Generating a Representative Sample of Brake Pad Wear Debris

Brake Manufacturers Council
Product Environmental Committee

January 27, 2006

Table of Contents

I. Introduction

II. Purpose

III. “Representative” Sample

IV. Analysis of the Prevalence of Copper

V. Material Selection Process

VI. Generation of Representative Samples

VII. Results

VIII. Discussion: Strengths and Limitations

IX. Summary

X. Contacts

XI. Appendices

A. Disc Brake Wear Debris Generation and Collection Protocol

B. Brake Dynamometer Test Report, Link/D99079A1, December 1, 2004

I. Introduction

This document summarizes the Brake Manufacturers Council's (BMC) methodology for generating a sample of brake pad wear debris (BPWD) for use by the Brake Pad Partnership for the purposes of characterizing the physical and chemical characteristics of the resultant material. The Brake Pad Partnership (BPP)[1] is conducting a set of interlinked technical studies to understand the potential role of copper from BPWD on the short- and long-term concentrations of copper in the San Francisco Bay. This methodology was developed in support of that effort with technical input and analysis from the Brake Manufacturers Council-Product Environmental Committee (BMC-PEC) in close consultation with the BPP Steering Committee.

II. Purpose

At the core of the BPP's effort to understand the transport and fate of copper from automobile BPWD in the environment are three computational models that simulate the movement of copper through the air, within the watershed, and in the bay. To provide input parameters for these models, the BPP has conducted stormwater quality monitoring and air deposition monitoring. The BPP is using the results of the physical and chemical characterization of the BPWD generated through the process described here to

1. Augment existing data on the aerodynamic particle size diameter of BPWD for use in the air deposition modeling effort;
2. Augment existing data on total copper in BPWD from the types of pads used in this sample to support the effort to estimate copper from vehicle brake sources;[2] and
3. Enhance the BPP's conceptual understanding of the potential for copper leaching from BPWD in the environment.

III. "Representative" Sample

Given the BPP's funding and time constraints, and the need to protect individual brake pad manufacturing companies' proprietary information, the BPP asked the BMC-PEC to develop a single sample of BPWD for chemical and physical characterization analyses. The BPP determined that its purposes would be served best by generating a sample that was representative with respect to (1) the types of driving conditions under which BPWD is produced in the San Francisco Bay Area, and (2) copper-containing brake pads.

A variety of factors can affect the generation of BPWD, including the type and composition of the brake pad, the type of vehicle, variable brake temperatures under different driving conditions,

---

[1] The Brake Pad Partnership is a collaborative effort to understand the impacts on the environment that may arise from brake pad wear debris generated in the use of passenger vehicles. Working together, manufacturers, regulators, stormwater management agencies, and environmentalists are developing an approach for evaluating potential impacts on water quality, using copper in the South San Francisco Bay as an example. Friction material manufacturers have committed to adding this evaluation approach to their existing practices for designing products that are safe for the environment while still meeting the performance requirements demanded of these important safety-related products. More information on the Brake Pad Partnership can be found at: http://www.suscon.org/brakepad/index.asp.

[2] All kinds of vehicles use brakes, including trains, airplanes, motorcycles, cars, light- and heavy-duty trucks, and off-road vehicles. For the purposes of its modeling efforts, the BPP developed source estimates of copper from all types of vehicles relevant to the study watershed: Rosselot, Kirsten Sinclair 2005. "Copper Released from Brake Lining Wear in the San Francisco Bay Area." Prepared for the Brake Pad Partnership by Process Profiles, Calabasas, California. May 2005. Available at: http://www.suscon.org/brakepad/pdfs/EstimatingCopperLoading_from_BrakeSourcesFinalReport.pdf.

and the frequency and intensity of braking. In 2002, the BMC in collaboration with the BPP completed the development of the Wear Debris Generation and Collection Protocol,[3] a reproducible, laboratory protocol for generating BPWD representative of that produced under on-road driving conditions. The protocol involves the use of a brake dynamometer—a laboratory machine that simulates on-road vehicle braking conditions—that is set up to allow the collection of the BPWD. The dynamometer protocol simulates the Los Angeles City Traffic (LACT) test, a mix of city and freeway driving that is considered to be sufficiently similar to driving conditions in the San Francisco region for the purposes of the BPP. Thus, to attain a BPWD sample that is representative with respect to the driving conditions under which BPWD is produced in the San Francisco Bay Area, the BMC and BPP opted to use the existing protocol.

