after less than 15 minutes of operation, while it was found that the titanium nitride coating had been worn completely through to the K-162B substrate after 30 minutes of operation. It should be pointed out, however, that the worst material combination had been used in both tests; i.e., a material or coating against itself. Had these two materials been tested, for example, against K-162B, a substantially improved performance may have been observed. Unfortunately, these two materials were obtained late in the program when K-162B rotors and blocks were not available.

3.5 High Load - High Temperature Oscillatory Tests

A total of six high load oscillatory tests were performed at 538°C (1000°F) over a 1.4×10^4 kPa (2000 lb/in^2) - 4.2×10^4 kPa (6000 lb/in^2) bearing pressure range. Table 3.12 summarizes the results of these experiments. In all cases, K-162B was employed as the moving specimen, while Si_3N_4, SiC, Refel, and K-162B itself were employed as the static components. As will be seen from Table 3.12 data, the static SiC and Si_3N_4 specimens suffered chipping and/or severe cracking under these high load-oscillatory conditions. Specimen damage, as would be expected, was more severe as unit loading was increased. In the case of K-162B, however, no chipping or cracking occurred on any specimen, regardless as to whether the material was employed as the moving or the static specimen. Maximum wear suffered by the moving K-162B specimens was a loss of 2.5 mg, which occurred after 1000 cycles under the most severe operating conditions of 4.2×10^4 kPa (6000 psi) at 538°C (1000°F).

4. CONCLUSIONS

The following conclusions are drawn by the author on the test results summarized in this report.

- Of the ten materials selected for study in this program, four are considered strong candidates for use as load bearing components in a high temperature - heavy duty diesel engine. They are: titanium carbide (K-162B), silicon nitride (Si_3N_4), and silicon carbide (both Norton Co. and Pure Carbon Products).

- Of these four materials, K-162B is considered the best, based on its (a) ability to transfer a thin, pseudo-fluid film to its mating surface, and (b) support high bearing pressures of 4.2×10^3 kPa ($\geq$ 6000 lb/in^2).

- Breakaway friction coefficients of most material combinations at temperatures between 316°C (600°F) and 650°C (1200°F) are three to four times higher than under dynamic conditions.

- Breakaway friction coefficients at room temperature are reasonably low, generally falling in the 0.25 to 0.35 range.

- Dynamic friction coefficients, particularly when K-162B is one of the load bearing components, fall in the 0.11 to 0.35 range.

- In general, breakaway friction coefficients decrease with increasing load and increase with increasing temperature over a 7000 kPa (1000 lb/in^2) pressure range and a 25°C to 650°C (75°F to 1200°F) temperature range.

- Dynamic test results on a K-162B rotor/SiC block material combination at 650°C (1200°F) and 5000 rpm indicate that subsequent to a brief run-in period, wear rates of the materials decrease significantly. This observation may also apply to other material combinations utilizing K-162B as one of the load bearing members.

- Dynamic test results on a K-162B rotor/SiC block indicate that little, if any, increase in wear rate is observed over a 2000 kPa to 4000 kPa (290 lb/in^2 to 590 lb/in^2) bearing pressure range at 650°C (1200°F) and 5000 rpm.

- Based on in-house program results as well as tests performed during this program, Si_3N_4 and K-162B exhibit superior thermal shock resistance. The author would grade the various ceramic, oxide, and carbide materials evaluated in the following order: Si_3N_4 and K-162B-even, SiC and Refel-Even, B_4C, and Al_2O_3.

- Boron carbide does not have adequate oxidation resistance at temperatures above ~538°C (~1000°F).

5. RECOMMENDATIONS

In view of the test results obtained during this program and described in this report, the following recommendation is made.

- A program should be undertaken that would encompass two primary tasks.

  (a) Select at least four of the most promising materials found from this particular program and/or other material investigations currently underway and thoroughly evaluate their dynamic friction/wear characteristics over a wider variety of operating conditions than was possible in this program.

  (b) Initiate a study of the fretting wear characteristics of the materials selected in Task (a). Recent advances in fretting wear testing techniques[1] now provide the capability of performing multiple fretting tests simultaneously over wide temperature ranges in a variety of controlled environments. A limited amount of data indicates that the resistance of some of the materials studied in this program to fretting wear is less than that of sliding wear.

6. REFERENCES

1 Raimondi, A. A., "Development of a Multiple-Specimen Fretting Wear Test Facility and Initial Test Results for Steam Generator Tube and Tube Support Materials", Westinghouse R&D Report, February 1983.

7. ACKNOWLEDGMENTS

The author wishes to thank Messrs. G. R. Kelecava and F. A. Weber for their valuable contributions during the performance of this program and to Messrs. H. Yacobucci and A. A. Raimondi for the helpful discussions held with them throughout the program.

APPENDIX A

Breakaway Friction Coefficients for Six Ceramic & Carbide Materials Against Each Other As Well As Themselves

Five Temperatures - Three Unit Loadings

TABLE 3.1

CANDIDATE MATERIALS SELECTED FOR EVALUATION

Name	Supplier	Identification
1. Silicon Nitride	Norton Company	Si_3N_4
2. Silicon Carbide	Norton Company	SiC
3. REFEL	Pure Carbon Company	SiC
4. Titanium Carbide	Kennametal	K-162B
5. Boron Carbide	Norton Company	B_4C
6. Chromium Carbide	Union Carbide (Hard Faced Coating on 304 SS substrate)	LC-1C
7. AmCerMet	AsTroMet	Calcium Fluoride/Barium Fluoride Impregnated Tribaloy 700
8. Transformation Toughened Zirconia	Westinghouse	ZRO_2
9. Titanium Nitride	Kennametal	TiN
10. Alumina	Coors	Al_2O_3

TABLE 3.2

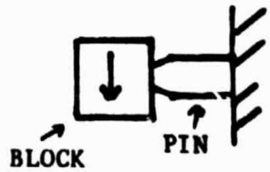
PHYSICAL PROPERTY DATA

SELECTED CANDIDATE MATERIALS FOR USE IN HIGH PERFORMANCE DIESEL ENGINE

Material	Supplier	Comp.	Binder	Specific Wt. g/cc	Hardness R_c	Coefficient Thermal Exp. m/m/K	Mechanical Strength MPa (psi x 10^3)			Mod. of Elasticity MPa (psi x 10^6)	Poisson's Ratio
							Comp.	Flex	Tensile		
K-162B	Kennametal	TiC	Ni-Mo	6.1	75	6.7×10^{-6}	4.1 (590)	1.6 (230)	-- --	413 (59)	0.24
Ad-995	Coors	Al_2O_3	--	3.9	79	6.3×10^{-6}	2.4 (345)	0.3 (45)	0.22 (31)	350 (50)	0.21
Silicon Carbide	Norton	SiC	12 w/o Si	3.1	85	4.3×10^{-6}	3.5 (500)	0.5 (75)	0.3 (43)	420 (60)	0.24
Silicon Carbide	Norton	Si_3N_4	MgO ~ 2 w/o	3.2	>90	3.1×10^{-6}	-- --	0.63 (90)	0.56 (80)	336 (48)	0.25
Refel	Pure Carbon	SiC	10% Si	3.1	~80	4.3×10^{-6}	3.0 (434)	0.5 (75)	0.3 (45)	420 (60)	0.24
Boron C-rbide	Norton	B_4C	--	2.5	>85	5.8×10^{-6}	2.9 (414)	-- --	0.3 (44)	455 (65)	--
AmCerMet	AstroMet	Ni-Cr*	--	6.9	82 (R_B)	--	0.55 (78)	>0.58 (>83)	-- --	140 (20)	--

TABLE 3.3

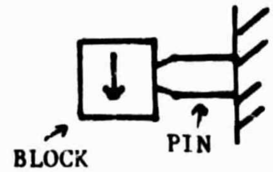
BREAKAWAY FRICTION COEFFICIENTS OF VARIOUS COUPLES TESTED



Block-Moving	Pin-Stationary: Si_3N_4	SiC	Refel	Al_2O_3	K-162B	B_4C
25°C - 700 kPa (75°F - 100 lbs/in^2)						
Si_3N_4	0.48	0.70	0.56	0.32	0.46	0.32
SiC	0.85	0.48	0.48	0.35	0.40	0.47
Refel	0.55	0.46	0.79	0.40	0.50	0.57
Al_2O_3	0.40	0.61	0.51	0.43	0.49	0.39
K-162B	0.38	0.38	0.32	0.66	0.61	0.53
B_4C	0.31	0.52	0.53	0.74	0.98	0.22
25°C - 3500 kPa (75°F - 500 lb/in^2)						
Si_3N_4	0.47	0.60	0.44	0.32	0.37	0.33
SiC	0.50	0.47	0.44	0.41	0.44	0.57
Refel	0.31	0.40	0.63	0.45	0.32	0.52
Al_2O_3	0.38	0.53	0.51	0.69	0.50	0.35
K-126B	0.29	0.51	0.32	0.64	0.36	0.41
B_4C	0.33	0.58	0.46	0.54	0.73	0.26
25°C - 7000 kPa (75°F - 1000 lb/in^2)						
Si_3N_4	0.49	0.67	0.43	0.29	0.30	0.26
SiC	0.36	0.41	0.38	0.34	0.41	0.43
Refel	0.29	0.46	0.49	0.38	0.36	0.46
Al_2O_3	0.37	0.49	0.46	0.64	0.43	0.31
K-162B	0.23	0.34	0.24	0.57	0.30	0.37
B_4C	0.32	0.63	0.42	0.56	0.70	0.38

TABLE 3.4

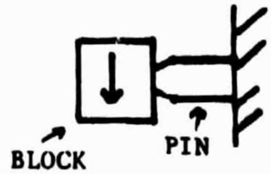
BREAKAWAY FRICTION COEFFICIENTS OF VARIOUS COUPLES TESTED



Block-Moving	Pin-Stationary Si_3N_4	SiC	Refel	Al_2O_3	K-162B	B_4C
316°C - 700 kPa (600°F - 100 lbs/in^2)						
Si_3N_4	0.84	1.1	0.70	0.96	0.65	0.76
SiC	0.66	0.58	0.61	0.49	0.66	0.52
Refel	0.56	0.50	0.55	0.66	0.69	0.48
Al_2O_3	0.57	0.75	0.63	1.2	0.61	0.76
K-162B	0.68	0.70	0.81	0.93	0.91	0.67
B_4C	0.58	0.83	0.67	1.31	0.98	0.91
316°C - 3500 kPa (600°F - 500 lb/in^2)						
Si_3N_4	0.78	0.98	0.56	0.71	0.59	0.64
SiC	0.55	0.60	0.56	0.48	0.64	0.57
Refel	0.36	0.47	0.71	0.60	0.54	0.59
Al_2O_3	0.66	0.70	0.63	0.89	0.60	0.48
K-162B	0.49	0.53	0.54	0.76	0.71	0.66
B_4C	0.69	0.91	0.55	1.11	0.87	0.73
316°C - 7000 kPa (600°F - 1000 lb/in^2)						
Si_3N_4	0.61	0.77	0.48	0.78	0.51	0.58
SiC	0.61	0.60	0.50	0.44	0.54	0.50
Refel	0.49	0.47	0.50	0.70	0.48	0.54
Al_2O_3	0.63	0.73	0.60	1.09	0.49	0.45
K-162B	0.46	0.71	0.47	0.76	0.78	0.75
B_4C	0.64	0.88	0.58	0.80	0.75	0.63

TABLE 3.5

BREAKAWAY FRICTION COEFFICIENTS OF VARIOUS COUPLES TESTED

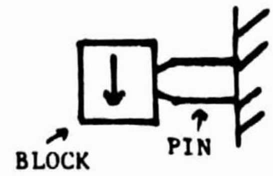


Block-Moving	Pin-Stationary					
	Si_3N_4	SiC	Refel	Al_2O_3	K-162B	B_4C
427°C - 700 kPa (800°F - 100 lbs/in^2)						
Si_3N_4	0.66	1.034	0.717	0.647	0.680	0.693
SiC	0.787	0.479	0.486	0.642	0.609	0.505
Refel	0.901	0.616	0.64	0.619	0.570	0.518
Al_2O_3	0.753	0.597	0.610	1.18	0.748	0.70
K-162B	0.687	0.620	0.870	0.692	0.81	0.72
B_4C	0.964	0.693	0.79	1.14	1.17	0.98
427°C - 3500 kPa (800°F - 500 lb/in^2)						
Si_3N_4	0.92	0.855	0.585	0.706	0.666	0.655
SiC	0.693	0.525	0.542	0.659	0.612	0.481
Refel	0.649	0.519	0.58	0.605	0.525	0.670
Al_2O_3	0.706	0.723	0.650	0.78	0.693	0.63
K-126B	0.512	0.945	0.723	0.640	0.74	0.82
B_4C	1.020	0.650	0.65	1.20	0.82	0.61
427°C - 7000 kPa (800°F - 1000 lb/in^2)						
Si_3N_4	0.51	0.735	0.497	0.700	0.548	0.621
SiC	0.606	0.549	0.493	0.489	0.544	0.427
Refel	0.560	0.465	0.64	0.651	0.515	0.696
Al_2O_3	0.700	0.602	0.525	1.18	0.560	0.62
K-162B	0.561	0.964	0.768	0.870	0.79	0.80
B_4C	0.930	0.705	0.66	0.89	0.74	0.61

TABLE 3.6

BREAKAWAY FRICTION COEFFICIENTS OF VARIOUS COUPLES TESTED

Pin-Stationary



538°C - 700 kPa (1000°F - 100 lbs/in^2)

	Si_3N_4	SiC	Refel	Al_2O_3	K-162B	B_4C
Si_3N_4	0.84	0.943	0.680	0.726	0.636	0.793
SiC	0.835	0.649	0.699	0.59	0.590	0.790
Refel	0.917	0.597	0.65	0.732	0.748	0.476
Al_2O_3	0.658	0.644	0.531	1.28	0.771	0.86
K-162B	0.834	0.603	0.745	0.784	0.91	0.77
B_4C	0.670	1.015	0.74	0.99	1.07	0.81

538°C - 3500 kPa (1000°F - 500 lb/in^2)

	Si_3N_4	SiC	Refel	Al_2O_3	K-162B	B_4C
Si_3N_4	0.87	0.811	0.553	0.788	0.589	0.768
SiC	0.547	0.576	0.631	0.633	0.561	0.691
Refel	0.605	0.564	0.51	0.833	0.652	0.638
Al_2O_3	0.563	0.628	0.512	0.75	0.723	0.59
K-162B	0.664	0.488	1.147	0.673	0.68	1.05
B_4C	0.865	0.980	0.59	0.93	0.89	0.75

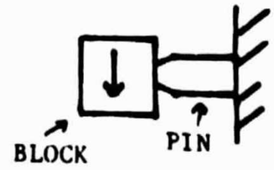
538°C - 7000 kPa (1000°F - 1000 lb/in^2)

	Si_3N_4	SiC	Refel	Al_2O_3	K-162B	B_4C
Si_3N_4	0.80	0.750	0.486	0.703	0.555	0.710
SiC	0.514	0.630	0.478	0.670	0.511	0.581
Refel	0.474	0.586	0.44	1.055	0.655	0.643
Al_2O_3	0.639	0.610	0.481	1.15	0.640	0.60
K-162B	0.573	0.404	0.961	0.620	0.54	0.78
B_4C	0.924	1.004	0.64	0.78	0.73	0.95

TABLE 3.7

BREAKAWAY FRICTION COEFFICIENTS
OF VARIOUS COUPLES TESTED

Pin-Stationary



	Si_3N_4	SiC	Refel	Al_2O_3	K-162B	B_4C
650°C - 700 kPa (1200°F - 100 lbs/in^2)						
Si_3N_4	0.87	0.87	0.65	0.74	0.47	0.64
SiC	0.73	0.69	0.77	0.62	0.57	0.60
Refel	0.69	1.00	0.55	0.57	0.84	0.73
Al_2O_3	0.88	0.61	0.83	1.50	0.85	0.89
K-162B	0.84	0.82	0.86	1.06	0.87	0.86
B_4C	0.68	0.68	0.86	0.98	1.28	1.50
650°C - 3500 kPa (1200°F - 500 lb/in^2)						
Si_3N_4	0.76	0.86	0.67	0.83	0.66	0.68
SiC	0.56	0.66	0.69	0.57	0.68	0.59
Refel	0.56	1.02	0.59	0.66	0.84	0.67
Al_2O_3	0.73	0.61	0.48	1.10	0.78	0.63
K-162B	0.67	1.25	1.06	1.14	0.82	0.98
B_4C	0.79	0.58	1.19	1.40	1.22	1.18
650°C - 7000 kPa (1200°F - 1000 lb/in^2)						
Si_3N_4	0.75	0.75	0.47	0.68	0.69	0.63
SiC	0.55	0.53	0.55	0.55	0.64	0.50
Refel	0.52	0.88	0.45	0.67	0.82	0.68
Al_2O_3	0.63	0.61	0.67	1.14	0.68	0.53
K-162B	0.61	1.29	0.99	0.97	0.69	0.79
B_4C	0.68	0.67	0.86	0.[illegible]2	0.79	1.19

TABLE 3.8

BREAKAWAY FRICTION COEFFICIENTS

Pin Material

	Si_3N_4	SiC	Refel	Al_2O_3	K-162B	Cr_3C_2*	Am Cer Met
	25°C (75)F) - 700 kPa (100 lb/in^2)						
Cr_3C_2	0.39	0.53	0.42	0.52	0.72	1.07	0.42
Am Cer Met	0.36	0.55	0.77	0.70	0.57	0.50	0.25
	25°C (75)F) - 3500 kPa (500 lb/in^2)						
Cr_3C_2	0.29	0.34	0.40	0.42	0.49	0.67	0.23
Am Cer Met	0.32	0.36	0.43	0.45	0.41	0.32	0.31
	25°C (75°F) - 7000 kPa (1000 lb/in^2)						
Cr_3C_2	0.28	0.27	0.29	0.52	0.38	0.74	0.23
Am Cer Met	0.28	0.24	0.36	0.37	0.35	0.37	0.26
	316°C (600°F) - 700 kPa (100 lb/in^2)						
Cr_3C_2	0.67	0.60	0.75	1.34	1.12	1.62	0.97
Am Cer Met	1.10	0.78	0.82	0.91	0.60	0.61	0.70
	316°C (600°F) - 3500 kPa (500 lb/in^2)						
Cr_3C_2	0.60	0.47	0.54	1.60	0.71	1.51	0.52
Am Cer Met	0.70	0.39	0.73	0.73	0.48	0.65	0.53
	316°C (600°F) - 7000 kPa (1000 lb/in^2)						
Cr_3C_2	0.71	0.52	0.50	1.13	0.95	0.96	0.68
Am Cer Met	0.68	0.49	0.67	0.90	1.14	0.54	0.58
	427°C (800°F) - 700 kPa (100 lb/in^2)						
Cr_3C_2	1.42	0.85	0.85	1.38	1.74	1.85	0.97
Am Cer Met	1.21	1.48	0.95	1.17	1.41	1.60	1.60
	427°C (800°F) - 3500 kPa (500 lb/in^2)						
Cr_3C_2	0.93	0.82	0.46	1.11	1.44	1.33	0.87
Am Cer Met	1.01	1.00	0.89	1.21	0.63	1.04	0.94
	427°C (800°F) - 7000 kPa (1000 lb/in^2)						
Cr_3C_2	0.81	0.72	0.40	1.03	1.20	0.96	0.43
Am Cer Met	1.12	1.15	0.94	1.17	1.08	1.01	0.92
	538°C (1000°F) - 700 kPa (100 lb/in^2)						
Cr_3C_2	1.39	1.65	1.14	2.02	1.76	1.88	1.90
Am Cer Met	1.62	1.70	1.58	1.70	1.20	1.76	1.95

*Chromi-m Carbide Hardface

TABLE 3.8 (Cont'd.)

