A PRACTICAL ASSESSMENT OF DATA REPEATABILITY & REPRODUCIBILITY IN TRIBOMETER TESTS FOR SPACE APPLICATIONS

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ABSTRACT

Practical data on friction, lubrication and wear is obtained from simple testing devices known as *"Tribometers"*. However, it has been recognised that tribological measurements made with idealised or over-simplified types of test apparatus are notoriously unreliable as performance indicators for real mechanisms. It is common for differing laboratories, using similar machines and test methods, to arrive at contradictory results. This paper summarises the results from two projects; a Tribometer Review aimed at understanding why there is so much variability in tribometer tests, and a Tribometer Round-Robin implemented to provide a practical assessment of data repeatability & reproducibility for space applications.

Keywords: *Tribometers, Space Applications, Friction, Wear & Lubrication, Data Repeatability & Reproducibility.*

1. INTRODUCTION

1.1 The Tribometer Review.

The tribometer review[1-4] concentrated on simple devices of the *pin-on-disc* or *disc-on-disc* type, characterised by a single tribo-contact under dynamic conditions, identifying the parameters influencing friction and wear data and the requirements for improvement. In addition, the operating capabilities, specific use and location of tribometers used for space applications were identified by performing a Tribometer Survey, focusing on research organisations in Europe, USA, Japan, CIS & India. The review concluded that tribometers are principally used to provide sets of relative friction coefficients and wear values using arbitrary test parameters, and to a lesser extent, simulative data in which the chosen parameters are based on a real application. The parameters revealed to influence test data in ***"arbitrary"*** and ***"simulative"*** tribo-testing are listed below:

Arbitrary Testing.

Not understanding the theoretical concepts. Inadequate characterisation of test specimens. Not validating the quality of surface coating & treatment processes. Not understanding the effect of inherent tribometer parameters on the friction and wear process. Non standardisation of test parameters, procedures & reporting formats for friction and wear data. Not performing enough tests to provide statistically useful data.

Simulative Testing.

Using tribometers because they are the only ones available and not the best device for the job. Not understanding what is happening in a real application so that information can be input to the requirements of a tribometer test. Not simulating the correct parameters.

The review concluded that, in arbitrary testing, tribometer data should be repeatable and reproducible, provided stringent operating procedures are defined. However, there are many difficulties in simulative tribo-testing, principally that the complexity of some engineering applications limits a true understanding of the relationship between tribometer test parameters and real life performance.

The project culminated in the production of an ESA approved *"Tribometer User's Guid-Lines For Space Mechanism Applications"*[2] to assist engineers unfamiliar with tribological testing in the methodology of good testing practices and in the identification of a device most able to solve a specific problem.

The recommendations made in these *Guide-Lines* were used to implement the Tribometer Round-Robin.

2. TRIBOMETER ROUND-ROBIN

The primary objective of the Round-Robin was to select a group of tribometers & provide a set of test conditions in which data repeatability# & reproducibility* could be assessed. A second aim was to study the influence of contact geometry and motion type on the test data.

The selection process was complex and it is not practical to discuss specific details in this paper. However, it is important to note that, in all instances, the tribometers selected were judged to possess suitable operating capabilities and performance requirements as defined in the *Guide-Lines*. The test parameters were related to space tribological applications, by selection of representative <u>material/ lubricant combinations</u>, <u>contact stresses</u>, <u>sliding speeds</u> and <u>test environments</u>.

The test program, materials and laboratories selected for the Round-Robin are listed in the following sections.

#***Repeatability*** refers to the variability in test results obtained by a single laboratory by one operator with a defined test apparatus, test procedure & test material. ****Reproducibility*** is the variability between results obtained from a different laboratory using a similar test apparatus, procedure & material.

Proc. Sixth European Space Mechanisms & Tribology Symposium, Technopark, Zürich, Switzerland, 4-6 October 1995 (ESA SP-374, August 1995)

2.1 Test Program.

The test program was split into three phases:

Phase (i) Assessment of the repeatability & reproducibility of friction and wear data of three tribo-materials commonly used in space applications using **five** nominally identical **pin-on-disc** *{face loaded}* tribometers (point contact & pure sliding motion (**Figure 1**)) located at five different test laboratories.

Phase (ii) & (iii) Assessment of the ability of two additional tribometers employing different contact geometries to rank the performance of the same set of tribo-materials. These tests were conducted on a **two-disc tribometer** *{edge loaded}* (line/elliptical contact & combined roll/sliding motion (**Figure 2**)) and a **two-disc tribometer** *{face loaded}* (flat contact & pure sliding motion (**Figure 3**)) located at two additional laboratories.

