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Research on Non-Traditional Materials for Friction Surfaces in Heavy Vehicle Disc Brakes*

A Compilation and Summary of Laboratory Test Data

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December 1, 2004

Dr. Peter J. Blau
Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN

*Research sponsored by the U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies, High Strength Weight Reduction Materials Program, under contract DE-AC05-00OR22725 with UT-Battelle LLC, Oak Ridge, Tennessee.

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The author wishes to acknowledge the able assistance of Brian C. Jolly, East Tennessee State University, for running many of these tests on the Sub-Scale Brake Tester, Hsin Wang and Ralph Dinwiddie, ORNL, for thermal property measurements, and many others who have helped in the design, assembly, and calibration of the SSBT. The encouragement of Phil Sklad, ORNL Program Manager, and the support from Sid Diamond, DOE, High-Strength Weight Reduction Materials Program, are also greatly appreciated. Research was conducted under contract DE-AC05-00OR22725 with UT-Battelle LLC, Oak Ridge, Tennessee.

PREFACE

This report is a summary and compilation of laboratory friction test data and analysis that was conducted over the past three years in our laboratory. These data were obtained for a variety of materials that have been under consideration for use as rotors and pads in the next generation of air disc foundation brakes for heavy trucks. Since this is exploratory research, it sometimes used one-of-a-kind samples of candidate materials that were prepared especially for this project. In other cases, tests were done on commercial products or niche-area brake products with the potential to be applied to trucks.

The data provided in this report were useful in establishing contact pressure, velocity, and temperature effects on the frictional behavior of various material combinations and therefore revealed both promising and problematic characteristics of certain sliding couples. The intent of this work is to help narrow the focus on materials with a balance of desirable characteristics: light weight for fuel-efficiency gains, high durability, and stable frictional characteristics over a range of operating conditions. More corrosion-resistant materials were favored since aggressive road deicing compounds are a growing threat to traditional iron-based brake materials. Much remains to be done, not only in selecting the most promising rotor materials but also in finding the best pad materials to mate with them, and in designing brake hardware to take into account the different thermal characteristics of alternative materials to steel and cast iron. The goals of this work must therefore include excellent stopping performance, resistance to environmental exposure, long life, and economic viability.

1.0 OBJECTIVE OF THIS PROJECT

The objective of this multi-year project is to identify, test, and analyze the friction and wear characteristics of advanced materials and surface treatments that enable weight reduction in truck brake components while equaling or bettering their performance. Materials of interest include intermetallic alloys, ceramic composites, titanium alloys, and novel surface treatments. The ultimate goal of this effort is to advance the state of the art in friction braking and to offer manufacturers and vehicle designers a basis for exploring new options in vehicle material selection.

This report supports the project objective by summarizing test data for a number of current material combinations of interest. The results presented here are not intended to constitute a final set of recommendations since much still remains to be done to determine the best combinations of advanced rotor and pad materials. Nor was this report intended to provide details on the statistical variation of parameters observed in individual tests, since that level of detail is better left to more extensive mechanistic studies. Rather this report provides an overview of trends in friction and temperature rise behavior and a rationale for subsequent decisions regarding the selection and evaluation of candidate materials for heavy truck brakes. It represents a compilation of work in progress toward a larger and more ambitious goal.

2.0 RATIONALE

Advanced aerodynamic designs and tires with lower rolling-resistance can improve fuel efficiency of trucks. However, as these approaches decrease the drag forces on trucks, the demands on their braking systems increase. Brake engineering involves design, instrumentation and controls, and materials development. This project specifically addresses the latter. Brake materials must exhibit a balance of properties including frictional stability over a wide temperature range, appropriate thermal properties, dimensional stability, corrosion resistance to road deicers, and wear resistance. From a practical standpoint, they must also be cost-competitive. Opportunities exist to employ advanced materials to create lighter-weight braking systems that will enable new technologies to raise the fuel-efficiency of a vehicle without compromising its safety and reliability, but a balance of engineering and financial considerations will drive the marketplace. Finally, the introduction of new government safety regulations and shorter stopping distance requirements by the Department of Transportation (DOT/NHTSA) will also influence the motivation to use more effective brake materials and system designs.

This project addresses the science and engineering of advanced structural materials and surface treatments that show potential as truck brake friction materials. Testing such new materials is made more cost-effective by using small specimens to screen the most promising candidates. To this end, a subscale brake tester (SSBT) was designed and built at Oak Ridge National Laboratory with the help of a team of individuals including:

R. D. Ott, J. C. McLaughlin, R. Dinwiddie – ORNL
M. Mosleh – Howard University
D. Dumitrescu – University of Michigan

The SSBT was instrumented to measure normal force, friction force, surface temperature and vibrations during sliding. An attachable water spray system enables the effects of wet and dry braking to be studied. Details are provided in Section 4.0. The SSBT has been a workhorse in studies involving a variety of both traditional and non-traditional brake materials. Analysis of SSBT results is being supplemented by optical microscopy, scanning electron microscopy, and transmission electron microscopy of friction-induced films. These more detailed studies are not reported here.

3.0 MATERIAL SELECTION AND PROPERTIES

The search for next-generation truck brake materials has involved identifying candidates and assimilating published and oral sources of information, including conducting our own tests to provide a basis to focus on leading candidates. Studies of the structure, composition, and physical properties of a variety of candidate materials eliminated those with low-softening-points, brittle behavior, corrosion sensitivity, and environmentally unacceptable wear by-products. A list of the materials that were evaluated, along with comments on their advantages and disadvantages, was presented in this project's FY 2003 Annual Report.

Table 1 summarizes the materials tested to-date. Most of the disc materials, particularly the composites, are not mass produced and therefore, special samples were purchased specifically for our research. The sliding partners (linings) for the disc materials were selected based on such factors as comparison with similar linings tested against cast iron, recommendations from suppliers, and materials having thermo-physical properties that made them likely partners for given disc materials. There is no solid scientific basis to make a priori selections of friction material couples. Most are based on empirical data, qualification testing, and best guesses from personal experience. Additional details on the test materials are given in Section 3.1 and their properties are given in Section 3.2. In Table 1, and henceforth, the acronym "MMC" stands for metal-matrix-composite.

Table 1. Candidate Friction Material Combinations

Disc Specimen Material	Mating Material(s)
Traditional grey cast iron	Jurid 539 disc brake lining Performance Friction Carbon-Metallic Pad (type 10) Armada AR2, AR4, AR5 drum brake lining materials
SiC particle reinforced Aluminum alloys (Al-MMC), supplied by PNNL in several forms	Specially formulated lining for Al-MMC (Plymouth Prowler)
Fe_3Al Intermetallic Alloy, specially prepared at ORNL	Jurid 539 disc brake lining
Ceramic composite (C/SiC) – GE Power Systems LLC, DOE Contract	Jurid 539 disc brake lining Same material as the disc
Ceramic composite (SiC/Si) – Redunndant Materials	Same material as the disc
Ceramic composite (C/SiC) – Starfire Systems	Carbon felt composite Copper-Carbon composite
Titanium alloys (Ti-6Al-4V, and Ti-6Al-2Sn-4Zr-2Mo) – TIMET Corp.	Jurid 539 disc brake lining
Titanium matrix composite (TiC) – CermeTi C-10, Dynamet Technologies	Jurid 539 disc brake lining Performance Friction Carbon-Metallic Pad (type 10)

3.1 *Factors in Material Down-Selection*. Over the course of this project, a number of factors were considered to limit the choice of materials from Table 1 to those that seemed most promising. Factors included published and experimentally-determined frictional behavior, fabrication and handling issues (brittleness, loose fibers), the kind of debris produced during sliding, corrosion resistance, and cost.

The decision not to pursue aluminum-based metal matrix composites in this project was based on several factors. First, Pacific Northwest National Laboratory (PNNL) currently has a DOE-funded program in that area. Secondly, ORNL conducted some preliminary tests on Al-MMC materials several years ago and found the friction against Plymouth Prowler brake linings (formulated for Al-MMC rotors) gave relatively low friction coefficients. We had concerns over the low melting temperature of the matrix and industry experience in which heavily loaded Al-MMC rotors distorted. Thirdly, correspondence with an experienced brake engineer from a major automaker contained the following significant concerns (summarized from e-mail correspondence):

> Cost: The cost of aluminum-based brake discs has always been underestimated because it is typically necessary to increase rotor size for thermal management and to achieve high temperature stiffness/strength. Increased disc size may also be unobtainable within the package limitations of vehicles light enough to use such discs. The extra step of applying a coating adds cost. Cost is the overwhelming barrier for implementing new technology. In foundation brake hardware, it is very difficult to demonstrate that the added cost is justified by improvements in performance or reductions in warranty costs.
>
> Warranty issues: The primary error made by advocates of Al brake technologies is in arguing that it will solve a lot of customer complaints that currently occur with gray iron discs, thus saving money in the long run. Unfortunately there is no industry evidence for a reduction in customer complaints, and even some evidence to the contrary – for example brake noise. We only need consider the natural damping characteristics of cast iron vs. Al. Finally, we cannot use Al-based discs on the front axle which is where the overwhelming majority of brake complaints originate.
>
> Performance concerns: There is a very long list of performance targets that brake systems must pass: friction stability, wear, resistance to distortion, thermal capacity, noise, fade, resistance to corrosion, dimensional stability, etc. In my experience, it is very difficult to get Al-based discs to pass some of the tests which result in high energy input over a length of time – i.e. mountain descent. Even when a safe temperature is maintained (such as on a rear axle) the thermal expansion of Al brakes generates significant vehicle vibration. Even for a coated disc, one would also have to validate that the failure modes would not be catastrophic. For example, in an over-heat situation, does the underlying Al melt and cause the entire coating to shear off? Other issues include thermal expansion mismatch between the coating the Al substrate, and pad-disc interactions. Also, new rubbing surfaces require a new friction pad - development of which is again a significant cost. Another significant material issue with Al-based discs is corrosion - if not, while not as light as aluminum MMC's still could save roughly 40% in weight over cast iron disc brakes of comparable dimensions as the data in Table 2 indicate. Of the disc, then of the coating, the disc-coating interface or at the hub-disc interface or the pad-disc interface. Corrosion is always presented as one of those cast iron disc issues that will be solved by Al-discs, when in reality in the wet, salty underbody environment Al just presents a different set of corrosion issues.