BREAKAWAY FRICTION COEFFICIENTS

Pin Material

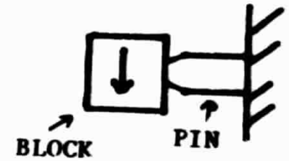
	Si_3N_4	SiC	Refel	Al_2O_3	K-162B	Cr_3C_2	Am Cer Met
		538°C (1000°F) - 3500 kPa (500 lb/in^2)					
Cr_3C_2	0.96	1.27	0.66	1.22	1.28	0.92	1.10
Am Cer Met	1.43	1.25	1.07	0.96	1.01	0.99	1.35
		538°C (1000°F) - 7000 kPa (1000 lb/lb/in^2)					
Cr_3C_2	0.83	1.04	0.47	1.05	1.04	0.65	0.88
Am Cer Met	1.22	0.92	1.11	0.91	0.96	0.96	1.26
		650°C (1200°F) - 700 kPa (100 psi)					
Cr_3C_2	2.15	1.62	1.54	2.66	1.79	1.93	2.01
Am Cer Met	1.58	1.67	1.28	1.38	1.43	1.61	1.94
		650°C (1200°F) - 3500 kPa (500 psi)					
Cr_3C_2	0.99	1.44	0.77	1.26	1.38	1.20	1.10
Am Cer Met	1.05	1.00	1.17	1.15	1.14	1.02	1.21
		650°C (1200°F) - 7000 kPa (1000 psi)					
Cr_3C_2	1.02	1.11	0.83	1.25	1.07	0.64	0.93
Am Cer Met	0.98	1.02	1.21	0.86	0.92	1.07	1.17

TABLE 3.9

BREAKAWAY FRICTION COEFFICIENT

Material: Pin- Titanium Nitride*
Block- Titanium Nitride*

0.076 cm/min
(0.030 inch/min)



Load	316°C (600°F) Strain**	f_{AV}	427°C (800°F) Strain**	f_{AV}	538°C (1000°F) Strain**	f_{AV}	650°C (1200°F) Strain**	f_{AV}	Room Temp. 25°C (78°F) Strain**	f_{AV}
700 kPa (100 lb/in^2)	(1) 424 (2) 452	0.95	(1) 412 (2) 412	0.90	(1) 446 (2) 454	0.97	(1) 469 (2) 424	0.97	(1) 352 (2) 350	0.76
3500 kPa (500 lb/in^2)	(1) 1446 (2) 1498	0.64	(1) 1405 (2) 1580	0.65	(1) 1770 (2) 1827	0.78	(1) 1734 (2) 1740	0.75	(1) 1130 (2) 1220	0.51
7000 kPa (1000 lb/in^2)	(1) 2630 (2) 2736	0.58	(1) 2904 (2) 3090	0.65	(1) 3016 (2) 3110	0.66	(1) 3568 (2) 3654	0.78	(1) 1772 (2) 1790	0.38

f_{AV} = Average Friction Coefficient

* = ~0.3 mil Coating on k-162B Substrate

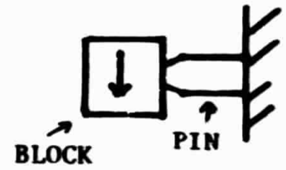
** = Micro-Inches

TABLE 3.10

BREAKAWAY FRICTION COEFFICIENT

Material: Pin- ZrO_2*
Block- ZrO_2*

0.076 cm/min
(0.030 inch/min)



Load	316°C (600°F) Strain**	316°C (600°F) f_{AV}	427°C (800°F) Strain**	427°C (800°F) f_{AV}	538°C (1000°F) Strain**	538°C (1000°F) f_{AV}	650°C (1200°F) Strain**	650°C (1200°F) f_{AV}	Room Temp. 25°C (78°F) Strain**	Room Temp. 25°C (78°F) f_{AV}
700 kPa (100 lb/in^2)	(1) 430 (2) 455	0.96	(1) 488 (2) 505	1.07	(1) 1094 (2) 1080	2.35	(1) 770 (2) 776	1.67	(1) 318 (2) 403	0.67
3500 kPa (500 lb/in^2)	(1) 1728 (2) 1830	0.77	(1) 2180 (2) 2292	0.97	(1) 4590 (2) 4736	2.02	(1) 4445 (2) 4860	2.02	(1) 1050 (2) 1055	0.46
7000 kPa (1000 lb/in^2)	(1) 4450 (2) 4660	0.99	(1) 6480 (2) 6680	1.42	(1) Friction Force Enceeded Strain Gauge Capability (2)		(1) (2)		(1) 1630 (2) 1680	0.36

f_{AV} = Average Friction Coefficient

* = Transformation Toughened

** = Micro-Inches

TABLE 3.11

DYNAMIC FRICTION-WEAR TEST RESULTS 30 MINUTE TEST DURATION

Run No.	Material Couple Rotor	Material Couple Block	Test Temp. °C (°F)	Final Temp. °C (°F)	Load kg (lbs)	Pressure** kPa (lb/in^2)	Speed rpm	Fric. Coef-f	Weight*** Change-mg	Average Wear Scar Width-mm	Comments On Performance
1*	Si_3N_4	Si_3N_4	316 (600)	460 (860)	1.7 (3.75)	260 (37)	5000	0.30	- 32	6.0	Rough
2*	Si_3N_4	Si_3N_4	427 (800)	532 (990)	1.7 (3.75)	210 (30)	5000	0.28	- 19	5.0	Rough
3*	Si_3N_4	Si_3N_4	R.T.	190 (375)	1.7 (3.75)	175 (25)	5000	0.32	- 8	4.3	Smooth
4*	Si_3N_4	Si_3N_4	316 (600)	452 (845)	1.7 (3.75)	175 (25)	2400	0.40	- 9	4.1	Rough
5	K-162	Si_3N_4	316 (600)	340 (644)	0.57 (1.25)	260 (37)	2400	0.52	- 0.3	0.15	Smooth
6	K-162	Si_3N_4	316 (600)	345 (652)	0.57 (1.25)	260 (37)	5000	0.21	+ 0.4	0.15	Smooth
7	K-162	Si_3N_4	316 (600)	368 (692)	1.7 (3.75)	700 (100)	2400	0.34	- 0.2	0.25	Smooth
8*	K-162	Si_3N_4	316 (600)	357 (675)	1.7 (3.75)	2600 (370)	5000	0.17	- 0.6	1.0	Smooth
9*	K-162	Si_3N_4	650 (1200)	683 (1262)	1.7 (3.75)	2600 (370)	5000	0.19	- 0.6	1.2	Smooth
10	K-162	SiC	316 (600)	416 (780)	1.7 (3.75)	706 (100)	5000	0.24	- 1.0	0.25	Smooth
11	K-162	SiC	482 (900)	549 (1020)	1.7 (3.75)	706 (100)	5000	0.26	- 0.5	0.20	Smooth
12	K-162	SiC	650 (1200)	767 (1306)	1.7 (3.75)	706 (100)	5000	0.19	- 0.5	0.20	Rough
13	B_4C	B_4C	316 (600)	468 (766)	1.7 (3.75)	560 (80)	5000	--	- 3.3	1.60	Rough-Chipped
14	Si_3N_4	Si_3N_4	316 (600)	480 (895)	1.7 (3.75)	420 (60)	5000	--	- 326	3.10	Block Chipped
15	Si_3N_4	Si_3N_4	482 (900)	560 (1040)	1.7 (3.75)	420 (60)	5000	--	- 30	3.40	Rotor Chipped
16	Si_3N_4	Si_3N_4	650 (1200)	--	1.7 (3.75)	--	5000	Block cracked after ~ 3 minutes			
17	Si_3N_4	Refel	316 (600)	511 (952)	1.7 (3.75)	~420 (~60)	5000	0.12	- 7.4	1.8	Rotor Chipped
18	Si_3N_4	Refel	482 (900)	641 (1184)	1.7 (3.75)	~420 (~60)	5000	0.20	- 6.0	2.3	Rotor Chipped
19*	Si_3N_4	K-162	316 (600)	363 (685)	1.7 (3.75)	2600 (370)	2400	0.18	- 0.4	1.1	Smooth
20*	Si_3N_4	K-162	482 (900)	546 (1015)	1.7 (3.75)	1645 (235)	2400	0.21	- 0.6	1.6	Smooth
21*	Si_3N_4	K-162	650 (1200)	702 (1295)	1.7 (3.75)	1160 (180)	2400	0.21	- 1.5	2.1	Smooth
22*	SiC	K-162	316 (600)	366 (690)	1.7 (3.75)	2030 (290)	2400	0.26	- 0.6	1.4	Rough Operation
23*	SiC	K-162	482 (900)	534 (993)	1.7 (3.75)	2030 (290)	2400	0.25	- 1.3	1.4	Rough Operation
24*	SiC	K-162	650 (1200)	688 (1270)	1.7 (3.75)	1160 (180)	2400	0.19	- 1.3	2.1	Rough Operation

*Block had flat face - Unless otherwise indicated, all other tests in this table were initiated with a 3 mm wide conformal radius on block face.

**Based on final scar width.

***Block

TABLE 3.11 (Cont'd.)

Run No.	Material Couple Rotor	Material Couple Block	Test Temp. °C (°F)	Final Temp. °C (°F)	Load kg (lbs)	Pressure** kPa (lb/in^2)	Speed rpm	Fric. Coef-f	Weight*** Change-mg	Average Wear Scar	Comments On Performance
25*	K-162	K-162	316 (600)	356 (674)	1.7 (3.75)	1.6 (235)	2400	0.24	- 0.8	1.6	Smooth
26*	K-162	K-162	482 (900)	502 (934)	1.7 (3.75)	1.6 (235)	2400	0.11	- 0.6	1.6	Smooth
27*	K-162	K-162	650 (1200)	674 (1245)	1.7 (3.75)	1.6 (235)	2400	0.15	- 0.6	1.6	Smooth
28*	Am Cer Met	Am Cer Met	316 (600)	371 (700)	1.7 (3.75)	1.3 (190)	2400	0.18	- 20	2.0	Smooth
29*	Am Cer Met	Am Cer Met	482 (900)	530 (985)	1.7 (3.75)	1.3 (190)	2400	0.17	+ 29	2.0	Smooth
30*	Am Cer Met	Am Cer Met	650 (1200)	713 (1315)	1.7 (3.75)	0.9 (135)	2400	0.21	+ 20	2.8	Smooth
31*	K-162	Si_3N_4	650 (1200)	Test terminated due to equipment malfunction after 16 minutes.							
32*	K-162	SiC	650 (1200)	713 (1315)	1.7 (3.75)	2 (290)	5000	0.11	- 0.7	1.4	Rough
33*	K-162	Refel	593 (1100)	632 (1170)	1.7 (3.75)	1.9 (268)	5000	0.1[illegible]	- 0.6	1.5	Int. Smooth
34*	Si_3N_4	K-162	650 (1200)	666 (1230)	1.7 (3.75)	1.9 (273)	5000	0.22	- 0.6	1.4	Smooth
35*	SiC	K-162	650 (1200)	663 (1225)	1.7 (3.75)	1.1 (163)	5000	0.31	- 2.2	2.4	Int.[a] Rough
36*	K-162	LC-1C	593 (1100)	624 (1155)	1.7 (3.75)	1.9 (268)	5000	0.19	+ 1.0	1.5	Smooth
37*	K-162	SiC	621 (1150)	650 (1205)	1.7 (3.75)	1.8 (255)	5000	0.16	- 1.2	1.5	Int.[a] Smooth
38*	K-162	SiC	650 (1200)	696 (1285)	3.4 (7.50)	4.1 (590)	5000	0.18	- 0.7	1.3	Int.[a] Smooth
39*	ZrO	ZrO	316 (600)	490 (915)	1.7	--	5000	Block split - heavy plug chipping			
40*	TiN	TiN	621 (1150)	650 (1200)	1.7 (3.75)	1.3 (190)	5000	0.12	- 1.6	2.1	Film Worn Through

*Block had flat face - Unless otherwise indicated, all other tests in this table were initiated with a 3 mm wide conformal radius on block face.

**Based on final scar width.

***Block

(a) Intermediate

TABLE 3.12

HIGH LOAD-HIGH TEMPERATURE OSCILLATORY TESTS 538°C (1000°F) - ± 0.76 CM (± 0.3 INCH) TRAVEL

Run	Material Combination: Moving	Material Combination: Static	Load kPa x 10^3 (lb/in^2)	No. Cycles	Wt Change-mg: Moving*	Wt Change-mg: Static	Final f	Comments
1	K-162B	Si_3N_4	14 (2000)	1000	+1.9	—	0.18	One static specimen broken
2	K-162B	Si_3N_4	28 (4000)	100		--	0.22	
			35 (5000)	125		--	--	
			42 (6000)	775	-2.0**	--	0.21	Both static specimens broken
3	K-162B	SiC	14 (2000)	500	+1.1	--	0.35	Both static specimens broken
4	K-162B	Refel	28 (4000)	1000	-1.0	0	0.22	One static specimen split
5	K-162B	K-162B	28 (4000)	500	~ 0	0	0.23	Contact areas high polished No chipping or cracking
6	K-162B	K-162B	42 (6000)	1000	-2.5	***	1.0(a)	High polish - no chipping or cracking

*Average of both specimens.

**Total weight loss over entire pressure range.

***One Static specimen gained 1.2 mg; one specimen lost 1.2 mg.

(a)Friction coefficient after 250 cycles was 0.45, after which a gradual increase to a final 1.0 took place.