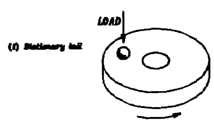

Figure 1 Pin-on-disc Tribometer

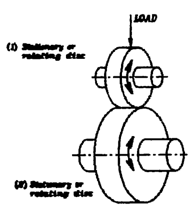

Figure 2 Two-Disc {edge loaded} Tribometer

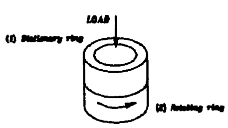

Figure 3 Two-Disc {face loaded} Tribometer

2.2 Test Materials.

The three material pairs pre-selected for investigation (**A, B & C**) and criteria for use are listed below:

A SAE 52100 Bearing Steel vs Sputtered Molybdenum Disulphide (MoS_2) Coated SAE 52100 Steel

B Lead Bronze (LB9) vs SAE 52100 Steel

C Vespel SP-3 vs SAE 52100 Steel

MoS_2 is a thin film solid lubricant frequently deposited on bearings, ball screws & gears for space applications.

Lead Bronze is used as a cage material in lead lubricated ball bearings, the most common dry lubricated system used in Europe on space mechanisms.

Vespel SP-3 is a self lubricating polyimide resin with 15% by weight MoS_2 , from which gears, couplings and lightly loaded components are often manufactured.

2.3 Laboratory Selection.

Seven laboratories were selected for participation. The names and locations are listed below:

Austrian Research Centre	Austria
B. Verkin. Institute	Ukraine
CSEM	Switzerland
Hosei University	Japan
Sulzer Innotec	Switzerland
National Aerospace Laboratory	Japan
National Physical Laboratory	UK

*

Phase (i) - The Pin-on-Disc study is complete. The test format, specimen, parameters, reporting, and test results are reviewed in this paper.
Phases (ii) & (iii) are due for completion in June 1995 and will be reviewed at a later date.

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3. ROUND-ROBIN - Pin-on-Disc Study.

3.1 Test Format.

The test format is outlined below:

Test Specimen

All test materials were procured, prepared, characterised & cleaned by ESTL following the recommendations listed in the *Guide-Lines*, before shipment to the participating laboratories.

Test Procedure

All materials were tested and analysed by the participating laboratories following instructions listed in a formal test procedure.

Test Results

All results were returned to ESTL to be correlated.

3.2 Test Specimen.

The test specimen chemical compositions and mechanical properties are listed in **Tables 1 & 2**. Material origin, processing history, preparation and characterisation techniques are summarised in **Table 3**. The specimen geometries are shown in **Figure 4.**

Table 1 Material Chemical Composition

Element	Composition (wt%)		
	52100 Steel	Lead Bronze	SP-3
Carbon	0.98-1.10		
Manganese	0.25-0.45	0.2max	
Phosphorous	0.025 max	0.1max	
Sulphur	0.025 max		
Silicon	0.15-0.30	0.02max	
Chromium	1.30-1.60		
Molybdenum	0.2 max		
Iron	remainder	0.25max	
Copper		80-87	
Tin		4-6	
Zinc		2.0 max	
Lead		8.0 to 10	
Nickel		2.0 max	
Aluminium		0.01 max	
Antimony		0.5 max	
Polyimide			85
MoS_2			15

Table 2 Referenced Mechanical Properties

	52100 Steel	Lead Bronze	Vespel SP-3
Product Form	Bar	Bar	Shaped Rod
Specification	AISI 52100 Steel	Glacier LB9 BS 1400 LB4-C	Vespel SP-3
Condition	Oil quenched @ 840°C Tempered @ 237°C		
Ult. Tensile Strength (MPa)	1764	230	53
Yield Stress (0.2%PS) (MPa)	1640	130	34.5[c]
Hardness	55 Rockwell C ~ 800 Hv[a]	60 Brinell ~160 Hv[a]	N/A N/A
Youngs Mod. (GPa)	210	130[b] (Cu)	3.275
Poissons Ratio	0.293	0.343[b] (Cu)	0.41

Data taken from **References 5-9.** In addition **[a]**: Measurement of Vickers hardness by ESTL. **[b]**: Youngs Modulus & Poissons Ratio for Lead Bronze is for Copper, the major element in Lead Bronze. **[c]**: Vespel does not plastically yield. For test purposes, the *"yield strength"* has been approximated to 65% of the ultimate tensile strength.