Titanium Alloys. Recent progress in extraction technology for titanium and its many applications in light weight aerospace structures encouraged us to consider of titanium as an alternative to Al-MMCs [1]. While not as light as aluminum-based MMC's, titanium alloys could still save roughly 40% of weight over cast iron disc brakes of comparable dimensions (see Table 2). Another factor in favor of titanium is

its corrosion resistance. The trucking industry has recently encountered significant problems in corrosion due to the use of more aggressive ice-melting compounds [2, 3]. These compounds have been especially harmful to drum brakes, producing the phenomenon known as 'rust jacking' in which the build-up of corrosion products leads to cracking and premature wear-out of S-cam brake shoe linings [4]. While unalloyed cast irons are particularly susceptible to corrosion in salt water under alternate immersion conditions [5], titanium alloys have particularly good resistance to aqueous corrosion with almost no detectable loss rates (see Table 3). Corrosion rates for SiC/Al particulate composites in sodium chloride solutions have been reported to be 40% higher than for Al-Cu alloy 2024 [7]. In splash tests, corrosion rates of up to 9.8 mils/yr were reported. Likewise, corrosion rates for Al MMCs in seawater have been found to be higher than for non-reinforced alloys. In contrast, titanium alloys are resistant to corrosion when galvanically coupled to other metals. Table 4 shows the galvanic series for flowing saltwater (4 m/s at 24°C). Protective coatings or other corrosion control measures may be required for steel or aluminum components in contact with Ti. Therefore, titanium-based alloys were selected for further study as candidate brake rotor materials.

Table 2. Typical Properties of Titanium Alloys, Aluminum MMCs, and Gray Cast Iron

	Units of measure	Ti - 6Al - 4V alloy	Al / 20% SiC Composite	Gray Cast Iron
Density	g/cm^3	4.4	~ 2.8	7.2
Melting point	°C	1650 - 1670	~ 630	1200 - 1300
Elastic modulus	GPa	107 – 122 (20 C) 105 – 111 (230 C)	~ 101.	~ 200. – 211.
Poissons ratio	(none)	0.31	~ 0.3	0.17
Thermal conductivity	W/m-°K	6.6 (20 C) 10.6 (315 C) 17.5 (650 C)	182.0	42.0 – 62.0
Specific heat	J/(kg - °K)	586. (20 – 570 C)	-	460.
Coefficient of thermal expansion	$x\ 10^{-6}$ / °K	9.0 (0 - 100 C) 9.4 (20 – 425 C) 9.7 (20 – 650 C)	-	8.1 – 19.3 (20 C)

Table references:

R. L. Hecht, R. B. Dinwiddie, W. D. Porter, and H. Wang (1996) "Thermal Transport Properties of Grey Cast Irons," Soc. of Automotive Engineers, paper number 962126.

W. J. Lackey, D. P. Stinton, G. A. Cerny, L. L. Fehrenbacher, and A.C. Schaffhauser (1983) Proc. International Symposium on Ceramic Components for Heat Engines, Hakone, Japan.

TIMET Corporation, Denver, CO, internet on-line alloy data sheets (2002).

P. J. Blau (2001) Compositions, Functions, and Testing of Friction Brake Materials and Their Additives, ORNL Tech. Rept., ORNL/TM-2001/64, 29 pp.

Table 3. Corrosion Rates for Titanium Alloy 6Al-4V in Aqueous Chloride Solutions [6]

Medium	Concentration (wt%)	Liquid Temperature (F)	Corrosion Rate (mils/yr)
Calcium chloride	28	208	2.7 – 2.9
Magnesium chloride	5 20 40	boiling boiling boiling	nil nil nil
Seawater	---	68	nil
Sodium chloride	20	68	nil

Table 4. Steady State Electrode Potential for Titanium in Flowing Saltwater [8]

Metal or Alloy	Steady-state electrode potential, V vs. SCE
Graphite	+ 0.25
Platinum	+ 0.15
Type 304 stainless (passivated)	- 0.05
Titanium	**- 0.10**
Silver	- 0.13
Type 304 stainless (active)	- 0.53
Cast iron	- 0.61
Aluminum (3003-H)	- 0.79
Zinc	- 1.03

Bare titanium alloys may not prove suitable as friction brake surfaces due to wear concerns. Therefore, it was also decided to include coated titanium alloys in this work. A company that supplies titanium rotors for racing applications has been contacted, several specimens have been obtained, and that activity is on-going at this writing. Results will be discussed in future reports.

Ceramic Composite Materials. Ceramic-based brake materials, particularly carbon-graphite and carbon-silicon carbide composites are either in use in selected applications or being actively pursued in the industry. Applications have included aircraft brakes, high-speed trains, race cars, and upscale sports cars. Limited, yet promising stopping tests have been performed on sports utility vehicles.

A recent article in a ceramics industry publication [9] lists justifications to try ceramic composites for passenger car brakes. They include low inertia, high wear life, and controllable friction – with the proper pad choice. The internet website for Starfire Systems [10], a supplier of material for this project, has claimed a number of advantages for silicon carbide-based brakes including the following:

- Up to one-third the weight of comparable steel
- Up to 20% lighter than carbon/carbon*
- Stable base friction coefficient ($\mu = 0.2$) that can be tailored to exceed $\mu = 0.35$
- Friction rises smoothly at the end of stop
- Significantly lower wear rates compared to carbon/carbon
- Less wear dust than carbon/carbon
- Greater mechanical stability than carbon/carbon
- Demonstrated 30-50% lower cost versus carbon/carbon, etc.

Starfire Systems rotors have recently performed well in motorcycle racing and in limited light-truck tests.

*Note: The density of Starfire Systems grade "T-300" is among the lowest of the composites produced by its products as is given as 2.10 g/cc. The claim of lighter weight might not be based on density alone since a number of carbon/carbon composites have densities considerably below 2.0 g/cc. If higher strength allows less material to be used, some weight advantage may be obtained.

Some reviews of currently sold ceramic composite brakes were less optimistic (e.g. [10]). The disadvantages were said to involve high frictional temperatures (upwards of 600° C) that flow into the caliper and the brake fluid. Ceramic brakes may require larger calipers and new brake fluid formulations to withstand the heat. Knuckles and bearings may also require heat protection. Significantly for warrantees, there was supposedly a noise problem with ceramic brakes. Porsche in particular has had to use lower noise pads, and that change supposedly provided no advantage in stopping over the standard

stock pads. The rotors may partially crack, and the price for the rotor and the six-piston calipers used in some designs is high. Whether ceramic composites will be economically and functionally suitable for heavy trucks remains to be demonstrated, but there is enough interest in these materials to include them in the current studies.

Bearing in mind the possibility that the aforementioned shortcomings could be remedied through optimized component design, compatible lining selection, and surface modifications, we chose to focus on both titanium-based brake rotor materials and on ceramic composite-based brake rotor materials. Neither of these seems to be a clear winner, but both have attractive advantages that merit further evaluation. During FY 2004, dozens of experiments were conducted to characterize the effects of speed and contact pressure on the friction coefficient and frictional temperature rise for both Ti-based and ceramic composite disc materials. Results of these tests are summarized in Section 5 of this report. First, however, the test materials and their sources are described.

3.2 *Test Materials and Sources*

Section 3.2.1 lists, in tabular form, materials that were used for sliders (as brake pads) and Section 3.1.2 lists materials used in the form of disc specimens (as brake rotor materials).

3.2.1 *Slider Materials*

Name	**Jurid 539**
Description	Commercial blend – appears semi-metallic
Supplier	Bendix CVS – Knorr Bremse
Method of procurement	Provided to us
Comment	Commercial disc brake lining material

Name	**Performance Friction – Carbon-Metallic Pads** (types 10 and 20)
Description	High-performance blend – semimetallic
Supplier	Fleetpride, Rutledge Pike, Knoxville
Method of procurement	Direct purchase
Comment	Recommended for automotive high-performance brakes

Name	**Armada AR2**
Description	Commercial brake drum lining material
Supplier	TruckPro, Knoxville, TN
Method of procurement	Direct purchase
Comment	Specimens cut from a brake shoe with the following edge code: AR2 4515 GD 23K FF CAM. Lining recommended for single- or tandem-axle tractor-trailers

Name	**Armada AR4**
Description	Commercial brake drum lining material
Supplier	TruckPro, Knoxville, TN
Method of procurement	Direct purchase
Comment	Specimens cut from a brake shoe with the following edge code: AR4 4515 GD 23K FF ANC. Higher torque than AR2, lining recommended for refuse trucks, cement mixers, and school buses.

Name	**Armada AR5**
Description	Commercial brake drum lining material
Supplier	TruckPro, Knoxville, TN
Method of procurement	Direct purchase
Comment	Specimens cut from a brake shoe with the following edge code: AR5 4515 GD 23K GG ANC. Highest torque of AR2, AR4 and AR5, recommended for tri-axle dump trucks.

