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FOREWORD

This interlaboratory measurement activity was made possible through the cooperation of a number of U.S. universities, industrial organizations, and government laboratories: Advanced Mechanical Technology, ALCOA, Argonne National Laboratory, Carborundum, Falex, Georgia Institute of Technology, GTE, Kodak, Midwest Research Institute, Massachusetts Institute of Technology, National Institute of Standards and Technology, Naval Research Laboratory, Oak Ridge National Laboratory, Pennzoil, Stevens Institute of Technology, and United Technology Research Center.

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1. EXECUTIVE SUMMARY

An interlaboratory measurement comparison was carried out among 16 U.S. tribology laboratories as part of a larger effort involving six countries within the VAMAS Wear Test Method Activity. This report provides a summary of the results reported by the U.S. laboratories, as they were made available to NIST which acted as the U.S. coordinating laboratory. This interlaboratory measurement round was the second such effort. The summary of the results of the first effort has been published previously [1,2]. At the conclusion of the first round, it was decided by the Wear Test Method Steering Group to carry out a second round to examine additional material pairs and also to investigate some different test conditions: a lower test load, and the use of a lubricant in the sliding contact region.

It was found in Round 2 that the test and measurement methods were well established (in agreement with Round 1), and that they were applicable to additional material combinations. Some problems were identified: differences among the test machines used, difficulty in measuring small wear volumes on some disk specimens, low load conditions showed more variability in wear and friction results, and lubricated conditions should involve higher loads and longer sliding distances.

The results of these two interlaboratory studies are being used in the process of developing a U.S. standard for pin-on-disk wear tests through the ASTM Committee G-2 on Wear and Erosion. That standard is currently in the process of achieving consensus agreement on the test method.

2. BACKGROUND OF VAMAS

In June 1982 the Versailles Summit Meeting of the Heads of States or Governments of Canada, France, Federal Republic of Germany, Italy, Japan, United Kingdom, United States of America, and the Commission of European Communities, among some 18 other project activities established a Project on Advanced Materials and Standards (VAMAS). The aim of VAMAS was to foster international collaborative projects aimed at providing the technical basis for drafting codes of practice and specifications for advanced materials. Examples would include advanced ceramics and composites that require a better understanding of properties and performance for innovative applications. It was thought that joint measurement activities at an early stage would foster cooperation among the countries, and help to remove restrictions and barriers to trade and development. VAMAS has as a stated purpose:

> "To stimulate the introduction of advanced materials into high technology products and engineering structures through international agreement on codes of practice and on performance standards, and through multilateral research aimed at furnishing the enabling scientific and metrological base necessary to achieve agreement on such standards".

Since 1982 VAMAS has initiated 14 Technical Working Areas as shown in Table 1. One of the first was the Working Group on Wear Test Methods. That group began planning work in Vancouver, Canada, in April 1985, under

Table 1. <u>VAMAS Technical Working Area</u>

1. Wear Test Methods
2. Surface Chemical Analysis
3. Ceramics
4. Polymer Blends
5. Polymer Composites
6. Superconducting and Cryogenic Structural Materials
7. Bioengineering Materials
8. Hot Salt Corrosion Resistance
9. Weld Characteristics
10. Materials Databanks
11. Creep Crack Growth
12. Efficient Test Procedures for Polymer Properties
13. Low Cycle Fatigue
14. Technical Basis for a Unified Classification System for Advanced Ceramics

the leadership of Prof. Horst Czichos, Bundesanstalt fur Materialprufung, F.R. Germany. The Group agreed then on a purpose:

- to formulate necessary conditions for conducting meaningful laboratory wear tests
- to perform comparative interlaboratory studies on selected advanced tribological materials
- to determine appropriate parameters of standard wear testing

Participants in that initial planning meeting are identified in Table 2. A survey was carried out within the group and including other established tribology laboratories, to determine the most commonly used tribology test method. This was identified to be unlubricated sliding using the pin-on-disk method. Plans were then laid for conducting interlaboratory tests on a set of materials that would be provided by members of the group. The countries involved and the number of participants in each country are identified in Table 3. Results of the first round of tests have been published [1,2] and are summarized in the next section.

Table 2. Participants in Initial VAMAS Wear Test Method Group Meeting (Vancouver, Canada)

Members of Working Party:

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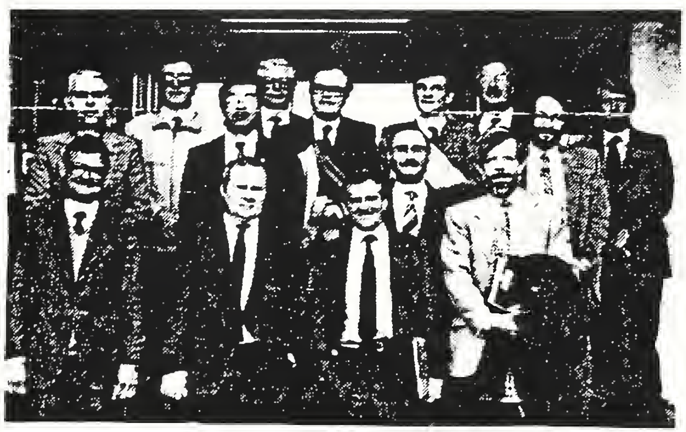

Table 3. Countries and Number of Participants for VAMAS Working Group on Wear Test Methods (August 1987)

Canada (4)

France (5)

FR Germany (4)

Italy (8)

Japan (6)

United Kingdom (5)

United States (10)

3. SUMMARY OF RESULTS FROM ROUND 1

It was agreed by the members of the Wear Test Method Group to conduct specific tests on one "advanced material", aluminum oxide, and one traditional material, AISI type 52100 bearing steel. The materials were provided to each laboratory in the form of disks and balls with the characteristics given in Table 4. The wear tests carried out utilized pin-on-disk apparatus in each laboratory where the specimen ball would be rigidly held against the rotating specimen disk. Both friction and wear were measured and reported. Test parameters were: load 10 N, sliding speed 0.1 m/s, temperature 23 C, and sliding distance 1 km.

Results from the interlaboratory tests (Round 1) are shown in Table 5. Reproducibility of friction and wear values was judged to be good in terms of usual tribological data; it ranged from about 10 - 20 % for friction, and from about 5 - 20 % for specimen (linear) wear loss. Two areas of concern were identified: effect of humidity level in the test atmosphere, and the effect of test machine differences in geometry and stiffness. A total of 9 U.S. laboratories and 22 other laboratories participated in Round 1 of the VAMAS Working Group.

Table 4. <u>Characterization of the Wear Test Samples</u>

	Composition (wt.%)	Texture	R_z (mean) (μm)	R_a (mean) (μm)	Hardness (HV 10)
Steel ball (100Cr6) (AISI 52100)[a]	0.95 - 1.10 C 0.15 - 0.35 Si 0.25 - 0.45 Mn	martensitic with minor carbides and austenite	0.100	0.010	838 ± 21
Steel disc (100Cr6) (AISI 52100)[b]	< 0.030 P < 0.030 S 1.35 - 1.65 Cr		0.952	0.113	852 ± 14
Alumina ball[c]	95 (Al_2O_3 with additives of TiO_2, MgO and ZnO)	equigranular alpha-alumina with very minor secondary phases	1.369	0.123	1610 ± 101 HV 0.2
Alumina disc[c]			0.968	0.041	1599 ± 144 HV 0.2

[a]Standard ball-bearing balls (SKF).
[b]Standard spacers for thrust bearings (INA).
[c]Manufactured by C.I.C.E. S.A.

Table 5. Interlaboratory Test Results from Round No. 1

Results of the round robin tests (AISI 52100 steel, α-Al_2O_3 ceramic, $F_N = 10$ N, $v = 0.1$ m s^{-1}, $T = 23$ °C, relative humidity 12% - 78%)

	Kit 1	*Kit 2*	*Kit 3*	*Kit 4*
	Steel–steel	*Ceramic–steel*	*Steel–ceramic*	*Ceramic–ceramic*
Coefficient of friction[a]	0.60 ± 0.11	0.76 ± 0.14	0.60 ± 0.12	0.41 ± 0.08
Number of data	109	75	64	76
Number of laboratories	26	26	23	26
Wear rate of system (μm km^{-1})[b]	70 ± 20	very small	81 ± 29	very small
Number of data	47		29	
Number of laboratories	11		11	
Ball wear scar diameter (mm)	2.11 ± 0.27	[c]	2.08 ± 0.35	0.3 ± 0.05
Number of data	102		60	56
Number of laboratories	23		21	19
Disc wear track width (mm)	[d]	0.64 ± 0.13	[d]	not measured
Number of data		54		
Number of laboratories		19		

[a]At 1000 m sliding distance.
[b]Determined from the wear curve (steady state range between 300 and 1000 m sliding distance).
[c]Material transfer from disc to ball.
[d]Material transfer from ball to disc.

4. MEASUREMENT PLAN FOR ROUND 2

A total of 16 U.S. laboratories agreed to participate in a second round as shown in Table 6 (the total world group was comprised of 38 laboratories). The U.S. group was divided into three sub-groups in order to carry out three different types of tests. The plan for standard test conditions was similar to that used in Round 1 except a new material was added, and a desired humidity level during the test was identified. The materials also used in Round 1 were AISI 52100 steel (HV 830 - 860), and alumina (95% Al_2O_3, balance TiO_2, MgO, ZnO; HV 1500 - 1700). The test material added for Round 2 was hot pressed silicon nitride (85% Si_3N_4, 8% Y_2O_3, 5% Al_2O_3; HV 1500 - 1800). A humidity of 50 ± 10 % (relative) was specified for the test environment. The other test parameters were: load 10 N, sliding speed 0.1 m/s, temperature 23 C, and sliding distance 1 km. Additional details on specimen size, cleaning methods, wear measurement methods, and reporting procedures are given in Appendix A along with an example of a data sheet and a list of the material combinations studied. Five U.S. laboratories followed this standard test plan.

Additional tests were defined for the two other sub-groups of U.S. laboratories involving low load conditions and lubricated conditions. The purpose was to determine whether the test method could be used under a wider range of conditions. One sub-group of 6 laboratories used a load of 2 N with otherwise the same test conditions. Another sub-group of 4 laboratories used the standard test parameters but with a supply of highly purified paraffin oil lubricant provided to the sliding contact zone.

Table 6. U. S. Participants in Wear Test Method Round 2

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5. RESULTS: STANDARD TEST CONDITIONS

Individual data sets are listed in Appendix B for each of the five U.S. laboratories that carried out the tests under the specified (standard) conditions. A summary of all Round 2 results is given in Table 7. For standard condition tests, Table 8 collects the individual raw data and gives the results of an analysis of those data. The analysis is divided into five groups, one for each of the specimen pairs. Average values and standard deviations for average friction, ball wear volume, disk wear volume, and total wear volume are given. Note that the standard deviation is calculated using the small sample method since n=4 in most cases. Graphical presentation of the friction data is shown in Fig.1 and the wear data in Fig.2. Ball wear volume was calculated using the approximate formula shown on the data sheet, Appendix A. Disk wear volume was to be calculated by measuring the average wear track cross-profile, computing the average cross-section area of the wear track, and multiplying by the mid-track circumference. The principal findings are:

(a) The lowest average friction coefficient is about 0.5 for the steel/steel couple.

(b) With ceramic/metal or ceramic/ceramic couples, the average friction coefficient is larger, about 0.7.

(c) Variability of average friction coefficient is large, typically about 15% for all combinations.

(d) The average ball wear volume is smallest for the mixed ceramic/ceramic couple and for steel/silicon nitride.

Table 7. Summary of Results for All Test Conditions

MATLS. BALL/ DISK	BALL MATERIAL	DISK MATERIAL	LOAD N	LUBE (YES/NO)	FRICTION AVERAGE	FRICTION SD	BALL WEAR VOL AVERAGE	BALL WEAR VOL SD	DISK WEAR VOL AVERAGE	DISK WEAR VOL SD	TOTAL WEAR VOL AVERAGE	TOTAL WEAR VOL SD
SN/SN	Si3N4	Si3N4	10.00	NO	0.64	0.09	0.0942	0.0108	0.1512	0.0775	0.2454	0.0883
SN/ALOX	Si3N4	AL203	10.00	NO	0.71	0.10	0.0436	0.0293	0.0579	0.0719	0.1015	0.1012
st/SN	AISI52100	Si3N4	10.00	NO	0.64	0.08	0.0267	0.0265	0.1032	0.0330	0.1299	0.0595
SN/st	Si3N4	AISI52100	10.00	NO	0.68	0.14	0.0826	0.0258	0.0899	0.0800	0.1725	0.1058
st/st	AISI52100	AISI52100	10.00	NO	0.51	0.12	0.1633	0.0796	0.0622	0.0745	0.2255	0.1541
SN/SN	Si3N4	Si3N4	2.00	NO	0.56	0.18	0.0111	0.0070	0.0404	0.0226	0.0515	0.0296
SN/ALOX	Si3N4	AL203	2.00	NO	0.57	0.20	0.0206	0.0022	0.0072	0.0057	0.0278	0.0079
st/SN	AISI52100	Si3N4	2.00	NO	0.67	0.25	0.0170	0.0164	0.0464	0.0312	0.0634	0.0476
SN/st	Si3N4	AISI52100	2.00	NO	0.55	0.29	0.0172	0.0094	0.0068	0.0066	0.0240	0.0160
st/st	AISI52100	AISI52100	2.00	NO	0.53	0.17	0.0348	0.0171	0.0002	0.0002	0.0350	0.0173
SN/SN	Si3N4	Si3N4	10.00	YES	0.10	0.02	2.44E-04	1.77E-04	0.0E+00	0.0E+00	0.0002	0.0002
SN/ALOX	Si3N4	AL203	10.00	YES	0.10	0.01	4.26E-05	2.24E-05	0.00E+00	0.00E+00	0.0000	0.0000
st/SN	AISI52100	Si3N4	10.00	YES	0.12	0.03	8.42E-04	7.76E-04	0.0E+00	0.0E+00	0.0008	0.0008
SN/st	Si3N4	AISI52100	10.00	YES	0.09	0.02	1.14E-04	6.60E-05	0.0E+00	0.0E+00	0.0001	0.0001
st/st	AISI52100	AISI52100	10.00	YES	0.11	0.02	2.34E-03	1.31E-03	0.0E+00	0.0E+00	0.0023	0.0013
SN/SN	Si3N4	Si3N4	30.00	YES	0.09	0.01	3.20E-04	4.05E-04	0.00E+00	0.00E+00	0.0003	0.0004
SN/ALOX	Si3N4	AL203	30.00	YES	0.09	0.00	1.29E-04	1.50E-05	0.00E+00	0.00E+00	0.0001	0.0000
SN/st	Si3N4	AISI52100	30.00	YES	0.10	0.00	1.34E-04	4.00E-05	0.00E+00	0.00E+00	0.0001	0.0000

Table 8. Summary of Results for Standard Conditions

LAB NUMBER	BALL MATERIAL	DISK MATERIAL	LOAD N	LUBE (YES/NO)	DISTANCE: AVERAGE m	SD m	AVERAGE FRICTION: AVERAGE	SD	WEAR VOLUME (mm^3) BALL: AVERAGE	SD	DISK: AVERAGE	SD	TOTAL: AVERAGE	SD
16	Si3N4	Si3N4	10.00	NO	1000	0	*1.08	*0.11	0.1130	0.0000	0.1185	0.0986	0.2315	0.1560
17	Si3N4	Si3N4	10.00	NO	1000	0	0.55	0.05	0.0863	0.0180	0.0660	0.0282	0.1523	0.0214
19	Si3N4	Si3N4	10.00	NO	1000	0	0.77	0.05	0.0883	0.0133	0.2473	0.0649	0.3357	0.0782
20	Si3N4	Si3N4	10.00	NO	1000	0	0.65	0.04	0.0933	0.0162	2.3461	1.4296	2.4394	1.4455
28	Si3N4	Si3N4	10.00	NO	1003	2	0.60	0.20	0.0902	0.0294	0.1728	0.1037	0.2631	0.1268
						AVG=	0.64	AVG=	0.0942	AVG=	0.5901	AVG=	0.6844	
						SD=	0.09	SD=	0.0108	SD=	0.9839	SD=	0.9833	
16	Si3N4	AL2O3	10.00	NO	1000	0	*1.07	*0.04	0.0557	0.0136	0.0107	0.0006	0.0663	0.0138
17	Si3N4	AL2O3	10.00	NO	1000	0	0.58	0.00	0.0870	0.0000	0.0540	0.0017	0.1410	0.0017
19	Si3N4	AL2O3	10.00	NO	1000	0	0.80	0.04	0.0216	0.0130	0.1607	0.0460	0.1822	0.0590
20	Si3N4	AL2O3	10.00	NO	1000	0	0.77	0.02	0.0403	0.0051	1.7000	0.3365	1.7392	0.3405
28	Si3N4	AL2O3	10.00	NO	1005	7	0.67	0.07	0.0136	0.0105	0.0061	0.0058	0.0198	0.0162
						AVG=	0.71	AVG=	0.0436	AVG=	0.3863	AVG=	0.4297	
						SD=	0.10	SD=	0.0293	SD=	0.7370	SD=	0.7348	
16	AISI52100	Si3N4	10.00	NO	1000	0	*1.04	*0.13	0.0186	0.0022	0.1290	0.0240	0.1476	0.0248
17	AISI52100	Si3N4	10.00	NO	1000	0	0.58	0.00	0.0147	0.0006	0.0903	0.0047	0.1050	0.0053
19	AISI52100	Si3N4	10.00	NO	1000	0	0.72	0.04	0.0739	0.0494	0.1310	0.0078	0.2049	0.0447
20	AISI52100	Si3N4	10.00	NO	1000	0	0.69	0.10	0.0137	0.0025	1.2061	0.2719	1.2198	0.2735
28	AISI52100	Si3N4	10.00	NO	1002	1	0.56	0.06	0.0127	0.0020	0.0624	0.0109	0.0751	0.0101
						AVG=	0.64	AVG=	0.0267	AVG=	0.3238	AVG=	0.3505	
						SD=	0.08	SD=	0.0265	SD=	0.4941	SD=	0.4884	
16	Si3N4	AISI52100	10.00	NO	1000	0	*1.50	*0.28	0.1183	0.0283	0.1713	0.0569	0.2897	0.0852
17	Si3N4	AISI52100	10.00	NO	1000	0	0.66	0.03	0.1000	0.0082	0.0437	0.0012	0.1437	0.0093
19	Si3N4	AISI52100	10.00	NO	1000	0	0.83	0.01	0.0590	0.0123	0.1423	0.0101	0.2013	0.0107
20	Si3N4	AISI52100	10.00	NO	1000	0	0.74	0.05	0.0746	0.0254	2.0800	0.2425	2.1540	0.2176
28	Si3N4	AISI52100	10.00	NO	1002	1	0.49	0.10	0.0612	0.0209	0.0023	0.0040	0.0635	0.0179
						AVG=	0.68	AVG=	0.0826	AVG=	0.4879	AVG=	0.5704	
						SD=	0.14	SD=	0.0258	SD=	0.8927	SD=	0.8891	
16	AISI52100	AISI52100	10.00	NO	1000	0	*1.36	*0.39	0.7895	0.0650	0.1493	0.0908	0.9388	0.1035
17	AISI52100	AISI52100	10.00	NO	1000	0	0.41	0.01	0.1513	0.0075	0.0000	0.0000	0.1513	0.0075
19	AISI52100	AISI52100	10.00	NO	1000	0	0.55	0.03	0.0610	0.0038	0.0993	0.0081	0.1603	0.0102
20	AISI52100	AISI52100	10.00	NO	1000	0	0.65	0.14	0.2510	0.0485	3.2251	1.5412	3.4761	1.5389
28	AISI52100	AISI52100	10.00	NO	1002	1	0.42	0.09	0.1900	0.0139	0.0003	0.0005	0.1903	0.0136
						AVG=	0.51	AVG=	0.2886	AVG=	0.6948	AVG=	0.9834	
						SD=	0.12	SD=	0.2884	SD=	1.4159	SD=	1.4330	

Note: *Value not included in average, SD.