Since its inception in 1996, the BPP has focused on Original Equipment Manufacturer (OEM) brake pads used on cars and light-duty trucks because this is the segment of the market for which the most significant amounts of copper were being used, and for which copper usage was anticipated to increase as manufacturers reformulated their products to meet the Federal Motor Vehicle Safety Standards which came into effect in 2000. OEM pads are ones that come on new vehicles, and do not include "aftermarket" or replacement pads. Not all OEM brake pads contain copper, however, and those that do can have different forms of copper as their initial ingredients. The following sections of this document explain how the copper-containing OEM brake pads were selected for generating the representative sample of BPWD.

IV. Analysis of the Prevalence of Copper Forms

A variety of forms of copper are used in brake pad formulations, including copper fiber, copper powder, brass fiber, brass powder, copper with organic complexes, copper sulfide, as well as other forms of copper compounds. The Copper Use Monitoring Program[4] reports on total copper used, and does not differentiate between different forms of copper.

Since the goal of the effort was to develop a sample of BPWD that is representative with respect to copper, it was important to understand the relative prevalence of the various forms of copper in use. Thus, the BMC-PEC conducted a follow-up survey of the manufacturers who reported on copper use in brake pads for model year 2002 (the most recent model year for which data were available), to determine the extent to which different forms of copper are being used.

---

[3] J. Trainor, T. Duncan, and R. Mangan, Disc Brake Wear Debris Generation and Collection, 2002-01-2595, SAE Technical Paper Series, SAE International, Warrendale, PA, 2002.

[4] As a part of the brake manufacturing industry's participation in the Brake Pad Partnership (BPP), the BMC-PEC voluntarily reports on the amount of copper used in OEM automotive friction materials (i.e., friction materials used in cars and light trucks, and not friction materials used on heavy-duty trucks, off-road vehicles, or motorcycles) on an annual basis. Information is compiled as part of the Copper Use Monitoring Program. "Friction materials" include disc brake pads (on front and rear brakes) and drum brake linings (on rear brakes only). The data are based on manufacturers' reporting of the actual copper content of their products. These data are collected and made available by the BMC-PEC in a manner that protects manufacturers' confidential business information, including the copper content of friction materials on specific new vehicles and the name of the manufacturer that supplies the friction materials. The BMC-PEC collects data for the top 20 to 25 best-selling vehicles, which comprise approximately 40% of the new cars and light trucks sold in the United States: Brake Pad Partnership 2004. Copper Use Monitoring Program Results for Model Years 1998 – 2002. Available at http://www.suscon.org/brakepad/pdfs/CuUMPFinalReport.pdf.

The BMC again used confidential reporting methods to protect the manufacturers' proprietary business information. The BMC-PEC member companies submitted information on the forms of copper used in each application to the BMC. The BMC then presented the PEC members with the data showing: (1) the materials letter code, (2) the percent of copper, (3) the form of copper, and (4) the percent of the top 20 sales volume that the material represented.

The copper types represented in the sample of wear debris are found in Table 1. Table 1 presents the aggregate results of the BMC-PEC survey of copper forms used. This table illustrates that the predominant forms of copper in brake pads are copper fiber and copper powder.

Table 1. BMC-PEC Copper Forms Survey for Model Year 2002 (99.09% Reported)

Forms of Copper	Fiber	Powder
Copper Fiber	●	
Copper Powder		●
Brass Fiber		
Bronze Powder		
Copper Fiber & Copper Powder	●	●
Copper Fiber & Organic Complexes	●	
Copper Powder & Bronze Fiber		●
Copper Powder & Copper Sulfide		●
Bronze Powder & Copper Sulfide		
Copper Fiber, Copper Powder & Organic Complexes	●	●

The BMC-PEC conducted a Pareto Analysis[5] on the survey data to mathematically determine the prevalence of the different copper forms in use. Pareto Analysis is a formal technique used to show the relative importance of differences among data. Table 2 contains the results of the Pareto analysis, which show that copper fiber use amounts to between 76.04 and 86.68% of the copper use, and copper powder amounts to between 2.38 and 13.85% of the copper use. Other forms of copper amount to between 0.00 and 5.30% of the copper use. Choosing friction materials containing copper in the forms of fiber and powder covers > 95 % of the copper compounds utilized in the 39% fraction of the new cars and light trucks sold in the United States in model year 2002.