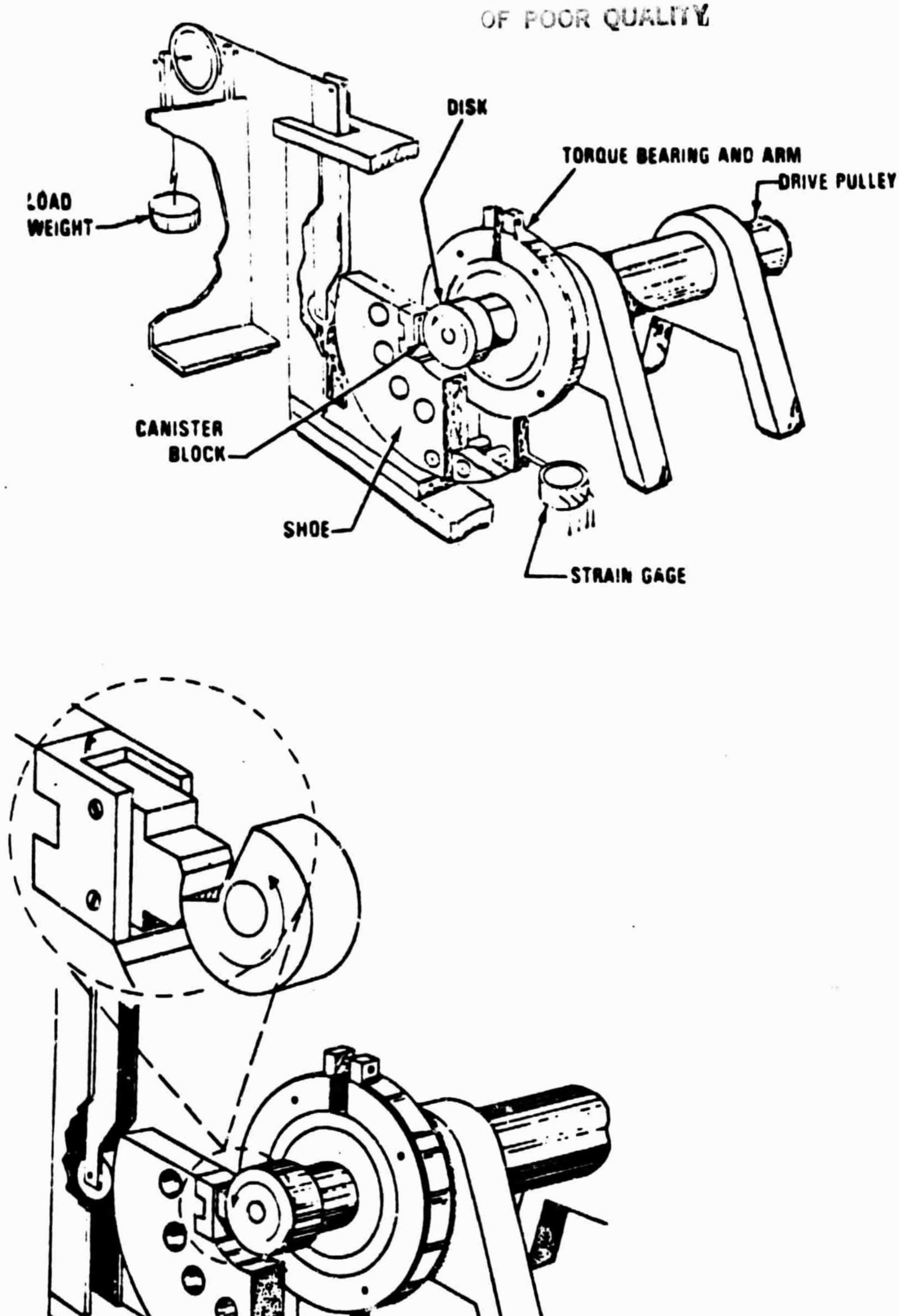


Fig. 2.1—Dynamic friction measuring device

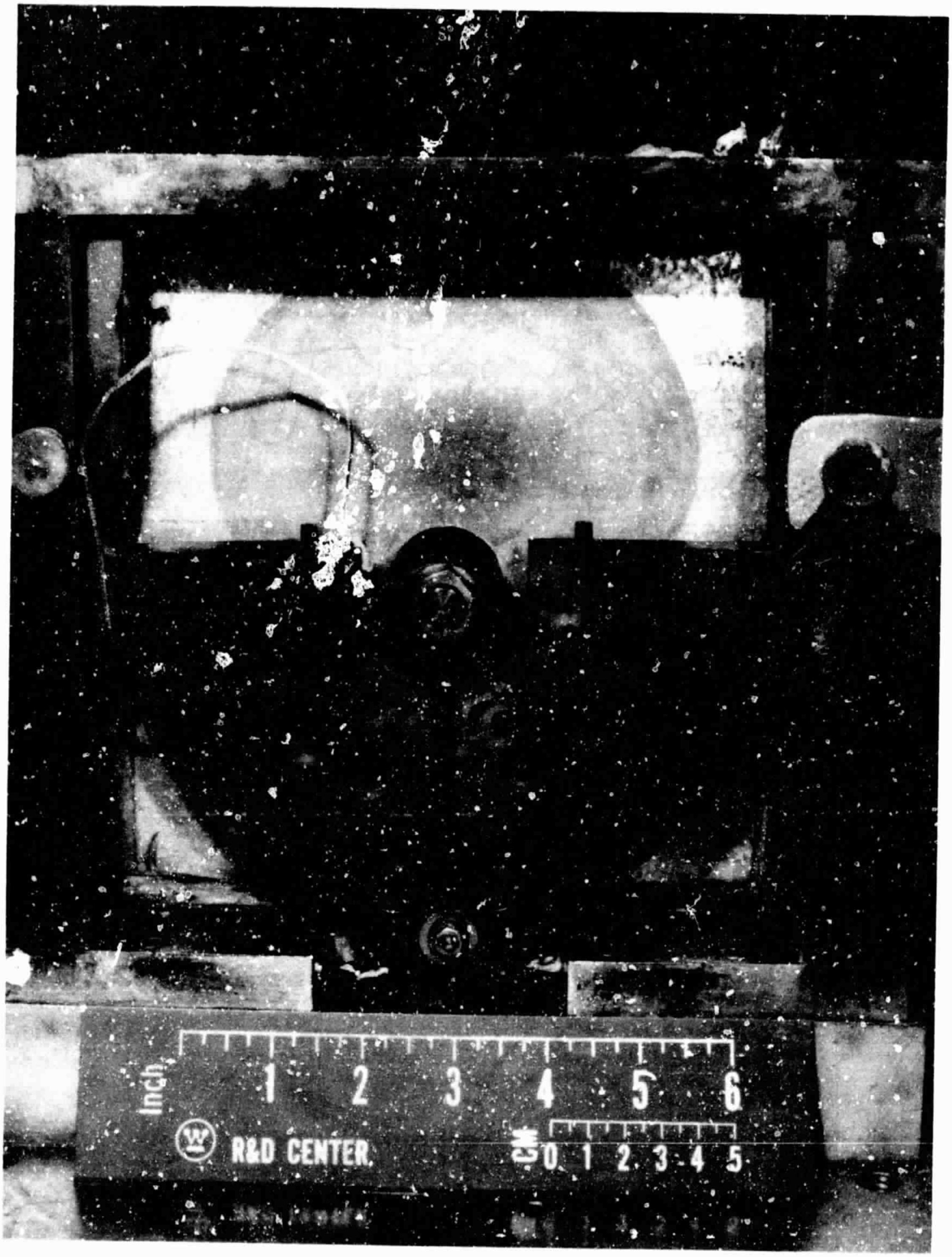


Fig. 2.2—Dynamic friction/wear tester with heaters removed

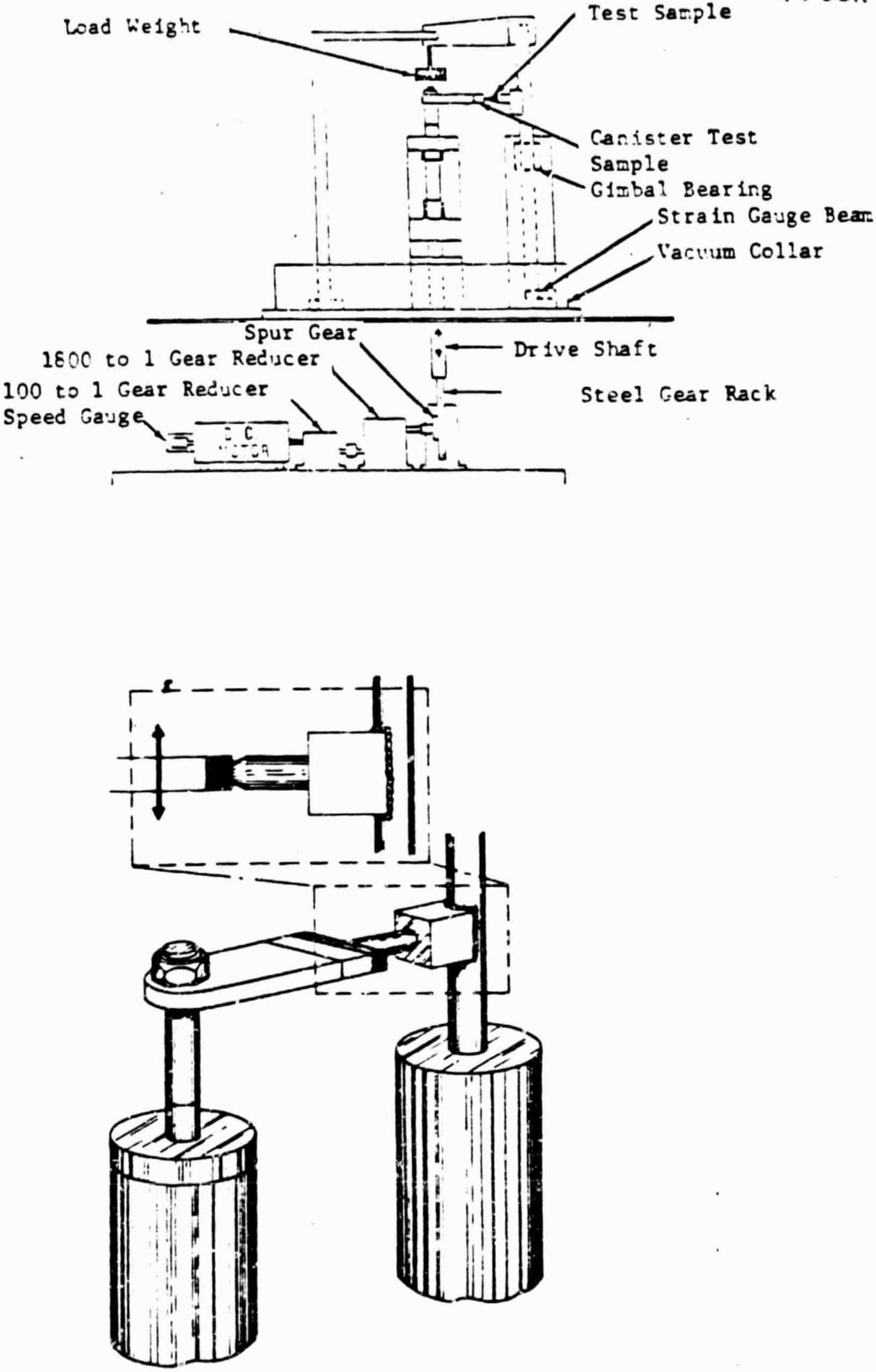


Fig. 2.3—Breakaway force measuring device

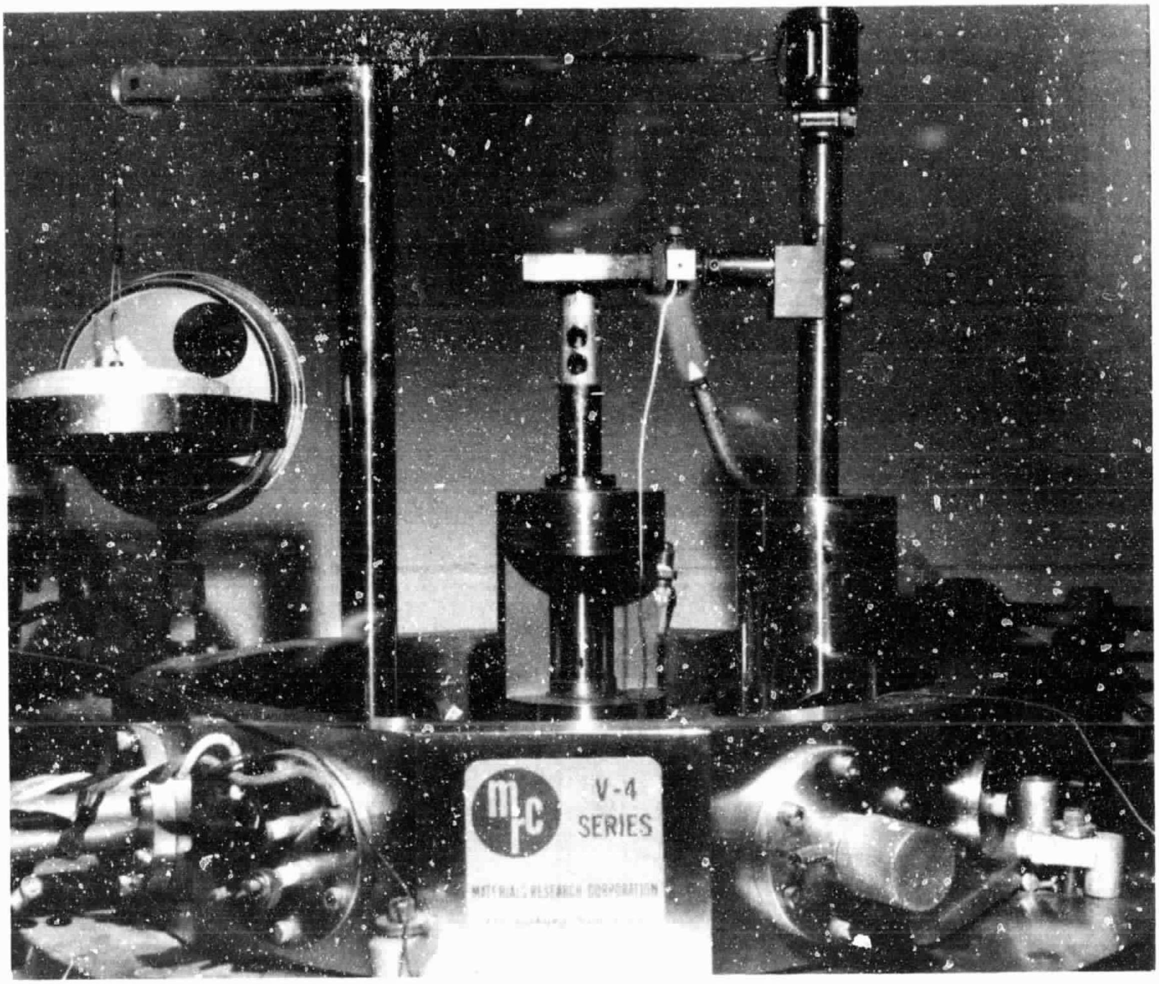


Fig. 2.4—Breakaway friction force measuring device

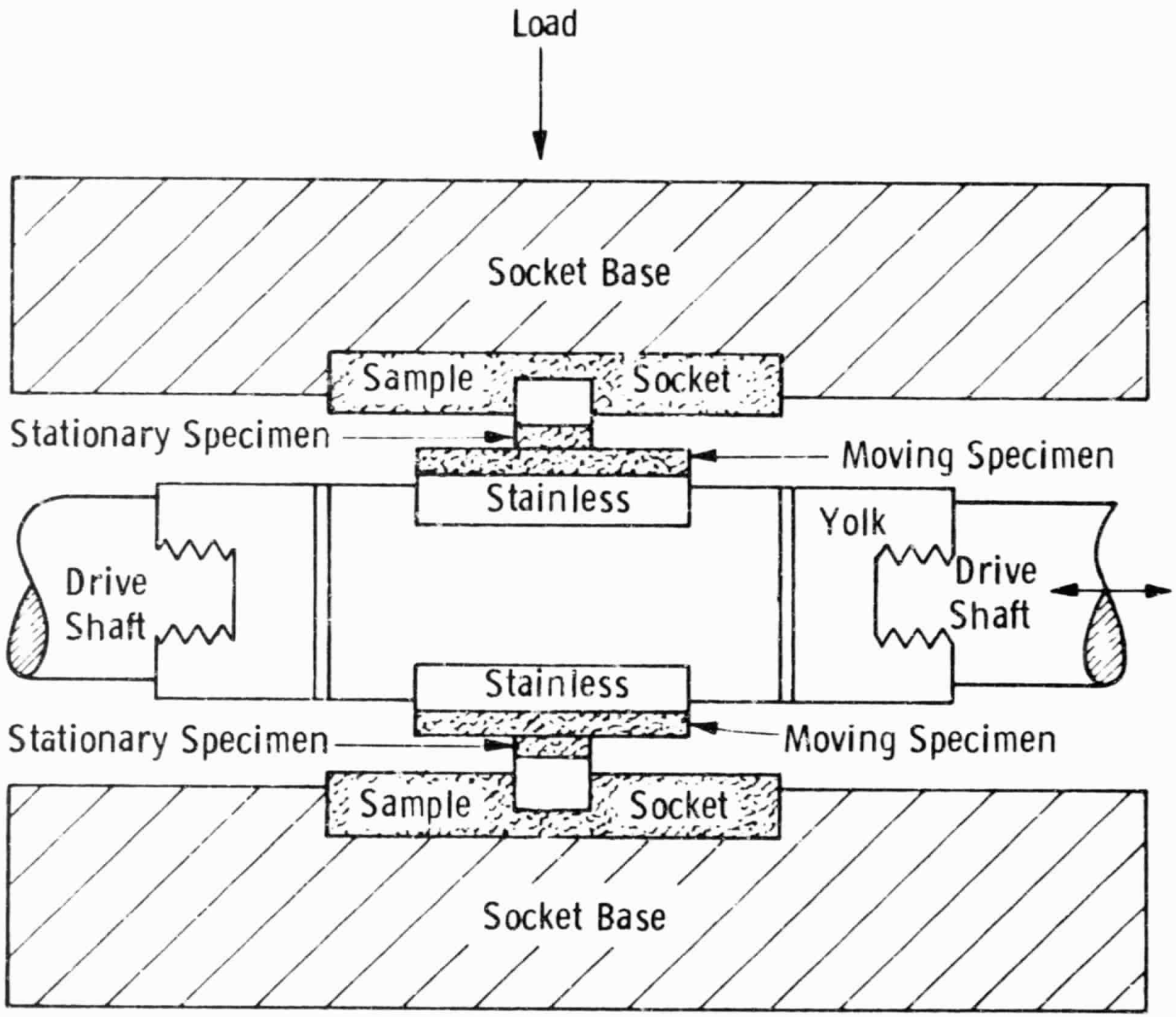


Fig. 2.5—Schematic of test sample holding fixture

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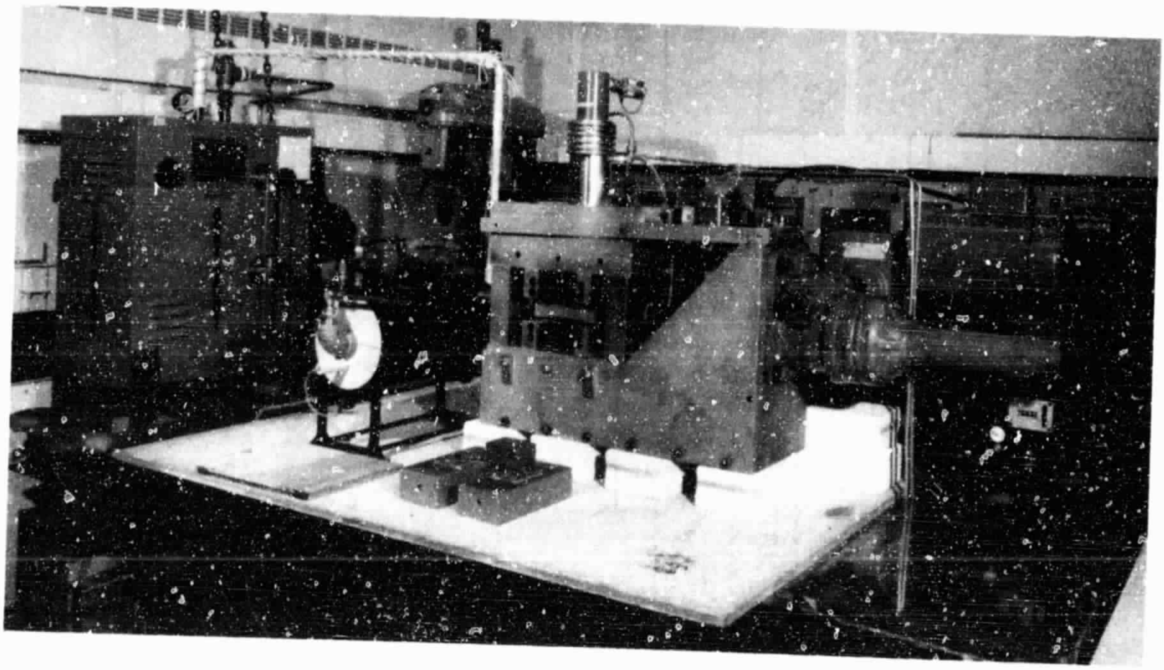


Fig. 2.6—Oscillatory friction/wear test apparatus

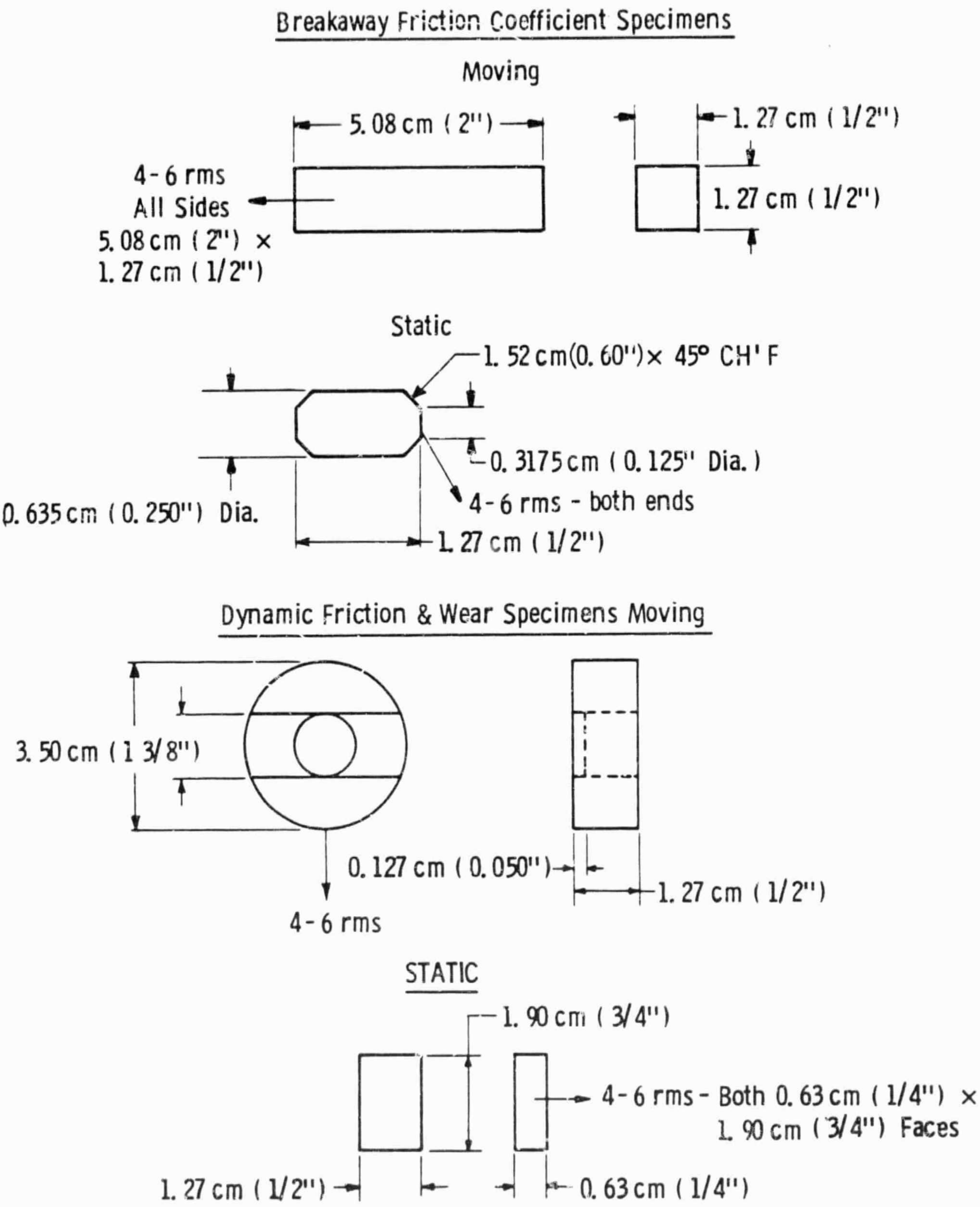
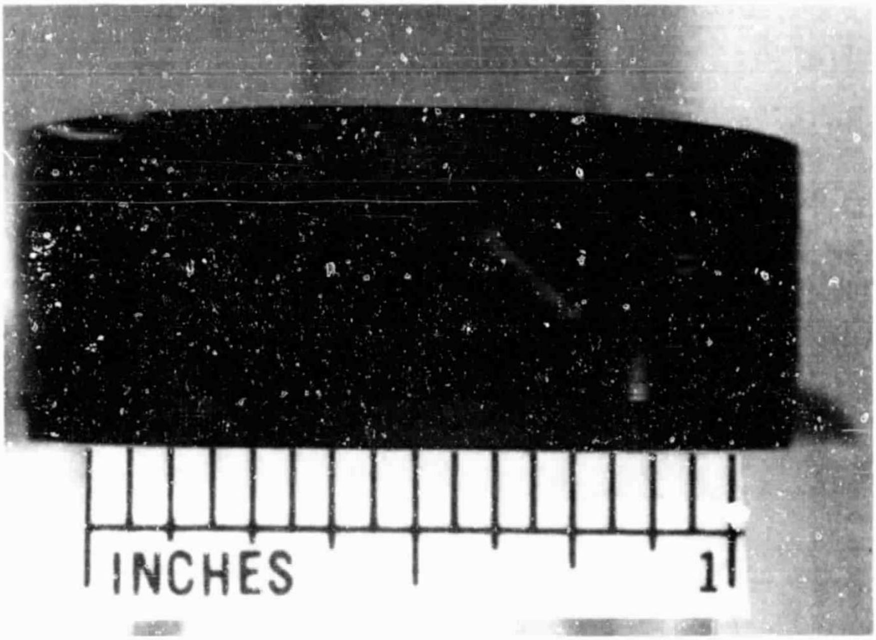
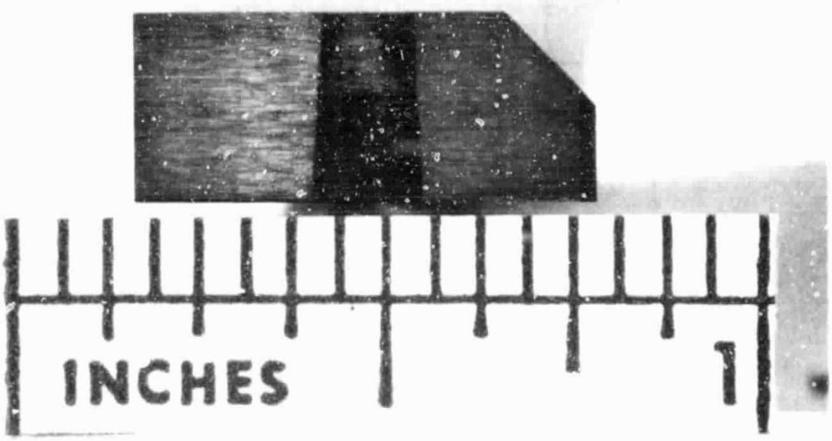