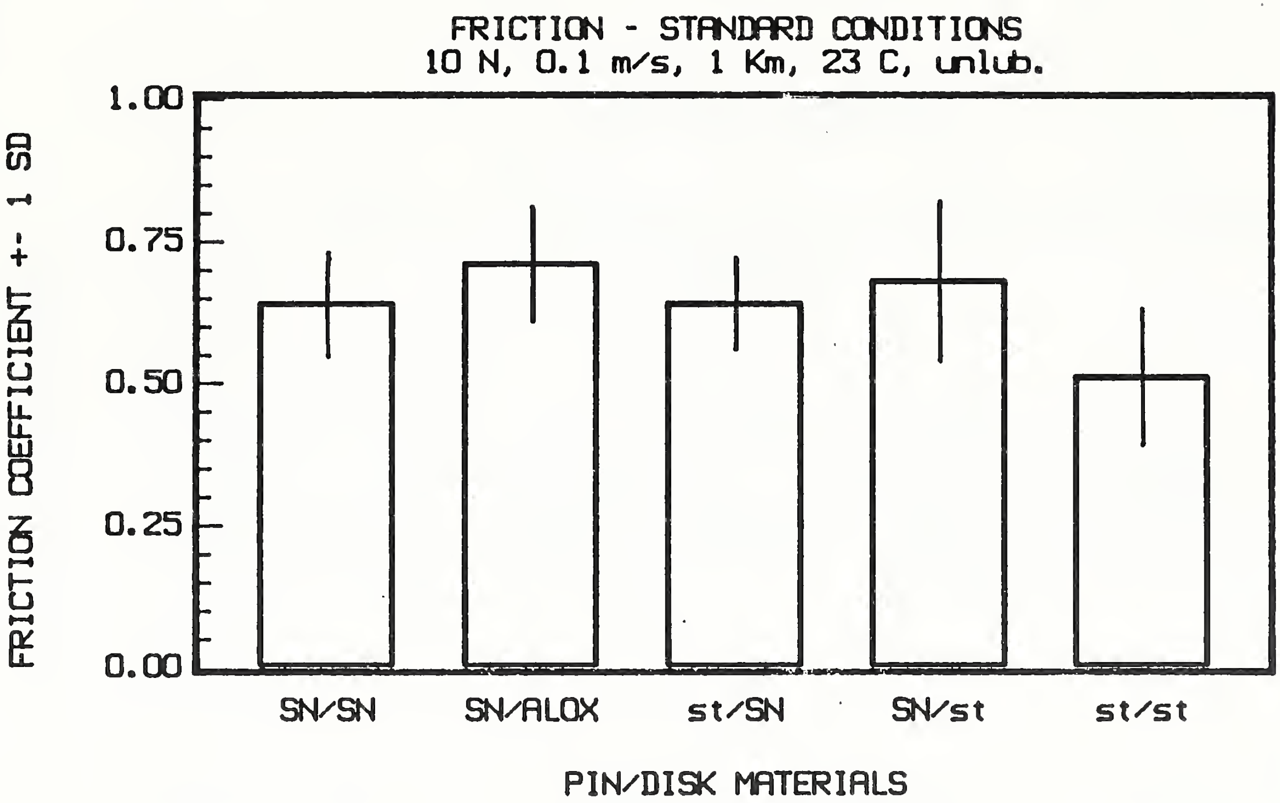


Fig. 1 Summary of friction coefficient results for standard conditions.

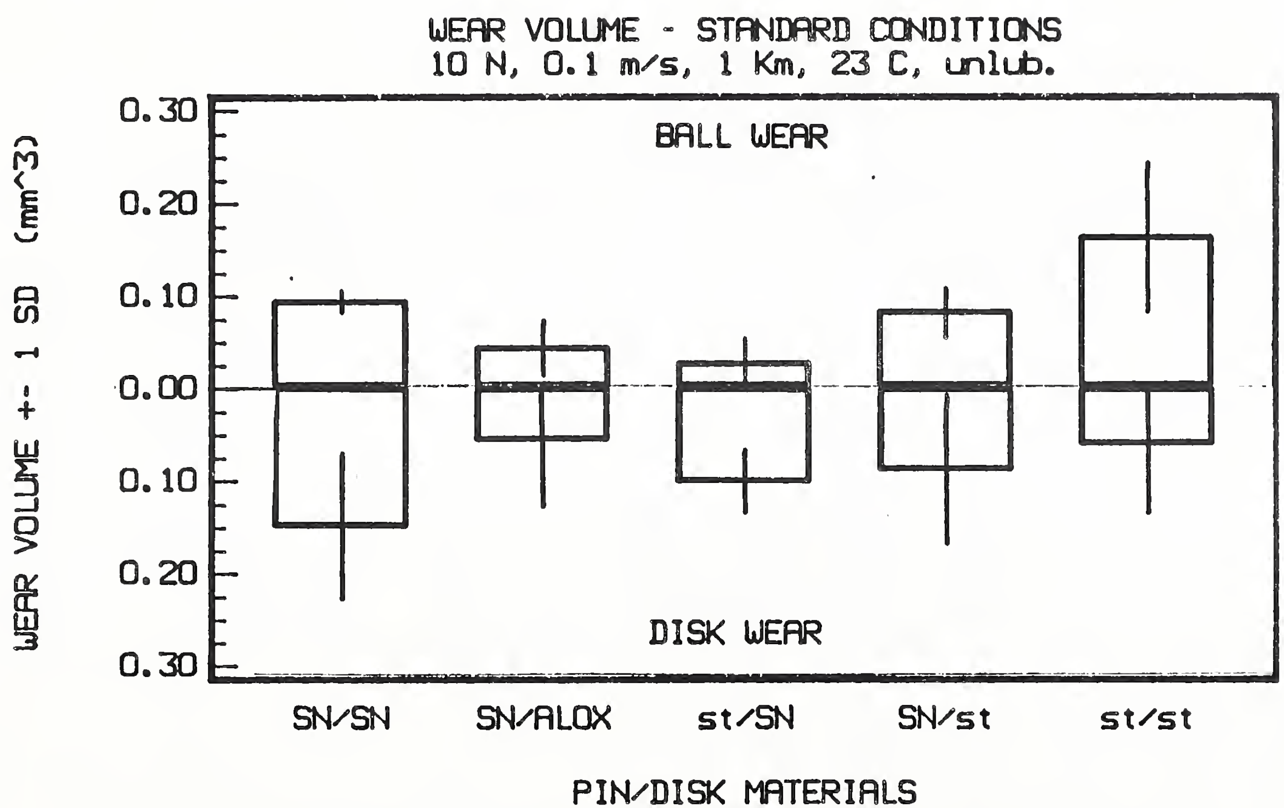


Fig. 2 Summary of wear results for standard conditions.

(e) The average ball wear volume is largest for the steel/steel couple.

(f) Variability in ball wear volume ranges from 11% for ceramic/ceramic to a large value of 50% for steel/steel.

(g) Average disk wear volume varies substantially among the labs. The cause may be related to different measurement methods used. It is difficult to determine any trends in disk wear volume in this small sample.

Examples of specific results are shown in Figs. 3, 4 and 5. Friction vs. time curves for a test under standard conditions for one of each of the five materials pairings are shown in Fig. 3. It is seen that slow, small decreases or increases in friction coefficient with time were found, with occasional abrupt but small changes probably due to wear debris effects in the contact gap. Two examples from the NIST measurements of profilometer tracings of disk wear tracks are shown in Fig. 4; each track was traced at four locations in order to obtain an average cross-sectional area of the wear track to use in computing the disk wear volume. The irregularities at the bottom of the wear track groove are thought to reflect roughness and possibly residual wear debris. Figure 5 shows two examples of the appearance (optical micrographs) of the ball wear scar and a portion of the disk wear track. Surface appearances suggest principally abrasive wear for the ceramic materials and deformation wear with some abrasion for the steel specimens.

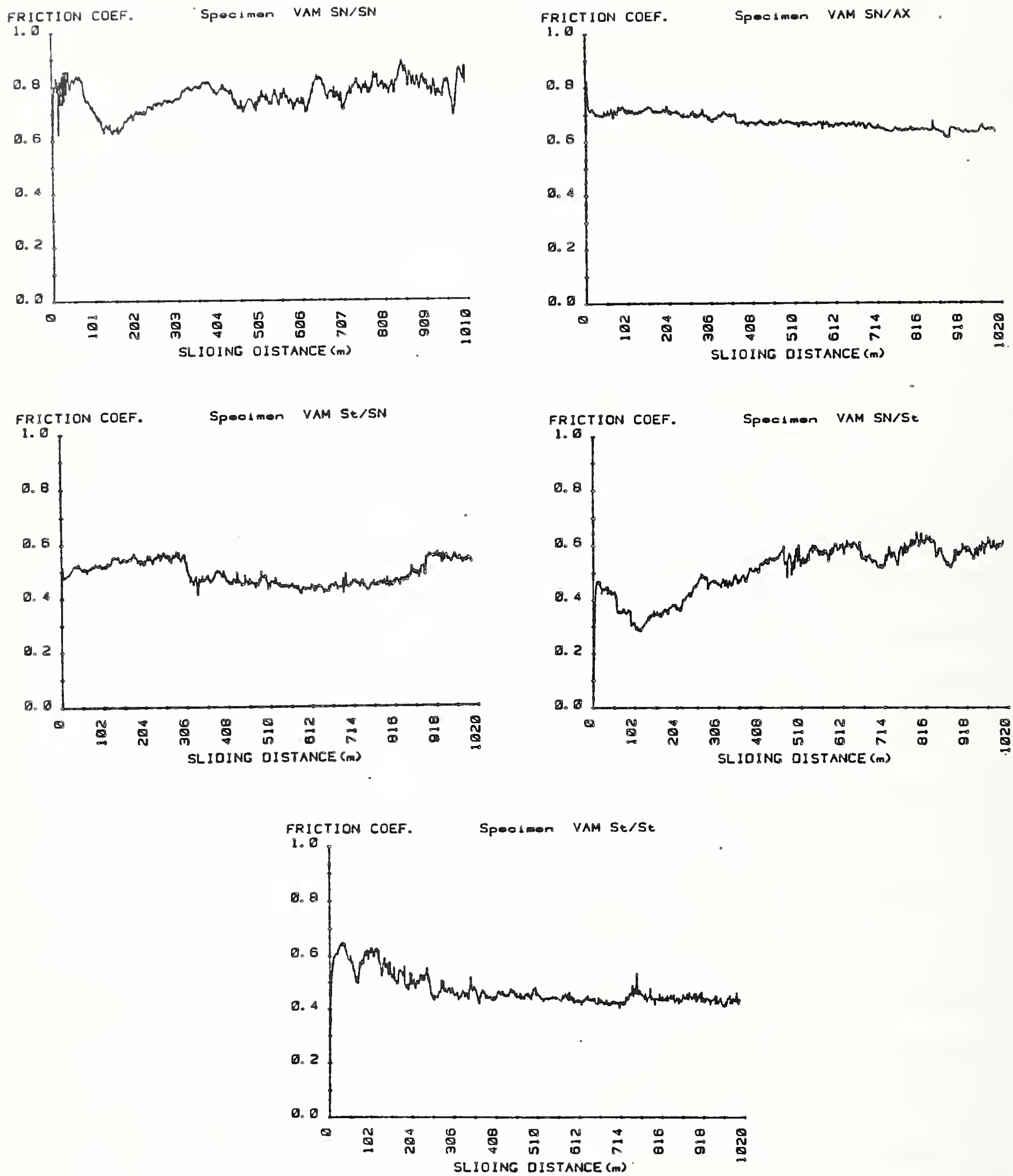
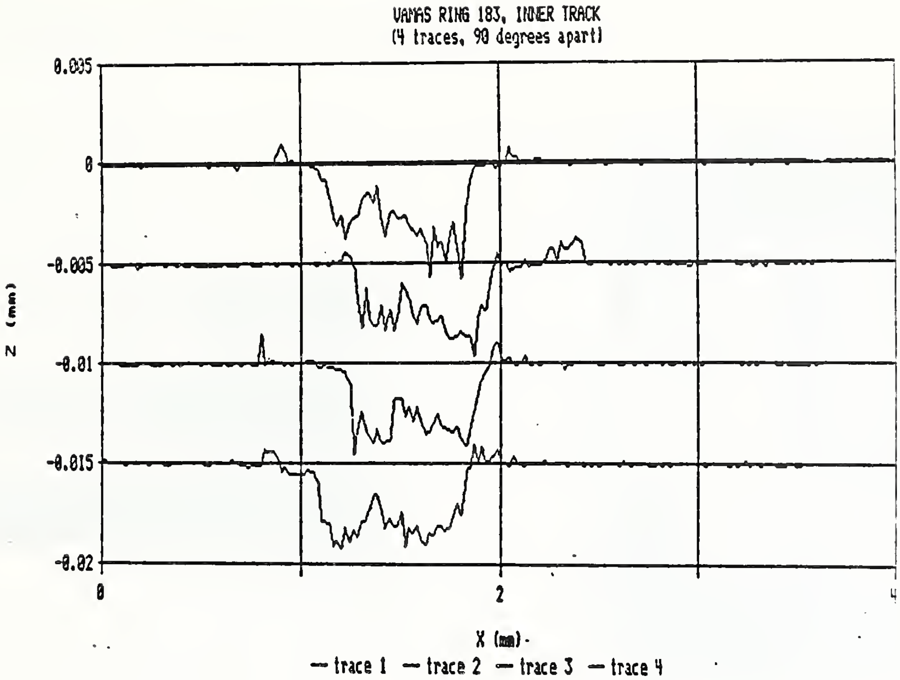


Fig. 3 Friction coefficient vs. sliding distance examples for each material studied under standard conditions.



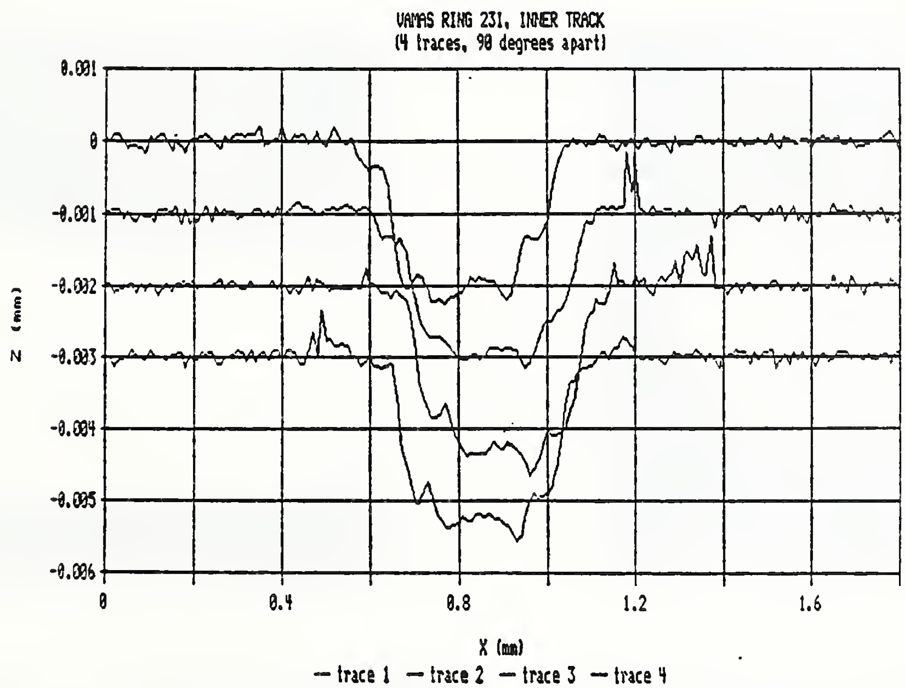


Fig. 4 Profilometer traces across wear track at four locations on disks from two tests under standard conditions.

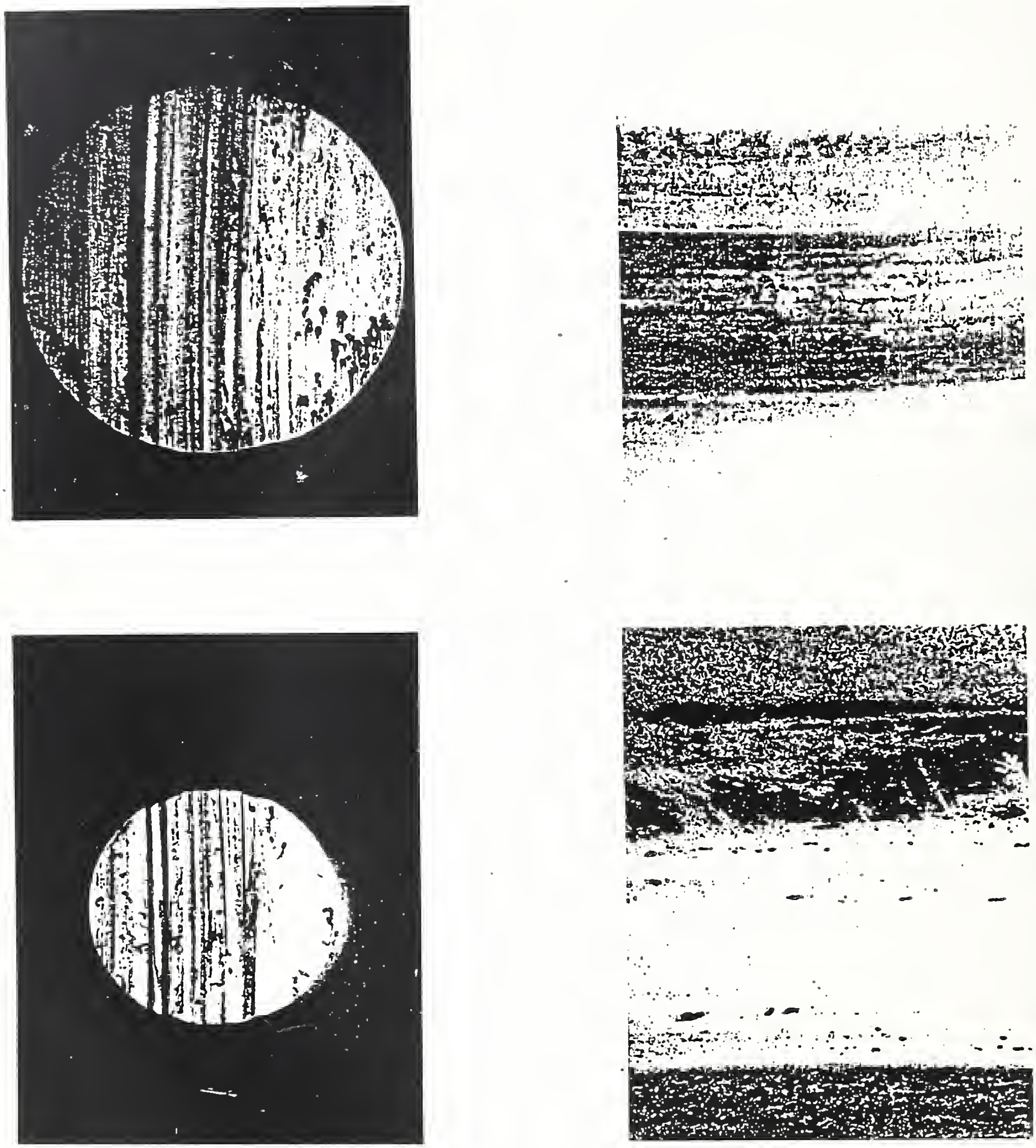


Fig. 5 Optical micrographs from (top) a silicon nitride ball and disk pair, and (bottom) a steel - silicon nitride ball and disk pair, both tested under standard conditions

6. RESULTS: LOW LOAD TEST CONDITIONS

Individual data sets are provided in Appendix B for each of the six U,S. laboratories that carried out the tests under the low load (2 N) condition. A summary of all Round 2 data is given in Table 7. For low load test conditions, Table 9 collects the individual raw data and gives the results of an analysis of those data. The analysis is divided into five groups, one for each of the specimen pairs. Average values and standard deviations for average friction, ball wear volume, disk wear volume, and total wear volume are given. Note that the standard deviation is calculated using the small sample method since n=6 in most cases. Graphical presentation of the friction data is shown in Fig. 6, and the wear data in Fig. 7. The principal findings are:

(a) There is considerable variation in friction coefficient for all materials, ranging from about 33% to 50%. This is larger than the variation found for the standard condition (10 N load).

(b) There is fair agreement on ball wear in some cases (about 11%), but also some disagreement for other materials up to about 50%.

(c) There is difficulty in measuring disk wear due to its small value at the low load, and considerable variation in the disk wear results for all materials.

Figure 8 shows two examples from the NIST measurements of friction vs. time curves for tests under low load conditions; more variation with time is seen there than for the higher (10 N) load under standard conditions.