Table 2. Pareto Analysis Survey Results

Survey Results	Pareto Analysis
Copper Fiber	> 76.04 – < 86.68 %
Copper Powder	> 2.38 – < 13.85 %
Copper Alloys/Compounds	> 0.00 – < 5.30 %

[5] For more information on Pareto Analysis, see http://www.isixsigma.com/tt/pareto/.

V. Material Selection Process

The results of the Pareto Analysis indicate that the large percentage of copper used in brake pads is in the form of copper fiber and copper powder. Wear debris generated from pads containing only copper fiber and only copper powder could be combined in the proportions obtained from the analysis to comprise the representative sample. Thus two car sets of materials containing copper fibers and one set containing copper powder were chosen.

The following were the steps taken to select the actual brake pads used in a manner that masked the identity of the actual brake pad product and its manufacturer.

1. The form of copper was determined using the vehicle/pad manufacturer's data from the copper monitoring study. Each manufacturer then prepared brake pads using the formula/compound used on that particular vehicle application but in the appropriate size and shape (FMSI # 7620-D752) required to generate wear debris by the BMC on the Link dynamometer, and submitted the parts to the BMC.

2. The BMC chose the one sample containing copper powder and two other samples containing copper fiber at random from those remaining. The three samples represented three different friction material manufacturers.

3. The three brake pad samples were labeled Material A, Material B, and Material C. The BMC retained a record of the copper content and form for each individual sample pad. This information may be disclosed only at the discretion of the BMC.

4. The permanently labeled materials were sent to the Link Testing Laboratories, Inc. for the generation of BPWD on a brake dynamometer according to the Wear Debris Generation and Collection Protocol[6] (The Protocol) previously developed by the BMC.

VI. Generation of Representative Sample

At Link, the three material samples were run in succession on a brake dynamometer to generate wear debris per The Protocol. Each material was run for a period of time proportional to the mass of the friction material and the sales penetration on vehicles in 2002. The mass of the friction material per vehicle times the number of vehicles sold for each of the three applications resulted in the total mass of friction material for each of Materials A, B, and C. These values were used to calculate the percentage of run time on the dynamometer or 26.4, 14.1, and 59.5 %, respectively. Based on a 24 hour run time and a budget of six days, actual run times were 38, 20.3 and 85.7 hours for Material A, B and C, respectively.

Each friction material exhibits a unique wear rate. After the first day of wear debris collection, the wear rate was calculated for each of the three materials. Material B exhibited the highest wear rate and Material C the lowest (See Table 3). The actual wear rates were used to confirm that sufficient BPWD could be collected in the budgeted six day generation run time. This

[6] J. Trainor, T. Duncan, and R. Mangan, Disc Brake Wear Debris Generation and Collection, 2002-01-2595, SAE Technical Paper Series, SAE International, Warrendale, PA, 2002.

allowed the planned physical and chemical characterization work to be completed by the Clemson University team directed by Mark Schlautman.

Upon completion of the successive wear debris generation runs for the three pads per The Protocol, all the wear debris was recovered from the dynamometer enclosure according to the procedures specified in The Protocol. Airborne wear debris was captured in three separate filters (one for each material A, B, C). Fallout wear debris was collected only at the end of all runs, generating a combined sample of non-airborne wear debris. Pad and rotor weight loss were analyzed on each material after the test to determine the total mass balance as shown in Table 3.

VII. Results

Data collected from the generation of BPWD is limited to the mass balance as reported in Table 3. Additional detailed information can be found in the Link test report (See Appendix B). The generation of a representative sample was intended to provide wear debris for use in physical and chemical characterization. For comparative purposes, it is understood within the industry that typically two to 4.5 volume percent of copper is utilized in this type of friction material[7]. This statement is confirmed in the literature. For example, Blau[8] cites the use of three percent copper fiber by volume in experimental friction material pad formulations.

[7] Private Communication.

8 P. J. Blau, Compositions, Functions and Testing of Friction Brake Materials and Their Additives, Oak Ridge National Laboratory, ORNTL/TM-2001/64, August 2001, p.16. See **http://www.ornl.gov/~webworks/cppr/y2001/rpt/112956.pdf**

VIII. Discussion: Strengths and Limitations

The BPP specifically set out to develop a BPWD sample that is representative with respect to (1) the types of driving conditions under which BPWD is produced in the San Francisco Bay Area, and (2) copper-containing brake pads. Given the constraints of time, resources, and what is feasible, however, there are uncertainties and caveats that should be taken into account in drawing any conclusions from tests performed on the sample. These include:

- **Sample type limitation**. The sample includes only OEM brake pads—i.e., brake pads used on cars and light trucks, and not aftermarket brake pads, or materials used on heavy-duty trucks, off-road vehicles, or motorcycles. It includes only brake pad materials, and not drum brake linings, which do not contain copper.