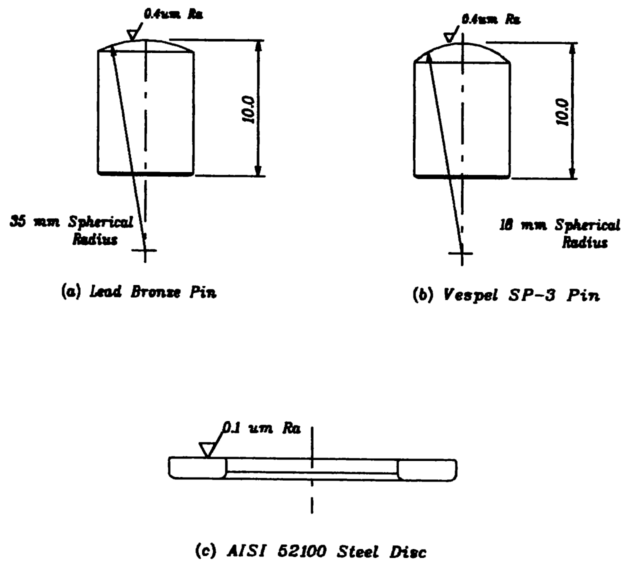

Figure 4 Test Specimen Geometries

Table 3 Specimen Processing & Characterisation

	Material Combination A		Material Combination B		Material Combination C	
DATA	**Specimen 1 Ball**	**Specimen 2 Disc**	**Specimen 1 Pin**	**Specimen 2 Disc**	**Specimen 1 Pin**	**Specimen 2 Disc**
Type	SAE 52100 Steel	MoS2/SAE 52100 Steel	Lead Bronze	SAE 52100 Steel	Vespel SP-3	SAE 52100 Steel
Product Name	Ball	WS Axial Brng. Washer	Bar	WS Axial Brng. Washer	Rod	WS Axial Brng. Washer
Manufacturer	Spheric Eng. Ltd	INA Rolling Brngs. Ltd.	Leeds Bronze Eng. Ltd.	INA Rolling Brngs. Ltd.	Dupont.	INA Rolling Brngs. Ltd.
Grade/Spec.	AFBMA Grade 5	DIN 620	Glacier - BS 1400 LB4C	DIN 620	SP-3	DIN 620
Preparation	Used "as received".	Used "as received".	Pin machined from bar to specified rad.of curv.	Used "as received".	Pin machined from bar to specified rad.of curv.	Used "as received".
Machining Process	None	None	Hobbing/End Milling.	None	Hobbing/End Milling.	None
Size (mm)	3.57 rad. of curv	OD 42, ID 25, Width 3	7 diameter & 10 length, 35 rad.of curv on pin tip	OD 42, ID 25, Width 3	7 diameter & 10 length, 18 rad.of curv on pin tip	OD 42, ID 25, Width 3
Data Measurements	*None*	*Ra, Hardness Hv.*	*None*	*Ra, Hardness Hv.*	*None*	*Ra, Hardness Hv.*
Ra (um)	*refer below*	0.05 to 0.12	Estimated @ 0.4	0.05 to 0.12	Estimated @ 0.4	0.05 to 0.12
Hardness (Hv)	"	754 to 821	162 to 196	754 to 821	Estimated @ 17 to 38	754 to 821
Data Reference	*AFBMA Ra Spec. YM, UTS, YS, PR, & CC.*	*DIN 620 Spec. YM, UTS, YS, PR, & CC.*	*COC & Data Sheet. YM, UTS, YS, PR, & CC.*	*DIN 620 Spec. YM, UTS, YS, PR, & CC.*	*COC & Data Sheet. YM, UTS, YS, PR, & CC.*	*DIN 620 Spec. YM, UTS, YS, PR, & CC.*
Ra (um)	0.02um	*see above*	*see above*	*see above*	*see above*	*see above*
Hardness (Hv)	Estimated @ 800	"	"	"	"	"
Cleaning	ESTL Proc. Ultrasonic - IPA & Arklone-P	ESTL Proc. Ultrasonic - IPA & Arklone-P	ESTL Proc. Ultrasonic - IPA & Arklone-P	ESTL Proc. Ultrasonic - IPA & Arklone-P	ESTL Proc. Ultrasonic - IPA & Arklone-P	ESTL Proc. Ultrasonic - IPA & Arklone-P
Lubricant	None	MoS2 on test face @ 1.0 +/- 0.2um thickness	None	None	None	None
Lubricant Measurements	*None*	*QC using Tribometer Test - XRF for thickness*	*None*	*None*	*None*	*None*
Storage	Heat sealed in Dry N2 filled Propafilm Bags with dessicant/humidity indicator until test	Heat sealed in Dry N2 filled Propafilm Bags with dessicant/humidity indicator until test	Heat sealed in Dry N2 filled Propafilm Bags with dessicant/humidity indicator until test	Heat sealed in Dry N2 filled Propafilm Bags with dessicant/humidity indicator until test	Heat sealed in Dry N2 filled Propafilm Bags with dessicant/humidity indicator until test	Heat sealed in Dry N2 filled Propafilm Bags with dessicant/humidity indicator until test

Note on Lubricant Measurements: Prior to despatch, the quality of the MoS_2 films were assured by performing a set of *"standard"* tribometer tests in a dry Nitrogen gas environment. **All films passes the ESTL QC procedure.**

3.3 Test Procedure

Each test procedure followed an identical format, the structure and contents of which is outlined below.

Section 1 - Test Specimen

Test Materials: Specimen Identification, Geometry, Packaging, Handling & Storage.

Section 2 - Test Parameters & Data Required

Test Parameters: Material Pairs A, B & C

Section 3 - Test Procedure & Reporting Format

Pre-Test Requirements: Calibration & Cleaning.
Test Schedule.
Reporting Format: Log Sheets for Raw Data, Test Rig & Peripheral Apparatus, Test Parameters & Residual Gas Analysis (optional).
Classification of Friction States: Reporting of Data
Wear Data: Measurement & Reporting
General Observations: Assessment & Reporting

Section 4 - Project Final Reporting & Deliverables

Final Reporting: Test Data Return Shipment

The test parameters and tribological measurements are listed in **Table 4.** Tribometer operating capabilities are reviewed later in **Section 4**. (**NOTE:** ESTL also performed the tests for Material Group A in order to define suitable failure criteria in the test procedure. This data is discussed later in **Section 4.1**)).

