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Metals and Ceramics Division

CERAMICS TECHNOLOGY PROJECT DATABASE: SEPTEMBER 1991 SUMMARY REPORT

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NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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CERAMICS TECHNOLOGY PROJECT DATABASE: SEPTEMBER 1991 SUMMARY REPORT*

ABSTRACT

The piston ring-cylinder liner area of the internal combustion engine must withstand very-high-temperature gradients, highly-corrosive environments, and constant friction. Improving the efficiency in the engine requires ring and cylinder liner materials that can survive this abusive environment and lubricants that resist decomposition at elevated temperatures. Wear and friction tests have been done on many material combinations in environments similar to actual use to find the right materials for the situation.

This report covers tribology information produced from 1986 through July 1991 by Battelle Columbus Laboratories, Caterpillar Inc., and Cummins Engine Company, Inc. for the Ceramic Technology Project (CTP). All data in this report were taken from the project's semiannual and bimonthly progress reports and cover base materials†, coatings, and lubricants. The data, including test rig descriptions and material characterizations, are stored in the CTP database and are available to all project participants on request. The objective of this report is to make available the test results from these studies, but not to draw conclusions from these data.

1. INTRODUCTION

Advanced engines operate at higher temperatures than normal diesel engines, so more refractory materials are needed for the components. Increasing the temperature also causes problems with the function and condition of the lubricants by breaking them down into corrosive byproducts and reducing lubricity on the contact surfaces. The new piston ring and cylinder liner materials must be able to withstand 10,000 h of operation under high-temperature, corrosive, and abrasive conditions to be considered usable on a commercial scale. While metals are commonly used in engines today, they lack the heat and corrosion resistance of ceramics and some cermets.

This report covers tribology information produced from 1986 through July 1991 by Battelle Columbus Laboratories, Caterpillar Inc., and Cummins Engine Company, Inc. for the Ceramic Technology Project (CTP) on numerous materials, including coatings and base materials, for use in the severe conditions of the cylinder. Most of the information was extracted from semiannual and bimonthly progress reports generated by the CTP.

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†For this report, "base material" refers to a material used by itself; it does not act as a coating on another material but may serve as a substrate. Base materials may be composed of ceramics, intermetallics, or metals, used alone or in combination.

Tribology data storage presented several problems not encountered in working with most of the other test data. The number of possible materials involved, the types of materials (coatings, base materials, ion implants), and the importance of lubricants required the addition of several new fields. Parameters omitted in the original file structure for wear data were added when the importance of those items was realized. New files were added to contain information associated with the new parameters.

2. DATABASE STATUS

The CTP database presently contains 6,309 results on 27 different types of tests, 338 material characterizations, 13 lubricant characterizations, 101 coating characterizations, and 1,953 other associated records. A more detailed description may be found in Table 1.

Progress made since the last report includes the addition of tribology test results, a coatings characterization file, a lubricant identification file, a material name cross-reference file, a new study-search field, and a data classification field. The new coating and lubricant files were necessary to describe more accurately the materials used in the tribology tests. The field additions were enhancements designed to help the user locate data faster.

Ceramics lack a standard, industry-accepted identification system available for other materials, such as the Unified Numbering System (UNS) for metals. A given ceramic may be known by several different names (Z-191 is also called PSZ, ZrO_2, and zirconia), each correct but all different as far as a computer query is concerned. The MATNAMES file was created to simplify choosing a material name for use in a database query. This file contains a list of material names used in the database, cross indexed to composition, manufacturer's, and generic designations, all indicating the same material. This file could be useful for locating aliases for each material. When a standard system is accepted by the ceramic industry, the new nomenclature will be incorporated into the database.

The WBS-STUDY field, to be included in every file record, was added to facilitate locating all the data from a particular study. Database personnel usually collect data from one testing facility's work on one subject covering a particular time span. Recalling the information from that one study is necessary to verify and tabulate the data.

Data classification identifies information in a property data record according to its level of evaluation. Most of the data stored in the CTP database are semi-raw test data, having been converted from instrument readings to stresses, strains, etc. Some data are reported only as averages. Nominal values may be included for a general material comparison. The DATA-CLASS field has four possible values: "TEST" for semi-raw test data; "AVG" for averaged data from several tests run under the same set of conditions; "NOM " for nominal, or typical, values; and "GOAL" for target values. If more than one test for a given set of conditions exists in a source, "TEST" is the default value. Otherwise, "AVG" is assumed.

Only the tribology data presently include values in the two fields mentioned above. Database personnel plan to extend the additions to the other contents as time allows.

3. TRIBOLOGY DATA BACKGROUND

Information for this report was produced by three tribology studies funded by the CTP. All three studies focused on developing materials for piston ring and cylinder liner components for low heat-loss diesel engines. The period used for this report began in 1986 and ended in July1991. Some of the work is continuing and will appear in future database summary reports.

K. F. Dufrane and P. A. Gaydos from Battelle Columbus Laboratories were the principal investigators for WBS *2.2.2–Studies of Dynamic Contact of Ceramics and Alloys for Advanced Heat Engines*. The main objective of this study was to develop an understanding of the tribological problems of ceramic interfaces in advanced heat engines based on test data. Target parameters were determined by running chrome-plated ring specimens against cast-iron cylinder specimens in a diesel environment at 100°C for 10,000 hours. Commercially available SAE 30 oil was used as the lubricant. Battelle's test rig simulated the ring-cylinder interface by using less expensive flat specimens for both ring and cylinder components. One cylinder specimen was fixed, while the other was mobile for load control. Two ring specimens were mounted with pivot pins at specimen centers to provide self-alignment. The ring specimens reciprocated along 108 mm of the cylinder specimens at 500 to 1500 rpm, averaging speeds of 1.8 to 5.4 m/s. Heated exhaust from a 4500-W diesel engine was passed through a chamber surrounding the test specimens.[1] Figure 1 shows a schematic diagram of this configuration. Materials tested include a variety of plasma-sprayed coatings as well as non-coating ceramics. Data from this study are tabulated in Appendix B, Section 2a. Since this work is continuing, any data generated in the future will be stored and reported as they become available.

C. D. Weiss, F. A. Kelley, and M. H. Haselkorn[2] were the investigators for WBS *1.3.1–Wear-Resistant Coatings*, the CTP part of Caterpillar's work on developing materials for in-cylinder components. This study involved more coatings than the Battelle study and included ceramics, cermets, metals, and enamels. Coating processes included plasma spraying, chemical and physical vapor deposition, low-temperature arc-vapor deposition, and dipping (with and without added particles) on hot and cold substrates. Initial candidate materials were screened at Caterpillar using a Falex Model 6 testing machine. Figure 2 shows a schematic diagram of the configuration. Disks of mild steel, tool steel, and cast iron were coated, then tested against pins of 440C steel, zirconia, and alumina. Materials that performed best were further tested on a Hohman Double-Rub Shoe Model 6 tester (Fig. 3). This configuration simulated the ring-cylinder contact interface by using a rotating disk to abrade two fixed shoes. Both shoes and the disk were coated with different combinations of materials. All Hohman tests were run at 350°C using a Lubrizol experimental synthetic oil. Average speed was 3.43 m/s with a load of 9.08 kg force.[2] The data sources did not list numeric values for all the wear coefficients but provided approximate levels of wear instead (low, medium, and high). Information in the database for this study is stored the way it appeared in the original data source. All Caterpillar test results are given in Appendix B, Sect. 2b.

Cummins Engine Company, like Caterpillar, has been making, designing, and developing engine components for many years. M. G. S. Naylor[3] was the principal investigator for WBS *1.3.1-Development of Wear-Resistant Coatings for Diesel Engine Components*. The main objective of this study was to develop coatings for in-cylinder components that would have wear coefficients of 5×10^{-12} to 5×10^{-11} $mm^3/mm/N$; have friction coefficients of 0.1 or better when lubricated and 0.2 or better unlubricated at room temperature and at 350°C; have good thermal shock resistance, high adherence, and substrate compatibility up to 650°C; and exhibit good uniformity and reproducibility.[3] All coatings were tested on a Cameron-Plint wear tester at 20 Hz with a 5-mm stroke length. The cylinder specimen was a flat, 7.5-mm-wide sample, while the ring had a cylindrical radius of 50 mm. Figure 4 shows the testing configuration with the specimens in the lubricant bath tub. CE/SF 15W40 mineral oil-based lubricant was used in both fresh (CE/SF15W40F) and engine-tested (CE/SF15W40U) specimens, added at the rate of one drop every 10 s for 6 h, if the test lasted that long. Unlubricated tests were run for only 30 to 60 min. Materials for this study included metal, cermet, and ceramic coatings slurry- or plasma-sprayed onto stainless steel, mild steel, tool steel, or cast-iron substrates. Several ion-nitrided specimens were also tested. Results from this study are listed in Appendix B, Sect. 2c.

Comparing test results from the different studies was hindered due to a difference in wear factor calculation methods. Battelle Columbus Laboratories and Caterpillar used the same method, but only a few of the Caterpillar tests were reported with numeric wear values.[2] Their wear factors were calculated by:

$$k = \frac{V}{Ld}$$

where k = wear factor, mm^3/Nm, (quantity of removed material per unit distance and force)
V = wear volume, mm^3, (quantity of material removed)
L = applied load, N, and
d = sliding distance, m. (1)

Battelle Columbus Laboratory also used the Archard equation to calculate wear in dimensionless units for a few tests:

$$V = \frac{kLd}{3H}$$

where V = wear volume, mm^3,
k = wear factor,
L = load, kgf,
d = sliding distance, mm, and
H = hardness, kgf/mm^2. (2)

The Cummins study used an Arrhenius function to determine the wear coefficient.[3]

$$W = W_o \exp\left(-\frac{Q}{RT}\right)$$

where W = wear coefficient, mm^3/mm/N, (quantity of removed material per unit distance per unit force)

W_o = constant,

Q = activation energy,

R = gas constant, and

T = absolute temperature.

Since the units for this equation were not consistent with those used by the other studies, a conversion factor was applied to correct the problem. The reader should remember the differences in the machines used to test the materials and the differences in wear factor calculations when comparing the data. Information presented in the appendices of this report is separated by study to avoid confusing the wear factor calculations.

4. TRIBOLOGY DATA STORAGE

Data used in this report are stored on a 20-MB Bernoulli cartridge using dBASE IV™ (version 1.1) on a Northgate 486/25 microcomputer. The database consists of 35 interrelated files linked by sets of codes and includes test results, material characterizations and background information, testing equipment details, and other test/specimen data. Figure 5 shows the relationships among the files used to store tribology data.

Tribology tests often use more than one material per test. Therefore, the number of material fields has been increased and each one coded to indicate which material was used in a specific position. Material fields ending with a "1" refer to the moving specimen; those ending with a "2" refer to the stationary specimen. Each position (moving or stationary) refers to a coating and batch code, a substrate and batch code, and a wear coefficient, if available. Base materials appear in the substrate fields whether they are coated or not. Only coating materials appear in the coating fields to avoid problems when a link is made to the associated characterization information. Coating background data are stored in a different file than base material background data. More information on the materials used in a test may be found in the COATINGS and MATLCHAR material characterization files.

Since the manufacturer's batch codes for the materials used in these studies were unknown, database personnel improvised batch codes as: Material supplier or lab doing the coating/coating method if material is a coating/testing or reporting facility. These homemade codes will be replaced with actual manufacturer's codes when possible.

The WEARDATA file contains all the test results. Each test record contains results and conditions for one test, one step in a multipart test, or on a group of tests run under the same conditions. The value in DATA-CLASS indicates whether the results are for one test (TEST), an average of several tests (AVG), or a nominal value (NOM). The defaults for DATA-CLASS are TEST if more that one result is listed for a given set of conditions and AVG otherwise.

Other fields provide links to other files containing additional information about the test or the materials. An affirmative value in the SEETEXT field indicates that additional comments on the results are available in the DATATXT file (for expanded test notes). Lubricant information may be found in the file LUBRICNTS using LUBRICANT as the key. TEST-RIG links the test results data with details about the test apparatus in the TESTBKGD file. Expanded references may be found in the file named CERSOURC. Chemistries, if available, may be found in the CHEMSTRY file using the material or coating name and related batch code as a key. Additional material or coating notes are located in TEXTUF, keyed by material or coating name and batch code. The WBS-STUDY and CLASS-IN fields are quick-search criteria fields normally used by database personnel for extracting information for reports but can be used by any user to retrieve all the information on one study in a file. REF-CODE links the test data with the information source in the CERSOURC file. Specific field listings for each file are shown in Tables 2 though 9.

Lubricants perform an important function in wear testing. By coating the contact surfaces, the lubricant can have a considerable effect on the wear life of a material. Notes about lubricant breakdown, by-product effects on material surfaces, and other important details should be included with other information about the lubricant. The LUBRICANTS file contains base stock information, supplier name, upper temperature limit for normal operation, and comments on other characteristics of importance for each lubricant used in the tribology studies.

Data tables for this report are organized according to type of data: Appendix A contains available background information on the materials presented in this report; Appendix B contains the experimental text data arranged in sections by property type. Some test data listed in Appendix B may not be represented by materials in Appendix A but will be included in a later report when such information becomes available. The policy for this database is to store the available information for future use, whether or not a complete set of information is available on a material. Complete sets are preferred and sought as time permits.

The dBASE IV program does not allow storage of superscripts or subscripts, so the numbers used in chemistries must be carefully coded. As a rule, the number or numbers immediately following a chemical abbreviation are subscripts. Numbers indicating multiple molecules are enclosed in parentheses. Alumina, Al_2O_3, would be coded as Al2O3; mullite, $2Al_2O_3+3SiO_2$, would be coded as (2)Al2O3+(3)SiO2. Superscripts, although rarely used in this database, are enclosed in backslashes: Ne^{12} would be Ne\12\.

5. SYSTEM ACCESS

Direct access to the master database is very limited to protect the integrity of the master files. Experience has shown that major disasters often occur when too many people have direct access to unprotected files at the microcomputer level. Since most users would prefer to have the data in a familiar format, to subset, analyze, and rearrange to suit their needs, this method satisfies both situations; the master files are protected, and the user gets the data in a readily consumable form. While direct access is faster, the process of downloading across phone lines can be time consuming and hazardous to the integrity of the data being transmitted. This database was designed as a repository, not a full-function analytical tool.

Access to the data is attained by calling the database administrator and requesting all files or just those pertaining to certain materials or test types. The information requested by the user (in the user-designated format, including software and disk type) will then be downloaded from the master files, reformatted, if necessary, and sent to the user when possible. No plans are being considered for direct access from outside systems at this time. Direct transfer is available by special arrangement but may be time consuming due to the sizes and numbers of files. No guarantee is given for the validity of data transmitted directly because of possible phone line problems. Until a computerized interface becomes available, the *CTP Data Base User's Guide* will be sent to all first-time users.

Several file formats, other than dBASE IV, are available for files downloaded for users. These formats have been categorized as either Apple Macintosh-compatible files (on 3.5-in. floppy disks), or IBM PC-compatible files (on 3.5-in. floppy disks up to 1.44 MB or 5.25-in. floppy disks from 360 KB to 1.2 MB). Available Macintosh file types include Microsoft EXCEL; SYLK; FOXBASE; and plain, printable ASCII. IBM file types are Lotus 1-2-3, Microsoft EXCEL, DIF, SDF, SYLK, plain ASCII, delimited ASCII, and dBASE IV. Other formats may be available by special arrangement. When requesting information from the database, users should indicate disk size, disk density, and file type.

With computer diseases becoming so rampant, users should be aware that precautions are taken to ensure that the disks they receive from the database are disease free. Only new disks are used for transmittals to avoid spreading any computer diseases that might be hiding. No recycled, reformatted disks are sent to users. Both the master system, a Northgate Elegance 486/25, and the Macintosh IIcx are checked regularly for such illnesses; none have been found so far. Use of both computers is limited to one person who carefully screens incoming software to avoid contamination of either system. No information is downloaded from public bulletin boards to either system. Both computers have virus detection software installed, and all efforts are made to ensure both systems stay disease free. If users have problems with disks received from the database, they should inform database personnel immediately so that steps can be taken to correct the problems.

6. FUTURE PLANS

Many changes and additions to the database have been made over the past two years. Some of the changes were made only to a selected set of data because of time constraints. Database personnel plan to do catch-up work for the database during FY 1992.

Plans are being made to write a computerized user interface using the dBASE IV programming language and to have the initial version completed some time in 1992. The interface will link the numerous database files together, providing better access to information in the system. This interface will be available to all users of the database who request it.

The next hardcopy update is scheduled for September 1992.

7. OTHER CTP DATABASE SUMMARY REPORTS

M. K. Booker, *Ceramics Technology for Advanced Heat Engines Project Data Base: A Summary Report*, ORNL/M-462, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Laboratory.

B. L. P. Booker, *Ceramics Technology for Advanced Heat Engines Project Data Base: September 1988 Summary Report*, ORNL/M-755, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Laboratory, March 1989.

B. L. P. Keyes, *Ceramics Technology for Advanced Heat Engines Project Data Base: March 1989 Summary Report*, ORNL/M-1098, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Laboratory, April 1990.

B. L. P. Keyes, *Ceramics Technology for Advanced Heat Engines Project Database: September 1989 Summary Report*, ORNL/M-1286, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Laboratory, October 1990.

B. L. P. Keyes, *Ceramics Technology Project Data Base: March 1990 Summary Report*, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Laboratory, in publication.

B. L. P. Keyes, *Ceramics Technology Project Data Base: September 1990 Summary Report*, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Laboratory, in publication.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. Peter A. Gaydos, "Current Progress in Studies of Dynamic Contact of Ceramics for Advanced Heat Engines," pp. 309-18 in *Proceedings of the Annual Automotive Technology Development Contractors' Coordination Meeting, Dearborn, Mich., October 22-25, 1990*, SAE P-243, Society of Automotive Engineers, Warrendale, Pa.

2. F. A. Kelley, M. H. Haselkorn, and C. D. Weiss, "Wear-Resistant Ceramic Coatings for Diesel Engine Components," pp. 261-72 in *Proceedings of the Annual Automotive Technology Development Contractors' Coordination Meeting, Dearborn, Mich., October 22-25, 1990*, SAE P-243, Society of Automotive Engineers, Warrendale, Pa.

3. M. G. S. Naylor, "Wear-Resistant Ceramic Coatings," pp. 273-82 in *Proceedings of the Annual Automotive Technology Development Contractors' Coordination Meeting, Dearborn, Mich., October 22-25, 1990*, SAE P-243, Society of Automotive Engineers, Warrendale, Pa.

TABLE 1. CTP DATABASE SUMMARY AS OF SEPTEMBER 30, 1991
(Numbers indicate records for each test type)

Material Class	Brazed Specimens MOR 4	Brazed Specimens Shear Str.	Brazed Specimens Toughness	Torsion	Tor. Fatigue	Creep	Cyclic Fatigue	Density	Dynamic Fatigue	Elasticity
Alumina							15		9	28
Alumina + reinforcing fibers								7		
Alumina + Zirconia										
Mullite										2
Mullite + reinforcing fibers										11
Silicon Carbide		12						10	13	15
Silicon Nitride	69	48		15	7	37	19	28	16	24
Silicon Nitride + reinforcing fibers							15	2		16
Zirconia	160	58	2				51	158		119
Zirconia + reinforcing fibers										
Other				6				4		
Total records	229	118	2	21	7	37	100	209	38	215

Material Class	Fracture Toughness	Hardness	Interrupted Fatigue	MOR 3 Pt Bend	MOR 4 Pt Bend	Oxidation Rate	Poisson's Ratio	Shear Modulus	Tensile	Thermal Conductivity
Alumina	39	4			411				28	3
Alumina + reinforcing fibers	39				144				11	34
Alumina + Zirconia					7					
Mullite	1			1	4					
Mullite + reinforcing fibers	12			9	22					
Silicon Carbide	29	27			236					
Silicon Nitride	94	112		10	647	1	2	1	75	9
Silicon Nitride + reinforcing fibers	53				144	3	17	16	86	9
Zirconia	347	24	239		1554				50	
Zirconia + reinforcing fibers					2				36	
Other	3	39			59					
Total records	617	206	239	20	3230	4	19	17	286	55

(CONTINUED)

TABLE 1. CTP DATABASE SUMMARY AS OF SEPTEMBER 30, 1991
(Numbers indicate records for each test type)

Material Class	Thermal Contraction	Thermal Diffusivity	Thermal Expansion	Thermal Shock	Torsion	X-Ray Diffraction	Material Char.	Chemistry
Alumina			1	2			13	14
Alumina + reinforcing fibers		18	4	6			94	
Alumina + Zirconia	23		21				8	
Mullite							2	
Mullite + reinforcing fibers							24	
Silicon Carbide			23			17	9	57
Silicon Nitride		10	44		3	49	56	7
Silicon Nitride + reinforcing fibers		17	14				53	
Zirconia						72	38	44
Zirconia + reinforcing fibers							5	
Other			35		4		36	17
Total records	23	45	142	8	7	138	338	139

Material Class	Wear & Friction	Coatings	Lubricants	
Alumina-based	9	3		
Alumina + reinforcing fibers	1			
Silicon Carbide	3			
Silicon Nitride	22			
Chromia-based	98	20		
Zirconia-based	13	15		
Enamels	5	10		
Other	126	53	13	
Total records	277	[illegible]	13	
Grand total test data records only				6309

TABLE 2

WEARDATA File Record Format
Wear Test Results

Field Name	Description
WBS_STUDY	Code made up of the CTP WBS number and responsible facility
TEST_ID	If present, a code denoting this test from all others
SPEC_ID	Specimen identification code
REF_CODE	Source of this information
COATING_1	Coating material for mobile specimen
BATCHID_C1	Batch code for COATING_1
SUBSTRAT_1	Substrate material for mobile specimen
BATCHID_S1	Batch code for SUBSTRAT_1
COATING_2	Coating material for stationary specimen
BATCHID_C2	Batch code for COATING_2
SUBSTRAT_2	Substrate material for stationary specimen
BATCHID_S2	Batch code for SUBSTRATE_2
LUBRICANT	Substance used to oil the contact surfaces in a test
TEST_RIG	Designation of the type of test apparatus used
DATA_CLASS	Type of data: TEST, AVG, NOM, TRGT
TEMP_C	Test temperature in centigrade
ENVIRONMNT	Atmosphere surrounding the specimens during testing
LOAD_N	Force placed on one surface normal to the other surface
COF_RANGE	Range of the coefficients of friction for the entire test
WEARUNITS	Units for WEARCOEF_1 and WEARCOEF_2
WEARCOEF_1	Calculated wear coefficient for the mobile specimen
WEARCOEF_2	Calculated wear coefficient for the stationery specimen
DURATN_MIN	Duration of the total test in minutes, including break-in period
SPEED	Speed of the mobile specimen, units shown with value
SEETEXT	A logical field indicating existence of more comments in DATATXT file
COMMENTS	A field for brief notes

TABLE 3

COATINGS File Record Format
Coating Characterization Information

Field Name	Description
COATING	Name of the coating as used in the database
BATCH_ID	Batch code for this specific coating
MAT_CLASS	Type of coating: CERAMIC, CERMET, or METAL
MATRIX	Chemical composition of the basic material
APPLY_TYPE	Method used to apply the coating to the substrate
OTHERNAME	Other names used for this coating
THICKNESS	Average thickness for this coating applied this way
WBS_STUDY	Code made up of the CTP WBS number and responsible facility
REF_CODE	Source of this information
TEXTUF	A logical field indicating that more information is available in the TEXTUF file, if the value is positive
COMMENTS	Brief notes on this material

TABLE 4

LUBRICNT File Record Format
Lubricant Background Information

Field Name	Description
LUBRICANT	Name given to lubricant as used in the database
FABRICATOR	The company producing the lubricant
BASE	The basic substance for this lubricant, such as mineral oil, polyalpha-olefin
MAX_TEMP_C	Maximum operating temperature, in centigrade, for this lubricant
TEXTUF	A logical field indicating that more information is available in the TEXTUF file, if the value is positive
WBS_STUDY	Code made up of the CTP WBS number and responsible facility
REF_CODE	Source of this information
COMMENTS	Brief notes on this lubricant

TABLE 5

MATLCHAR File Record Format
Material Characteristics Information

Field Name	Description
MATERIAL	Name of material as used in the database
MAT_CLASS	Classification of material based on its primary matrix: PSZ, SIN, SIC, ALO
BATCH_ID	Batch code for this specific material
CLASS_IN	Class code used by database personnel for extracting data for reports
WBS_STUDY	Code made up of the CTP WBS number and responsible facility
FABRICATOR	Company producing the material
FAB_NAME	Producing company's name for the material
VINTAGE	Date material was made
MATRIX	Primary compound or chemicals in a material
ADDITIVES	Enhancers added to the primary matrix
DENSIFY	Process used to increase density of the material, if ceramic
DENSTY_GCC	Density of the material, in grams/cubic centimeter
THDENS_PCT	Theoretical density, expressed as a percentage
MOE_MPA	Young's modulus at room temperature, in gigapascals
MOR_MPA	Rupture strength at room temperature, in megapascals
TYPE_HARD	Type of hardness test used for HARDNESS value
HARDNESS	Value for hardness using type of test indicated in TYPE_HARD
THERM_EXP	Coefficient of thermal expansion, in $1 \times 10^{-6}/°C$
COEF_FRICT	Coefficient of friction
POISSONS	Poisson's ratio for this material
TYPE_KIC	Type of toughness test used to produce KIC_MPAM value(K_{Ic})
KIC_MPAM	Fracture toughness (K_{IC}), in MPa/m
REF_CODE	Source of this information

TABLE 6

CHEMSTRY File Record Format

Chemical Compositions

Field Name	Description
MATERIAL	Name of material as used in the database
BATCH_ID	Batch code for this specific material
CLASS_IN	Class code used by dtabase personnel for extracting data for reports
REF_CODE	Source of this information
WBS_STUDY	Code made up of the CTP WBS number and responsible facility
ANALYSIS	Type of analysis performed
CONDITION	Processing state material was in at time of analysis
UNITS	Units used for the quantities in the CHEM_INFO field
CHEM_INFO	Chemistry information as element: quantity, eg. Al:20.0, Si:10.3, C:3.9.
TEXTUF	A logical field that, if positive, indicates more information is available in the text file TEXTUF for this material and batch code.
COMMENTS	Brief notes on the chemistry of this material

TABLE 7

TESTBKGD File Record Format

Test Background Information

Field Name	Description
TEST_RIG	Name or designation given to testing apparatus as used in the database
TEST_TYPE	Name of the test data file containing the data that was run on this test rig; for example, WEARDATA.
REF_CODE	Information source
SEQ	Sequence number for one line of text in a single test rig description
TEST_BKGD	The field that contains the actual text information. Each test rig description may have one or as many records as needed to describe completely the test procedures, equipment, or other noteworthy details.