Fig. 2.7 — Breakaway & dynamic friction — wear specimen geometry

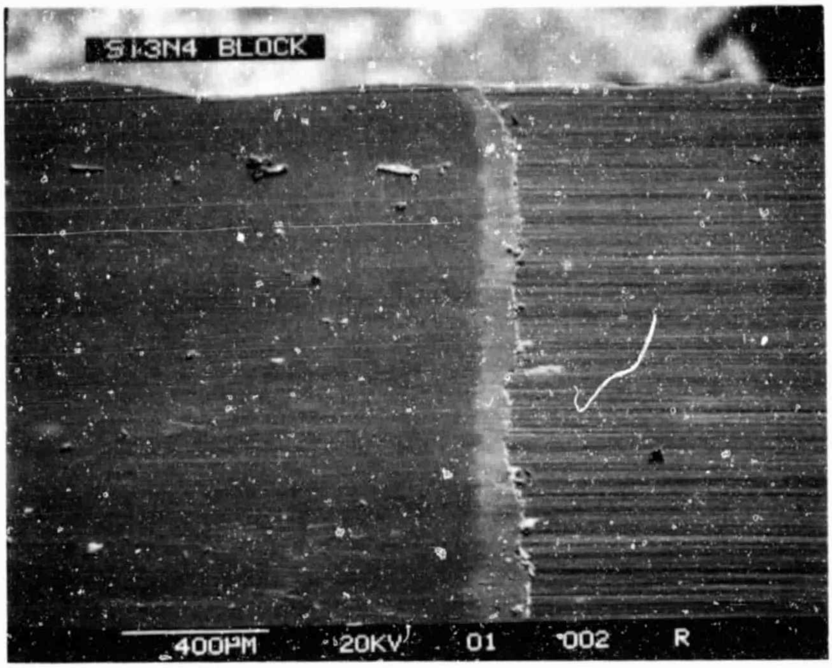


Wear Track on Titanium Carbide (K-162B) Plug -- Run #7



Wear Track on Silicon Nitride (Si_3N_4) Block – Run #7

Fig. 3.1–Wear track on silicon nitride (Si_3N_4) block and plug-run #7



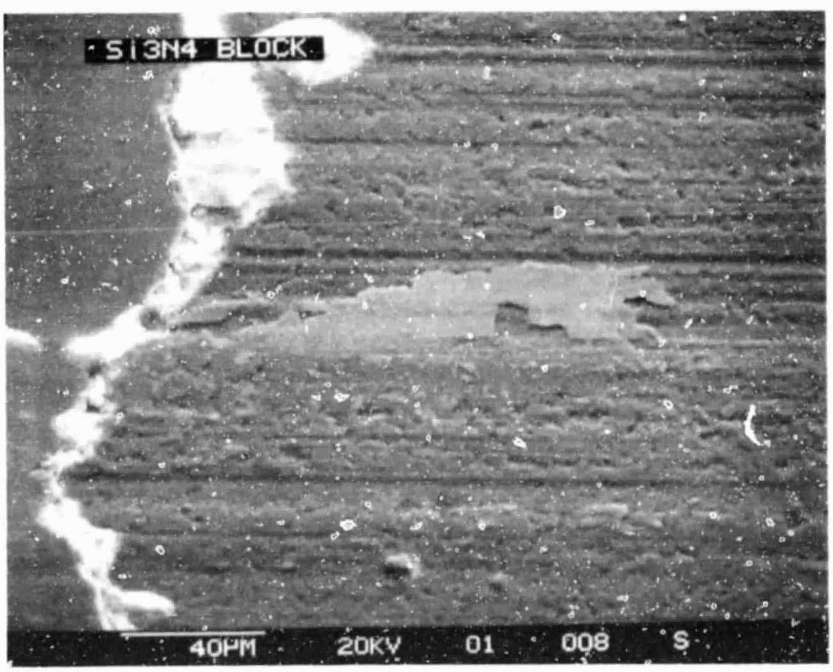


Fig. 3.2—Scanning electron microscope views of Si_3N_4 wear track - run #31-1200°F - 5000 rpm upper-50X; lower - 500X

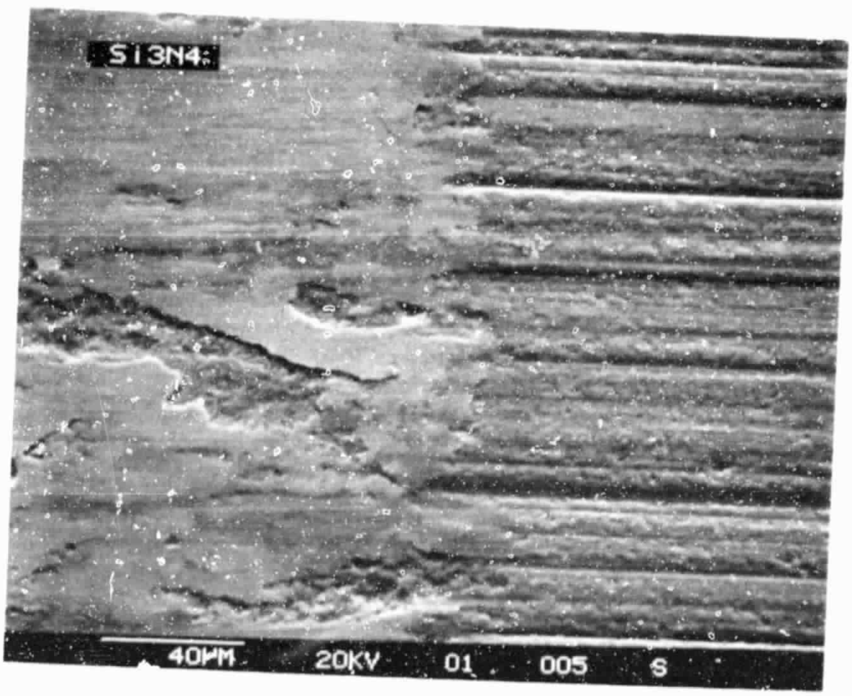


Fig. 3.3—Scanning electron microscope views of wear material on Si_3N_4 Block-run #31-1200°F-5000 rpm - upper- 2000X; lower 500 X

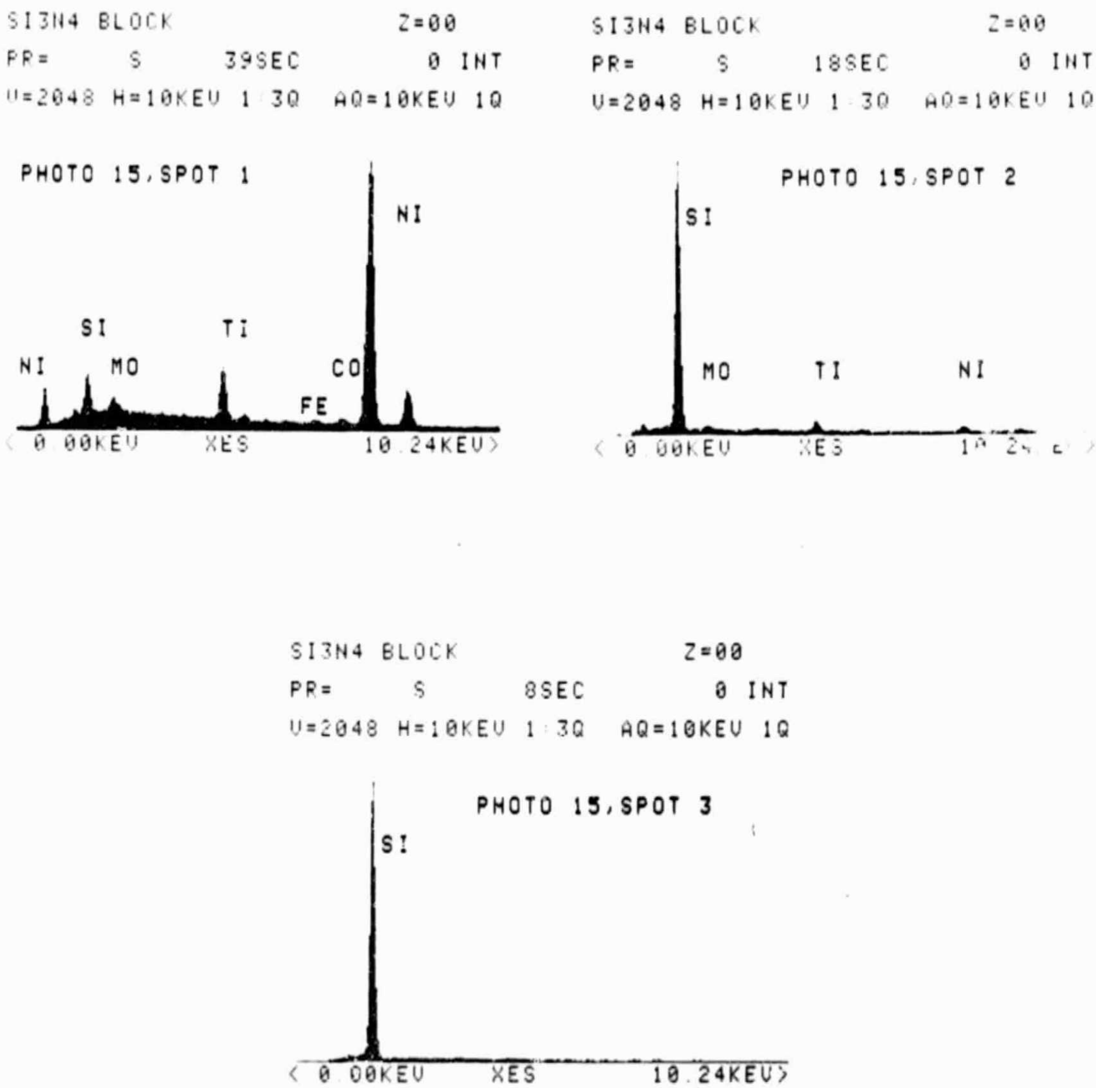
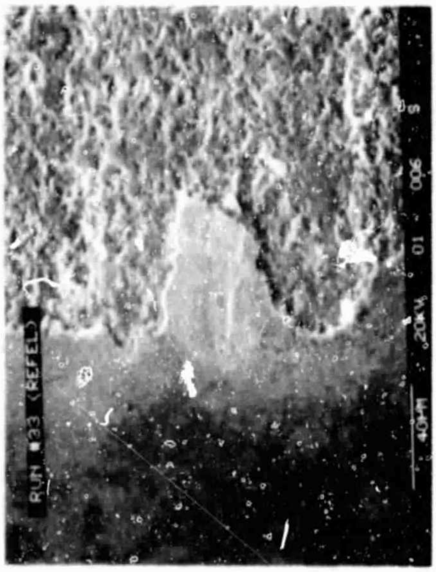
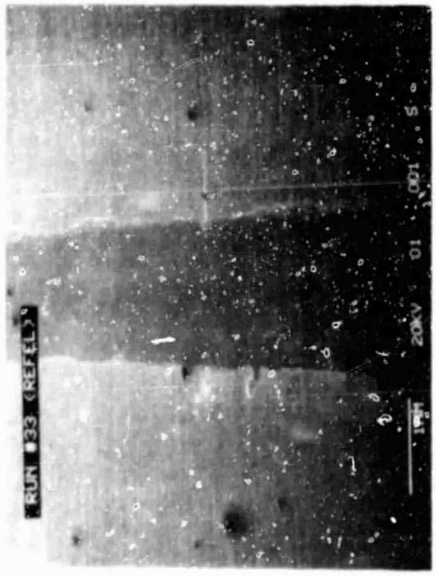


Fig. 3.4—Emission dispersive x-ray analyses of Si_3N_4 wear particles - run #31 - 650°C (1200°F) - 5000 RPM



500X

2000X



20X

2000X

Fig. 3.5—SEM photographs of Refel (SiC) stationary block operating against K-162B rotor - run #33 - 1200°F - 5000 rpm

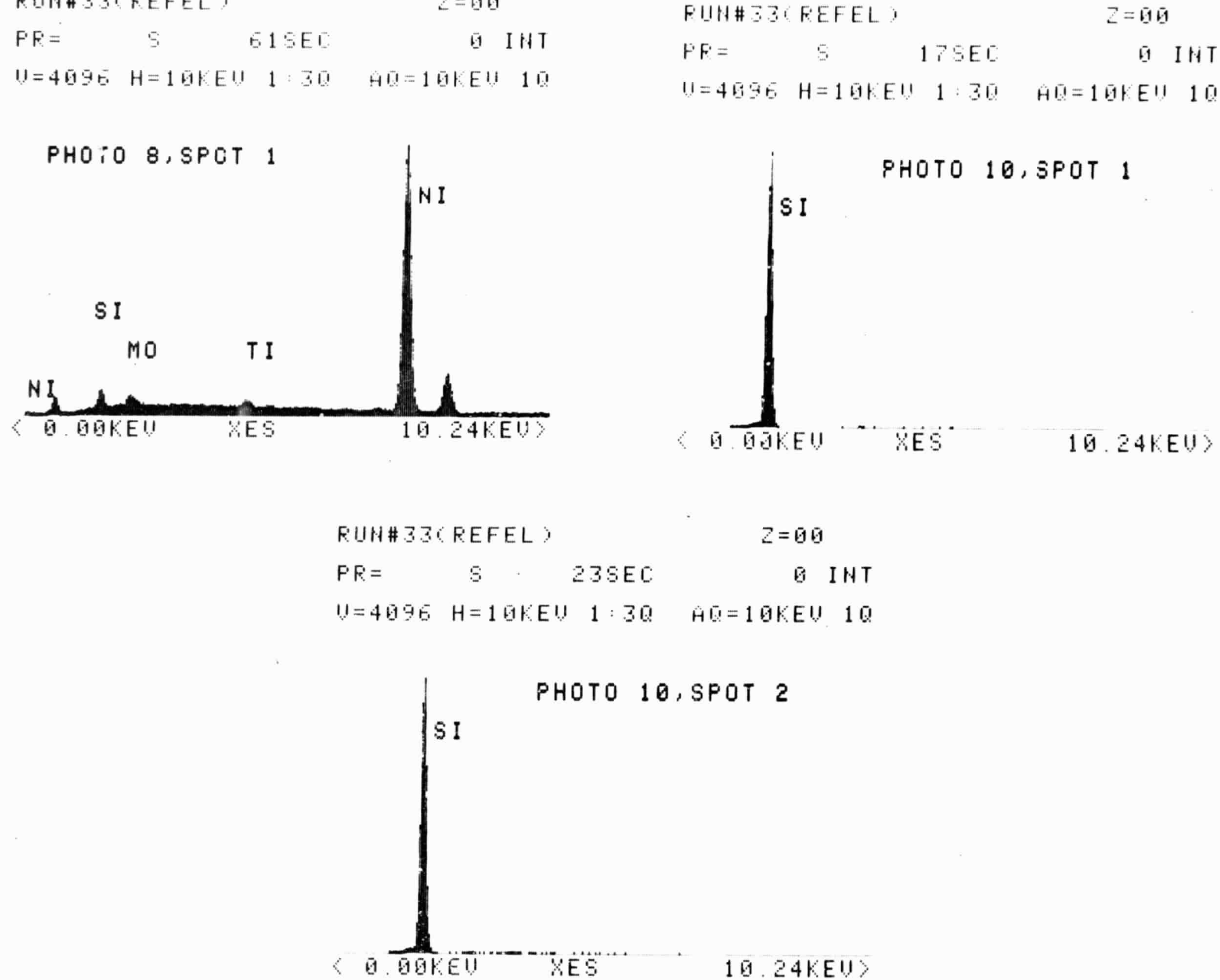
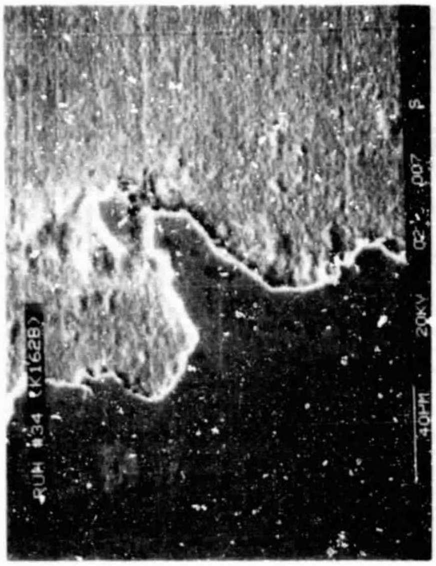
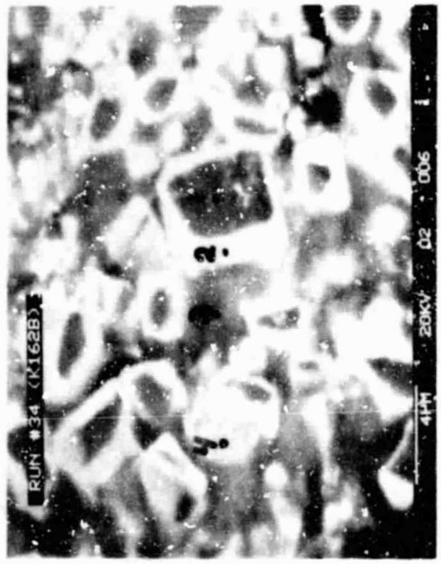


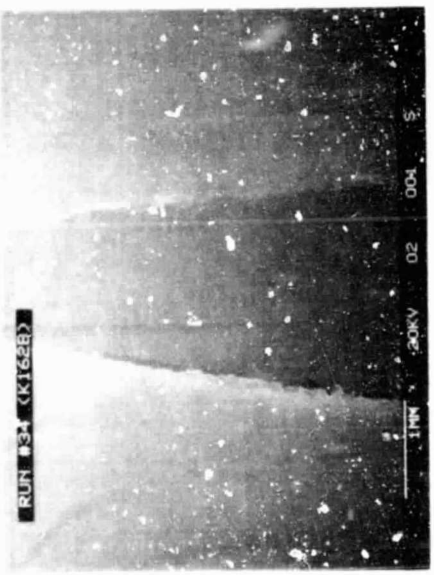
Fig. 3.6—Emission dispersive x-ray analyses of Refel stationary block-run #33 - 650°C (1200°F)



500X



5000X



20X

2000X

Fig. 3.7--SEM photographs of K-162B (TiC) stationary block operating against Si_3N_4 rotor - run #34 - 1200°F - 5000 rpm

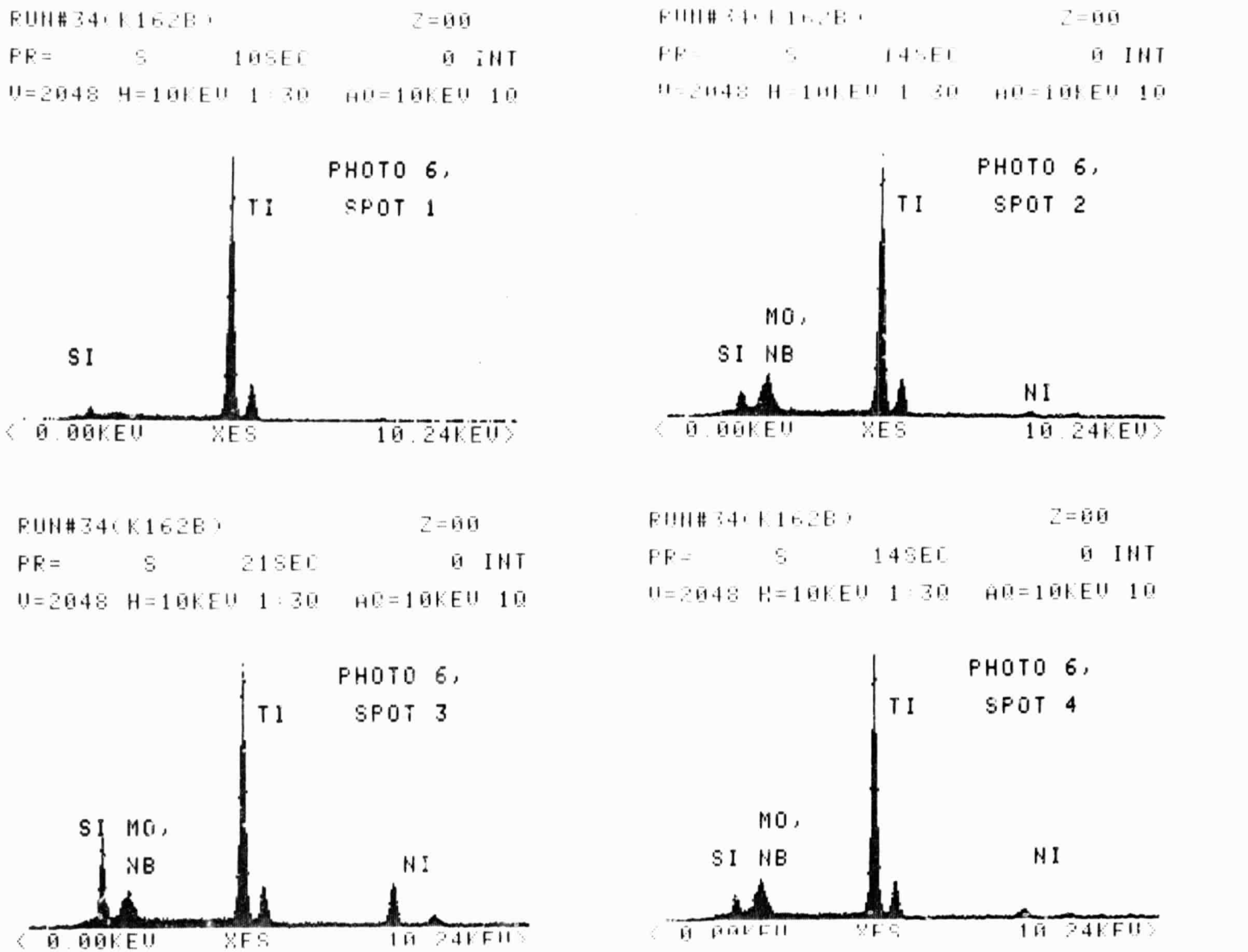


Fig. 3.8—Emission dispersive x-ray analyses of K-162B stationary block-run #34 - 650^{0}C (1200^{0}F)