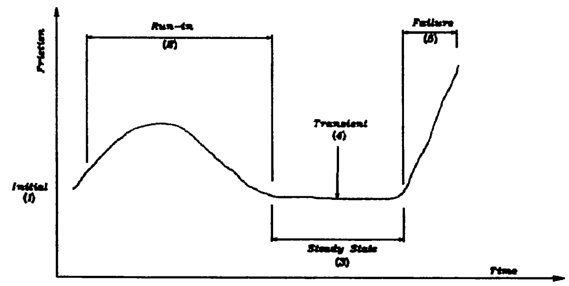

Figure 5 Classification of Friction States

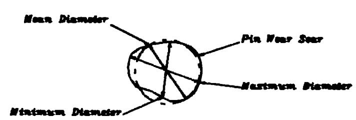

Figure 6 Pin Wear Scar Measurement

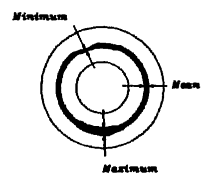

Figure 7 Disc Wear Track Measurement

Table 4 Test Parameters & Tribological Measurements

Test Parameters		Material Combination A	B	C
Load	N	10	5	5
Contact Stress	*MPa*	*821 (mean Hertzian)*	*124 (mean Hertzian)*	*22 (mean Hertzian)*
Motion Type	-	Sliding (unidirectional rotation)	Sliding (unidirectional rotation)	Sliding (unidirectional rotation)
Motion Speed	rpm	300	60	60
Track Radius	m	0.016	0.016	0.016
Circumference	*m*	*0.1*	*0.1*	*0.1*
Sliding Speed	*m/sec*	*0.5*	*0.1*	*0.1*
Atmosphere	torr	Vacuum < 5x10E-6	Vacuum < 5x10E-6	Vacuum < 5x10E-6
Characterisation	-	Mass spectrum (if available)	Mass spectrum (if available)	Mass spectrum (if available)
Temperature	deg C	20+/- 2	20+/- 2	20+/- 2
Test Completion Criteria	-	Friction > 0.1 (0.15 during run-in)	Run for max of 10,000 revs (sliding distance 1,000m) or a friction force limit of 0.5.	Run for max of 10,000 revs (sliding distance 1,000m) or a friction force limit of 0.5.
No. Tests Required	-	3	3	3
Test Time	*hours*	*48*	*3*	*3*
Friction Data	-	Report mean & peak friction as a function of test duration. Classify as shown in Figure 5.	Report mean & peak friction as a function of test duration Classify as shown in Figure 5.	Report mean & peak friction as a function of test duration Classify as shown in Figure 5.
Endurance Data	revs	Report test endurance	Report test endurance	Report test endurance
Ball/Pin Wear	mm	No wear data required	Measure pin wear scar diameter (to calculate specific wear rate) as shown in Figure 6.	Measure pin wear scar diameter (to calculate specific wear rate) as shown in Figure 6.
Disc Wear	mm	No wear data required	Measure disc wear track width as shown in Figure 7.	Measure disc wear track width as shown in Figure 7.
Observations	-	Identify shape of wear scar and presence of any transfer material by colour, texture & distribution.	Identify shape of wear scar and presence of any transfer material by colour, texture & distribution.	Identify shape of wear scar and presence of any transfer material by colour, texture & distribution.

ADDITIONAL NOTES: **Contact Stress (Load):** Group A - represents a typical contact stress in a ball bearing (ball-race interaction). Groups B & C - relate to material properties (~65% of the Yield Strength). **Motion Speed:** All motion parameters were chosen to reflect tribometer operating capabilities. **Environment:** All tests were conducted in vacuum representative of the space mechanism environment. **Test Completion Criteria:** Group A represents the onset of lubricant failure/loss. Groups B & C - chosen to ensure resulting wear scar was practical to measure. **Data:** Friction data measured as standard. Wear measurements required to calculate the average specific wear rate. Group A pin wear scar not required as most of the wear occurs during film failure, a process which is very difficult to quantify.

4. TEST RESULTS

The test results and presentation format are summarised below. Individual test laboratories are not referred to by name, but by a number (1-5):

Tribometer Operating Capabilities.

The operating capabilities of each tribometer used in Phase (i) of the Round-Robin are listed in **Table 5**.

Friction Data.

The mean friction coefficients, as functions of disc revolutions, for each material group tested are presented in graphical format as follows:
Figure 8: Results from Test Group A
Figure 9: Results from Test Group B
Figure 10: Results from Test Group C

Wear Data.

Pin wear scar measurements and the calculated specific wear rates for Test Groups B & C are listed in **Table 6**.

4.1 ESTL Test Data - Material Group A.

Thin film solid lubricants are notoriously difficult to assess, therefore ESTL performed Test Group A, to characterise the film performance. The tests were conducted following the test procedure and using a tribometer *"nominally identical"* to that used by **Laboratories 2 & 3**, except for one difference, all tests were conducted in a dry nitrogen environment. (ESTL MoS_2 films have frequently been tested in dry nitrogen and vacuum to compare performance and no significant variations in film endurance or steady-state friction coefficient have been recorded). From the test data obtained at ESTL, film lifetimes of 400,000 to 800,000 disc revolutions and mean steady-state friction coefficients of 0.01 to 0.02 were anticipated.