Table 9. Summary of Results for Low Load (2N) Conditions

LAB NUMBER	BALL MATERIAL	DISK MATERIAL	LOAD N	LUBE (YES/NO)	DISTANCE: AVERAGE m	SD m	AVERAGE FRICTION: AVERAGE	SD	WEAR VOLUME (mm^3) BALL: AVERAGE	SD	DISK: AVERAGE	SD	TOTAL: AVERAGE	SD
26	Si3N4	AL2O3	2.00	NO	1000	0	0.73	0.01	0.0181	0.0026	0.0110	0.0016	0.0292	0.0022
27	Si3N4	AL2O3	2.00	NO	1000	0	0.63	0.04	0.0184	0.0010	0.0000	0.0000	0.0184	0.0010
28	Si3N4	AL2O3	2.00	NO	1004	4	0.38	0.23	0.0216	0.0018	0.0052	0.0008	0.0268	0.0012
29	Si3N4	AL2O3	2.00	NO	1000	0	0.29	0	0.0240	0.0009	0.0124	0.0073	0.0242	0.0216
30	Si3N4	AL2O3	2.00	NO	1000	0	0.59	0.04	0.0207	0.0006	0.8333	0.2225	0.8540	0.2225
42	Si3N4	AL2O3	2.00	NO	1000	0	0.80	0.00	0.0209	0.0009				
						AVG=	0.57	AVG=	0.0206	AVG=	0.1724	AVG=	0.1905	
						SD=	0.20	SD=	0.0022	SD=	0.3695	SD=	0.3709	
26	Si3N4	Si3N4	2.00	NO	1000	0	0.64	0.04	0.0240	0.0032	0.0589	0.0042	0.0829	0.0011
27	Si3N4	Si3N4	2.00	NO	1000	0	0.67	0.01	0.0061	0.0015				
28	Si3N4	Si3N4	2.00	NO	1003	3	0.60	0.30	0.0109	0.0035	0.0152	0.0219	0.0261	0.0186
29	Si3N4	Si3N4	2.00	NO	1000	0	0.22	0.13	0.0112	0.0039	0.0470	0.0016	0.0582	0.0023
30	Si3N4	Si3N4	2.00	NO	1000	0	0.54	0.12	0.0036	0.0001	0.6620	0.0555	0.6656	0.0555
42	Si3N4	Si3N4	2.00	NO	1000	0	0.70	0.05	0.0109	0.0037				
						AVG=	0.56	AVG=	0.0111	AVG=	0.1958	AVG=	0.2082	
						SD=	0.18	SD=	0.0070	SD=	0.3015	SD=	0.2961	
26	Si3N4	AISI52100	2.00	NO	1000	0	0.76	0.06	0.0339	0.0338	0.0131	0.0135	0.0470	0.0473
27	Si3N4	AISI52100	2.00	NO	1000	0	0.81	0.06	0.0160	0.0005	0.0000	0.0000	0.0160	0.0005
29	Si3N4	AISI52100	2.00	NO	1000	0	0.28	0.01	0.0162	0.0105	0.0073		0.0235	0.0105
30	Si3N4	AISI52100	2.00	NO	1000	0	0.42	0.25	0.0101	0.0077	0.1143	0.0127	0.1244	0.0051
42	Si3N4	AISI52100	2.00	NO	1000	0	0.83	0.03	0.0197	0.0004				
						AVG=	0.55	AVG=	0.0172	AVG=	0.0337	AVG=	0.0527	
						SD=	0.29	SD=	0.0094	SD=	0.0540	SD=	0.0496	
26	AISI52100	Si3N4	2.00	NO	1000	0	0.78	0.06	0.0115	0.0010	0.0491	0.0021	0.0606	0.0011
27	AISI52100	Si3N4	2.00	NO	1000	0	0.85	0.04	0.0093	0.0014				
29	AISI52100	Si3N4	2.00	NO	1000	0	0.26	0.03	0.0463	0.0379	0.0120	0.0083	0.0583	0.0296
30	AISI52100	Si3N4	2.00	NO	1000	0	0.61	0.01	0.0073	0.0013	0.0780	0.0444	0.0853	0.0434
42	AISI52100	Si3N4	2.00	NO	1000	0	0.83	0.01	0.0107	0.0004				
						AVG=	0.67	AVG=	0.0170	AVG=	0.0464	AVG=	0.0681	
						SD=	0.25	SD=	0.0164	SD=	0.0312	SD=	0.0141	
26	AISI52100	AISI52100	2.00	NO	1000	0	0.67	0.09	0.0145	0.0019	0.0004		0.0149	
27	AISI52100	AISI52100	2.00	NO	1000	0	0.60	0.01	0.0378	0.0103	0.0000	0.0000	0.0378	0.0103
29	AISI52100	AISI52100	2.00	NO	1000	0	0.29		0.0298					
30	AISI52100	AISI52100	2.00	NO	1000	0	0.43	0.01	0.0305	0.0020	3.4077	0.1842	3.4382	0.1846
42	AISI52100	AISI52100	2.00	NO	1000	0	0.67	0.03	0.0613	0.0079				
						AVG=	0.53	AVG=	0.0348	AVG=	1.1360	AVG=	1.1636	
						SD=	0.17	SD=	0.0171	SD=	1.8548	SD=	1.8572	

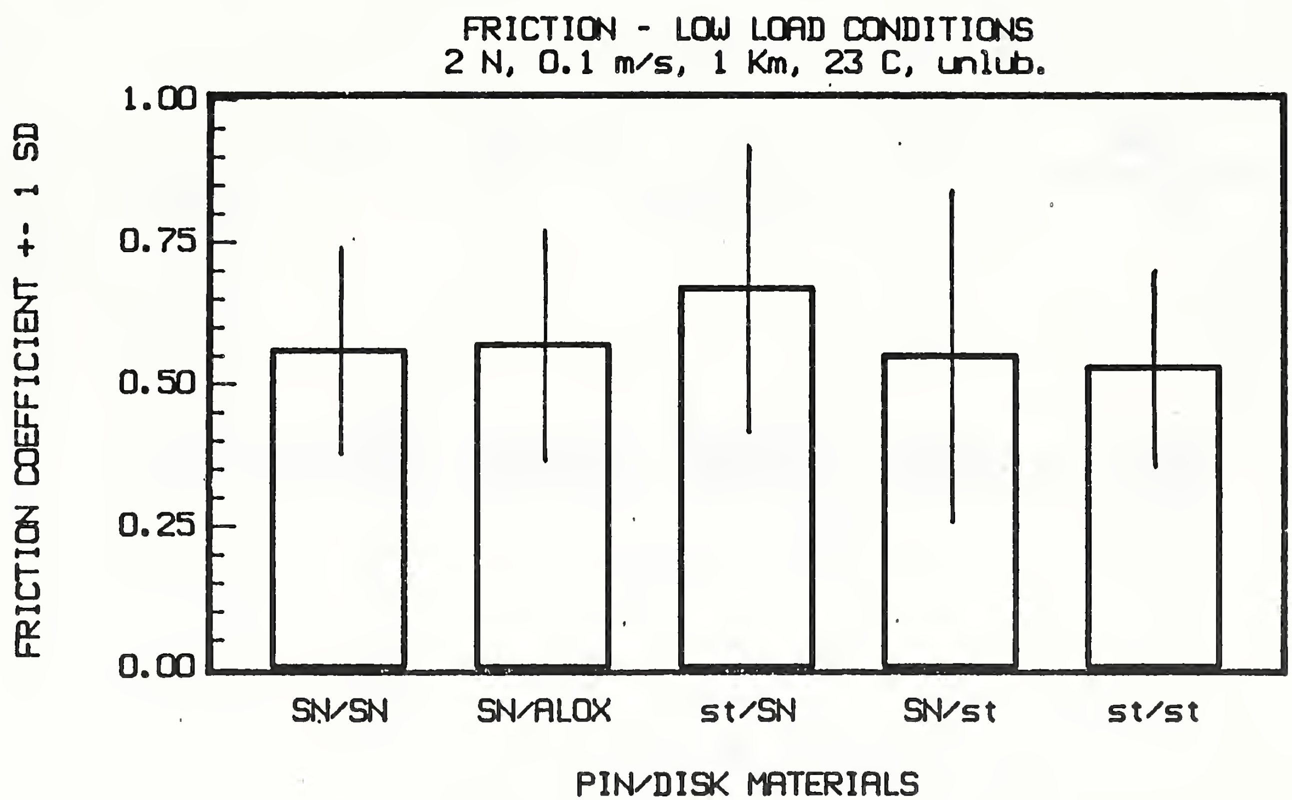


Fig. 6 Summary of friction coefficient results for 2 N load conditions.

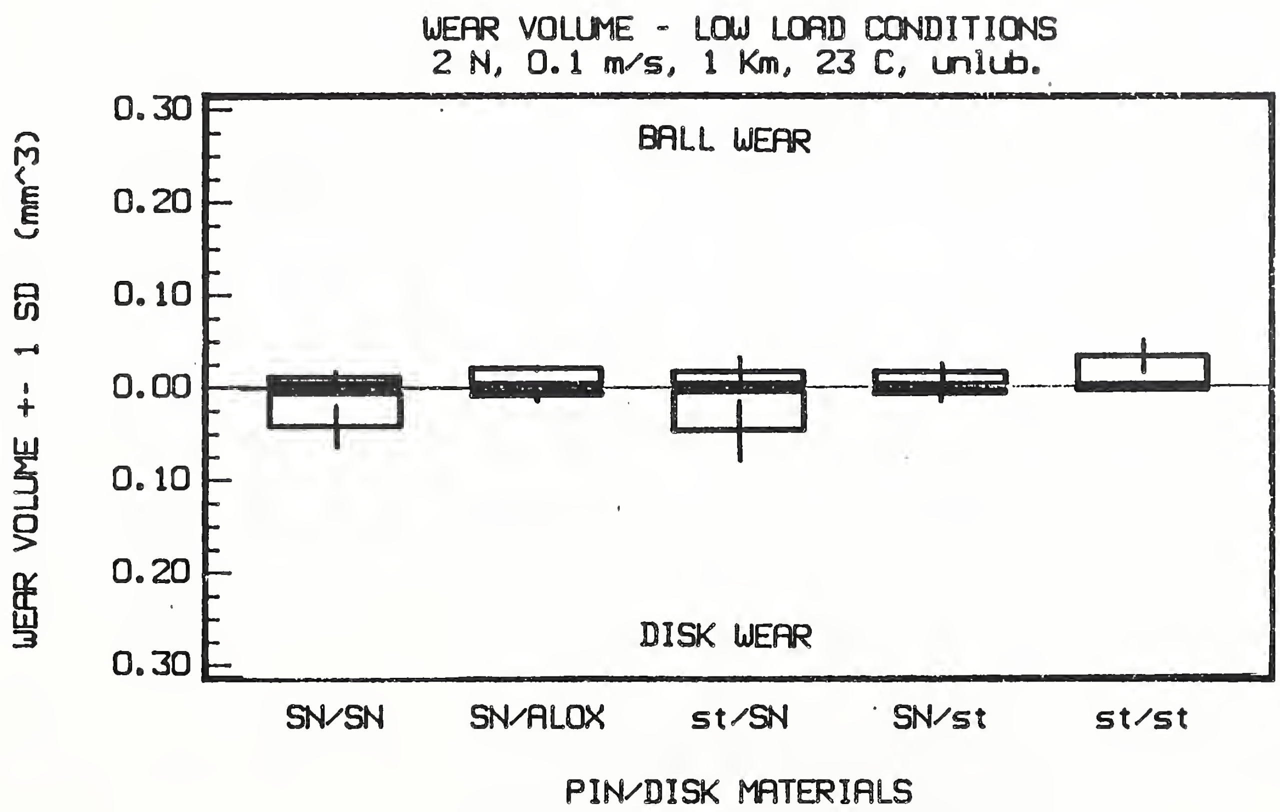
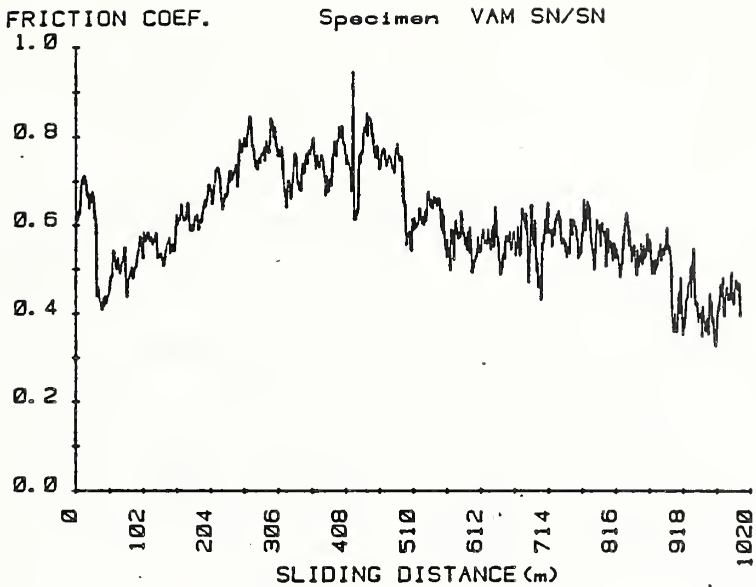


Fig. 7 Summary of wear results for 2 N load conditions.



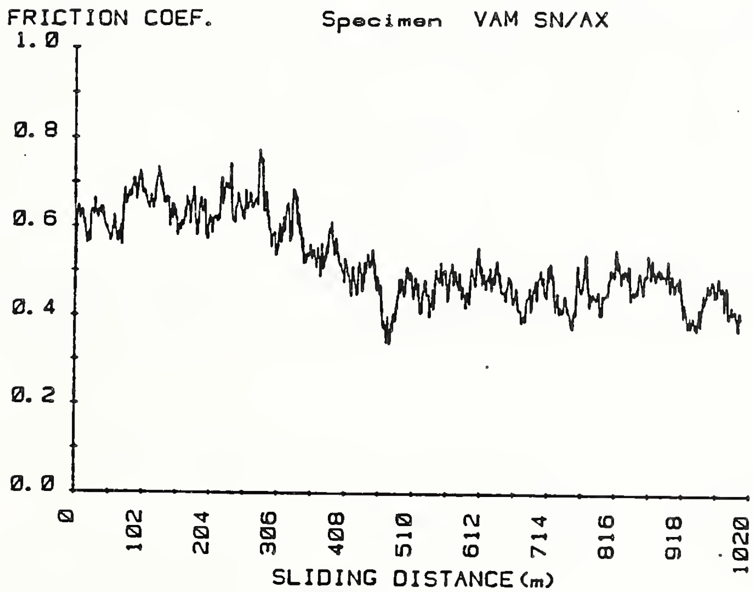


Fig. 8 Friction coefficient vs. sliding distance examples for two materials studied under 2 N load conditions.

Figure 9 shows an example of a wear track trace from an aluminum oxide disk.

7. RESULTS: LUBRICATED TEST CONDITIONS

Individual data sets are provided in Appendix B for each of the four U.S. laboratories that carried out the tests under lubricated conditions using a highly purified paraffin oil (25.9 cs viscosity at 40 C). The oil was prepared by percolation through an alumina absorbant column under nitrogen gas pressure. Most of the tests were conducted under otherwise standard conditions. One laboratory conducted a few tests at a 30 N load. A summary of all Round 2 results is given in Table 7. For lubricated test conditions, Table 10 collects the individual raw data and gives the results of an analysis of those data. The analysis is divided into five groups, one for each of the specimen pairs. Average values and standard deviations for average friction, ball wear volume, disk wear volume, and total wear volume are given. Note that the standard deviation is calculated using the small sample method since n=4 in most cases. Graphical presentation of the friction data is shown in Fig. 10 and the wear data in Fig. 11. The principal findings are:

(a) Average friction values are closely similar for all five material combinations, ranging from 0.09 to 0.12.

(b) Variation in friction values among the laboratories ranged from 10% to 50%.

(c) Ball wear volume is lowest for the material combinations including a ceramic member, ranging from 4×10^{-5} to 8×10^{-4} mm^3. The steel/steel test ball wear volume is largest at 2×10^{-3} mm^3.

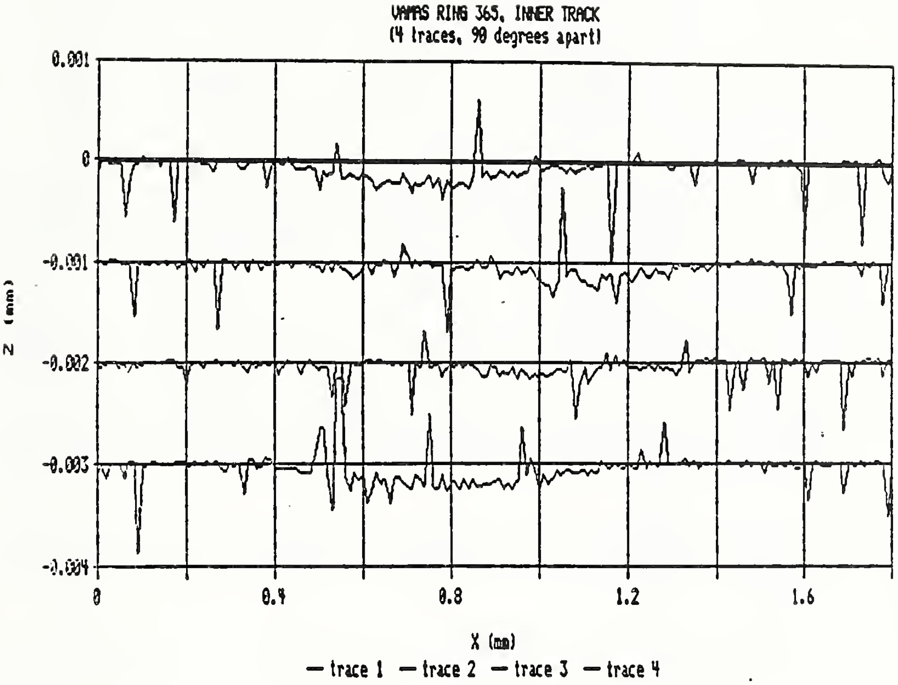


Fig. 9 Profilometer traces across wear track at four locations on a disk from a test under 2 N load conditions.

Table 10. Summary of Results for Lubricated Conditions

LAB NUMBER	BALL MATERIAL	DISK MATERIAL	LOAD N	LUBE (YES/NO)	DISTANCE: AVERAGE m	SD m	AVERAGE FRICTION: AVERAGE	SD	WEAR VOLUME (mm^3) BALL: AVERAGE	SD	DISK: AVERAGE	SD	TOTAL: AVERAGE	SD
34	Si3N4	Si3N4	10.00	YES	1000	0	0.12	0.01	2.20E-04	2.00E-05	0.00E+00	0.00E+00	2.20E-04	2.00E-05
36	Si3N4	Si3N4	10.00	YES	1000	0	0.08	0.02	1.00E-04	7.17E-05	0.00E+00	0.00E+00	1.00E-04	7.17E-05
37	Si3N4	Si3N4	10.00	YES	1000	0	0.10	0.01	5.00E-04	4.33E-04	0.00E+00	0.00E+00	5.00E-04	4.33E-04
39	Si3N4	Si3N4	9.87	YES	1232	39	0.08	0.00	1.57E-04	8.81E-05	5.16E-02	1.99E-03	5.18E-02	1.94E-03
						AVG=	0.10	AVG=	2.44E-04	AVG=	1.29E-02	AVG=	1.32E-02	
						SD=	0.02	SD=	1.77E-04	SD=	2.58E-02	SD=	2.58E-02	
28	Si3N4	AL2O3	10.00	YES	1001	1	0.09	0.03	6.87E-05	1.85E-06	0.00E+00	0.00E+00	6.87E-05	1.85E-06
36	Si3N4	AL2O3	10.00	YES	1000	0	0.10	0.01	2.95E-05	2.45E-06	0.00E+00	0.00E+00	2.95E-05	2.45E-06
37	Si3N4	AL2O3	10.00	YES	996	9	0.12	0.01	1.93E-05	8.08E-06	0.00E+00	0.00E+00	1.93E-05	8.08E-06
39	Si3N4	AL2O3	9.87	YES	1086	0	0.09	0.00	5.29E-05	5.48E-06	0.00E+00	0.00E+00	5.29E-05	5.48E-06
						AVG=	0.10	AVG=	4.26E-05	AVG=	0.00E+00	AVG=	4.26E-05	
						SD=	0.01	SD=	2.24E-05	SD=	0.00E+00	SD=	2.24E-05	
28	Si3N4	AISI52100	10.00	YES	1002	1	0.07	0.02	7.08E-05	1.85E-06	6.20E-03	9.14E-03	6.27E-03	9.14E-03
36	Si3N4	AISI52100	10.00	YES	1000	0	0.10	0.01	6.61E-05	1.11E-05	0.00E+00	0.00E+00	6.61E-05	1.11E-05
37	Si3N4	AISI52100	10.00	YES	1000	0	0.11	0.00	1.10E-04	2.65E-05	0.00E+00	0.00E+00	1.10E-04	2.65E-05
39	Si3N4	AISI52100	9.87	YES	1086	0	0.09	0.00	2.08E-04	2.39E-04	0.00E+00	0.00E+00	2.08E-04	2.39E-04
						AVG=	0.09	AVG=	1.14E-04	AVG=	1.55E-03	AVG=	1.66E-03	
						SD=	0.02	SD=	6.60E-05	SD=	3.10E-03	SD=	3.07E-03	
34	AISI52100	Si3N4	10.00	YES	1000	0	0.16	0.05	1.43E-03	1.49E-03	0.00E+00	0.00E+00	1.43E-03	1.49E-03
36	AISI52100	Si3N4	10.00	YES	1000	0	0.10	0.00	8.96E-05	1.54E-05	0.00E+00	0.00E+00	8.96E-05	1.54E-05
37	AISI52100	Si3N4	10.00	YES	1047	40	0.12	0.02	2.61E-04	1.48E-04	0.00E+00	0.00E+00	2.61E-04	1.48E-04
39	AISI52100	Si3N4	9.87	YES	1086	0	0.09	0.01	1.59E-03	5.65E-04	4.57E-02	9.41E-03	4.73E-02	9.86E-03
						AVG=	0.12	AVG=	8.42E-04	AVG=	1.14E-02	AVG=	1.23E-02	
						SD=	0.03	SD=	7.76E-04	SD=	2.28E-02	SD=	2.33E-02	
34	AISI52100	AISI52100	10.00	YES	1000	0	0.14	0.03	1.55E-03	1.08E-03	0.00E+00	0.00E+00	1.55E-03	1.08E-03
36	AISI52100	AISI52100	10.00	YES	1000	0	0.10	0.01	1.41E-03	4.63E-04	0.00E+00	0.00E+00	1.41E-03	4.63E-04
37	AISI52100	AISI52100	10.00	YES	1000	0	0.09	0.01	2.17E-03	5.51E-04	0.00E+00	0.00E+00	2.17E-03	5.51E-04
39	AISI52100	AISI52100	9.87	YES	1187	102	0.11	0.01	4.24E-03	9.65E-04	6.34E-02	3.24E-02	6.76E-02	3.32E-02
						AVG=	0.11	AVG=	2.34E-03	AVG=	1.58E-02	AVG=	1.82E-02	
						SD=	0.02	SD=	1.31E-03	SD=	3.17E-02	SD=	3.30E-02	
36	Si3N4	Si3N4	30.00	YES	1000	0	0.09	0.01	3.20E-04	4.05E-04	0.00E+00	0.00E+00	3.20E-04	4.05E-04
36	Si3N4	Al2O3	30.00	YES	1000	0	0.09	0.00	1.29E-04	1.50E-05	0.00E+00	0.00E+00	1.29E-04	1.50E-05
36	Si3N4	AISI52100	30.00	YES	1000	0	0.10	0.00	1.34E-04	4.00E-05	0.00E+00	0.00E+00	1.34E-04	4.00E-05