TABLE 8

DATATXT File Record Format
Extended Comments for Specific Test Results

Field Name	Description
MATERIAL	Name of the material tested
BATCH_ID	Batch code or lot number for the material
CLASS_IN	Class code used by database personnel for extracting data for reports
WBS_STUDY	Code made up of the CTP WBS number and responsible facility
TEST_TYPE	Name of the test data file containing the data that was run on this test rig; for example, WEARDATA.
SPEC_ID	Identification code for the sample referred to in the following TEXT field
SEQ	Sequence number for one line of text for a single set of notes
TEXT	The field that contains the actual text information. Each set of notes per individual test may have as many of these records as needed to store the information.

TABLE 9

MATNAMES File Record Format
Thesaurus of Material Names

Field Name	Description
MATERIAL	Name of the material tested
MAT_TYPE	General type of material (eg. ceramic, cermet, braze, metal, etc.)
NAME_CHEM	Name of material based on its chemistry (eg. Cr2O3-5%SiO2-3%TiO2 for M136)
NAME_COMM	Name of material as assigned by the manufacturer (eg. ARTUFF for Al_2O_3+SiCw)
NAME_OTHER	Names that may be assigned to this material other than those already listed.

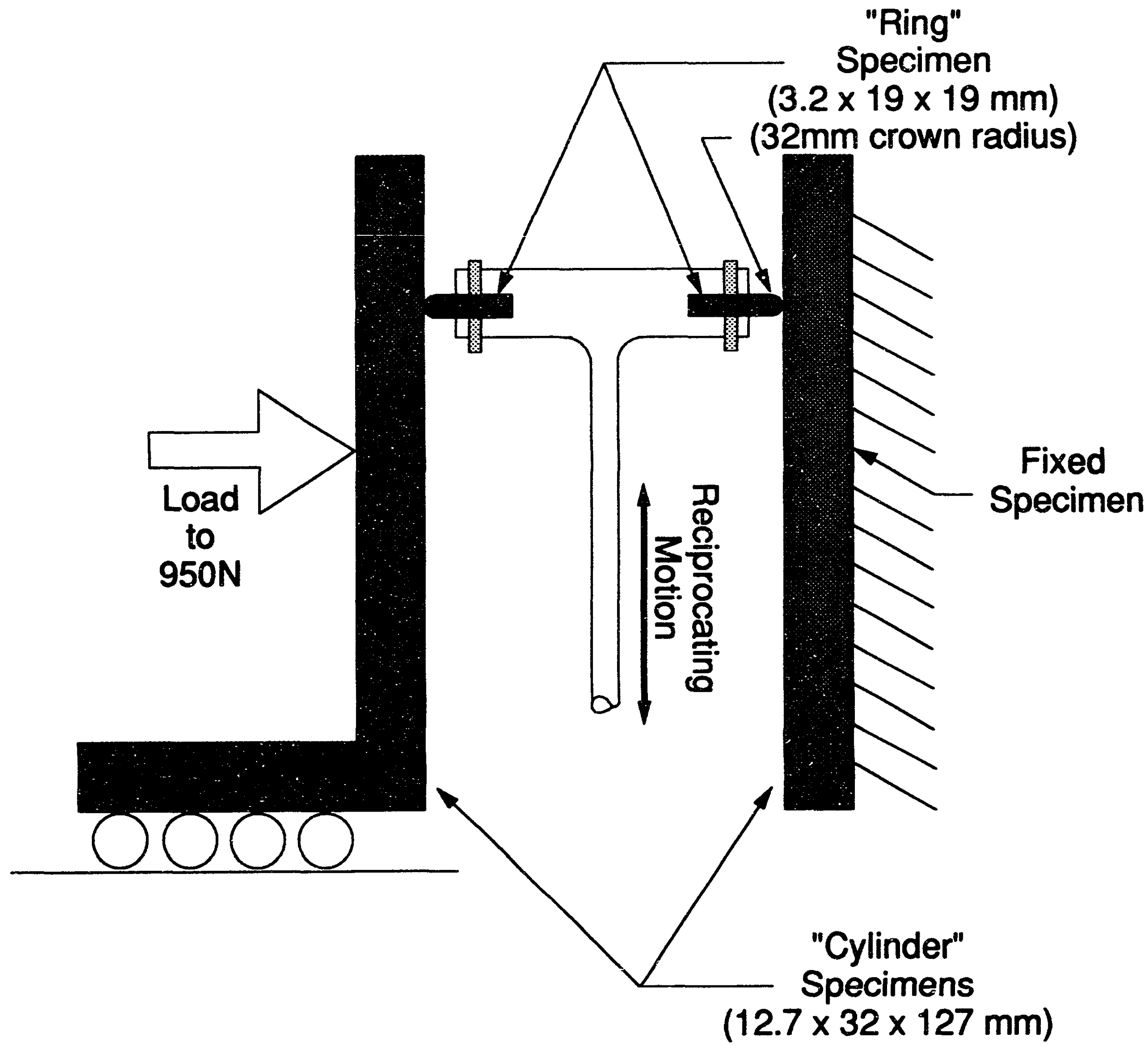

Figure 1. Flat Specimen Configuration for the Battelle Columbus Laboratory Ring-Cylinder Wear Tests

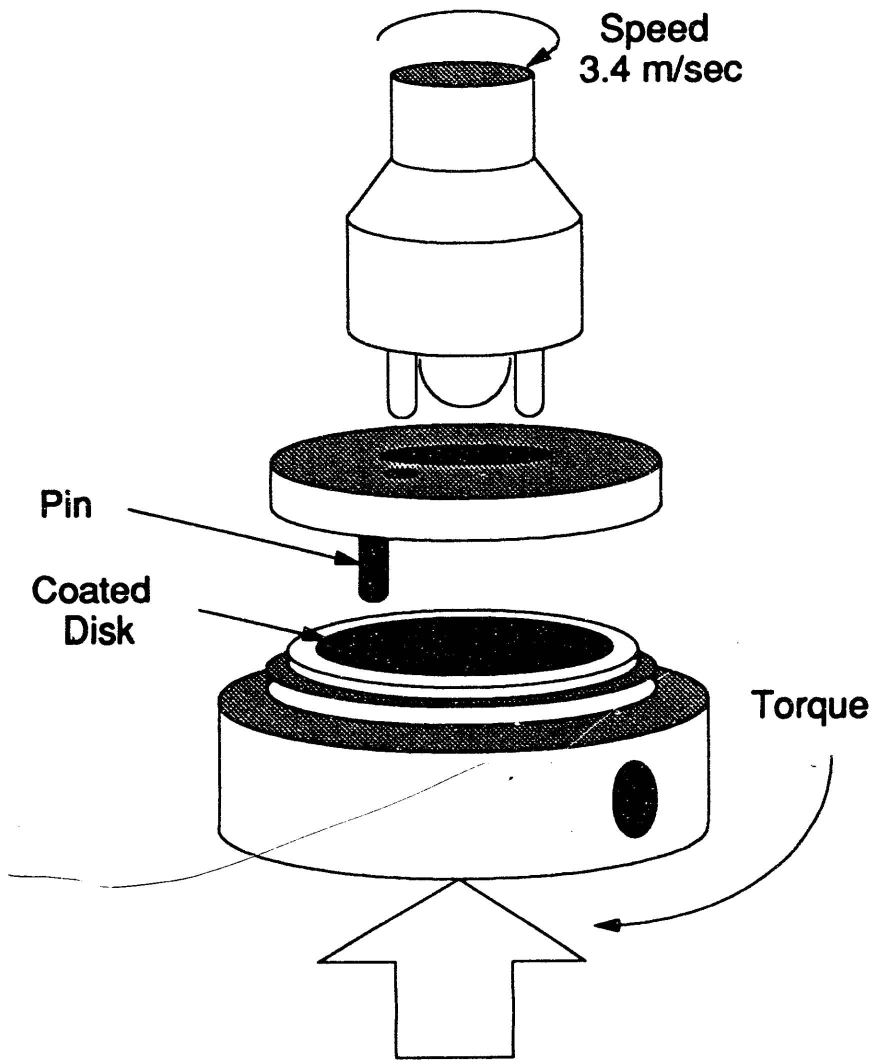

Figure 2. Falex Model 6 Pin-on-Disk Tester[2] (Caterpillar, Inc.)

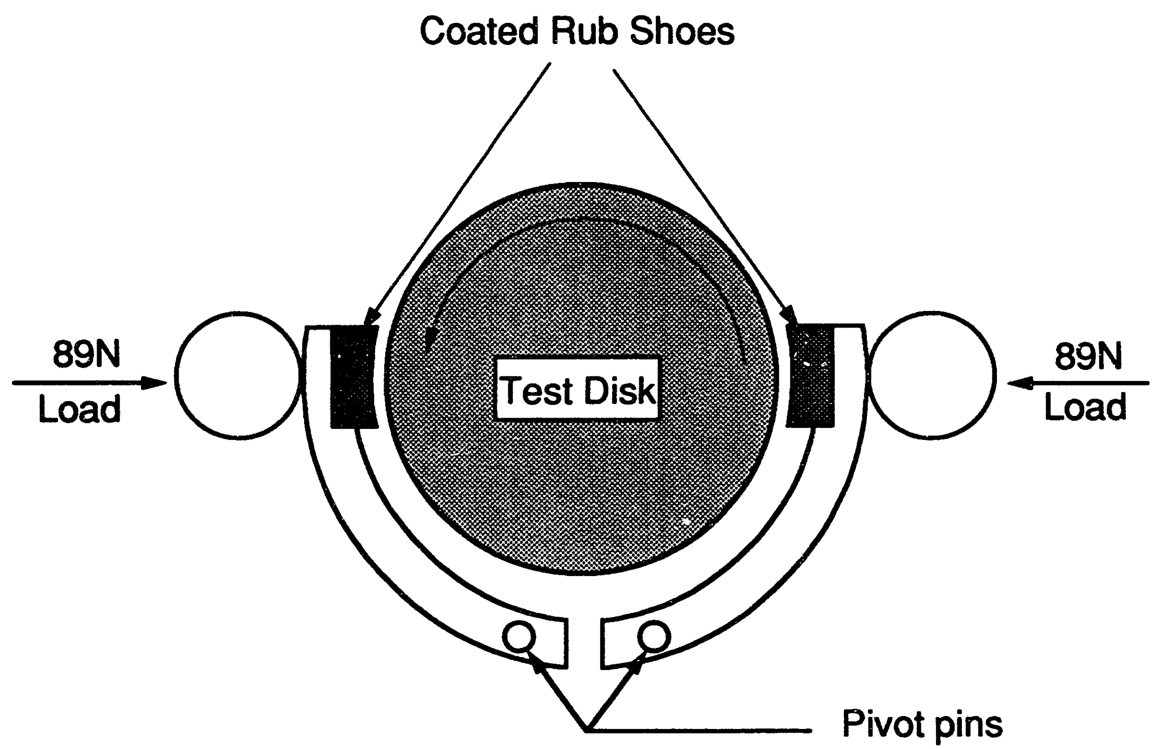

Figure 3. Hohman Double-Rub Shoe Tester Model A-6 Test Configuration (Caterpillar, Inc.)

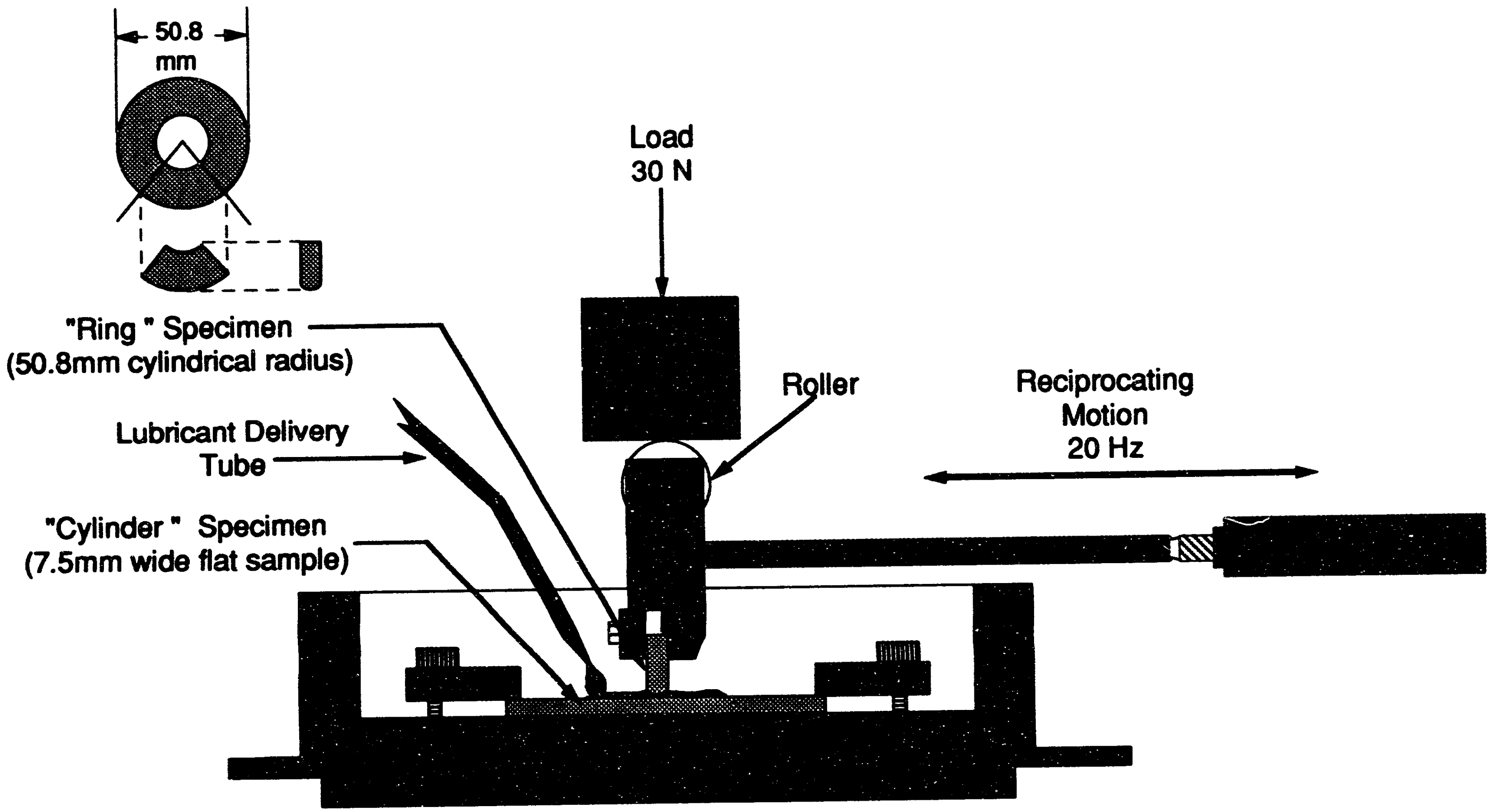

Figure 4. Cameron-Plint Wear Tester
(Cummins Engine Company)

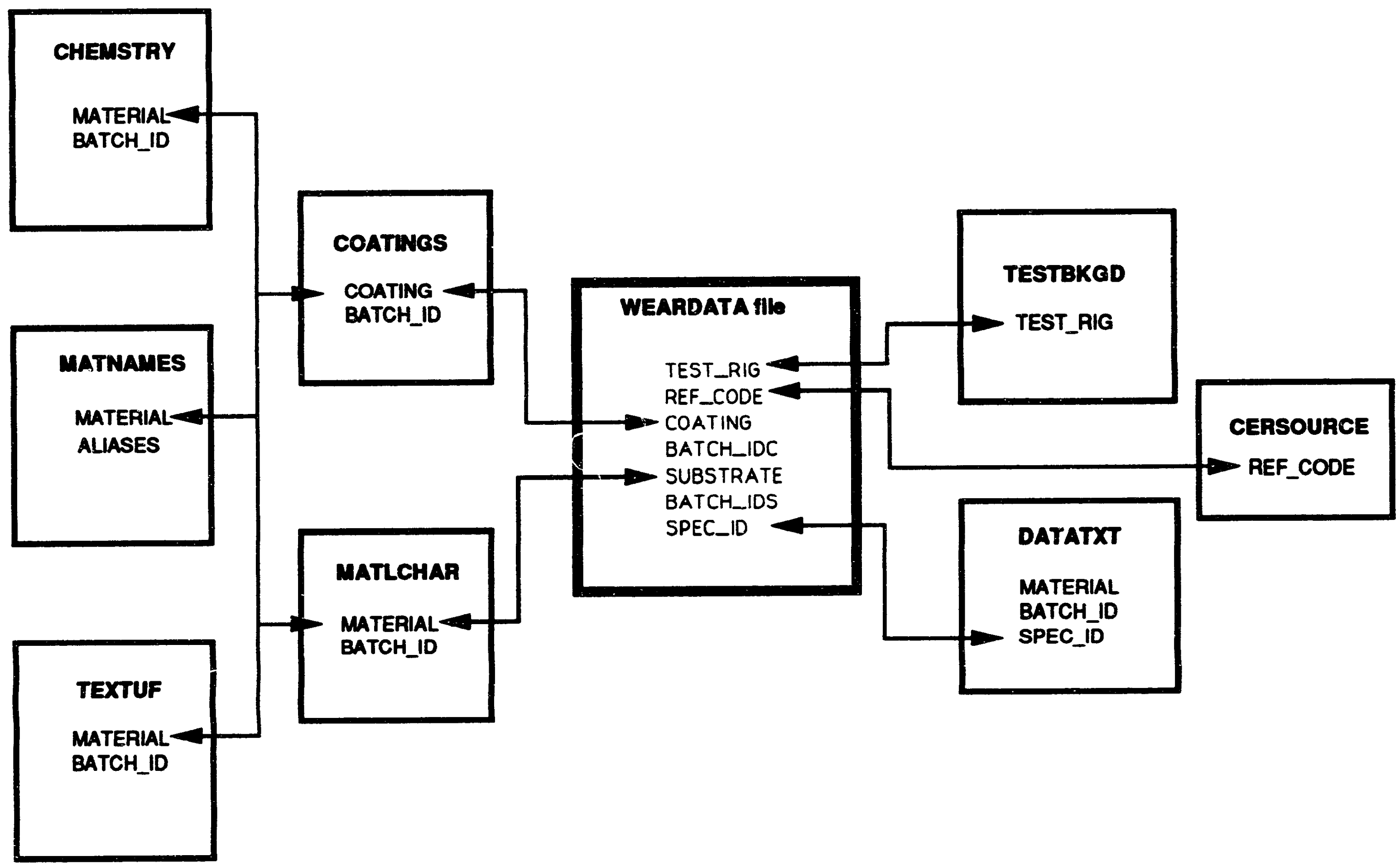

Figure 5. Interfile Linkage Map For Wear and Friction Data

APPENDIX A. MATERIAL CHARACTERISTICS AND BACKGROUND DATA

Section 1. Background Information on Base Materials

MATERIAL	MATERIAL CLASS	BATCH CODE	MANUFACTURER	MANUFACTURER'S DESIGNATION	MATRIX	DENSIFICATION METHOD
BATTELLE COLUMBUS LABORATORY						
Al2O3+SiCw	ALO/SICW	ARCO/TRIB/BCD	ARCO Chemical Company	ARTUFF A4AS	Al2O3+SiC whiskers	
SIALON	SIALON	KENNMTL/TRIB/BCD	Kennametal, Inc.	SIALON	Si+Al2O3+N	
SIALON+SiCW	SIALON/SICW	KENNMTL/TRIB/BCD	Kennametal, Inc.		Si+Al2O3+N, SiC whiskers	
HEXOLOY SA	SIC ALPHA	CARBRNDM/SIC/BCD	Carborundum Co.	ALPHA SiC	alpha phase SiC	SINTERED
Si3N4	SIN	CERCOM/TRIB/BCD	Cercom, Inc.		Si3N4	
Si3N4	SIN	MSU/TRIB/BCD	Michigan State Unversity		Si3N4	
Si3N4+Ne-ION*	SIN	MSU/TRIB-Ne/BCD	Michigan State Unversity		Ne-ion implanted Si3N4	
NC-132	SIN HIPED	NORTON/SIN/BCD	Norton/TRW Ceramics	NORALIDE	2w%W,.5w%Mg,.25w%Al,bal Si3N4	HIP'ed
TS-PSZ	ZRO-PSZ/MGO	NILCRA/MgPSZ/BCD	Nilcra	TS GRADE PSZ	3.3w%Mg0,3w%HfO2,bal ZrO2	
Z-191	ZRO-PSZ/YO	NGK/YPSZ/BCD	NGK-Locke	Z-191	5.4w%Y2O3,bal-ZrO2	
ATTZ	ZRO-TTZ/ALO	TOYA/2Y20A/BCD	Toya Soda Manu.	2Y20A	3.6w%Y2O3,20w%Al2O3,bal ZrO2	
K162B	CERMET	KENNMTL/BCD	Kennametal, Inc.		TiC-Ni/Mo	
PS212	COMPOSITE	NASALRC/PS/BCD	NASA Lewis Research Ctr.		Cr3C2,BaF2/CaF2,Ag	
AISI 1020 STEEL	METAL	UNKNOWN/TRIB/BC		1020 STEEL		
AISI 410 STEEL	METAL	WEARTECH/BCD		410 SS		
CAST IRON	METAL	CATPLR/CL1/BCD	Caterpillar, Inc.		3.3w%C,2.3w%Si,.7w%Mn,bal Fe	
MOLALLOY	METAL/LUBRICANT	PURECARB/MOS/BCD	Pure Carbon	MOLALLOY	MoS2	
WSe2/GaIn	METAL/LUBRICANT	BATTELLE/DJBOES	Battelle Columbus Div.		WSe2,Ga,In	
CATERPILLAR						
Al2O3	ALO	FALEX-PIN/CAT			Al2O3	
17-4PH STEEL	METAL	CATPLR/TRIB		17-4 PH SS	17-4 PH stainless steel	
440C STEEL	METAL	FALEX-PIN/CAT		AISI 440C		
AiSI 1010	METAL	CATPLR/TRIB			C,Si,Mn,P,S,Fe(bal.)	
AISI 1018	METAL	CATPLR/TRIB				
CAST IRON	METAL	CATPLR/TRIB				
CAST IRON/H-13†	METAL	CATPLR/TRIB	UNKNOWN		Disks=CAST IRON or H-13 STEEL	
H-13 STEEL	METAL	CATPLR/TRIB		H-13		
Si3N4	SIN	FALEX-PIN/CAT			Si3N4	
ZrO2	ZRO	FALEX-PIN/CAT			ZrO2	

* Ring specimens made of Si3N4 were each implanted with 6 doses of 10.E+12 particles of 20 Ne-ions. This ion is similar in size to 22Na ion, and should produce similar radiation damage. Each dose was implanted to different depths, ranging from <5 to around 10 micrometers.