Material Groups B & C were not specifically tested by ESTL to characterise the performance.

4.2 Discussion.

Test Group A - MoS_2 Lubricated Steel.

The friction data from Test Group A was repeatable and reproducible (when steady-state was achieved), however, the endurance data was varied. Unexpectedly low endurance values were recorded by Labs 3 & 4, Labs 1 & 5 were also lower than expected, only Lab 2 obtained results consistent with ESTL test data.

Analysis of the test results did not reveal the cause of the data variability. Tribometer tests conducted by ESTL on the returned discs showed that the MoS_2 films had not degraded. Variations in loading sequences, stop/start intervals during testing, vibrations at the contacting interfaces and characterisation of the vacuum environment were noted to vary amongst the test laboratories, however there was no evidence to conclude that these changes contributed to the large spread in MoS_2 film lifetimes. It would be beneficial to repeat Test Group A using a test procedure that eliminates the variations listed above to ascertain if reproducibility in film performance can be achieved.

Test Group B & C Lead Bronze & Vespel SP-3.

The friction and wear data generated in the Lead Bronze and Vespel SP-3 tests were almost identical *"in tribological terms"*, with 4 of the 5 laboratories obtaining repeatable & reproducible results. Additional tests conducted at $ESTL_{[10]}$ indicated that the high friction coefficients recorded by Lab 1 in the Vespel SP-3 tests were probably caused by high partial pressures of H_20 (H_2, N_2 & O_2 also considered) in the vacuum system. The additional tests also indicated that unlike ESTL MoS_2 films, dry N_2 gas is not a suitable substitute for vacuum when testing Vespel $SP\text{-}3_{[10]}$.

5 CONCLUSIONS

ESTL performed a Tribometer Review and prepared a set of Guide-Lines, on which, the test procedures for the Tribometer Round-Robin were based. The test results showed that the vacuum level and its characterisation can significantly influence tribometer test data. Repeatability & reproducibility in friction and wear data can be obtained using bulk self lubricating composites of Lead Bronze and Vespel SP-3 by following the recommendations made in the Guide-Lines. However, for MoS_2 lubricated steel, its viability has yet to be established.

ACKNOWLEDGEMENTS

The authors would like to thank all the Test Laboratories who participated in this project for their valuable contributions.

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Table 5 Tribometer Operating Capabilities

	SPECIFICATION	LABORATORY No. 1	2	3	4	5
1	**LOCATION**					
	Location	-	Laboratory	-	Air Cond. Room	Laboratory
	Room Temperature	20 'C	22 'C	20+/- 5 'C	20 'C	18+/-2 'C
	Control Accuracy	*1%*	*10%*	*1%*	*5%*	*5%*
	Room Humidity	40% RH	40% RH	15-70% RH	UN	55+/-5% RH
	Control Accuracy	*10%*	*20%*	*5%*	*UN*	*5%*
	Containment	Vacuum Chamber	-	-	Vacuum Chamber	Vacuum Chamber
	Vibration Isolation	Silent Blocks	Rubber Plates & Bellows	Bellows & Special Suspension	Not Insulated	Base Separator
	Natural Frequency (Hz)	UN	-	-	UN	NR
	Cleaning & Solvents	Ethanol	Acetone, Ethanol	Alcohol	Acetone Wipes	Benzine, Acetone,
2	**ENVIRONMENT**					
	Temperature Control	None	EBRO BHX900	Numerical Thermometer	Air Conditioner	Thermocouple
	Control Accuracy	*UN*	*10%*	*1%*	*5%*	*5%*
	Temperature Sensor	None	EBRO BHX900	Thermometer Hygrometer	Thermocouple	Thermocouple
	Sensor Accuracy	*UN*	*1%*	*1%*	*5%*	*1%*
	Vacuum Pumps	Rotary & Turbo	Turbo Molecular	Mechanical & Turbo Molecular	Ion Pump & Titanium Sub.	Mechanical, Diffusion & Cryo.
	Vacuum Measurement	Pirani & Penning	Penning & Pirani	Pirani Cold Cath.	B-A Gauge	Pirani & Ion
	Residual Gas Analysis	NA	Quadrupole Mass. Spec	-	Quadrupole Mass. Spec	RF Single Pole Mass. Spec.
3	**SPECIMEN**					
	Specimen Clamping	Spring Holders	Disc - Mandrel Pin - Holder	Disc - Mandrel Pin - Holder	Bolt	Mechanical Clamps
	Specimen Alignment	Visual Method	Level Detector & Optical Sensor	Pivoting Arm	-	By Design of Specimen Holders
	Specimen Storage	As in Test Proc.	As in Test Proc.	As in Test Proc.	-	As in Test Proc.
4	**LOADING**					
	Loading Method	Dead Weight	Dead Weight	Dead Weight	Dead Weight	Dead Weight
	Load Measurement	Dead Weight	Dead Weight	Dead Weight	Not Measured	Dead Weight
	Loading Accuracy	*5%*	*2%*	*<1%*	*2%*	*1%*
5	**MOTION**					
	Type of Motor	DC	DC- Servo	DC	Induction	AC
	Motor Coupling	V-Belt Drive	V-Belt Drive	Belt	Timing Belt	V-Belt
	Motion Control System	PLC	Encoder	Tachymetric	Inverter	Magneto-Electric
	Sensor Type	Tachogenerator	Integrated	Stop Watch	Tachometer	Magneto-Electric
	Speed Control Accuracy	*1%*	*<1%*	*2%*	*2%*	*1%*
6	**FRICTION DATA**					
	Force Transducer	Inductance	Inductance	LVDT Inductance	Leef Spring & Strain Gauge	Strain Gauge
	Recording Device	Chart Recorder & Data Logger	Chart Recorder & Data Logger	Chart Recorder	Pen Recorder	Chart Recorder
	Freq. Response	UN	<10Hz	-	0.5Hz	NR
	Friction Data Accuracy	*10%*	*5%*	*<1%*	*2%*	*5%*