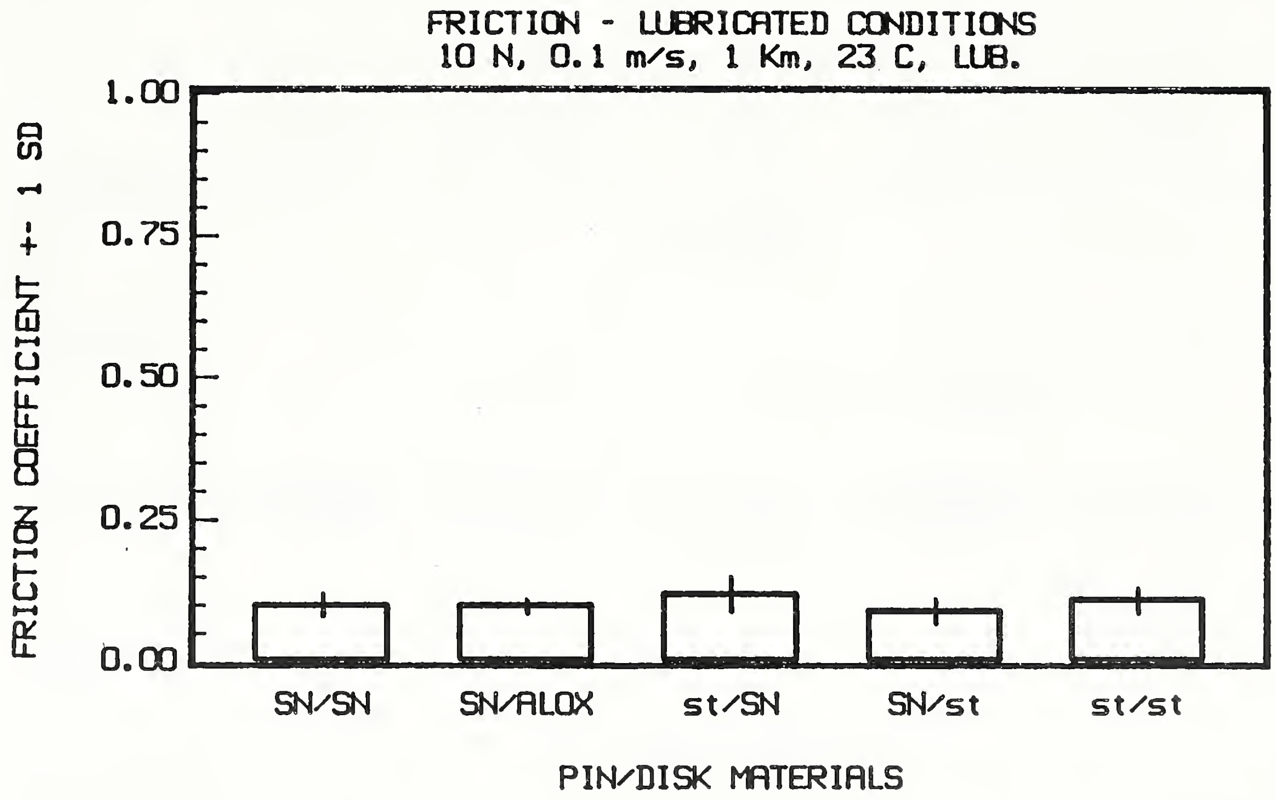


Fig. 10 Summary of friction coefficient results for lubricated conditions.

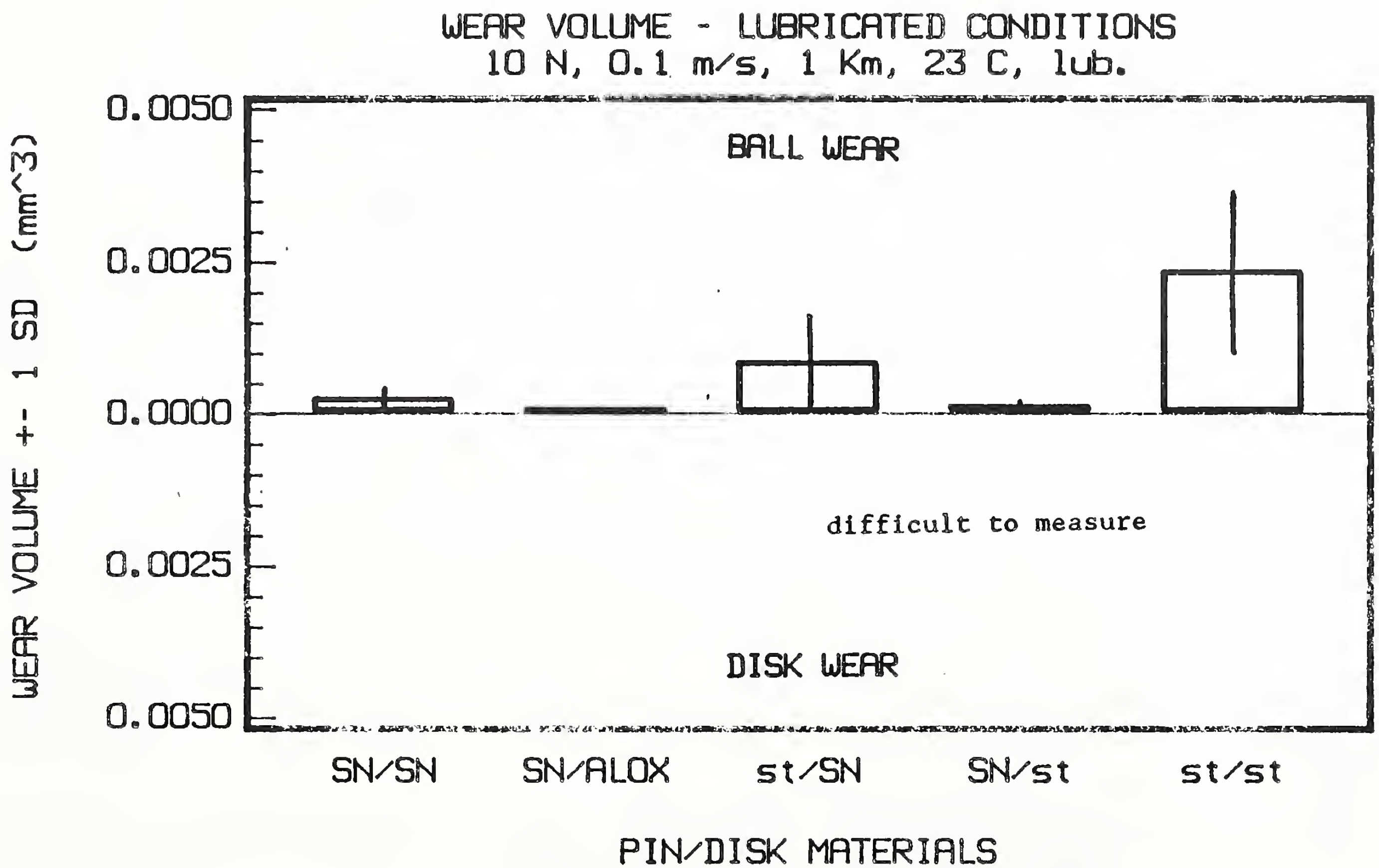


Fig. 11 Summary of wear results for lubricated conditions.

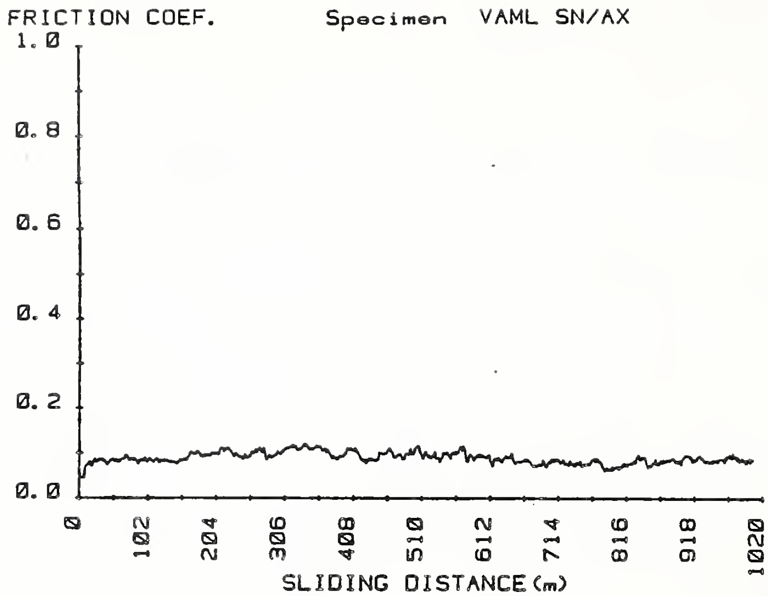
(d) Disk wear is very small and difficult to measure in most cases, although one lab reported values as high as $6x10^{-2}$ mm^3.

(e) Tests conducted at 30 N loads showed similar friction, slightly increased ball wear, and unmeasureable disk wear.

Figure 12 shows two examples from the NIST measurements of friction vs. time curves for tests under lubricated conditions. The curves show less variation and smaller absolute values than for unlubricated conditions, as would be expected. An example of a wear track trace from a steel disk is shown in Fig. 13; in such cases it was difficult to measure the small wear volume involved.

8. SUMMARY AND CONCLUSIONS

The results of Round 2 for the U.S. laboratories showed (in agreement with Round 1) that the test and measurement methods used were well established, and further that the methods were applicable to additional material combinations. It was agreed that standardization efforts through the ASTM will be pursued based on the VAMAS results. Some problems were identified in connection with differences among the test systems used in Round 2; improved machine characterization is needed. Data variability would probably be reduced if the test systems were more identical. It was also noted that wear volume on the disk specimen was difficult to measure accurately, and that work should be done to improve that situation.



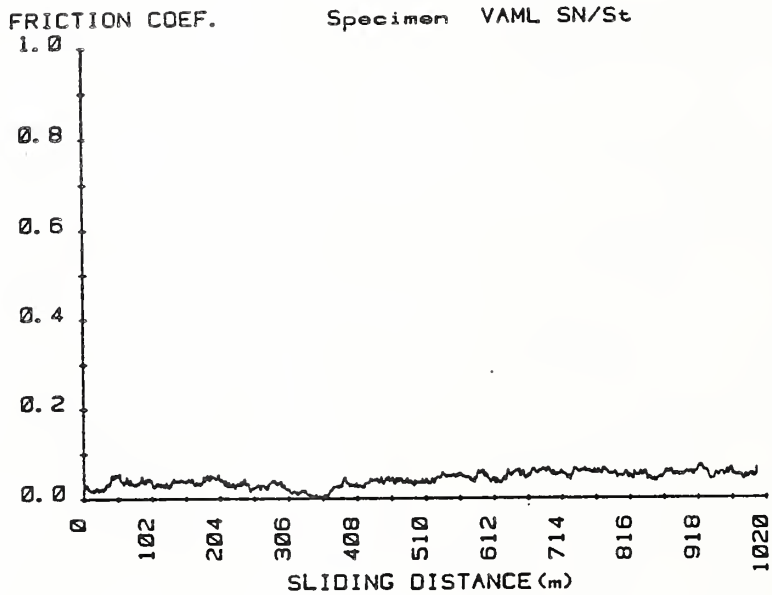


Fig. 12 Friction coefficient vs. sliding distance examples for two materials studied under lubricated conditions.

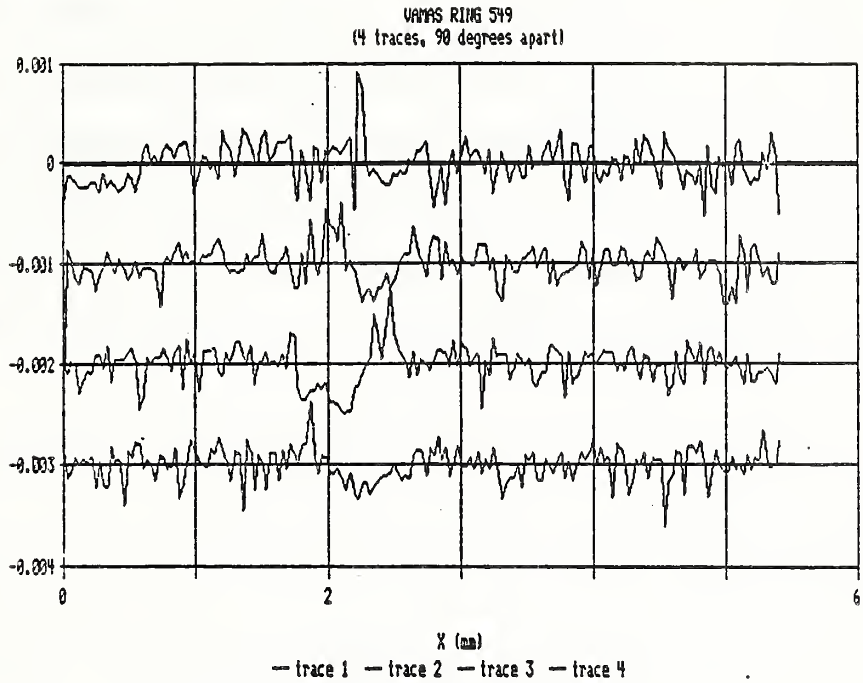


Fig. 13 Profilometer traces across wear track at four locations on a disk from a test under lubricated conditions.

A number of specific recommendations for future improvements in the test protocol were developed. It was felt important to provide more precise definitions of friction terms such as initial, final, and average. There should be a better surface finish on the specimens, particularly on steel. There should be clear instructions on the method for measuring disk wear profiles. One laboratory suggested a different, more accurate formula for calculating ball wear. A desirable, parallel effort to improve measurement capability would involve circulating some worn specimens to compare the wear volume measurement method itself.

Improvements were also suggested for the report form associated with the test. It was felt important to provide more space on the data form for comments, with prompts to enter the information. There should also be a report section for showing surface photographs and profiles together.

Recommendations were developed for the non-standard test conditions. A longer sliding distance should be used at the 2 N load to obtain greater total wear that could be more precisely measured. Further, the 2 N load may be too low for some equipment designs. The lubricated testing probably should be carried out at higher loads and for longer sliding distances to obtain sufficient wear on both members. Slower sliding speeds or higher loads should be used to ensure boundary lubrication conditions.

ACKNOWLEDGEMENTS

The leadership and overall support for this effort (as part of the total world effort) that was provided by Horst Czichos and colleagues at B.A.M. was crucial to its success. The cooperation and dedicated effort received from the individuals involved in these measurements at the laboratories indicated in Table 6 is also gratefully acknowledged. The assistance of P. Pei at NIST in providing refined paraffin oil for certain tests was appreciated. Considerable work and data analysis was done at NIST by Eric Whitenton, and by University of Maryland co-operative students, Bill Duvall and Tim Strakna.

REFERENCES

1. H. Czichos, S. Becker, and J. Lexow, "Multilaboratory Tribotesting: Results from the Versailles Advanced Materials and Standards Programme on Wear Test Methods". Wear 114, 109-130 (1987).
2. H. Czichos and A.W. Ruff, " Results of the VAMAS Interlaboratory Study on Wear Test Methods", VAMAS Bulletin No. 5, 1-5 (1987).

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APPENDIX A: TEST INSTRUCTIONS AND DATA SHEET

INSTRUCTION SHEET

FOR VAMAS-PROJECT ROUND ROBIN

WEAR TEST METHODS

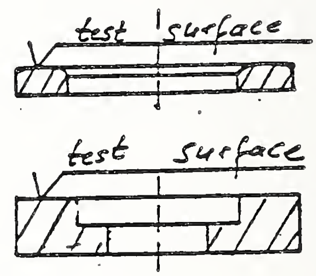
Please Perform Tests at the following Agreed Test Procedure *

1. Test System

- Stationary ball (10 mm diameter) against rotating disc (40 mm outer diameter, 32 mm standard wear track diameter, and 29 or 35 mm optional for additional runs, see point 4)
- rotation in the horizontal plane
- direction of rotation of disc to be indicated by each laboratory
- Ball and disc are to be protectively stored in plastic containers.
- The enclosed ball clamping (designed by NPL) should be used where applicable. Otherwise, holders for disc and ball are to the discretion of each laboratory.
- Please report (if possible) vibrations (e.g. vibration amplitudes and frequency distribution) of test rig at stated location, if changed or new since the first round robin.
- Report stiffness-data of the test rig (if available), if changed or new since the first round robin.

2. Materials

Disc: AISI 52100
alpha-Al_2O_3
Si_3N_4
Ball: AISI 52100
Si_3N_4



3. Lubricant

No lubricant will be used in this round robin test.

4. Operating Variables

- Motion: Continuous unidirectional sliding
- Velocity: 0.1 m/s
- Normal Load: 10 N
  Optional: 50 N on 35 mm track in standard atmosphere
- Temperature: 23 ± 1 °C
- Sliding distance: 1000 m
- Atmosphere: laboratory air, 50 ± 10 % relative humidity
  Optional: "as dry as possible" on 29 mm track, 10 N load
- Number of tests: 3

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*If other conditions are used please indicate them.

5. Preparation of Surfaces

-Specimen are to be used as received, i.e. no mechanical surface finishing is necessary.

-Surfaces are to be cleaned immediately prior to each test.

a) Ultrasonic agitation in trichloroethane, 10 minutes

b) Ultrasonic agitation in methanol, 10 minutes

c) Rinsing with methanol

d) Drying in a drying oven at 120°C, 30 min

-Chemicals of pure quality are to be used.

-Samples are to be stored and transported in desiccators.

6. Measurements

! Please, use the evaluation sheets !

a) Wear:

(Please define whether wear of ball, wear of disc, or total wear of both ball and disc are measured.)

-Wear continuously measured and recorded (system wear)

-Wear scar diameter on ball to be measured with an optical microscope

-Profilogram results of surfaces of both, ball and disc, after the test

b) Friction:

(Please define whether the friction force or the friction torque are measured.)

-Submit a simplified graph giving the fluctuations as defined in the evaluation sheet

-Suggested chart speed 20 cm/h

7. Post-Measurement Handling

-Indicate the sample number with a water resistant felt pen on the side of the disc which was not subjected to wear.

-Mark the worn area on the ceramic balls with a water resistant felt pen or correction fluid for each test.

-After the first and second test turn the ceramic ball into a new position without contaminating the sample.

-Put the samples back into the bags immediately after the test and the examinations in order to avoid mixing of samples

8. Examination

Surfaces are optionally to be examined by optical photography and SEM techniques.

9. Report

All results should be reported to Prof. Czichos, BAM, by

-, 1988.