† Source did not distinguish between cast iron and H-13 tool steel as substrates.

Section 1. Background Information on Base Materials, continued

MATERIAL	MATERIAL CLASS	BATCH CODE	MANUFACTURER	MANUFACTURER'S DESIGNATION	MATRIX	DENSIFICATION METHOD
CUMMINS ENGINE COMPANY						
422 STEEL	METAL	WISCON/TRIB/CEC	Wiscon Centrifugal	422 STEEL	13Cr,1Ni,1Mo,1W,.3V,.2C,Fe	
GRAY IRON	METAL	CUMMINS/TRIB/CEC	Cummins Engine Company	GRAY IRON	Fe	
H-13 STEEL	METAL	WISCON/TRIB/CEC	Wiscon Centrifugal	H 13 STEEL		
HK40 STEEL	METAL	WISCON/TRIB/CEC	Wiscon Centrifugal	HK40	26Cr,20Ni,.2-.6C,Fe	
HP GRAY IRON	METAL	CUMMINS/TRIB/CEC	Cummins Engine Company		High phosphorus pearlitic iron	
INCONEL 625	METAL	WISCON/TRIB/CEC	Wiscon Centrifugal	INCO 625	22Cr,9Mo,4Nb,.06C,5Fe,Ni-based	
INCONEL 718	METAL	CUMMINS/TRIB/CEC	Cummins Engine Company	INCONEL 718	19Cr,.08C,29Fe,Ni-based	
NIRESIST 1	METAL	CUMMINS/TRIB/CEC	Cummins Engine Company	Niresist		
PG CAST IRON	METAL	CUMMINS/TRIB/CEC	Cummins Engine Company	CAST IRON	Fe, Pearlitic gray cast iron	
PH GRAY IRON	METAL	CUMMINS/TRIB/CEC	Cummins Engine Company		Low alloy pearlitic gray iron	

SECTION 2. BACKGROUND INFORMATION ON COATINGS

COATING	BATCH CODE	COMPOSITION	TYPE OF COATING APPLICATION	MATERIAL SOURCE	ALIASES
Coatings from Battelle Columbus Laboratory Study					
CA815	WEARTECH/ESA/BCD	Cr3C2,Ni	ELECTROSPARK ALLOYED	Wear Technology	
CERATEK	PCKTECH/BCD	Au-Co-Ni (bonded to Si3N4)		PCK Technology	
Cr	BATTELLE/EP/BCD	Cr	ELECTROPLATED	Battelle Columbus	
Cr2O3	CERAC/PS/BCD	5w%Cr, bal Cr2O3	PLASMA SPRAYED	Cerac/Battelle Columbus	C-1225
Cr2O3	BATTELLE/PS/BCD	Cr2O3	PLASMA SPRAYED	Battelle Columbus	
Cr2O3+N-ION	BATTELLE/PS/BCD	Cr2O3+N-ion implant	PLASMA-SPRAYED	Battelle Columbus	BEAMALLOY
Cr3C2	METTECH/PS/BCD	20w%Cr3C2,12w%Ni,9w%W,bal Cr	PLASMA-SPRAYED	Metallurgical Tech.	
M130	METCO/PS/BCD	13w%Ti02,87w%Al2O3	PLASMA-SPRAYED	Metco Div.	METCO 130
M136CP	METCO/PS/CAT	Cr2O3,SiO2	PLASMA SPRAYED	Caterpillar(1.3.1 STUDY)	METCO 136
M350A	METCO/PS/CAT	High C,Fe,Mo	PLASMA SPRAYED	Caterpillar(1.3.1 STUDY)	
M501	METCO/PS/BCD	30w%Mo,12Cr,2.5B,3Fe,bal Ni	PLASMA-SPRAYED	Metco Div.	METCO 501
M63/M130	BATTELLE/METCO-2L	M63 base coat, M130 top coat	PLASMA-SPRAYED	Metco Div.	
MOLY	WEARTECH/ESA/BCD	Mo	ELECTROSPARK ALLOYED	Wear Technology	Molybdenum
P312M	PLASMADYNE/PS/BCD	MoSi2	PLASMA SPRAYED COATING	Plasmadyne	PLASMALLOY
SCA1000	KAMAN/DC/BCD	Cr2O3	DRAIN CAST COATING	Kaman Scientific Corp.	Cr2O3
T400	SDS/PS/BCD	28w%Mo,34Ni,9Cr,1Fe,2Si,bal Co	PLASMA-SPRAYED	Stoody-Deloro Stellite	TRIBALOY 400
VA20	WEARTECH/ESA/BCD	WC,TaC,TiC,Ni	ELECTROSPARK ALLOYED	Wear Technology	
VR73	WEARTECH/ESA/BCD	WC,TaC,TiC,Co	ELECTROSPARK ALLOYED	Wear Technology	
WC	SDS/HVOF/BCD	12w%Co,bal WC	HIGH VELOCITY OXY FUEL(JETKOTE	Stoody-Deloro Stellite	JK114
WC+Mo	WEARTECH/ESA/BCD	WC base coat, Mo top coat	ELECTROSPARK ALLOYED	Wear Technology	duplex
Coatings from Caterpillar Study					
25%M143/75%M461	CATPLR/PSG/CAT	25v% METCO 143+75v% METCO 461	PLASMA-SPRAYED	Caterpillar	
25%ZrO2/75%M461	CATPLR/PSG/CAT	25v%ZIRCOA ZrO2+75v%METCO 461	PLASMA-SPRAYED	Caterpillar	
50%M143/50%M461	CATPLR/PSG/CAT	50v% METCO 143+50v% METCO 461	PLASMA-SPRAYED	Caterpillar	
50%ZrO2/50%M461	CATPLR/PSG/CAT	50v%ZIRCOA ZrO2+50v%METCO 461	PLASMA-SPRAYED	Caterpillar	
75%M143/25%M461	CATPLR/PSG/CAT	75v% METCO 143+25v% METCO 461	PLASMA-SPRAYED	Caterpillar	
75%ZrO2/25%M461	CATPLR/PSG/CAT	75v%ZIRCOA ZrO2+25v%METCO 461	PLASMA-SPRAYED	Caterpillar	

SECTION 2. BACKGROUND INFORMATION ON COATINGS, continued

COATING	BATCH CODE	COMPOSITION	TYPE OF COATING APPLICATION	MATERIAL SOURCE	ALIASES
Coatings from Caterpillar Study					
AMDRY 961	AMDRY/CAT	(bond coat)	PLASMA-SPRAYED	Amdry	
CIPE	CATPLR/DIP/CAT	BaO, CaO, B2O3, SiO2	DIPPED AND FIRED	A.I. Andrews	Cast Iron Porcelain Enamel
CM500L	AIRPROD/CVD/CAT	W/WC	CHEMICAL VAPOR DEPOSITED	Air Products & Chemicals, Inc.	
Co-ENAMEL	UILL/PS/CAT	Cobalt-based enamel	PLASMA-SPRAYED	A.I. Andrews/Solar Turbines	
Co-ENAMEL+Cr2O3	UILL/PS/CAT	Cr2O3 in Co-based enamel	PLASMA-SPRAYED	A.I. Andrews/Solar Turbines	
Co-ENAMEL+Cr3C2	UILL/PS/CAT	Cr3C2 in Co-based enamel	PLASMA-SPRAYED	A.I. Andrews/Solar Turbines	
Co-ENAMEL+ZrO2	UILL/PS/CAT	ZrO2 in Co-based enamel	PLASMA-SPRAYED	A.I. Andrews/Solar Turbines	
Cr3C2	SYLVESTR/CVD/CAT	Cr3C2	CVD-high temp	Sylvester and Co.	
CrN	LTAVD/CAT	CrN	LOW TEMP. ARC VAPOR DEP.	UNKNOWN	
ENAM-1	CAT/DIP/CAT	Text gave no details	DIPPED AND FIRED	Caterpillar	
ENAM-1+50%Cr2O3	CAT/DIP/CAT	50v%Cr2O3 particles in enamel base	DIPPED AND FIRED	Caterpillar	
ENAM-1+60%Cr2O3	CAT/DIP/CAT	60v%Cr2O3 particles in enamel base	DIPPED AND FIRED	Caterpillar	
ENAM-1+70%Cr2O3	CAT/DIP/CAT	70v%Cr2O3 particles in enamel base	DIPPED AND FIRED	Caterpillar	
ENAM2	SOLTURB/SLSP/CAT	Vitreous phase ceramic	SLURRY SPRAYED	Solar Turbines	VPC
M136CP	METCO/PS/CAT	Cr2O3,SiO2	PLASMA-SPRAYED	Metco Div.	METCO 136CP
M143	METCO/PS/CAT	ZrO2,18%TiO2,10%Y2O3	PLASMA-SPRAYED	Metco Div.	METCO 143, ZTY
M19E	METCO/PS/CAT	NiCr powder	PLASMA-SPRAYED	Metco Div.	METCO 19E
M350A	METCO/PS/CAT	Mo,Fe,C	PLASMA-SPRAYED	Metco Div.	METCO 350A
M461	METCO/PS/CAT	(bond coat)	PLASMA-SPRAYED	Metco Div.	METCO 461
M461/M143-2L	METCO/PS-2L/CAT	See note 1 below.	PLASMA-SPRAYED	Metco Div.	
M461/M143-3L	METCO/PS-3L/CAT	See note 2 below.	PLASMA-SPRAYED	Metco Div.	
M461/ZIRCOA-2L	METZIR/PS-2L/CAT	See note 3 below.	PLASMA-SPRAYED	Metco Div., Zircoa	
M461/ZIRCOA-3L	METZIR/PS-3L/CAT	See note 4 below.	PLASMA-SPRAYED	Metco Div., Zircoa	
M461/ZIRCOA-4L	METZIR/PS-4L/CAT	See note 5 below.	PLASMA-SPRAYED	Metco Div., Zircoa	

Notes

1. 2-Layered coating: M461 base coat, M143 top coat.
2. 3-Layered coating: M461 base coat, 50% M461- 50% M143 mid coat, M143 top coat.
3. 2-Layered coating: M461 base coat, Zircoa top coat.
4. 3-Layered coating: M461 base coat, 50% M461-50% Zircoa mid coat, Zircoa top coat.
5. 4-Layered coating: M461 base coat, 50%-50% M461-Zircoa coat, 25%M461-75% Zircoa coat, Zircoa top coat.

SECTION 2. BACKGROUND INFORMATION ON COATINGS, continued

COATING	BATCH CODE	COMPOSITION	TYPE OF COATING APPLICATION	MATERIAL SOURCE	ALIASES
Coatings from Caterpillar Study					
M66F-NS	METCO/PS/CAT	High-Co,Mo,Cr	PLASMA-SPRAYED	Metco Div.	METCO 66F-NS
M70C	METCO/PS/CAT	Cr3C2	PLASMA-SPRAYED	Metco Div.	METCO 70C
M750F	METCO/PS/CAT	High-Mo,Ni,Cr powder	PLASMA-SPRAYED	Metco Div.	METCO 750F
MAE7023	METCO/PS/CAT	High Mo alloy	PLASMA-SPRAYED	Metco Div.	METCO AE7023
PS212	HOHMAN/APS/CAT	Cr3C2,BaF2,CaF2,Ag	PLASMA-SPRAYED	Hohman	
Ti(C,N)	SYLVESTR/CVD/CAT	Ti with oxides of C and N	CVD-MID TEMPERATURE	Sylvester and Co.	
TiC/TiN	SYLVESTR/CVD/CAT	TiN layer+ TiC layer	CVD-HIGH TEMPERATURE	Sylvester and Co.	
TiN	BALZERS/PSEB/CAT	TiN	PLASMA-SPRAY/VAPOR DEPOSITION	Balzers	
TiN	CATERPLR/AE/CAT	TiN	PLASMA SPRAY/VAP.DEP./ARC EVAP	Caterpillar	
TiN	RICHTER/VDHC/CAT	TiN	PLASMA SPRAY/VAP.DEP./HOL.	Richter Precision	
WC	SFL/CVD/CAT	Tungsten carbide	CVD	San Fernando Labs.	
ZrO2	ZIRCOA/PS/CAT	ZrO2	PLASMA-SPRAYED	Zircoa	ZIRCOA
ZrO2	PVD/CAT	ZrO2	PHYSICAL VAPOR DEPOSITION		
Coatings from Cummins Study					
Al2O3-26%ZrO2	BIRL/APS/CEC	Al2O3,26%ZrO2	AIR PLASMA SPRAYED	Basic Ind.Resrch Lab,NwU	
Al2O3-41%ZrO2	BIRL/APS/CEC	Al2O3,41%ZrO2	AIR PLASMA SPRAYED	Basic Ind.Resrch Lab,NwU	
ARMACOR M	APSMAT/APS/CEC	Proprietary, Fe-based	AIR PLASMA SPRAYED	APS Materials	
ARMACOR T	APSMAT/APS/CEC	Proprietary, Fe-based	AIR PLASMA SPRAYED	APS Materials	
B4C	APSMAT/VPS/CEC	B4C	VAPOR PLASMA SPRAYED	Stark	
Cr	APSMAT/APS/CEC	Cr	AIR PLASMA SPRAYED	APS Materials	
Cr	CUMMINS/EP/CEC	Cr	ELECTROPLATED	Cummins Engine Company	
Cr2O3	APSMAT/APS/CEC	Cr2O3	AIR PLASMA SPRAYED	Union Carbide Corp.	UCAR
Cr2O3	BIRL/APS/CEC	Cr2O3	AIR PLASMA SPRAYED	Basic Ind.Resrch Lab,NwU	
Cr2O3	BIRL/HVOF/CEC	Cr2O3	HIGH VELOCITY OXY FUEL	Basic Ind.Resrch Lab,NwU	
Cr2O3-50%Al2O3	BIRL/APS/CEC	Cr2O3,50%Al2O3	AIR PLASMA SPRAYED	Basic Ind.Resrch Lab,NwU	
Cr2O3-STELLITE6	APSMAT/APS/CEC	Cr2O3,33%STELLIT6,3%SiO2,2%TiO	AIR PLASMA SPRAYED	APS Materials, METCO	

SECTION 2. BACKGROUND INFORMATION ON COATINGS, continued

COATING	BATCH CODE	COMPOSITION	TYPE OF COATING APPLICATION	MATERIAL SOURCE	ALIASES
Coatings from Cummins Study					
Cr3C2-NiCr	UTRC/HVOF/CEC	Cr3C2,NiCr	HIGH VELOCITY OXY FUEL,JETKOTE	United Tech.Research Ctr	DIAMALLOY 3007
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	Cr3C4,WC,NiCrCo	HIGH VELOCITY OXY FUEL,JETKOTE	Boyd Machine and Repair	
FERROTIC CM	APSMAT/LPPS/CEC	45%TiC,high Cr tool steel	LOW PRESSURE PLASMA SPRAYED	APS Materials	
FERROTIC CS40	APSMAT/LPPS/CEC	45%TiC,martensitic stnls steel	LOW PRESSURE PLASMA SPRAYED	APS Materials	
FERROTIC HT6A	APSMAT/LPPS/CEC	35%TiC,Ni-based alloy	LOW PRESSURE PLASMA SPRAYED	APS Materials	
M106FP	UTRC/APS/CEC	Cr2O3,2%SiO2,2%other oxides	AIR PLASMA SPRAYED	Metco Div.	METCO 106FP
M136	APSMAT/APS/CECA	Cr2O3,5%SiO2,3%TiO2	AIR PLASMA SPRAYED	Metco Div.	METCO 136
M136	BOYD/APS/CECB	Cr2O3,5%SiO2,3%TiO2	AIR PLASMA SPRAYED	Metco Div.	METCO 136
M136-15%Al2O3	APSMAT/APS/CEC	Cr2O3,15%Al2O3,4%SiO2,3%TiO2	AIR PLASMA SPRAYED	Metco Div.	METCO 136+15%Al2O3
M136-3%SiO2	APSMAT/APS/CEC	Cr2O3,3%SiO2,3%TiO2	AIR PLASMA SPRAYED	APS Materials & METCO	METCO 136+3%SiO2
M136-8%SiO2	APSMAT/APS/CEC	Cr2O3,8%SiO2,3%TiO2	AIR PLASMA SPRAYED	APS Materials, METCO	METCO 136+8%SiO2
M143	UTRC/APS/CEC	ZrO2,18%TiO2,10%Y2O3	AIR PLASMA SPRAYED	Metco Div.	ZTY
M447	METCO/CEC	(bond coat)	AIR PLASMA SPRAYED	Metco Div.	METCO 447
Mo-Ni	BIRL/APS/CEC	Mo, Ni	AIR PLASMA SPRAYED	Basic Ind.Resrch Lab,NwU	
Mo-Ni	BIRL/HVOF/CEC	Mo, Ni	HIGH VELOCITY OXY FUEL SPRAYED	Basic Ind.Resrch Lab,NwU	
Mo-MoO2	BIRL/APS/CEC	Mo, O2	AIR PLASMA SPRAYED	Basic Ind.Resrch Lab,NwU	
NiCrBSi	UTRC/HVOF/CEC	Ni, Cr, B, Si	HIGH VELOCITY OXY FUEL SPRAYED	United Tech.Research Ctr	
TRIBOLITE	APSMAT/APS/CEC	Proprietary composition	AIR PLASMA SPRAYED	APS Materials	
WC-12%Co	APSMAT/APS/CEC	88%WC,12%Co	AIR PLASMA SPRAYED	Miller Thermal pwdr 1172	
WC-12%Co	APSMAT/LPPS/CEC	88%WC,12%Co	LOW PRESSURE PLASMA SPRAYED	Miller Thermal pwdr 1172	
WC-12%Co	APSMAT/HVOF/CEC	88%WC,12%Co	HIGH VELOCITY OXY FUEL SPRAYED	Miller Thermal pwdr 1172	
WC-12%Co	BIRL/HVOF/CEC	88%WC,12%Co	HIGH VELOCITY OXY FUEL SPRAYED	Turbine Metal Technology	
WC-12%Co+B	BIRL/HVOF/CEC	Borided 88%WC-12%Co	HIGH VELOCITY OXY FUEL SPRAYED	Turbine Metal Technology	

Section 3. Background Information on Lubricants

LUBRICANT	MANUFACTURER	LUBRICANT BASE	COMMENTS
SDL-1	Unknown	POLYALPHAOLEFIN	Good to 250°C. Tenacious decomposition
SAE10	Unknown	MINERAL OIL	
SAE30	Unknown	PETROLEUM	
LB625	Union Carbide	POLYALKYLENE GLYCOL	
LB650X	Union Carbide	POLYALKYLENE GLYCOL	
X-1P*	Dow Chemical	X-1P Fluid	Stable to 400°C, usable to 650°C.
OS-80001H	Lubrizol	POLYOLESTER	
OS-75725L	Lubrizol	POLYOLESTER	
OS-124†	Dow Chemical	POLYPHENYL ETHER	
BASE L	Lubrizol	POLYOLESTER	Base for OS-75725L (without additives).
BASE H	Lubrizol	POLYOLESTER	Base for OS-80001H (without additives).
CE/SF 15W40F	Unknown	MINERAL OIL	Commercially available oil
CE/SF 15W40U	Unknown	MINERAL OIL	CE/SF 15W40F run through an engine. About 3% soot.
EXP-SYN	Lubrizol	UNKNOWN	Experimental synthetic lubricant
P-A-O BASE	Unknown	POLYALPHAOLEFIN	Poly-alpha-olefin base stock
SRM OIL	Unknown	MINERAL OIL	Super-refined mineral oil

* More oil than usual was needed to lubricate materials at test temperatures.

† This lubricant burned off cleanly during hot-plate tests, but didn't have enough viscosity at test temperatures (370-460°C) to adequately lubricate materials.

Section 4. Enamel Characterization Information

COATING*	VOLUME % Cr_2O_3 ADDED	BATCH CODE	TEMP °C	DENSITY g/cm^3	HARDNESS 15-y	COEFFICIENT OF THERMAL EXPANSION 10.E-06/°C	COMMENTS
ENAM-1	0%	CAT/DIP/TRIB	20	2.4200	96	7.90	Basic enamel coating
ENAM-1/50%Cr2O3	50%	CAT/DIP/TRIB	20	3.3000	95	7.70	
ENAM-1/60%Cr2O3	60%	CAT/DIP/TRIB	20	3.5700	95	7.70	
ENAM-1/70%Cr2O3	70%	CAT/DIP/TRIB	20	3.8700	90	7.50	

*Coatings were applied to cast iron substrates.