Table 6 Pin Wear Data

Lab.	*Test No.*	Av. Wear Scar (mm) Diameter	Radius	Revs	Distance (m)	Sp. Wear Rate x10-15m/Nm	*Test No.*	Av. Wear Scar (mm) Diameter	Radius	Revs.	Distance (m)	Sp. Wear Rate x10-15m/Nm
1	*B-4*	3.23	1.615	10000	1068	28.6	*C-7*	1.7	0.85	10000	1068	4.27
	B-5	2.76	1.38	10000	1068	15.2	*C-8*	1.08	0.54	10000	1068	0.695
	B-6	2.46	1.23	3000	320	32.1	*C-9*	1.03	0.515	10000	1068	0.575
2	*B-4*	2.23	1.115	10000	1005	6.9	*C-7*	1.18	0.59	10100	1015	1.04
	B-5	2.02	1.01	10100	1015	4.6	*C-8*	0.69	0.345	9900	995	0.124
	B-6	2.29	1.145	10100	1015	7.6	*C-9*	0.73	0.365	10100	1015	0.153
3	*B-4*	2.02	1.01	10000	1005	4.65	*C-7*	0.76	0.38	10000	1005	0.181
	B-5	1.73	0.865	10000	1005	2.5	*C-8*	1.08	0.54	10000	1005	0.738
	B-6	1.93	0.965	10000	1005	3.87	*C-9*	1.09	0.545	10000	1005	0.766
4	*B-4*	2.08	1.04	10000	1005	5.22	*C-7*	1.05	0.525	10000	1005	0.66
	B-5	2.85	1.425	10000	1005	18.4	*C-8*	0.92	0.46	10000	1005	0.389
	B-6	2.59	1.295	10000	1005	12.6	*C-9*	1.32	0.66	10000	1005	1.65
5	*B-4*	3.1	1.55	10800	1086	23.9	*C-7*	1.4	0.7	10800	1086	1.93
	B-5	3.1	1.55	10800	1086	23.9	*C-8*	0.9	0.45	10800	1086	0.33
	B-6	3.5	1.75	10800	1086	38.8	*C-9*	0.9	0.45	10800	1086	0.33