- **Sample size limitation**. The sample is drawn from a list of 20 of the top 25 selling vehicles for model year 2002, which comprises 39% of the new cars and light trucks sold in the United States for that model year. Not all of these 20 vehicles have copper-containing brake pads.

- **Copper forms**. The sample includes three copper-containing formulations, for which BPWD was generated for periods of time reflecting the relative market-share of the copper-containing brake pads in the top 25 selling vehicles for which data were available. Although these pads were selected based on the types of copper used, their wear properties are not necessarily similar to the range of formulations they are intended to represent. This difference may have resulted in the over- or under-generation of BPWD relative to on-road conditions, or potentially a shift in the particle size distributions measured.

- **National sample**. The sample is drawn from the top selling vehicles nationally, and scaled by type of copper using national sales data. It is not tailored to the 2002 vehicle fleet mix in the Bay Area. It is not anticipated, however, that if it were possible to use data on the Bay Area vehicle fleet mix that there would be a significant change in the selection and apportionment of the sample.

- **Laboratory vs. on-road driving**. The BPWD generation was completed utilizing a laboratory dynamometer based on actual data from vehicle testing. Although the dynamometer was programmed to simulate on-road driving conditions, there are inherent differences in the laboratory and on-road conditions. For example, the partitioning of the wear debris to the air, apparatus, and floor in the laboratory is not affected by the bumps and road shocks that likely influence the initial partitioning of BPWD in the environment.

- **Laboratory collection limitations**. The BPWD generation and collection protocol is designed to collect particulate brake pad wear material. It is important to recognize that the BPWD includes debris from both the pad and the rotor. In addition, it does not include any gaseous byproducts. In addition, the material was generated in a dynamometer laboratory in which other brake materials were being tested at the same time. It is possible that the laboratory environment unknowingly introduced contaminating BPWD into the representative sample. It is not known how these factors might affect the characterization results, including the aerodynamic particle size diameter and the total copper analyses.

- **Scaling of pads' run times with copper types to market share**. Although there were a number of ways to design the procedure for collecting the BPWD from the dynamometer, the proportional run time scenario was the most economical method. This method maximized the run time per material without cleaning the test chamber between the three materials. Therefore, the wear debris was obtained based on the mass of friction material per vehicle, the sales penetration, and the wear rates of Materials A, B, and C. It is anticipated that other weighting methods would have resulted in BPWD with similar characteristics.

- **Material preparation**. Material preparation, such as scorching, can affect the wear of a brake pad. The pads used in this test were all prepared by the manufacturers as they normally prepare their products for delivery. It is not known to what extent differences in preparation and surface treatments may have affected the amount of BPWD generated by the three pads used in the representative sample.

- **Actual sales data, copper content, and copper types.** The sample development process used here is based on manufacturers' reporting of the actual copper content of their products, the types of copper used, and actual sales figures for each model year. These data were collected and made available by the BMC-PEC in a manner that protects manufacturers' confidential business information, including the copper content of friction materials on specific new vehicles and the name of the manufacturer that supplies the friction materials. As such, this information was developed based on the most comprehensive and reliable data available regarding the copper content of automotive friction materials in the United States. This information was developed voluntarily by the BMC-PEC as a part of its members' participation in the Brake Pad Partnership, and would not be collected and made publicly available without the Partnership's cooperative approach.

- **Rotors.** Malibu rotors available from GE dealerships were used for collection of the wear debris on the dynamometer. They are damped cast iron G125SP-1 (G274M) which specifies the Cu content as 0.30% max. Since the friction materials tested are generally kind to the rotor, the amount of Cu coming from the rotor is negligible.