SECTION 5. CHEMISTRIES

MATERIAL	BATCH CODE	TESTING FACILITY	CONDITION	UNITS	CHEMISTRY INFORMATION
M130	METCO/PS/BCD	BATTELLE	As recieved	% of total	TiO_2:13., Al_2O_3:87.
M501	METCO/PS/BCD	BATTELLE	As recieved	% of total	Mo:0.30, Cr:0.12, B:0.025, Fe:0.0275, C:0.0075, Ni:balance
DIESEL EXHAUST	BCD TEST ENVIRON.	BATTELLE	at 80psig,304°C	varied	NO_x:385ppm, NO:335ppm, O_2:13.4%, CO_2:6.2%, CO:560ppm, H_2O:7.66%, excess air:70%, particulates:26.3mg/m3
DIESEL EXHAUST	BCD TEST ENVIRON.	BATTELLE	at 100psig,310°C	varied	NO_x:450ppm, NO:400ppm, O_2:12.9%, CO_2:5.6%, CO:580ppm, H_2O:7.29%, excess air:48%, particulates:27.9mg/m3
DIESEL EXHAUST	BCD TEST ENVIRON.	BATTELLE	at 120psig,333°C	varied	NO_x:540ppm, NO:500ppm, O_2:12.1%, CO_2:5.2%, CO:608ppm, H_2O:7.3%, excess air:31%, particulates:27.7mg/m3
AISI 1010 STEEL	NOMINAL	BATTELLE	20°C	%	C:0.08-0.13, Si:0.1max, Mn:0.30-0.60, P:0.040, S:0.050, Fe:balance
AISI 1080 STEEL	NOMINAL	2.2.2-BCD	20°C	%	C:0.74-0.88, Si:0.05-0.30max, Mn:0.60-0.90, P:0.040, S:0.050, Fe:balance
INCONEL 625	CEC1	CUMMINS	20°C	%	Cr:20.00-23.00, Mo:8.00-10.00, C:0.10, Ti:0.40, Al:0.40, Fe:5.00, Mn:0.50, Si:0.50, P:0.015, S:0.015, Ca+Ta:3.15-4.15, Ni:balance
STELLITE 6	CEC1	CUMMINS	20°C	%	C:0.90-1.4, Cr:27.00-31.00, Ni:3.0, Mo:1.50, W:3.5-5.50, Fe:3.00, Mn:1.00, Si:1.50, Co

APPENDIX B. TEST RESULTS

SECTION 1. TEST RIG DESCRIPTIONS

TEST RIG	DESCRIPTION
RING-CYLINDER (Battelle Columbus Laboratory)	Test apparatus consisted of flat, rectangular "ring" specimens (3.2x19x19mm) with a contact surface of 3.2x19mm(crowned at a 32mm radius for assured contact) sliding against two rectangular flat "cylinder" specimens(12.7x32x127mm) perpendicular to the ring specimens. Lubricants varied and are listed in the test results records. Specimens were either monolithics or coated steels. The ring specimens were gripped on center pivots for self alignment. A reciprocating motion over 108mm was used to imitate the piston action. The actual test rig was contained in a chamber to evaluate environmental factors on the wear resistance. Each test was made up of 3 phases: a 60 minute break-in phase, then two 120-minute runs. Tests were stopped after each phase for wear measurements and to ensure that wear was confined to the outer 10 micrometers of surface. Test conditions were: 500 rpm, 12.3N ring load, and SDL-1 lubricant, unless listed otherwise. All except three tests were run in a diesel environment, heated to 350C before entering the testing chamber. Some specimens didn"t survive the entire test period due to excessive wear rates. Wear factor (k)= (wear volume,V, in mm^3)/((applied load,L, in N)*(sliding distance,d, in meters)). Ring wear was used because primary wear seemed to be on the rings. Liquid lubricants were more effective than other forms.
FALEX 6 (Caterpillar)	Tests were run on a Falex Model 6 Multi-specimen Test Machine using the pin-on-disk configuration. Tests usually were performed at 350°C at 3.4 meters/second with a nominal load of 22.25 Newtons. Resistive heating coils were located in the oil reservoir and in cavities in the table on which the specimen was mounted. The entire test specimen was submerged in lubricant during testing. Oil was carried to the

SECTION 1. TEST RIG DESCRIPTIONS, continued

TEST RIG	DESCRIPTION
FALEX 6 (continued)	reservoir by a peristaltic pump at 3.6 milliliters per minute. Each test was run for 30 minutes. before it was stopped for evaluation. If the wear rate was acceptable, the test was restarted and the process of checking every 30 minutes was continued until 2 hours total test time had elapsed. A Form Talysurf was used to determine the extent of wear. For the 1.3.1-Caterpillar study, the Falex tests were used to screen initial candidate materials for the piston rings and cylinder liners.
HOHMAN A-6 (Caterpillar)	The Hohman A-6 Double Rub Shoe Friction and Wear Test Machine has been used for many years to evaluate coatings. Two shoe specimens were mounted on either side of a rotating disk specimen. The shoe specimens, shaped to conform to the disk perimeter, were loaded in "nutcracker" fashion against the edges of the disk specimen. Tests were performed at about 350C; shoe load was 89 Newtons; disk velocity wa 3.4 meters/second. Test specimens were surrounded by two heating plates embedded in insulating blocks. Specimens were lubricated with an experimental synthetic oil from Lubrizol, dripped from hypodermic syringes placed over each contact interface. This particular machine was modified with a 3 horsepower motor to allow for testing of specimens with higher friction coefficient values. Tests were performed at Caterpillar.
CAMERON-PLINT (Cummins Engine Company)	Tests were performed using a Cameron-Plint TE77 reciprocating wear tester. Conditions provided by this machine best emulate wear where the piston ring direction reverses on the cylinder liner. Tests were run with fresh, used and no lubrication. The cylinder specimen was a flat coupon: the ring specimen was barrel-shaped with a 50.8millimeter radius. The ring oscillated against the cylinder at 20 hertz using a 5 millimeter strike.

SECTION 1. TEST RIG DESCRIPTIONS, continued

TEST RIG	DESCRIPTION
CAMERON-PLINT (continued)	The nominal load was 225N on the 7.49 millimeter flat cylinder specimen. Lubricant, when used, was supplied at 1 drop every 10 seconds, or 10.7 cubic centimeters per hour. Test durations were 6 hours for lubricated tests and 1 hour for dry tests. Wear measurements were calculated from scar width measurements, and for the liner from stylus profilometry measurements. Tests were performed at Cummins Engine Company.

SECTION 2a. WEAR TEST DATA FROM BATTELLE COLUMBUS LABORATORY

All tests were run in a diesel environment.

RING MATERIAL	BATCH CODE	CYLINDER MATERIAL	BATCH CODE	TEST NO.	TEMP °C	RING WEAR mm3/Nm	FRICTION COEFFICIENT RANGE	RING LOAD N/mm	LUBRICANT	SPEED	TEST DURATION minutes	COMMENTS
ATTZ	TOYA/2Y20A/BCD	ATTZ	TOYA/2Y20A/BCD	R54	25		0.12		SAE10	15cm/sec		
HEXOLOY SA	CARBRNDM/SIC/BCD	HEXOLOY SA	CARBRNDM/SIC/BCD	R10	20	4.E-08	0.04-0.08	17.0	SAE10	500-1500 RPM		
HEXOLOY SA	CARBRNDM/SIC/BCD	HEXOLOY SA	CARBRNDM/SIC/BCD	R55	25		0.07-0.04	18.0	SAE10	1100 cm/sec		
Z-191	NGK/YPSZ/BCD	HEXOLOY SA	CARBRNDM/SIC/BCD	R58	25		0.05-0.09		SAE10	500-1500RPM		
NC-132	NORTON/SIN/BCD	NC-132	NORTON/SIN/BCD	R9	260	5.E-08	0.05-0.06	12.3	SDL-1	500-1500 RPM		
NC-132	NORTON/SIN/BCD	NC-132	NORTON/SIN/BCD	R59	25	HIGH	0.23	12.3	NONE	500-1500RPM	8	
NC-132	NORTON/SIN/BCD	NC-132**	NORTON/SIN/BCD	R8	260	2.E-08	0.04-0.08	15.7	SDL-1	500-1500 RPM		Ceraprep surface preparation on cylinder specimen.
NC-132	NORTON/SIN/BCD	PS212	NASALRC/PS/BCD	R71	538		0.13-0.16	10.3	NONE	500-1500	5	Rig broke, test stopped
PS212	NASALRC/PS/BCD	PS212	NASALRC/PS/BCD	R69	538	2E-05	0.26-0.28	10.3	NONE	500-1500 RPM	10	
HEXOLOY SA	CARBRNDM/SIC/BCD	TS-PSZ	NILCRA/MgPSZ/BCD	R57	25		0.1		NONE	500-1500RPM		
TS-PSZ	NILCRA/MgPSZ/BCD	TS-PSZ	NILCRA/MgPSZ/BCD	R53	25		0.12		SAE10	8.3cm/sec		
Z-191	NGK/YPSZ/BCD	Z-191	NGK/YPSZ/BCD	R16	20	6.E-06	0.13-0.16	12.3	SAE10	500-1500 RPM		
Z-191	NGK/YPSZ/BCD	Z-191	NGK/YPSZ/BCD	R17	540	2.E-05	0.3-0.6	12.3	NONE	500-1500 RPM		

RING MATERIAL	BATCH CODE	SUBSTRATE MATERIAL	BATCH CODE	TEST NO.	TEMP °C	RING WEAR mm3/Nm	FRICTION COEFFICIENT RANGE	RING LOAD N/mm	LUBRICANT	SPEED rpm	TEST DURATION minutes	COMMENTS
Cyliner Liner = Al2O3+SiC whiskers(ARCO/TRIB/BCD)												
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	BCD/TRIB/SUBSTRT	R7	260	2.E-08	0.04-0.08	15.7	SDL-1	500-1500		
WC	SDS/HVOF/BCD	AISI 1020 STEEL	BCD/TRIB/SUBSTRT	R3	260	5.E-09	0.04-0.09	14.5	SDL-1	500-1500		

SECTION 2a. WEAR TEST DATA FROM BATTELLE COLUMBUS LABORATORY, continued

All tests were run in a diesel environment.

RING MATERIAL	BATCH CODE	RING SUBSTRATE	TEST NO.	TEMP °C	RING WEAR mm3/Nm	CYLINDER WEAR mm3/Nm	FRICTION COEFFICIENT RANGE	RING LOAD N	LUBRICANT	SPEED rpm	TEST DURATION minutes	COMMENTS
Cylinder Liner = Cr2O3(BATTELLE/PS/BCD) plasma-sprayed on AISI 1020 Steel												
Al2O3+SiCw	ARCO/TRIB/BCD	AISI 1020 STEEL	R18	260	8.E-09		0.03-0.08	12.3	SDL-1	500-1500		
MOLALLOY	PURECARB/MOS/BCD	AISI 1020 STEEL	R77	20	1.9E-05		0.24-0.60	4.8	NONE	300	60	1hr breakin before test
PS212	NASALRC/BCD	AISI 1020 STEEL	R88	260	8.3E-06		0.05-0.08	10.3	SDL-1	500-1500	60	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	88A	20	3E-08			12.3	SDL-1	500	60	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	88B	20	2E-08			12.3	SDL-1	500	120	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	88C	20	2E-08			12.3	SDL-1	500	120	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	91A	20	1E-08			12.3	SDL-1	500	60	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	91B	20	6E-09			12.3	SDL-1	500	120	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	91C	20	1E-08			12.3	SDL-1	500	120	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	92RA	20	8E-08			12.3	SDL-1	500	60	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	92RB	20	1E-08			12.3	SDL-1	500	120	
Si3N4	MSU/TRIB/BCD	AISI 1020 STEEL	92RC	20	2E-08			12.3	SDL-1	500	120	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	89A	20	2E-08			12.3	SDL-1	500	60	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	89B	20	2E-08			12.3	SDL-1	500	120	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	89C	20	2E-08			12.3	SDL-1	500	120	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	90A	20	3E-08			12.3	SDL-1	500	60	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	90B	20	1E-08			12.3	SDL-1	500	120	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	92LA	20	6E-08			12.3	SDL-1	500	60	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	92LB	20	6E-09			12.3	SDL-1	500	120	
Si3N4+Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	92LC	20	2E-08			12.3	SDL-1	500	120	
Si3N4-Ne-ION	MSU/TRIB-Ne/BCD	AISI 1020 STEEL	90C	20	2E-08			12.3	SDL-1	500	120	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R78	20	2.8E-06		0.07-0.15	10.3	NONE	289	60	1hr breakin before test
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R79	20	8.1E-07		0.05-0.10	10.3	NONE	492	240	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R80	20	2.7E-07		0.02-0.06	10.3	NONE	500	240	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R81	20	4.2E-07		0.02-0.07	10.3	NONE	500	240	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R82	20	5.0E-07		0.02-0.04	10.3	NONE	500	240	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R83	25	2.6E-07		0.03-0.06	10.3	NONE	500	120	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R84	260	1.5E-06		0.05-0.13	10.3	NONE	500	240	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R85	260	1.8E-07		0.06-0.09	10.3	NONE	500	240	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R86	315	1.1E-06		0.03-0.07	10.3	NONE	500	240	
WSe2/GaIn	BATTELLE/DJBOES	AISI 1020 STEEL	R87	360	3.2E-06		0.03-0.10	10.3	NONE	500	240	

SECTION 2a. WEAR TEST DATA FROM BATTELLE COLUMBUS LABORATORY, continued

All tests were run in a diesel environment.

RING MATERIAL	BATCH CODE	RING SUBSTRATE	TEST NO.	TEMP °C	RING WEAR mm3/Nm	CYLINDER WEAR mm3/Nm	FRICTION COEFFICIENT RANGE	RING LOAD N/mm	LUBRICANT	SPEED rpm	TEST DURATION minutes	COMMENTS
Cylinder Liner = CAST IRON(CATPLR/CL1)												
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R2	100	3.E-09		0.03-0.04	12.3	SDL-1	500-1500		
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R12	260	4.E-07		0.07-0.10	15.7	SDL-1	500-1500		
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R46	20	<0.013mm		0.06-0.07	16.0	SDL-1		120	
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R47	310	HIGH		0.13	10.0	SDL-1		240	Wore through Cr layer
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R89A	25	1.2E-09		0.02-0.06		SDL-1	500-1500	60	Step 1 of 2-brkin
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R89B	460	2.9E-07		0.23-0.32		X-1P	500-1500		Step 2 of 2
Cylinder Liner = HEXOLOY SA (CARBRNDM)												
M130	METCO/PS/BCD	AISI 410 STEEL	R41	538	SPALLED			1.6	NONE	1000	1	Ring coat spalled
M130	METCO/PS/BCD	AISI 410 STEEL	R42	316	SPALLED			1.6	NONE	1000	1	
M501	METCO/PS/BCD	AISI 410 STEEL	R43	371	0.15mm		0.6-0.3	1.8	NONE	1000	20	Coating intact
M63/M130	BATTELLE/PS-2L	AISI 410 STEEL	R45	288				1.8	NONE	1000	2	Cylinder specimen broke
P312M	PLASMADYNE/PS/BCD	AISI 410 STEEL	R44	399	>.203mm		0.2	1.8	NONE	1000	15	Coating wore off
Cylinder Liner = K162B(KENNMTL)												
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R49A	20	3E-06*			12.3	SDL-1	500	60	Step 1 of 4
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R49B	100	6E-07*			12.3	SDL-1	500	240	Step 2 of 4
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R49C	260	1E-06*			12.3	SDL-1	500	240	Step 3 of 4
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R49D	260	1.4E-07*			12.3	SDL-1	500	450	Step 4 of 4
Cylinder Liner = NC-132(NORTON)												
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R14	260	4.E-06		0.14	12.3	SDL-1	500-1500		
Cylinder Liner = PS212(NASALRC)												
CA815	WEARTECH/ESA/BCD	AISI 410 STEEL	R72	538	2.4E-03*	3.2E-03*	0.16-0.26	10.3	NONE	500-1500	10	
Cr2O3+N-ION	BATTELLE/PS/BCD	AISI 1020 STEEL	R73	538	1.2E-05*	1.2E-02*	0.26-0.31	10.3	NONE	500-1500	10	
Cylinder Liner = Si3N4(CERCOM)												
WC	SDS/HVOF/BCD	AISI 1020 STEEL	R61	260	6E-07*		0.03-0.06		SDL-1	500-1500		
Cylinder Liner = TS-PSZ(NILCRA)												
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R56	25			0.02		SAE10	500-1500		TEI was observed

*=dimensionless

SECTION 2a. WEAR TEST DATA FROM BATTELLE COLUMBUS LABORATORY, continued

All tests were run in a diesel environment.

RING MATERIAL	BATCH CODE	RING SUBSTRATE	TEST NO.	TEMP °C	RING WEAR mm3/Nm	CYLINDER WEAR mm3/Nm	FRICTION COEFFICIENT RANGE	RING LOAD N/mm	LUBRICANT	SPEED rpm	TEST DURATION minutes	COMMENTS
Cylinder Liner = Z-191(NGK)												
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R15	260	4.E-06		0.2-0.3	12.3	SDL-1	500-1500		
Cr	BATTELLE/EP/BCD	AISI 1020 STEEL	R48	20			0.2		SAE10			
Cylinder Liner = CERATEK (PCK TECHNOLOGY PROPRIATARY COATING) on Si3N4												
WC	SDS/HVOF/BCD	AISI 1020 STEEL	R60	260	1E-06*		0.03-0.06		SDL-1	500-1500		
Cylinder Liner = Cr2O3(CERAC) plasma-sprayed on AISI 1020 STEEL												
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R35	260	1.8E-08		0.03-0.07	10.3	BASE-[illegible]	500	240	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R36	260	1.9E-08		0.05-0.08	10.3	BASE-H	500	240	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R37	370	1.8E-07		0.09-0.18	10.3	BASE-H	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R38	370	6.0E-07		0.03-0.06	10.3	BASE-L	500	75	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R23	100	4.9E-08		0.06-0.08	10.3	LB625	500	480	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R11	260	9.E-08		0.02-0.16	12.3	LB625	500		
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R26	260	2.7E-07		0.02-0.08	10.3	LB625	500	60	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R30	300	7.6E-07		0.05-0.13	10.3	LB625	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R28	260	3.3E-07		0.02-0.06	10.3	LB650X	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R27	300	2.7E-07		0.02-0.06	10.3	LB650X	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R33	370	3.2E-07		0.03-0.06	10.3	OS-124	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R34	460	2.2E-06		0.14-0.19	10.3	OS-124	500	30	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R22	260	2.4E-08		0.07-0.09	10.3	OS-75725L	500	60	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R25	370	2.1E-07		0.13-0.25	10.3	OS-75725L	500	240	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R31	260	7.7E-07		0.07-0.09	10.3	OS-80001H	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R39	260	7.8E-07		0.06-0.08	10.3	OS-80001H	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R29	370	3.6E-07		0.07-0.10	10.3	OS-80001H	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R40	370	9.5E-08		0.06-0.10	10.3	OS-80001H	500	120	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R6	260	2.E-08		0.05-0.08	13.4	SDL-1	500-1500		
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R32	460	5.1E-08		0.07-0.10	10.3	X-1P	500	240	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R24	460	5.1E-08		0.07-0.10	10.3	X-1P	500	240	
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R62A	25	5E-06*			12.3	LB625	500-1500	60	Step 1 of 4-break-in
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R62B	100	1E-06*			12.3	LB625	500-1500	60	Step 2 of 4
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R62C	260	3E-06*		0.06-0.16	10.3	LB625	500-1500	240	Step 3 of 4
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R62D	260	7E-06*		0.06-0.16	10.3	LB625	500-1500	240	Step 4 of 4
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R62E	260	3E-06*		0.05-0.14	10.3	LB650X	500-1500	240	Step B1-see texxt
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R62F	260	6E-06*		0.05-0.14	10.3	LB650X	500-1500	240	Step B2- see text
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R67A	25	2E-05*		0.45	10.3	LB625	500-1500	60	Step 1 of 2

*=dimensionless

SECTION 2a. WEAR TEST DATA FROM BATTELLE COLUMBUS LABORATORY, continued

All tests were run in a diesel environment.

RING MATERIAL	BATCH CODE	RING SUBSTRATE	TEST NO.	TEMP °C	RING WEAR mm3/Nm	CYLINDER WEAR mm3/Nm	FRICTION COEFFICIENT RANGE	RING LOAD N	LUBRICANT	SPEED rpm	TEST DURATION minutes	COMMENTS
Cylinder Liner = Cr2O3(CERAC) plasmy-sprayed on AISI 1020 steel												
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R67B	316	4E-05*		0.13		LB625	500-1500	60	Step 2 of 2
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R74	260	3.7E-08		0.02-0.09		SDL-1	500-1500		Test run in air
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R75	260	2.8E-08		0.03-0.10		SDL-1	500-1500		Test run in inert nitrogen
Cr2O3	CERAC/PS/BCD	AISI 1020 STEEL	R76	260	8.8E-08		0.06-0.19		SDL-1	500-1500		Test run in steam
Cr3C2	METTECH/PS/BCD	AISI 1020 STEEL	R13	260	3.E-07		0.13	14.0	SDL-1	500-1500		
VA20	WEARTECH/ESA/BCD	AISI 410 STEEL	R4	260	9.E-09		0.03-0.06	12.3	SDL-1	500-1500		
VR73	WEARTECH/ESA/BCD	AISI 410 STEEL	R20	260	2.E-08		0.05-0.09	12.3	SDL-1	500-1500		
WC	SDS/HVOC/BCD	AISI 1020 STEEL	R5	260	1.E-08		0.03-0.08	13.9	SDL-1	500-1500		
WC+Mo	WEARTECH/ESA/BCD	AISI 410 STEEL	R21	260	2.E-06		0.04	12.3	SDL-1	500-1500		
Cylinder Liner = Cr2O3 (implanted with nitrogen ions) plasma-sprayed on AISI 1020 steel												
Cr2O3+N-ION	BATTELLE/PS/BCD	AISI 1020 STEEL	R19	260	2.E-08		0.04-0.08	12.3	SDL-1	500-1500		
Cylinder Liner = M350A(METCO) plasma-sprayed on Cast Iron or H-13 Steel												
M136CP	METCO/PS/CAT	CAST IRON/H-13	R91	260	4E-09		0.08-0.11		SDL-1	500-1500	240	Step 1 of 2
M136CP	METCO/PS/CAT	CAST IRON/H-13	R92	260	2E-08		0.09-0.13		SDL-1	500-1500	240	Step 2 of 2
M136CP	METCO/PS/CAT	CAST IRON/H-13	R93	260	4E-09		0.10-0.13		SDL-1	500-1500	240	Step 1 of 3
M136CP	METCO/PS/CAT	CAST IRON/H-13	R94	260	2E-08		0.07-0.10		SDL-1	500-1500	240	Step 2 of 3
M136CP	METCO/PS/CAT	CAST IRON/H-13	R95	260	1E-08		0.08-0.10		SDL-1	500-1500	480	Step 3 of 3
M136CP	METCO/PS/CAT	CAST IRON/H-13	R96	260	7E-09		0.13-0.20		OS-80001H	500-1500	240	Step 1 of 3
M136CP	METCO/PS/CAT	CAST IRON/H-13	R97	315	1E-08		0.11-0.14		OS-80001H	500-1500	240	Step 2 of 3
M136CP	METCO/PS/CAT	CAST IRON/H-13	R98	315	4E-08		0.10-0.14		OS-[illegible]001H	500-1500	240	Step 3 of 3

*=dimensionless

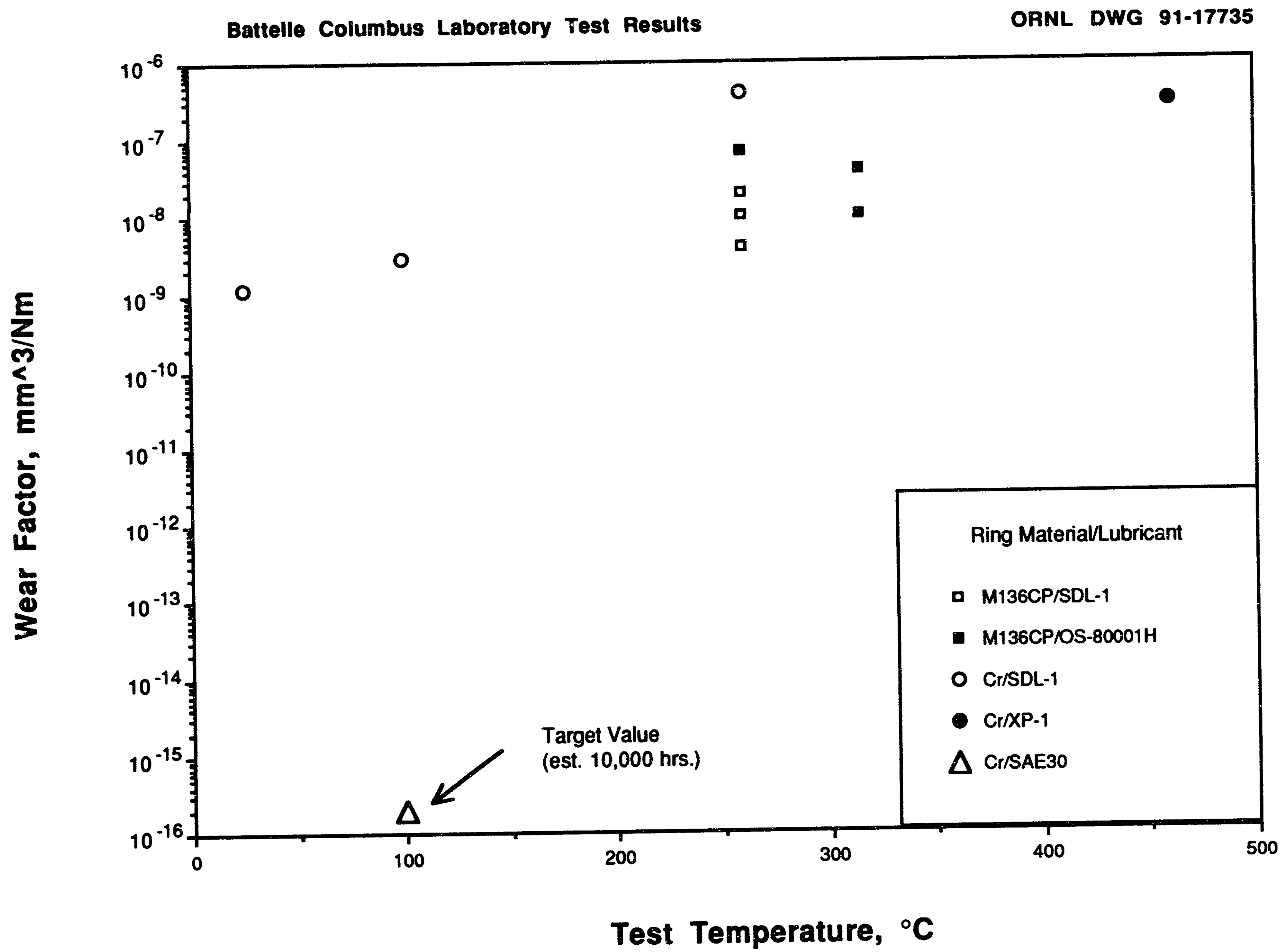

Figure B1. A comparison of plasma-sprayed M136CP rings run against plasma-sprayed M350A cylinders to chrome-plated rings run against cast-iron cylinders using different lubricants.