Name	**Carbon fabric**
Description	Woven structure
Supplier	Starfire Systems, Malta, NY
Method of procurement	Supplied with the test discs we purchased from them, same as the disc specimen material
Comment	Experimental material

Name	**Carbon felt**
Description	Composite formulation
Supplier	Starfire Systems, Malta, NY
Method of procurement	Supplied with the test discs we purchased from them
Comment	Experimental material

Name	**Copper/Carbon**
Description	Composite formulation
Supplier	Starfire Systems, Malta, NY
Method of procurement	Supplied with the test discs we purchased from them
Comment	Experimental material

Name	**SiC/Si**
Description	Layered structure
Supplier	Redunndant Materials, Clarence Center, NY
Method of procurement	Supplied with the discs we purchased from them
Comment	Same material as the discs we ordered (see below)

3.2.2 *Disc Materials*

The following provides information on the disc materials used in these experiments.

Name	**C/SiC disc**
Description	Polymer Infiltration and Pyrolysis (PIP) involves soaking a fiber preform or powder compact with a liquid polymer precursor that converts to ceramic material upon pyrolysis. Starfire polymer derived silicon carbide is claimed to be stable up to 1900°C (500°C higher than competing polymer precursors, substantiated by a NASA contractor for the CRV program). It cures by low temperature thermal cross-linking, affording rigidity for ease of handling and intermediate machining to near net shape. Hydrogen gas is the only effluent of pyrolysis, allowing a very high 80-85% yield of silicon carbide ceramic. The samples we obtained were 2D reinforced with a high modulus graphite fiber.
Supplier	Starfire Systems, Malta NY
Method of procurement	Direct purchase

Name	**SiC/Si discs**
Description	Carbide material by electromagnetic processing US Patent No. 6,699,450. Conversion of layered graphite foil into a SiC/Si composite by direct RF heating of the graphite in the presence of a reactive element, in this case Si. 5" diam. ½" thick composite formed with less than a 10 minute heat cycle.
Supplier	Redunndant Materials, Inc, Clarence Center, NY
Method of procurement	Direct purchase
Comment	Surface appears to be large islands of the converted layers, but with some areas of rougher, granular appearance, probably the result of grinding not exactly parallel to the lay-up.

Name	**C/SiC discs**
Description	Conversion of graphite textile into SiC with residual C by infiltration and reaction with Si at high temperature.
Supplier	GE Power Systems Composites (formerly Honeywell Advanced Composites Inc.) Newark, Delaware
Method of procurement	Resulting from a DOE funded program 1999-2002

Name	**CermeTi C-10**
Description	Ti-based composite CermeTi materials are a family of particle-reinforced titanium matrix composites. These particles add wear resistance, hardness, modulus (stiffness) and elevated temperature strength to the titanium alloy. These enhancements result while maintaining key advantageous properties of titanium alloys such as lightweight, corrosion resistance, and nonmagnetic properties. Produced by Dynamet's CHIP (cold plus hot isostatic pressing) powder metal technology. Can further be formed by subsequent forging or extrusion. CermeTi materials are machinable, although they will cause greater tool wear than machining conventional titanium alloys. CermeTi-C is reinforced with titanium carbide (TiC) particles. CermeTi-B materials are reinforced with TiB whisker-like particles formed from the addition of TiB_2 to the powder blend.
Supplier	Dynamet, Burlington, MA
Method of procurement	Direct purchase

3.3 *Properties of Test Materials*

The density and thermal conductivity of the test materials was obtained from several sources including, the manufacturers of the materials. In some cases, we measured the thermal conductivity and material density at Oak Ridge National Laboratory. A compilation of these data is given in Table 5.

Table 5. Density and Thermal Conductivity of Test Materials

Use	Material	Density (data source) (g/cm^3)	Thermal Conductivity (data source) ($W/m\text{-}^oK$)
Disc specimens	Gray cast iron	7.2 (1)	36.9 (2)
	C/SiC ceramic (GE Power Systems)	2.4-2.5 (3)	14.8 (2)
	C/SiC ceramic (Starfire Systems)	1.99 (4)	3.1-3.2 (5)
	SiC/Si (Redunndant Materials)	2.94 (4)	50 – 70 (6)
	CermeTi C-10 (Dynamet)	4.44 (4)	8.2 (5)
Pad specimens	Jurid 539 (Knorr-Bremse)	3.14 (4)	Not measured
	Performance Friction Carbon Metallic	2.96 (4)	Not measured
	Carbon felt (Starfire Systems)	2.13 (4)	Not measured
	Carbon fabric (Starfire Systems)	2.04 (4)	3.1-3.2 (5)
	Copper carbon (Starfire Systems)	2.23 (4)	Not measured
	SiC/Si (Redunndant Materials)	2.89 (4)	Not measured

Data sources:

1. E. R. Booser, ed. (1997) Tribology Data Handbook, CRC Press, Boca Raton, Florida, p. 472, 494
2. R. B. Dinwiddie (2001) measurements on the test discs used in this work at ORNL.
3. T. Walker, M. Purdy, S. Vaidvaraman, M. Black, S. Horst, "CCAB Test Program," pres. Amer. Cera. Soc. Conference, Cocoa Beach, Jan 2001.
4. Measured at ORNL by B. C. Jolly (2004)
5. H. Wang (2004) measurements on test discs used in this work at ORNL.
6. Supplier data, for flow in the direction perpendicular to the surface, value more than twice that is obtained for heat flow in the plane of the disc (120-150 W/m-K).

4.0 FRICTION TEST METHOD

The sub-scale brake testing apparatus (SSBT), Fig. 1, was designed to conduct sliding friction and wear studies on experimental, non-traditional brake materials. It uses a flat-faced square (12.7 x 12.7 mm) block loaded against a spinning disk (127 mm diameter and 16 mm thick). Prior to testing, the turned sliding faces of the discs were finished on 120 grit alumina abrasive paper. The lay of the abrasion marks was in the circumferential direction, as they would be in a turned disc brake rotor. An initial set of drags at 150 N normal force (approximately 1 MPa) was used to run-in the test surfaces. Typically two normal forces, 150 or 300 N, were used. Typical sliding speeds in theses experiments were 2, 6, 10, and 15 m/s.

Friction force was measured by the load cell connected to the pivoting arm. It was converted to friction coefficient by dividing by the instantaneously measured normal force and was recorded during the test. The disc surface temperature was measured by an infrared temperature probe with a 3 mm spot size aimed at the center of the wear track at approximately the 1 o'clock position while the pad was at the 9 o'clock position (clockwise rotation). Previous tests with an IR camera indicated a negligible temperature difference between the sensor's field of view and the area just outside the contact area of the pad. The data collection rate was either 64 or 128 data per second. Emissivity data were obtained for each test disc material and used to calibrate the IR probe. Typical tests involved five constant speed drags of 20 seconds with 10 seconds between each drag. The temperature tended to ratchet up since 10 seconds was not sufficient to cool the disc surface back to room temperature between drags. Thus friction coefficient could be obtained over a range of temperatures. There is often a concern that subscale tests do not correlate with full-size component tests, so a comparison of SSBT friction data with that calculated from standard dynamometer tests is presented in the Appendix.

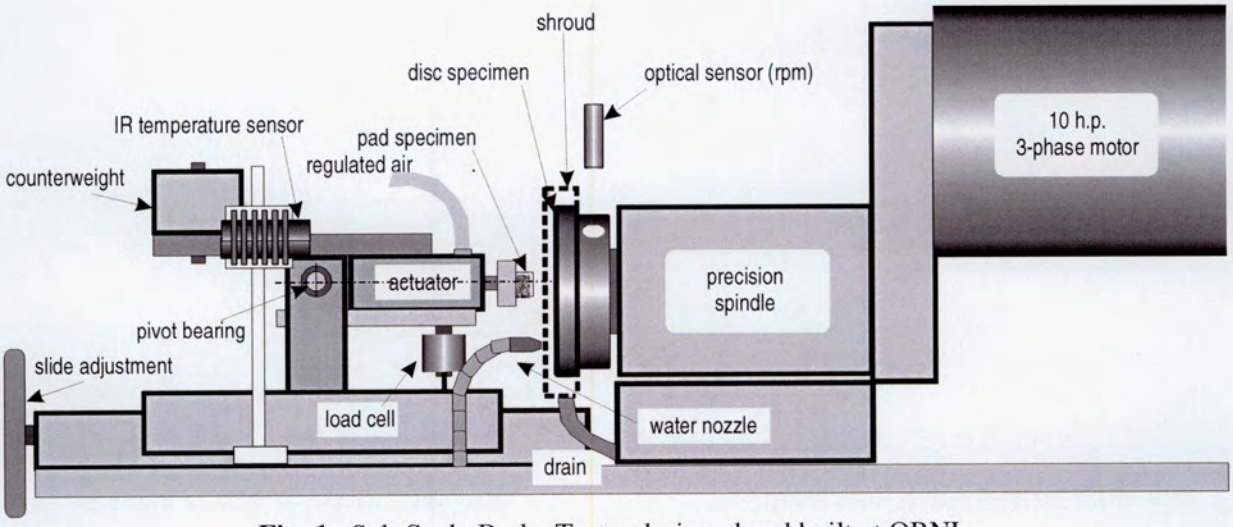

Fig. 1. Sub-Scale Brake Tester designed and built at ORNL.

5.0 FRICTION AND TEMPERATURE DATA

The friction coefficient is defined as the dimensionless ratio of the force opposing relative motion between to contacting bodies to the (normal) force holding the bodies together. Friction coefficients were obtained for a variety of material combinations, sliding speeds and contact pressures. These data are presented in the following sections and arranged by disc material. Gray cast iron with various commercial friction materials sliding against it was used as the reference material with which to compare the other disc materials that were evaluated in these experiments.