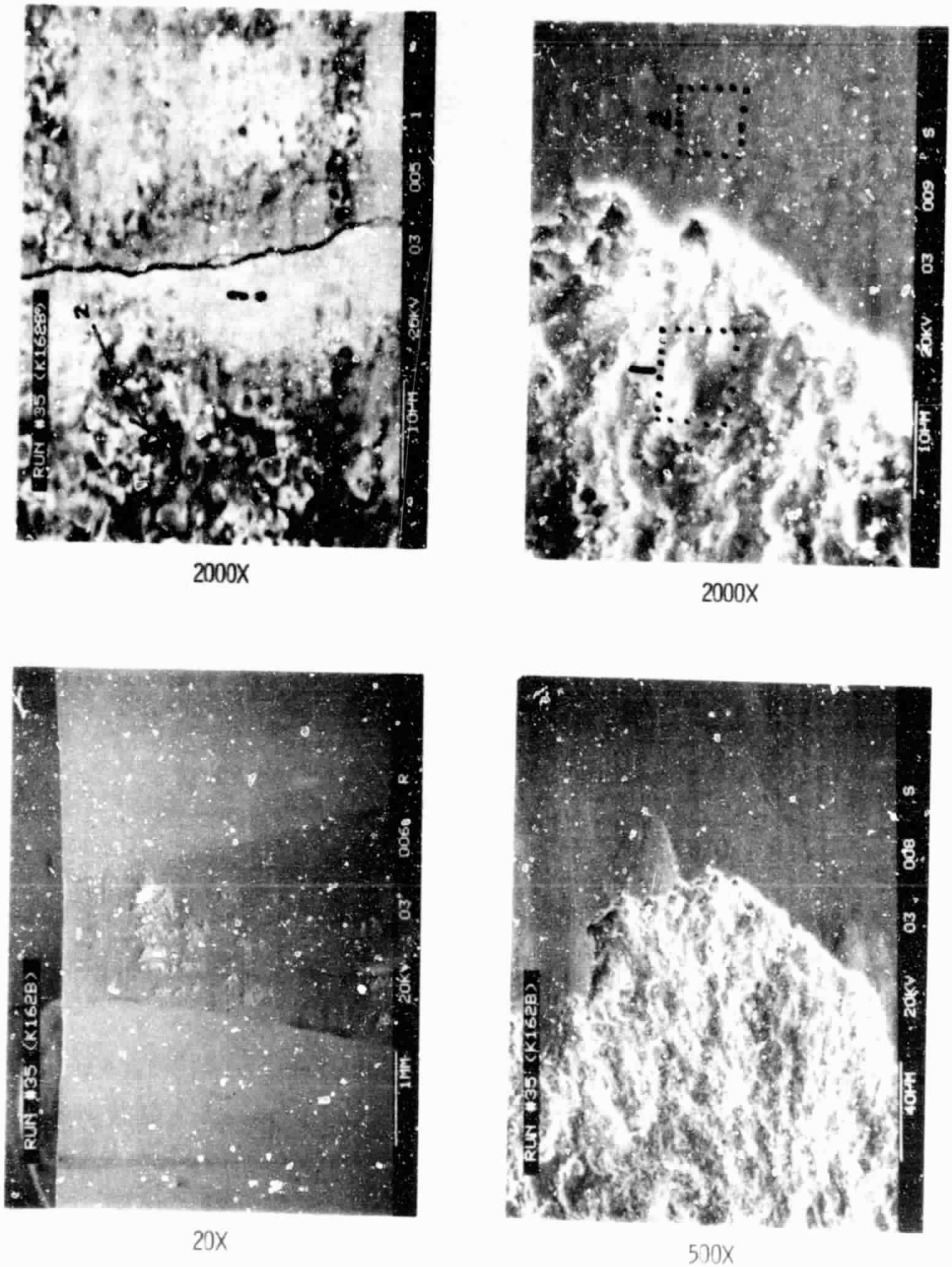


Fig. 5.9—SEM photographs of K-162B (TiC) stationary block operating against SiC rotor - run #35 - 1200°F - 5000 rpm

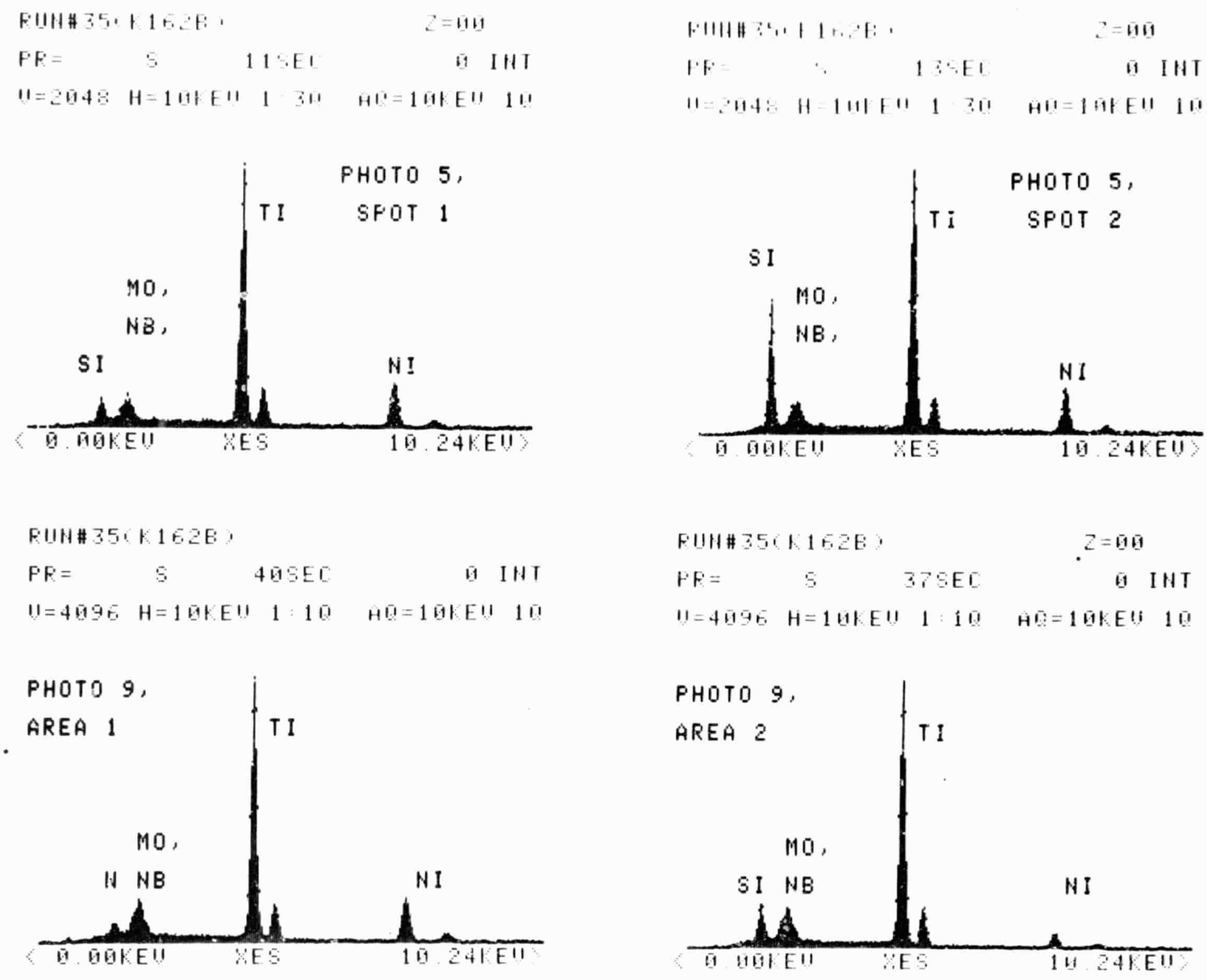
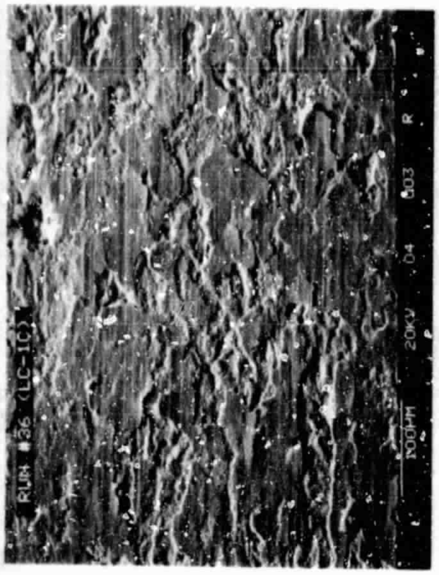
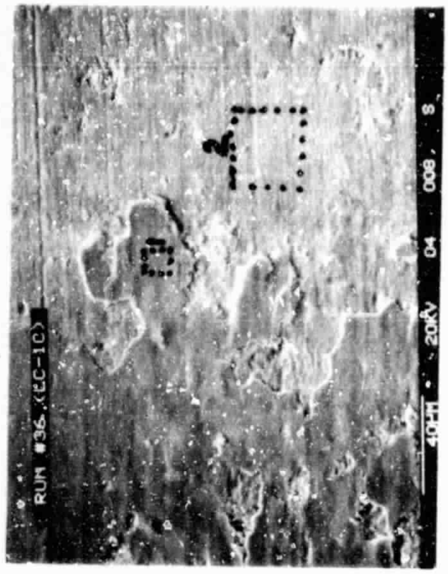


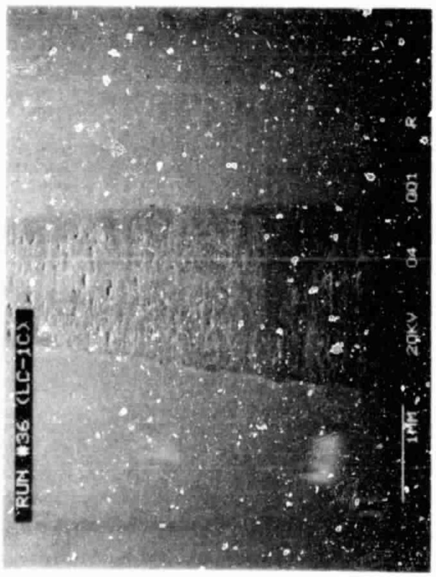
Fig. 3.10—Emission dispersive x-ray analyses of K-162B stationary block-run #35 - 650°C (1200°F)



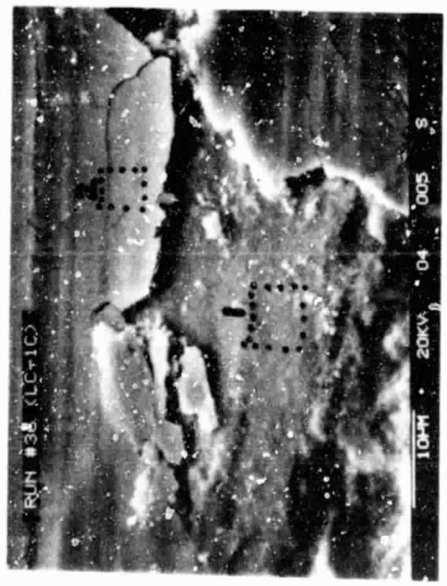
200X



500X



20X



2000X

Fig. 3.11—SEM photographs of LC-1C hard faced (chromium carbide) stationary block operating against K-162B rotor - run #36 - 1200°F - 5000 rpm

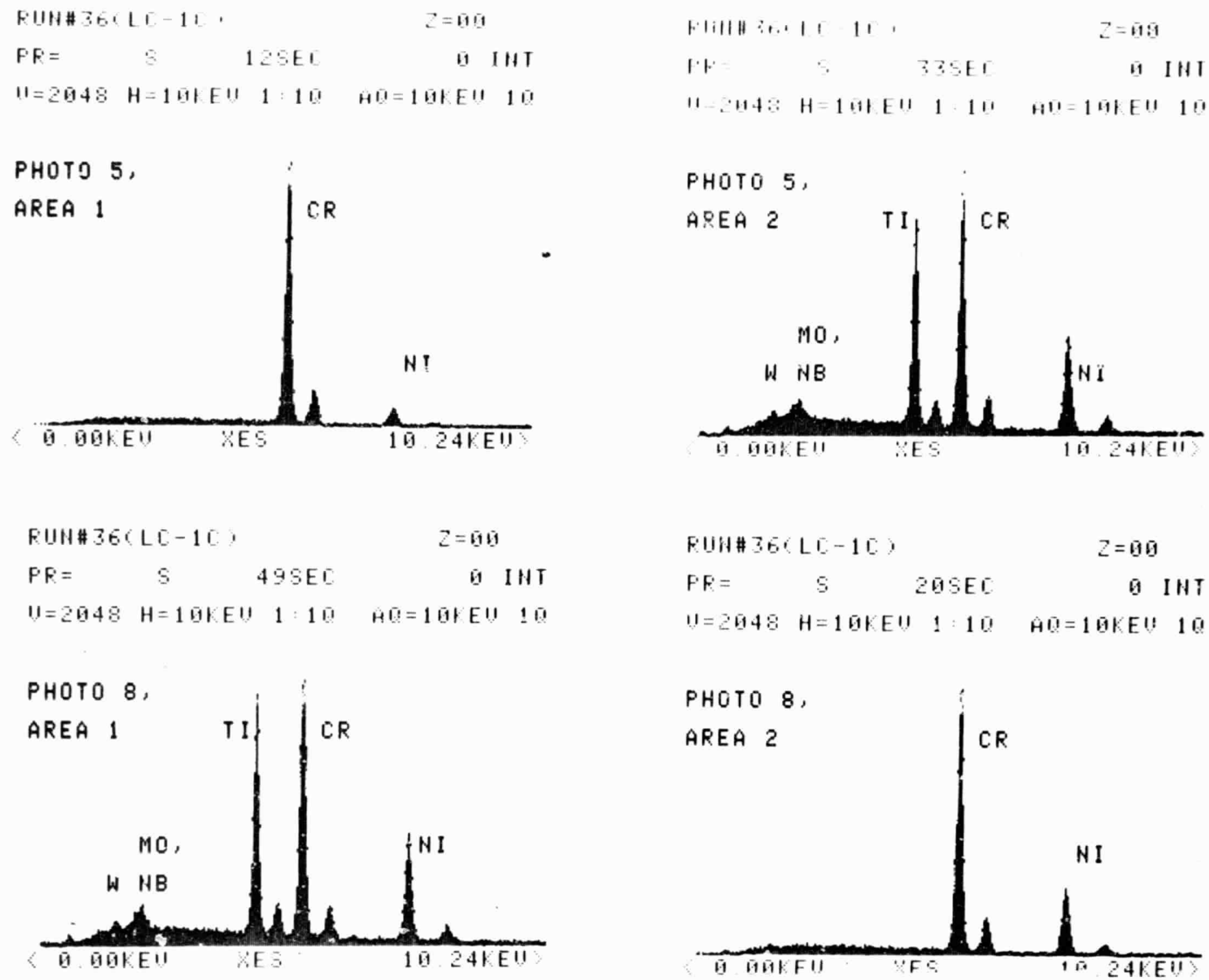


Fig. 3.12—Emission dispersive x-ray analyses of LC-1C hard faced stationary block - run #36 - 650°C (1200°F)

TABLE A-1

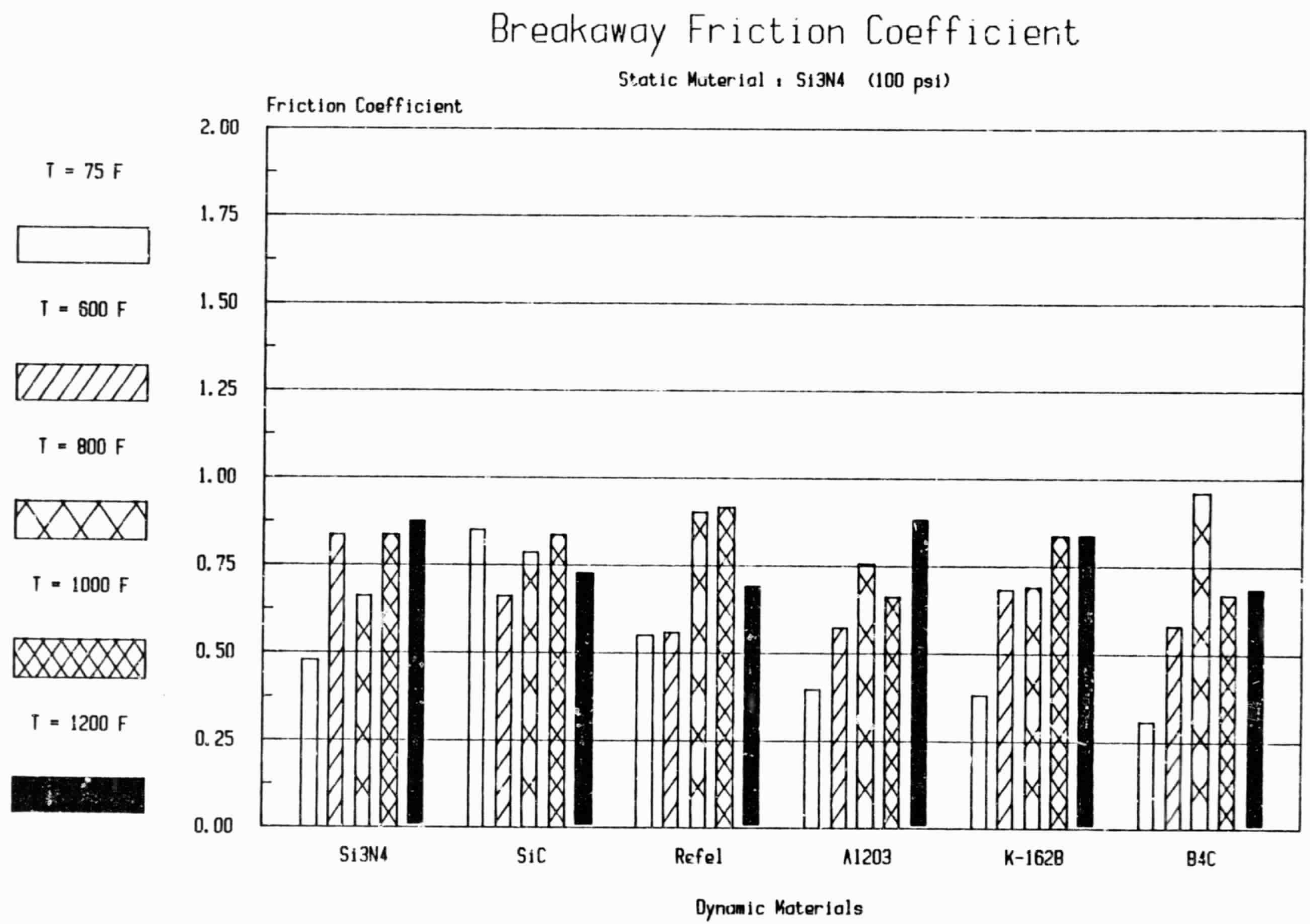

Breakaway Friction Coefficient
Static Material : Si3N4 (100 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al203
K-162B
B4C
Dynamic Materials

TABLE A-2

Breakaway Friction Coefficient

Static Material : Si3N4 (500 psi)