Reports should in particular comprise:

-Information on the test setup (if modified or new since the first round robin)

-Photographs of surfaces (optional)

-Graphs of wear and friction

-Additional information on deviations from agreed conditions or other information concerning the test (e.g. vibrational characteristics, results of optional test runs)

V A M A S 2. ROUND ROBIN ON WEAR TEST METHODS

EVALUATION SHEET

LABORATORY NO.   KIT.:

	ball:	disk:
1		
2		
3		

		TEST 1	TEST 2	TEST 3
TEST CONDITIONS				
sliding distance	(m)			
load	(N)			
velocity	(m/s)			
wear track diameter	(mm)			
ambient temperature	(C)			
relative humidity	(%)			
FRICTION AND WEAR RESULTS				
coefficient of friction				
value at the beginning				
value at the end				
maximum value				
average at steady conditions				
vertical displacement (total linear wear)	(μm)			
ball: wear scar diameter $d_{\perp}$	(mm)			
wear scar diameter $d_{\parallel}$	(mm)			
wear volume W_b	* (mm^3)			
disk: wear track width	(mm)			
wear track depth	(μm)			
planimetric wear	(μm^2)			
wear volume W_d	** (mm^3)			

*) $W_b = \pi d^4/64r$
r = ball radius; d = wear scar diameter

**) $W_d = 2\pi R\, d^3/12r$
R = wear track radius; d = wear track width

Observations:

Material Combinations (Round 2)

Ball	Disk
Si_3N_4	Si_3N_4
Si_3N_4	52100 Steel
Si_3N_4	Al_2O_3
52100 Steel	Si_3N_4
52100 Steel	52100 Steel

INDIVIDUAL LABORATORIES - STANDARD CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
16		Si3N4	2C0069	Si3N4	2C0041																			
		Si3N4	2C0069	Si3N4	2C0042	1000	10.00		0.10	32.0	24	35	0.91	0.84	0.90	0.90	1.040	1.040	1.040	0.1130	32.0	0.0380		0.1510
		Si3N4	2C0069	Si3N4	2C0043	1000	10.00		0.10	32.0	25	35	0.84	1.16	1.69	1.26	1.040	1.040	1.040	0.1130	32.0	0.1990		0.3120
					AVG=	1000									AVG=	1.08			AVG=	0.1130	AVG=	0.1185	AVG=	0.231
					SD=	0									SD=	0.11			SD=	0.0000	SD=	0.0986	SD=	0.156
17		Si3N4	2C0075	Si3N4	2C0044	1000	10.00		0.10	32.0	19	50	0.50	0.52	0.61	0.50	1.625	1.625	1.625	0.0680	32.0	0.0730		0.141
		Si3N4	2C0075	Si3N4	2C0045	1000	10.00		0.10	32.0	20	50	0.60	0.52	0.61	0.50	1.727	1.727	1.727	0.0870	32.0	0.0900		0.177
		Si3N4	2C0075	Si3N4	2C0046	1000	10.00		0.10	32.0	23	50	0.54	0.58	0.50	0.50	1.803	1.803	1.803	0.1040	32.0	0.0350		0.139
					AVG=	1000									AVG=	0.53			AVG=	0.0863	AVG=	0.0660	AVG=	0.152
					SD=	0									SD=	0.05			SD=	0.0180	SD=	0.0282	SD=	0.021
19		Si3N4	2C0074	Si3N4	2C0050	1000	10.00		0.10	32.0	23	62	0.42	0.81	0.89	0.82	2.160	2.120	2.140	0.1030	32.0	0.3160		0.419
		Si3N4	2C0074	Si3N4	2C0051	1000	10.00		0.10	32.0	23	48	0.35	0.75	0.94	0.74	2.020	1.960	1.990	0.0770	32.0	0.1070		0.264
		Si3N4	2C0074	Si3N4	2C0052	1000	10.00		0.10	32.0	22	50	0.63	0.74	0.82	0.74	2.060	2.020	2.040	0.0850	32.0	0.2390		0.324
					AVG=	1000									AVG=	0.77			AVG=	0.0883	AVG=	0.2473	AVG=	0.335
					SD=	0									SD=	0.05			SD=	0.0133	SD=	0.0649	SD=	0.078
20		Si3N4	2C0067	Si3N4	2C0053	1000	10.00		0.10	31.8	24	17	0.58	0.67	0.67	0.67	1.676	1.676	1.676	0.0775	31.0	0.0116		0.089
		Si3N4	2C0067	Si3N4	2C0054	1000	10.00		0.10	31.3	24	17	0.58	0.60	0.60	0.60	1.029	1.029	1.029	0.1098	31.5	3.6403		3.750
		Si3N4	2C0067	Si3N4	2C0055	1000	10.00		0.10	32.0	25	28	0.60	0.67	0.67	0.67	1.753	1.753	1.753	0.0926	32.0	2.5863		2.678
					AVG=	1000									AVG=	0.65			AVG=	0.0933	AVG=	2.3461	AVG=	2.439
					SD=	0									SD=	0.04			SD=	0.0162	SD=	1.4296	SD=	1.44
28	1 2/3	Si3N4	SN028	Si3N4	SN103	1003	10.00	9940	0.10	32.1	23	12	0.57	0.83	0.86	0.83	1.660	1.670	1.665	0.0763	32.1	0.2110		0.287
	12 3/18	Si3N4	SN028	Si3N4	SN091	1003	10.00	9860	0.10	32.7	23	12	0.44	0.39	0.74	0.45	1.635	1.630	1.637	0.0704	32.7	0.0555		0.125
	13 3/24	Si3N4	SN028	Si3N4	SN092	1001	10.00	9850	0.10	35.9	23	39	0.35	0.52	0.65	0.52	1.080	1.090	1.085	0.1240	35.9	0.2520		0.376
					AVG=	1003									AVG=	0.60			AVG=	0.0902	AVG=	0.1728	AVG=	0.263
					SD=	2									SD=	0.20			SD=	0.0294	SD=	0.1037	SD=	0.126

INDIVIDUAL LABORATORIES - STANDARD CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
16		Si3N4	2CB010	Al2O3	1C0325	1000	10.00		0.10	32.0	35	40	1.33	1.07	1.33	1.09	1.640	1.640	1.640	0.0710	32.0	0.0110		0.0820
		Si3N4	2CB010	Al2O3	1C0326	1000	10.00		0.10	32.0	24	38	1.29	1.03	1.29	1.02	1.460	1.560	1.510	0.0510	32.0	0.0100		0.0610
		Si3N4	2CB010	Al2O3	1C0327	1000	10.00		0.10	32.0	25	36	1.39	1.03	1.39	1.10	1.440	1.480	1.460	0.0450	32.0	0.0110		0.0560
					AVG=	1000									AVG=	1.07			AVG=	0.0557	AVG=	0.0107	AVG=	0.0663
					SD=	0									SD=	0.04			SD=	0.0134	SD=	0.0006	SD=	0.0130
17		Si3N4	2CB019	Al2O3	1C0381	1000	10.00		0.10	32.0	26	50	0.62	0.54	0.62	0.58	1.727	1.727	1.727	0.0870	32.0	0.0550		0.1420
		Si3N4	2CB019	Al2O3	1C0382	1000	10.00		0.10	32.0	25	50	0.62	0.54	0.62	0.58	1.727	1.727	1.727	0.0870	32.0	0.0550		0.1420
		Si3N4	2CB019	Al2O3	1C0383	1000	10.00		0.10	32.0	24	50	0.62	0.54	0.62	0.58	1.727	1.727	1.727	0.0870	32.0	0.0520		0.1390
					AVG=	1000									AVG=	0.58			AVG=	0.0870	AVG=	0.0540	AVG=	0.1410
					SD=	0									SD=	0.00			SD=	0.0000	SD=	0.0017	SD=	0.0017
19		Si3N4	2CB021	Al2O3	1C0377	1000	10.00		0.10	32.0	23	54	0.14	0.00	0.93	0.82	1.660	1.640	1.650	0.0364	32.0	0.2120		0.2484
		Si3N4	2CB021	Al2O3	1C0378	1000	10.00		0.10	32.0	24	50	0.42	0.83	0.90	0.83	1.260	1.240	1.250	0.0120	32.0	0.1230		0.1350
		Si3N4	2CB021	Al2O3	1C0379	1000	10.00		0.10	32.0	23	57	0.56	0.74	0.90	0.75	1.360	1.340	1.350	0.0163	32.0	0.1470		0.1633
					AVG=	1000									AVG=	0.80			AVG=	0.0216	AVG=	0.1607	AVG=	0.1822
					SD=	0									SD=	0.04			SD=	0.0130	SD=	0.0460	SD=	0.0590
20		Si3N4	2CB020	Al2O3	1C0388	1000	10.00		0.10	32.7	24	10	0.04	0.82	0.84	0.80	1.397	1.397	1.397	0.0374	32.7	1.7556		1.7930
		Si3N4	2CB020	Al2O3	1C0392	1000	10.00		0.10	31.0	24	10	0.82	0.76	0.82	0.76	1.397	1.397	1.397	0.0374	31.0	1.3377		1.3751
		Si3N4	2CB020	Al2O3	1C0396	1000	10.00		0.10	32.2	25	10	0.76	0.70	0.70	0.76	1.473	1.473	1.473	0.0462	32.2	2.0034		2.0496
					AVG=	1000									AVG=	0.77			AVG=	0.0403	AVG=	1.6989	AVG=	1.7392
					SD=	0									SD=	0.02			SD=	0.0051	SD=	0.3365	SD=	0.3405
28	4 2/4	Si3N4	SN020	Al2O3	ALOI295	1016	10.00	10001	0.10	35.8	24	14	0.20	0.93	0.68	0.70	1.310	1.300	1.305	0.0289	35.8	0.0146		0.0435
	16 3/20	Si3N4	SN059	Al2O3	ALOI365	1001	10.00	9851	0.10	35.8	22	20	0.25	0.70	0.82	0.75	0.935	0.914	0.925	0.0072	35.8	0.0027		0.0099
	17 3/29	Si3N4	SN059	Al2O3	ALOI366	1002	10.00	9851	0.10	31.9	23	24	0.19	0.63	0.73	0.63	0.909	0.889	0.899	0.0064	31.9	0.0023		0.0087
	34 5/12	Si3N4	SN028	Al2O3	ALOI270	1002	10.00	9851	0.10	31.0	25	35	0.24	0.57	0.64	0.60	1.027	1.077	1.052	0.0120	31.0	0.0050		0.0170
					AVG=	1005									AVG=	0.67			AVG=	0.0136	AVG=	0.0061	AVG=	0.0198
					SD=	7									SD=	0.07			SD=	0.0105	SD=	0.0058	SD=	0.0162

INDIVIDUAL LABORATORIES - STANDARD CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
16		AISI52100	1SP446	Si3N4	2CP143	1000	10.00		0.10	37.0	24	44	1.06	0.48	1.53	1.14	1.232	1.190	1.211	0.0210	32.0	0.1290		0.1500
		AISI52100	1SD447	Si3N4	2CP146	1000	10.00		0.10	32.0	24	40	0.83	1.02	1.12	0.09	1.164	1.120	1.142	0.0167	32.0	0.1050		0.1217
		AISI52100	1SP440	Si3N4	2CP147	1000	10.00		0.10	32.0	23	46	1.04	0.18	1.22	1.10	1.200	1.134	1.167	0.0182	32.0	0.1530		0.1712
					AVG=	1000									AVG=	1.04			AVG=	0.0186	AVG=	0.1290	AVG=	0.1476
					SD=	0									SD=	0.13			SD=	0.0022	SD=	0.0240	SD=	0.0740
17		AISI52100	1SD449	Si3N4	2C0148	1000	10.00		0.10	32.0	22	50	0.62	0.64	0.64	0.58	1.092	1.092	1.092	0.0140	32.0	0.0950		0.0990
		AISI52100	1SD450	Si3N4	2C0149	1000	10.00		0.10	32.0	22	50	0.71	0.64	0.71	0.58	1.120	1.120	1.120	0.0150	32.0	0.0940		0.1090
		AISI52100	1SD452	Si3N4	2C0150	1000	10.00		0.10	32.0	19	50	0.71	0.64	0.71	0.50	1.120	1.120	1.120	0.0150	37.0	0.0920		0.1070
					AVG=	1000									AVG=	0.50			AVG=	0.0147	AVG=	0.0903	AVG=	0.1050
					SD=	0									SD=	0.00			SD=	0.0006	SD=	0.0047	SD=	0.0053
19		AISI52100	1SD458	Si3N4	2C0154	1000	10.00		0.10	32.0	25	67	0.63	0.70	0.70	0.70	2.100	2.000	2.050	0.0955	32.0	0.1350		0.7305
		AISI52100	1SD459	Si3N4	2C0155	1000	10.00		0.10	32.0	21	70	0.42	0.60	0.80	0.69	2.180	2.160	2.170	0.1080	32.0	0.1220		0.7308
		AISI57100	1SD460	Si3N4	2C0156	1000	10.00		0.10	32.0	23	50	0.28	0.77	0.94	0.76	1.380	1.360	1.370	0.0173	32.0	0.1360		0.1533
					AVG=	1000									AVG=	0.72			AVG=	0.0739	AVG=	0.1310	AVG=	0.2045
					SD=	0									SD=	0.04			SD=	0.0494	SD=	0.0078	SD=	0.0447
20		AISI52100	1SD464	Si3N4	2C0157	1000	10.00		0.10	31.0	26	19	0.78	0.73	0.73	0.78	1.118	1.067	1.092	0.0140	31.0	1.4711		1.485
		AISI52100	1SD465	Si3N4	2C0158	1000	10.00		0.10	31.5	27	10	0.62	0.49	0.62	0.58	1.048	1.018	1.029	0.0110	31.5	0.9278		0.938
		AISI57100	1SD466	Si3N4	2C0159	1000	10.00		0.10	31.5	27	19	0.53	0.56	0.77	0.77	1.143	1.118	1.130	0.0160	31.5	1.2194		1.235
					AVG=	1000									AVG=	0.69			AVG=	0.0137	AVG=	1.2061	AVG=	1.219
					SD=	0									SD=	0.10			SD=	0.0025	SD=	0.2719	SD=	0.773
28	20 4/8	AISI52100	st485	Si3N4	SN182	1001	10.00	9851	0.10	35.9	24	33	0.30	0.57	0.63	0.59	1.042	1.009	1.025	0.0108	35.9	0.0603		0.071
	21 4/8	AISI57100	st485	Si3N4	SN182	1002	10.00	9851	0.10	32.2	24	33	0.28	0.53	0.56	0.50	1.116	1.101	1.108	0.0148	32.2	0.0527		0.067
	22 4/4	AISI52100	st485	Si3N4	SN231	1002	10.00	9851	0.10	32.1	23	43	0.21	0.58	0.71	0.60	1.086	1.036	1.068	0.0174	32.1	0.0742		0.086
					AVG=	1002									AVG=	0.56			AVG=	0.0127	AVG=	0.0624	AVG=	0.075
					SD=	1									SD=	0.06			SD=	0.0020	SD=	0.0109	SD=	0.010

INDIVIDUAL LABORATORIES - STANDARD CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY %RH	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
16		Si3N4	2CB071	AISI52100	1SD423	1000	10.00		0.10	32.0	23	33	0.88	1.40	1.86	1.40	1.820	1.760	1.790	0.1010	32.0	0.1410		0.2420
		Si3N4	2CB071	AISI52100	1SD424	1000	10.00		0.10	32.0	24	34	0.94	1.27	1.54	1.29	1.800	1.800	1.800	0.1030	32.0	0.1360		0.239
		Si3N4	2CB071	AISI52100	1SD425	1000	10.00		0.10	32.0	24	33	0.96	1.77	2.80	1.82	2.000	1.968	1.980	0.1510	32.0	0.2370		0.380
					AVG=	1000									AVG=	1.50			AVG=	0.1183	AVG=	0.1713	AVG=	0.289
					SD=	0									SD=	0.20			SD=	0.0283	SD=	0.0569	SD=	0.085
17		Si3N4	2CB058	AISI52100	1SD426	1000	10.00		0.10	32.0	20	50	0.10	0.65	0.69	0.69	1.778	1.778	1.778	0.0980	32.0	0.0430		0.141
		Si3N4	2CB058	AISI52100	1SD427	1000	10.00		0.10	32.0	22	50	0.10	0.64	0.69	0.64	1.753	1.753	1.753	0.0930	32.0	0.0430		0.136
		Si3N4	2CB058	AISI52100	1SD428	1000	10.00		0.10	32.0	22	50	0.65	0.62	0.65	0.64	1.829	1.829	1.829	0.1090	32.0	0.0450		0.154
					AVG=	1000									AVG=	0.66			AVG=	0.1000	AVG=	0.0437	AVG=	0.143
					SD=	0									SD=	0.03			SD=	0.0082	SD=	0.0012	SD=	0.009
19		Si3N4	2CB043	AISI52100	1SD432	1000	10.00		0.10	32.0	23	57	0.14	0.83	0.95	0.82	1.780	1.760	1.770	0.0482	32.0	0.1410		0.189
		Si3N4	2CB043	AISI52100	1SD433	1000	10.00		0.10	32.0	22	53	0.14	0.82	0.89	0.84	1.980	1.940	1.960	0.0724	32.0	0.1330		0.205
		Si3N4	2CB043	AISI52100	1SD434	1000	10.00		0.10	32.0	23	71	0.21	0.83	0.89	0.83	1.860	1.820	1.840	0.0563	32.0	0.1530		0.20
					AVG=	1000									AVG=	0.83			AVG=	0.0590	AVG=	0.1423	AVG=	0.201
					SD=	0									SD=	0.01			SD=	0.0123	SD=	0.0101	SD=	0.010
20		Si3N4	2CB042	AISI52100	1SD435	1000	10.00		0.10	33.0	25	29	0.29	0.71	0.71	0.71	1.702	1.702	1.702	0.0823	33.0	2.0605		2.14
		Si3N4	2CB042	AISI52100	1SD436	1000	10.00		0.10	32.4	25	33	0.50	0.71	0.76	0.71	1.778	1.753	1.765	0.0953	32.4	1.8468		1.942
		Si3N4	2CB042	AISI52100	1SD437	1000	10.00		0.10	33.0	24	17	0.73	0.76	0.80	0.80	1.473	1.473	1.473	0.0462	33.0	2.3307		2.37
					AVG=	1000									AVG=	0.74			AVG=	0.0746	AVG=	2.0793	AVG=	2.15
					SD=	0									SD=	0.05			SD=	0.0254	SD=	0.2425	SD=	0.21
28	25 4/11	Si3N4	SN131	AISI52100	st549	1001	10.00	9851	0.10	33.5	23	22	0.20	0.57	0.61	0.55	1.405	1.469	1.437	0.0410	33.5	0.0070		0.04
	26 4/8	Si3N4	SN131	AISI52100	s1459	1002	10.00	9851	0.10	31.7	22	33	0.05	0.60	0.65	0.55	1.570	1.553	1.562	0.0584	31.7	0.0000		0.05
	27 4/7	Si3N4	SN131	AISI52100	st460	1002	10.00	9851	0.10	32.0	23	33	0.05	0.38	0.57	0.30	1.688	1.727	1.707	0.0834	32.0	0.0000		0.08
					AVG=	1002									AVG=	0.49			AVG=	0.0612	AVG=	0.0023	AVG=	0.06
					SD=	1									SD=	0.10			SD=	0.0209	SD=	0.0040	SD=	0.01

INDIVIDUAL LABORATORIES - STANDARD CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
16		AISI52100	ISB590	AISI52100	ISD513	1000	10.00		0.10	32.0	24	37	0.78	0.93	1.93	1.14	2.920	2.960	2.940	0.7335	32.0	0.2300		0.9635
		AISI52100	ISB591	AISI52100	ISD514	1000	10.00		0.10	32.0	24	36	0.89	1.46	2.10	1.82	3.000	2.960	2.980	0.7742	32.0	0.0510		0.8252
		AISI52100	ISB592	AISI52100	ISD515	1000	10.00		0.10	32.0	25	32	0.95	0.96	1.56	1.13	3.040	3.080	3.060	0.8600	32.0	0.1670		1.0270
					AVG=	1000									AVG=	1.36			AVG=	0.7895	AVG=	0.1493	AVG=	0.9388
					SD=	0									SD=	0.39			SD=	0.0650	SD=	0.0908	SD=	0.1035
17		AISI52100	ISB589	AISI52100	ISD516	1000	10.00		0.10	32.0	22	50	0.20	0.64	0.92	0.40	1.981	1.981	1.981	0.1510	32.0	0.0000		0.1510
		AISI52100	ISB587	AISI52100	ISD517	1000	10.00		0.10	32.0	22	50	0.20	0.54	0.73	0.40	2.007	2.007	2.007	0.1590	32.0	0.0000		0.1590
		AISI52100	ISB588	AISI52100	ISD518	1000	10.00		0.10	32.0	23	50	0.38	0.50	0.69	0.42	1.956	1.956	1.956	0.1440	32.0	0.0000		0.1440
					AVG=	1000									AVG=	0.41			AVG=	0.1513	AVG=	0.0000	AVG=	0.1513
					SD=	0									SD=	0.01			SD=	0.0075	SD=	0.0000	SD=	0.0075
19		AISI52100	ISB581	AISI52100	ISD522	1000	10.00		0.10	32.0	23	65	0.35	0.57	0.68	0.58	1.860	1.860	1.860	0.0580	32.0	0.1050		0.1630
		AISI52100	ISB582	AISI52100	ISD523	1000	10.00		0.10	32.0	24	66	0.16	0.51	0.66	0.52	1.860	1.860	1.860	0.0588	32.0	0.0900		0.1488
		AISI52100	ISB583	AISI52100	ISD524	1000	10.00		0.10	32.0	25	54	0.28	0.55	0.67	0.56	1.920	1.900	1.910	0.0653	32.0	0.1030		0.1683
					AVG=	1000									AVG=	0.55			AVG=	0.0610	AVG=	0.0993	AVG=	0.1603
					SD=	0									SD=	0.03			SD=	0.0038	SD=	0.0081	SD=	0.0102
20		AISI52100	ISB580	AISI52100	ISD525	1000	10.00		0.10	33.0	28	22	0.69	0.58	0.53	0.49	2.210	2.210	2.210	0.2341	33.0	1.5660		1.8001
		AISI52100	ISB640	AISI52100	ISD526	1000	10.00		0.10	35.3	26	15	0.62	0.76	0.76	0.71	2.159	2.159	2.159	0.2133	35.3	4.6121		4.8254
		AISI52100	ISB641	AISI52100	ISD527	1000	10.00		0.10	33.2	27	15	0.71	0.87	0.87	0.76	2.362	2.362	2.362	0.3057	33.2	3.4971		3.8028
					AVG=	1000									AVG=	0.65			AVG=	0.2510	AVG=	3.2251	AVG=	3.4761
					SD=	0									SD=	0.14			SD=	0.0485	SD=	1.5412	SD=	1.5389
28	31 4/6	AISI52100	st485	AISI52100	st460	1001	10.00	9851	0.10	35.5	24	37	0.11	0.43	0.64	0.43	2.068	2.075	2.071	0.1810	35.5	0.0009		0.1819
	32 4/5	AISI52100	st485	AISI52100	st461	1003	10.00	9862	0.10	32.2	24	35	0.09	0.50	0.63	0.50	2.139	2.143	2.141	0.2060	32.2	0.0000		0.2060
	33 4/6	AISI52100	st485	AISI52100	st461	1001	10.00	9851	0.10	35.3	23	37	0.40	0.32	0.50	0.33	2.074	2.084	2.079	0.1830	35.3	0.0000		0.1830
					AVG=	1002									AVG=	0.42			AVG=	0.1900	AVG=	0.0003	AVG=	0.1903
					SD=	1									SD=	0.09			SD=	0.0139	SD=	0.0005	SD=	0.0136