5.1 *Friction Data for Cast Iron Discs – Baseline Data*

Friction coefficients for various sliding speeds and pad materials are shown in Figs. 2 and 3. Typical kinetic friction coefficients for automotive and truck brakes are in the range 0.30 – 0.55, but values outside this range are not uncommon. This range seems to agree with the SSBT test results shown in Figs. 2 and 3. Note that Armada materials are designed for drum brakes and that the Performance Friction materials are marketed for high-performance automotive disc brakes. Jurid 539 is the only material tested that was specifically designed for air disc truck brakes. In some of the figure legends that follow, the abbreviation GCI is sometimes used to refer to gray cast iron.

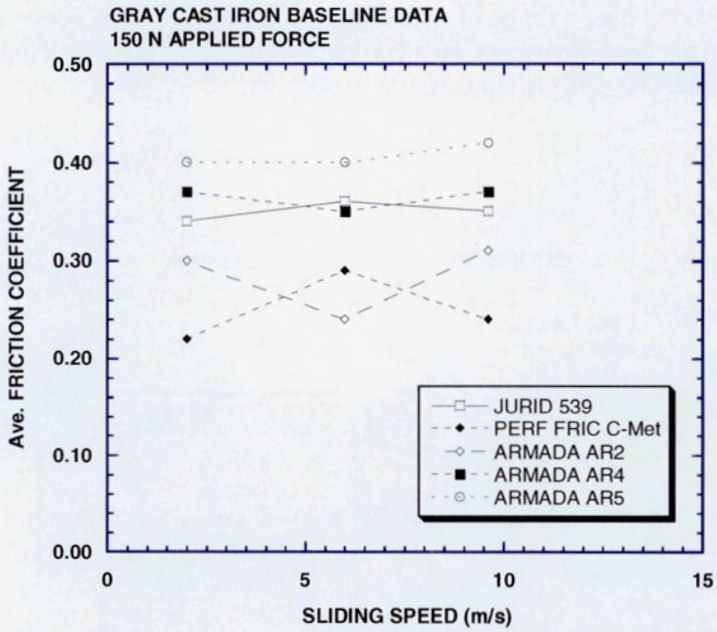

Fig. 2. Average friction coefficient per drag for cast iron discs at 150 N normal force.

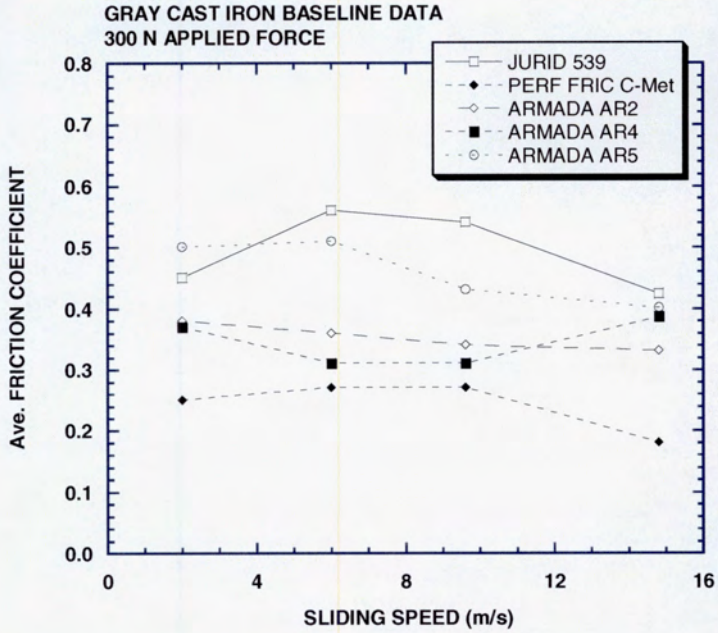

Fig 3. Average friction coefficient per drag for cast iron discs at higher normal force (300 N). Each datum is the average of five drags.

As shown in Figs. 2,3, the Jurid 539 lining produced the highest friction coefficients against cast iron. At the higher applied force, there was an indication of a drop in friction at the highest sliding speed, and that kind of behavior is suggestive of the phenomenon known as fade.

5.2 *Friction Data for Ceramic-Based Discs*

Earlier tests were conducted on C/SiC materials, during a collaborative research project with GE Power Systems. The heterogenous internal structure of the disc materials is shown by the IR image of a disc taken at 140°C (Fig. 4.) It was found in ORNL tests and in tests performed at a contract testing laboratory that self-mated combinations of such materials, however, tended to give reasonable friction results. A C/SiC pad rubbing against C/SiC or against gray cast iron produces different frictional behavior after many drags (see Fig. 5). At higher numbers of drags, the friction of the self-mated combination seems to be almost 50% higher than that for the C/SiC pad against cast iron. Data comparing repeated drags of the Jurid 539 lining on cast iron with self-mated C/SiC is shown in Fig. 6.

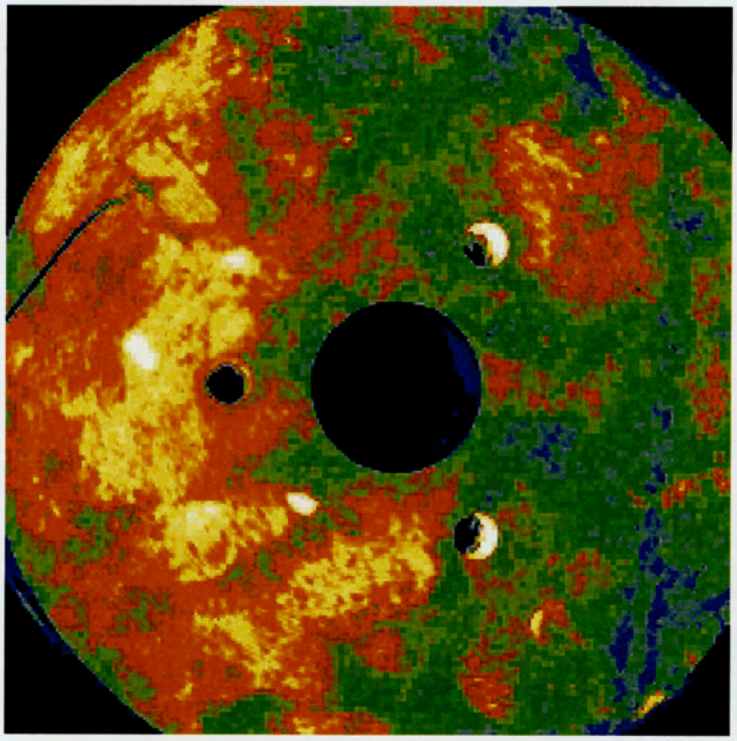

Fig. 4. Infrared image of a C/SiC disc specimen heated by a hot plate to 140° C. The center mounting hole is 25.4 mm in diameter and the overall disc diameter is 127 mm.

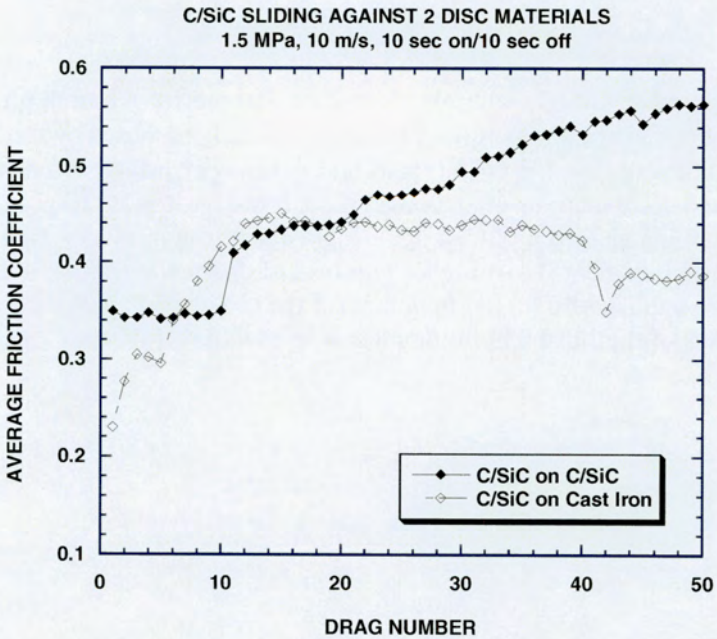

Fig 5. Average friction coefficient per drag for C/SiC pads sliding against two disc materials.

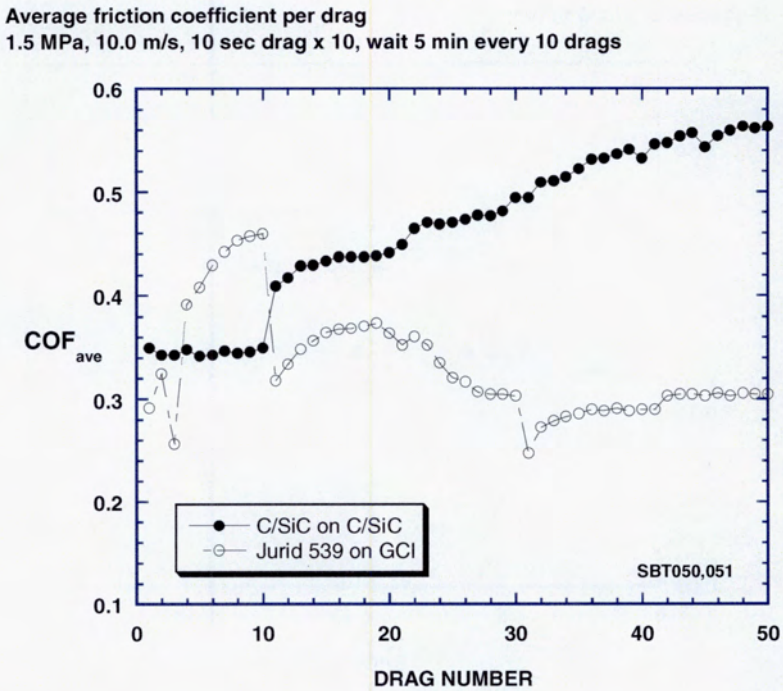

Fig. 6. Friction versus drag number for self-mated C/SiC materials and Jurid 539 on cast iron.