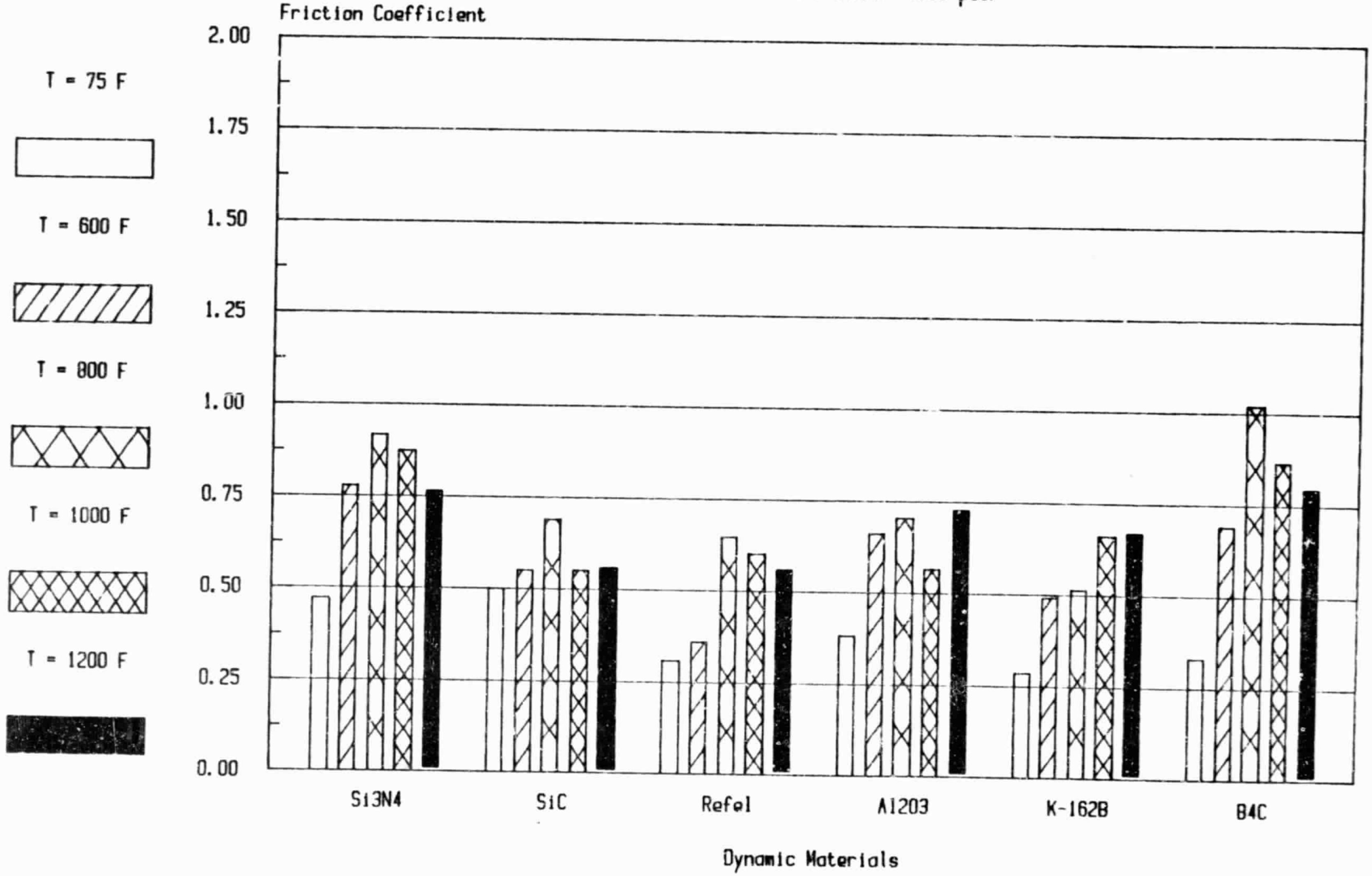
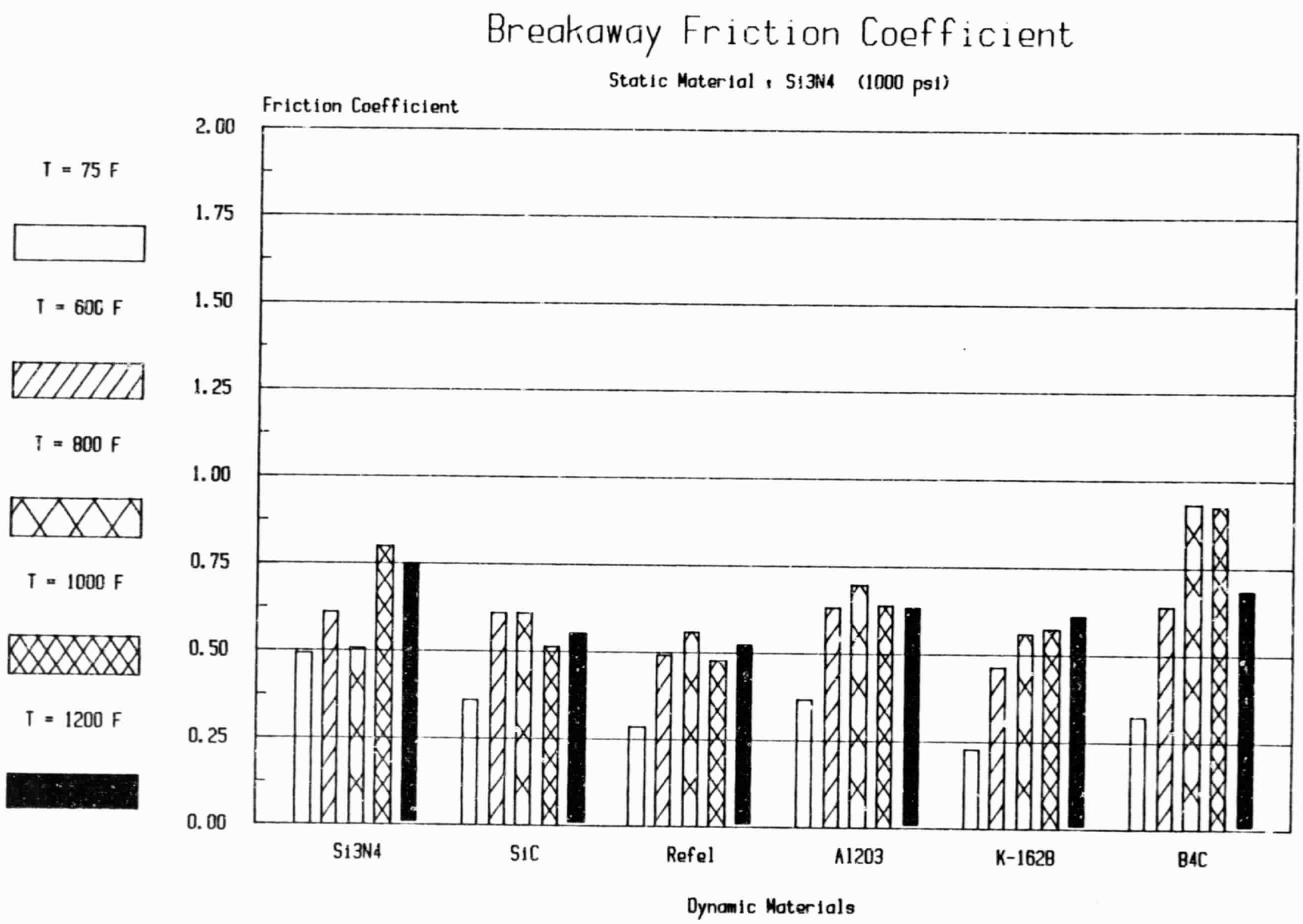
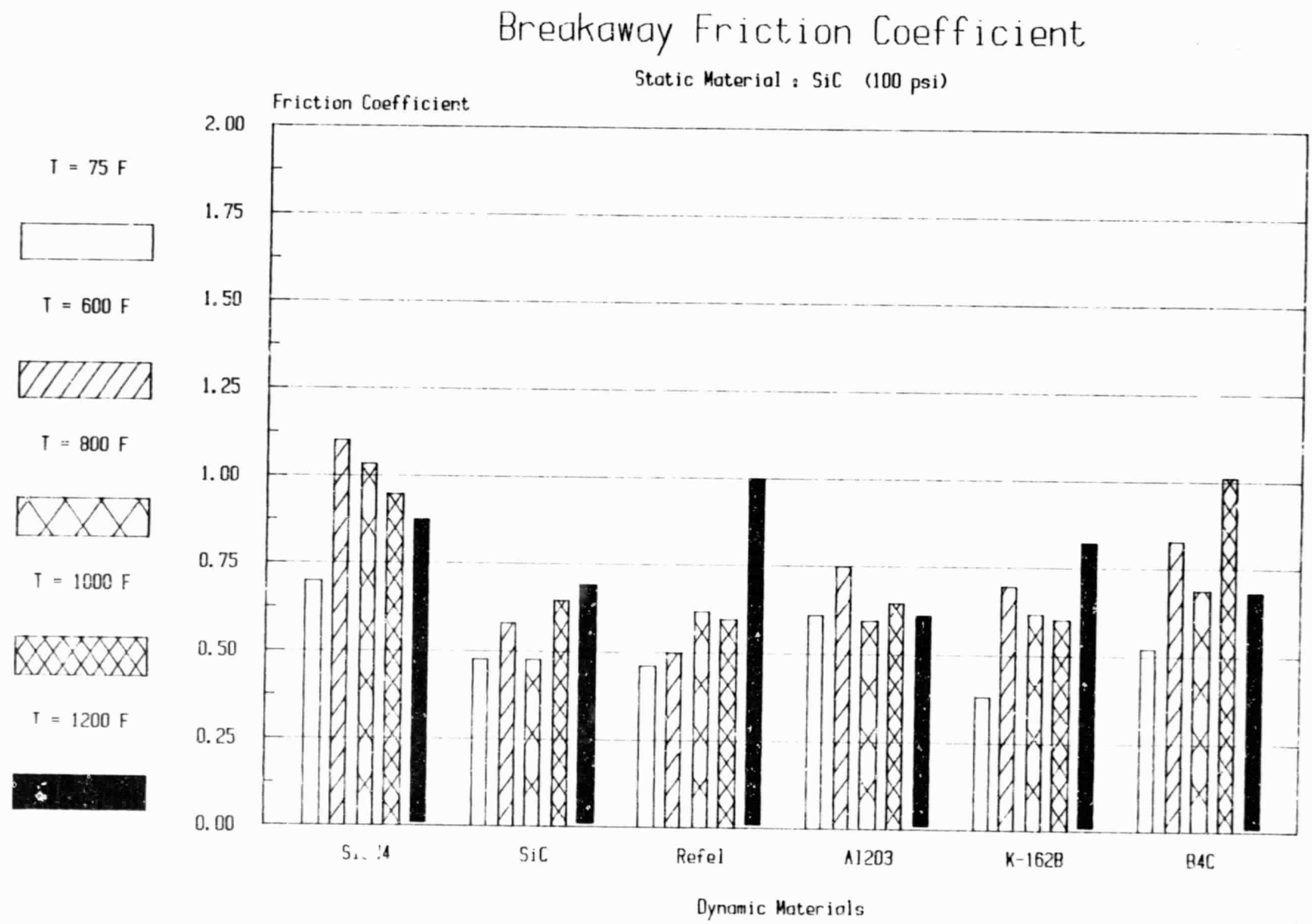


TABLE A-3



Breakaway Friction Coefficient
Static Material : Si3N4 (1000 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al2O3
K-162B
B4C
Dynamic Materials

TABLE A-4



Breakaway Friction Coefficient
Static Material : SiC (100 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
SiC
Refel
Al2O3
K-162B
B4C
Dynamic Materials

TABLE A-5

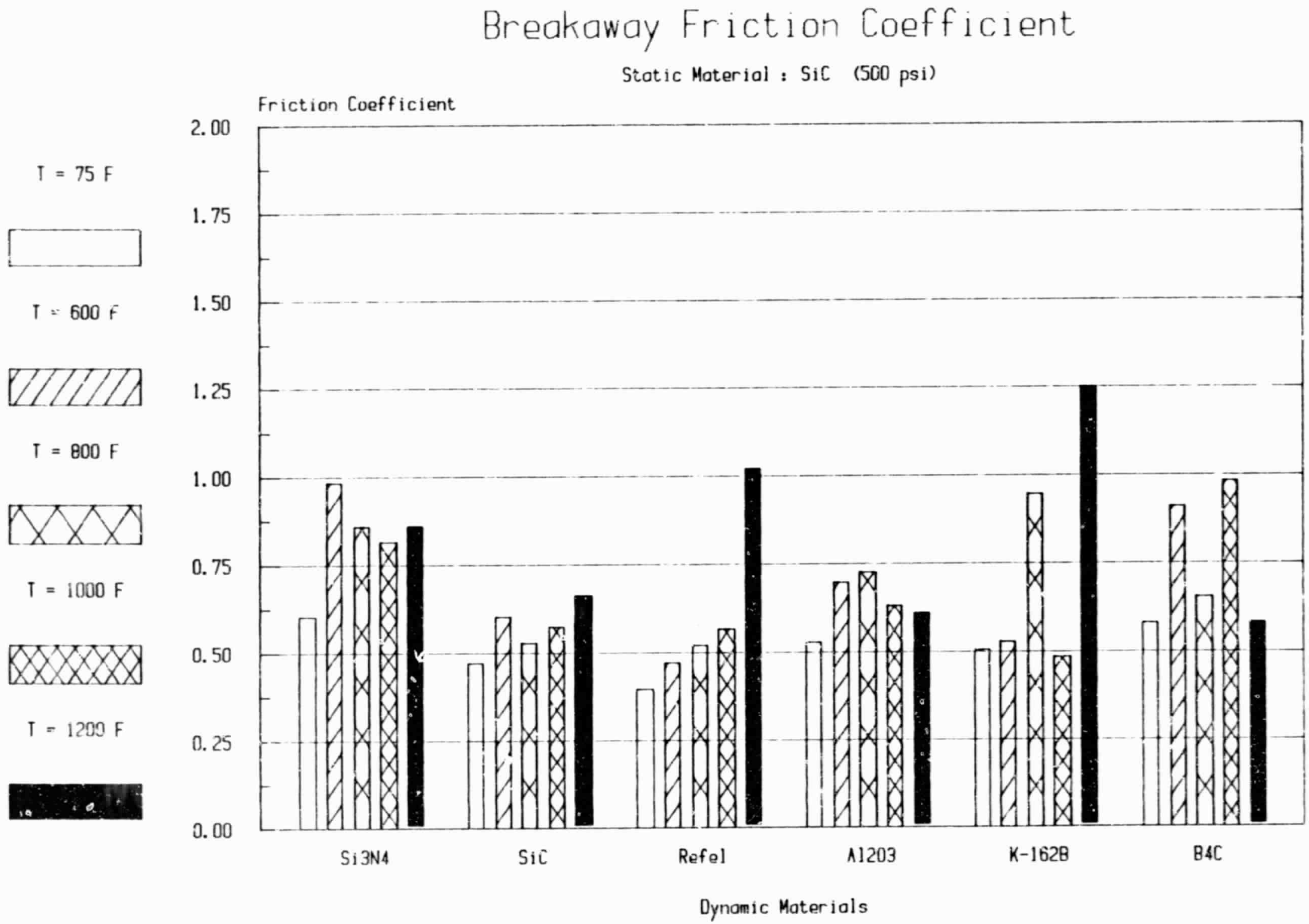
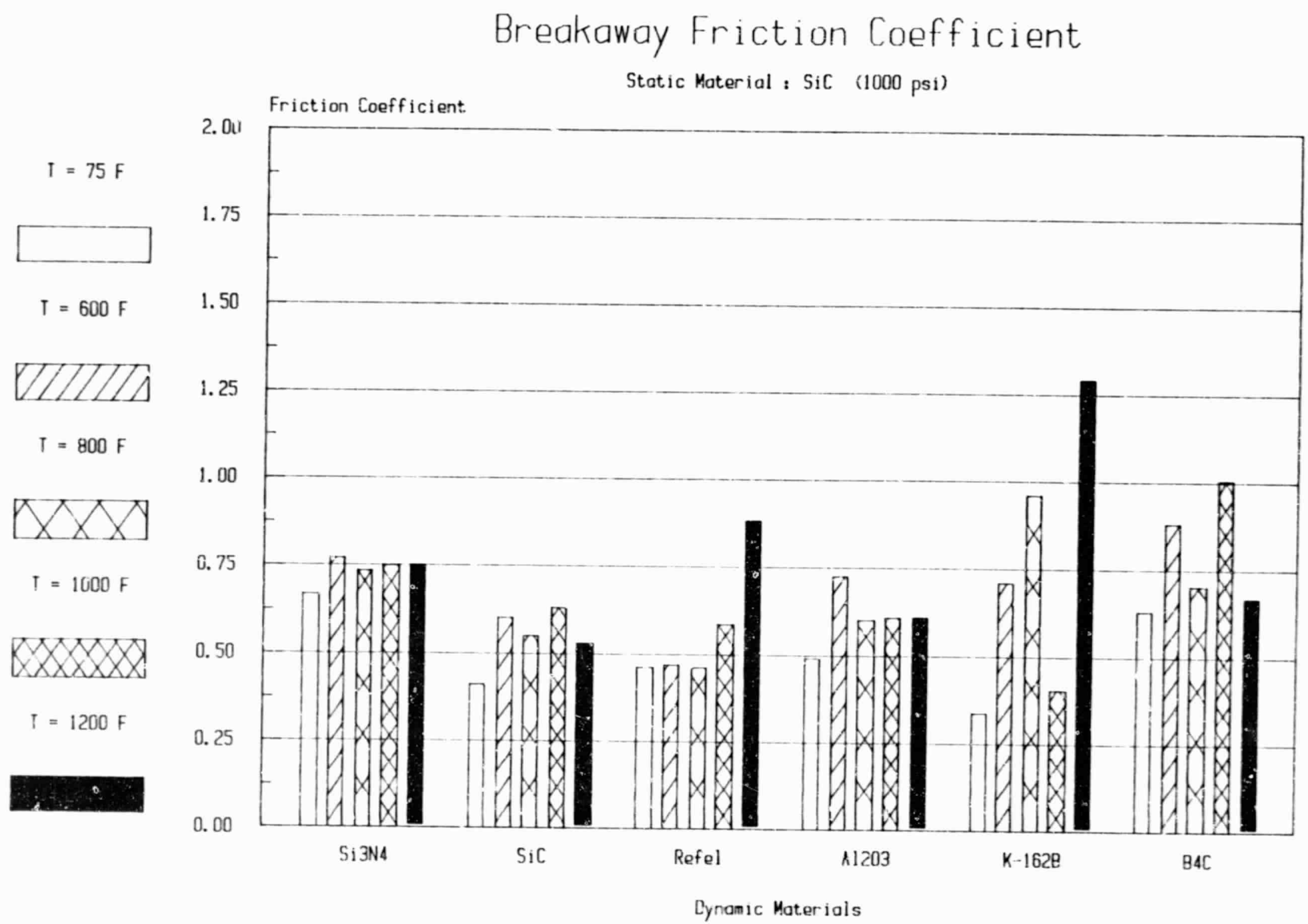

Breakaway Friction Coefficient
Static Material : SiC (500 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al2O3
K-162B
B4C
Dynamic Materials

TABLE A-6



Breakaway Friction Coefficient
Static Material : SiC (1000 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al203
K-162B
B4C
Dynamic Materials

TABLE A-7

Breakaway Friction Coefficient

Static Material : Refel (100 psi)