INDIVIDUAL LABORATORIES - LOW LOAD (2N) CONDITIONS

*** VAMAS RESULTS ALL LABS(6/88) ***SUMMARY AT A341***

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM cm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
25		Si3N4	2CB016	Al203	1CD369	1000	2.00		0.10	32.0	23	45	0.42	0.78	0.78	0.76	1.211	1.187	1.199	0.0203	32.0	0.0092		0.0295
		Si3N4	2CB018	Al203	1CD370	1000	2.00		0.10	32.0	23	45	0.53	0.88	0.88	0.70	1.160	1.195	1.178	0.0189	32.0	0.0123		0.0312
		Si3N4	2CB018	Al203	1CD371	1000	2.00		0.10	32.0	23	45	0.53	0.88	0.88	0.74	1.095	1.147	1.116	0.0152	32.0	0.0116		0.0268
					AVG=	1000									AVG=	0.73			AVG=	0.0181	AVG=	0.0110	AVG=	0.0292
					SD=	0									SD=	0.03			SD=	0.0026	SD=	0.0016	SD=	0.0022
27		Si3N4	2CB093	Al203	1CD312	1000	2.00		0.10	32.0	23	52	0.96	0.63	0.96	0.62	1.180	1.190	1.185	0.0194	32.0	0.0000		0.0194
		Si3N4	2CB098	Al203	1CD316	1000	2.00		0.10	32.0	23	52	0.91	0.66	0.91	0.60	1.170	1.170	1.170	0.0184	32.0	0.0000		0.0184
		Si3N4	2CB098	Al203	1CD320	1000	2.00		0.10	32.0	23	52	0.92	0.62	0.92	0.68	1.170	1.140	1.155	0.0175	32.0	0.0000		0.0175
					AVG=	1000									AVG=	0.63			AVG=	0.0184	AVG=	0.0000	AVG=	0.0184
					SD=	0									SD=	0.04			SD=	0.0010	SD=	0.0000	SD=	0.0010
28	5 2/7	Si3N4	SN028	Al203	ALOX295	1008	2.00	9907	0.10	32.2	23	11	0.46		0.67	0.60	1.220	1.170	1.195	0.0197	32.2	0.0060		0.0257
	18 3/28	Si3N4	SN059	Al203	ALOX365	1002	2.00	9E51	0.10	32.3	23	20	0.40	0.15	0.47	0.15	1.211	1.235	1.223	0.0219	32.3	0.0047		0.0265
	19 3/30	Si3N4	SN059	Al203	ALOX366	1001	2.00	9850	0.10	35.9	23	33	0.11	0.40	0.74	0.40	1.247	1.236	1.241	0.0233	35.9	0.0048		0.0281
					AVG=	1004									AVG=	0.38			AVG=	0.0216	AVG=	0.0052	AVG=	0.0268
					SD=	4									SD=	0.23			SD=	0.0018	SD=	0.0008	SD=	0.0012
29		Si3N4	2CB091	Al203	1CD384	1000	2.00		0.10	32.0	24					0.29	1.220	1.220	1.220	0.0247	32.0	0.0064		0.0311
		Si3N4	2CB091	Al203	1CD404	1000	2.00		0.10	32.0	24					0.29	1.240	1.240	1.240	0.0232	32.0	0.0184		0.0416
					1CD400																			0.0000
					AVG=	1000									AVG=	0.29			AVG=	0.0240	AVG=	0.0124	AVG=	0.0242
					SD=	0									SD=	0.00			SD=	0.0009	SD=	0.0073	SD=	0.0216
30		Si3N4	2CB038	Al203	1CD357	1000	2.00		0.10	32.0	23	60	0.38	0.50	0.65	0.55	1.200	1.190	1.195	0.0200	32.0	0.8350		0.8550
		Si3N4	2CB038	Al203	1CD358	1000	2.00		0.10	32.0	23	53	0.63	0.60	0.72	0.60	1.210	1.210	1.210	0.0210	32.0	1.0550		1.0760
		Si3N4	2CB038	Al203	1CD359	1000	2.00		0.10	32.0	23	58	0.64	0.69	0.77	0.63	1.220	1.200	1.210	0.0210	32.0	0.6100		0.6310
					AVG=	1000									AVG=	0.59			AVG=	0.0207	AVG=	0.8333	AVG=	0.8540
					SD=	0									SD=	0.04			SD=	0.0006	SD=	0.2225	SD=	0.2225
42		Si3N4	2CB115	Al203	1CD406	1000	2.00		0.10	32.0	21	52	1.00	0.75	1.00	0.80	1.175	1.210	1.193	0.0195	32.0			
		Si3N4	2CB115	Al203	1CD407	1000	2.00		0.10	32.0	24	52	0.92	0.74	0.92	0.80	1.205	1.230	1.218	0.0216	32.0			
		Si3N4	2CB115	Al203	1CD408	1000	2.00		0.10	32.0	23	52	0.93	0.77	0.94	0.80	1.195	1.235	1.215	0.0214	32.0			
					AVG=	1000									AVG=	0.80			AVG=	0.0209	AVG=		AVG=	
					SD=	0									SD=	0.00			SD=	0.0009	SD=		SD=	

INDIVIDUAL LABORATORIES - LOW LOAD (2N) CONDITIONS

*** VAMAS RESULTS ALL LABS(6/28) ***SUMMARY AT A341***

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
26		Si3N4	2CB061	Si3N4	2CD070	1000	2.00		0.10	32.0	23	45	0.49	0.67	0.78	0.68	1.276	1.314	1.295	0.0276	32.0	0.0543		0.0819
		Si3N4	2CB061	Si3N4	2CD071	1000	2.00		0.10	32.0	23	45	0.28	0.64	0.67	0.64	1.230	1.208	1.219	0.0217	32.0	0.0624		0.0841
		Si3N4	2CB061	Si3N4	2CD072	1000	2.00		0.10	32.0	23	45	0.21	0.64	0.64	0.60	1.253	1.212	1.233	0.0227	32.0	0.0600		0.0827
					AVG=	1000									AVG=	0.64			AVG=	0.0240	AVG=	0.0589	AVG=	0.0829
					SD=	0									SD=	0.04			SD=	0.0032	SD=	0.0042	SD=	0.0011
27		Si3N4	2CB060	Si3N4	2CD073	1000	2.00		0.10	32.0	25	53	0.84	0.67	0.84	0.67	0.890	0.860	0.875	0.0058	32.0			
		Si3N4	2CB060	Si3N4	2CD074	1000	2.00		0.10	32.0	23	53	0.84	0.67	0.84	0.67	0.940	0.940	0.940	0.0077	32.0			
		Si3N4	2CB060	Si3N4	2CD075	1000	2.00		0.10	32.0	24	53	0.89	0.66	0.89	0.66	0.840	0.840	0.840	0.0048	32.0			
					AVG=	1000									AVG=	0.67			AVG=	0.0061	AVG=		AVG=	
					SD=	0									SD=	0.01			SD=	0.0015	SD=		SD=	
28	14 3/21	Si3N4	SN026	Si3N4	SN091	1001	2.00	9651	0.10	36.1	22	9	0.34	0.39	0.62	0.30	1.046	1.045	1.045	0.0117	36.1	0.0025		0.0142
	15 3/22	Si3N4	SN028	Si3N4	SN092	1007	2.00	9900	0.10	32.2	23	11	0.48	0.88	1.17	0.90	1.092	1.092	1.092	0.0140	32.2	0.0025		0.0165
	35 5/13	Si3N4	SN029	Si3N4	SN231	1001	2.00	9851	0.10	35.9	25	45	0.43	0.46	0.82	0.60	0.925	0.916	0.921	0.0071	35.9	0.0405		0.0476
					AVG=	1003									AVG=	0.60			AVG=	0.0109	AVG=	0.0152	AVG=	0.0261
					SD=	3									SD=	0.30			SD=	0.0035	SD=	0.0219	SD=	0.0186
29		Si3N4	2CB073	Si3N4	2CD095	1000	2.00		0.10	32.0	24					0.33	1.200	1.000	1.100	0.0144	32.0	0.0457		0.0601
		Si3N4	2CB073	Si3N4	2CD096	1000	2.00		0.10	32.0	24						0.950	0.950	0.950	0.0080	32.0	0.0483		0.0563
					AVG=	1000									AVG=	0.33			AVG=	0.0112	AVG=	0.0470	AVG=	0.0582
					SD=	0									SD=	0.00			SD=	0.0039	SD=	0.0016	SD=	0.0021
30		Si3N4	2CB052	Si3N4	2CD097	1000	2.00		0.10	32.0	23	60	0.65	0.43	0.88	0.46	0.795	0.785	0.790	0.0036	32.0	0.7070		0.7106
		Si3N4	2CB052	Si3N4	2CD098	1000	2.00		0.10	32.0	23	60	0.65	0.69	0.75	0.68	0.780	0.765	0.773	0.0035	32.0	0.6790		0.6825
		Si3N4	2CB052	Si3N4	2CD099	1000	2.00		0.10	32.0	23	54	0.50	0.43	0.70	0.48	0.765	0.770	0.768	0.0036	32.0	0.6000		0.6036
					AVG=	1000									AVG=	0.54			AVG=	0.0036	AVG=	0.6620	AVG=	0.6656
					SD=	0									SD=	0.12			SD=	0.0001	SD=	0.0555	SD=	0.0555
42		Si3N4	2CB130	Si3N4	2CD202	1000	2.00		0.10	32.0	23	52	0.87	0.63	0.90	0.69	1.110	1.120	1.115	0.0152	32.0			
		Si3N4	2CB130	Si3N4	2CD203	1000	2.00		0.10	32.0	27	51	0.90	0.62	0.91	0.66	0.985	1.000	0.993	0.0095	32.0			
		Si3N4	2CB130	Si3N4	2CD204	1000	2.00		0.10	32.0	25	52	0.67	0.73	0.88	0.76	0.950	0.960	0.955	0.0082	32.0			
					AVG=	1000									AVG=	0.70			AVG=	0.0109	AVG=		AVG=	
					SD=	0									SD=	0.05			SD=	0.0037	SD=		SD=	

INDIVIDUAL LABORATORIES - LOW LOAD (2N) CONDITIONS

*** VAMAS RESULTS ALL LABS(6/88) ***SUMMARY BY A141***

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
26		AISI52100	1SB479	Si3N4	2CD175	1000	2.00		0.10	32.0	23	45	0.35	0.78	0.78	0.73	1.050	1.027	1.039	0.0114	32.0	0.0499		0.0613
		AISI52100	1SB480	Si3N4	2CD176	1000	2.00		0.10	32.0	23	45	0.25	0.78	0.92	0.77	1.012	1.027	1.020	0.0106	32.0	0.0506		0.0612
		AISI52100	1SB481	Si3N4	2CD177	1000	2.00		0.10	32.0	23	45	0.21	0.78	0.88	0.85	1.062	1.065	1.064	0.0126	32.0	0.0467		0.0593
					AVG=	1000									AVG=	0.78			AVG=	0.0115	AVG=	0.0491	AVG=	0.0606
					SD=	0									SD=	0.06			SD=	0.0010	SD=	0.0021	SD=	0.0011
27		AISI52100	1SB482	Si3N4	2CD178	1000	2.00		0.10	32.0	23	52	0.83	0.86	0.86	0.84	0.990	0.990	0.990	0.0094	32.0			
		AISI52100	1SB483	Si3N4	2CD179	1000	2.00		0.10	32.0	23	58	0.89	0.89	0.89	0.89	1.020	1.020	1.020	0.0106	32.0			
		AISI52100	1SB484	Si3N4	2CD180	1000	2.00		0.10	32.0	23	58	0.88	0.83	0.88	0.82	0.950	0.940	0.945	0.0078	32.0			
					AVG=	1000									AVG=	0.85			AVG=	0.0093	AVG=		AVG=	
					SD=	0									SD=	0.04			SD=	0.0014	SD=		SD=	
29		AISI52100	1SB488	Si3N4	2CD184	1000	2.00		0.10	32.0	23					0.22	1.690	1.660	1.675	0.0773	32.0	0.0052		0.0825
		AISI52100	1SB489	Si3N4	2CD185	1000	2.00		0.10	32.0	23					0.29	1.120	1.120	1.120	0.0154	32.0	0.0187		0.0341
					AVG=	1000									AVG=	0.26			AVG=	0.0463	AVG=	0.0120	AVG=	0.0583
					SD=	0									SD=	0.04			SD=	0.0379	SD=	0.0083	SD=	0.0296
30		AISI52100	1SB491	Si3N4	2CD187	1000	2.00		0.10	32.0	23	60	0.59	0.60	0.70	0.60	0.969	0.969	0.969	0.0087	32.0	0.0475		0.0562
		AISI52100	1SB492	Si3N4	2CD186	1000	2.00		0.10	32.0	23	60	0.60	0.60	0.70	0.60	0.921	0.925	0.923	0.0071	32.0	0.0575		0.0646
		AISI52100	1SB493	Si3N4	2CD189	1000	2.00		0.10	32.0	23	60	0.62	0.60	0.72	0.62	0.905	0.875	0.890	0.0062	32.0	0.1290		0.1352
					AVG=	1000									AVG=	0.61			AVG=	0.0073	AVG=	0.0780	AVG=	0.0953
					SD=	0									SD=	0.01			SD=	0.0013	SD=	0.0444	SD=	0.0434
42		AISI52100	1SBX28	Si3N4	2CD232	1000	2.00		0.10	32.0	29	50	0.92	0.83	0.95	0.84	1.020	1.045	1.033	0.0112	32.0			
		AISI52100	1SBX29	Si3N4	2CD233	1000	2.00		0.10	32.0	23	51	0.88	0.83	0.93	0.83	1.010	1.025	1.018	0.0105	32.0			
		AISI52100	1SBX30	Si3N4	2CD234	1000	2.00		0.10	32.0	23	51	0.85	0.75	0.87	0.83	1.015	1.020	1.018	0.0105	32.0			
					AVG=	1000									AVG=	0.83			AVG=	0.0107	AVG=		AVG=	
					SD=	0									SD=	0.01			SD=	0.0004	SD=		SD=	

INDIVIDUAL LABORATORIES - LOW LOAD (2N) CONDITIONS

*** VAMAS RESULTS ALL LABS(6/86) ***SUMMARY AT A341***

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
26		Si3N4	2CB032	AISI52100	1SD453	1000	2.00		0.10	32.0	23	45	0.42	0.88	0.88	0.76	1.082	1.107	1.095	0.0141	32.0	0.0066		0.0207
		Si3N4	2CB032	AISI52100	1SD454	1000	2.00		0.10	32.0	23	45	0.53	0.87	0.87	0.70	1.119	1.092	1.106	0.0147	32.0	0.0041		0.0188
		Si3N4	2CB032	AISI52100	1SD455	1000	2.00		0.10	32.0	23	45	0.25	0.92	0.99	0.81	1.612	1.689	1.651	0.0729	32.0	0.0287		0.1016
					AVG=	1000									AVG=	0.76			AVG=	0.0339	AVG=	0.0131	AVG=	0.0470
					SD=	0									SD=	0.06			SD=	0.0338	SD=	0.0135	SD=	0.0473
27		Si3N4	2CB030	AISI52100	1SD456	1000	2.00		0.10	32.0	24	50	0.89	0.82	1.00	0.84	1.140	1.110	1.125	0.0157	32.0	0.0000		0.0157
		Si3N4	2CB030	AISI52100	1SD457	1000	2.00		0.10	32.0	24	50	1.00	0.79	1.00	0.85	1.140	1.110	1.125	0.0157	32.0	0.0000		0.0157
		Si3N4	2CB030	AISI52100	1SD458	1000	2.00		0.10	32.0	23	52	1.00	0.77	1.00	0.75	1.140	1.140	1.140	0.0166	32.0	0.0000		0.0166
					AVG=	1000									AVG=	0.81			AVG=	0.0160	AVG=	0.0000	AVG=	0.0160
					SD=	0									SD=	0.06			SD=	0.0005	SD=	0.0000	SD=	0.0005
29		Si3N4	2CB027	AISI52100	1SD462	1000	2.00		0.10	29.0	23					0.27	1.220	1.220	1.220	0.0217	29.0			
		Si3N4	2CB027	AISI52100	1SD463	1000	2.00		0.10	29.0	24					0.29	0.805	0.805	0.805	0.0041	29.0			
		Si3N4	2CB027	AISI52100	1SD464	1000	2.00		0.10	29.0	23					0.27	1.250	1.220	1.235	0.0228	29.0	0.0073		0.0301
					AVG=	1000									AVG=	0.28			AVG=	0.0162	AVG=	0.0073	AVG=	0.0235
					SD=	0									SD=	0.01			SD=	0.0105	SD=		SD=	0.0105
30		Si3N4	2CB026	AISI52100	1SD465	1000	2.00		0.10	32.0	23	59	0.13	0.35	0.40	0.14	0.585	0.595	0.590	0.0012	32.0	0.1290		0.1302
		Si3N4	2CB026	AISI52100	1SD466	1000	2.00		0.10	32.0	23	58	0.65	0.50	0.74	0.58	1.124	1.119	1.122	0.0155	32.0	0.1070		0.1225
		Si3N4	2CB026	AISI52100	1SD467	1000	2.00		0.10	32.0	23	58	0.65	0.55	0.72	0.55	1.087	1.079	1.083	0.0135	32.0	0.1070		0.1205
					AVG=	1000									AVG=	0.42			AVG=	0.0101	AVG=	0.1143	AVG=	0.1244
					SD=	0									SD=	0.25			SD=	0.0077	SD=	0.0127	SD=	0.0051
42		Si3N4	2CB125	AISI52100	1SD594	1000	2.00		0.10	32.0	[illegible]	53	0.97	0.85	1.00	0.85	1.190	1.205	1.198	0.0202	32.0			
		Si3N4	2CB125	AISI52100	1SD595	1000	2.00		0.10	32.0	[illegible]	51	1.05	0.82	1.05	0.85	1.180	1.190	1.185	0.0193	32.0			
		Si3N4	2CB125	AISI52100	1SD596	1000	2.00		0.10	32.0	25	51	0.77	0.78	0.85	0.80	1.180	1.195	1.198	0.0195	32.0			
					AVG=	1000									AVG=	0.83			AVG=	0.0197	AVG=		AVG=	
					SD=	0									SD=	0.03			SD=	0.0004	SD=		SD=	

INDIVIDUAL LABORATORIES - LOW LOAD (2N) CONDITIONS

*** VAMAS RESULTS ALL LABS(6/88) ***SUMMARY AT A341***

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CURRENT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3		TOTAL W V mm^3
25		AISI52100	1SB622	AISI52100	1SD543	1000	2.00		0.10	32.0	23	45	0.42	0.78	0.88	0.77	1.122	1.138	1.130	0.016	32.0	0.0004		0.0164
		AISI52100	1SB623	AISI52100	1SD544	1000	2.00		0.10	32.0	23	45	0.25	0.78	0.78	0.65	1.046	1.073	1.060	0.0124	32.0			
		AISI52100	1SB624	AISI52100	1SD545	1000	2.00		0.10	32.0	23	45	0.25	0.71	0.71	0.59	1.110	1.117	1.114	0.0151	32.0			
					AVG=	1000									AVG=	0.67			AVG=	0.0145	AVG=	0.0004	AVG=	0.0164
					SD=	0									SD=	0.09			SD=	0.0019	SD=		SD=	
27		AISI52100	1SB619	AISI52100	1SD546	1000	2.00		0.10	32.0	24	54	0.62	0.60	0.62	0.61	1.350	1.350	1.350	0.0326	32.0	0.0000		0.0326
		AISI52100	1SB620	AISI52100	1SD547	1000	2.00		0.10	32.0	23	68	0.59	0.58	0.75	0.60	1.320	1.350	1.335	0.0312	32.0	0.0000		0.0312
		AISI52100	1SB621	AISI52100	1SD548	1000	2.00		0.10	32.0	24	52	0.71	0.60	0.94	0.60	1.500	1.500	1.500	0.0497	32.0	0.0000		0.0497
					AVG=	1000									AVG=	0.60			AVG=	0.0378	AVG=	0.0000	AVG=	0.0378
					SD=	0									SD=	0.01			SD=	0.0103	SD=	0.0000	SD=	0.0103
29		AISI52100	1SB613	AISI52100	1SD552	1000	2.00		0.10	29.0	22					0.29	1.320	1.320	1.320	0.0298	29.0			
					AVG=	1000									AVG=	0.29			AVG=	0.0298			AVG=	
					SD=	0									SD=				SD=				SD=	
30		AISI52100	1SB610	AISI52100	1SD555	1000	2.00		0.10	32.0	23	56	0.45	0.60	0.80	0.42	1.342	1.360	1.351	0.0327	32.0	3.5140		3.5467
		AISI52100	1SB611	AISI52100	1SD556	1000	2.00		0.10	32.0	23	56	0.37	0.45	0.51	0.43	1.310	1.310	1.310	0.0299	32.0	3.5140		3.5429
		AISI52100	1SB612	AISI52100	1SD557	1000	2.00		0.10	32.0	23	56	0.44	0.43	0.55	0.43	1.310	1.330	1.320	0.0300	32.0	3.1950		3.2250
					AVG=	1000									AVG=	0.43			AVG=	0.0305	AVG=	3.4077	AVG=	3.4382
					SD=	0									SD=	0.01			SD=	0.0020	SD=	0.1342	SD=	0.1845
42		AISI52100	1SB609	AISI52100	1SD564	1000	2.00		0.10	32.0	21	53	0.65	0.70	0.72	0.66	1.525	1.530	1.528	0.0534	32.0			
		AISI52100	1SB649	AISI52100	1SD565	1000	2.00		0.10	32.0	23	52	0.68	0.67	0.68	0.65	1.580	1.580	1.590	0.0612	32.0			
		AISI52100	1SB650	AISI52100	1SD566	1000	2.00		0.10	32.0	25	52	0.75	0.69	0.82	0.71	1.630	1.640	1.635	0.0693	32.0			
					AVG=	1000									AVG=	0.67			AVG=	0.0613	AVG=		AVG=	
					SD=	0									SD=	0.03			SD=	0.0079	SD=		SD=	