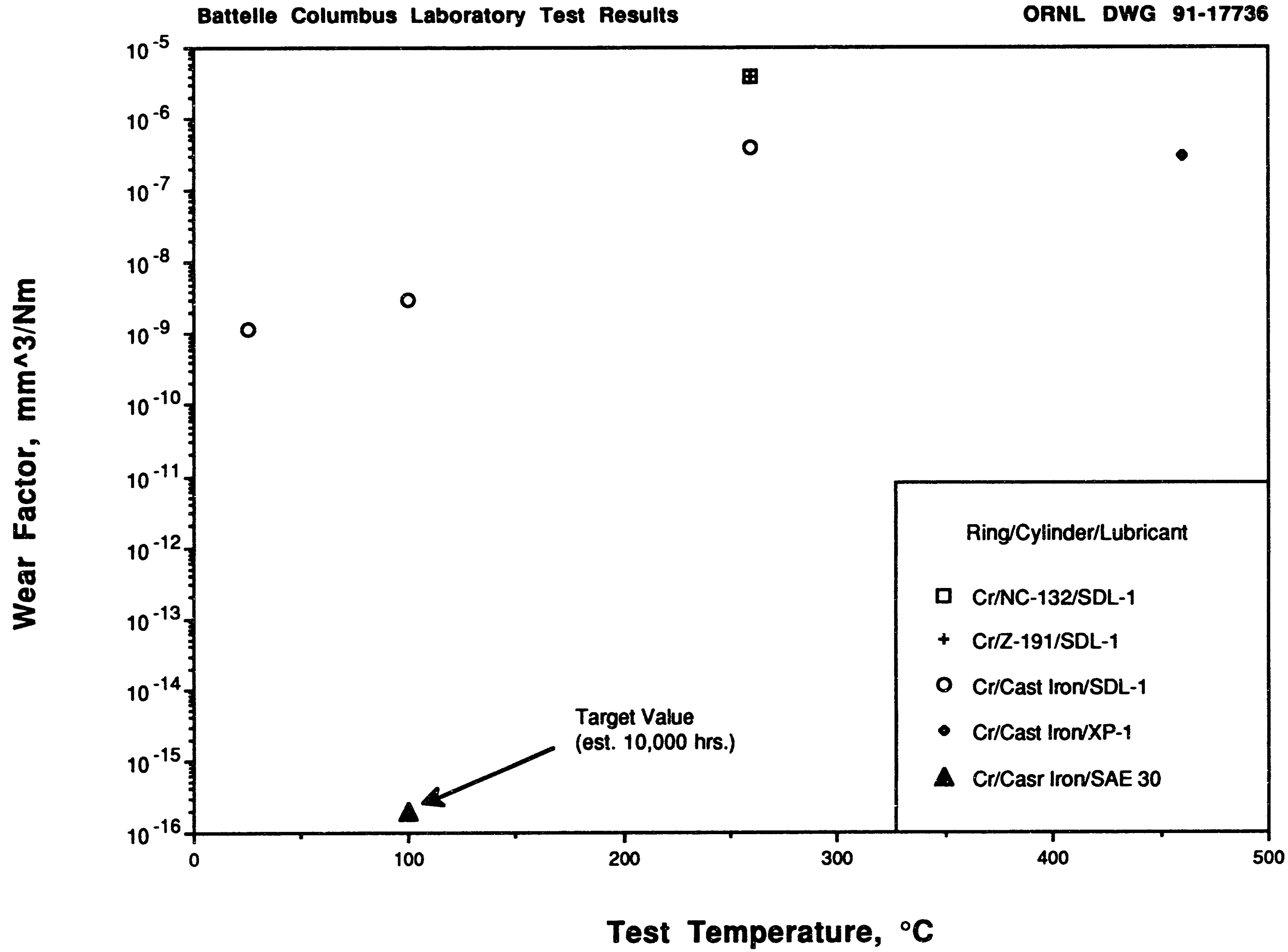

Figure B2. Chrome-plated rings run against cast iron cylinder liners exhibit less wear than when run against ceramic cylinder liners.

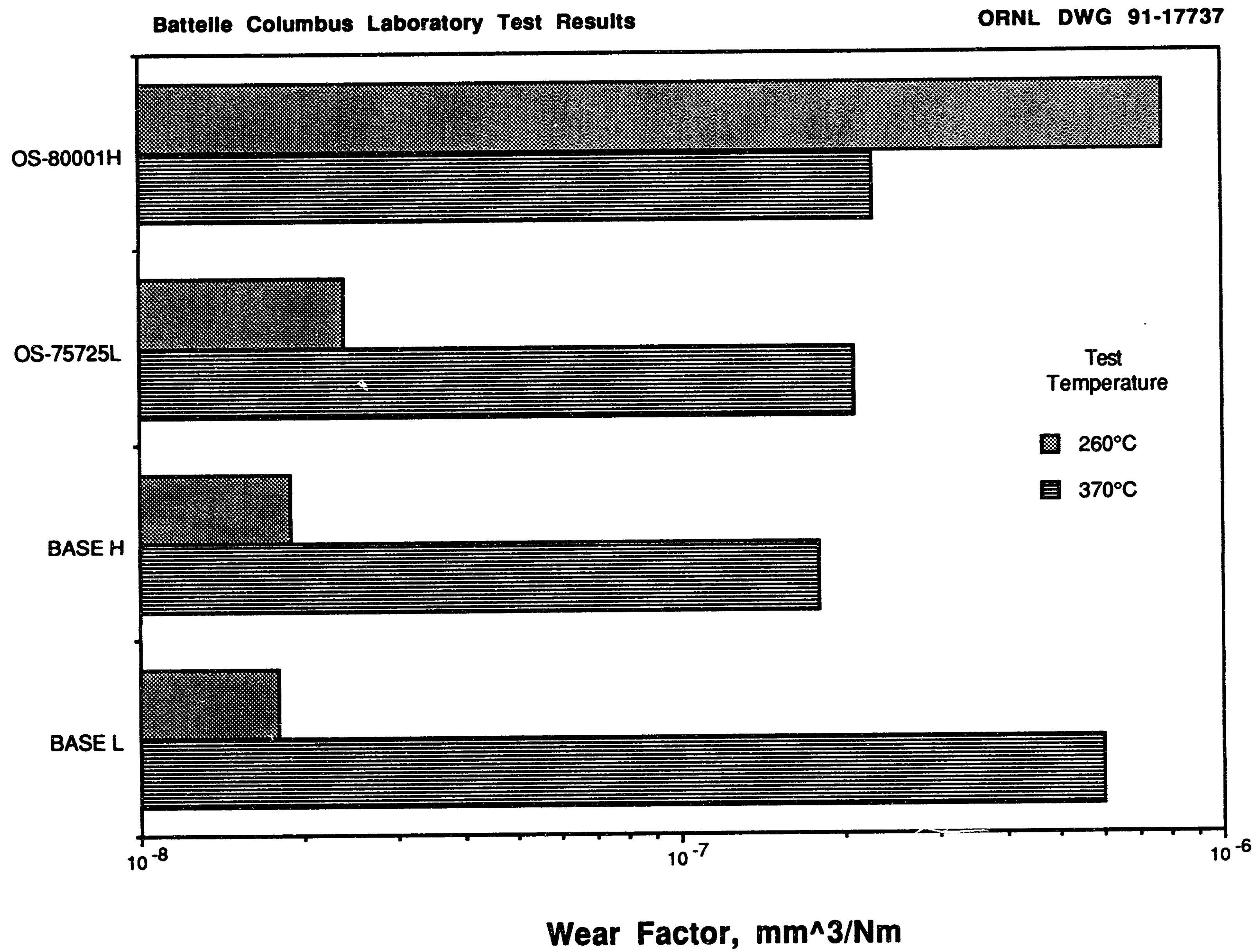

Figure B3. Effects of test temperature on the lubricating ability of four liquid lubricants used in Cr_2O_3 ring-Cr_2O_3 cylinder tests.

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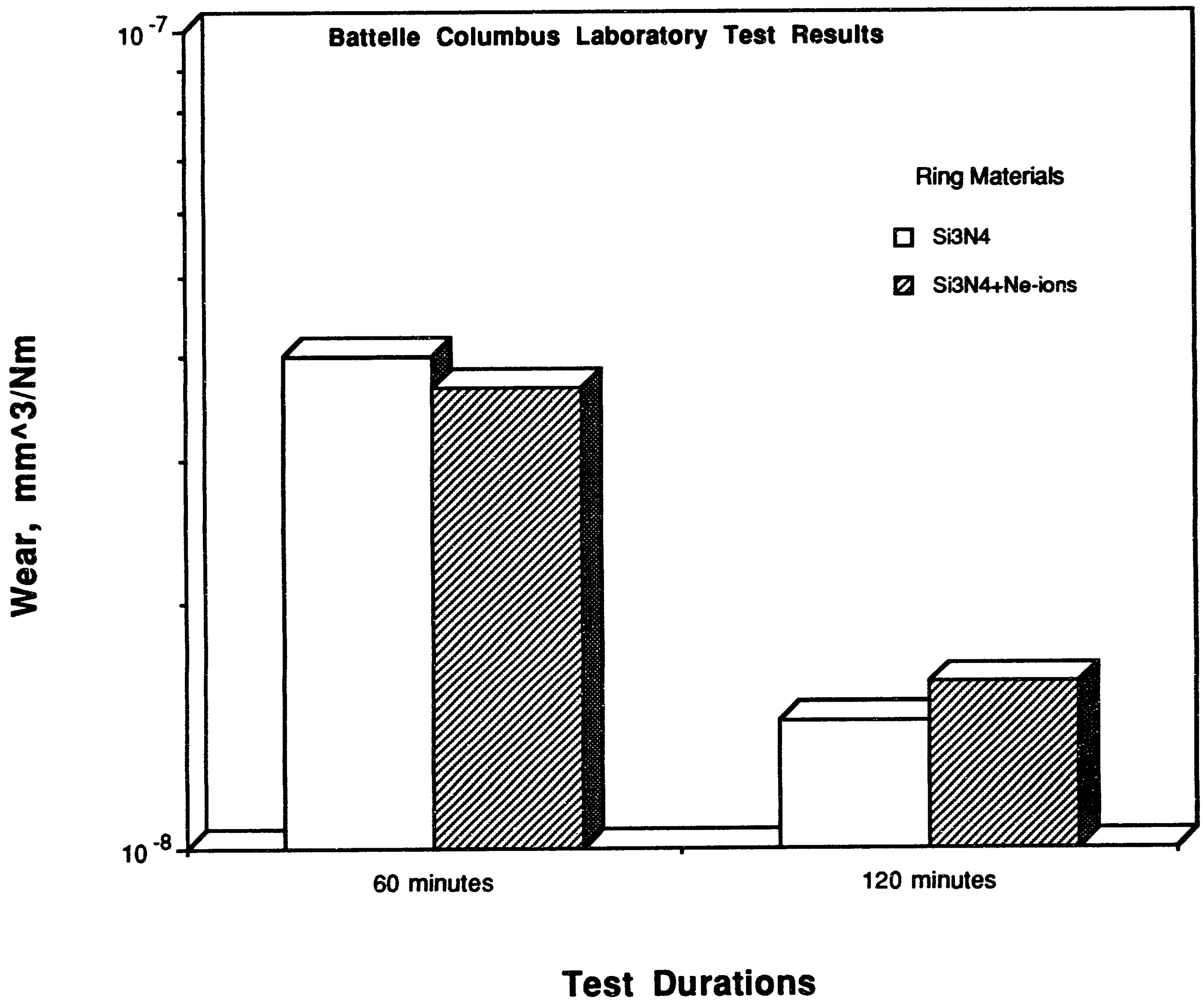


Figure B4. Tests showed that Ne-ion implants have little effect on the wear resistance of Si_3N_4 rings run against Cr_2O_3 at 20°C using SDL-1 lubricant. Average values were used to construct the graph.

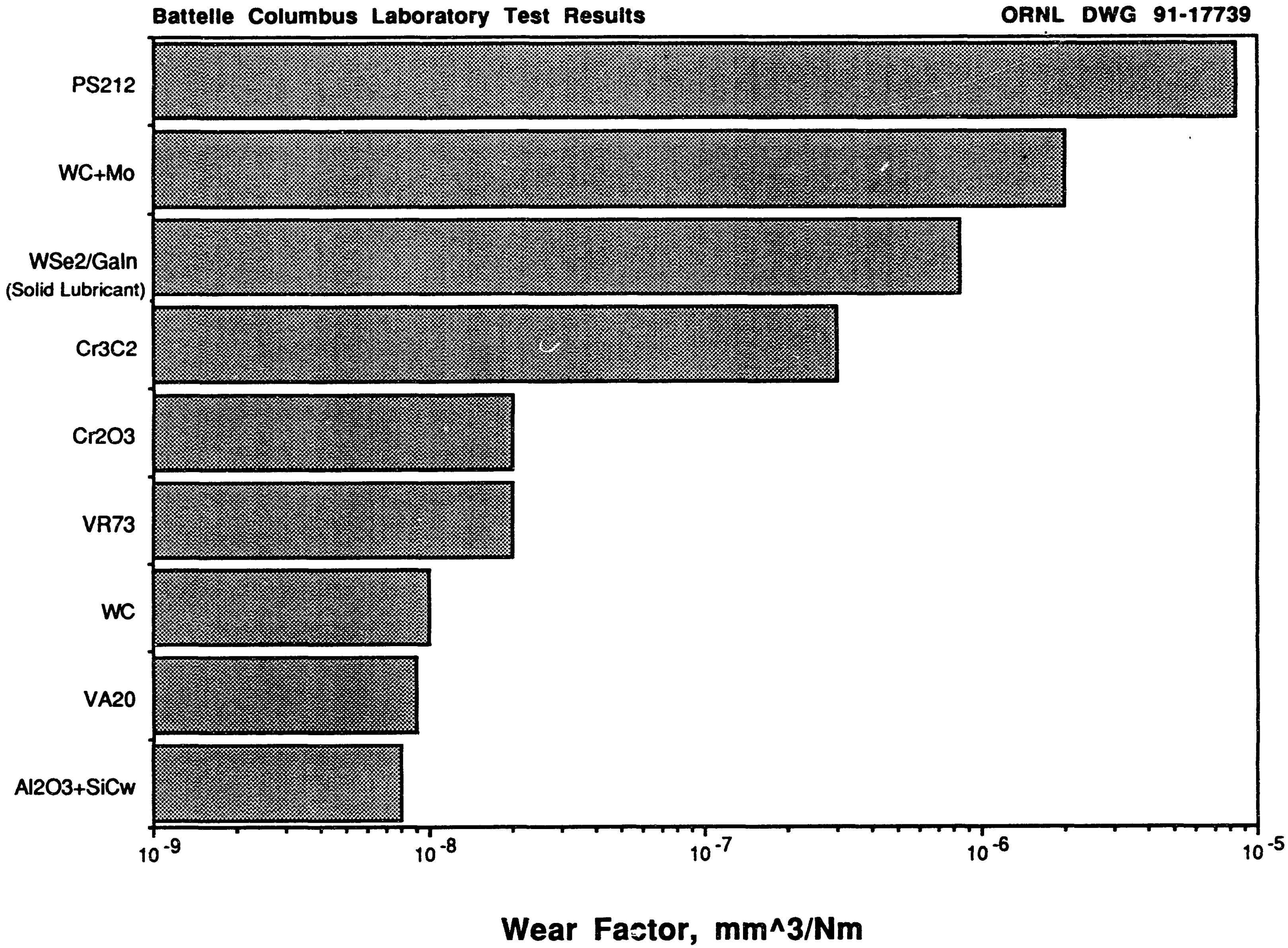


Figure B5. A comparison of wear factors for various ring materials run against plasma-sprayed Cr_2O_3 cylinders at 260°C using SDL-1 lubricant with the non-solid-lubricant ring materials.

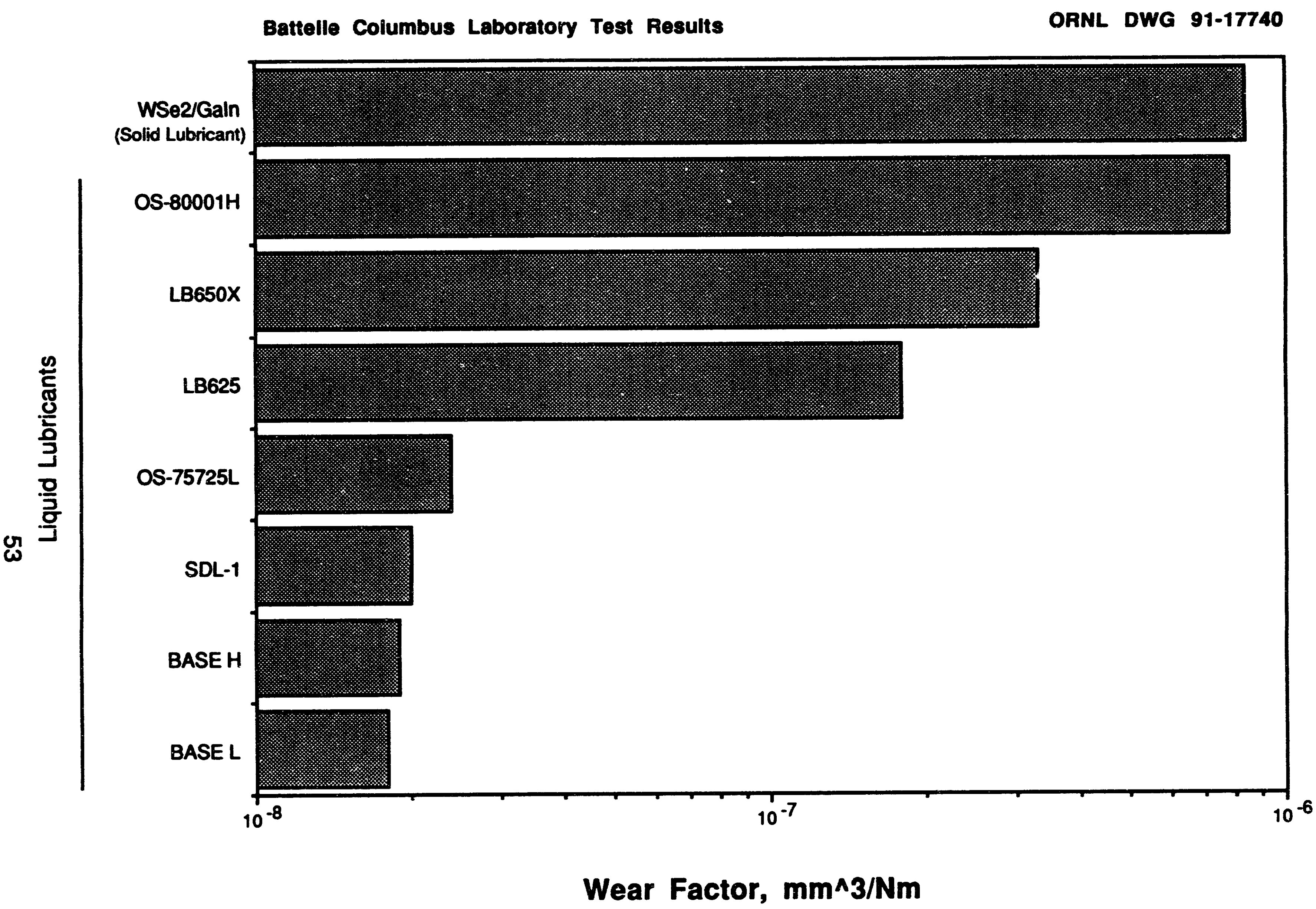


Figure B6. The solid-lubricant ring, run against a Cr_2O_3 cylinder, showed no advantage over liquid lubricants used in Cr_2O_3 ring-Cr_2O_3 cylinder tests. Temperature for all was 260°C.