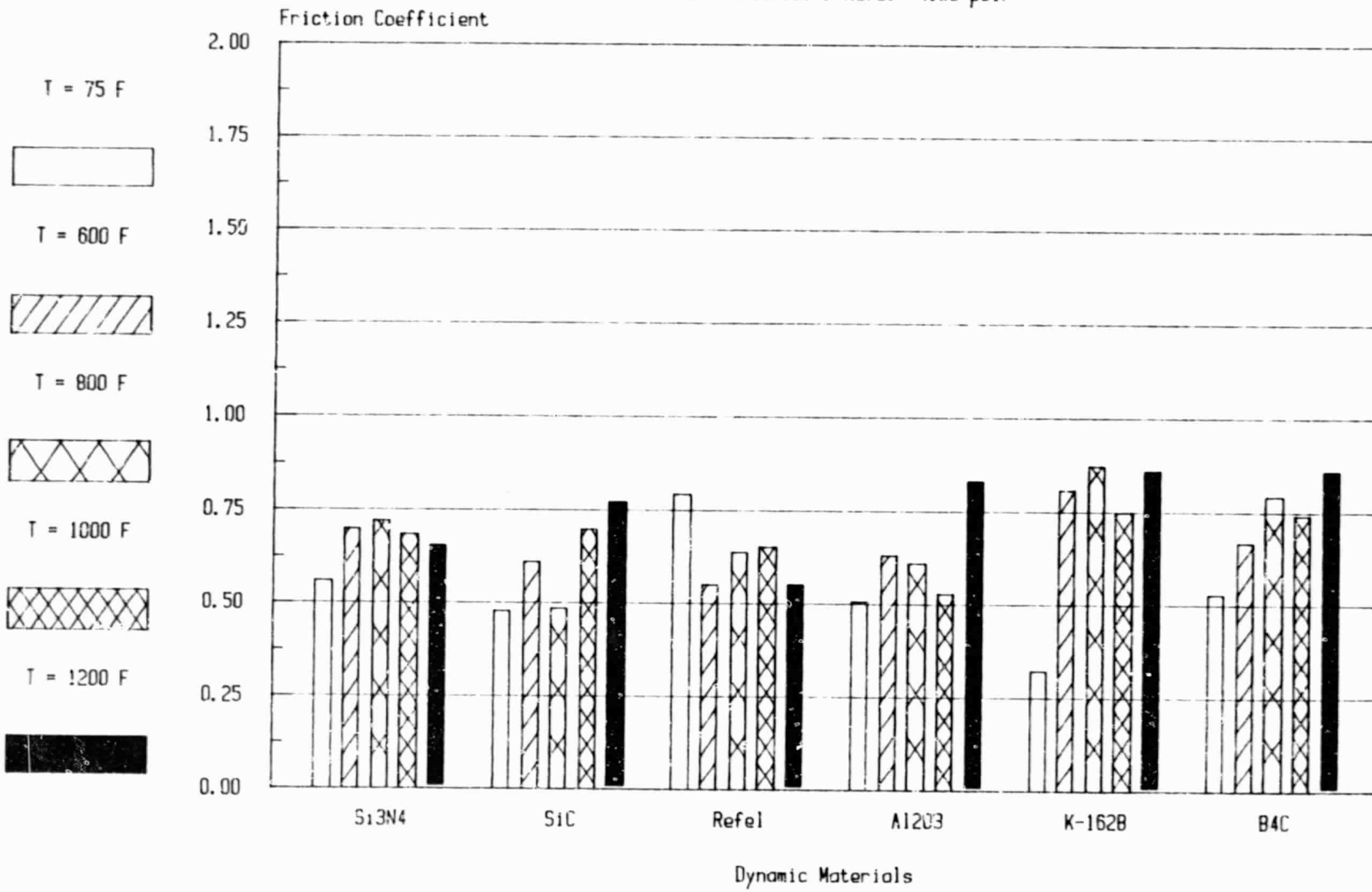
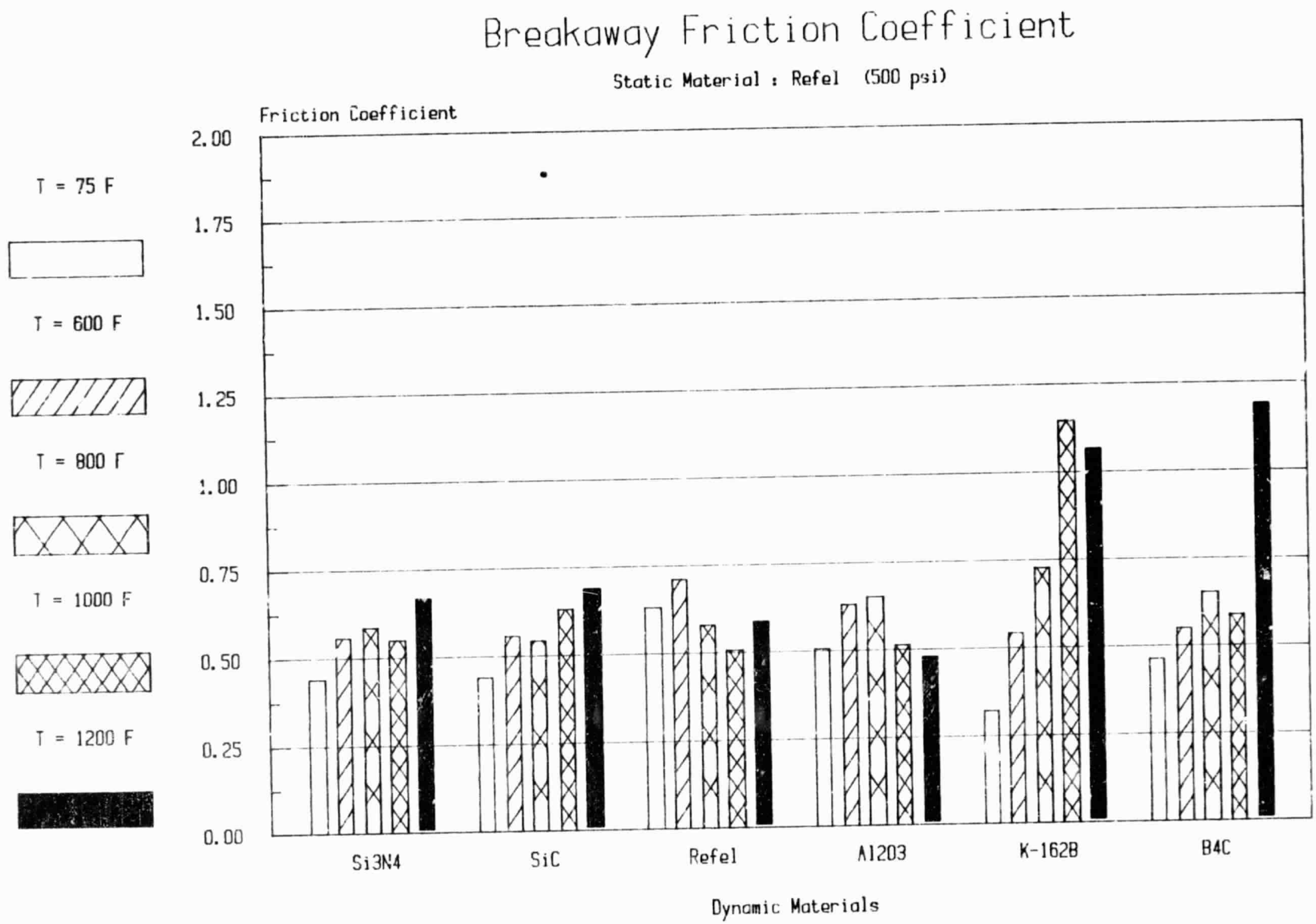


TABLE A-8



Breakaway Friction Coefficient
Static Material : Refel (500 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al203
K-162B
B4C
Dynamic Materials

TABLE A-9

Breakaway Friction Coefficient

Static Material : Refel (1000 psi)

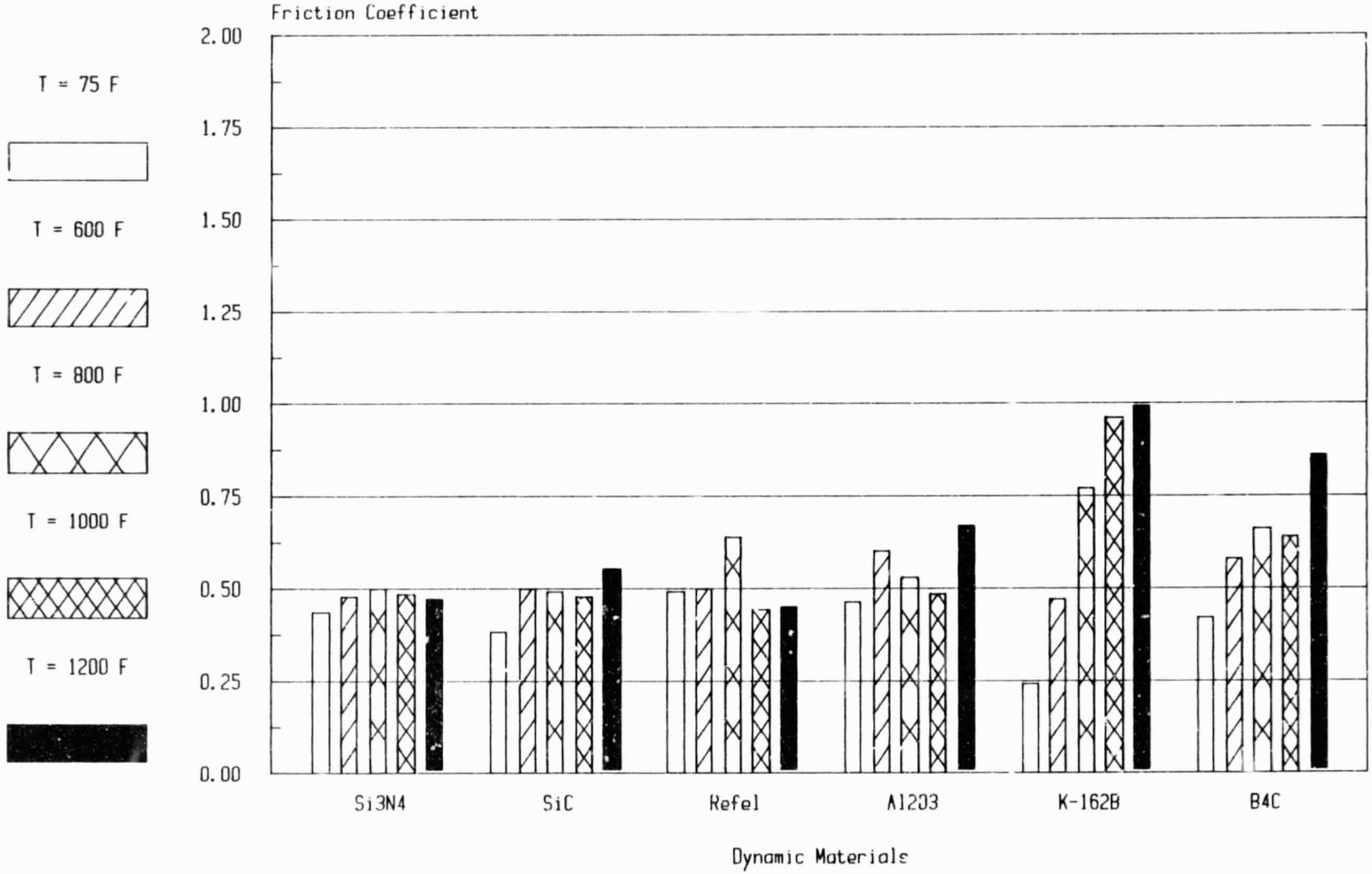
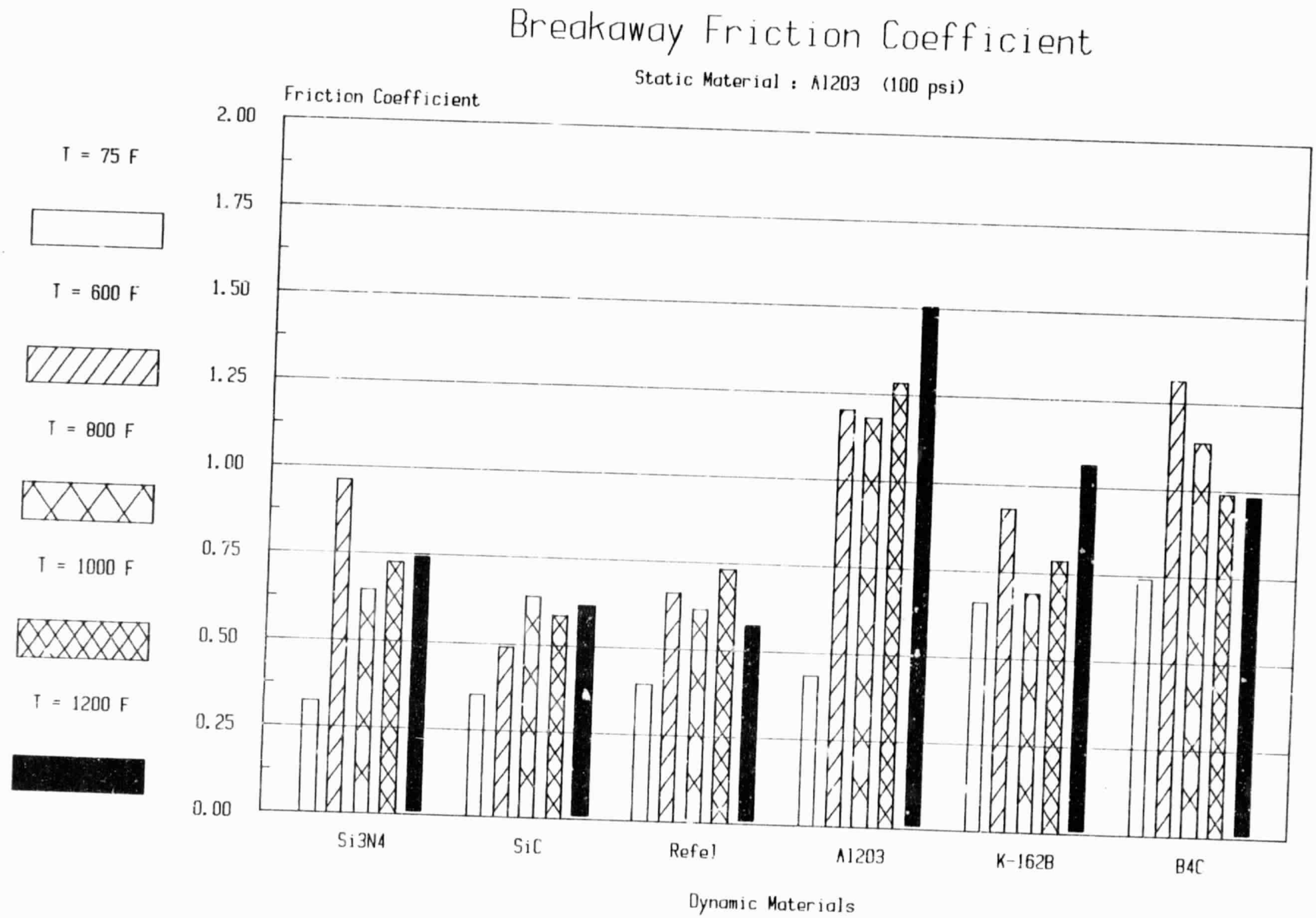
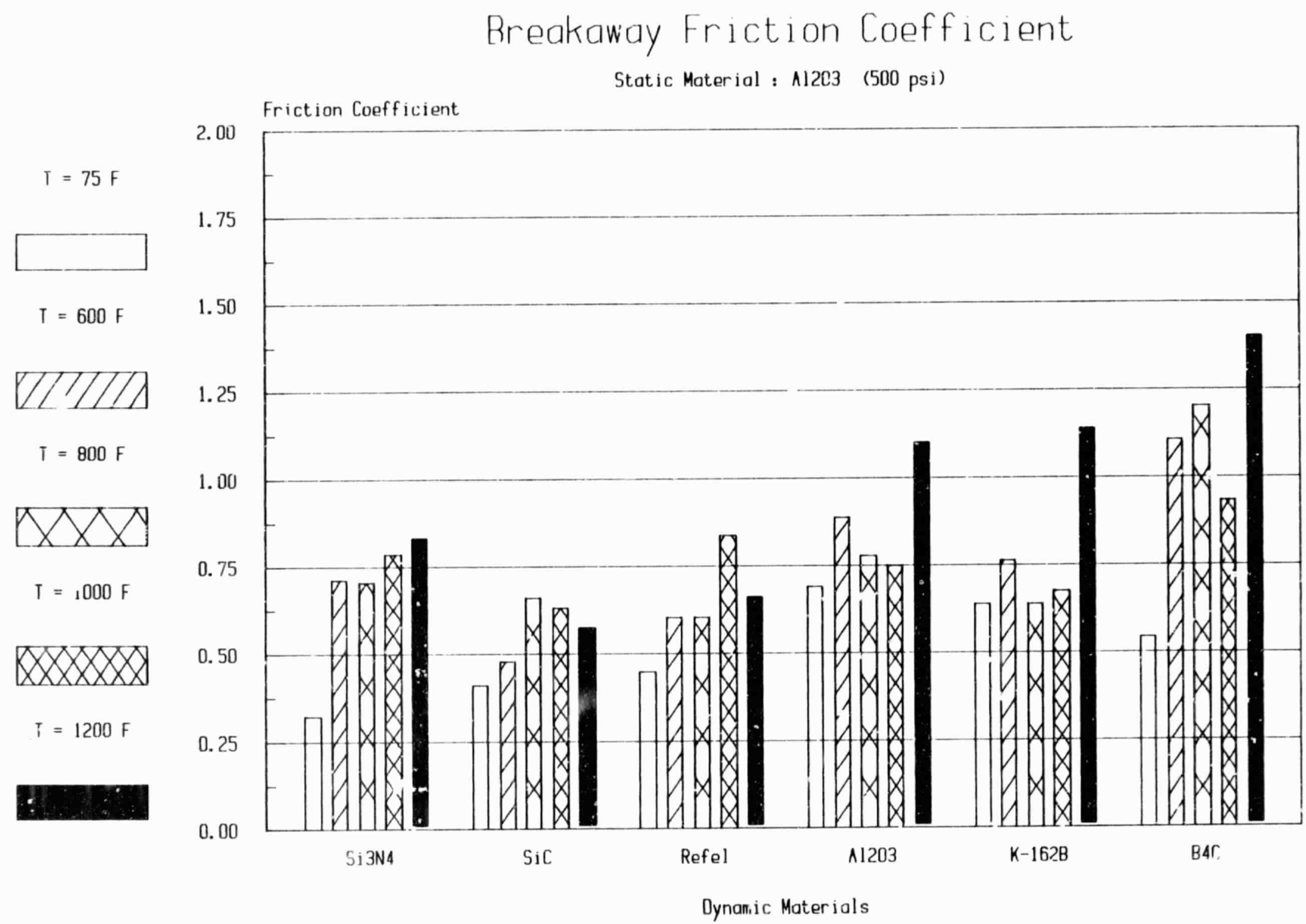


TABLE A-10



Breakaway Friction Coefficient
Static Material : Al203 (100 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al203
K-162B
B4C
Dynamic Materials

TABLE A-11



Breakaway Friction Coefficient
Static Material : Al2O3 (500 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al2O3
K-162B
B4C
Dynamic Materials

TABLE A-12

Breakaway Friction Coefficient

Static Material : Al203 (1000 psi)

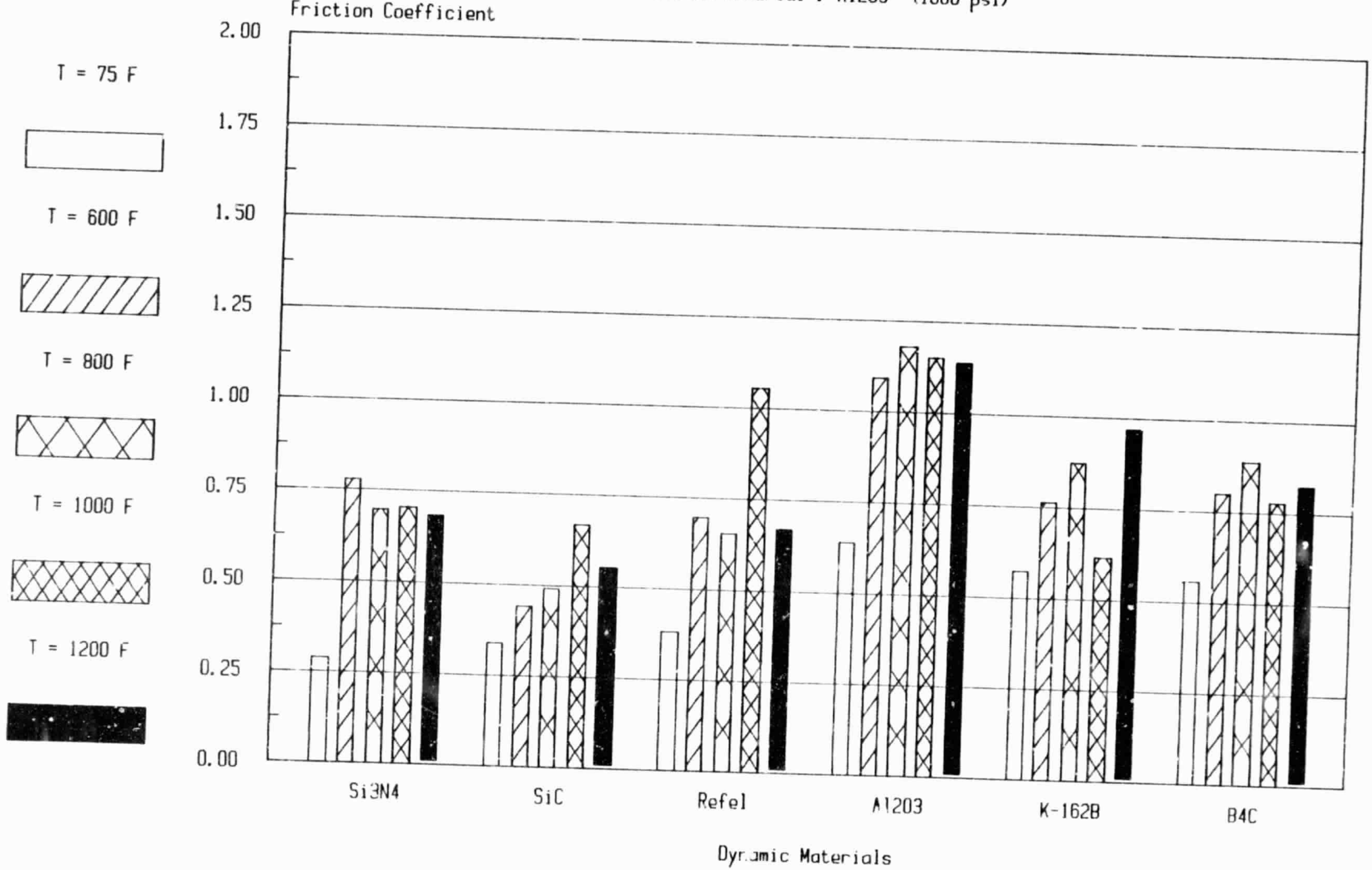


TABLE A-13

Breakaway Friction Coefficient

Static Material : K-162B (100 psi)