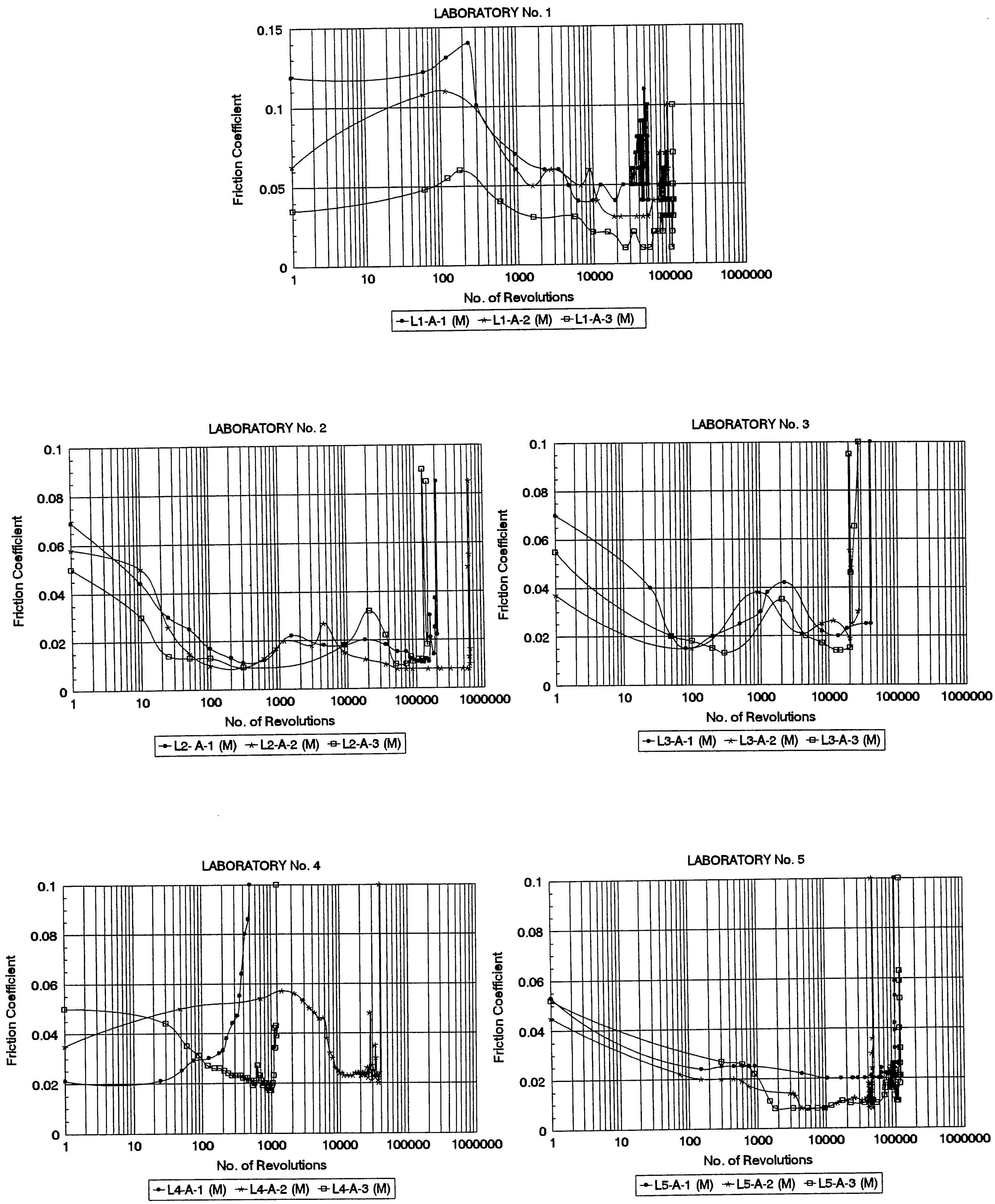

Figure 8 Friction & Endurance Data from Material Group A - SAE 52100 Steel Ball vs MoS_2 Lubricated SAE 52100Steel Disc.