SECTION 2b. WEAR TEST RESULTS FROM CATERPILLAR

FALEX TESTS PERFORMED IN AIR AT 350°C, LUBRICATED WITH AN EXPERIMENTAL SYNTHETIC LUBRICANT (EXP-SYN)

PLASMA SPRAYED COATINGS

DISK COATING	BATCH CODE	DISK SUBSTRATE	PIN MATERIAL	FRICTION COEF. RANGE	DISK WEAR	PIN WEAR	TEST DURATION minutes	COMMENTS
CM500L	AIRPROD/CVD/CAT	H-13 STEEL	440C STEEL	0.3-0.9	HIGH	HIGH	240	
CM500L	AIRPROD/CVD/CAT	H-13 STEEL	ZrO2	0.3-0.9	HIGH	HIGH	240	
M136CP	METCO/PS/CAT	CAST IRON	440C STEEL	0.04-0.18	MED	MED	240	
M136CP	METCO/PS/CAT	CAST IRON/H-13 (AVG)	ZrO2	0.09-0.18	LOW	LOW	240	
M143	METCO/PS/CAT	CAST IRON/H-13 (AVG)	ZrO2	0.18-0.37	HIGH	HIGH	240	
M19E	METCO/PS/CAT	CAST IRON	440C STEEL	0.11-0.15	LOW	MED	240	
M19E	METCO/PS/CAT	CAST IRON	ZrO2	0.09-0.15	LOW	LOW	240	
M350A	METCO/PS/CAT	CAST IRON/H-13 (AVG)	440C STEEL	0.04-0.18	MED	MED	240	
M350A	METCO/PS/CAT	CAST IRON/H-13 (AVG)	ZrO2	0.04-0.13	LOW	LOW	240	
M66F-NS	METCO/PS/CAT	CAST IRON/H-13 (AVG)	440C STEEL	0.18-0.33	MED	MED	240	
M66F-NS	METCO/PS/CAT	CAST IRON/H-13 (AVG)	ZrO2	0.18-0.22	MED	MED	240	
M750F	METCO/PS/CAT	CAST IRON/H-13 (AVG)	440C STEEL	0.02-0.11	MED	MED	240	
M750F	METCO/PS/CAT	CAST IRON/H-13 (AVG)	ZrO2	0.07-0.13	LOW	LOW	240	
MAE7023	METCO/PS/CAT	CAST IRON/H-13 (AVG)	440C STEEL	0.09-0.24	LOW	MED	240	
MAE7023	METCO/PS/CAT	CAST IRON/H-13 (AVG)	ZrO2	0.04-0.22	LOW	MED	240	
PS212	HOHMAN/APS/CAT	CAST IRON/H-13 (AVG)	440C STEEL	0.09-0.26	MED	MED	240	
PS212	HOHMAN/APS/CAT	CAST IRON/H-13 (AVG)	ZrO2	0.04-0.15	MED	LOW	240	
ZrO2	ZIRCOA/PS/CAT	UNKNOWN	440C STEEL	0.15-0.24	MED	LOW-MED	240	
ZrO2	ZIRCOA/PS/CAT	UNKNOWN	ZrO2	0.13-0.20	MED	LOW-MED	240	

SECTION 2b. WEAR TEST RESULTS FROM CATERPILLAR,continued

FALEX TESTS PERFORMED IN AIR AT 350°C, LUBRICATED WITH AN EXPERIMENTAL SYNTHETIC LUBRICANT (EXP-SYN)

CHEMICAL OR PHYSICAL VAPOR DEPOSITED

DISK COATING	BATCH CODE	DISK SUBSTRATE	PIN MATERIAL	FRICTION COEF. RANGE	DISK WEAR	PIN WEAR	TEST DURATION minutes	COMMENTS
CrN	SYLVESTR/CVD/CAT	H-13 STEEL	440C STEEL	0.10-0.11	MED	LOW	240	
CrN	SYLVESTR/CVD/CAT	H-13 STEEL	ZrO2	0.08-0.19	LOW	LOW	240	
Cr3C2	SYLVESTR/CVD/CAT	H-13 STEEL	440C STEEL	0.24-0.31	MED	HIGH	240	
Cr3C2	SYLVESTR/CVD/CAT	H-13 STEEL	Al2O3	0.11-0.22	MED	LOW	240	
Cr3C2	SYLVESTR/CVD/CAT	H-13 STEEL	Si3N4	0.13-0.59	LOW	MED	240	
Cr3C2	SYLVESTR/CVD/CAT	H-13 STEEL	ZrO2	0.09-0.18	MED	LOW	240	
Ti(C,N)	SYLVESTR/CVD/CAT	17-4PH STEEL	440C STEEL	0.18-0.22	MED	MED	240	
Ti(C,N)	SYLVESTR/CVD/CAT	17-4PH STEEL	440C STEEL	0.24-0.24	MED	HIGH	240	
Ti(C,N)	SYLVESTR/CVD/CAT	17-4PH STEEL	Al2O3	0.08-0.15	LOW	LOW	240	
Ti(C,N)	SYLVESTR/CVD/CAT	17-4PH STEEL	ZrO2	0.07-0.1	LOW	LOW	240	
TiC/TiN	SYLVESTR/CVD/CAT	H-13 STEEL	440C STEEL	0.24-0.24	MED	HIGH	240	
TiC/TiN	SYLVESTR/CVD/CAT	H-13 STEEL	440C STEEL	0.18-0.22	MED	MED	240	
TiC/TiN	SYLVESTR/CVD/CAT	H-13 STEEL	Al2O3	0.08-0.11	LOW	LOW	240	
TiC/TiN	SYLVESTR/CVD/CAT	H-13 STEEL	ZrO2	0.10-0.13	LOW	LOW	240	
ZrO2	PVD/CAT	MILD STEEL	440C STEEL	0.04-0.10	LOW		240	
ZrO2	PVD/CAT	MILD STEEL	Al2O3	**	HIGH			**WORE THRU DISK COAT
ZrO2	PVD/CAT	MILD STEEL	ZrO2	0.08-0.14	LOW	LOW	240	

ENAMEL COATINGS

DISK COATING	BATCH CODE	DISK SUBSTRATE	PIN MATERIAL	FRICTION COEF. RANGE	DISK WEAR	PIN WEAR	TEST DURATION minutes	COMMENTS
ENAM2	SOLTURB/SLSP/CAT	UNKNOWN	440C STEEL	**	HIGH			**EXCESSIVE DISK WEAR
ENAM2	SOLTURB/SLSP/CAT	UNKNOWN	Al2O3	**	HIGH			**EXCESSIVE DISK WEAR
ENAM2	SOLTURB/SLSP/CAT	UNKNOWN	ZrO2	0.04-0.12	LOW	LOW		

SECTION 2b. WEAR TEST RESULTS FROM CATERPILLAR, continued

FALEX TESTS PERFORMED IN AIR AT 350°C, LUBRICATED WITH AN EXPERIMENTAL SYNTHETIC LUBRICANT (EXP-SYN)

ENAMEL COATINGS

DISK COATING	BATCH CODE	DISK SUBSTRATE	PIN MATERIAL	FRICTION COEF. RANGE	DISK WEAR	PIN WEAR	TEST DURATION minutes	COMMENTS
Co-ENAMEL+Cr_2O_3	UILL/PS/CAT	CAST IRON	440C STEEL	0.09-0.31	LOW-MED	MED	240	
Co-ENAMEL+Cr_2O_3	UILL/PS/CAT	CAST IRON	ZrO_2	0.07-0.22	LOW-MED	MED	240	
Co-ENAMEL+Cr_3C_2	UILL/PS/CAT	CAST !RON	ZrO_2	0.07-.018	MED	LOW-MED	240	
Co-ENAMEL+ZrO_2	UILL/PS/CAT	CAST IRON	ZrO_2	0.25			30	FAILED BEFORE 30 MIN

SECTION 2b. WEAR TEST RESULTS FROM CATERPILLAR, continued

HOHMAN A-6 TESTS RUN IN AIR AT 350°C, LUBRICATED WITH AN EXPERIMENTAL SYNTHETIC LUBRICANT (EXP-SYN)

SHOE COATING	SHOE SUBSTRATE	DISK COATING	DISK SUBSTRATE	FRICTION COEF. RANGE	SHOE WEAR mm3/Nm	DISK WEAR mm3/Nm	TEST DURATION minutes	COMMENTS
M136CP(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.17	LOW	HIGH	13	SPALLED IN BREAK-IN
M136CP(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.20	LOW	HIGH	14	
M136CP(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.04-0.21	5.69E-09	<1.E-03		
M136CP(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.17	LOW	MED	120	
M136CP(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.09-0.18	1.69E-09	3.34E-06		
M136CP(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.01-0.1	LOW	LOW	1440	
M350A(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.14	LOW	MED	680	
M350A(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.1-0.16	LOW	LOW	424	
M350A(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.11	LOW	HIGH	5	
M350A(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.20	LOW	HIGH	5	
M350A(METCO/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.04-0.33	2.08E-08	4.90E-08		
M350A(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.02-0.10	LOW	LOW	900	
M350A(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.01-0.1	LOW	LOW	1420	
M350A(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.18	LOW	MED	370	
M350A(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.01-0.10	LOW	LOW	1455	
M350A(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.04-0.21	5.68E-10	3.36E-08		
M350A(METCO/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.02	LOW	MED		
PS212(HOHMAN/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.21	LOW	HIGH	120	
PS212(HOHMAN/PS)	CAST IRON	CrN (LTAVD)	CAST IRON	0.04-.022	7.80E-09	1.04E-04		
PS212(HOHMAN/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.04	LOW	LOW-MED	480	
PS212(HOHMAN/PS)	CAST IRON	M136CP(METCO/PS)	CAST IRON	0.06-0.22	7.63E-07	9.11E-09		

NOTES: LTAVD= low temperature arc vapor deposition, CVD = chemical vapor deposition, PS=plasma sprayed.

SECTION 2b. WEAR TEST RESULTS FROM CATERPILLAR

HOHMAN A-6 TESTS RUN IN AIR AT 350°C

SHOE COATING	SHOE SUBSTRATE	DISK COATING	DISK SUBSTRATE	FRICTION RANGE	SHOE WEAR mm3/N-m	DISK WEAR mm3/N-m	TEST DURATION minutes	COMMENTS
Ti(C,N)(SYLVESTR/CVD)	17-4PH STEEL	CrN (LTAVD)	CAST IRON	0.17	MED	HIGH	11	
Ti(C,N)(SYLVESTR/CVD)	17-4PH STEEL	CrN (LTAVD)	CAST IRON	0.10	LOW	MED	30	
Ti(C,N)(SYLVESTR/CVD)	17-4PH STEEL	CrN (LTAVD)	CAST IRON	0.08-0.10	7.32E-10	7.72E-06		
Ti(C,N)(SYLVESTR/CVD)	17-4PH STEEL	M136CP(METCO/PS)	CAST IRON	0.19	LOW	HIGH	120	
Ti(C,N)(SYLVESTR/CVD)	17-4PH STEEL	M136CP(METCO/PS)	CAST IRON	0.08-0.23	3.50E-09	1.52E-05		
Ti(C,N)(SYLVESTR/CVD)	17-4PH STEEL	M350A(METCO/PS)	CAST IRON	0.17-0.22	LOW	HIGH	241	
CrN (CVD)	CAST IRON	M350A(METCO/PS)	CAST IRON	0.01-0.18	SPALLED	LOW	150	

NOTES: LTAVD= low temperature arc vapor deposition, CVD = chemical vapor deposition, PS=plasma sprayed.

SECTION 2c. WEAR TEST RESULTS FROM CUMMINS ENGINE COMPANY

CAMERON-PLINT TESTS

All tests run at 20 Hz over 5 mm at 225N load.

RING COATING	COATING BATCH CODE	RING SUBSTRATE	SUBSTRATE BATCH CODE	TEMP. °C	RING WEAR mm3/Nm	LINER WEAR mm3/Nm	AVERAGE FRICTION COEF.	LUBRICANT	TEST DURATION minutes
CYLINDER MATERIAL = ION-IMPLANTED TYPE 1 NIRESIST									
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	200	1.55E-09	1.67E-05	0.39	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	365	1.39E-08	1.23E-05	0.16	CE/SF 15W40F	360
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	153	1.41E-08	4.80E-08	0.213	CE/SF 15W40F	360
CYLINDER MATERIAL = GRAY CAST IRON									
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	196	2.48E-09		0.318	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	200	3.34E-09		0.251	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	276	1.66E-08		0.174	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	287	2.05E-08		0.223	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	358	2.25E-08		0.132	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	361	4.17E-08		0.177	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	200	6.20E-09		0.227	SRM OIL	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	348	1.59E-08		0.357	SRM OIL	360
CYLINDER MATERIAL = GRAY IRON									
Al2O3-26%ZrO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	1.29E-08		0.12	CE/SF 15W40F	360
Al2O3-26%ZrO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	344	1.75E-07		0.11	CE/SF 15W40F	360
Al2O3-26%ZrO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	205	9.17E-09		0.095	CE/SF 15W40U*	360
Al2O3-41%ZrO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	6.38E-09	4.55E-08	0.12	CE/SF 15W40F	360
Al2O3-41%ZrO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	344	6.68E-08		0.10	CE/SF 15W40F	360
Cr2O3	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	3.42E-09	1.14E-07	0.120	CE/SF 15W40F	360
Cr2O3	BIRL/APS/CEC	422 STEEL	WISCON/CEC	350	2.76E-08	1.34E-06	0.09	CE/SF 15W40F	360
Cr2O3	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	1.48E-09	5.86E-08	0.09	CE/SF 15W40U*	360
Cr2O3	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	1.52E-06	2.59E-05	0.47	NONE	60
Cr2O3	BIRL/HVOF/CEC	422 STEEL	WISCON/CEC	200	5.47E-09		0.12	CE/SF 15W40F	360
Cr2O3-50%Al2O3	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	1.36E-08	3.98E-07	0.12	CE/SF 15W40F	360
Cr2O3-50%Al2O3	BIRL/APS/CEC	422 STEEL	WISCON/CEC	356	3.76E-08		0.16	CE/SF 15W40F	360

*Lubricant included 3.3% soot

SECTION 2c. WEAR TEST RESULTS FROM CUMMINS ENGINE COMPANY, continued

CAMERON-PLINT TESTS

All tests run at 20 Hz over 5 mm at 225N load.

RING COATING	COATING BATCH CODE	RING SUBSTRATE	SUBSTRATE BATCH CODE	TEMP. °C	RING WEAR mm3/Nm	LINER WEAR mm3/Nm	AVERAGE FRICTION COEF.	LUBRICANT	TEST DURATION minutes
CYLINDER MATERIAL = GRAY IRON									
FERROTIC CM	APSMAT/LPPS/CEC	422 STEEL	WISCON/CEC	356	1.15E-07		0.10	CE/SF 15W40F	360
FERROTIC CS40	APSMAT/LPPS/CEC	422 STEEL	WISCON/CEC	353	2.90E-08		0.08	CE/SF 15W40F	360
FERROTIC HT6A	APSMAT/LPPS/CEC	422 STEEL	WISCON/CEC	356	7.62E-08		0.095	CE/SF 15W40F	360
M136-15%Al2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	207	5.56E-09		0.12	CE/SF 15W40F	360
Mo-MoO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	1.28E-08	1.22E-07	0.12	CE/SF 15W40F	360
Mo-MoO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	341	6.45E-08		0.12	CE/SF 15W40F	360
Mo-Ni	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	3.46E-08	1.84E-07	0.11	CE/SF 15W40F	360
Mo-Ni	BIRL/APS/CEC	422 STEEL	WISCON/CEC	350	1.81E-07	5.52E-05	0.14	CE/SF 15W40F	360
Mo-Ni	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	8.37E-08	7.08E-07	0.14	CE/SF 15W40U*	360
Mo-Ni	BIRL/APS/CEC	422 STEEL	WISCON/CEC	200	2.38E-05	4.28E-04	0.70	NONE	60
Mo-Ni	BIRL/HVOF/CEC	422 STEEL	WISCON/CEC	200	2.83E-08		0.10	CE/SF 15W40F	360
WC-12%Co	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	200	3.60E-09	2.02E-06	0.14	CE/SF 15W40F	360
WC-12%Co	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	350	5.64E-09	1.30E-05	0.16	CE/SF 15W40F	360
WC-12%Co	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	200	3.55E-09			CE/SF 15W40U*	360
WC-12%Co	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	200	3.83E-06	2.71E-04	0.48	NONE	60
WC-12%Co	APSMAT/LPPS/CEC	HK40 STEEL	WISCON/CEC	200	1.63E-09	2.23E-06	0.14	CE/SF 15W40F	360
WC-12%Co	APSMAT/LPPS/CEC	HK40 STEEL	WISCON/CEC	350	1.73E-08	1.61E-05	0.26	CE/SF 15W40F	360
WC-12%Co	APSMAT/LPPS/CEC	HK40 STEEL	WISCON/CEC	200	2.96E-09		0.13	CE/SF 15W40U*	360
WC-12%Co	APSMAT/LPPS/CEC	HK40 STEEL	WISCON/CEC	200	2.21E-06	2.47E-04	0.50	NONE	60
CYLINDER MATERIAL = H-13 STEEL									
Al2O3-41%ZrO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	461	9.83E-11		0.12	P-A-O BASE	360
Al2O3-41%ZrO2	BIRL/APS/CEC	422 STEEL	WISCON/CEC	449	7.73E-11		0.10	P-A-O BASE	360
Cr3C2-NiCr	UTRC/HVOF/CEC	422 STEEL	WISCON/CEC	448	1.44E-10		0.17	P-A-O BASE	360

*Lubricant included 3.3% soot

SECTION 2c. WEAR TEST RESULTS FROM CUMMINS ENGINE COMPANY, continued

CAMERON-PLINT TESTS

All tests run at 20 Hz over 5 mm at 225N load.

RING COATING	COATING BATCH CODE	RING SUBSTRATE	SUBSTRATE BATCH CODE	TEMP. °C	RING WEAR mm3/Nm	LINER WEAR mm3/Nm	AVERAGE FRICTION COEF.	LUBRICANT	TEST DURATION minutes
CYLINER MATERIAL = HIGH PHOSPHORUS GRAY IRON									
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	151	4.62E-10	2.08E+02	0.208	CE/SF 15W40F	360
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	257	2.06E-09	1.72E+02	0.172	CE/SF 15W40F	360
CYLINDER MATERIAL= PEARLITIC HARDENED GRAY IRON									
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	203	8.60E-10		0.120	CE/SF 15W40F	360
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	347	1.71E-07		0.200	CE/SF 15W40F	360
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	213	1.60E-06		0.50	NONE	60
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	207	2.61E-08	7.47E-07	0.124	CE/SF 15W40F	360
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	232	7.53E-09	7.29E-07	0.121	CE/SF 15W40F	360
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	236	7.44E-09	1.15E-06	0.117	CE/SF 15W40F	360
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	353	1.74E-07	6.66E-06	0.156	CE/SF 15W40F	360
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	405	2.24E-08	8.73E-07	0.197	CE/SF 15W40F	360
Cr2O3-STELLITE6	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	248	1.60E-06	8.01E-05	0.502	NONE	60
Cr3C2-NiCr	UTRC/HVOF/CEC	422 STEEL	WISCON/CEC	200	1.48E-09		0.118	CE/SF 15W40F	360
Cr3C2-NiCr	UTRC/HVOF/CEC	422 STEEL	WISCON/CEC	340	1.13E-08		0.107	CE/SF 15W40F	360
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	149	4.78E-09	1.33E-08	0.223	CE/SF 15W40F	360
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	148	3.98E-09	1.47E-08	0.228	CE/SF 15W40F	360
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	359	2.03E-07		0.129	CE/SF 15W40F	360
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	148	3.76E-08	4.06E-07	0.121	CE/SF 15W40U*	360
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	148	2.49E-09	1.61E-08	0.213	CE/SF 15W40F	360
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	150	2.72E-09	1.59E-08	0.230	CE/SF 15W40F	360
M136-8%SiO2	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	204	7.33E-09		0.119	CE/SF 15W40F	360
M136-8%SiO2	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	237	2.10E-08	5.16E-07	0.118	CE/SF 15W40F	360
M136-8%SiO2	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	353	9.65E-09		0.104	CE/SF 15W40F	360

*Lubricant included 3.3% soot

SECTION 2c. WEAR TEST RESULTS FROM CUMMINS ENGINE COMPANY, continued

CAMERON-PLINT TESTS

All tests run at 20 Hz over 5 mm at 225N load.

RING COATING	COATING BATCH CODE	RING SUBSTRATE	SUBSTRATE BATCH CODE	TEMP. °C	RING WEAR mm3/Nm	LINER WEAR mm3/Nm	AVERAGE FRICTION COEF.	LUBRICANT	TEST DURATION minutes
CYLINDER MATERIAL= PEARLITIC HARDENED GRAY IRON									
M136-8%SiO2	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	368	1.50E-08	2.72E-06	0.100	CE/SF 15W40F	360
M136-8%SiO2	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	204	2.39E-08		0.146	CE/SF 15W40U*	360
M136-8%SiO2	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	206	2.98E-06	4.63E-05	0.571	NONE	60
M143	UTRC/APS/CEC	422 STEEL	WISCON/CEC	204	8.51E-08		0.128	CE/SF 15W40F	360
M143	UTRC/APS/CEC	422 STEEL	WISCON/CEC	350	1.26E-06		0.110	CE/SF 15W40F	360
CYLINDER MATERIAL = PEARLITIC HARDENED GRAY CAST IRON									
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	151	6.04E-10	8.22E-09	0.210	CE/SF 15W40F	360
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	146	4.08E-10	1.15E-08	0.204	CE/SF 15W40F	360
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	257	3.17E-09	7.88E-07	0.171	CE/SF 15W40F	360
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	256	1.44E-09	9.53E-07	0.169	CE/SF 15W40F	360
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	149	1.84E-09	1.24E-07	0.196	CE/SF 15W40U*	360
CYLINDER MATERIAL= SCA SPRAYED ONTO GRAY CAST IRON									
M136	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	262	4.59E-09	7.94E-07	0.196	CE/SF 15W40F	360
M136	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	275	2.35E-07	6.30E-08	0.108	CE/SF 15W40F	360
M136	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	344	7.70E-08	6.42E-08	0.109	CE/SF 15W40F	360
M136	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	353	4.49E-08	1.71E-07	0.110	CE/SF 15W40F	360
M136	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	259	1.03E-07	1.23E-07	0.223	CE/SF 15W40U*	360
M136	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	436	2.60E-06	7.53E-07	0.75	NONE	60
CYLINDER MATERIAL = SCA SPRAYED ONTO PEARLITIC GRAY CAST IRON									
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	149	6.16E-09	1.08E-07	0.219	CE/SF 15W40F	360
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	148	9.12E-09	7.42E-08	0.216	CE/SF 15W40F	360
WC-12%Co	BOYD/HVOF/CEC	HK40 STEEL	WISCON/CEC	255	2.95E-08	1.63E-07	0.180	CE/SF 15W40F	360

*Lubricant included 3.3% soot

SECTION 2c. WEAR TEST RESULTS FROM CUMMINS ENGINE COMPANY, continued

CAMERON-PLINT TESTS

All tests run at 20 Hz over 5 mm at 225N load.