The average friction coefficient per drag (5 drags) as a function of sliding speed for the Starfire Systems ceramic composite material and for gray cast iron (GCI) discs are shown in Figs. 7 and 8. The material pairs are identified in the legend.

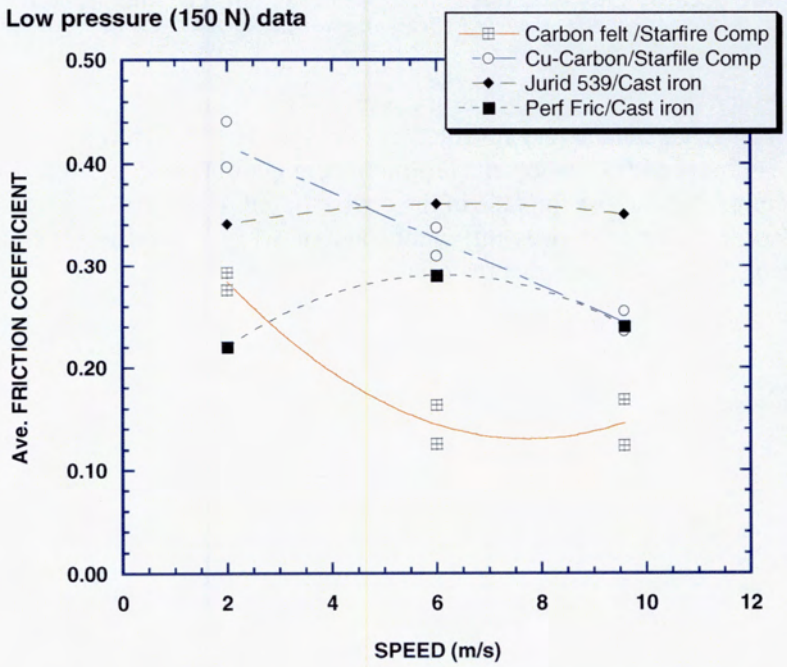

Fig 7. Effect of sliding speed on the friction of a ceramic composite at 150 N force.

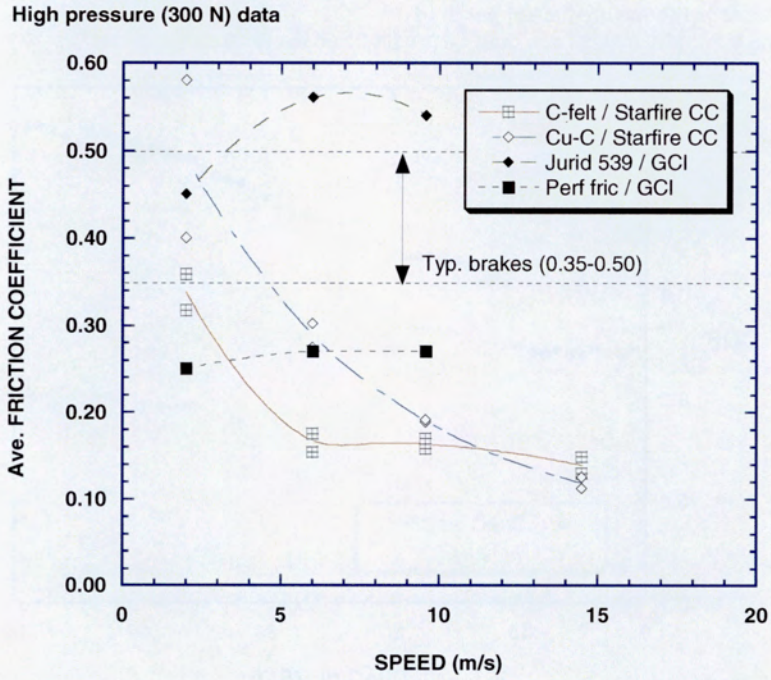

Fig 8. Effect of sliding speed on the friction of a ceramic composite at 300 N force.

Most data from Figs. 7 and 8 indicate a significant reduction in the sliding friction coefficient as the speed increases. This result was unexpected since other silicon carbide/carbon materials tested previously under self-mated conditions (GE Power Systems material) maintained the friction level even as the severity of the sliding conditions (speed and pressure) increased. Friction values at the higher sliding speeds are problematic for braking because they would require considerable force (line pressure) to maintain an effective level of stopping torque.

A summary of the friction data for the SiC/Si disc materials (Redunndant Materials) is given in Fig. 9. While friction coefficients are satisfactory for intermediate speeds, the high force low speed friction values are too high. High-speed friction results (15 m/s) were not obtained because one of the disc specimens cracked completely across the face in the course of conducting a 10 m/s test. The cause of the fracture was not determined, but there was sufficient concern over the presence of brittle phases in the micro-structure to defer further tests on this material.

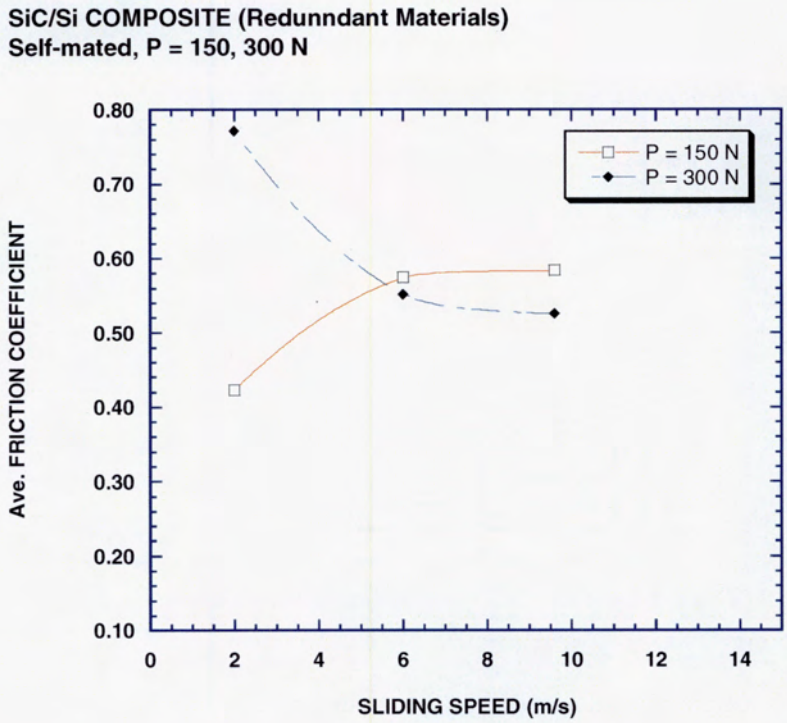

Fig 9. Friction coefficient for self-mated SiC/Si material at two normal forces.

5.3 *Friction Data for Titanium-Based Discs*

Data from tests with bare Ti-6Al-4V alloy provided by Titanium Metals Corporation (TIMET), sliding against Jurid 539, are shown in Fig. 10. The friction coefficient of this material combination tended to decrease with increasing sliding speed, but generally fell within the normal range for brakes. Wear rates, however, were unacceptable and the ignition/sparking of the wear particles was observed in higher-energy braking tests. It was concluded that bare titanium would not provide an acceptable friction surface. Thus, two alternatives: coated titanium and titanium composite materials were considered instead.

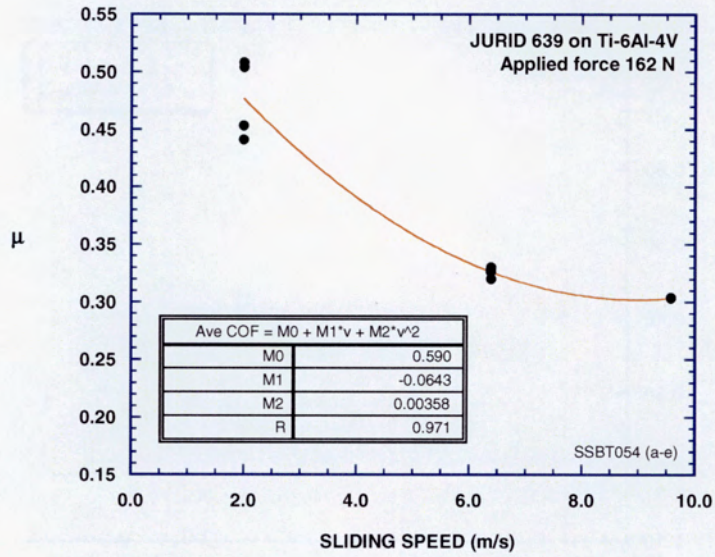

Fig. 10. Effect of sliding speed on the friction of Ti-6Al-4V against Jurid 539.

Friction coefficient data for CermeTi C-10, a Ti-based composite material, running against two friction materials at two levels of applied force are shown in Fig. 11. There is an apparent improvement in the friction level as the speed increases (c.f. Fig 6 for the Ti-6Al-4V). The Jurid material had higher friction than the Performance Friction lining material at all speeds and normal forces.