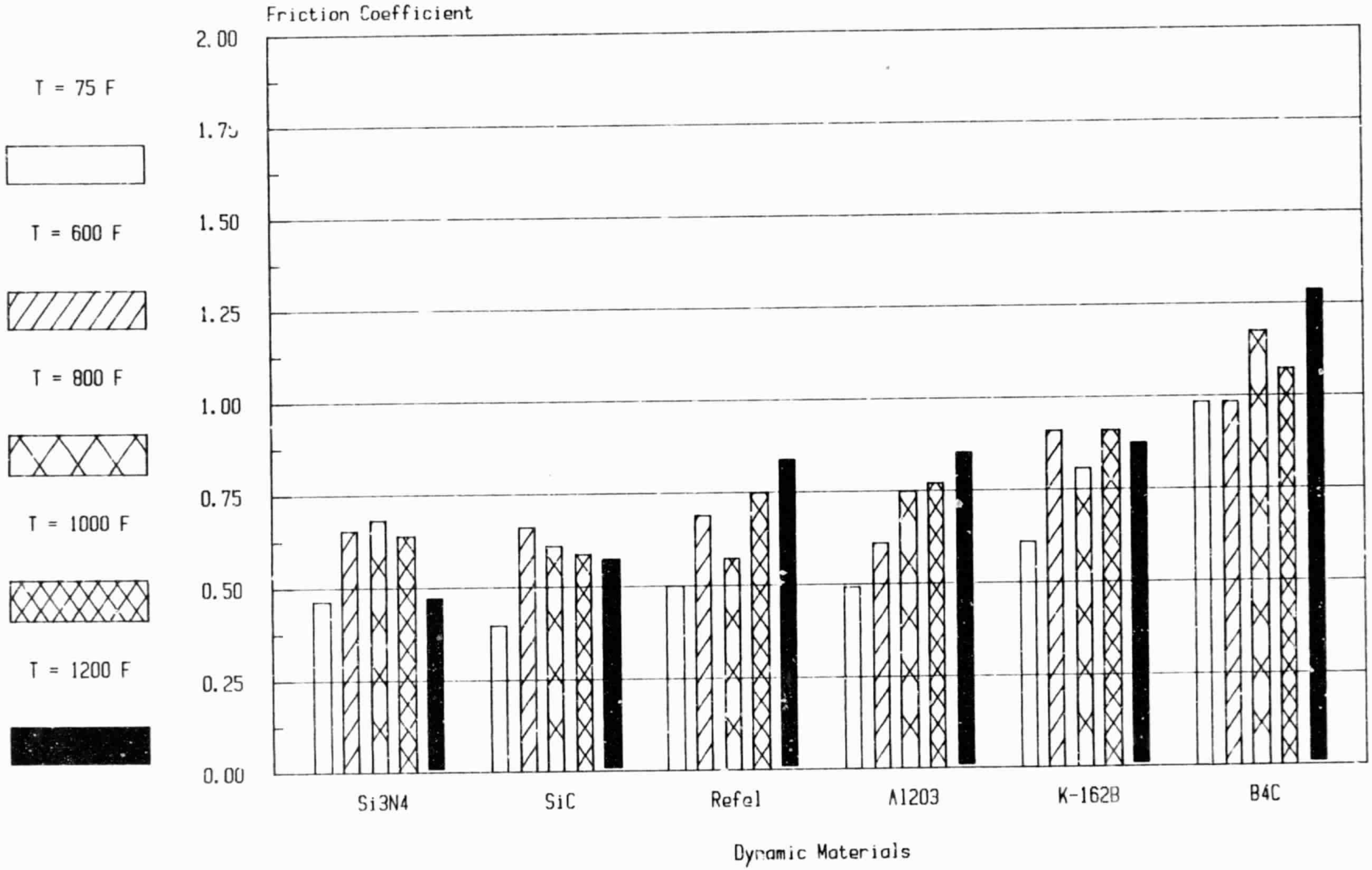
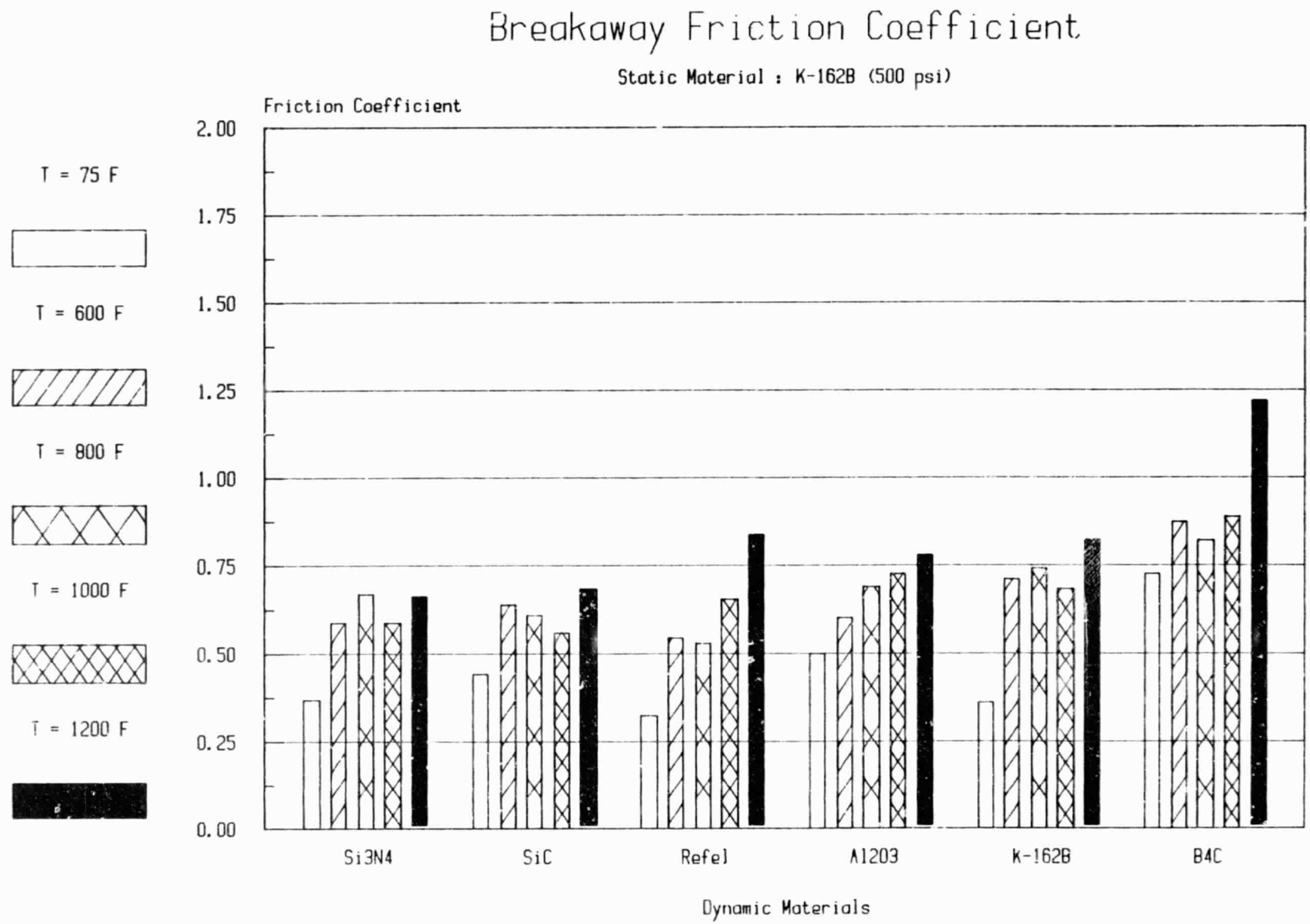


TABLE A-14



Breakaway Friction Coefficient
Static Material : K-162B (500 psi)
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Si3N4
SiC
Refel
Al203
K-162B
B4C
Dynamic Materials

TABLE A-15

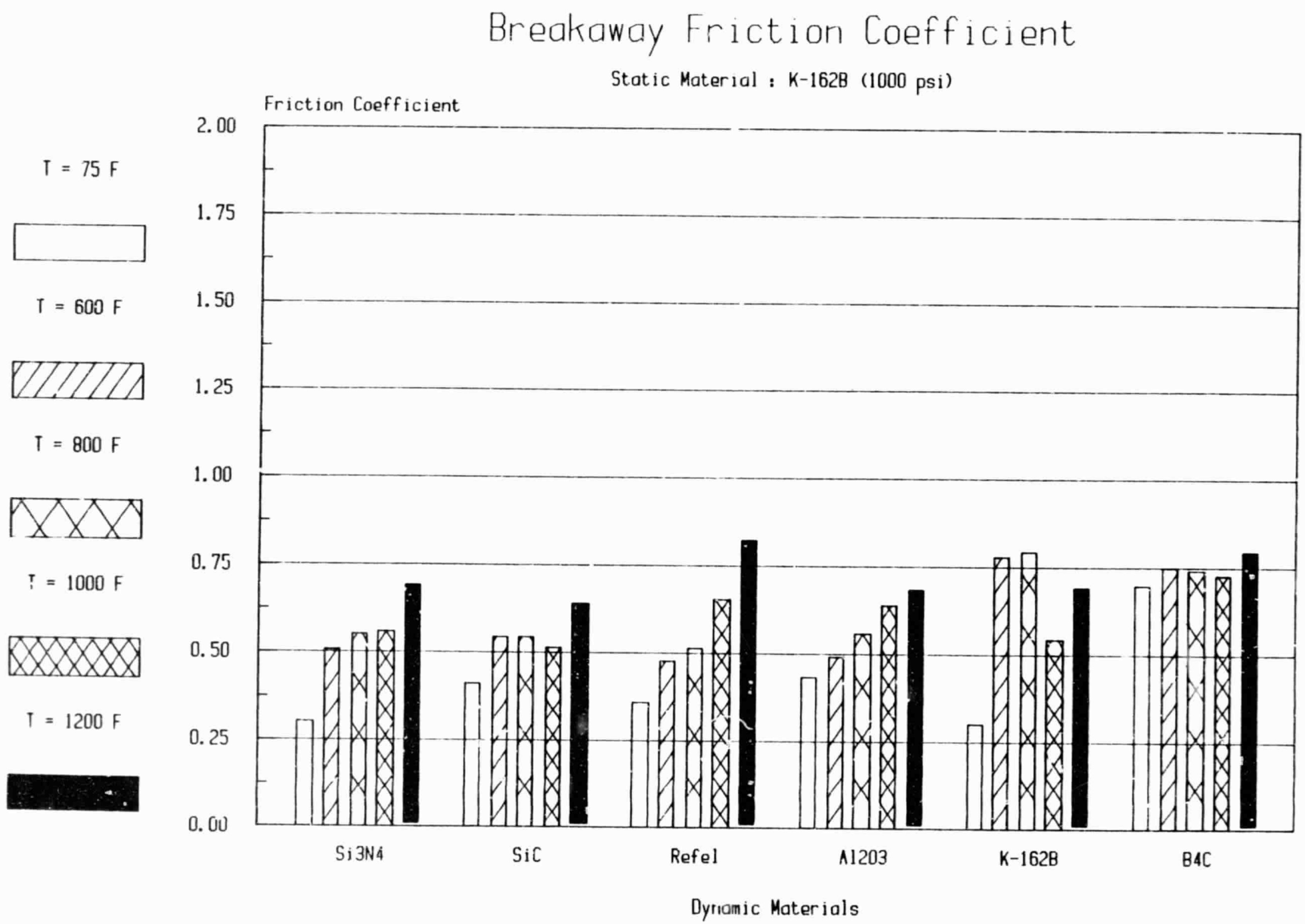
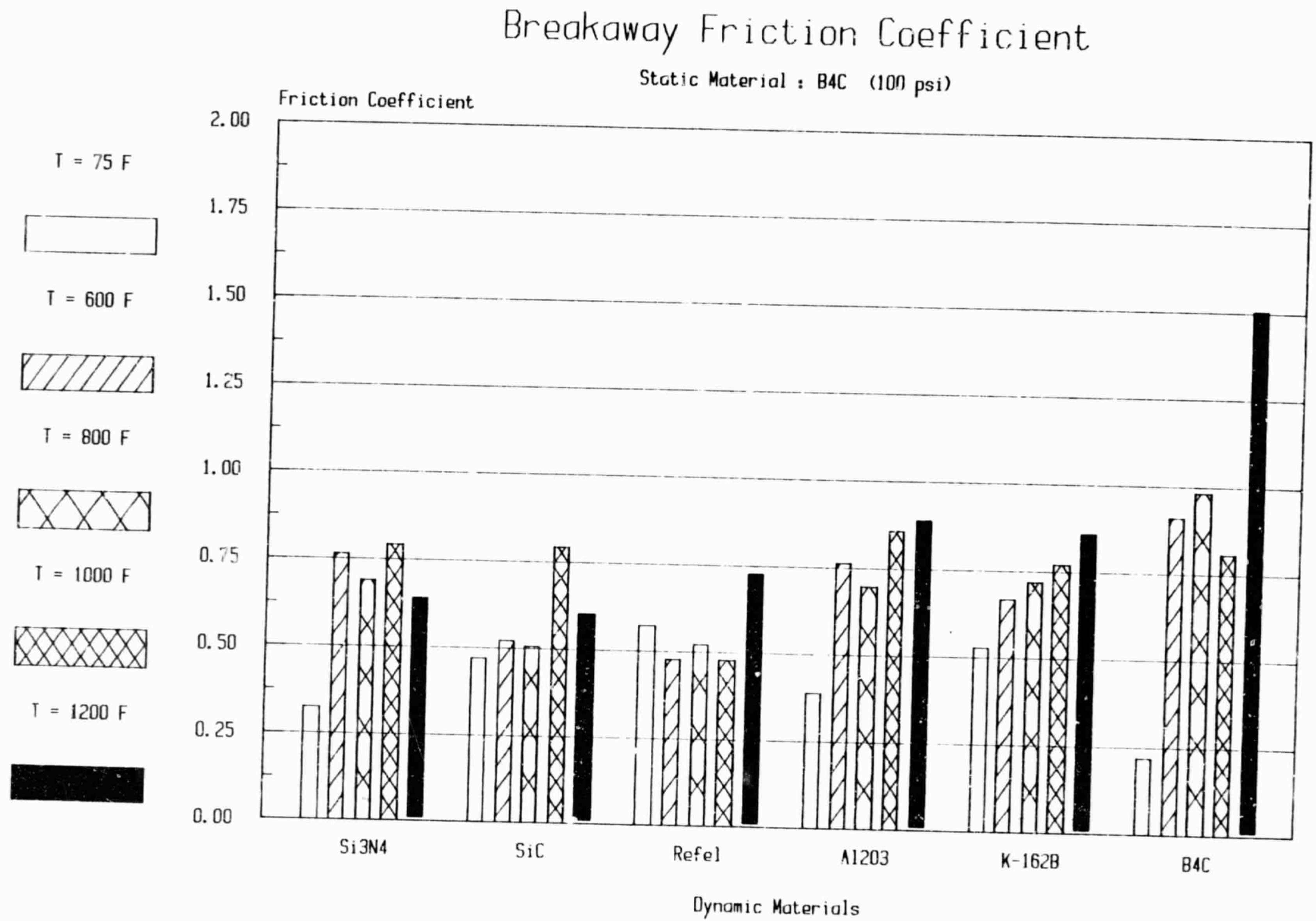

Breakaway Friction Coefficient
Static Material : K-162B (1000 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al203
K-162B
B4C
Dynamic Materials

TABLE A-16



Breakaway Friction Coefficient
Static Material : B4C (100 psi)
Friction Coefficient
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
T = 75 F
T = 600 F
T = 800 F
T = 1000 F
T = 1200 F
Si3N4
SiC
Refel
Al203
K-162B
B4C
Dynamic Materials

TABLE A-17

Breakaway Friction Coefficient

Static Material : B4C (500 psi)

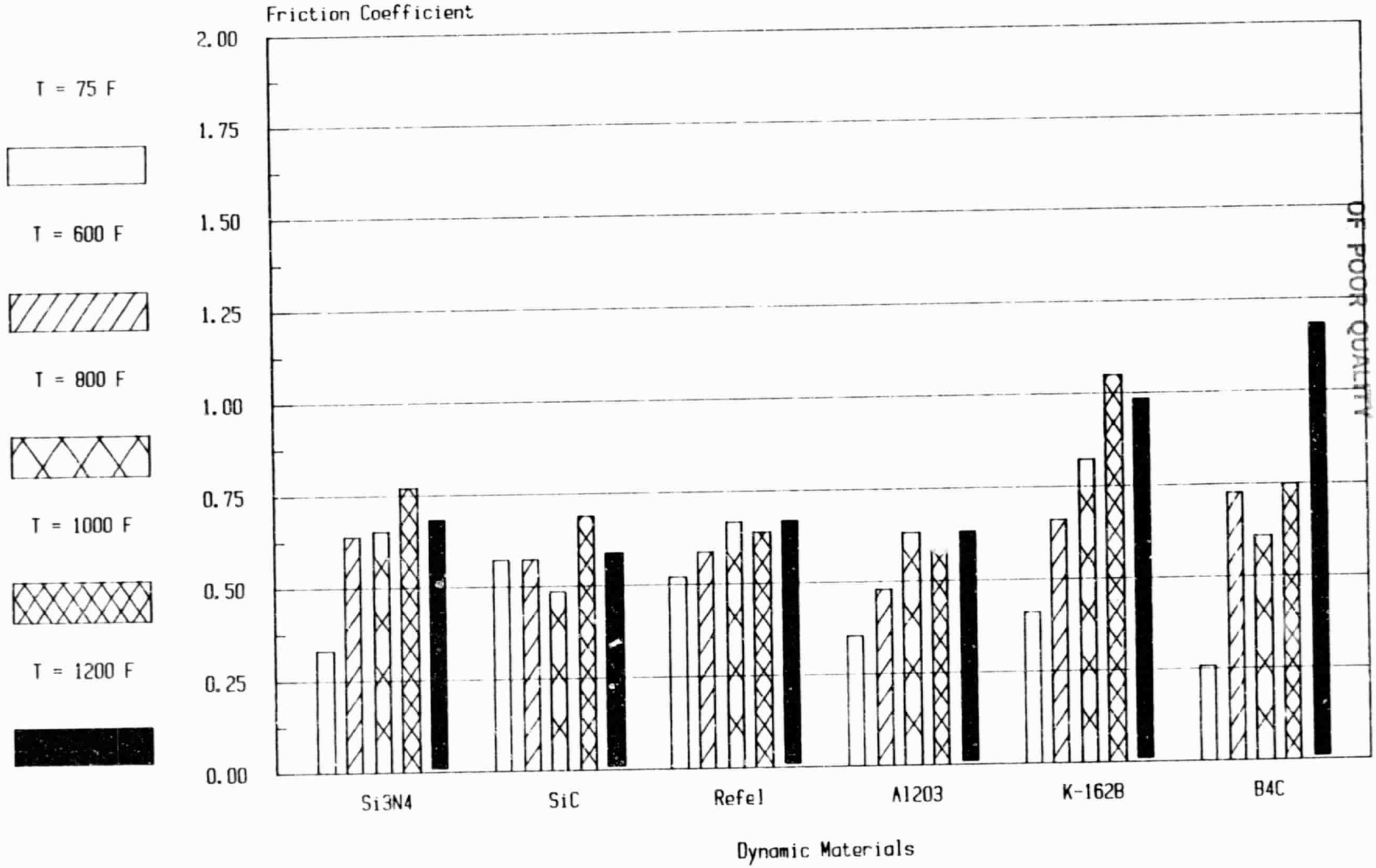


TABLE A-18

Breakaway Friction Coefficient

Static Material : B4C (1000 psi)