RING COATING	COATING BATCH CODE	RING SUBSTRATE	SUBSTRATE BATCH CODE	TEMP. °C	RING WEAR mm3/Nm	LINER WEAR mm3/Nm	AVERAGE FRICTION COEF.	LUBRICANT	TEST DURATION minutes
CYLINDER MATERIAL = SCA SPRAYED ONTO PEARLITIC HARDENED GRAY CAST IRON									
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	197	2.32E-07		0.248	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	332	2.44E-07		0.130	CE/SF 15W40F	360
CYLINDER MATERIAL = POLISHED SCA SPRAYED ONTO PH-GRAY CAST IRON									
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	197	7.87E-08		0.227	CE/SF 15W40F	360
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	WISCON/CEC	351	2.77E-06		.884	NONE	60

*Lubricant included 3.3% soot

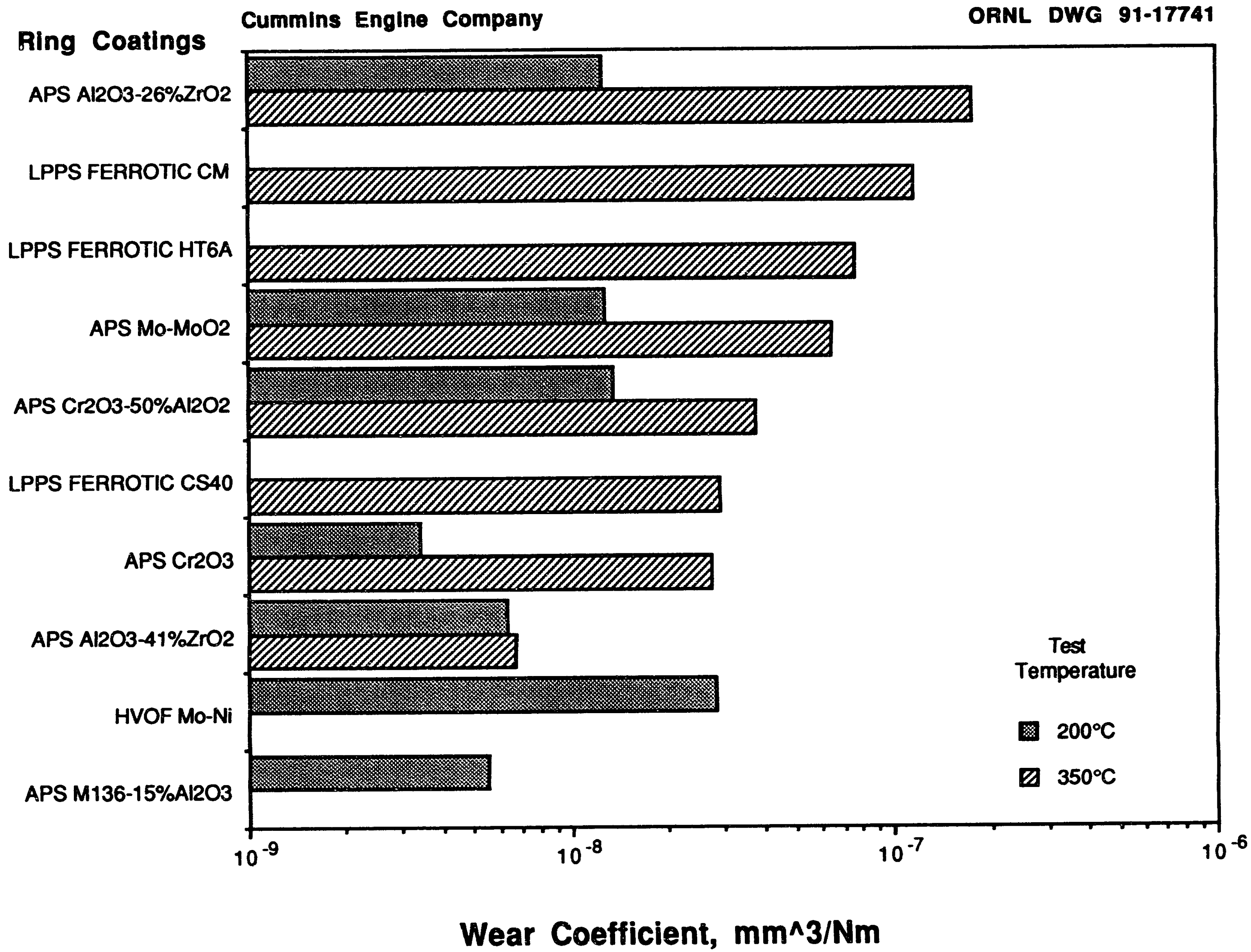


Figure B7. Temperature effects on the wear coefficient of several ring coatings run against gray iron in fresh CE/SF 15W40.

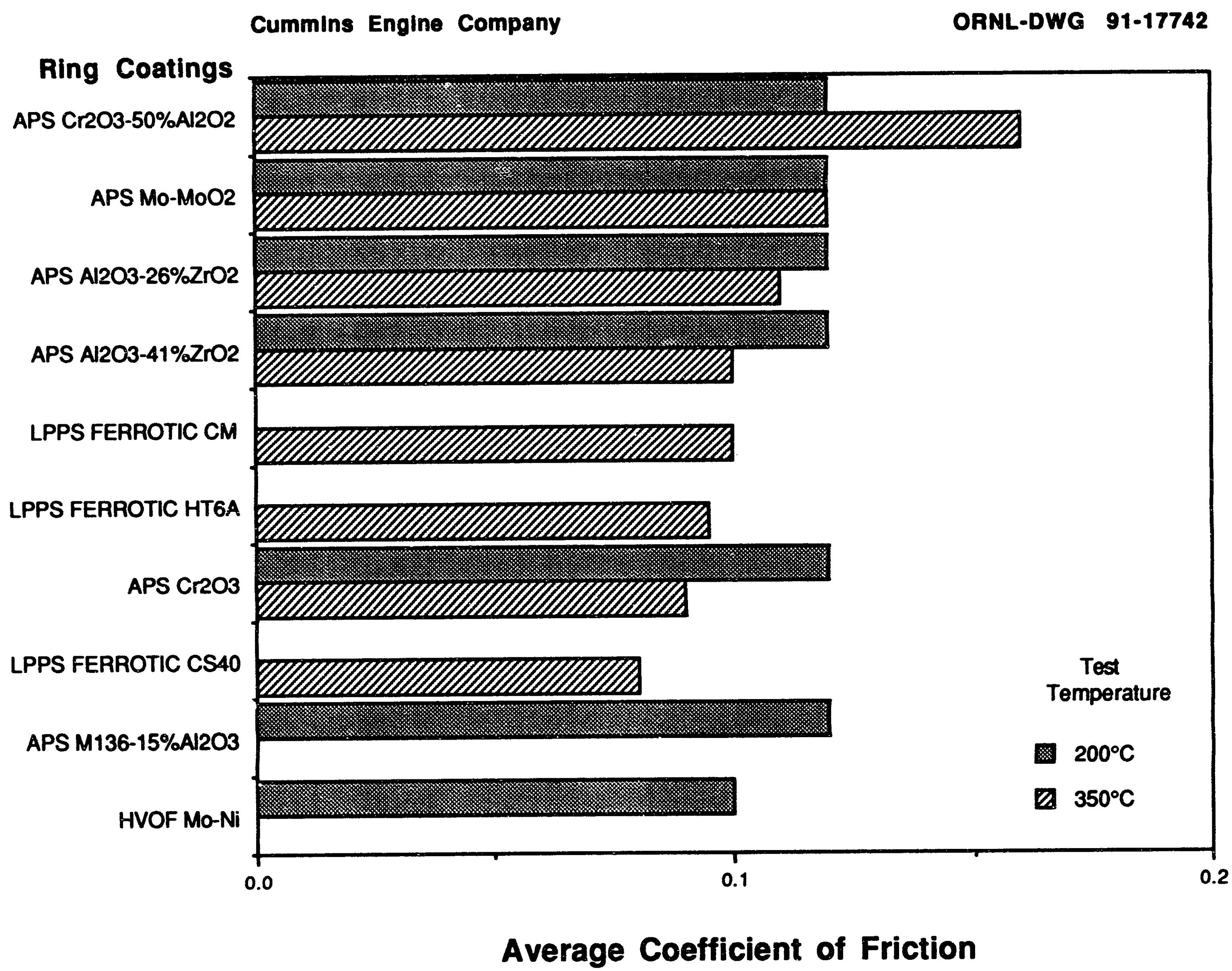


Figure B8. Temperature effects on the average friction coefficient of several ring coatings run against gray iron in fresh CE/SF 15W40.

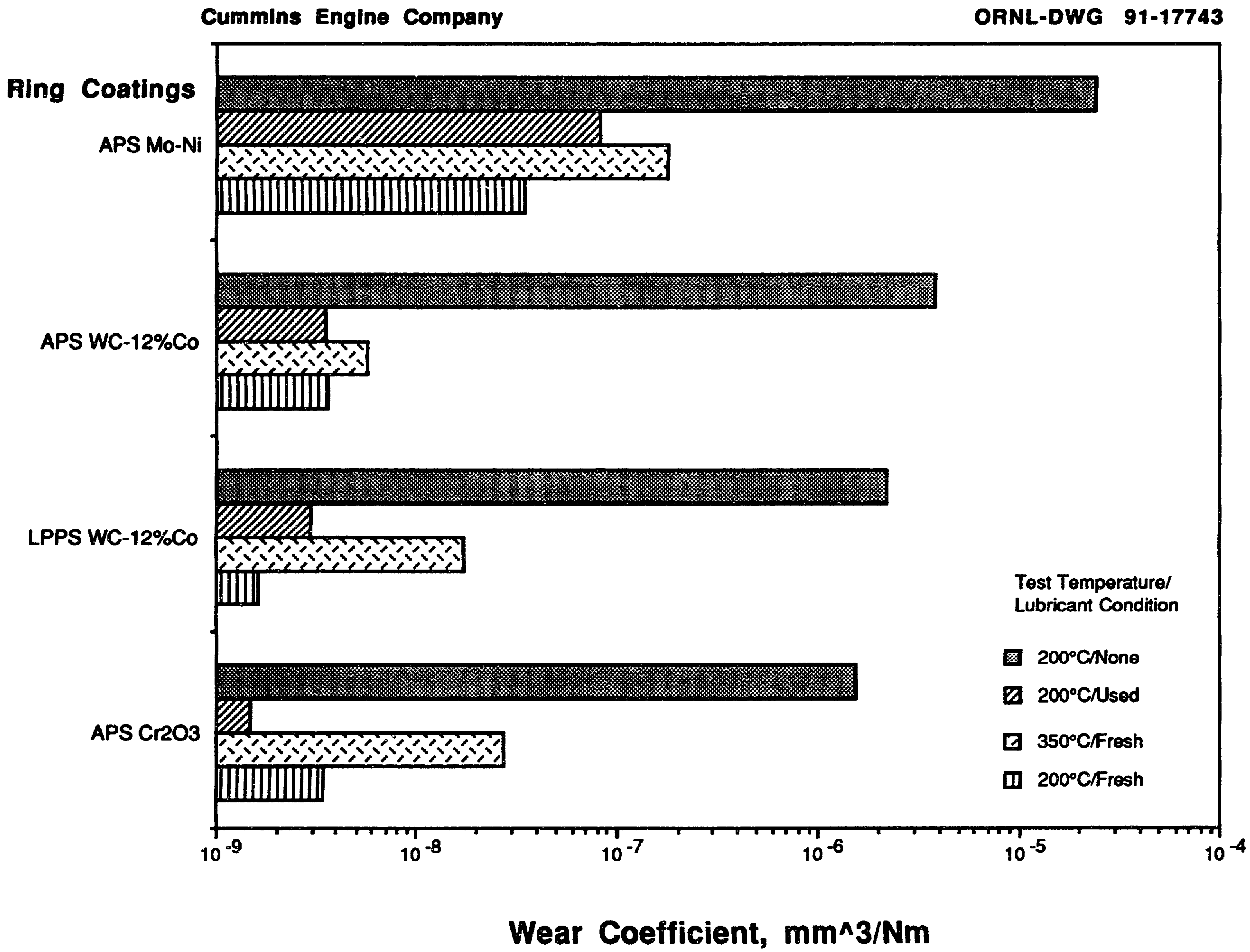


Figure B9. Temperature and lubricant effects on the wear of four ring coatings run against gray iron using fresh and used CE/SF 15W40 lubricant.

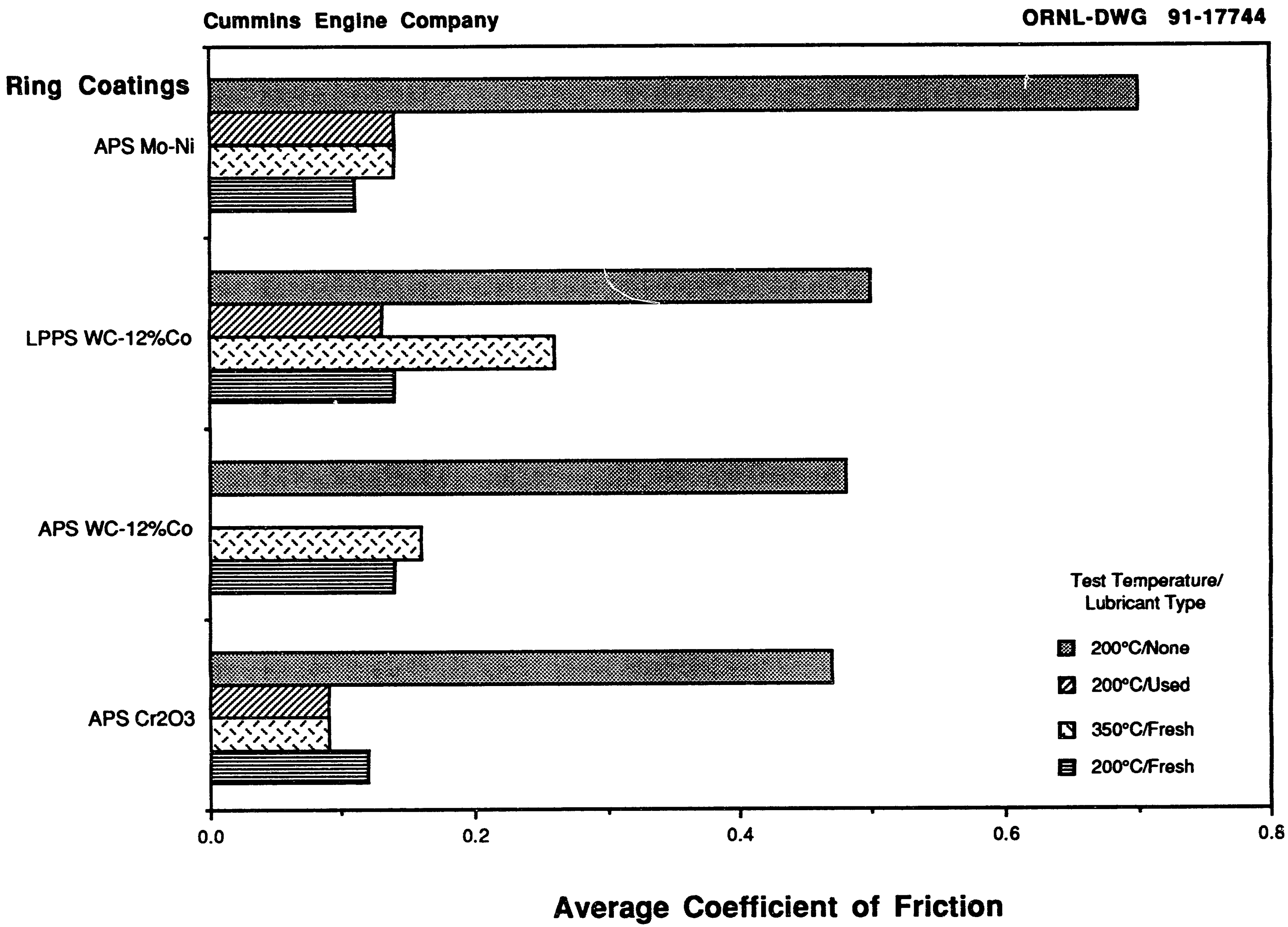
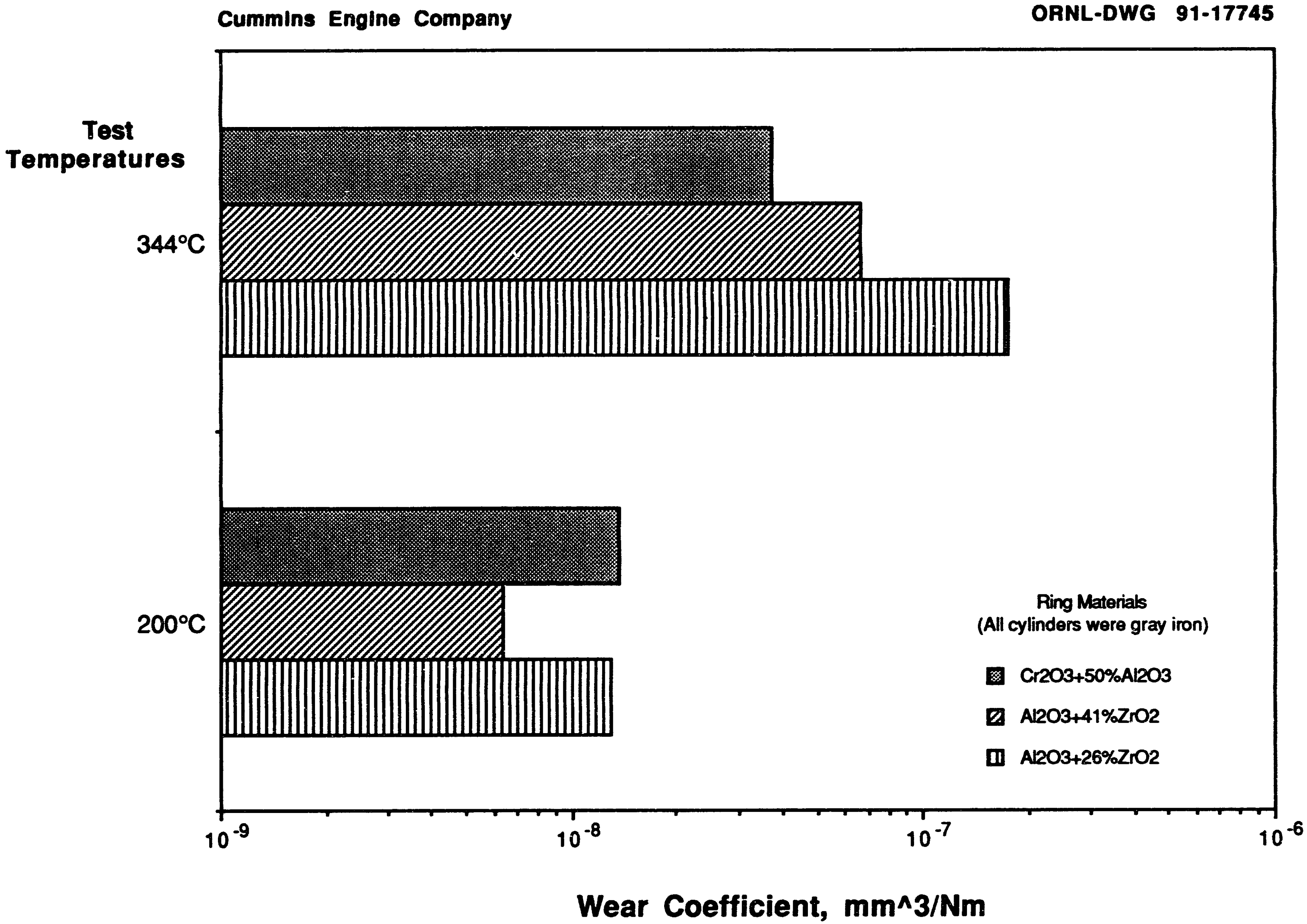


Figure B10. Temperature and lubricant type effects on the average friction coefficient of several ring coatings run against gray iron using CE/SF 15W40 as the lubricant.



Firgure B11. Cameron-Plint test results show variations in wear resistance for several coatings containing alumina. All tests were run in fresh CE/SF 15W40.

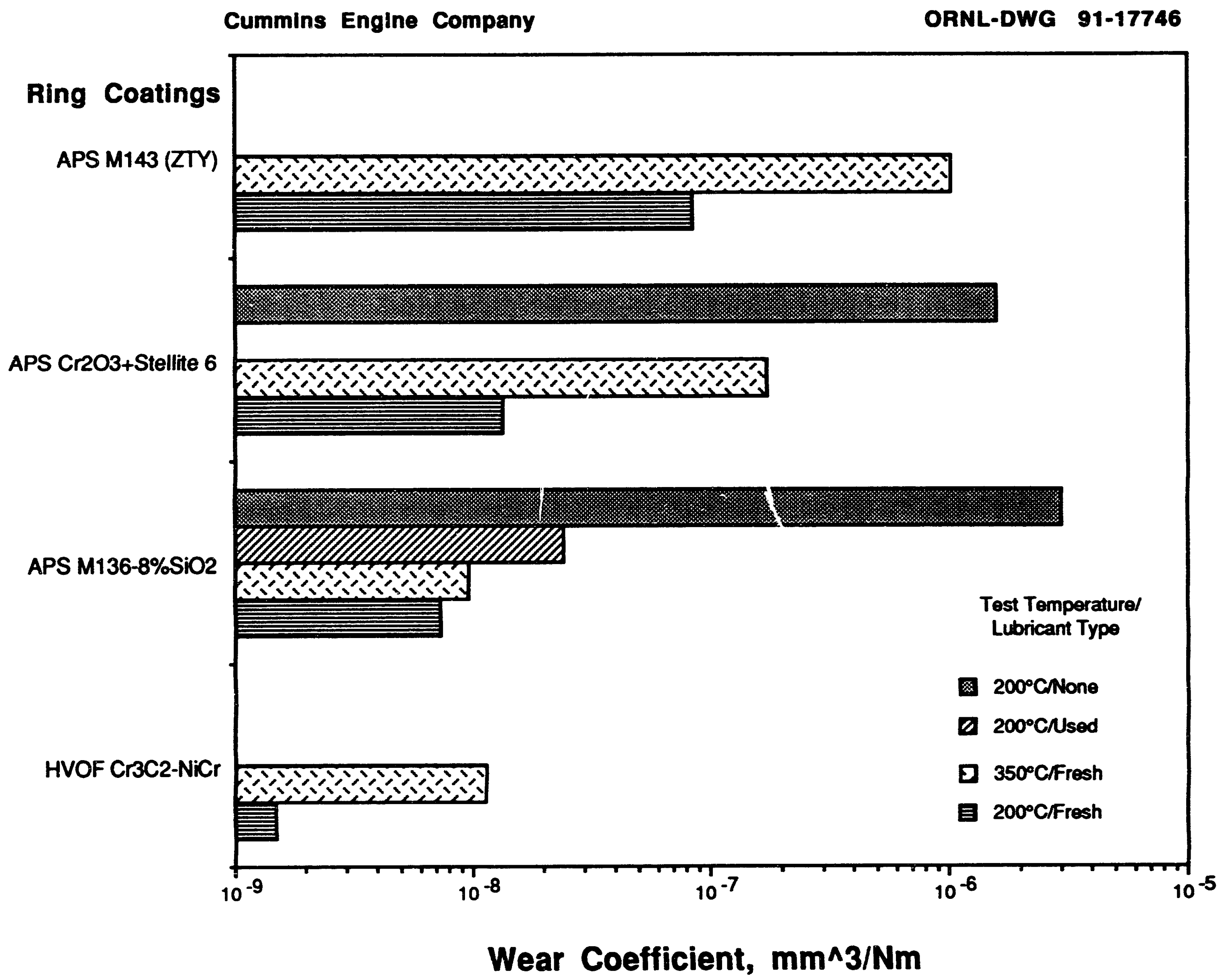


Figure B12. A comparison of wear coefficients for ring coatings run against pearlitic hardened gray iron using fresh and used CE/SF 15W40, or no lubricant.