INDIVIDUAL LABORATORIES - LUBRICATED CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3	TOTAL W V mm^3
34	1L	Si3N4	2CB132	Si3N4	2CD226	1000	10.00		0.10	33.4	22	41	0.12	0.13	0.16	0.12	0.390	0.385	0.388	0.0002200	33.4	0.0000000	0.0002200
	2L	Si3N4	2CB132	Si3N4	2CD227	1000	10.00		0.10	33.4	23	49	0.11	0.11	0.15	0.11	0.395	0.395	0.395	0.0002400	33.4	0.0000000	0.0002400
	3L	Si3N4	2CB132	Si3N4	2CD228	1000	10.00		0.10	33.4	21	56	0.11	0.12	0.18	0.12	0.370	0.375	0.373	0.0002000	33.4	0.0000000	0.0002000
					AVG=	1000									AVG=	0.12			AVG=	0.0002200	AVG=	0.0000000	AVG= 0.0002200
					SD=	0									SD=	0.01			SD=	0.0000200	SD=	0.0000000	SD= 0.0000200
36	1L	Si3N4	2CB134	Si3N4	2CD220	1000	10.00		0.10	32.0	23	43	0.11	0.09	0.11	0.10	0.346	0.346	0.346	0.0001407	32.0	0.0000000	0.0001407
	2L	Si3N4	2CB134	Si3N4	2CD221	1000	10.00		0.10	32.0	23	53	0.11	0.09	0.12	0.09	0.269	0.279	0.274	0.0000553	32.0	0.0000000	0.0000553
	3L	Si3N4	2CB134	Si3N4	2CD222	1000	10.00		0.10	32.0	23	47	0.11	0.09	0.12	0.09	0.226	0.226	0.226	0.0000256	32.0	0.0000000	0.0000256
	4L	Si3N4	2CB134	Si3N4	2CD220	1000	10.00		0.10	35.0	23	43	0.09	0.06	0.09	0.06	0.370	0.365	0.368	0.0001791	35.0	0.0000000	0.0001791
					AVG=	1000									AVG=	0.08			AVG=	0.0001002	AVG=	0.0000000	AVG= 0.0001002
					SD=	0									SD=	0.02			SD=	0.0000717	SD=	0.0000000	SD= 0.0000717
37	1L	Si3N4	2CB135	Si3N4	2CD217	1000	10.00			32.0	23	53	0.10	0.09	0.11	0.09	0.570	0.570	0.570	0.0010000	32.0	0.0000000	0.0010000
	2L	Si3N4	2CB135	Si3N4	2CD218	1000	10.00		0.10	32.0	33	44	0.11	0.10	0.12	0.10	0.400	0.400	0.400	0.0002500	32.0	0.0000000	0.0002500
	3L	Si3N4	2CB135	Si3N4	2CD219	1000	10.00		0.10	32.0	32	50	0.11	0.10	0.11	0.10	0.400	0.400	0.400	0.0002500	32.0	0.0000000	0.0002500
					AVG=	1000									AVG=	0.10			AVG=	0.0005000	AVG=	0.0000000	AVG= 0.0005000
					SD=	0									SD=	0.01			SD=	0.0004330	SD=	0.0000000	SD= 0.0004330
39	1L	Si3N4	2CB127	Si3N4	2CD211	1255	9.87		0.12	37.0	20	62	0.10	0.09	0.11	0.08	0.387	0.387	0.387	0.0002200	37.0	0.0523000	0.0525200
	2L	Si3N4	2CB127	Si3N4	2CD212	1255	9.87		0.12	37.0	20	62	0.10	0.09	0.10	0.09	0.275	0.275	0.275	0.0000561	37.0	0.0532000	0.0532561
	3L	Si3N4	2CB127	Si3N4	2CD213	1187	9.87		0.11	35.0	20	62	0.12	0.09	0.12	0.09	0.375	0.375	0.375	0.0001940	35.0	0.0494000	0.0495940
					AVG=	1232									AVG=	0.08			AVG=	0.0001567	AVG=	0.0516333	AVG= 0.0517900
					SD=	39									SD=	0.00			SD=	0.0000881	SD=	0.0019858	SD= 0.0019371
28	10L 2/11	Si3N4	SN039	Al203	ALDX296	1001	10.00	9851	0.10	36.3	23	20	0.06	0.09	0.12	0.09	0.288	0.293	0.291	0.0000694	36.3	0.0000000	0.0000694
	23L 4/20	Si3N4	SN039	Al203	ALDX367	1001	10.00	9851	0.10	35.8	23	16	0.09	0.12	0.15	0.12	0.291	0.283	0.287	0.0000666	35.8	0.0000000	0.0000666
	24L 4/21	Si3N4	SN039	Al203	ALDX367	1002	10.00	9851	0.10	32.0	23	18	0.14	0.08	0.14	0.07	0.291	0.291	0.291	0.0000701	32.0	0.0000000	0.0000701
					AVG=	1001									AVG=	0.09			AVG=	0.0000687	AVG=	0.0000000	AVG= 0.0000687
					SD=	1									SD=	0.03			SD=	0.0000019	SD=	0.0000000	SD= 0.0000019
36	1L	Si3N4	2CB111	Al203	1CD437	1000	10.00		0.10	32.0	23	50	0.11	0.09	0.11	0.09	0.240	0.231	0.236	0.0000302	32.0	0.0000000	0.0000302
	2L	Si3N4	2CB111	Al203	1CD438	1000	10.00		0.10	32.0	23	50	0.11	0.11	0.12	0.11	0.236	0.221	0.229	0.0000268	32.0	0.0000000	0.0000268
	3L	Si3N4	2CB111	Al203	1CD439	1000	10.00		0.10	32.0	24	44	0.10	0.09	0.11	0.09	0.236	0.240	0.238	0.0000315	32.0	0.0000000	0.0000315
					AVG=	1000									AVG=	0.10			AVG=	0.0000295	AVG=	0.0000000	AVG= 0.0000295
					SD=	0									SD=	0.01			SD=	0.0000024	SD=	0.0000000	SD= 0.0000024
37	1L	Si3N4	2CB107	Al203	1CD448	988	10.00		0.10	32.0	28	44	0.14	0.11	0.14	0.11	0.290	0.260	0.275	0.0000280	32.0	0.0000000	0.0000280
	2L	Si3N4	2CB107	Al203	1CD452	994	10.00		0.10	32.0	26	49	0.12	0.11	0.13	0.12	0.220	0.220	0.220	0.0000120	32.0	0.0000000	0.0000120
	3L	Si3N4	2CB107	Al203	1CD456	1006	10.00		0.10	32.0	26	43	0.13	0.12	0.13	0.12	0.250	0.240	0.245	0.0000180	32.0	0.0000000	0.0000180
					AVG=	996									AVG=	0.12			AVG=	0.0000193	AVG=	0.0000000	AVG= 0.0000193
					SD=	9									SD=	0.01			SD=	0.0000081	SD=	0.0000000	SD= 0.0000081
39	1L	Si3N4	2CB112	Al203	1CD433	1086	9.87		0.10	32.0	21	62	0.10	0.09	0.12	0.09	0.260	0.260	0.260	0.0000466	32.0	0.0000000	0.0000466
	2L	Si3N4	2CB112	Al203	1CD434	1086	9.87		0.10	32.0	21	62	0.10	0.09	0.12	0.09	0.280	0.280	0.280	0.0000561	32.0	0.0000000	0.0000561
	3L	Si3N4	2CB112	Al203	1CD435	1086	9.87		0.10	32.0	21	62	0.10	0.08	0.10	0.09	0.280	0.280	0.280	0.0000561	32.0	0.0000000	0.0000561
					AVG=	1086									AVG=	0.09			AVG=	0.0000529	AVG=	0.0000000	AVG= 0.0000529
					SD=	0									SD=	0.00			SD=	0.0000055	SD=	0.0000000	SD= 0.0000055

INDIVIDUAL LABORATORIES - LUBRICATED CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3	TOTAL W V mm^3
28	28L 4/14	Si3N4	SN039	AISI52100	s1549	1002	10.00	9851	0.10	31.8	23	22	0.03	0.06	0.07	0.05	0.291	0.290	0.290	0.0000698	31.8	0.0000000	0.0000698
	29L 4/15	Si3N4	SN039	AISI52100	s1550	1002	10.00	9851	0.10	32.1	23	29	0.04	0.09	0.10	0.07	0.285	0.295	0.290	0.0000696	32.1	0.0167000	0.0167696
	30L 4/15	Si3N4	SN039	AISI52100	s1550	1001	10.00	9851	0.10	35.7	23	28	0.10	0.10	0.13	0.09	0.293	0.294	0.294	0.0000729	35.7	0.0019000	0.0019729
					AVG=	1002									AVG=	0.07			AVG=	0.0000708	AVG=	0.0062000	AVG= 0.0062708
					SD=	1									SD=	0.02			SD=	0.0000019	SD=	0.0091428	SD= 0.0091419
36	1L	Si3N4	2CB119	AISI52100	1SD612	1000	10.00		0.10	32.0	23	36	0.11	0.11	0.11	0.11	0.284	0.288	0.286	0.0000657	32.0	0.0000000	0.0000657
	2L	Si3N4	2CB119	AISI52100	1SD613	1000	10.00		0.10	32.0	23	50	0.10	0.10	0.10	0.10	0.298	0.298	0.298	0.0000774	32.0	0.0000000	0.0000774
	3L	Si3N4	2CB119	AISI52100	1SD614	1000	10.00		0.10	32.0	23	43	0.10	0.10	0.10	0.10	0.274	0.274	0.274	0.0000553	32.0	0.0000000	0.0000553
					AVG=	1000									AVG=	0.10			AVG=	0.0000661	AVG=	0.0000000	AVG= 0.0000661
					SD=	0									SD=	0.01			SD=	0.0000111	SD=	0.0000000	SD= 0.0000111
37	1L	Si3N4	2CB120	AISI52100	1SD609	1000	10.00		0.10	32.0	30	48	0.11	0.11	0.11	0.11	0.300	0.300	0.300	0.0000800	32.0	0.0000000	0.0000800
	2L	Si3N4	2CB120	AISI52100	1SD610	1000	10.00		0.10	32.0	35	45	0.11	0.11	0.11	0.11	0.330	0.330	0.330	0.0001200	32.0	0.0000000	0.0001200
	3L	Si3N4	2CB120	AISI52100	1SD611	1000	10.00		0.10	32.0	32	53	0.11	0.11	0.11	0.11	0.340	0.340	0.340	0.0001300	32.0	0.0000000	0.0001300
					AVG=	1000									AVG=	0.11			AVG=	0.0001100	AVG=	0.0000000	AVG= 0.0001100
					SD=	0									SD=	0.00			SD=	0.0000265	SD=	0.0000000	SD= 0.0000265
39	1L	Si3N4	2CB122	AISI52100	1SD603	1086	9.87		0.10	32.0	20	62	0.10	0.09	0.11	0.10	0.300	0.300	0.300	0.0000795	32.0	0.0000000	0.0000795
	2L	Si3N4	2CB122	AISI52100	1SD604	1086	9.87		0.10	32.0	20	62	0.09	0.08	0.10	0.09	0.470	0.480	0.475	0.0004840	32.0	0.0000000	0.0004840
	3L	Si3N4	2CB122	AISI52100	1SD605	1086	9.87		0.10	32.D	20	62	0.10	0.09	0.10	0.09	0.280	0.290	0.285	0.0000614	32.0	0.0000000	0.0000614
					AVG=	1086									AVG=	0.09			AVG=	0.0002083	AVG=	0.0000000	AVG= 0.0002083
					SD=	0									SD=	0.00			SD=	0.0002389	SD=	0.0000000	SD= 0.0002389
34	1L	AISI52100	1SB152	Si3N4	2CD256	1000	10.00		0.10	33.4	22	48	0.11	0.21	0.33	0.21	0.750	0.740	0.745	0.0031000	33.4	0.0000000	0.0031000
	2L	AISI52100	1SB153	Si3N4	2CD257	1000	10.00		0.10	33.4	22	50	0.12	0.11	0.19	0.12	0.545	0.555	0.550	0.0009400	33.4	0.0000000	0.0009400
	3L	AISI52100	1SB154	Si3N4	2CD258	1000	10.00		0.10	33.4	22	38	0.13	0.16	0.18	0.13	0.400	0.400	0.400	0.0002500	33.4	0.0000000	0.0002500
					AVG=	1000									AVG=	0.16			AVG=	0.0014300	AVG=	0.0000000	AVG= 0.0014300
					SD=	0									SD=	0.05			SD=	0.0014868	SD=	0.0000000	SD= 0.0014868
36	1L	AISI52100	1SB146	Si3N4	2CD250	1000	10.00		0.10	32.0	24	40	0.08	0.11	0.11	0.11	0.308	0.308	0.308	0.0000883	32.0	0.0000000	0.0000883
	2L	AISI52100	1SB147	Si3N4	2CD251	1000	10.00		0.10	32.0	24	37	0.10	0.10	0.11	0.10	0.288	0.303	0.296	0.0000749	32.0	0.0000000	0.0000749
	3L	AISI52100	1SB148	Si3N4	2CD252	1000	10.00		0.10	32.0	23	47	0.11	0.09	0.12	0.10	0.322	0.322	0.322	0.0001055	32.0	0.0000000	0.0001055
					AVG=	1000									AVG=	0.10			AVG=	0.0000896	AVG=	0.0000000	AVG= 0.0000896
					SD=	0									SD=	0.00			SD=	0.0000154	SD=	0.0000000	SD= 0.0000154
37	1L	AISI52100	1SB143	Si3N4	2CD247	1003	10.00		0.10	32.0	34	57	0.13	0.14	0.14	0.14	0.530	0.520	0.525	0.0003700	32.0	0.0000000	0.0003700
	2L	AISI52100	1SB144	Si3N4	2CD248	1081	10.00		0.10	35.0	27	45	0.11	0.14	0.15	0.13	0.510	0.500	0.505	0.0003200	35.0	0.0000000	0.0003200
	3L	AISI52100	1SB145	Si3N4	2CD249	1056	10.00		0.10	34.0	23	47	0.12	0.11	0.13	0.10	0.370	0.370	0.370	0.0000920	34.0	0.0000000	0.0000920
					AVG=	1047									AVG=	0.12			AVG=	0.0002607	AVG=	0.0000000	AVG= 0.0002607
					SD=	40									SD=	0.02			SD=	0.0001482	SD=	0.0000000	SD= 0.0001482
39	1L	AISI52100	1SB137	Si3N4	2CD241	1086	9.87		0.10	32.0	20	60	0.09	0.09	0.12	0.09	0.630	0.630	0.630	0.0015000	32.0	0.0511000	0.0526000
	2L	AISI52100	1SB138	Si3N4	2CD242	1086	9.87		0.10	32.0	20	60	0.10	0.08	0.11	0.08	0.690	0.690	0.690	0.0021900	32.0	0.0511000	0.0532900
	3L	AISI52100	1SB139	Si3N4	2CD243	1086	9.87		0.10	31.0	20	60	0.10	0.09	0.13	0.09	0.580	0.580	0.580	0.0010700	31.0	0.0348000	0.0358700
					AVG=	1086									AVG=	0.09			AVG=	0.0015867	AVG=	0.0456667	AVG= 0.0472533
					SD=	0									SD=	0.01			SD=	0.0005650	SD=	0.0094108	SD= 0.0098643

INDIVIDUAL LABORATORIES - LUBRICATED CONDITIONS

LAB	TEST # DATE	BALL MATERIAL	BALL #	DISK MATERIAL	DISK #	DISTANCE m	LOAD N	TEST TIME s	VELOCITY m/s	DISK TRACK DIAM mm	TEMP deg C	CORRECT HUMIDITY RH%	INITIAL FRICT COEF	FINAL FRICT COEF	MAX FRICT COEF	AVG FRICT COEF	BALL perp mm	SCAR para mm	BALL SCAR AVG mm	BALL W V mm^3	DISK TRACK DIAM mm	DISK W V mm^3	TOTAL W V mm^3
34	1L	AISI52100	1SBX22	AISI52100	1SD588	1000	10.00		0.10	33.4	23	34	0.11	0.11	0.18	0.11	0.548	0.548	0.548	0.0008800	33.4	0.0000000	0.0008800
	2L	AISI52100	1SBX23	AISI52100	1SD589	1000	10.00		0.10	33.4	22	36	0.11	0.16	0.23	0.16	0.562	0.562	0.562	0.0009800	33.4	0.0000000	0.0009800
	3L	AISI52100	1SBX24	AISI52100	1SD590	1000	10.00		0.10	33.4	23	38	0.11	0.15	0.22	0.15	0.730	0.730	0.730	0.0027900	33.4	0.0000000	0.0027900
					AVG=	1000									AVG=	0.14			AVG=	0.0015500	AVG=	0.0000000	AVG= 0.0015500
					SD=	0									SD=	0.03			SD=	0.0010750	SD=	0.0000000	SD= 0.0010750
36	1L	AISI52100	1SBX16	AISI52100	1SD582	1000	10.00		0.10	32.0	24	58	0.11	0.09	0.13	0.09	0.654	0.644	0.649	0.0017417	32.0	0.0000000	0.0017417
	2L	AISI52100	1SBX17	AISI52100	1SD583	1000	10.00		0.10	32.0	24	58	0.10	0.08	0.12	0.09	0.553	0.543	0.548	0.0008854	32.0	0.0000000	0.0008854
	3L	AISI52100	1SBX18	AISI52100	1SD584	1000	10.00		0.10	32.0	23	50	0.10	0.11	0.11	0.11	0.630	0.644	0.637	0.0016164	32.0	0.0000000	0.0016164
					AVG=	1000									AVG=	0.10			AVG=	0.0014145	AVG=	0.0000000	AVG= 0.0014145
					SD=	0									SD=	0.01			SD=	0.0004625	SD=	0.0000000	SD= 0.0004625
37	1L	AISI52100	1SBX1	AISI52100	1SD579	1000	10.00		0.10	32.0	27	45	0.12	0.09	0.13	0.09	0.670	0.660	0.665	0.0019000	32.0	0.0000000	0.0019000
	2L	AISI52100	1SBX2	AISI52100	1SD580	1000	10.00		0.10	32.0	25	43	0.13	0.08	0.14	0.09	0.660	0.650	0.655	0.0018000	32.0	0.0000000	0.0018000
	3L	AISI52100	1SBX3	AISI52100	1SD581	1000	10.00		0.10	32.0	30	59	0.12	0.07	0.14	0.08	0.740	0.720	0.730	0.0028000	32.0	0.0000000	0.0028000
					AVG=	1000									AVG=	0.09			AVG=	0.0021667	AVG=	0.0000000	AVG= 0.0021667
					SD=	0									SD=	0.01			SD=	0.0005508	SD=	0.0000000	SD= 0.0005508
39	1L	AISI52100	1SBX7	AISI52100	1SD570	1086	9.87		0.10	32.0	21	62	0.11	0.11	0.12	0.11	0.760	0.750	0.755	0.0032100	32.0	0.0262000	0.0294100
	2L	AISI52100	1SBX8	AISI52100	1SD571	1187	9.87		0.11	35.0	21	62	0.11	0.10	0.14	0.11	0.850	0.850	0.850	0.0051200	35.0	0.0786000	0.0837200
	3L	AISI52100	1SBX9	AISI52100	1SD572	1289	9.87		0.12	38.0	21	62	0.12	0.10	0.13	0.10	0.830	0.810	0.820	0.0044000	38.0	0.0853000	0.0897000
					AVG=	1187									AVG=	0.11			AVG=	0.0042433	AVG=	0.0633667	AVG= 0.0676100
					SD=	102									SD=	0.01			SD=	0.0009646	SD=	0.0323611	SD= 0.0332170
36	5L	Si3N4	2CB134	Si3N4	2CD221	1000	30.00		0.10	35.0	23	69	0.10	0.09	0.10	0.09	0.356	0.341	0.349	0.0001448	35.0	0.0000000	0.0001448
	6L	Si3N4	2CB134	Si3N4	2CD222	1000	30.00		0.10	35.0	23	61	0.11	0.10	0.11	0.10	0.240	0.240	0.240	0.0000326	35.0	0.0000000	0.0000326
	7L	Si3N4	2CB134	Si3N4	2CD220	1000	30.00		0.10	29.0	24	66	0.10		0.11	0.09	0.534	0.529	0.532	0.0007835	29.0	0.0000000	0.0007835
					AVG=	1000									AVG=	0.09			AVG=	0.0003203	AVG=	0.0000000	AVG= 0.0003203
					SD=	0									SD=	0.01			SD=	0.0004050	SD=	0.0000000	SD= 0.0004050
36	4L	Si3N4	2CB111	Al2O3	1CD437	1000	30.00		0.10	35.0	25	59	0.10	0.09	0.10	0.09	0.327	0.327	0.327	0.0001123	35.0	0.0000000	0.0001123
	5L	Si3N4	2CB111	Al2O3	1CD438	1000	30.00		0.10	35.0	25	67	0.10	0.09	0.10	0.09	0.341	0.341	0.341	0.0001327	35.0	0.0000000	0.0001327
	6L	Si3N4	2CB111	Al2O3	1CD439	1000	30.00		0.10	35.0	24	70	0.10	0.09	0.10	0.09	0.356	0.337	0.347	0.0001415	35.0	0.0000000	0.0001415
					AVG=	1000									AVG=	0.09			AVG=	0.0001288	AVG=	0.0000000	AVG= 0.0001288
					SD=	0									SD=	0.00			SD=	0.0000150	SD=	0.0000000	SD= 0.0000150
35	4L	Si3N4	2CB119	AISI52100	1SD612	1000	30.00		0.10	35.0	25	59	0.10	0.09	0.10	0.10	0.298	0.356	0.327	0.0001123	35.0	0.0000000	0.0001123
	5L	Si3N4	2CB119	AISI52100	1SD613	1000	30.00		0.10	35.0	24	70	0.10	0.10	0.11	0.10	0.380	0.356	0.368	0.0001800	35.0	0.0000000	0.0001800
	6L	Si3N4	2CB119	AISI52100	1SD614	1000	30.00		0.10	35.0	24	70	0.10	0.10	0.12	0.10	0.337	0.313	0.325	0.0001095	35.0	0.0000000	0.0001095
					AVG=	1000									AVG=	0.10			AVG=	0.0001339	AVG=	0.0000000	AVG= 0.0001339
					SD=	0									SD=	0.00			SD=	0.0000400	SD=	0.0000000	SD= 0.0000400

APPENDIX C: DRAFT ASTM STANDARD FOR PIN-ON-DISK WEAR TESTING

(<u>NOTE:</u> This Committee G-2 draft is unapproved at this date.)