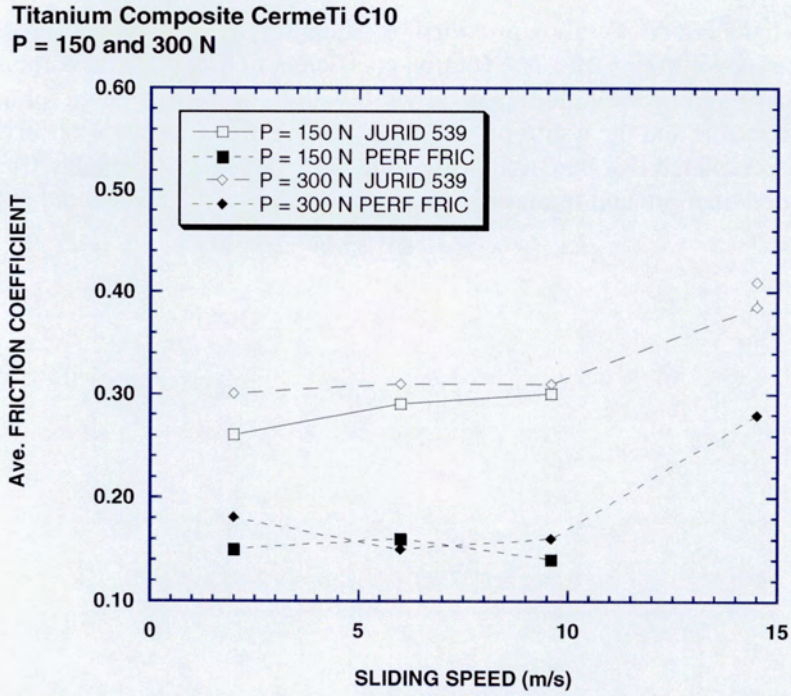

Fig. 11. Effect of sliding speed on average friction per drag for two lining materials on CermeTi C-10.

Friction and wear tests of Ti-based alloy discs coated using a proprietary thermal stray process have been conducted, but specific test data on those discs will be reported later. Results, however, indicated a marked sensitivity of the friction coefficient to temperature. Therefore, thermal management seems to be a general concern for using advanced brake materials, whether dealing with ceramic composites or Ti-based materials.

5.4 *Temperature Data*

The temperature of the contact surfaces of the disc was measured by a 3 mm spot diameter IR probe (emissivity calibrated) aimed at the wear path approximately 120 degrees away from the contact point. For a given testing system, the friction-induced temperature rise is usually linearly related to the amount of frictional work done during sliding. The work is the product of the friction force and the sliding distance, expressed in N-m or Joules. For different disc/pad material combinations, the frictional work is distributed differently between the disc and pad. This effect is shown in Fig. 12 for two pad materials sliding on cast iron. Note that the speed of sliding affects the rate of frictional energy input but the distance of sliding provides the total frictional work. Since the relationship between work and temperature rise is basically linear, we can define a parameter that can be used to portray how efficiently certain material combinations convert friction into heating the disc surface. In our experiments, the frictional heating parameter (Φ) seems to be relatively constant for a given material pair – irrespective of load and sliding speed. It is therefore defined as follows:

$$\Phi = \frac{\Delta T}{W} = \frac{\Delta T}{Fx} = \frac{\Delta T}{\mu P v t} \qquad (1)$$

where, ΔT = the measured temperature rise during the drag (°C), W = frictional work (J), F = friction force (N), x = sliding distance per drag (m), P = applied normal force (N), μ = friction coefficient, v = velocity of sliding (m/s), t = time of sliding (s). Values of the frictional heating parameter for the materials tested in this work were measured in a number of experiments and are listed in Table 6. Note that these values are of the order of 10^{-2} to 10^{-3} oC/J but there is a considerable difference for different material pairs. The higher the frictional heating parameter, the hotter the disc gets for a given level of frictional energy input.

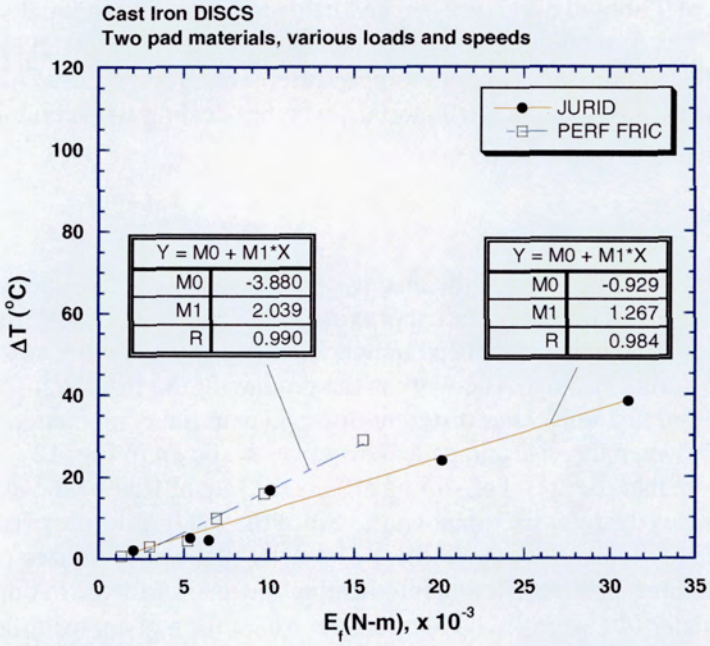

Fig. 12. Frictional work versus rise in disc wear track temperature for cast iron tests.

Table 6
Frictional Heating Parameter (Φ) for Various Pad and Disc Combinations

Disc	Pad	Number of tests	(k_{th}) disc (W/m-K)	Average Φ 10^{-3} (°C/J)	Std. Dev. Φ 10^{-3} (°C/J)
Cast iron	Jurid 539	7	42. - 57.*	1.18	0.39
	Armada AR2	7		1.28	0.09
	Armada AR4	7		1.04	0.29
	Armada AR5	8		1.09	0.21
	Perform. Friction Carbon Metallic	7		1.23	0.53
CermeTi C-10 (Dynamet)	Jurid 539	8	8.21**	6.33	1.21
	Performance Friction Carbon Metallic C-10	8		6.33	1.42
SiC Ceramic (Starfire Systems)	Carbon-Copper	14	3.11 – 3.26 ****	11.94	4.09
	Carbon-Felt	14		20.84	4.87
	Perform. Friction Carbon Metallic	4		17.44	3.59
SiC/Si (Redunndant Mat.)	SiC/Si (Redunndant Mat.)	6	50-70 (X-Y)*** 120-150 (Z)***	2.52	0.31

*P. Blau, compiled data from "Compositions, Functions and Testing of Brake Materials and Their Additives," ORNL TM 2001-64, Oak Ridge National Laboratory, (2001).
**Measured by H. Wang, ORNL, with the transient plane source method (hot disc)
***Supplier data
****Measured by H. Wang, ORNL, with the one side method (3.114) and two-disk method (3.260)

Table 6, has a number of interesting features. For example, there is a significant difference in Φ between the two ceramic composites. The SiC/Si (Redunndant Materials) runs considerably cooler than the SiC composite from Starfire and had a much lower standard deviation in Φ. In contrast to the C/SiC Starfire composite whose Φ varies considerably from one pad material to another, the baseline cast iron stays cool for a given level of frictional work input and is least affected by the choice of pad material. With regard to the two Ti-based materials, the coated disc has only slightly lower thermal conductivity than the CermeTi composite yet it is more than 2.5 times more efficient in converting frictional work into disc surface heating. Therefore the parameters shown in Table 6 do not provide enough information to reach a conclusion.

There is no clear universal relationship between Φ and k_{th} of the disc material, but the lower thermal conductivity discs tend to have higher Φ. Measurements of the k_{th} of the pad materials are planned and that information will help to address pad/disc heat partitioning in more detail.

The relationship between the disc surface temperature and the frictional behavior is generally non-linear for the majority of materials tested. Extensive temperature data exists for each SSBT test, but in this report a few selected examples are presented to illustrate the behavior of the major disc materials.

Ceramic-Based Discs. Figs. 13 and 14 show the average disc surface temperature rise per drag for Starfire Systems ceramic composites compared with cast iron discs at different contact forces. This type of non-linear behavior was typical and illustrates the complexity of the balance between heat generation, partition into the pad and disc at different temperatures, and cooling of the disc surface. Data from pairs of tests (scatter) seems relatively narrow so trends appear real.

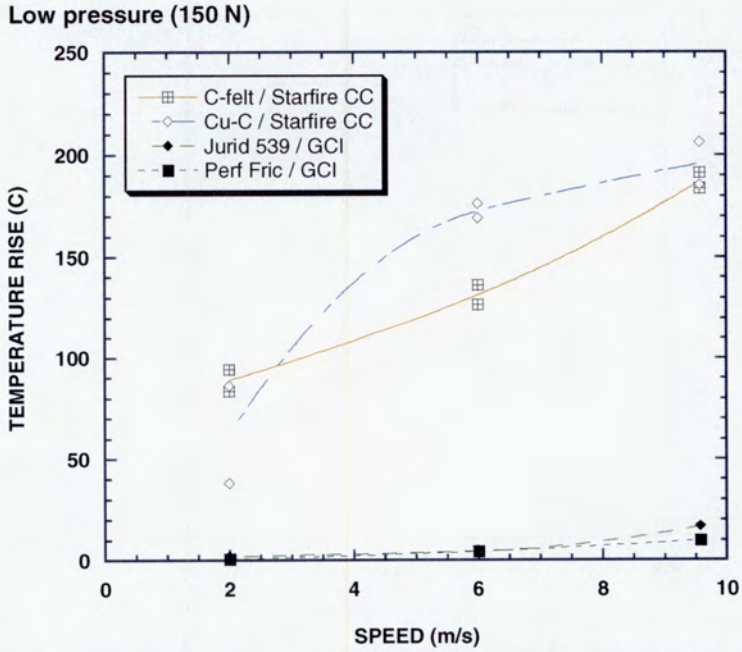

Fig. 13. Effect of sliding speed on temperature for ceramic composite and cast iron discs at 150 N load.