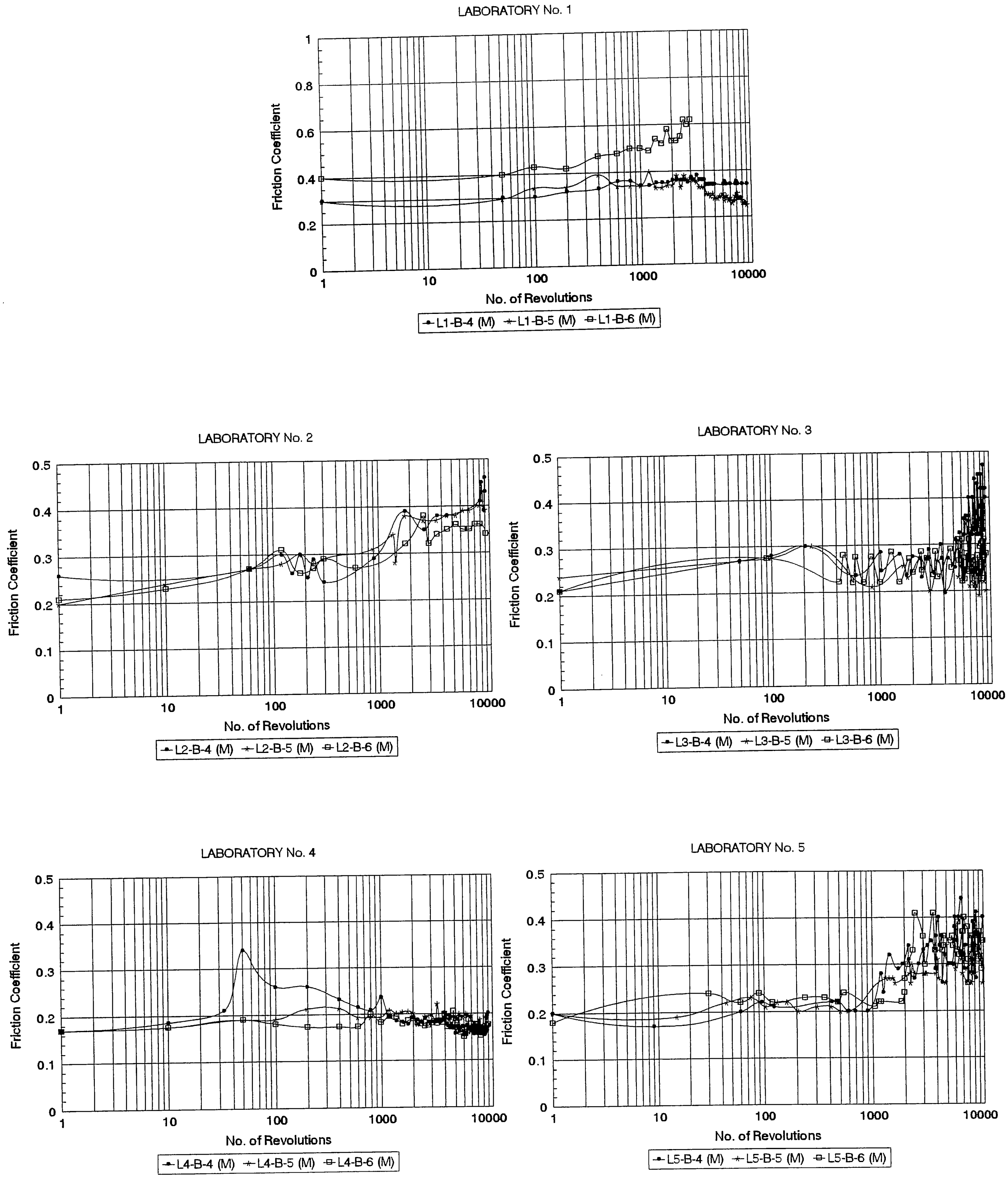

Figure 9 Friction Data from Material Group B - Lead Bronze Pin vs SAE 52100Steel Disc.

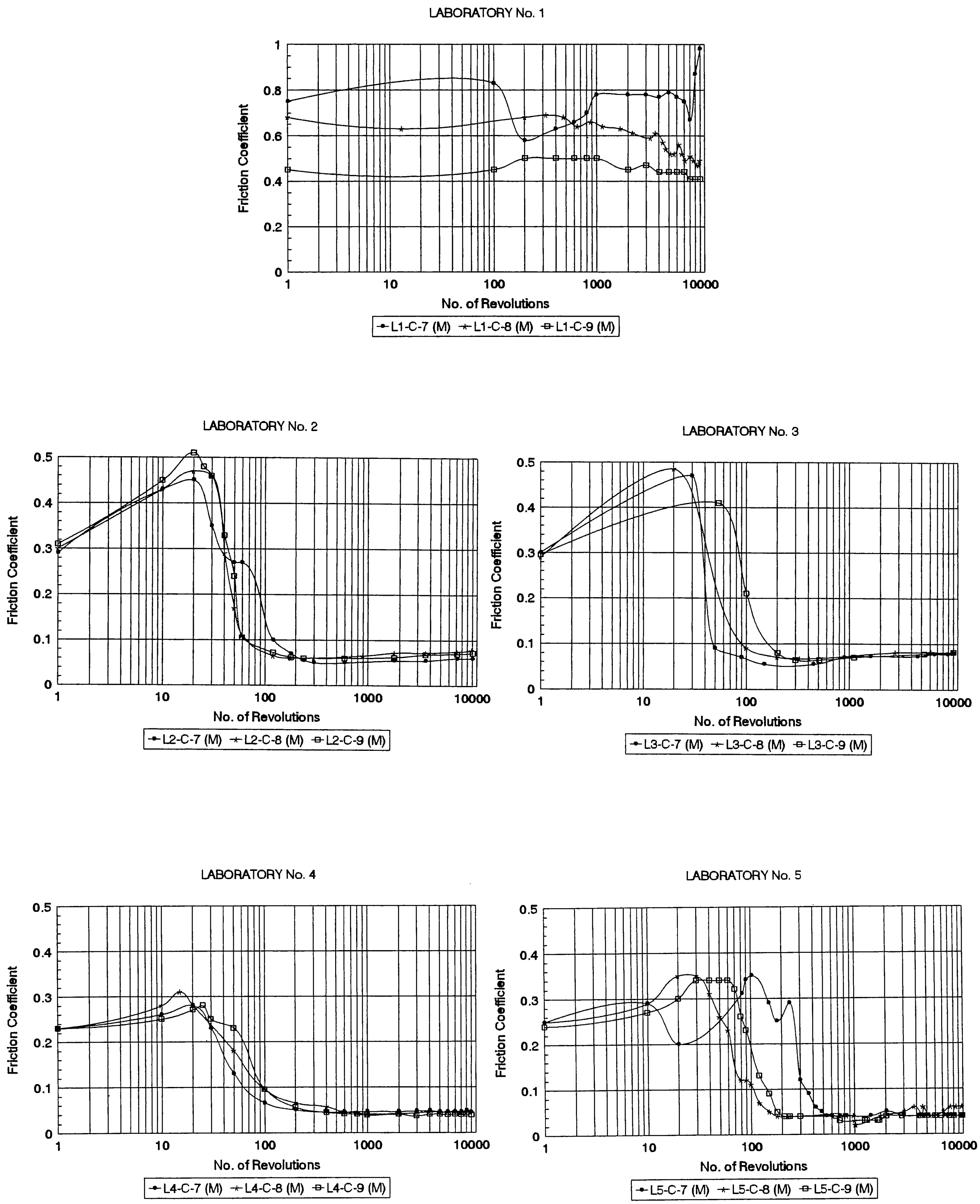

Figure10 Friction Data from Material Group C - Vespel SP-3 Pin vs SAE 52100Steel Disc.