Standard Test Method for

WEAR TESTING WITH A PIN-ON-DISK APPARATUS[1]

(Draft #7 - 6/30/89)

DRAFT COPY

This standard is issued under the fixed designation G--, the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parenthesis indicates the year of last reapproval. A superscript epsilon (e) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes a laboratory procedure for determining the wear of materials during sliding using a pin-on-disk apparatus. Materials are tested in pairs under nominally non-abrasive conditions. The principal areas of experimental attention in using this type of apparatus to measure wear are described. The coefficient of friction may also be determined.

1.2 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

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[1]This test method is under the jurisdiction of ASTM Committee G-2 on Wear and Erosion and is the direct responsibility of Subcommittee G02.40 on Non-Abrasive Wear.

2. Referenced Documents

2.1 ASTM Standards:

E 122 Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process[2]

E 177 Recommended Practice for Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material[2]

E 178 Recommended Practice for Dealing with Outlying Observations[2]

G 40 Terminology Relating to Erosion and Wear[3]

3. Summary of Test Method

3.1 For the pin-on-disk wear test, two specimens are required. One, a pin with a radiused tip, is positioned perpendicular to the other, usually a flat circular disk. A ball, rigidly held, is often used as the pin specimen. The test machine causes either the disk specimen or the pin specimen to rotate about the disk center. In either case the sliding path is a circle on the disk surface. The plane of the disk may be oriented either horizontally or vertically (Note: wear results may differ for different orientations). The pin specimen is pressed against the disk at a specified load usually by means of an arm or lever and attached weights. Other loading methods have been used, e.g., hydraulic or pneumatic (Note: wear results may differ for different loading methods).

3.2 Wear results are reported as volume loss in cubic millimeters for the pin and the disk separately. When two different materials are tested, it is recommended that each material be tested in both the pin and disk

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[2]Annual Book of ASTM Standards, Vol 14.02.

[3]Annual Book of ASTM Standards, Vol 03.02.

positions.

3.3 The amount of wear is determined by measuring appropriate linear dimensions of both specimens before and after the test, or by weighing both specimens before and after the test. If linear measures of wear are used, the length change or shape change of the pin, and the depth or shape change of the disk wear track (in millimeters) are determined by any suitable metrological technique, such as electronic distance gauging or stylus profiling. Linear measures of wear are converted to wear volume (in cubic millimeters) by using appropriate geometric relations. Linear measures of wear are used frequently in practice since mass loss is often too small to measure precisely. If loss of mass is measured, the mass loss value is converted to volume loss (in cubic millimeters) using an appropriate value for the specimen density.

3.4 Wear results are usually obtained by conducting a test for a selected sliding distance and for selected values of load and speed. One set of test conditions that was used in an interlaboratory measurement series is given in Tables 1,2 as a guide. Other test conditions may be selected depending on the purpose of the test.

3.5 Wear results may in some cases be reported as plots of wear volume vs sliding distance using different specimens for different distances. Such plots may display non-linear relationships between wear volume and distance over certain portions of the total sliding distance, and linear relationships over other portions. Causes for such differing relationships include initial "break-in" processes, transitions between regions of different dominant wear mechanisms, etc. The extent of such non-linear periods depends on the details of the test system, materials, and test conditions.

3.6 It is not recommended that continuous wear depth data obtained from position-sensing gauges be used because of the complicated effects of wear debris and transfer films present in the contact gap, and interferences from thermal expansion or contraction.

4. **Significance and Use**

4.1 The amount of wear in any system will, in general, depend upon a number of system factors such as the applied load, machine characteristics, sliding speed, sliding distance, the environment, and the material properties. The value of any wear test method lies in predicting the relative ranking of material combinations. Since the pin-on-disk test method does not attempt to duplicate all the conditions that may be experienced in service (for example; lubrication, load, pressure, contact geometry, removal of wear debris, and presence of corrosive environment), there is no assurance that the test will predict the wear rate of a given material under conditions differing from those in the test.

5. **Apparatus**

5.1 General Description -- Figure 1 shows a schematic drawing of a typical pin-on-disk wear test system, and photographs of two differently designed apparatus[4]. One type of typical system consists of a driven spindle and chuck for holding the rotating disk, a lever-arm device to hold the non-rotating pin, and attachments to allow the pin specimen to be forced against the rotating disk specimen with a controlled load. Another

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[4]A number of other reported designs for pin-on-disk systems are given in "A Catalog of Friction and Wear Devices", Am. Soc. Lub. Eng.(1973). A commercially built machine is available from Falex Corporation, 2055 Comprehensive Drive, Aurora. IL 60505.

type of system loads a pin rotating about the disk center against a stationary disk. In any case the wear track on the disk is a circle, involving multiple wear passes on the same track. The system may have a friction force measuring system, for example a load cell, that allows the coefficient of friction to be determined.

5.2 Motor Drive -- A variable speed motor, capable of maintaining constant speed (± 1% of rated full load motor speed) under load is required. The motor should be mounted in such a manner that its vibration does not affect the test. Rotating speeds are typically in the range 0.3-3 rad/s (60-600 rev/min).

5.3 Revolution Counter -- The machine shall be equipped with a revolution counter or its equivalent that will record the number of disk revolutions, and preferably have the ability to shut off the machine after a preselected number of revolutions.

5.4 Pin Specimen Holder and Lever Arm -- In one typical system, the stationary specimen holder is attached to a lever arm which has a pivot. Adding weights, as one option of loading, produces a test force proportional to the mass of the weights applied. Ideally, the pivot of the arm should be located in the plane of the wearing contact to avoid extraneous loading forces due to the sliding friction. The pin holder and arm must be of substantial construction to reduce vibrational motion during the test.

5.5 Wear Measuring Systems -- Instruments to obtain linear measures of wear should have a sensitivity of 2.5 μm or better. Any balance used to measure the mass loss of the test specimen shall have a sensitivity of 0.1 mg. or better; in low wear situations greater sensitivity may be needed.

6. Test Specimens and Sample Preparation

6.1 Materials -- This test may be applied to a variety of materials. The only requirement is that specimens having the specified dimensions can be prepared and that they will withstand the stresses imposed during the test without failure or excessive flexure. The materials being tested shall be described by dimensions, surface finish, material type, form, composition, microstructure, processing treatments, and indentation hardness (if appropriate).

6.2 Specimens -- The typical pin specimen is cylindrical or spherical in shape. Typical cylindrical or spherical pin specimen diameters would range from 2 mm to 10 mm. The typical disk specimen diameters would range from 30 mm to 100 mm and have a thickness in the range of 2 mm to 10 mm. Specimen dimensions used in an interlaboratory test with pin-on-disk systems are given in Table 1.

6.3 Surface finish -- A ground surface roughness of 0.8 μm (32 μ inch) arithmetic average or less is usually recommended. [Note: rough surfaces make wear scar measurement difficult]. Care must be taken in surface preparation to avoid subsurface damage that alters the material significantly. Special surface preparation may be appropriate for some test programs. State the type of surface and surface preparation in the report.

7. Test Parameters

7.1 Load -- Values of the force in N at the wearing contact.

7.2 Speed -- The relative sliding speed between the contacting surfaces in m/s.

7.3 Distance -- The accumulated sliding distance in m.

7.4 Temperature -- The temperature of one or both specimens at locations close to the wearing contact.

7.5 Atmosphere -- The atmosphere (laboratory air, relative humidity, argon, lubricant, etc.) surrounding the wearing contact.

8. Procedure

8.1 Immediately prior to testing, and prior to measuring or weighing, the specimens must be cleaned and dried. Care must be taken to remove all dirt and foreign matter from the specimens. Non-chlorinated, non-film-forming cleaning agents and solvents shall be used. Materials with open grains must be dried to remove all traces of the cleaning fluids which may be entrapped in the material. Steel specimens having residual magnetism should be demagnetized. The methods used for cleaning shall be reported.

8.2 Measure appropriate specimen dimensions to the nearest 2.5 μm or weigh the specimens to the nearest 0.0001 g.

8.3 Insert the disk securely in the holding device so that the disk is fixed perpendicular ($\pm$ 1 deg.) to the axis of rotation.

8.4 Insert the pin specimen securely in its holder and, if necessary, adjust so that the specimen is perpendicular ($\pm$ 1 deg.) to the disk surface when in contact, in order to maintain the necessary contact conditions.

8.5 Add the proper mass to the system lever or bale to develop the selected force pressing the pin against the disk.

8.6 Start the motor and adjust the rotation speed to the desired value while holding the pin specimen out of contact with the disk. Stop the motor.

8.7 Set the revolution counter (or equivalent) to the desired number of revolutions.

8.8 Begin the test with the specimens in contact under load. The test is stopped when the desired number of revolutions is achieved. Tests should not be interrupted or restarted.

8.9 Remove the specimens and clean off any loose wear debris. Note the existence of features on or near the wear scar such as: protrusions, displaced metal, discoloration, microcracking, or spotting.

8.10 Remeasure the specimen dimensions to the nearest 2.5 μm or reweigh the specimens to the nearest 0.0001 g, as appropriate.

8.11 Repeat the test with additional specimens to obtain sufficient data for statistically significant results.

9. Calculation and Reporting

9.1 The wear measurements should be reported as the volume loss in cubic millimeters for the pin and disk, separately.

9.1.1 The following equations shall be used for calculating volume losses when the pin has initially a spherical end shape of radius R and the disk is initially flat, under the conditions that only one of the two members wears significantly:

$$\text{Pin (spherical end) volume loss, mm}^3 = \frac{\pi\ (\text{wear scar diameter, mm})^4}{64\ (\text{sphere radius, mm})}$$

assuming that there is <u>no significant disk wear</u>. This is an approximate geometric relation that is correct to 1 percent for (wear scar diameter/ sphere radius) < 0.3, and is correct to 5 percent for (wear scar diameter/ sphere radius) < 0.7. The exact equation is given in Appendix 1.

$$\text{Disk volume loss, mm}^3 = \frac{\pi\ (\text{wear track radius, mm})\ (\text{track width, mm})^3}{6\ (\text{sphere radius, mm})}$$

assuming that there is <u>no significant pin wear</u>. This is an approximate geometric relation that is correct to 1 percent for (wear track width/sphere radius) < 0.3, and is correct to 5 percent for (wear track width/sphere radius) < 0.8. The exact equation is given in Appendix 1.

9.1.2 Calculation of wear volumes for pin shapes of other geometries shall use the appropriate geometric relations, recognizing that assumptions regarding wear of each member may be required to justify the assumed final geometry.

9.1.3 Wear scar measurements should be done at least at two representative locations on the pin surfaces and disk surfaces, and the final results averaged.

9.1.4 In situations where both the pin and the disk wear significantly, it will be necessary to measure the wear depth profile on both members. A suitable method would use stylus profiling. Profiling is the only approach to determine the exact final shape of the wear surfaces and thereby to calculate the volume of material lost due to wear. In the case of disk wear, the average wear track profile can be integrated to obtain the track cross-section area, and multiplied by the average track length to obtain disk wear volume. In the case of pin wear, the wear scar profile can be measured in two orthogonal directions, the profile results averaged, and used in a figure-of-revolution calculation for pin wear volume.

9.1.5 While mass loss results may be used internally in laboratories to compare materials of equivalent densities, this standard reports wear as volume loss so that there is no confusion caused by variations in density.

Care should be taken to use and report the best available density value for the materials tested when calculating volume loss from measured mass loss.

9.1.6 The following equation for conversion of mass loss to volume loss shall be used:

$$\text{Volume loss, mm}^3 = \frac{\text{Mass loss, g}}{\text{Density, g/cm}^3} \times 1000$$

9.2 If the materials being tested exhibit considerable transfer between specimens without loss from the system, volume loss may not adequately reflect the actual amount or severity of wear. In these cases, this test and method for reporting wear should not be used.

9.3 Friction coefficient, defined as the ratio of friction force to applied load, should be reported when available. The conditions associated with the friction measurements, e.g. initial, steady-state, etc., shall be described.

9.4 Adequate specification of the materials tested is important. As a minimum the report should specify material type, form, processing treatments, surface finish, and specimen preparation procedures. If appropriate, indentation hardness should be reported.

10. Precision and Bias

10.1 The precision and bias of the measurements obtained with this test procedure will depend upon the test parameters chosen.

10.2 The reproducibility of repeated tests on the same material will depend upon material homogeneity, machine and material interaction, and careful adherence to the specified procedure by the machine operator.

10.3 Normal variations in the procedure will tend to reduce the accuracy of the method as compared to the accuracy of such material property tests as hardness, density, or thermal expansion rate. Properly conducted tests should, however, maintain a within-laboratory coefficient of variation of 20 % or less for wear loss values. Table 2 contains wear data obtained from interlaboratory tests (see Note below). Those tests have shown acceptable within-laboratory variation, and further, a between-laboratory coefficient of variation of 40 %.

Note -- The interlaboratory data given in Tables 1 and 2 resulted through the cooperation of 31 institutions in 7 countries with the help of the following National Representatives within the VAMAS (Versailles Advanced Materials and Standards) Working Party on Wear Test Methods: J. Molgaard, Canada; M. Godet, France; H. Czichos, Germany (Chairman); A. G. Gandini, Italy; K. Matsumo, Japan; T. S. Eyre, UK; S. Hsu and A.W. Ruff, USA. Additional data have been filed at ASTM Headquarters and may be obtained by requesting RR: ______________.

10.4 In any test series, all data must be considered in the calculation, including outliers (data exceeding the obvious range); they are treated according to ASTM E178.

10.5 While two or more laboratories may develop test data which is within the acceptable coefficient of variation for their own individual test apparatus, the actual data of each laboratory may be relatively far apart. The selection of sample size and the method for establishing the significance of the difference in averages shall be agreed upon between laboratories and shall be based on established statistical methods of Recommended Practice E 122, Recommended Practice E 177, and STP 15D.[5]

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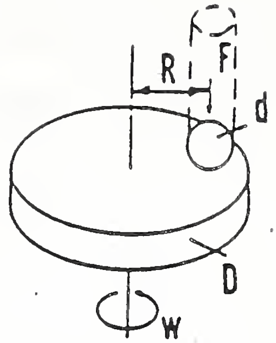
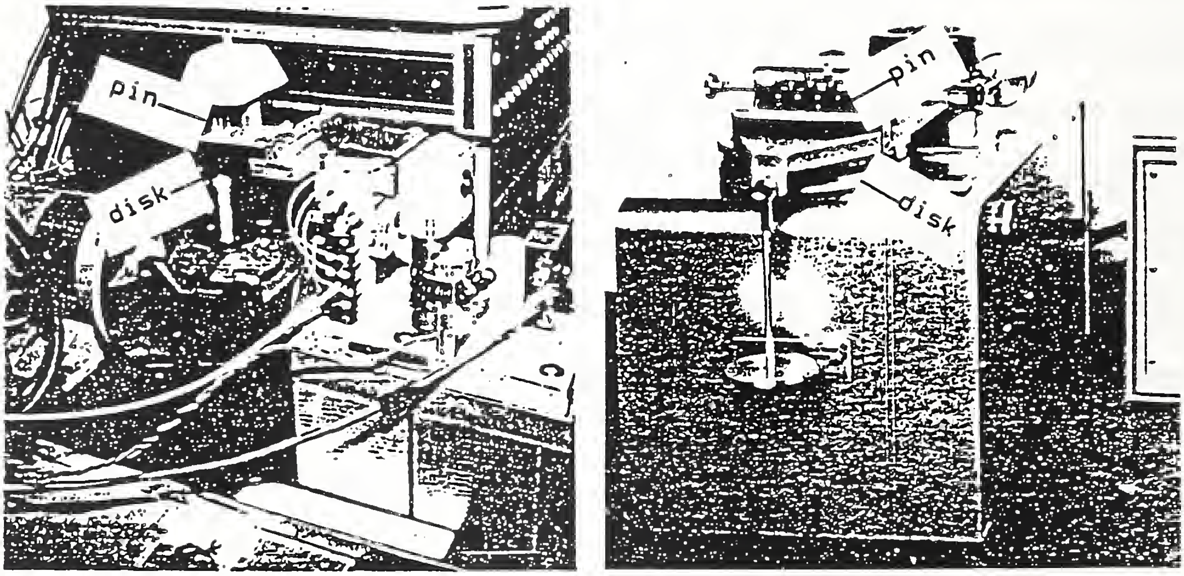
[5]Manual on Quality Control of Materials, ASTM STP 15D, Am. Soc. Testing Mats., 1951.



(a)



(b)

Figure 1. (a) Schematic of pin-on-disk wear test system. F is the normal force on the pin, d is the pin or ball diameter, D is the disk diameter, R is the wear track radius, and w is the rotation velocity of the disk. (b) Photographs of two different designs.

Table 1. Characteristics of the Interlaboratory Wear Test Specimens
(see note in 10.3 for information)

	Composition (wt.%)	Microstructure	Hardness (HV 10)	Roughness[d] R_z (mean) (µm)	Roughness[d] R_a (mean) (µm)
Steel ball (100Cr6) (AISI 52100)[a] Diameter 10 mm	1.35-1.65 Cr, 0.95-1.10 C, 0.15-0.35 Si, 0.25-0.45 Mn, <0.030 P, <0.030 S	martensitic with minor carbides and austenite	838 ± 21	0.100	0.010
Steel disc (100Cr6) (AISI 52100)[b] Diameter 40 mm	(as above)	" " "	852 ± 14	0.952	0.113
Alumina ball[c]	95% Al_2O_3 (with additives of TiO_2, MgO and ZnO)	equi-granular alpha alumina with very minor secondary phases	1610 ± 101 (HV 0.2)	1.369	0.123
Alumina disc[c]	(as above)		1599 ± 144 (HV 0.2)	0.968	0.041

[a]Standard ball-bearing balls (SKF)
[b]Standard spacers for thrust bearings (INA)
[c]Manufactured by C.I.C.E.S.A.
[d]Measured by stylus profilometry. R_z is maximum peak-to-valley roughness. R_a is arithmetic average roughness.

Table 2. Results of the Interlaboratory Tests (see note in 10.3)

Results (ball) (disk)	Steel-steel	Alumina-steel	Steel-alumina	Alumina-alumina
	Specimen Pairs			
Ball wear scar diameter (mm)	2.11 ± 0.27 (2.11 ± 0.27)	NM	2.08 ± 0.35 (2.03 ± 0.41)	0.3 ± 0.06 (0.3 ± 0.06)
Ball wear volume (10^{-3} mm^3)	97.3 (97.3)	-----	91.9 (83.3)	0.04 (0.04)
Number of values	102 (102)	-----	60 (64)	56 (59)
Disk wear scar width (mm)	NM	0.64 ± 0.12 (0.64 ± 0.12)	NM	NM
Disk wear volume (10^{-3} mm^3)	-----	480 (480)	-----	-----
Number of values	-----	60 (60)	-----	-----
Friction coefficient	0.60 ± 0.11	0.76 ± 0.14	0.60 ± 0.12	0.41 ± 0.08
Number of values	109	75	64	76

TEST CONDITIONS: $F = 10$ N; $v = 0.1$ ms^{-1}, $T = 23°C$; relative humidity range 12%-78%; laboratory air; sliding distance 1000 m; materials: steel = AISI 52100; alumina = α-Al_2O_3.

NOTES
(1) Numbers in parentheses refer to all data received in the tests. In accordance with ASTM E178, outlier data values were identified in some cases and discarded, resulting in the numbers without parentheses. The differences are seen to be small.
(2) Values preceded by ± are one standard deviation.
(3) Between 11 and 23 laboratories provided these data.
(4) Calculated quantities (e.g., wear volume) are given as mean values only.
(5) Values labeled "NM" were found to be smaller than the reproducible limit of measurement.

Appendix 1

Exact equations for determining wear volume loss are as follows for:

A spherical ended pin:

$$\text{Pin volume loss} = (\pi h/6)[3d^2/4 + h^2]$$

where $h = r - [r^2 - d^2/4]^{1/2}$

d = wear scar diameter

r = pin end radius

assuming no significant disk wear.

A disk:

$$\text{Disk volume loss} = 2\pi R\ [r^2 \sin^{-1}(d/2r) - (d/4)(4r^2 - d^2)^{-1/2}]$$

where R = wear track radius

d = wear track width

assuming no significant pin wear.

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

An interlaboratory comparison of tribological measurements was carried out among 16 U.S. laboratories as part of a large world effort involving six countries within the VAMAS (Versailles Advanced Materials and Standards) activity. Results for friction and wear of five material pairs are described in the report, along with a statistical analysis of the data, and interpretation of some of the findings.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

advanced materials; ceramics; friction; round-robin; sliding, tribology; VAMAS; wear

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