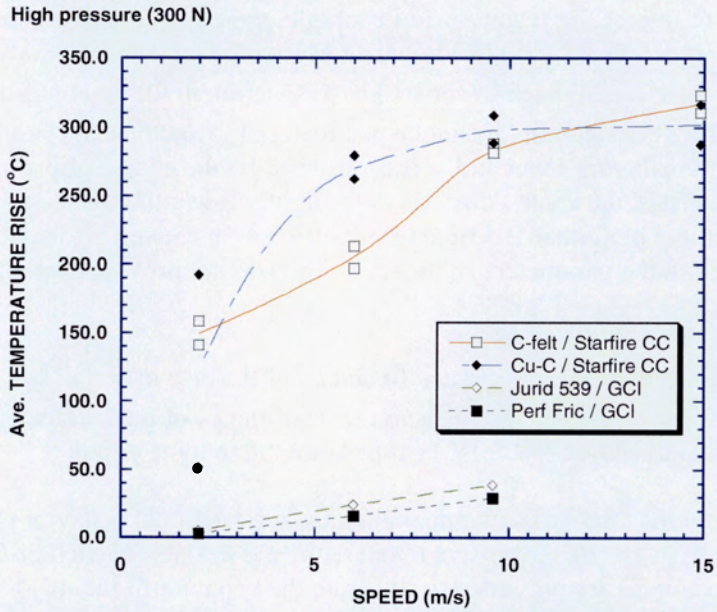

Fig. 14. Effect of sliding speed on temperature for ceramic composite and cast iron discs at 300 N load.

Titanium Alloy Discs. The temperature rise associated with the sliding speed was more linear in the case of bare titanium alloys. The two alloys (Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo), obtained in billet form from TIMET Corp. and machined into test discs, were finished to 120 grit and tested against Jurid 539 at 150 N force. Results are shown in Fig. 15. There was more test-to-test variation at higher speed.

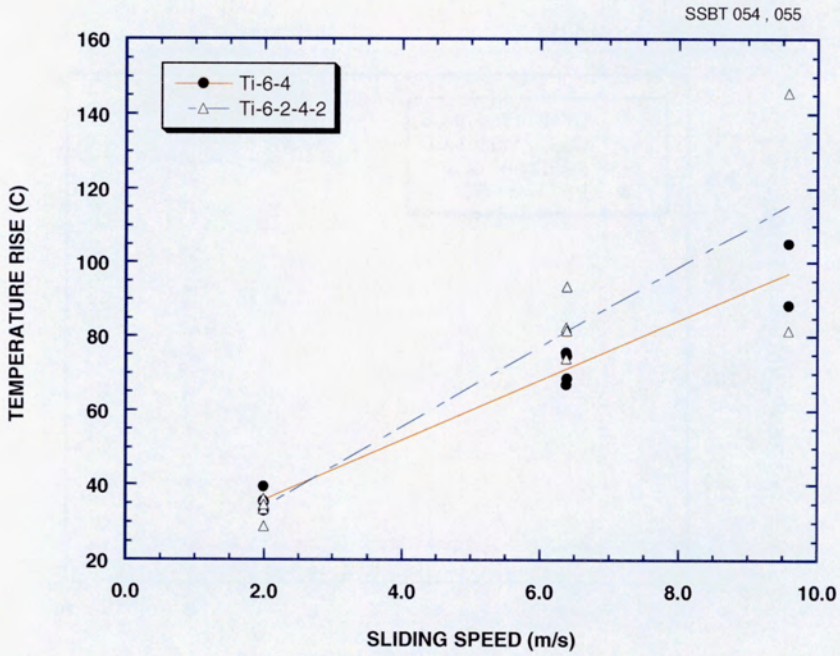

Fig. 15. Disc temperature rise as a function of sliding speed for bare Ti alloys.

For the Ti-6Al-4V alloy, the temperature rise was approximately 8.1 degrees C for every 1 m/s increase in sliding speed. For the other alloy it was about 10.7 degrees per m/s.

Temperature rise results for other Ti-based materials are summarized in Fig. 16. Temperature rises per unit increase in speed were least for cast iron discs (open symbols) and highest for the titanium alloys (solid symbols). The Performance Friction pads tended to have lower friction than the Jurid 539 pads against a given disc material.

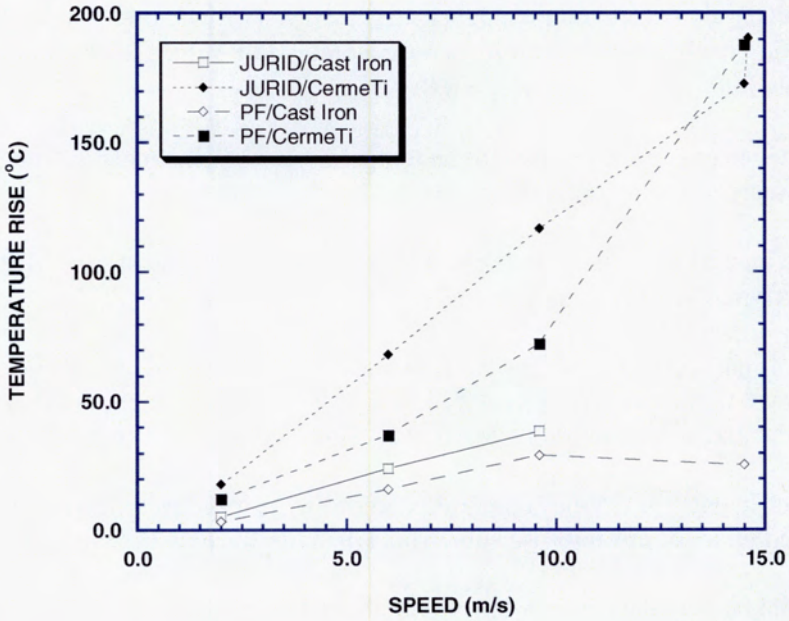

Fig. 16. Average temperature rise per 20-second drag versus sliding speed data for Ti-based and cast iron test discs.

6.0 SUMMARY AND CONCLUSIONS

More than 130 tests and test series were conducted with the ORNL sub-scale brake material testing apparatus on a variety of traditional and experimental brake materials. Various trends in material behavior could be observed.

- Despite a relatively narrow range in test loads and a somewhat wider range of sliding speeds, kinetic friction coefficients ranged from unacceptably low values of about $\mu = 0.1$ to unacceptably high values of about $\mu = 0.8$.

- The dependence of friction coefficient on temperature was non-linear and no general relationships could be discerned for the range of materials.

- For tests on bare Ti alloys and for tests on Starfire SiC discs against several slider materials, the friction coefficient tended to decrease as sliding speed increased.

- Tests on self-mated SiC/Si composites at two different forces and sliding speeds of 6-10 m/s gave relatively level friction coefficients (0.5-0.6), but at low pressures the friction coefficient at 2 m/s was about 0.4 and at high pressure nearly 0.8. The disc specimen cracked through the Si phases.

- Friction coefficients for CermeTi titanium composite material were relatively insensitive to sliding speed up to 10 m/s but rose somewhat when the speed was nearly 15 m/s.

- The frictional heating parameter was used to characterize the efficiency by which frictional work was converted into disc surface temperature rise. On this basis, cast iron discs remained coolest irrespective of the sliding partner and the Starfire Ceramic Discs had the highest tendency to convert available frictional energy to disc heat.

The test results described here summarize a larger volume of information developed on candidate friction materials over the past several years. They reveal some important trends and raise engineering considerations, and the data will be used to further down-select promising truck brake disc materials. Pad material selection remains a significant problem since the right pad can make all the difference between an effectively-performing disc and an unsatisfactory one. Pad/disc compatibility will be a subject for further study and analysis. When suitable combinations are determined, the next step in development will be subjecting full-sized components to inertia dynamometer trials.

7.0 REFERENCES

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[4] D. F. Wilson, E. A. Kenik, and P. J. Blau (2002) *Evaluation of Corrosion Failure in Tractor-Trailer Brake System*, ORNL tech. report. ORNL/TM-2002/161, 21 pp.

[5] ASM Handbook (1987) Vol. 13, Corrosion, ASM International, Materials Park, OH, p. 570.

[6] D. W. Stough (1956) "The Corrosion of Titanium," Titanium Metallurgical Lab. Rept. No. TML 57, Battelle Memorial Institute, Columbus, OH, pp. 109-111.

[7] Ref. 5, p. 860.

[8] Ref. 5, p. 675.

[9] V. Kevorkian (2002) "Ceramic Brake Rotor for Passenger Cars," Amer. Ceramic Society Bulletin, Vol. 81 (4), pp. 27-29.

[10] Website: http://www.starfiresystems.com

[11] Website: http://www.movit.de/

APPENDIX A

COMPARISON
ORNL TEST DATA WITH FULL SCALE DYNAMOMETER DATA

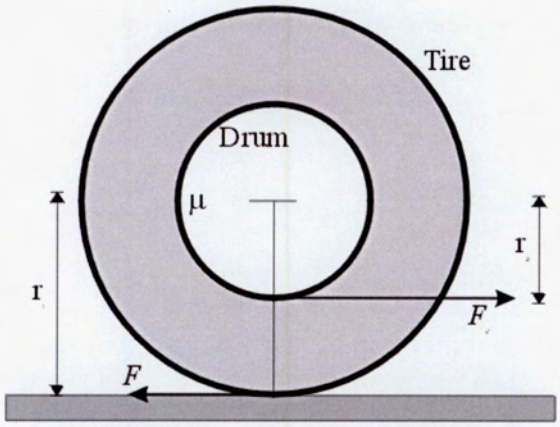

Fig. A1. Forces and radii for the drum and tire.