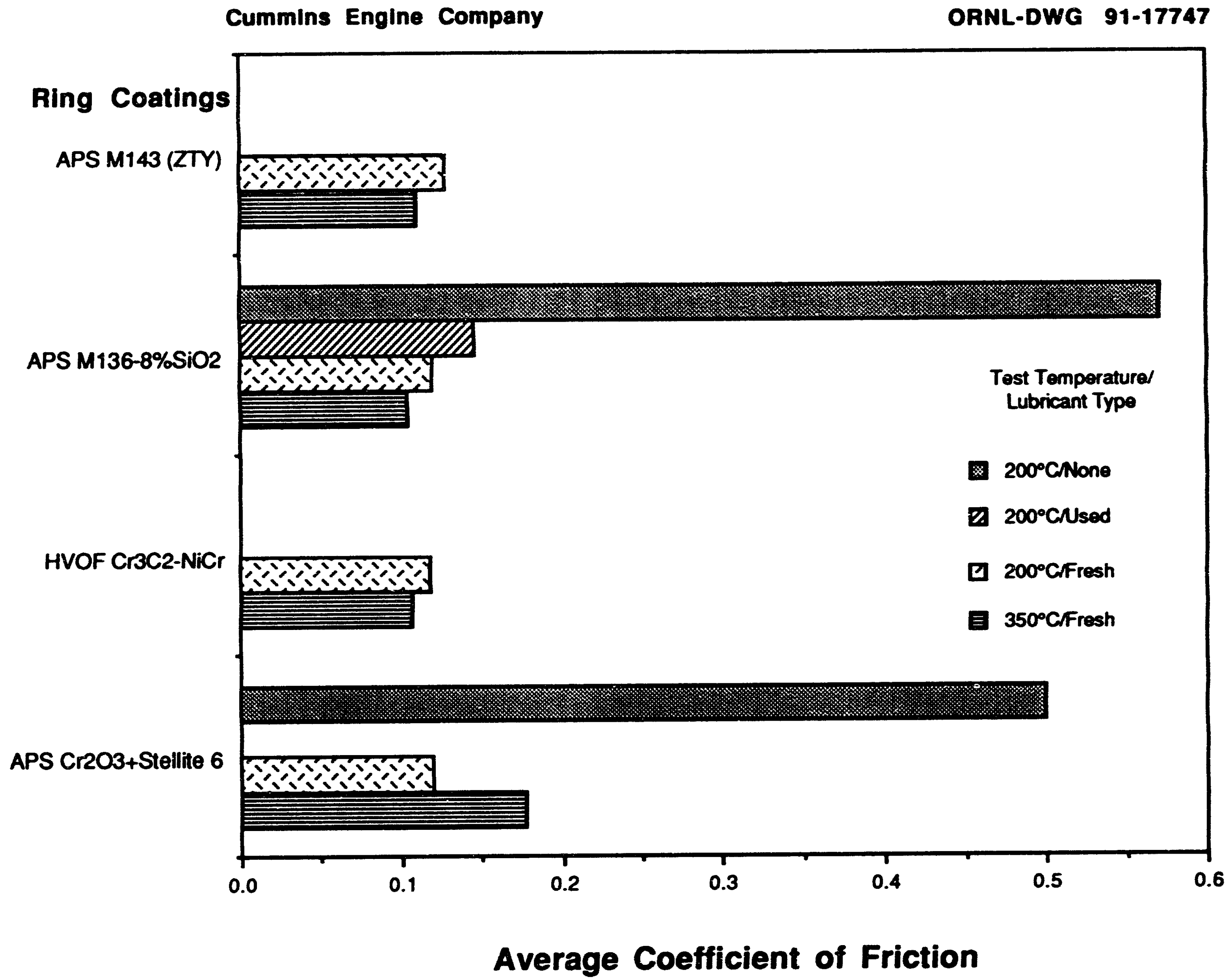


Figure B13. Temperature effects on the average friction coefficients for four ring coatings run against pearlitic hardened gray iron in fresh and used CE/SF 15W40, or unlubricated.

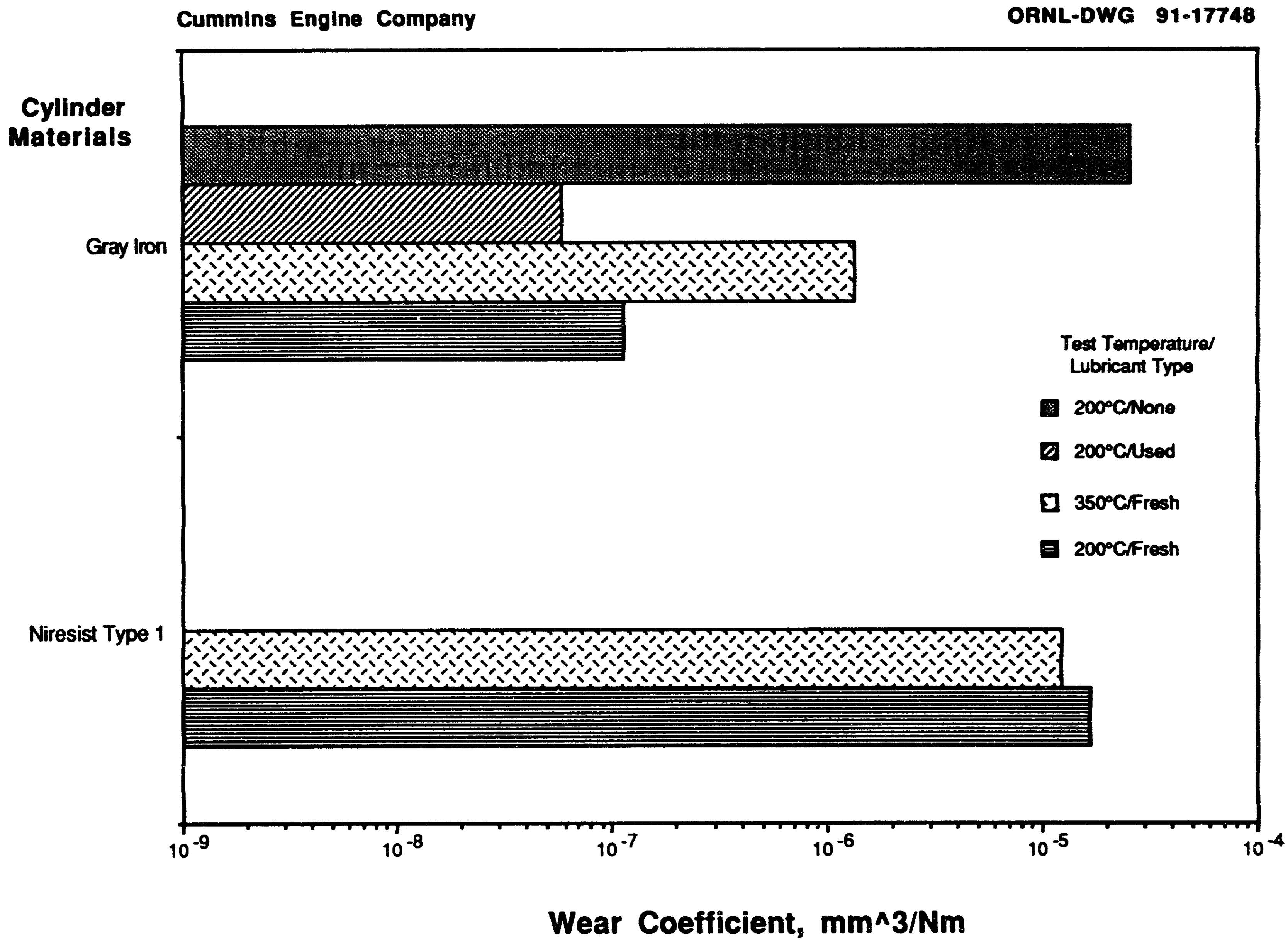


Figure B14. Temperature and lubricant effects on two cylinder materials run against air plasma-sprayed Cr2O3 rings using fresh and used CE/SF 15W40.

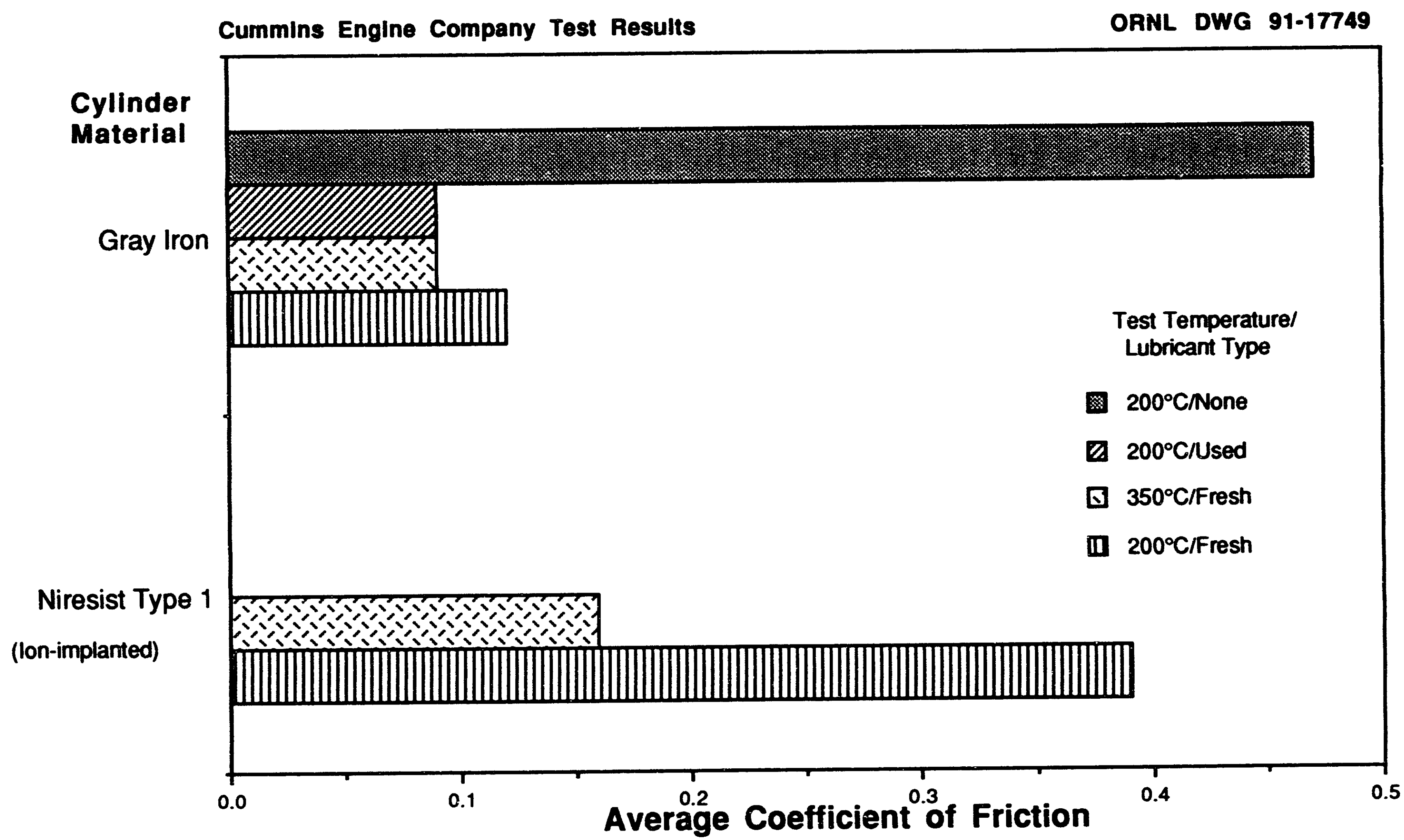


Figure B15. Temperature and lubricant effects on the friction of two cylinder materials run against air plasma-sprayed Cr2O3 rings using fresh and used CE/SF 15W40.

SECTION 3A. INDIVIDUAL TEST NOTES

BATTELLE COLUMBUS LABORATORY TEST NOTES

TEST NUMBER	TEXT
R4	Good wear resistance, but cylinder specimens' surfaces showed cracking in the contact areas, although these areas were highly polished.
R8	A proprietary surface preparation, CERATEK, was applied by PCK Technology on the silicon nitride cylinder specimens. This process produces an Au/Co/Ni alloy coat bonded to the Si3N4 surface. Mating ring speimens of cobalt-bonded tungsten carbide were used with the special Si3N4 cylinders. Specimen break-in was performed at room temperature and 100C.
R11	After 1 hour break-in at room temperature(20C), ring wear coef.(rwc) was 5.e-06, 1.E-06 after 1 hour at 100C, 3.E-06 after 4 hours at 260C, 7.E-06 after 4 more hours at 260C. Friction coefficient rnage = 0.06 to 0.16. The LB625 removed old deposits in test chamber formed by SDL-1, but had higher wear rates in general, possibly due to lack of ZDP, an anti-wear additive found in SDL-1.
R15	Thermo-elastic instability occurred throughout test as visible hot spots. Cylinger specimens were badly cracked from thermal shock associated with TEI. Cr plating was worn through after 60 minutes of running at 10N/mm.
R16	High wear rate was caused by thermo-elastic instability, which showed up as hot spots and streaks on cylinder specimens.
R17	Ring specimens wore 0.05mm in 3 minutes of operation. Surfaces of rings and cylinder specimens were extensively cracked. The edges of ring specimens were chipped away in stair-step cracks following original surface cracks.
R23	Ring and cylinder specimens came from tests on LB625(see test-ids=R32,R26, R30, and R11), thus started life with a 12-hour "break-in". The LB-650X left more deposits with it decomposed, although it was more thermally stable.
R29	High porosity in the ring coatings could be the cause of high wear rates.
R31	High porosity in the ring coatings could be the cause of high wear rates.
R33	The OS-124 burned off very cleanly during the test, but did not seem to have enough usable viscosity left at test temperatures to adequately lubricate the ring/cylinder interface.
R34	Test had to be shut down after 30 minutes due to high friction and higher than normal fluid consumption needed to run quietly. Higher volitility of OS-124 was most likely the reason for need for higher lubrication flow rate.

SECTION 3A. INDIVIDUAL TEST NOTES, continued

BATTELLE COLUMBUS LABORATORY TEST NOTES

TEST NUMBER	TEXT
R39	This test is a re-test of R29 and R31, using new specimens with better coatings. Quality of the coat does make a difference.
R41	No reliable friction coefficient could be measured due to short duration, but very loud squealing during testing suggests high readings.
R42	No reliable friction coefficients could be measured due to short duration, but very loud squealling during test suggests high readings.
R43	A coating of M501 transferred to the SiC cylinder and the sliding was actually occurring on self-mated M501.
R45	Ring material is M130(alumina-titania) with a molybdenum base coat. Test was stopped when one of the cylinder specimens fractured(due to warpage of its ped-
R47	Ring specimen was worn through the .10mm thick Cr coating to base metal after 1 hour of operation. Entire test chamber was coated with a tenacious black layer of lubricant decomposition products. The cylinder specimens were grooved, and heavily coated with tenacioys layer of wear debris and lub. decomp. products.
R48	Thermo-elastic instability was observed. 0.05mm of the Cr coating was worn off, and the Z-191 had thermal cracks.
R53	High ring wear rate was caused by thermo-elastic instability, showing up as hot spots and streaks on cylinder specimens.
R54	High wear rate due to thermo-elastic instability, showing up as hot spots and streaks on the cylinder specimens.
R55	Operating speeds varied from 500 to 1500 RPM. Ring load varied from 12 to 18N/mm and coefficient of friction decreased from 0.07 to 0.04. Original wear was due to "seating of specimens". Hydrodynamic lubrication aided decrease in coefficnt of friction. Some surface smearing and fine abrasion occurred, but no thermal cracks were seen. Ring wear after 4 hours was 0.025mm. Abrasion scratches in some locations suggest effect of grain orientation on resistance to scratching.
R56	Thermo-elastic instability was observed.
R57	Thermo-elastic instability was observed on the MG-PSZ before the ring specimens fractured. No hydrodynamic lubrication occurred.

SECTION 3A. INDIVIDUAL TEST NOTES, continued

BATTELLE COLUMBUS LABORATORY TEST NOTES

TEST NUMBER	TEXT
R58	No thermo-elastic instability was observed. Rings had slight wear and were highly polished as well as thermal-crack free. Thermal properties of the cylinder appear to be more important than for the rings.
R59	No thermal shock was observed. Edges of the rings were chipped but not fractured
R67	New ring and cylinder specimens were used for this examination of LB-650X.
R62E	R62E was run using the same specimen as the other R62 tests, but a different lubricant, LB650X, was used for this part of the test.
R62F	R62F was run using the same specimen as the other R62 tests, and the same lubricant, LB650X, used in the R62E test.
R69	Micrograph showed that rough surfaces transferred material and transverse cracks perpendicular to sliding direction were present. The cracks are typical of dry sliding with soft, lubricious coatings.
R71	Test actually ran for less than 10 minutes before ring specimen holder broke off the sliding arm. Ring specimens shattered, so ring wear coefficient couldn't be measured.
R72	Cylinder wear coefficient was 3.2e-03. Ring coating wore through during test.
R73	Cylinder wear coefficient was 1.2E-02 with 15 micrometers of coating wear. Ring specimen holders broke off after about 10 minutes. A combination of high temps, fatigue and high frictional forces are probable causes of rig failure.
R88	Wear was so high during break-in period that the coating was completeley removed so the test was discontinued.
R90	More oil than usual was needed to keep specimens lubricated. Also, rings loads had to be reduced during the test run.
92LA	See text for R92RA.
92RA	In this set of tests a normal Si3N4 specimen was mounted in the right ring specimen holder (R92Rn tests) and a 20Ne-ion implanted Si3N4 specimen was placed in the left(R92Ln tests). Both were tested simultaneously using the 3-phase test described in TESTBKGD under BCD-RC3.

Section 4. Thermal Expansion Test Results

COATING	COATING BATCH CODE	SUBSTRATE	SUBSTRATE BATCH CODE	TEMP. °C	COEFFICIENT OF THERMAL EXPANSION 10.E-06/°C	COMMENTS
25%M143/75%M461	CATPLR/PSG/CAT			400	12.39	Coating is 25% M143, 75% M461
50%M143/50%M461	CATPLR/PSG/CAT			400	11.08	Coating is 50% M143, 50% M461
75%M143/25%M461	CATPLR/PSG/CAT			400	9.77	Coating is 75% M143, 25% M461
25%ZRO2/75%M461	CATPLR/PSG/CAT			400	11.00	Coating is 25% ZrO2, 75% M461
50%ZRO2/50%M461	CATPLR/PSG/CAT			400	10.90	Coating is 50% ZrO2, 50% M461
75%ZRO2/25%M461	CATPLR/PSG/CAT			400	9.50	Coating is 75% ZrO2, 25% M461
AMDRY 961	AMDRY/CAT			400	13.79	Amdry 961 is a base coat
AMDRY 961	AMDRY/CAT			200	12.58	Amdry 961 is a base coat
-	-	CAST IRON	CAT/TRIB	400	14.40	Substrate only
ENAM-1	CAT/DIP/TRIB	CAST IRON	CAT/TRIB	20	7.90	Basic enamel coating
ENAM-1/50%Cr203	CAT/DIP/TRIB	CAST IRON	CAT/TRIB	20	7.70	Enamel with 50v% Cr2O3 particles
ENAM-1/60%Cr203	CAT/DIP/TRIB	CAST IRON	CAT/TRIB	20	7.70	Enamel with 60v% Cr2O3 particles
ENAM-1/70%Cr203	CAT/DIP/TRIB	CAST IRON	CAT/TRIB	20	7.50	Enamel with 70v% Cr2O3 particles
-	-	H-13 STEEL	CAT/TRIB	400	12.20	Substrate only
M143	METCO/PS/CAT			200	7.57	
M143	METCO/PS/CAT			400	8.46	
M19E	METCO/PS/CAT			400	11.79	
M19E	METCO/PS/CAT			200	10.70	
M350A	METCO/PS/CAT			200	8.85	
M350A	METCO/PS/CAT			400	11.09	
M461	METCO/PS/CAT			200	12.33	M461 is a base coat
M461	METCO/PS/CAT			400	13.70	M461 is a base coat
M461	METCO/PS/CAT			400	13.70	M461 is a base coat
M66F-NS	METCO/PS/CAT			200	9.90	
M66F-NS	METCO/PS/CAT			400	11.38	
M70C	METCO/PS/CAT			200	8.35	
M70C	METCO/PS/CAT			400	9.48	

Section 4. Thermal Expansion Test Results

COATING	COATING BATCH CODE	SUBSTRATE	SUBSTRATE BATCH CODE	TEMP. °C	COEFFICIENT OF THERMAL EXPANSION 10.E-06/°C	COMMENTS
M750F	METCO/PS/CAT			200	10.62	
M750F	METCO/PS/CAT			400	11.30	
MAE7023	METCO/PS/CAT			200	4.27	
MAE7023	METCO/PS/CAT			400	4.75	
-	-	PS212	HOHMAN/APS/CAT	200	9.76	
-	-	PS212	HOHMAN/APS/CAT	400	11.37	
ZrO2	ZIRCOA/PS/CAT			200	7.95	
ZrO2	ZIRCOA/PS/CAT			400	8.09	

Section 5. Hardness Data

AVERAGE KNOOP HARDNESS (100g LOAD) FOR SEVERAL CUMMINS COATINGS

COATING MATERIAL	BATCH CODE	SUBSTRATE MATERIAL	TEMP °C	HARDNESS kg/mm2	COMMENTS
Al2O3-26%ZrO2	BIRL/APS/CEC	422 STEEL	200	1050	
Al2O3-41%ZrO2	BIRL/APS/CEC	422 STEEL	200	840	
ARMACOR M	APSMAT/APS/CEC	HK 40 STEEL	200	760	
Cr	APSMAT/APS/CEC	422 STEEL	200	250	
Cr	CUMMINS/EP/CEC	DUCTILE IRON	200	880	
Cr2O3	APSMAT/APS/CEC	HK40 STEEL	200	770	
Cr2O3	BIRL/APS/CEC	422 STEEL	200	1440	
Cr2O3	BIRL/HVOF/CEC	422 STEEL	200	1320	
Cr2O3-50%Al2O3	BIRL/APS/CEC	422 STEEL	200	650	
Cr3C2-NiCr	UTRC/HVOF/CEC	422 STEEL	200	990	
Cr3C2-WC-NiCrCo	BOYD/HVOF/CEC	HK 40 STEEL	200	1000	
FERROTIC CM	APSMAT/LPPS/CEC	422 STEEL	200	990	
FERROTIC CS40	APSMAT/LPPS/CEC	422 STEEL	200	940	
FERROTIC HT6A	APSMAT/LPPS/CEC	422 STEEL	200	620	
M106FP	UTRC/APS/CEC	422 STEEL	200	850	
M136	APSMAT/APS/CECA	HK40 STEEL	200	960	
M136	BOYD/APS/CECB	HK40 STEEL	200	1020	
M136-15%Al2O3	APSMAT/APS/CEC	HK40 STEEL	200	1260	
M143	UTRC/APS/CEC	422 STEEL	200	450	
Mo-MoO2	BIRL/APS/CEC	422 STEEL	200	770	
Mo-Ni	BIRL/APS/CEC	422 STEEL	200	510	
Mo-Ni	BIRL/HVOF/CEC	422 STEEL	200	540	

AVERAGE KNOOP HARDNESS (100g LOAD) FOR SEVERAL CUMMINS COATINGS

COATING MATERIAL	BATCH CODE	SUBSTRATE MATERIAL	TEMP °C	HARDNESS kg/mm2	COMMENTS
NiCrBSi	UTRC/HVOF/CEC	422 STEEL	200	900	
SCA*	CUMMINS/SS/CEC		200	960	8 Densifications
SCA*	CUMMINS/SS/CEC		200	960	12 Densifications
SCA*	CUMMINS/SS/CEC		200	1030	16 Densifications
TRIBOLITE	APSMAT/APS/CEC	422 STEEL	200	630	
WC-12%Co	APSMAT/APS/CEC	HK 40 STEEL	200	1240	
WC-12%Co	APSMAT/HVOF/CEC	HK 40 STEEL	200	880	
WC-12%Co	APSMAT/LPPS/CEC	HK 40 STEEL	200	1130	
WC-12%Co	BIRL/HVOF/CEC	422 STEEL	200	960	
WC-12%Co	BOYD/HVOF/CEC	HK 40 STEEL	200	1120	
WC-12%Co+B	BIRL/HVOF/CEC	422 STEEL	200	1490	

*These three measurements were taken on the same specimens after increasing periods of densification.

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