Table 3. Link BPWD Generation Data

	Initial Weight (g)	Final Weight (g)	Mass Loss (g)
Material A			
Inboard Pad	384.9	380.3	4.6
Outboard Pad	340.7	336.1	4.6
Rotor	6330.7	6329.0	1.7
Material B			
Inboard Pad	325.1	317.8	7.3
Outboard Pad	358.4	351.3	7.1
Rotor	6329	6325.7	3.3
Material C			
Inboard Pad	389.7	387.2	2.5
Outboard Pad	338.3	335.3	3.0
Rotor	6376.9	6376.0	0.9
Total Rotor/Pad Loss (g)			**35.0**

	Initial Weight (g)	Final Weight (g)	Mass Gain (g)
Material A Tray	80.2	80.6	0.4
Material B Tray	26.3	27.0	0.7
Material C Tray	26	26.1	0.1
High Flow Filter	180.1	202.6	22.5
Wash Down	1162.0	1165.0	3.0
Sample Transition Tray	26.2	29.8	3.6
Total Component Gain (g)			**30.3**
Recovery %			**86.6**

Comments

The mass balance values in the Link report are incorrect (see Appendix B). Due to a weighing error by the third party analytical laboratory used by Link, the mass of wear debris obtained from the wash down of the high flow filter was recorded incorrectly as 18.4 g instead of 3.0 g. This value is listed correctly in Table 3. The total mass of BPWD was 30.3 g.

Actual test conditions and stop data are listed in Appendix B. The fallout directly to the ground was very minimal, most was either swept away as airborne particles or was attached to the rim, caliper, and knuckle. The sample transition tray (cumulative) collected debris fallout from the fixture as the sample was being changed on the dynamometer. All collected material, four tin foil trays, one bag containing six high volume filters, and a jar with wash down extract, were sent to Clemson University care of Mark Schlautman.

IX. Summary

This report presents the Brake Manufacturers Council's (BMC) methodology for generating a representative sample of brake pad wear debris (BPWD) with respect to copper for use by the Brake Pad Partnership (BPP) in characterizing the physical and chemical characteristics of the resultant material. This data will be used by the BPP in a set of interlinked technical studies designed to understand the potential role of copper from BPWD on the short- and long-term concentrations of copper in the San Francisco Bay.

The methodology was developed with technical input and analysis from the Brake Manufacturers Council-Product Environmental Committee (BMC-PEC) in close consultation with the BPP Steering Committee. The sample development process is based on actual 2002 model year data presented voluntarily by the BMC-PEC for OEM brake pad friction materials used on cars and light trucks. The data does not include friction materials used on heavy-duty trucks, off-road vehicles, or motorcycles.

The three materials used in this study represent approximately 39% of the new car and light trucks sold in the United States in model year 2002. The representative sample of wear debris was collected from the three materials on the basis of the chemical form of copper, the mass of friction material per vehicle, the sales penetration on vehicles in 2002, and the unique wear rate of each material. The BPWD was collected using a reproducible and practical dynamometer-based procedure for generating and collecting disc brake wear debris.

The data supplied by the BMC-PEC is the most comprehensive and reliable data available regarding the copper content of automotive friction materials in the United States and would not be collected and made public without the Partnership's cooperative approach.

X. Contacts

Link Testing Laboratories, Inc.
13840 Elmira Avenue
Detroit Mi, 48227-3017
Phone 313.933.4900
www.linkeng.com

Brake Manufacturers Council
10 Laboratory Dr.
Research Triangle, NC 27709
www.brakecouncil.org
Society of Automotive Engineers (SAE)
400 Commonwealth Drive Warrendale, PA 15096-0001 USA
www.sae.org

Professor Mark Schlautman, Ph.D.
Environmental Chemistry; Soil & Water Quality
Department of Environmental Toxicology
Clemson Institute of Environmental Toxicology
509 Westinghouse Rd.
PO Box 709
Pendleton, SC 29670

XI. Appendices

A. The Disc Brake Wear Debris Generation and Collection (SAE Document 2002-01-2595) abstract is as follows:
This paper describes a reproducible and practical dynamometer-based procedure for generating and collecting disc brake wear debris. The procedure is intended to provide friction material producers, brake system suppliers and other interested researchers a standardized protocol for generating and collecting brake wear debris. A standardized procedure for generating and collecting wear debris is the starting point for characterizing a disc brake material and assessing its impact on the environment.

The paper can be purchased at www.sae.org using the following link:
http://www.sae.org/servlets/productDetail?PROD_TYP=PAPER&PROD_CD=2002-01-2595

B. Brake Dynamometer Test Report, Link/D99079A1, December 1, 2004. The report can be found on the Sustainable Conservation website using the following link:
http://www.suscon.org/brakepad/documents.asp