To check the reasonableness of SSBT data, we compared data obtained for drum-type brakes using standard industry protocols with friction coefficients we obtains on the same lining materials. The braking force F_b at the tire/pavement interface can be calculated from the following quantities (see also Fig. A1):

p = air line pressure (psi)
A = cross-sectional area of the actuator (in2)
S = length of the slack adjuster (in)
r_d = radius of the brake drum (in)
r_c = radius of the cam (in)
r_t = mean static rolling radius of the tire (in)
μ = mean friction coefficient

in addition, we define

F_d = reaction force on the drum due to friction (lbs-f)
T = braking torque (in-lbs)
P_d = effective normal force acting on the drum (lbs-f)

The standard equation for braking force, using the above nomenclature, is:

$$F_b = \frac{2pAS\mu r_d}{r_c r_t} \tag{1}$$

From the equations of static equilibrium, and the definition for torque, we have

$$T = F_b\, r_t = F_d\, r_d \tag{2}$$

Equation (1) can be rearranged as,

$$F_b r_t = T = \frac{2pAS\mu}{r_c} r_d \tag{3}$$

and,

$$F_d = \frac{2pAS}{r_c}\mu \tag{4}$$

From the definition of the friction coefficient we can find the equivalent normal force,

$$\mu = \frac{F_d}{P_d} \tag{5}$$

and, therefore,

$$P_d = \frac{2pAS}{r_c} \tag{6}$$

We can estimate the friction coefficient for the lining against the drum from:

$$T = F_d r_d = \mu\left(\frac{2pAS}{r_c}\right) r_d \tag{7}$$

or rearranging,

$$\mu = \left(\frac{T}{p}\right)\left(\frac{r_c}{2ASr_d}\right) \tag{8}$$

The first factor on the r.h.s. is the ratio of the torque to the line pressure, and the dimensions of the mechanical components are grouped into the second factor, which we can call "KA", where A is the chamber size.

$$\mu = \mathrm{KA}\ (T/p). \tag{9}$$

For a typical S-cam drum with a 30 in2 chamber or a 24 in2 chamber, the constant K becomes*

$K_{30} = 0.0001837$ $\qquad$ $K_{24} = 0.0002296$

<u>Example</u>: For a lining having a measured (dynamometer test) torque of 60,000 in-lbs at 40 psi, with a Type 30 chamber, the friction coefficient is:

$$\mu = 0.0001837\left(\frac{60{,}000}{40}\right) = 0.276$$

Fig. A2, on the following page, is a plot of the ratio of (T/p) to friction coefficient for two chamber sizes. It is also possible to estimate the torque produced at a given air line pressure and friction coefficient:

$$T = \mu p / K_A \tag{10}$$

A plot of torque for a range of μp products is given in Fig. A3.

*Note: assumes that $S = 5.5$ in, $r_d = 8.25$ in, $r_c = 0.5$ in, $r_t = 19.2$ in

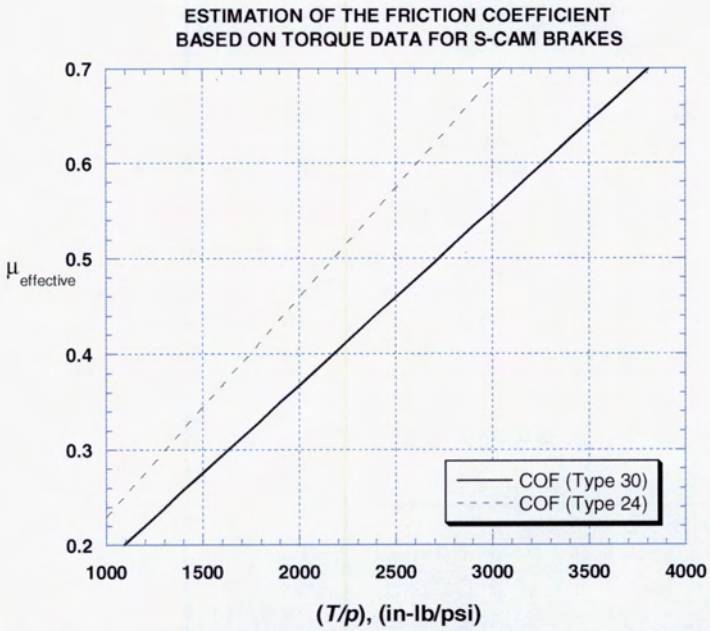

Fig. A2. Estimate of brake lining friction coefficient based on the ratio of the torque to the air pressure.

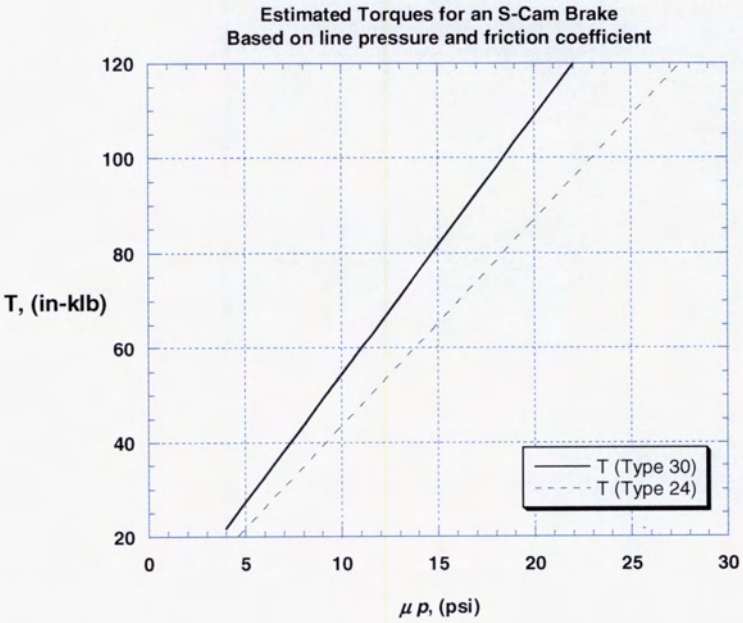

Fig. A3. Estimate of torque from the product of friction force and line pressure.

Correlation of ORNL Subscale Dynamometer Data with Calculated Torques. Data from test runs of AR2, AR4 and AR5 linings against cast iron were conducted previously. Friction coefficients for these runs, measured under several different contact conditions are compared with the calculated friction coefficients based on published TMC RP 628 data for 40 psi line pressure for the same linings. The test conditions highlighted in bold match are within (+/- 0.05) of the friction coefficients calculated from the reported RP 628 torque values. The last column on the right is the difference between the ORNL measurements of friction and those calculated from RP628 torque data, expressed as a percentage. Those with differences less than 10% are highlighted in bold.

Table A1
Comparison of SSBT Test Data with Calculated Friction Coefficients from FMVSS 121 Dynamometer Data.

Lining Material	**Test conditions**	**Reported T** (40 psi air pressure) (in-lb)	**Calculated μ** from Eqn. (9) or **Measured μ** from SSBT	**Difference** Measured μ vs calc μ (%)
Armada AR-2	FMVSS 121 dyno	58,581	0.269	
	ORNL SSBT 3.2 MPa, 1.9 m/s		0.312	16.0
	ORNL SSBT 3.2 MPa, 6.0 m/s		**0.283**	5.2
	ORNL SSBT 3.2 MPa, 10.0 m/s		0.318	18.2
	ORNL SSBT 4.6 MPa, 2.0 m/s		**0.269**	0.0
	ORNL SSBT 5.1 MPa, 6.0 m/s		0.297	10.4
	ORNL SSBT 5.1 MPa, 10.0 m/s		0.327	21.6
Armada AR-4	FMVSS 121 dyno	64,716	0.297	
	ORNL SSBT 2.5 MPa, 1.9 m/s		**0.303**	2.0
	ORNL SSBT 2.5 MPa, 6.0 m/s		**0.278**	6.4
	ORNL SSBT 2.6 MPa, 10.0 m/s		**0.306**	3.0
	ORNL SSBT 5.6 MPa, 2.0 m/s		0.251	15.5
	ORNL SSBT 5.6 MPa, 6.0 m/s		0.262	11.8
	ORNL SSBT 5.6 MPa, 10.0 m/s		0.343	15.5
Armada AR-5	FMVSS 121 dyno	79,678	0.366	
	ORNL SSBT 4.4 MPa, 1.9 m/s		0.416	13.7
	ORNL SSBT 4.4 MPa, 6.0 m/s		0.432	18.0
	ORNL SSBT 3.2 MPa, 10.0 m/s		0.472	29.0
	ORNL SSBT 10.7 MPa, 2.2 m/s		**0.395**	7.9
	ORNL SSBT 8.5 MPa, 6.5 m/s		0.419	14.5

The friction coefficients we 'back-calculated' from torque data seemed slightly lower than one might expect from the edge codes ratings, but on the other hand, edge codes are determined from the FAST procedure and might not correlate with lining performance on a dynamometer test.

Acronyms

FAST Friction Assessment and Screening Test, a laboratory scale pad on disc test, described in SAE standard J 661.

SSBT The ORNL sub-scale brake materials testing system

TMC RP 628 A test method primarily developed for aftermarket drum brake lining stopping torque and published as a recommended practice by the Technology and Maintenance Council. It is based on the dynamometer portion of the more comprehensive Federal Motor Vehicle Safety Standard 121.

Type 24, 30 This designation refers to the air brake actuator piston area in square inches.

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